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Title:
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An Unsupervised Method for Characterising the Operation of Bulk Handling Conveyor Belt Systems In-Service

Owen Freeman Gebler

A dissertation submitted to the University of Bristol in accordance with the requirements for award of the degree of Engineering Doctorate in Systems in the Faculty of Engineering.

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Abstract

Conveyor belt systems (CBS) are a fundamental class of asset throughout bulk handling industries, which provide materials transfer functionality within processes spanning all stages of a material's life, from initial extraction through to end-of-life disposal or reuse. The generic function a CBS affords can result in a single system being used in a diverse range of applications throughout its service life, including exposure to different materials, environments and throughputs. However, regardless of the specific application a CBS will be expected to realise very high levels of availability, such that the occurrence of costly process downtime is minimised.

To support the realisation of such levels of availability, increasingly across industry continuous monitoring (CM) of systems is being implemented, to provide greater insight into the operation of systems. Development within the area of CM has historically been driven by the needs of high value industries such as aerospace and renewables, thus, it cannot be assumed that existing solutions represent the most appropriate form of CM for CBS applications. Furthermore, the interrogation of raw CM parameters requires effort and expertise from practitioners in order to elicit actionable insights, which cannot be assumed available across operations.

Accordingly, this thesis reports the development of a practical method for observing the operation of a CBS in-service, using continuous monitoring techniques. Initially, current practice and challenges faced by industrial practitioners are investigated through interactions with a manufacturer and an operator of bulk handling CBSs. From these interactions an opportunity to realise improvements across the design, operation and maintenance of CBSs through the adoption of CM is established. Next, through a series of laboratory and industrial trials a range of CBS parameters are investigated and evaluated within the context of continuous monitoring, from which motor electrical power consumption (MEPC) is identified as most appropriate given the specific characteristics of bulk handling applications. Finally, a data processing method for translating raw MEPC parameters into actionable insights is developed, comprising the production of three data descriptors, each of which provides a quantification of a specific aspect of CBS operation, related to its usage or health. Finally, the application and potential utility therein of the method is demonstrated through further industrial trials.

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Author's Declaration

"I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author."

SIGNED .... DATE ....

List of Publications

Listed here are the publications that have been produce over the course of the research presented in this thesis:

O. Freeman Gebler, B. Hicks, A. Harrison, M. Barker, and P. Stirling, '*Towards the Implementation of a Predictive Maintenance Strategy*: *Lessons Learned from a Case Study within a Waste Processing Plant*', in European Conference of the Prognostics and Health Management Society 2016, 2016, pp. 1–17.

O. Freeman Gebler, B. Hicks, A. Harrison, and M. Barker, '*Investigating the Diagnostic Capabilities of Monitored System Parameters to Support Improvements in Conveyor Operation and Maintenance*', in First World Congress on Condition Monitoring, 2017.

O. Freeman Gebler, B. Hicks, A. Harrison, and M. Barker, '*On the Feasibility of Inferring the Applied Mechanical Loading of a Conveyor System Test Rig from Monitored System Parameters*', in 30th Conference on Condition Monitoring and Diagnostic Engineering Management, 2017, pp. 1–13.

O. Freeman Gebler, B. Hicks, J. Yon, and M. Barker, '*Characterising Conveyor Belt System Usage from Drive Motor Power Consumption and Rotational Speed*: *A Feasibility Study*', in European Conference of the Prognostics and Health Management Society 2018, 2018, vol. 4, pp. 1–16.

O. Freeman Gebler, B. Hicks, J. Yon, '*Characterising the response of motor electrical power consumption to changes in the operation of a bulk handling conveyor belt system*', (*In review*).

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List of Abbreviations

AE	acoustic emission
AN	audible noise
CBS	conveyor belt system
CBM	Condition-based maintenance
CCTs	Conveyor Characterisation Tests
CdM	condition monitoring
CEMA	Conveyor Equipment Manufacturers Association
CER	Conveyor Emulation Rig
CM	continuous monitoring
CMS	continuous monitoring system
COTS	commercial off-the-shelf
CSCR	capacitor-start-capacitor-run
CS	capacitor-start
CWT	continuous wavelet transform
DAQ	data acquisition
DoL	direct-on-line
DWT	discrete wavelet transform
FMEA	failure mode and effect analysis
FMSA	failure mode and symptoms analysis
FFT	fast Fourier transform
FUP	functional usage profile
HMI	human-machine interface
HUMS	health and usage monitoring system
IVHM	integrated vehicle health management
MEPC	motor electrical power consumption
MEMS	microelectromechanical systems

MTBF	mean time between failure
MBT	mechanical and biological treatment
NDT	non-destructive testing
OEE	overall equipment effectiveness
OEM	original equipment manufacturer
OLM	operational loads monitoring
PdM	predictive maintenance
PHM	prognostics and health management
PM	preventative maintenance
PPM	planned preventative maintenance
RCM	reliability-centred maintenance
RM	reactive maintenance
RPM	revolutions per minute
RTD	resistance temperature device
SCADA	supervisory control and data acquisition
SHM	structural health monitoring
WM	waste management

Chapter 1: **Introduction**

Worldwide, the mass movement of commodities is fundamental to the functioning of today's society. Raw materials are transported from their extraction point to processing plants, foodstuffs are transported from fields to factories and goods are transported from manufacturing plants to retailers and ultimately consumers.

Such handling of individual items or bulk materials underpins many major global industries, enabling the functioning of supply chains throughout industries such as logistics, consumer goods and pharmaceuticals. Whilst historically such mass movement of materials was achieved through manual handling methods, driven by demands from operators for increased throughput, efficiency and safety such methods have been superseded by modern materials handling equipment.

Across industry a wide range of mechanical conveying systems have been developed to satisfy the volumetric demands of operators such as chain conveyors, screw conveyors or pneumatic (capsule) systems. Whilst a wide array of solutions exist, in situations requiring a regular flow of materials from one location to another conveyor belt systems (CBSs) typically find employment. These systems use some form of moving flexible belt to carry material along their length, in doing so conveying it over that distance, with a general-use system comprising the basic form depicted in Figure 1.1.

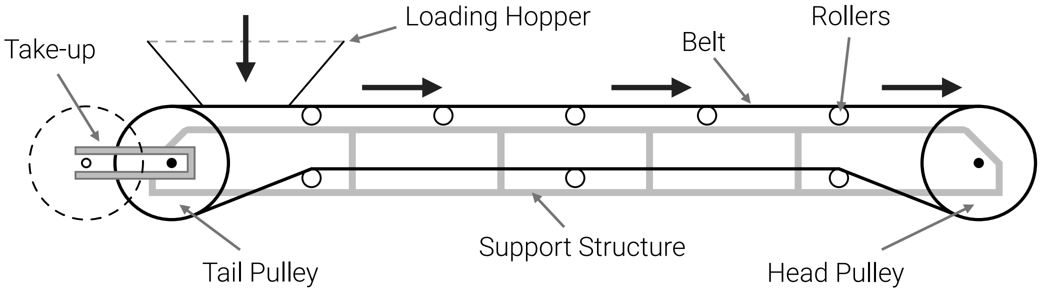

Figure 1.1: Anatomy of a typical single drive conveyor belt system.

In many materials handling industries CBSs have become the de facto solution for moving materials at volume, with more than 2.5 million systems estimated to be operating worldwide [1]. A 3-4% cumulative annual growth rate (CAGR) has been estimated for the global conveyor market between 2014-2020 [2], with the Conveyor Equipment Manufacturers Association

(CEMA) estimating that shipments of systems in 2018 in North America alone totalled nearly $18billion [3], highlighting the prosperity of the industry.

Applications of CBSs can broadly be split into two categories, *unitized handling* and *bulk handling*, based upon the properties of the materials conveyed. In *unitized handling* conveyed material is formed of individual elements which largely move independently of each other, such as palletized goods, whereas in bulk handling conveyed material is loose in form and consists of many particles or granules of different sizes randomly grouped together to form a bulk. Common examples of bulk materials include soil and cement [4]. As such, a unitized load represents a discrete flow of material, whereas a bulk load will tend to represent a more continuous flow. The inherent differences in the characteristics of unitized and bulk loads are reflected in the form of CBSs used for each application as well as their operation, as summarised in Table 1.1.

Table 1.1: Typical characteristics of unit and bulk handling conveyor belt systems.

Characteristic	Class	
	Unit handling	Bulk handling
Example load	Parcels, baggage, pallets	Ores, rubble, waste
Product type	Discrete	Loose
Purpose	Distribution/sorting	General processing/relocation
Location	Indoors	Indoors or outdoors
Environment	Well controlled	Aggressive and varied
Length	1-5m	3m-1km
Speed	Medium to fast	Slow to medium
Supervision	Typically unsupervised	Varies
Loading	Manual	Manual/machinery

Unitized loads are present in a wide range of applications such as food and beverage production, logistics and distribution, and baggage handling. Loads can be inherently unitized in nature (e.g. parcels or baggage) or individual items can be transformed into unitized form via a number of different methods, such as palletisation. Doing so provides a number of advantages to operators, including higher volumetric throughput due to easier handling, better containment of product and reduced damage due to increased protection. As such, unitization of products is common when transporting fast-moving consumer goods (e.g. food products or toiletries) and consumer electronics (e.g. televisions), helping to minimise lost product.

CBSs are frequently selected to move unitized loads across industry within manufacturing or distribution processes. Within food and beverage and pharmaceutical manufacturing plants CBSs are able to provide both horizontal and vertical conveyance of product at high volumes with minimal damage in a cost-effective manner, supporting tasks such as transporting raw materials into and from storage vessels, moving product along production lines and sorting finished product for packaging purposes [5], [6]. Minimising potential for product contamination is critical in these industries to satisfy relevant health and safety legislation. As such, they have pioneered the development of new conveyor technologies such as stainless steel and plastic slatted belts, which are able to more easily realise required levels of cleanliness throughout operation.

In logistics, fully automated conveyor systems enable inbound shipments, both land and air, to be processed and sorted into outbound stations at levels far beyond those achievable via manual means. For example, UPS's air hub in Cologne, Germany, has capacity for sorting up to 190,00 shipments per hour thanks to the utilisation of one such automated sorting system (ASS) [7], enabling the demands of e-commerce to be satisfied, despite the boom in volumes observed in recent years [8]. Similarly, modern baggage handling systems rely on CBSs to satisfy the throughput demands of airlines due to their ease of installation and flexibility [9], with the airport sector predicted to be the largest and fastest-growing sector for CBSs by 2025, driven by expansion within Asia-Pacific markets [10]. Small-scale systems at check-in desks enable the efficient loading of baggage of various form factors whilst simultaneously weighing each item. Larger systems provide the means to integrate different continuous streams of baggage from check-in through the core of the airport to the appropriate aircraft and, finally, carousel-type systems enable the reclaiming of baggage at the aircraft's destination.

Applications of CBSs for the transport of bulk materials are similarly extensive, with producers and processors of materials such as aggregates, paper, metals and cereals all heavily utilising systems for mass transport. Within the mining sector CBSs are increasingly replacing mobile haulage equipment for the transport of material from the point of extraction to processing facilities, due to their lower operating cost and ability to operate continuously [11]. For example, the mining operator Vale has estimated that the replacement of over 100 haulage trucks by 37km of CBSs at its S11D iron ore project in Brazil has realised a reduction in diesel fuel consumption and annual CO_2 emissions of as much as 77% [12]. Such applications employ the longest and largest systems in existence, with single spans over 10km common, as well as belt speeds greater than $5ms^{-1}$.

Similarly, construction firms are often favouring CBSs over manual methods for the removal of waste material from sites, to realise improvements in performance, costs and safety [13]. By removing manual transport of materials on site increased rates of material extraction can be realised due to uninterrupted operation, expenditure on wages is reduced and the exposure of workers to potential hazards is minimised. One manufacturer estimates that cost reductions of as much as 90% are potentially realisable through the replacement of manual labourers with a single CBS [14]. CBSs also provide the primary means for transporting household waste within waste processing plants, where typically a complex network of CBSs will be employed to move residual waste between various sorting and separation processes prior to disposal or reuse.

Common to all bulk handling applications of CBSs is an emphasis on material containment. In contrast to unitized loads, bulk materials possess an inherent tendency to both escape the confines of a belt[1], as well as to build-up in certain locations, such as transfer points. In addition, bulk materials are often more damaging to systems, through both mechanical impacts and wear, as well as through ingress of material, particularly into sliding contact areas, leading to premature wear and/or blockages. Such characteristics are reflected in the design of systems for bulk handling applications, where an emphasis is placed on robustness of systems. Features such as wider, troughed belts as well as steel-reinforced belts are innovations developed to support required levels of system reliability [15]. In contrast, much of the focus of innovation and design in relation to systems for unitized applications has been on supporting technologies rather than CBSs themselves, due to an absence of issues related to the act of conveying. For example, recent developments include systems for tracking individual units as they're handled, using various wireless communication-based technologies and the automated handling of units at the input and output of systems. These innovations are seeking to realise improvements in throughput whilst minimising loss of units [9].

However, whilst design of unitized loads systems has seen significant investment in recent years driven by the boom in e-commerce (AKA the 'Amazon effect' [16]), to date bulk handling systems have seen far less investment. As a consequence of tighter operating margins and

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[1] Conveyed material which leaves the confines of a system unintentionally is referred to as fugitive.

minimal capex resulting from falling commodities prices, the design of bulk handling CBSs has remained relatively unchanged over the past decades.

1.1 Operational Environments

Fundamentally, the purpose of a CBS is to provide a continuous flow of material between operations [15]. The generic function afforded by a CBS can result in a single system being used in a diverse range of applications throughout its service life, as operators respond to changing requirements by repurposing equipment. This includes the transport of different materials, each of which will typically be aggressive in nature, as well as a wide range of harsh operating environments, spanning extremes in parameters such as temperature, humidity and utilisation.

In many applications an individual CBS will operate as an element within an overall sequential process, with each CBS thus representing a single-point-of-failure. Designing redundancy into a process through parallel configuration of systems can mitigate this risk, but typically incurs financial cost and increased complexity. Physical constraints may also make parallel installations unfeasible, particularly in applications such as subsurface mining and complex construction work, where spatial constraints are common. Consequently, parallelisation is not widely practiced and many CBSs exist within a single flow line.

Whilst the value of an overall process is clearly significant to an operator, each CBS will typically represent little intrinsic value due to its simple construction. Instead, a CBS derives value through its ability to facilitate value-generating processes; for example, a mining company's revenue is generated primarily through the sale of material not its transport; a construction firm creates infrastructure not materials removal; and a waste management operator treats raw waste to permit its disposal.

Accordingly, CBS operations often constitute low-value-high-volume scenarios, in which multiple nominally identical systems are operated simultaneously within an overall sequential process. Such characteristics are in contrast to many industrial processes which comprise either the operation of a small number of high value critical systems (low-volume-high-value e.g. power plant generators) or multiple high-value systems of nominally identical form operating in parallel, where the failure of an individual system doesn't directly affect the operation of others (high-volume-high-value parallel e.g. aircraft, wind turbines).

1.2 Effectiveness of Systems

Given the demands placed upon CBSs and their criticality in supporting overarching processes, maximising the effectiveness of each system (and the ability to quantify it therein) is of primary interest to operators. A common industrial measure used to assess the effectiveness of a process is its overall equipment effectiveness (OEE), which describes how well a system is operating compared to its theoretical maximum. OEE is typically calculated based upon some combination of availability, quality and performance metrics i.e.:

$$OEE = Availability \cdot Performance \cdot Quality$$

Here, *availability* describes the ratio between the time when a system is able to operate and when it is not, *performance* describes the ratio between the actual output of a system compared to its designed output and *quality* describes the ratio of acceptable to defective goods produced by the process [17]. Within the context of CBS operation each of these metrics has a different significance to operators:

- **Availability**
  CBSs are commonly required to operate near perpetually and, with each individual system typically representing a single point of failure within an overall process, near constant availability is therefore crucial.

- **Performance**
  The operation of a CBS is essentially binary; they are either able to operate or they are not - typically no further gradation of performance exists. Whilst in some applications a degree of consideration for efficiency of operation will be made (e.g. energy consumption), essentially as long as a system is operable an operator will generally be satisfied.

- ***Quality***
  The operation of a CBS should fundamentally have no impact upon the state of the material being conveyed, therefore, assessment of quality has little relevance in this context. Again, a system is either operable or it is not.

Accordingly, it can be asserted that the effectiveness of a CBS can most suitably be assessed through its realised availability alone. System availability is the inverse of system downtime - that is, the time when a system is not able to operate - therefore, to maximise availability system downtime must be minimised. Broadly, periods of downtime can be split into two categories: planned and unplanned, with unplanned downtime typically more impactful to operators due to its unscheduled nature. The cost of unplanned process downtime varies significantly between industries and applications, with determining an accurate quantification of its cost a challenge in itself. However, it has been suggested that lost production within an open-pit mine can be as high as ~$300k/hr [18]. Consequently, availability demands on systems are stringent; operators need to have confidence that systems are going to be operational when demanded, thus minimising the potential for costly unplanned process downtime.

Over the past decades, CBSs across applications have demonstrated very high levels of reliability, however, as with any mechanical asset, a CBS is not immune to issues. Inevitably at some point in its service life a system's ability to satisfy availability demands will be compromised, the consequences of which can be significant, ranging from missed flights [19] to nationwide power outages [20].

1.3 Challenges Faced

While operators demand high availability, across industry they are facing a number of challenges in realising targets, placing greater strain on systems as well as the personnel responsible for operating and maintaining their function.

In many bulk handling industries budgets are tightening and external pressures are increasing. Globally, the rising cost of energy is forcing operators to place greater emphasis on the efficiency of systems to support increases in profitability [5], [21]. The value of commodities has typically fallen, forcing operators within the mining industry to find ways of mining at lower cost [22]. Furthermore, the cost of labour continues to increase, driving down profits further. For example, over the period from 2007-2017 the average salary of a construction worker in the UK was estimated by the Office of National Statistics to increase from ~£500 to ~£600 per week, finishing 2017 as the second-highest earning sector in the UK [23]. Inevitably, such increased costs are going to impact upon the level of investment made by operators in supporting resources, such as maintenance personnel and spares.

Whilst demands on systems continue to rise, a marked reduction in funding available to operators has occurred in many industries. Within the UK waste management industry local authorities have seen as much as 40% of funding cut since 2010, with similar cuts expected over the period from 2014 to 2019, forcing operators to seek improvements in the efficiency and performance of their waste management systems whilst simultaneously reducing costs [24]. All the while levels of waste for disposal continue to rise year on year and ever more stringent legislation such as the removal of the Climate Change Levy for Renewables [25] has further impacted upon the profitability of waste management processes.

As a consequence of such reductions in funding, investment in new infrastructure has, in many cases, been limited, creating a compounding effect in which operators are seeking to make improvements in process efficiency whilst facing the challenges associated with ageing plant.

1.4 The Advent of Data

To realise increases in profitability operators are faced with the task of extracting increased performance from existing assets [21], enabled by improvements in the design, operation and maintenance of systems. In order to realise such improvements operators must, first, understand current operations. However, at present operators have minimal ability to observe how systems are being used in-service and thus it is challenging to assess the relationship between operation and resulting performance of systems.

Such challenges are not unique to operators of CBSs, with operators throughout industry seeking to better understand how systems are being used and performing in-service. Increasingly, real-time operational data is being leveraged to address such aspirations, enabled by advancements in supporting technologies such as the ‘Industrial Internet of Things’ and ‘Industry 4.0’. Together, these technologies have made the continuous acquisition, transmission, processing and storage of component-level parameters such as temperature and vibration both technically and economically feasible to wider industry, allowing operational data to be transformed into information, knowledge and ultimately wisdom [26]. More than 8 billion devices were estimated to already be connected to the Industrial Internet in 2017 [27], with forecasts predicting its worth in the US alone to be over $151bn by 2020 [28], indicating its increasing importance to industry. With the technical and financial barriers to the continuous collection of operational data largely removed, opportunities to apply continuous monitoring approaches to CBSs have become a realistic proposition.

Often, continuous monitoring of systems is adopted to enable the implementation of condition monitoring techniques. As defined by BS ISO 13372 the condition monitoring of a system comprises "the continuous acquisition and processing of information and data that indicate the state of that system over time" [29]. Accordingly, continuous monitoring can permit operators increased observability of system operation in-service, enabling any changes in usage and performance to be identified and responded to. Operational patterns can be adjusted to extract maximum life from systems, maintenance decisions can be supported by actual performance observations and, longer-term, system designs can be updated to mitigate for observed issues.

By gaining continuous insight into the state of engines during flight, aircraft operators are realising reductions in time consumed by in-service maintenance operations, in doing so supporting reductions in 'time on the ground' to satisfy regulator targets [30][2]. Operators within the offshore wind sector are exploiting in-service data to enable inspection intervals to be increased, thus reducing costly on-site operations [32], enabling the current trend for larger turbines in remoter locations to be offset [33]. Similarly within the nuclear industry where the conducting of inspections directly impacts upon the operability of plant, the utilisation of operational data can enable physical inspection intervals to be increased as well as giving foresight of impending maintenance requirements [34]. Such information is essential to nuclear operators; process dynamics dictate that plants cannot be instantly shutdown, so advance warning of issues can support significant improvements in maintenance planning. The advent of in-service operational data can also bring cohesion to distributed systems such as rail networks, enabling operators to realise efficiency gains through improved communication [35]–[37].

To date, the development of continuous monitoring techniques has primarily been driven by the needs of the aerospace sector, where initial assumptions were that the high cost of failures associated with the low-volume-high-value assets operated within the industry could extract the most value from the technology [38]. Given the safety-related constraints of the industry, increased understanding of system condition in-service offers an opportunity for operators to demonstrate airworthiness within more cost-effective maintenance regimes.

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[2] Flight 2050: Europe's Vision for Aviation [30] has specified a number of targets that directly relate to a reduction in time-on-the-ground. It has been suggested that these targets create an "overwhelming necessity for IVHM [31]."

As of today, continuous monitoring technologies have seen little application to the operation of CBSs, restricted by a number of factors [39]:

- **Access to state-of-the-art**
  Historically materials handling industries have not been engaged with the latest advances in technology, resulting in a somewhat 'agricultural' approach being employed. Conversely, technology developers have neglected these industries in favour of higher-profile industries such as aerospace and automotive.

- **Operational constraints**
  High availability demands mean there is little opportunity for new technology implementation, particularly if implementation may disrupt day-to-day operations.

- **Financial viability**
  Despite facilitating overall processes of high value, conveyor assets within bulk handling industries are themselves relatively low in value. As a result, the implementation of a continuous monitoring solution, which may require both hardware and software requisitions, can be prohibitively expensive. Direct costs associated with maintenance actions are generally relatively insignificant, therefore unless the introduction of new technology can demonstrate a clear return-on-investment resulting from improvements in process availability/throughput, demonstrating a viable financial proposal can be challenging.

- **Technical suitability**
  Assets are operated intensely and in harsh environments, therefore the technology must be able to withstand this abuse, as well as account for the wide range of use-cases potentially experienced by a single asset.

Historically the conveyor market has been seen by manufacturers as a 'race to the bottom', with each competing to produce the cheapest and most durable systems [40]. CBSs are typically seen by operators as a 'necessary evil' and a drain on resources, with each seeking to keep expenditure on systems to an absolute minimum as a result [41]. Accordingly, little innovation within the design and operation of systems has been observed in recent years, with only incremental refinements of mature designs observed, such as improvements in material containment and idler losses, for example [15].

Given the nature of the challenges faced by operators of CBSs, the adoption of continuous monitoring principles has potential to support operators in the pursuit of availability improvements. However, given the unique characteristics of CBS operation it cannot be assumed that continuous monitoring techniques developed in other industries are directly transferrable or even feasible here. Accordingly, this thesis seeks to assess the potential affordances of continuous monitoring technologies to operators and manufacturers of bulk handling conveyor belt systems, within the context of supporting improvements in the design, operation and maintenance of systems.

1.5 Structure of Thesis

This thesis represents the compilation of a number of distinct research activities, all of which are united by the common theme of continuous monitoring of bulk handling conveyor belt systems operation. Through completion of these activities this work first seeks to understand current practice and the challenges associated with the design, operation, and maintenance of bulk handling conveyor belt systems. Based upon these challenges the potential affordances of continuous monitoring in this context are examined and ultimately an appropriate implementation of continuous monitoring for bulk handling applications is developed and trialled, based upon the specific requirements of such applications.

Together, these research activities are structured within this thesis as follows:

Chapter 2: *The Design and Operation of Conveyor Belt Systems*

First, existing practice in the design and operation of CBSs is assessed to enable a greater understanding of what is currently implemented by manufacturers and operators, as well as the challenges they face in satisfying operational demands. Through this analysis, a reliance upon visual inspection methods for the assessment of systems is identified as a limitation of existing practices, both in-service as well as in the design of systems.

Chapter 3: *The Maintenance of Conveyor Belt Systems*

Next, through analysis of literature historical and state-of-the-art maintenance practices implemented throughout industry are explored. To better understand current practice within bulk handling applications specifically a series of interviews are conducted with members of the maintenance team at one of the Operator’s plants. Overall, existing practice is found to be based around reactive approaches, supplemented by some preventative actions. Based upon the characteristics of CBSs and the bulk handling industries it is concluded that predictive approaches to the maintenance of CBSs are not feasible to implement, nor necessarily appropriate.

Chapter 4: *The Principles and Practice of Continuous Monitoring*

In Chapter 4 an overview of the general concept of continuous monitoring is provided, as well as a summary of its current application to CBSs as described within extant literature, both academic and industrial. Additionally, the findings from an industrial system monitoring trial are reported, as conducted at one of the Operator's plants.

Chapter 5: *Aim & Methodology*

Based upon the challenges facing manufacturers and operators of system identified within Chapters 2, 3 and 4, Chapter 5 defines four research questions to be addressed in this thesis. In particular, it is proposed that by incorporating continuous monitoring technologies into existing maintenance practices objective data can be used to supplement existing visual inspection approaches to the assessment of systems. Subsequently, a methodology combining aspects of experimental and analytical work is defined.

Chapter 6: *Evaluation of Monitored CBS Parameters – Experimental Design*

Within even a relatively simple system such as a CBS a wide range of potential physical parameters can feasibly be monitored. Each parameter has a different associated cost to acquire as well as value in terms of the utility of the insight they permit. Accordingly, Chapter 6 describes the design of a laboratory-based test rig used to assess the characteristics of a range of feasibly monitorable system parameters, such that the sensitivity of each to changes in system operation can be evaluated.

Chapter 7: *Evaluation of Monitored CBS Parameters – Results & Findings*

This chapter describes the testing procedure implemented on the constructed laboratory-based test rig, and provides an overview of the data acquired, leading to an evaluation of each parameter's suitability within the context of monitoring CBS operation. From this evaluation, motor electrical power consumption (MEPC) parameters are identified as the most suitable to monitor in bulk handling CBS applications.

Chapter 8: *Characterisation of Conveyor Belt System Operation – Experimental Design*

Whilst operation of the laboratory-based test rig enabled the rough characteristics of monitored parameters to be evaluated, given the abstracted form of the rig compared to an industrial system the sensitivity of parameters to actual changes in system operation is unknown. Therefore, Chapter 8 describes a body of testing conducted to characterise the operation of an industrial CBS, during which the sensitivity of MEPC parameters to changes in system operation and the occurrence of faults is evaluated.

Chapter 9: *Characterisation of Conveyor Belt System Operation – Results & Findings*

This chapter presents the findings from completion of the Conveyor Characterisation Tests (CCTs) described in Chapter 8. Overall, MEPC parameters are seen to present a good degree of sensitivity to changes in system operation and the occurrence of specific faults across scenarios, providing insight into both the health and usage of the subject system.

Chapter 10: *The Development of Data Descriptors for Characterising CBS Operation*

During Chapter 8, relationships are identified between changes in the operation of a CBS and the response of MEPC parameters. However, in order to elicit and leverage these relationships raw data must be interrogated, requiring manual effort from suitably experienced personnel. As identified in Chapters 2, 3 and 4, industrial practitioners typically have minimal spare capacity and/or expertise to conduct such analysis in-service, therefore, in Chapter 10 a method for automating the data interrogation processes is developed, comprising the generation of three data descriptors. Descriptors provide a simplified and abstracted view of MEPC parameters, providing actionable insight to personnel, as a supplement to existing visual inspection methods.

Chapter 11: *An Application of the Proposed Data Descriptors*

Following on from the development of data descriptors as presented within Chapter 10, in this chapter the completion of a short body of industrial testing is presented, through which a typical application of the proposed data descriptors is illustrated, and their potential utility assessed. Tests served to enable the evaluation of two aspects: firstly, the degree to which the observations of CBS operation made during completion of CCTs (Chapters 8 and 9) extend beyond that specific CBS and secondly, the insight which can be obtained from the application of the proposed data descriptors to a generic CBS.

Chapter 12: *Discussion*

This chapter provides a discussion of the implications of the conducted research in the broader context of the research questions defined in Chapter 5. In addition, the potential industrial implications of the research findings are considered, and the steps required to enable industrial implementation at scale are reflected on.

Chapter 13: *Conclusions and Further Work*

Finally, the thesis is concluded with a summary of the research conducted and the key findings that can be drawn from its completion, as well as an overview of how the research could further be developed in the future.

1.6 Industrial Engagement

From its inception this research has been supported by Stirling Dynamics, a specialist engineering consultancy operating primarily within the aerospace industry, where it provides expertise within the areas of system simulation, modelling and control.

The Company has targeted a diversification of the markets within which it operates to support expansion of revenue streams, enabled by the development of technical capabilities within areas novel to the Company. In this vein, the field of condition monitoring, and specifically its application to the operation of conveyor belt systems, was identified by the Company as an area in which the development of a technical capability could support such a market diversification. As such, this research project was initiated as a partnership between Stirling Dynamics and the University of Bristol to explore the state-of-the-art in condition monitoring and assess its applicability to conveyor belt systems within the bulk handling industries.

Furthermore, throughout this research project, engagement with industry has been supported through direct interactions with both a manufacturer and an operator of bulk handling industry conveyor belt systems, enabling the requirements/needs of different industrial stakeholders to be better understood, as well as affording access to industrial installations.

N.b. through this thesis reference will be made to each industrial partner as either 'the Manufacturer' or 'the Operator' respectively.

1.6.1 The Manufacturer

The Manufacturer is a small-to-medium enterprise (SME) that designs, manufactures and supplies a range of conveyor belt systems to various industries, primarily within the UK. The company is responsible for the complete provision of all systems within the ranges offered, from design, through manufacturing and delivery, to subsequent maintenance.

The majority of systems produced by the Manufacturer are reflective of the form of a Basic CBS, as described in Chapter 2, however, a number of more specialist forms are offered where operator requirements demand. Across the product range, belt widths from 0.3-1.5m are possible, along with lengths between 1-10m.

Figure 1.2: Examples of CBSs produced by the Manufacturer (images courtosy of the Manufacturer).

The primary market for the Manufacturer is the general construction industry, with additional significant volumes within the waste processing and water treatment industries. The majority of the Manufacturer's revenue is obtained through the leasing of systems, wherein systems are temporarily installed at an operator's site for only a finite duration, after which they are returned to the company. Some permanent installations are also delivered, however, this represents a small proportion of overall systems.

The demands of operators within the construction industry can be relatively volatile, with conveyor requirements often changing on a daily basis, in response to external factors such as the weather conditions and emergent process issues. To ensure the Manufacturer is able to service such demands they have developed a very dynamic approach to the provision of systems. This includes implementing a modular approach to the design of systems as well as ensuring a large quantity of stock is held in perpetuity, which together enable them to provide a guaranteed next day delivery service to customers across the majority of the range.

1.6.2 The Operator

The Operator runs four mechanical and biological treatment (MBT) plants throughout the UK, processing residual municipal solid waste (MSW), AKA 'black bag' waste. An MBT process comprises a number of pre-treatment technologies which contribute to the diversion of MSW from landfill when operated as part of a wider integrated approach involving additional treatment stages. As such, the MBT process compliments, but does not replace, other waste management technologies such as recycling and composting as part of an integrated waste management system [42].

Each plant comprises a series of CBSs which are used to transfer waste sequentially between various subprocesses within the overall MBT process, such as eddy current separation to remove non-ferrous metals and optical separation to remove specific types of plastics. The Operator's plants range in size from the smallest processing ~60k tonnes per annum to the largest processing ~190k tonnes per annum. Typically, each plant is operated on a nominal schedule of 6.5 days uptime followed by 0.5 days planned downtime.

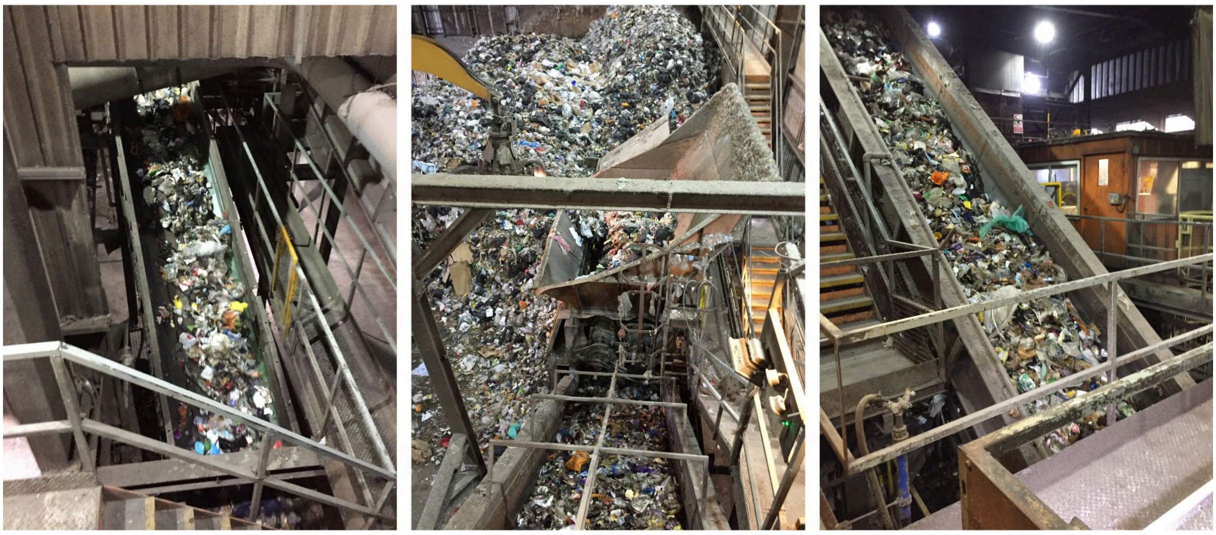

Figure 1.3: CBSs in operation within a waste processing facility, illustrating the diverse nature of municipal solid waste.

Due to the diverse nature of the MSW processed at plants the environment within each is considered extremely aggressive, with significant fluctuation between extremes in temperature and humidity common. Plants are operated under the supervision of teams of plant technicians who are responsible for controlling the overall process and addressing any flow-related issues, such as product build-up. Each plant technician is typically responsible for managing the operation of around 15 CBSs. To address more serious issues which may adversely affect CBSs a dedicated team of maintenance personnel are also located at each plant.

Chapter 2: The Design and Operation of Conveyor Belt Systems

As identified in Chapter 1 system availability is the critical measure for assessing the performance of bulk handling conveyor belt systems (CBSs). In this context, availability is used to describe the ability of a system to be in a state to perform as and when required, under given conditions, assuming the necessary external resources are provided [43]. Accordingly, availability can be described as an engineering function while utilisation is a production function, that is, a system can have high availability without necessarily being highly utilised. It is the responsibility of the engineering team to ensure that periods of system downtime are not dictated by system availability. Broadly, the availability of a system is dictated by three factors: its design, its operation and its maintenance i.e.:

- **Design**
  The possible uptime of an asset can be limited by its design. This can be due to technical limitations e.g. material wear rates, or commercial limitations e.g. mandatory OEM stipulations to retain warranties.
- **Operation**
  The manner in which an asset is used will affect the level of downtime incurred, such as the level of loading experienced, operating procedures adhered to, materials conveyed etc.
- **Maintenance**
  The effectiveness of an asset's maintenance actions will affect its availability, both in terms of how much downtime is incurred due to the occurrence of breakdowns (unplanned), as well as the downtime required to correct or prevent further downtime (planned).

In this chapter current practice in the design and operation of bulk handling conveyor belt systems is explored through the examination of extant literature, both industrial and academic, and the reporting of a series of conducted industrial trials.

2.1 Design

Across manufacturers the design of conveyor belt systems (CBS) has converged to a near identical form. In its simplest form a CBS consists of a flexible loop of material (belt) passing over two (or more) rotating drums, known as pulleys, supported on a series of smaller rollers (idlers) between the pulleys. In the most common configuration one pulley (head) will be driven directly by an electric motor via a reduction gearbox, whilst the second pulley (tail) will be only passively driven (Figure 2.1). A CBS designed for generic use will be constructed from commercial off the shelf (COTS) parts where possible, including bearings and drive elements, helping to minimise the cost of production as well as improving maintainability.

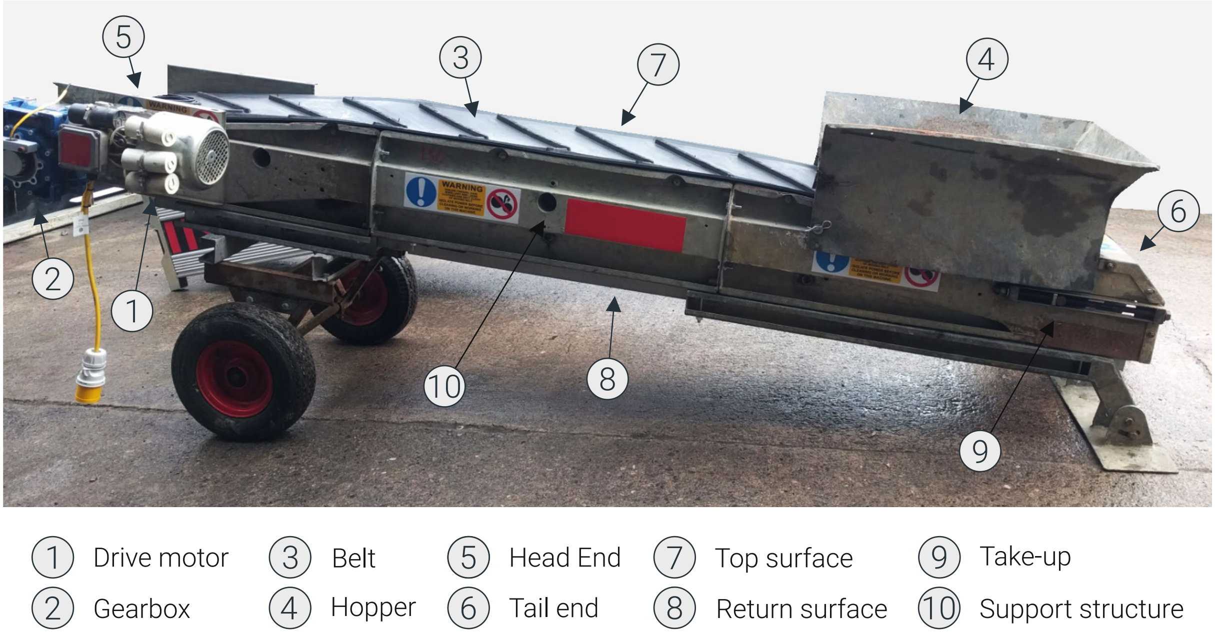

Figure 2.1: The anatomy of a Basic conveyor belt system.

In general, all materials handling industries can be considered to have a common top-level requirement (i.e. provide a continuous flow of materials) and thus demand on their conveyor systems. However, differences across industries such as specific materials conveyed, operational environments, and legislative and safety constraints are reflected in variances in the specific form of CBS most commonly employed within each industry. As such, for certain applications more specialist forms of systems do exist, such as pipe conveyors or air-supported conveyors. These systems are typically employed where environmental protection is of concern, both in terms of keeping conveyed material contaminant free as well as preventing it from contaminating its surroundings, or where extremely high throughput is demanded. However, for the majority of applications a design of the simple form described will be employed [21].

The scale of systems also varies significantly across applications, ranging from the multi-kilometre long, metres wide systems found in certain mining applications, to centimetre wide systems employed on construction sites where access is challenging. Systems can also be designed for fixed installation or mobile, able to be relocated 'on the fly' as the needs of an operator change, for example, in underground mines where systems will be relocated as the specific point of extraction moves [44].

While it is acknowledged that a wide array of specific configurations of CBS exist[3], the subject of this research concerns the Basic class of conveyor belt systems as defined by the Conveyor Equipment Manufacturers Association (CEMA), which describes systems having the following properties [15]:

- *A single flight of less than 800ft (~244m) in length.*
- *A single free-flowing load point.*
- *Inclined or horizontal but without curves.*
- *A belt with a fabric carcass.*
- *Flat or equal roll troughing idlers.*
- *A single drive.*
- *Unidirectional or reversing up to 500fpm* (~$2.5ms^{1}$).
- *A single gravity or fixed take-up.*
- *A maximum belt tension of 12000lbf (~16270Nm).*

In addition, a Basic system will typically have a belt width of between 0.3-1m moving at a linear speed of ~1-3ms^{-1}, permitting a throughput of roughly 20-100 tonnes/hour, dependent upon the characteristics of the specific bulk material being conveyed.

N.b. Throughout this thesis the term *CBS* is used specifically in reference to a conveyor belt system of Basic form, operating in a bulk handling application.

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[3] See [45] for an overview of less common CBS configurations.

2.1.1 CBS Components

A Basic CBS is constructed from five primary elements: a drive unit to provide power, a belt to support conveyed material, a series of rollers and pulleys to both transmit power to and support the belt, and a support structure. In this section an overview of the design and function of each element is provided.

Drive Unit

Invariably, a conveyor belt system will be driven by an electric motor, providing the power required to move the belt and any loaded material. In the vast majority of systems an induction motor will be employed, primarily due to their ability to realise high reliability even when subjected to continuous duty, whilst their robustness to harsh environments and low cost further increase their appropriateness for CBS applications [46]. As indicated by its name, an induction motor utilises the principles of electromagnetic induction to provide a means for converting energy between electrical and kinetic forms. An induction motor is comprised of two primary elements, a stator and rotor, the interaction between which enables the production of torque at the motor output shaft. In operation the stator remains stationary whilst the rotor rotates within it, supported on rolling elements bearings. As the two components are physically separated by an air-gap minimal wear between mating surfaces occurs in operation, enabling an induction motor to operate continuously without issue.

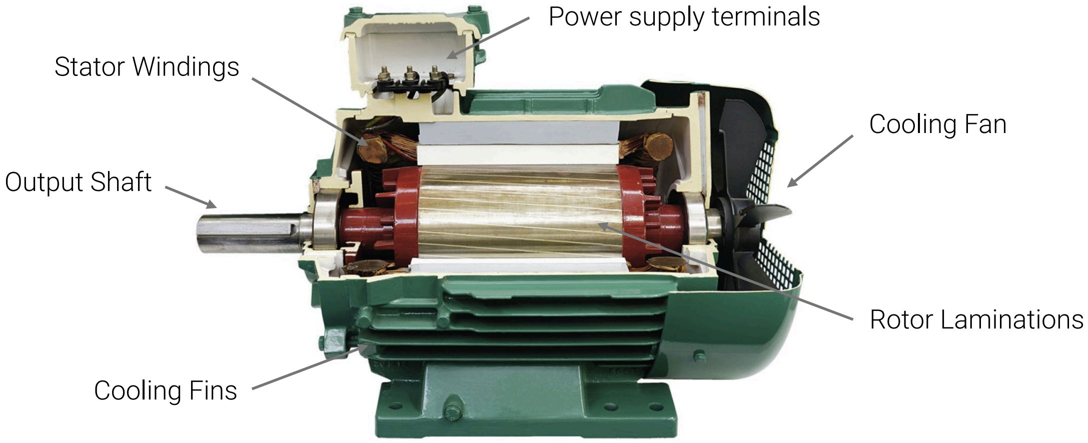

Figure 2.2: Cutaway diagram of a TEFC induction motor, showing the major components (adapted from [47]).

The typical nominal power of a drive motor ranges from 1-20kW for light duty systems, up to over 1MW for large scale systems such as those used in overland transport within the mining industry [4]. Most commonly systems are configured with a single drive unit, located at the head end where material is discharged, as in a Basic system. To provide the additional power required to move heavy-duty systems additional intermediary drive units can be used, located at intervals along the belt length, known as centre or mid drive units [48]. Drive units are mostly either directly coupled to a pulley via a flexible coupling or indirectly via a chain drive[4].

To protect drive units from the environments in which they operate a totally enclosed, fan cooled (TEFC) design is typically specified, in which the motor's core is physically isolated from the external environment, preventing the circulation of environmental air inside the motor. In order to provide sufficient cooling to the motor whilst it operates a fan is rigidly coupled to the non-drive end of the motor shaft, circulating air through the rotor-stator air gap to generate forced convection (Figure 2.2).

Drive units can be powered via a single or multiple phase configuration, with the choice typically dictated by the available electrical supply; for fixed installations three phase power supplies are commonly available and so three phase motors will be used due to their greater efficiency. However, in many mobile installations only a single-phase supply will be available, possibly from a portable generator, necessitating the use of a single-phase motor. In such situations a capacitor-start-capacitor-run (CSCR)[5] induction motor is commonly selected, offering improved efficiency over alternative configurations such as the simpler capacitor start (CS) or shaded pole configuration. The operation of a CSCR (or CS) motor is based upon the principle of using capacitors to create an artificial second electrical phase from a single-phase supply to generate an electrical field which rotates electrically at the supply frequency, enabling motors to be self-starting.

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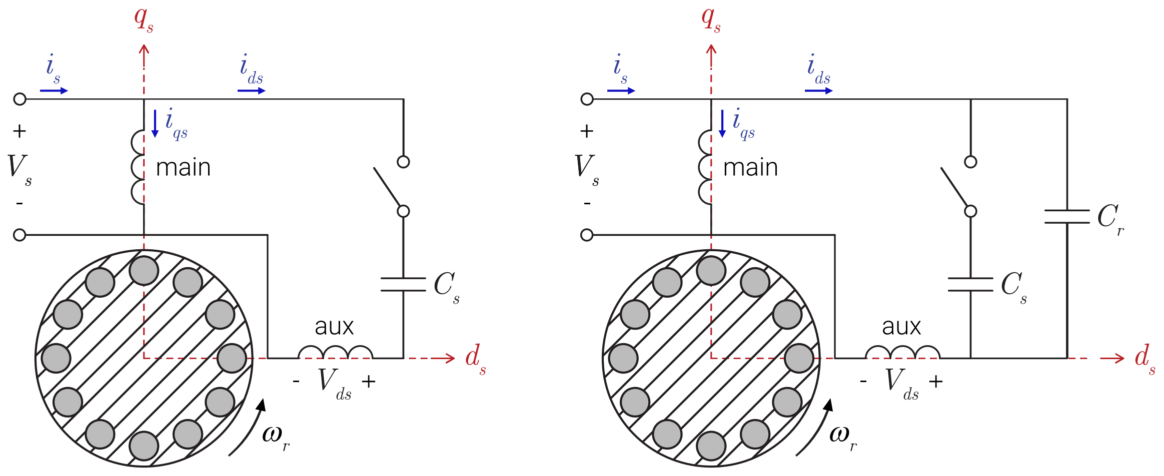
[4] Again, further variants exist such as fluid couplings, however, these represent uncommon use cases beyond the scope of a Basic system.

[5] Also sometimes referred to as a *two value* motor.



Capacitor-start

Capacitor-start-capacitor-run

Figure 2.3: Electrical configuration of a capacitor-start (CS) and capacitor-start-capacitor-run (CSCR) motor.

Typically, CBSs are powered via fixed frequency supplies (as provided via mains power or portable generators) causing motors to run at a constant[6] speed under steady state operation[7]. However, increasingly variable frequency drives (VFD) are being adopted as the means of driving CBSs, permitting variable speed operation as well as increasing power efficiency. Historically, due to the cost of VFDs their use was restricted to systems where variable speed was essential, however, in recent decades the cost of VFD technologies has fallen dramatically, making their utilisation viable in most applications. For small-to-medium scale systems powered via a fixed frequency supply predominantly a direct-on-line (DoL) connection will be used to start a motor, in which full line voltage is applied to the stator windings immediately upon starting. When a DoL connection is used to start a motor from standstill the initial current drawn by the motor can be as high as 10 or 20 times the motor's rated current [49], potentially causing damage to the motor. Therefore, it is common for systems to employ some form of soft-starting device to limit the current drawn by the motor as it ramps up to operating speed.

To provide a more appropriate combination of power and speed to a belt typically the motor output is coupled to a reduction gearbox. Gearboxes can utilise a worm drive, spur gear or bevel

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[6] Given the load/slip characteristics of an induction motor the exact operating speed will vary with load, however, under steady state conditions the speed will remain approximately constant.

[7] The synchronous (i.e. zero slip) speed of an induction motor is dictated by the motor's construction and the supply frequency.

gear configuration in an inline or right-angled arrangement and are both lubricated and passively cooled via a wet sump arrangement.

Belts

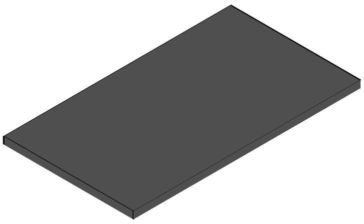
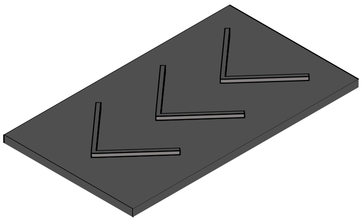
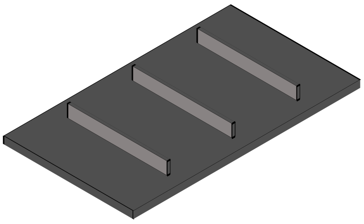
A system's belt is typically considered its most critical component and represents a significant proportion of the capital cost of a system [4], [15]. Fundamentally, a belt provides the means for turning the rotational motion of a drive motor into linear movement and thus enables the conveyance of material. Whilst single material belts do find use in certain applications, in most cases a modern belt will constitute a composite construction, consisting of a carcass or core component, laminated between layers of a covering component. Here, the core serves to support the tensile forces applied to the belt by the driving action of the head pulley as well as by the impact of material loaded onto the belt, while the cover provides protection to the core, reducing damage caused by conveyed material [4].

The carcass of a belt is produced from interwoven longitudinal (warp) and transverse (weft) cords of flexible material to provide the necessary tensile strength to transmit power whilst retaining flexibility [50]. The choice of fibre is dependent upon the tensile strength required, as dictated by each application; in light-duty systems (typically up to 10m in length) the carcass will normally be some form of synthetic fibre such as polyester, whereas for more heavy-duty applications a steel fibre may be employed. Layers of a natural or synthetic rubber compound (e.g. PVC) are then used to cover the carcass, not only adding protection but also increasing surface friction to aid material conveyance.

To transform two-dimensional belting material into a three-dimensional continuous loop two ends must be brought together and joined, for which two primary techniques exist: mechanical splicing and vulcanisation. In mechanical splicing the two free ends of the belting material are butted either side of a flexible steel hinge to which they are then mechanically fastened. In vulcanising the two free ends are overlapped and a vulcanising press is used to apply appropriate heat and pressure such that the ends fuse. Between the two techniques mechanical splicing is significantly cheaper and faster to complete, however, at the cost of strength and durability [15].

As illustrated in Table 2.1, a variety of carrying surface patterns exist, ranging from smooth belts to cleated or paddled belts, the latter of which can be used to increase system capacity and/or enable conveying up steeper inclines. In addition, the transverse profile of the belt can be flat or troughed to increase capacity and reduce material spillage.

Table 2.1: Overview of common belt surfaces and their associated characteristics.

Belt type	Description	Usage	
Plain	No surface pattern.	Employed in horizontally operated systems.	
Chevron	V-shaped longitudinal pattern, with cross-sectional area of approx. 10x10mm.	Employed in systems operated up to 20° incline.	
Cleated	Transverse sections, with cross-sectional area of approx. 50x8mm.	Employed for systems inclined greater than 20°.	

Pulleys and Rollers

At either end of a system a pulley will be located to allow the belt to bend around from the top carrying surface to the bottom (or return) side [13]. In a single drive unit system one pulley will be directly driven (referred to as the head pulley) and one will be passive (referred to as the tail pulley), with the belt driven in a direction such that the top surface is pulled towards the head pulley. Pulleys are typically constructed from a hollow steel drum of ~0.3-0.5m diameter, rigidly mounted to a solid steel shaft, supported by a rolling element bearing at either side which act to support radial and axial loads whilst minimising torsional load. The outer surface of each pulley is typically coated in some form of rubber compound to improve friction between the pulley and belt and thus minimise transmission losses through slippage.

In between the end pulleys a series of rollers are commonly located at intervals, used to support the mass of the belt and conveyed material as it moves along the length of the conveyor. Rollers are of similar construction to pulleys but with a smaller diameter (~50-100mm) and without any external lagging.

Support Structure

The support structure provides a means to locate the pulleys and rollers and is typically constructed from extruded steel sections fastened together to produce the required span. By raising or lowering one end of the support structure the inclination of a CBS can be adjusted. Additionally, for smaller Basic systems a wheelset can be included to enable the system to be manually repositioned as required. To add tension to the belt some form of take-up device is used, which, within a Basic system, will usually be of either fixed or gravity weight form. In a fixed take-up system tension is applied to the belt by physically changing the centre distance between the head and tail pulleys, commonly via a screw mechanism, which must be manually adjusted. In a gravity weight take-up system a constant pre-tension is applied to the belt by a hanging mass, sized appropriately to permit dynamic changes in belt length of ~1-2% when operating typically [45].

2.1.2 Design Practices

To support the design of CBSs a number of resources are available, such as ISO 5048:1989[8] and the Conveyor Equipment Manufacturers' Association's Belt Conveyors for Bulk Materials, which provide technical guidance for design choices based upon compiled industrial experience. As with all standardisation conformity to such resources serves to ensure compatibility across systems where relevant, as well as compliance with relevant legislation/codes. More generally, they allow access to best practice across industry, enabling individual manufacturers to leverage experience from peers without having to acquire such knowledge directly. However, whilst industrial resources can support designers of systems their value is limited; such resources are inherently generalised and based upon assumptions of factors such as operational environments and maintenance practices, meaning the degree to which they remain valid for each specific user's instance will vary. For example, ISO 5048:1989 provides a method for calculating the driving force required to drive a system based upon its expected operational conditions, however, such approximations limit the accuracy of the method, as noted by the standard's technical committee itself *"Attention is drawn to the many varied factors which influence the driving force on the driving pulley and which make it extremely difficult to predict the power requirement*

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[8] Continuous mechanical handling equipment -- Belt conveyors with carrying idlers -- Calculation of operating power and tensile forces.

exactly... [this International Standard] is limited in terms of precision... many factors are not taken into account in the formulae" [51]. Similarly, when specifying COTS components such as bearings a number of resources are available to designers, with all major manufacturers providing life estimation tools to support bearing selection, as well as ISO 281:2007[9] [52]. However, again the models used within such tools are based upon empirical evidence and contain a number of significant assumptions which limit their accuracy in a general case. For example, the SKF Bearing Life Estimation [53] is based upon eight assumptions relating to factors such as installation, lubrication and operating conditions, all of which must be satisfied in order for an accurate life to be produced. In practice such assumptions are rarely entirely valid, and as a consequence much design practice is based upon 'best guess' approaches developed through experience and updated in a heuristic manner. Inevitably, such practices will likely result in initial designs being suboptimal. Further, even if designs are initially appropriate, with time, they may become suboptimal as the usage patterns and/or environmental conditions of a CBS change, as well as its condition, for example if a system is operated outside of its design envelope or beyond its designed life.

In order to address such issues a manufacturer can undertake a series a 'design out' activities, a process in which the design of a system is modified to prevent or minimise the occurrence of issues which have been observed in-service. As such, design out activities can be considered a form of maintenance activity; by reducing the actual occurrence of issues overall maintenance effort is reduced [54]. Whilst a heuristic approach to the design of systems can mitigate for such issues by evolving and adapting the design of the system, to conduct such interventions the manufacturer must have visibility/understanding of how systems are performing in-service in order to implement suitable design modifications. However, with CBSs typically operated remotely from manufacturers they are therefore likely to be reliant upon operators feeding back such information to trigger and inform redesign activities.

This information may not be timely, it may not be accurate, or, it may not be present at all, and is at the discretion of operators. As such, the ability of a manufacturer to both assess performance and identify issues and to make appropriate design modifications in response may be restricted. In mining, for example, it has been suggested that mine operators are becoming more aware of the importance of providing timely, accurate information to conveyor system designers and suppliers in order to ensure proper system sizing, to move away from a 'best

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[9] Rolling bearings -- Dynamic load ratings and rating life.

guess' approach as practiced presently. By relying on best guesses both the manufacturer and customer are exposed to risk, through warranty and liability concerns, unnecessary downtime and ultimately financial loss [55].

To address such limitations a shift towards more data-driven design practices has emerged across industry, in which objective, verifiable and quantitative data is used to support design decision-making processes, collected from actual systems operating 'in the field' [56]. This information can be collected continuous throughout the life of each system using various sensor technologies and compiled by the manufacturer into a historian capturing the operation of all systems, enabling baseline performance to be understood and fed into subsequent designs, or even immediate updates, where applicable [57]. For example, through its built-in Internet connectivity the Tesla Model S automobile is able to feed back data acquired via each car's sensors to the company who then utilise it to update the design of the autopilot function, which, in turn, can be 'pushed' back down to each vehicle without requiring removal from service [58]. Similarly, GE collate the data collected by each individual wind turbine into a central repository upon which fleet-wide analytics can be performed, enabling optimisation of operational variables such as blade angles, as well as feeding into the design of the next generation of system [59].

2.1.3 Industrial Practice: Case Study

Given the predominantly industry-led nature of conveyor belt systems applications little literature exists within the area of systems design. Therefore, to better understand typical CBS design practices the process followed by the Manufacturer in both designing and specifying systems for applications was captured through informal discussions.

A total of three meetings were held, two conducted at the Manufacturer's premises and one at the University of Bristol. Each meeting was attended by the major stakeholders within the Manufacturer's operations and technical teams, including the Managing Director and Head of Operations and members of the University's Design and Manufacturing Futures Laboratory.

The initial meeting served primarily as a means to introduce personnel across parties, as well as to convey the wider context of the research programme being conducted. In addition, the Manufacturer provided an overview of their business model, major markets and volumes, as well as the typical customer experience, from system specification, through assembly and on-site commissioning to collection and decommissioning back at their premises. The second meeting focused on identifying the fidelity of data currently captured by the Manufacturer during each customer installation, both prior to delivery as well as during on-site visits, leading on from which the potential affordances of continuous monitoring were discussed through the completion of a ‘brainstorming’ activity. Finally, the third meeting focused on feeding back research findings to the Manufacturer, and discussing the implications of these across the design, operation and maintenance of systems.

Whilst each meeting served a specific high-level purpose an unstructured interview approach was implemented to foster an organic elicitation of ideas, issues and requirements. Meetings were conducted at an interval of approximately 6-12months, with minutes taken during each for later review. Prior to the commencement of the initial meeting a tour was provided to University personnel to understand the process of producing a CBS to a specific specification from the on-site parts inventory, as well as the typical overhaul process applied to systems once returned to the Manufacturer by a customer.

All conveyor belt systems offered by the Manufacturer are designed and manufactured in-house, from a single premise. In general, a modular approach to the mechanical design of systems is followed, enabling systems to be physically reconfigured to different overall lengths. For each application a number of configuration options must be specified, as dictated by the requirements of each customer, and supported by a site survey conducted by the Manufacturer. Firstly, based upon the characteristics of the specific application an appropriate model is selected from the Manufacturer’s range, and an overall system length and belt width is defined. Next, the nominal power of the drive motor and the belt type are defined, based upon the expected throughput, inclination, distance to move and method of loading (manual, digger etc.), as estimated by the customer. These selections are aided by general guidelines developed by the Manufacturer, as well as the in-house experience of personnel, however, in practice the exact requirements of each customer are difficult to assess a priori, therefore, typically conservative estimates are employed to ensure a minimum level of performance can be guaranteed. For example, a wider belt with a more powerful motor will be specified to ensure anticipated peak demands can be met. As such, the specification of systems does not necessarily produce appropriately configured systems. For example, it may be that the throughput of material is significantly overestimated, resulting in an oversized motor operating at low efficiency, or, conversely if throughput is underestimated an undersized motor may be unable to satisfy requirements and/or it may incur damage due to overloading.

Once a system has been installed onto a customer site the Manufacturer has limited visibility of how it is operated beyond informal discussions with the customer. Their primary source of design feedback comes via visual inspection of returned systems, conducted on an ad-hoc basis, the outputs from which are not formally documented. As a result, the Manufacturer's design activities constitute essentially open-loop processes, in which little feedback exists to describe the relationship between system specification, operation and subsequent performance. Given the Manufacturer's business model is primarily based around the leasing of systems this lack of visibility of operation limits their ability to understand how systems are used across different applications. For example, a system delivered to a construction site for a period of 6 weeks may have been operated at high load near continuously, or, it may have sat idle and seen only minimal periodic use; once the system has been returned to the Manufacturer it requires comprehensive, resource-intensive investigation to determine the condition and thus maintenance requirements, which may not be financially viable or may not even produce accurate assessment.

2.2 Operation

Once in service a CBS has no control over its operation, instead it must respond to the demands placed upon it by the overarching process in which it operates. Whilst the primary requirement of a CBS will always be to provide the capability to move materials the conditions to which it is subjected while satisfying that demand can vary dramatically, in terms of configuration, utilisation, throughput, autonomy and environment, as summarised in Table 2.2.

Table 2.2: Common variable aspects of CBS operation.

Operational condition	Description	Examples
Configuration	The physical arrangement of a system	Inclination, belt tension
Utilisation	The frequency at which a system will be operated	Continuous, periodic
Application	The type of material a system must convey	Aggregate, refuse, soil
Throughput	The quantity of material a system must convey	Tonnes per hour
Autonomy	The degree to which a system's operation will be supervised	Continuous, periodic
Environment	The nature of the conditions within which a system must operate	Temperature, humidity

Different industries and operators can place substantially different demands upon nominally identical systems in-service, driven by both technical and commercial demands. For example, at the Operator's plants systems will typically be operated on a pattern of 24hr 6.5 days per week where possible, whereas the systems supplied by the Manufacturer have no typical pattern of utilisation, with some systems operated near continuously and others only very infrequently.

2.2.1 Operational Loading

Regardless of the specific conditions in which a system must operate, across all applications systems will be subjected to similar mechanical loads, albeit at differing magnitudes. In this context the term load describes the extent to which a part or system is exposed to external influences, such as compression, tension or shear forces [60]. Loads will be a combination of both static (time-invariant i.e. those present regardless of a system's operational state) and dynamic (time variant i.e. those generated as a consequence of a system operating) forms. Primary static loads include the weight of the system itself (*dead load*) and the tension within the belt[10] (*tension load*), in addition to a range of typically less significant static loads which can be present, such as *spillage loads* and *expansion loads* [15]. Primary dynamic loads experienced by a system are those arising from the loading and subsequent conveying of material along the belt, referred to as the *live load*. The loading of material onto a system's belt will cause a number of effects including compression of the belt through its thickness due to the impact of the material, extension of the belt along its length due to the inertia of the material's mass and braking of the drive system due to the decelerating force also resulting from the inertia of the added mass.

How a system is loaded in-service will directly relate to the life that can be realised by that asset; within a mechanical system externally applied loads such as the loading of material translate into internal loads within components such as deformation of crystal lattices, which will ultimately induce failure within a material at the molecular level [60]. Fundamentally, a failure process arises from an imbalance between the load on a system and that system's load carrying capacity. A system's load carrying capacity is defined during its design phase and so, once in service, is essentially fixed. In a typical probabilistic design approach a system will be designed such that it should be capable of withstanding expected extrema in loading without failing. In contrast, the manner in which a system is used in-service will directly dictate the form and magnitude of the loads it experiences. Whilst a system may be capable of operating indefinitely if used in a moderate manner, as the severity of usage is increased the rate at which its life is consumed will increase commensurately and failures become more likely. A vehicle driven at a constant speed over a certain distance would be expected to realise greater reliability than a vehicle driven in an alternating pattern of acceleration and deceleration over the same distance; the extreme loading caused by hard acceleration places undue stress on the vehicle, accelerating degradation processes. Within the context of a CBS a similar comparison can be made between two systems conveying the same total mass of material but with differing temporal distributions; a system in which material is loaded at a constant, moderate rate will be subjected to lower loading than a system periodically loaded with a greater quantity of material and would thus be expected to realise a greater service life. It can thus be asserted that the service life of an asset can be directly influenced by its operator. For example, by reducing typical material throughput mechanical wear in the belt can be reduced, by reducing belt speeds

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[10] In practice, the effect of the tension within a belt will produce a quasi-static load on a system due to kinetic, thermal etc. effects.

inertial forces in rotating components and thus vibration forces can be reduced minimising premature degradation, or by ensuring belts are tensioned as low as feasible rolling resistance can be reduced and with it thermal losses in the drivetrain. Persistently overloading an induction machine will cause overheating of windings and bearings, which can lead to damage and ultimately induce premature failure. Operating a machine with a service factor of 1 at 115% load for extended periods will cause a temperature increase of ~15-20°C and for every 10°C increase in general machine temperature the remaining thermal life of its insulation will typically halve [61].

Inevitably, external operational demands will constrain the degree to which the engineering team can dictate usage patterns (i.e. throughput), however, theoretically they are able to affect the severity of usage to minimise extrema in loading e.g. by ensuring conveyed material is distributed as uniformly as possible. However, in practice, implementing such principles may be challenging within an industrial environment. To do so would require personnel to understand how systems are loaded in real-time i.e. material throughput, number of start-ups, blockages etc., which relies upon an assumption that system operation is observable and observed.

2.2.2 Observation of Operation

Due to the historically high levels of reliability demonstrated by CBSs, combined with the relatively high cost of manual labour it is common for systems to be operated without continuous supervision. Instead, an individual operative(s) will often be responsible for supervising the operation of a number of systems simultaneously, identifying emergent issues and taking appropriate action in response. In this way operators are able to reduce remuneration costs without significantly impacting operation, in theory. In many bulk handling industries such practice is referred to as ‘walking the belt’ and constitutes a person(s) physically moving between systems (either walking or driving depending upon the scale of the system) and conducting a visual inspection of each in turn, typically without interrupting the operation of systems. Further, in instances where systems are portable (e.g. leased systems) maintenance personnel will be physically restricted from systems, reliant instead only upon scheduled on-site inspections or return-to-base inspections.

The specific form of a visual inspection will vary across applications, however, in the broadest sense a visual inspection constitutes the process of using the eye, alone or in conjunction with various aids, as the sensing mechanism to make judgments about the external condition of an asset to be inspected [62]. During a visual inspection of a CBS typically minor adjustments or cleaning may be performed where required, with any more serious issues noted for later attention [21]. Such problems range from simple service actions such as regreasing which can be completed in-service in short time to more involved actions such as complete belt replacement, requiring process downtime and significant personnel and material resources. Typical issues identified through walking the belt can relate to material conveyed by the system (e.g. build-up or spillage) or to issues associated with the system itself (e.g. belt damage, collapsed bearing).

Whilst a visual inspection can provide valuable insight into the state of systems their efficacy is compromised by a number of issues. Inherently, a visual inspection requires personnel to be permitted close proximity to systems, something which carries significant health and safety concerns. For example, between 2000-2007 a CBS was the most common type of machinery involved with severe accidents within the US mining industry, where it is considered industry practice to allow workers to perform duties such as the clearance of material near operating machinery [63]. Furthermore, even if access is permitted the effectiveness of inspections is limited by physical human capabilities; there is an upper limit on what can be identified with the naked eye as well as scope for errors or omissions in inspections cause by unintended human negligence. Further, even if issues can be identified a subjective decision must be made by personnel as to their significance, creating potential for inconsistency across a maintenance team. As noted by Mobley [64] *"Most of the visual inspections that are performed as part of a preventive maintenance program are ineffective. The primary reasons for this ineffectiveness is that the methods used are almost totally subjective. For example, a preventive task may read, "Check V-belt tension and correct as necessary." How should the technician check tension? Where should he or she measure? What tension levels are acceptable? Effective visual inspection must be quantifiable, and all personnel must universally apply the methods used."*

Problems can also arise from over-familiarity with systems; an operative may become conditioned to 'see what they expect to see', rather than approaching an inspection with an objective mind, leading to issues going unnoticed [21]. As a consequence, not only are operators limited in their ability to understand the impact of system usage upon system condition, issues can be exacerbated due to delays between the emergence and subsequent identification of issues.

2.2.3 Disruption to Operation

Over many decades CBSs have proven capable of very high availability across industry; the Conveyor Equipment Manufacturer's Association reports that in most applications a CBS will realise greater than 90% availability, with fewer than 2% of downtime due to unplanned stoppages [15]. Despite this, inevitably, as with any mechanical system, driven by the impact of external loading some form of issue will eventually be encountered which may compromise their operability. Understanding the typical form of such failures is of vital importance to operators, enabling appropriate actions to be planned and executed, such that downtime can be minimised. Within the context of bulk handling CBSs little publicly available data exists describing common failure modes. Furthermore, give the impact of variation between usage and environmental conditions across even similar applications it cannot necessarily be assumed that data can validly be extrapolated across applications. Therefore, an investigation into the typical failure characteristics of a CBS operating in light bulk handling applications was conducted, comprising three primary activities. Firstly, to identify the most impactful issues which can feasibly afflict a CBS (i.e. those which immediately impact the operability of a system upon occurrence) a failure mode and effect analysis (FMEA) was conducted. Next, to understand the impact of typical operation on components a sample of previously operated CBS motors were physically assessed through a series of benchtop inspections. Finally, to characterise the issues most frequently occurring within a typical industrial application an analysis of maintenance records from across the Operator's plants was completed.

As defined by BS EN IEC 60812:2018, FMEA describes a systematic method of evaluating an item or process to identify the ways in which it might potentially fail, and the effects of the mode of failure upon the performance of the item or process and on the surrounding environment and personnel [65]. An analysis of a Basic CBS was conducted from first principles with support from key literature (e.g. [17], [46]) and the output was subsequently validated through discussions with the Manufacturer. The conducted FMEA (Appendix D:) indicates that there are two primary issues which can feasibly prevent a CBS from operating; a loss of conveyancing ability due to belt loss (either as a result of damage or due to a belt tracking off its pulleys) or a loss of drive (either due to power supply issues or motor issues).

Belt failure can manifest in two ways: those which develop gradually and those which develop rapidly. A *gradual* type of failure describes the process of a belt's condition progressively degrading over time, typically due to mechanical abrasion or plastic deformation, until catastrophic failure occurs. This process can take a matter of weeks or even months dependent upon the specific mode of failure and environmental conditions. Accordingly, the progression of a gradual failure can feasibly be observed if physical indicators of degradation can be identified (e.g. changes in geometry).

In contrast, a *rapid* failure describes a scenario in which a belt is severed entirely across its width, typically through sliding contact with part of the support structure (e.g. the sharp edge of a worn idler shaft) or due to the slicing action of a conveyed foreign object. Accordingly, in a rapid failure the condition of a belt can progress from healthy to failed in a matter of seconds, making identification beforehand unfeasible ([13], [21]). As noted by Hoggan [66] *"In C&D* [construction and demolition] *applications, many of the belts fail catastrophically before wear ever becomes an issue. The wrong material hitting the belt just right results in a belt failure."*

However, whilst detecting the onset of a rapid failure before occurrence may not be possible, detection once occurred is still of potential value to an operator, ensuring systems can be brought to a stop, minimising material build-up and potential for damage to components. Given the possibility of systems operating without direct supervision personnel may only be able to infer the occurrence of a belt failure from its impact upon material flow at a point downstream, by which time damage may already have been incurred. If belt failures were able to be automatically detected personnel could enact a timelier response and implement a more controlled system shutdown.

The loss of a system's belt due to tracking off will arise if uneven tension is applied across the width of the belt and corrective action is not taken. However, the design of a CBS will always incorporate some form of belt retention system, either passive (i.e. a hard edge AKA skirting) or active (e.g. a dedicated belt alignment mechanism) to minimise the occurrence of such an event. Furthermore, it is increasingly common for systems to incorporate alignment sensing devices (e.g. limit or proximity switches) to automatically bring a system to a controlled stop before total belt loss occurs [15]. Poor tracking of a belt (e.g. running hard against an edge) is possible and common [40], which, whilst not resulting in system inoperability immediately, is still undesirable. Unnecessary contact between a belt and its support structure will increase rolling resistance causing power consumption to increase and thus running costs and can also contribute to a gradual failure mode through mechanical abrasion.

System failure due to power supply issues can be considered an event external to a CBS and instead a failure of the infrastructure around a system. However, given the remote locations in which CBS are often employed power supply quality and integrity cannot be assumed and so should be accounted for in the specification of a system.

Motors of the form employed within a CBS find widespread use throughout industry precisely due to their proven long-term reliability across diverse applications. Regardless, as with any mechanical system the potential for failure remains a possibility, with much literature reporting figures describing common modes and rates of failure for induction motors. However, the validity of such figures can be limited in practice, with much data being either outdated[11], inapplicable (relates to machines of much greater capacities e.g. >1MV generators) or trivial in nature (relates to failures seeded within a laboratory environment without solid industrial grounding). As such, the applicability of such data to induction motors employed within CBSs operating in bulk handling applications cannot be assumed.

2.2.4 Assessment of In-service CBS Motors

Given the criticality of the motor to the operation of a CBS the impact of typical industrial operation upon the condition of motors was investigated through the conduction of a series of benchtop assessments of motors provided by the Manufacturer, each of which was previously in-service. It should be noted that the purpose of conducting assessments was not to compile a statistically significant dataset describing the condition of used motors, but instead to elicit qualitative insights into the impact of typical operation on motors in a more general sense.

Three motors of a nominally identical form were tested, constituting single-phase, capacitor-start-capacitor-run configurations, with a totally enclosed fan cooled (TEFC) design and a squirrel cage rotor construction (Table 2.3).

Table 2.3: Specification of tested motors.

Parameter	Value	Parameter	Value
Rated power	2.2kW	Power factor	0.98
Operating voltage	110Vac	Duty	S1 (continuous)
Supply frequency	50Hz	Protection	IP55
Synchronous speed	1350rpm	Mounting	B14

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[11] Many authors still rely upon the figures provided in the IEEE's *'Report of large motor reliability survey of industrial and commercial installations'* published in 1985 to justify the execution of their research…

All motors provided by the Manufacturer were from systems previously in-service, and thus were considered used, however, the actual operational state of each was not understood i.e. it was not known whether each motor had been removed due to failure or whether it was considered still perfectly operational.

To assess the condition of each motor a series of identical benchtop tests were conducted on each. A general procedure was developed based upon the guidelines provided in the IEEE Std. 1415-2006: Guide for Induction Machinery Maintenance Testing and Failure Analysis [61], which would enable obvious signs of damage and deterioration to be identified. The procedure implemented consisted of static tests and a no-load test i.e. motor outputs were not connected to any load.

The primary steps within the developed procedure were as follows:

1. *Assign motor unique ID and nameplate information.*
2. *Visually assess the external condition of the motor, noting any signs of damage and general cleanliness.*
3. *Assess the rotor's freedom of rotation via manual rotation of the output shaft*
4. *Measure the earth continuity between the motor casing and earth.*
5. *Visually assess the condition of the external connection terminals, noting any signs of damage or evidence of water ingress.*
6. *Measure the inter-winding continuity.*
7. *Measure the resistance across each winding.*
8. *Perform an insulation resistance test.*
9. *Visually assess the external condition of all capacitors.*
10. *Measure the resistance of each capacitor.*
11. *Measure the capacitance of each capacitor.*
12. *Visually assess the rotor fan, noting any damaged or missing blades.*
13. *Visually assess the condition of the centrifugal switch, noting any signs of damage or corrosion, and ensure mechanism operates freely.*
14. *Assess the condition of the rotor bearings, noting any signs of damage, and rotate the rotor to assess freedom of rotation.*
15. *Visually assess the condition of the stator and rotor elements, noting any signs of damage, corrosion and general cleanliness.*
16. *Connect motor to power momentarily to verify no-load operation.*

The assessment process combined elements of visual inspection, mechanical inspection and parameter measurement. Where quantitative measurements were to be taken a simple pass/fail assessment was made based upon predefined acceptance levels. Levels were defined based upon a combination of best practice, IEEE Std. 1415-2006 recommendations and existing practices employed by the Manufacturer's maintenance personnel.

Findings

Exhaustive results from the tests conducted can be found in Appendix A:. Overall, all motors tested were found to be operable and in good condition generally, with no obvious degradation or damage identified. Induction motors of TEFC form are designed inherently for continuous operation in aggressive environments, and as such high levels of robustness and reliability are expected. However, some indicators of change in condition of specific elements within each motor were identified.

Motor M1 was found to fail an insulation resistance test, suggesting that some degree of degradation to the windings' insulation had occurred, possibly as a consequence of operating in the presence of moisture and/or contaminants [67]. In addition, an increased resistance across its capacitors was measured when compared to M2 and M3, which may affect the relative phase between the main and auxiliary windings and thus the efficiency of the motor.

The general appearance of motor M2 appeared the worse of the three, with notable corrosion present both externally on the casing and internally to the stator and rotor (Figure 2.4).

Figure 2.4: Examples of corrosion present within the centrifugal switch (l) and stator (r) of motor M2.

Some degree of resistance to rotation was identified within the rotor, likely a consequence of increased friction caused by the presence of corrosion within the start winding centrifugal switch. When manually manipulated the centrifugal switch of M2 was found to present significant resistance to movement when compared to motors M1 and M3, indicating reduced performance. However, otherwise motor M2 passed all tests.

Motor M3 also presented a notably unclean appearance, with a number of indentations identified, likely caused by external strikes to the motor casing. In addition, its start capacitor was heavily dented and run capacitor R1 appeared to have been replaced at some point. Accordingly, the start capacitor was found to fail a test of capacitance, with only 0.003μF measured in comparison to its nominal capacitance of 60μF. A significant level of corrosion had also occurred along the surface of the motor's rotor, the majority of which was noted as being located at the output end of the rotor.

Summary of Findings

Overall, the three motors were found to be in generally good condition, despite obviously having seen service, reflecting the 'bulletproof' nature of this class of motor. No issues were identified with any bearings, fans or windings across all motors. However, despite their solid, robust and reliable characteristics some potential degradation was identified within motors, even in such a limited dataset.

The occurrence of significant corrosion to components was identified. This is likely a consequence of the operational environments to which systems have been subjected. The Manufacturer places no restriction on the conditions in which a system can operate, therefore, it is common for systems to experience extremes in temperature and moisture. By way of a example, the Manufacturer reported a system found to have been partially buried into the ground in order to fit into a limited space within a construction site.

Whilst the occurrence of corrosion to motor components may not necessarily directly cause a motor to fail to operate it could feasibly cause a significant reduction in performance. For example, corrosion within a start winding centrifugal switch could cause the switch to fail to change state. Consequences of this include potentially a reduction in operating efficiency or, if failed in an open state an inability of the motor to start. The Manufacturer has little ability to prevent the occurrence of corrosion; any restrictions placed upon customers in relation to when and where systems can be operated is likely to affect their competitiveness negatively. Directly identifying the occurrence of corrosion in-service is likely to be both technically and financially infeasible, however, it may be possible to infer the presence of corrosion from secondary effects. For example, corrosion within a centrifugal switch may cause an increase in the time taken to switch state due to increased friction/stiction, which would be reflected in an increased time taken to reach operating speed, a parameter which can feasibly be monitored in-service.

Damage occurring within motor capacitors was also identified, suggesting it to be a feasible failure mode. The cause of such damage could be a multitude of events, such as a consequence of an external strike, random failure or a result of overloading. A damaged capacitor is likely to cause a reduction in motor performance and/or complete lack of operation, dependent upon the specific characteristics of the damage i.e. in which capacitor the damage occurs. The occurrence of a change in winding capacitance is likely to affect the motor's power factor, which could therefore potentially be used as a diagnostic feature to aid the identification of such damage.

Discussion with the Manufacturer revealed that regular occurrences of 'no fault found' (NFF) issues were being reported by maintenance personnel wherein a customer would report a system to have failed on-site, but once returned to the Manufacturer the failure could not be replicated. Many of the potential issues identified within the assessed motors possess characteristics which make them liable to present intermittently, such as corrosion to contacts, suggesting the Manufacturer could potentially benefit from having a greater understanding of the conditions in which systems are being operated by customers on-site.

2.2.5 Analysis of Maintenance Records

To better understand the typical nature of issues encountered within an industrial application of bulk handling CBSs an analysis of the maintenance records completed at each of the Operator's four plants during 2015 to early 2016 was conducted. The conducted analysis served to enable the assessment of three primary objectives:

1. *Which issues are most impactful across plants in terms of downtime incurred?*
2. *What actions are taken to correct the most impactful issues?*
3. *How much time is required to correct each occurrence of the most impactful issues?*

Using the presented method, a qualitative analysis of textual maintenance records is undertaken, enabling a number of key conclusions to be drawn in line with objectives I, II and III.

Data Background

At each plant operated by the Operator all actions taken by members of each maintenance team are required to be manually logged by personnel once completed. For each action a range of metadata associated with the action is recorded, as described in Table 2.4, which together comprises a single record.

The process for entering record metadata comprises the completion of a mixture of constrained and unconstrained fields. Whilst the Operator mandates that personnel report all actions completed across plants, due to the manual nature of the recording process it cannot be guaranteed that all actions completed are reported.

Table 2.4: Overview of raw metadata fields as recorded by maintenance personnel.

Name	Description	Entry Type	Notes
Job ID	A unique identifier associated with each job completed	Constrained (autogenerated)	
Timestamp	The day during which the job was conducted	Constrained (autogenerated)	No time resolution greater than day is provided
Site	The site at which the job was conducted	Constrained (selected from list)	Records cover 4 MBT plants, all of similar forms, however, there is some variability, particularly in size/throughput, with Plant A being significantly larger than the other 3.
Asset ID	A unique identifier associated with the asset being maintained	Constrained (selected from list)	
Personnel	The name of the person(s) who completed the action recorded	Unconstrained (manual text entry)	Each person enter as a separate field (max 3)
Time taken	An estimate of the time, in hours, taken to complete the action	Unconstrained (manual numeric entry)	This is provided to a resolution of 0.5hrs
Breakdown description	A description of the issue which has triggered the completion of the action described within the entry	Unconstrained (manual text entry)	
Repair description	A description of the action taken in response to the specific breakdown	Unconstrained (manual text entry)	
Parts used	A summary of new parts used during the completion of the action described within the entry	Unconstrained (manual text entry)	
Additional comments	An optional field, used to log any additional comments associated with the entry	Unconstrained (manual text entry)	Optional (at the discretion of the personnel entering the record)

A list of all maintenance records logged across all plants (hereafter referred to as A, B, C and D) during the period from January 2015 to April 2016 was provided by the Operator, comprising a total of 4484 records. The records included all maintenance actions logged, not just those associated with conveyors.

An exhaustive list of assets across plants was not provided, therefore, only those assets requiring actions during the specific period are represented within the body of records. Additionally, operational data (e.g. overall plant running status, daily throughput etc) was not provided by the Operator, meaning the impact of each action upon plant operation cannot be determined directly, nor can the relationship between plant throughput and number of actions completed be assessed. Similarly, personnel availability during the period is not known, therefore, the impact of personnel availability on the number of actions completed cannot be determined. The nature of each action, whether it be reactive or preventative, is also not explicitly stated within each record, however, it is often possible to infer this from the type of action undertaken.

Data Cleaning

In order to facilitate analysis of records a data preprocessing ('cleaning') phase was first conducted, comprising three steps. Firstly, all records were filtered by *Asset ID* such that only those records relating to conveyor belt assets[12] remained. Additionally, Plant B was found to only have a single CBS asset, with only seven maintenance records associated with it, therefore, Plant B was not included within the cleaned dataset as it was felt that its presence may unfairly skew analysis.

Next, any erroneous records, where data was incomplete, duplicate or ambiguous were removed, and any obvious typographical errors were corrected. Finally, all unconstrained text entry fields were mapped to relevant high-level categories. The purpose of this step was to enable quantitative analysis of records, by ensuring fundamentally identical actions possess consistent metadata. Accordingly, for each of the *Issue*, *Component* and *Action* fields a list of categories was defined, based upon a distillation of the information input by maintenance personnel within the raw dataset.

For example, records described as '*Tear in conveyor belt*' and '*Conveyor damaged (belt)*' within the raw dataset are not directly comparable despite both describing the same fundamental issue. Therefore, within the cleaned dataset both are assigned to the *Belt Damaged* category within the Issue field, ensuring both are counted when the number of damaged belts are totalled. The cleaned dataset output from the preprocessing comprised 463 records, with each record comprising 9 fields. An exhaustive description of the format of cleaned records and the issue, component and action categories used within the cleaned dataset is provided in Appendix B:.

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[12] In addition to records with the term *CONV* in their Asset ID field this also included records with either *DDS* (double drum separator) or *EDDY* (Eddy current separator) in their Asset ID field, as these assets incorporate dedicated conveyor belt systems.

Data Analysis

This section presents a high-level analysis of the cleaned dataset, investigating the characteristics of the various metadata fields associated with each record.

Temporal Distribution of Records

When records of all types are viewed by the month in which they occurred (Figure 2.5) a degree of seasonal variation can be observed, with significantly fewer jobs being completed during the summer months, compared to winter.

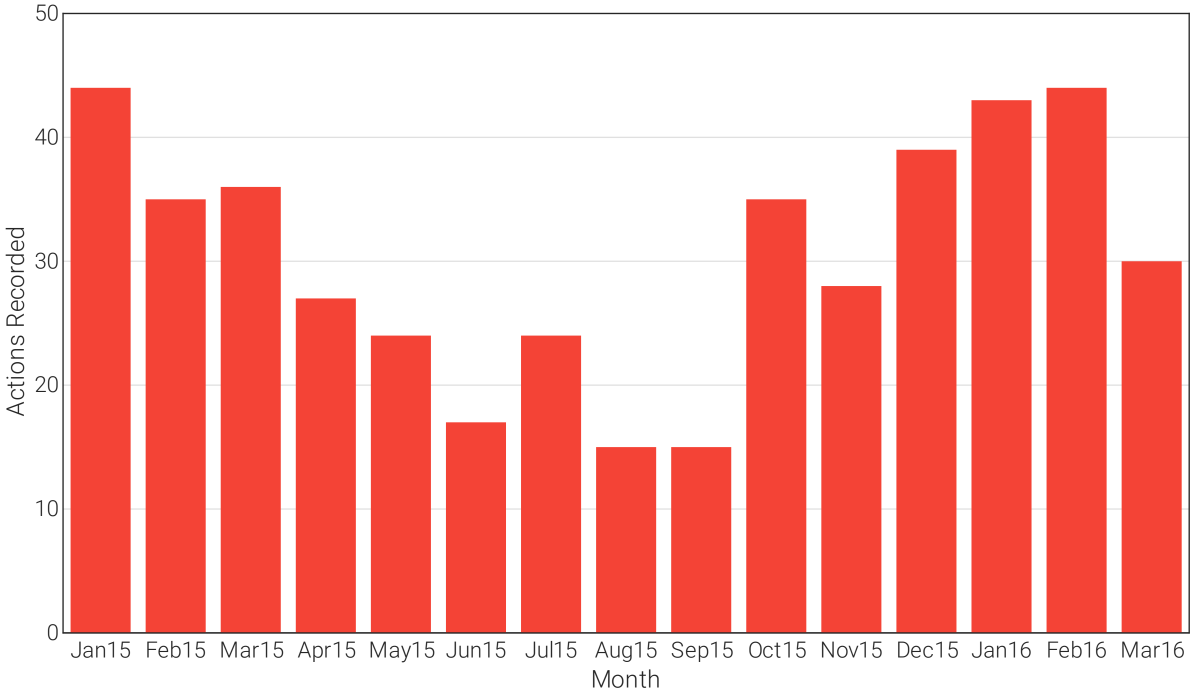

Figure 2.5: Total number of actions recorded across all plants, by month.

Such observation is likely to be a consequence of one or more factors, including:

1. **Environmental conditions**

   It can be expected that CBSs will operate more reliably in warmer, drier weather.

2. **Availability of personnel**

   Typically, more annual leave is taken during the summer months compared to the winter, reducing the resource available to complete maintenance actions.

3. **Demands of assets**

   The Operator reports that demand on plants is increased during winter months, increasing the maintenance effort required.

Geographical Distribution of Records

When the distribution of maintenance records by plant is viewed it can be seen that the majority of records relate to actions completed at plant A, reflecting its greater size, in terms of both conveyor assets and throughput.

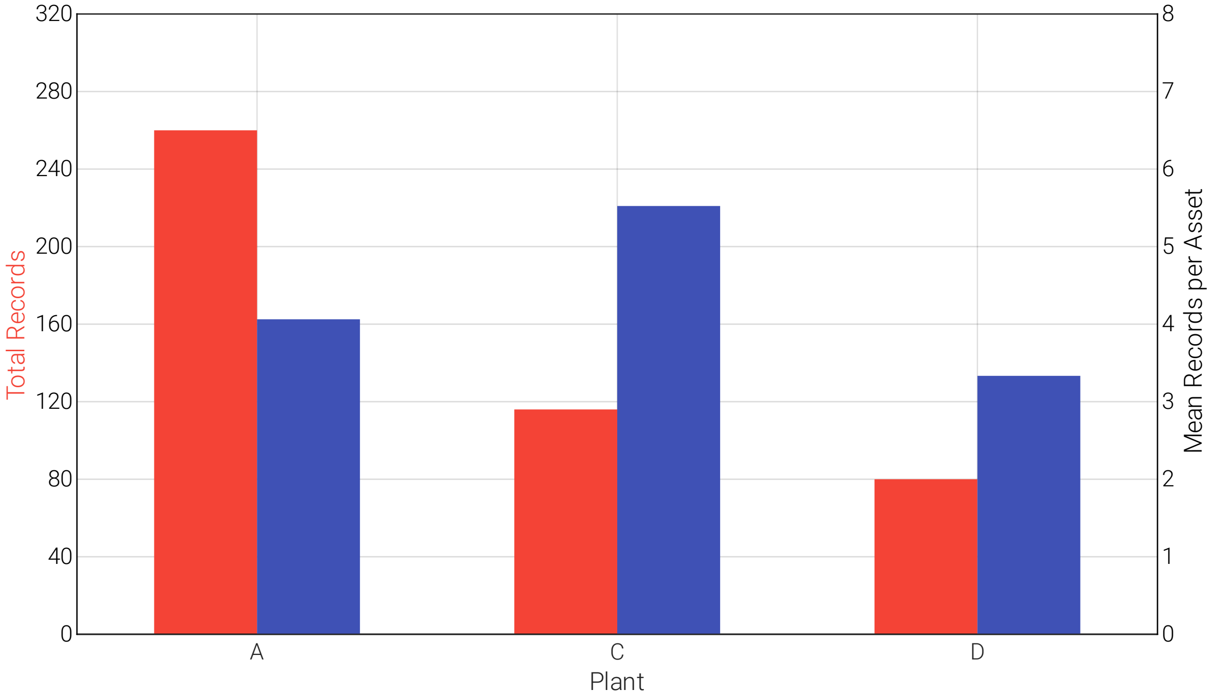

Figure 2.6: Total and per asset number of actions recorded by plant.

However, when the number of actions at each plant is normalised by the number of assets at each plant a relatively constant ratio is observed across plants, with plants A, B and C completing 4, 5.5 and 3.2 records per asset respectively. This suggests that all plants are performing similarly, in terms of the rate of actions completed.

Asset Distribution of Records

Across all assets the total time recorded against each asset indicates that actions are not uniformly distributed, and instead effort against a small number of assets represents a significant proportion of all maintenance effort (Figure 2.6).

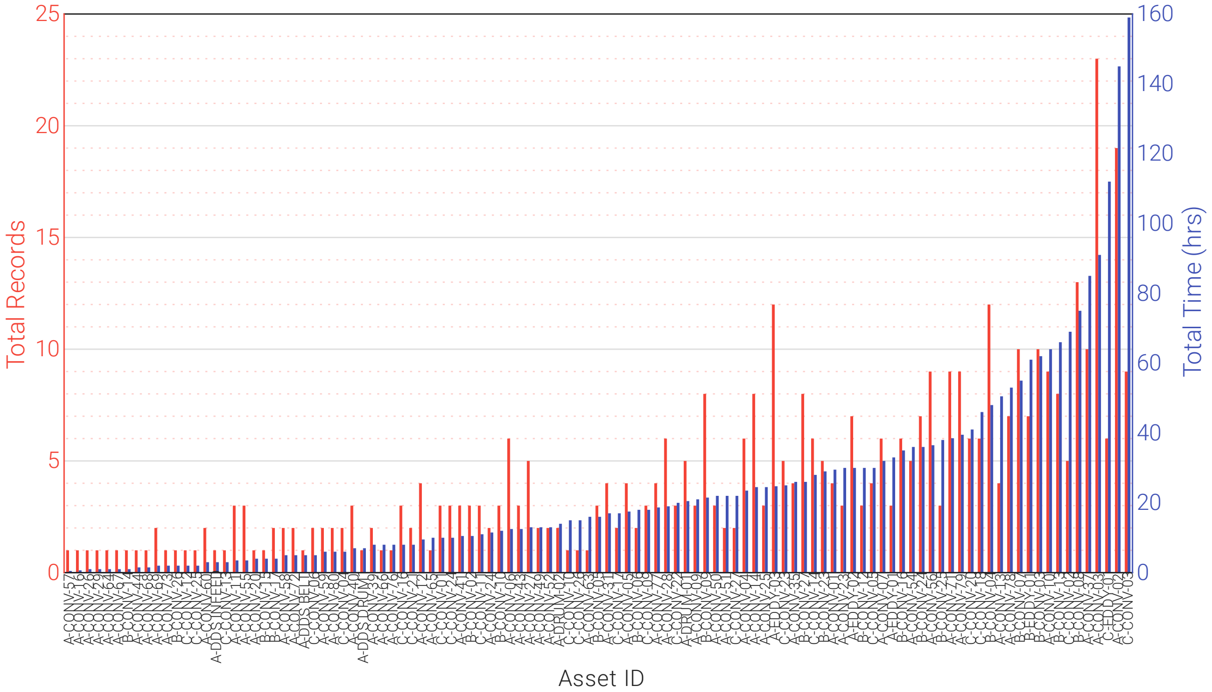

Figure 2.7: Total number of actions recorded against and time taken by asset.

Generally, the number of records comprising the total time increases accordingly, however, the top time consumer *C-CONV-*03 can be seen to comprise fewer records than may be expected, indicating its total may be skewed by a single or few large records. Records associated with *C-CONV-*03 show that the majority of time consumed against it (120 out of a total of 159 hours) was a result of a single action, in which a worn belt was replaced.

The underlying cause of such a non-uniform distribution of actions across assets could be attributed to various circumstances and to identify the exact presence of which would require further physical investigation. It may be that certain assets experience more abuse loads due to their location within the overall process (e.g. assets at early stages of process will encounter unsorted MSW which will have a more diverse constitution), driving degradation. Alternatively, it may be that certain assets are easier to inspect due to their physical location, so therefore issues are able to be identified earlier and thus have lower severity. Or, it may be that certain assets experience worse physical conditions due to their location (e.g. assets located beneath other assets may experience increased buildup of produce due to spillage) or their time in service.

Records by Issue

Analysing records by type of issue (Figure 2.8) indicates that the *Unspecified* and *Miscellaneous* categories are two of the three most time-consuming issues addressed. The nature of issues which have been categorised as either *Unspecified* or *Miscellaneous* will typically not compromise the operability of the plant i.e. a shutdown is not required. Additionally, each category can be considered a 'catch all', encompassing a range of different specific issues, resulting in the high frequencies of occurrence as observed. However, the high occurrence of actions within the *Unspecified* category suggests either the rationale for conducting these actions is not being well documented, or that well-evidenced decisions are often absent.

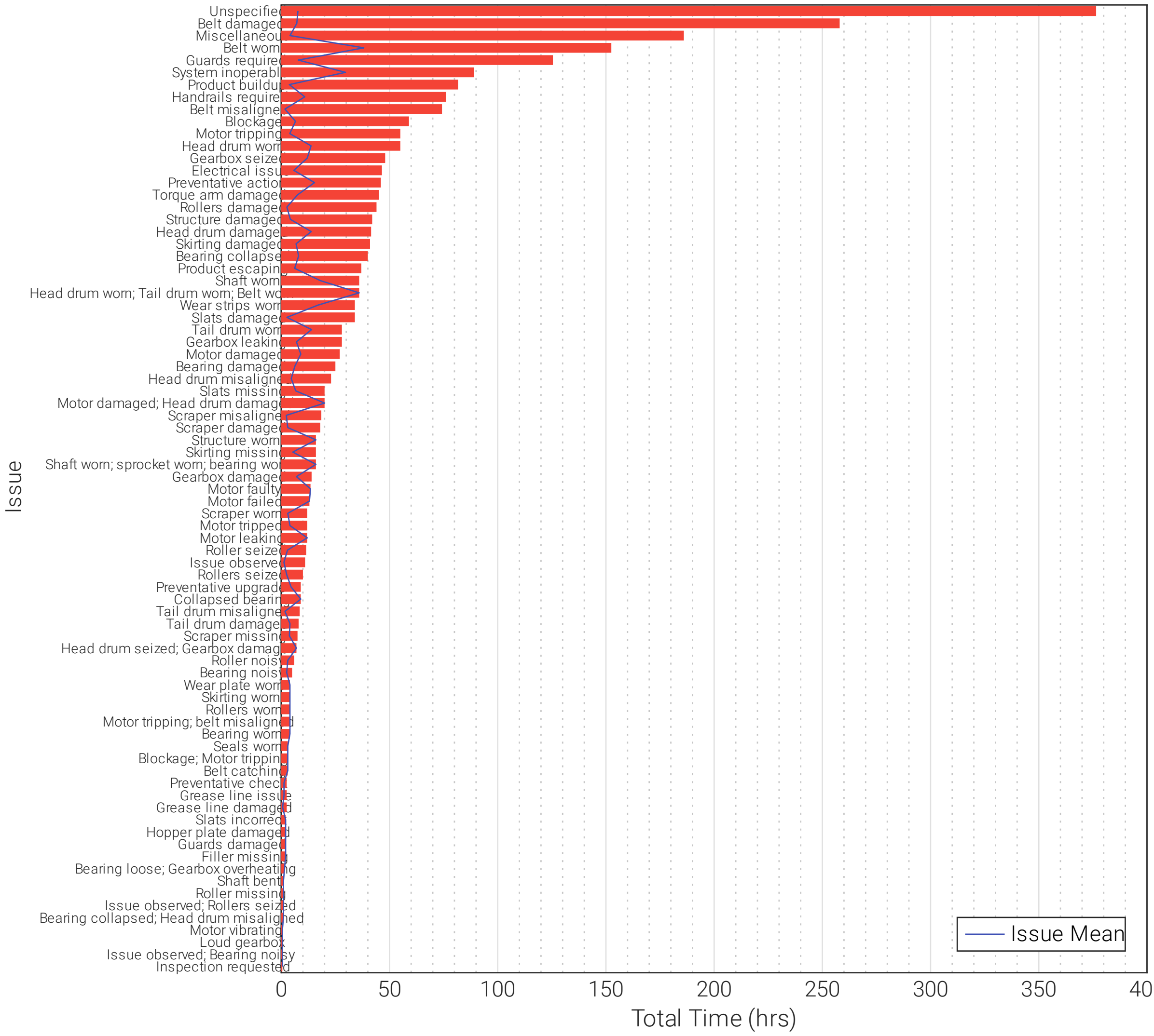

Figure 2.8: Total number of actions recorded by issue type.

Two of the other three categories of issue within the top five relate to belt issues (*belt misaligned*, *belt damaged*), and if these are considered in conjunction they would represent the single largest consumer of time. In contrast to the *Unspecified* or *Miscellaneous* issues, the occurrence of either of these two categories of issue can be expected to have a direct impact on the operability of a plant, due to both either requiring an asset stoppage in order to address the issue, or inherently causing an unplanned stoppage, making their occurrence much more impactful to the Operator. The *System inoperable* category, the sixth most time-consuming issue, will inherently impact upon the operability of a plant. However, much like the *Motor tripping* category, its average time to address is very low, suggesting similar 'tripping'-type events are the underlying cause, possibly obscured due to the manner of recording.

The *Guards required* category is another significant consumer of time, however, such actions are both one-off as well as planned (as opposed to reactive), so they can be expected to present lower impact to the Operator. *Product Buildup*, typically a consequence of inadequate cleaning, is the seventh most time-consuming issue, suggesting either existing cleaning schedules are inadequate, or are not being implemented as required.

More generally, no obvious relationship between the frequency of occurrence of an issue and the average time required to address it can be identified (Figure 2.8) i.e. the most common issues encountered don't necessarily consume the most time to address. This implies that in order to minimise overall maintenance expenditure on assets it may be more appropriate to focus on reducing the occurrence of failures in the first place, rather than trying to minimise the time taken to complete corrective actions once a failure has actually occurred.

The top three consumers of time by average time taken by occurrence are *Belt Worn, Head drum worn*; *Tail drum worn*; *Belt worn* and *System inoperable,* where *System inoperable* comprises three records, with actions of *Motor and gearbox replaced, Electrical repair* and *System replaced*. All three of these represent replacements of major components, requiring significant effort to first remove existing damaged component and then install new ones. Typically, the rationale for conducting such component replacements is not well captured within records. However, it can be assumed that such significant actions would not be undertaken unless considered essential and are thus likely to represent reactive actions required to restore operability of a system.

Records by Component

Analysis of records by the primary component to which they relate shows that on average the most time-consuming actions are those associated with motors, gearboxes, head pulleys, belts and structures (Figure 2.9). Actions associated with a conveyor's structure are typically one-off (e.g. during the reporting period new directives were enacted which required the installation of system guards) and/or do not interrupt the operation of a system, and hence they can be considered to have a lower impact on availability.

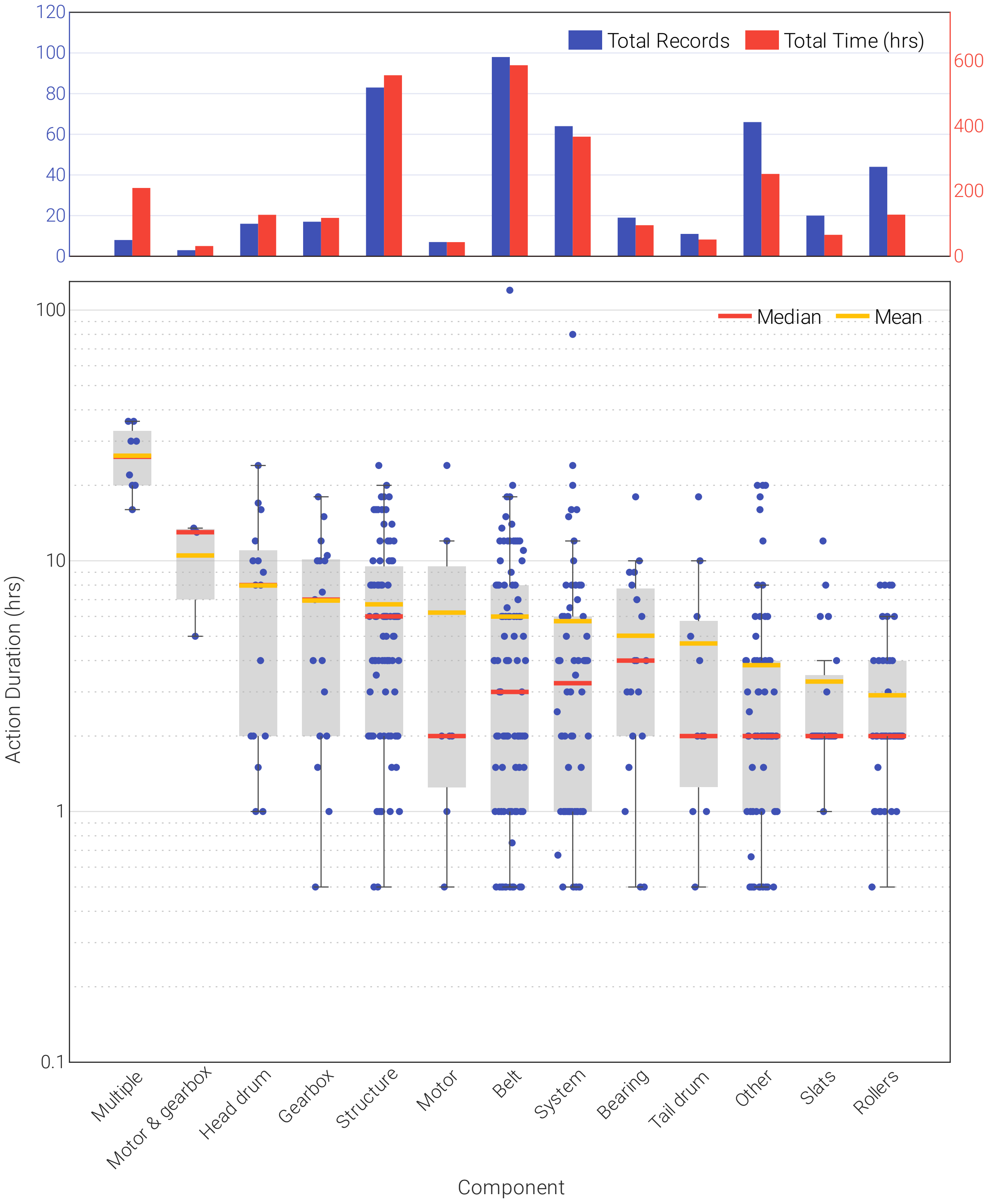

Figure 2.9: Total number of actions recorded against and time taken by component.

The highest mean time to complete category relates to records describing the completion of multiple sub-actions, for example a replacement of a belt and both head and tail pulleys (Figure 2.9). Unsurprisingly, the more actions described within a single record the more time is consumed completing the overall action.

Actions within the *Motor*, *Gearbox* and *Head pulley* categories also have high average times to complete, however, in absolute terms each category is a relatively small consumer of time. The majority of motor and gearbox actions represent complete replacements, for motors typically where motor 'burnt out' (i.e. damage to windings) has occurred in response to a system blockage, and for gearboxes when oil leaks have occurred, often leading to the seizing of an output shaft. It is also common for both a motor and gearbox to be replaced simultaneously, in an opportunistic manner regardless of actual condition; the two are physical coupled therefore with one removed the task of replacing the other is greatly simplified.

The *Belt* issues category is both the most frequently occurring as well as the greatest total consumer of time. Additionally, the majority of actions within the *Multiple* category also relate to belt issues, further increasing the total number of belt related issues. It should be noted that actions within the *Belt* category do not necessarily describe a complete replacement of a belt; often belts are repaired by rejoining ('clipping') a damaged belt, therein delaying the requirement for replacement. Also, a large proportion of actions within the *Belt* category reflect belt removal and retracking actions, conducted as sub-actions within an overarching primary action, such as a pulley replacement. However, regardless of the specific form of action taken a belt-related issue will always incur downtime as a system must be stopped to complete such actions.

A significant number of records are also associated with the *System* category, which primarily describes cleaning actions. These records reflect only those cleaning actions recorded by maintenance personnel, it can be assumed that the majority of cleaning actions will be conducted by plant technicians and thus will not be reflected within maintenance records. Whilst cleaning actions are frequent they typically require minimal time to complete, usually between 0.5-1 hour.

Records by Action

When the actions conducted within each records are analysed, as with anaylsis of issues, the most time-consuming actions are belt replacements, structural upgrades, the combined replacement of a motor and geabox, and cleaning, which together represent ~43% of total effort (Figure 2.10).

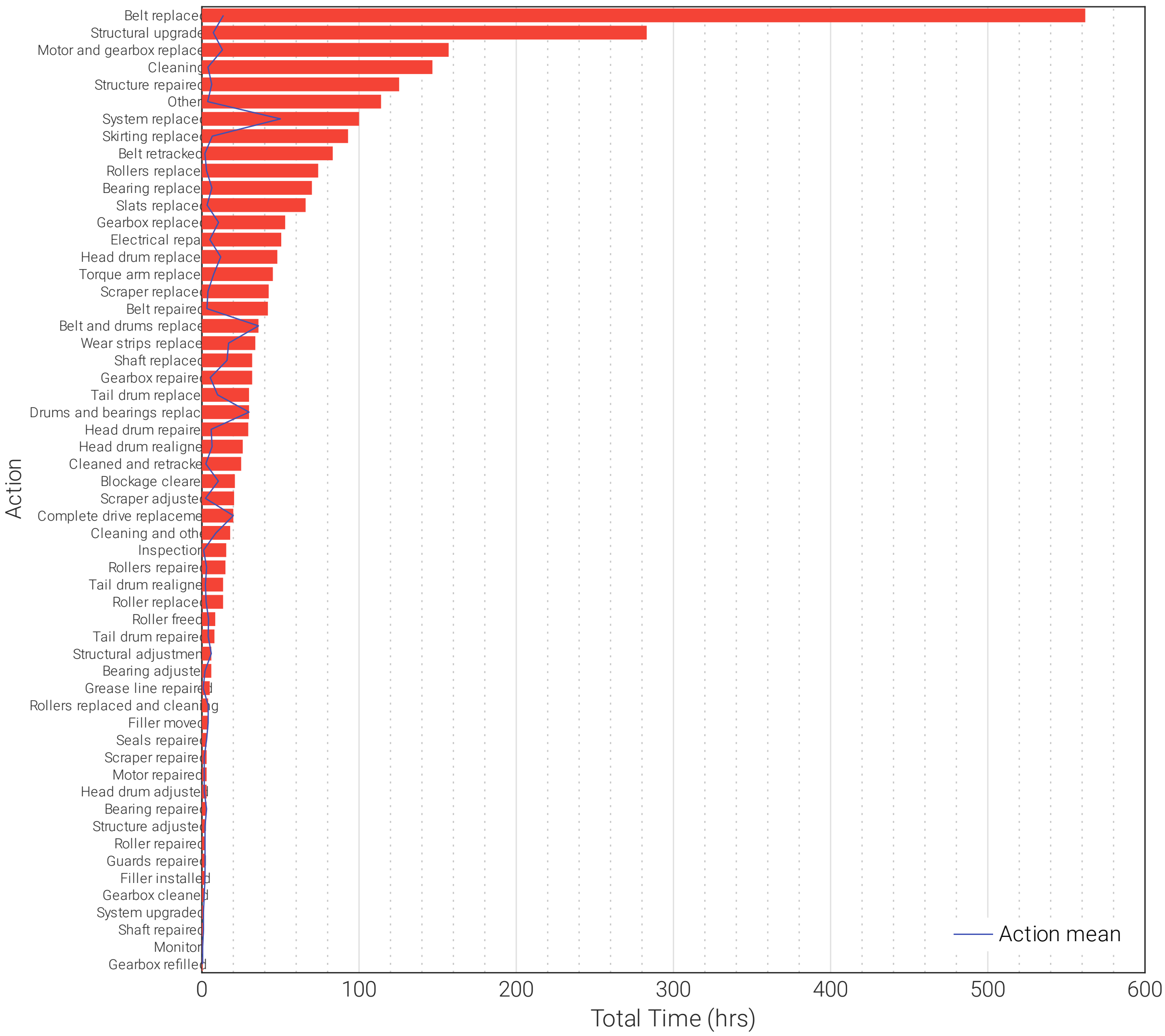

Figure 2.10: Total number of actions recorded by action type.

The most time-consuming action in terms of average time to complete is *System replaced*, as would be expected an entire replacement of a system represents the most resource-intensive action conducted on-site.

Summary of Findings

From the quantitative analysis of on-site maintenance records conducted the following conclusions are made against the objectives defined in Section 2.2.5.

1. **Which issues are most impactful across plant in terms of downtime incurred?**
   - *A small number of issue types constitute the majority of time consumed across plants. The greatest single consuming issue category was Unspecified, suggesting improvements in the recording process may be of benefit to the Operator.*

- *The next greatest consumers were issues related to belts, issues which will always incur system downtime.*
- *Beyond these, issues associated with motors and gearboxes were significant consumers. Typically, the nature of these issues is such that they can be considered eminently avoidable if they are detected in a timely manner (e.g. leaking gearbox leading to seized output shaft, product buildup leading to motor overheating etc.).*
- *In addition, the distribution of actions across assets is not uniform, with certain assets requiring far more resource. Without further on-site investigation the exact cause of this cannot be determined.*

2. **What actions are taken to correct the most impactful issues?**
   - *Typically, the most resource consuming actions are those which involve the replacement of components (e.g. belts, motors, pulleys). Furthermore, the more components replaced within a single record the more time consumed (e.g. simultaneous motor and gearbox replacement).*
   - *Simple cleaning of assets was found to be a commonly performed action by the maintenance team, in response to spot blockages and the build-up of product.*
   - *The retracking of belts by adjustment of tension is also commonly required.*

3. **How much time is required to correct each occurrence of the most impactful issues?**
   - *No clear correlation between the total and mean time consumed per issue was identified, however, as could be expected the more involved a corrective action is the more time it consumes to correct on average e.g. if multiple components are replaced simultaneously the total length of the action is increased.*
   - *Amongst issues which directly incur process downtime those associated with belts (i.e. replacement or repair) require the most time to correct on average, reflecting the involvedness of belt actions*

2.3 Implications for Research

An examination of current practice in the design and operation of CBSs within bulk handling applications demonstrated a number of challenges faced by both manufacturers and operators in satisfying availability demands.

The design of CBSs has converged to a common form across manufacturers, with COTS parts heavily utilised supporting reductions in cost and high levels of reliability. However, efforts to extract even greater reliability from systems appear to be restricted by the limited performance data available to designers, preventing the closure of the design loop. Designers are often working on assumptions about operational conditions and usage, based upon ad-hoc interactions with end users, compromising their ability to adequately design and specify systems for the diverse operational environments encountered.

The generic form represented by a Basic CBSs means nominally similar systems can experience vastly different usage patterns across applications, leading to significant variance in realised reliability and maintenance requirements. Manufacturers and operators are often unable to observe usage as a result of either health and safety related constraints (Operator) or remote operation of systems (Manufacturer), limiting their ability to plan appropriate responses. Similarly, lack of visibility of operation creates a disconnect between the manner in which systems are used in the present and the effect of this upon long-term health, fuelling a culture of 'short-termism'; little consideration is given to how the usage of a system will impact upon its realised service life.

The impact of belt and motor related issues were identified as the most significant in-service issues, with either capable of rendering a system inoperable. An assessment of previously in-service drive motors indicated that the effect of operating within aggressive environments is minimal on the condition of motors, reflecting the robustness of the induction motor. In contrast, an analysis of maintenance records from one of the Operator's sites indicated that belt issues are prevalent and carry a significant cost to the Operator, in terms of both incurred downtime and parts and labour costs. An absence of repair work was also identified at the Operator's Plant, with the majority of actions comprising complete replacements of components. Due to the low cost of COTS parts in many instances the condition of components is considered only a binary state, either *healthy* or *failed*.

Overall, both the Manufacturer and Operator were found to be reliant upon subjective visual inspection methods to assess the condition of assets in-service, with the effectiveness of such practices compromised by both the restricted access to plant as well as inherent subjectivity. Reliance upon periodic visual inspection prevents the observation of abuse loads and timely detection of functional failures.

Chapter 3: The Maintenance of Conveyor Belt Systems

As stated in Chapter 2, the availability of a CBS is dictated by its design, its operation and its maintenance. Accordingly, and following on from Chapter 2, firstly in this chapter historical and state-of-the-art industrial maintenance practices are examined through a review of extant literature. Subsequently, to understand how maintenance is currently implemented within bulk handling applications specifically a series of interviews are conducted with maintenance personnel from one of the Operator's plants.

To mitigate for the operational issues which a mechanical system will inevitably experience maintenance must be performed. Within an engineering context maintenance in the broadest sense can be described as any action taken to preserve the function of an asset as required by its stakeholders, within a defined operating context [17], [38]. A similar concept is that of *reliability*, which is used to describe the ability of an item to perform a required function under given conditions for a given time interval [43].

Thus, when an asset fails its reliability is impacted and it must be maintained in order to return it to an operable state. Maintenance of systems is therefore critical in realising high levels of operational availability, as demanded of assets such as CBSs. This criticality is reflected in the size of the maintenance sector, which in the USA alone is estimated to cost industry over $300 billion per annum [46], [68], with maintenance activities in the mining sector accounting for 30% of operating costs alone [69].

Fundamentally, the purpose of maintenance is to mitigate for the failure of assets, either by preventing their occurrence in the first place or by correcting any failures which do occur to restore the operability of an asset. Therefore, the concept of maintaining an asset based upon its failure might seem trivial, however, in practice defining exactly when an asset has failed can be challenging. Within literature a range of generic definitions for the concept of an asset failing are offered, such as "*the loss of the ability of an item to perform a required function*" [43] or "*reaching such a state that the intended function of the part or system can no longer be fulfilled*" [60], however, the exact definition of failure will almost always be application-specific and often non-trivial to determine. For example, ISO281-2007 defines the life of a bearing as "*the number of revolutions which one of the bearing rings or washers makes in relation to the other ring or washer before the first evidence of fatigue develops in the material of one of the rings or washers or one of the rolling elements.*" Within the context of a safety-critical application, such as an aircraft or train it may be appropriate to replace a bearing at the first sign of any degradation in condition, to minimise the risk of catastrophic failure in the future. However, within less safety-critical applications, or where there is little to no financial penalty associated with a bearing failing, such as manufacturing equipment, the reduced impact of a bearing failure occurring may render corrective action at this stage unnecessary and thus such a definition of life not suitable.

The implications upon maintenance effectiveness of an unsuitable definition of failure are potentially significant. If failure criteria are too conservative components can be replaced prematurely and thus maximum life not extracted and additional costs incurred, both financial and operational. If failure criteria are overly optimistic then excessive failures can be encountered, reducing reliability as well as incurring unnecessary financial and operational costs too. Ultimately, it can be asserted that the effectiveness of a maintenance approach is inherently related to the failure criteria defined, which must be considered on an application-specific basis.

Development in the area of maintenance practices has historically been driven by safety critical fields, from where it has subsequently disseminated into other industries over time. Within industries such as aerospace, both civil and military, and nuclear power generation, catastrophic failures of systems are unacceptable which has forced operators to place greater emphasis on reducing both the likelihood and impact of system failures, leading them to invest heavily in research and development within the area of maintenance [54]. Further, these industries typically carry significant financial penalties for unplanned downtime placing greater importance on reliability to ensure system availability is maximised.

3.1 Maintenance Approaches

Across industry three primary approaches to the maintenance of systems are practiced, each of which represents a distinct generation, developed sequentially over the 20th century from reactive (RM) through preventative (PM) to predictive (PdM). As summarised in Table 3.1, *reactive* describes an approach in which an asset is maintained in response to a functional failure to restore it to an operational state, *preventative* describes an approach in which an asset is maintained at fixed intervals (e.g. every 100 running hours) regardless of its actual condition in an attempt to prevent failures from occurring and *predictive* describes an approach in which the condition of an asset is monitored whilst it is in operation and it is preventatively maintained when its condition is observed to have degraded to a predefined level, before a functional failure is realised.

Table 3.1: Comparison of characteristics of major approaches to maintenance[13].

	Description	Advantages	Disadvantages
1st REACTIVE	'Fix it when it breaks' approach	Easy to implement, maximum life drawn from component	Incurs downtime, difficult to schedule maintenance personnel
2nd PREVENTATIVE (PLANNED PREVENTATIVE)	Asset is maintained at fixed schedule (time or operation based)	Potential to reduce overall downtime, increased scheduling efficiency	Unnecessary action potentially taken, failures still possible, maximum life of component not realised
3rd PREDICTIVE (CONDITION-BASED)	Observe condition of asset and maintain based upon progression of condition	Minimise downtime, schedule actions efficiently, monitor operating characteristics	Resource intensive to implement – cost, labour, required known failure characteristics

3.1.1 Reactive

A *reactive* maintenance approach describes the most conceptually simplistic strategy, one in which maintenance interventions are conducted only in response to the occurrence of a functional failure. Accordingly, reactive approaches are often referred to as *run-to-failure* and as such, a period of unplanned downtime will be incurred each time a failure occurs, the length of which will be dictated by the corrective action required to restore the asset to an operable state.

A reactive approach offers the advantage of not only being simple to implement but also will extract the maximum possible life from an asset; interventions will only be taken when absolutely necessary. However, implementation of a reactive approach requires an agile maintenance team, capable of correcting issues in a timely manner and a comprehensive inventory of spare parts to be held in perpetuity if downtime is to be minimised. An inability to plan maintenance actions in advance exaggerates the task of the maintenance team and, as noted by Starr et. al. [54], inevitably issues will occur at the least convenient time. Consequently, a reactive approach will typically represent the least cost-effective maintenance approach and as such rarely will an operator rely primarily upon maintaining assets reactively [64].

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[13] For an in depth analysis of the major maintenance paradigms see [54].

3.1.2 Preventative

A *preventative* approach (AKA *planned preventative maintenance* (PPM)) describes a proactive strategy in which maintenance interventions are conducted at fixed intervals irrespective of the actual condition of an asset, with the aim of preventing the occurrence of failures. Intervals can be defined based on a number of different criteria, however, typically absolute time elapsed or running hours are used e.g. monthly or every 1000 hours of operation. Accordingly, a preventative approach is also often referred to as *time-based maintenance*.

As actions are scheduled regardless of the actual condition of assets a preventative approach affords maintenance personnel much greater ability to plan activities ahead of time and thus more evenly distribute actions. Furthermore, historically there was a general perception in industry that there was a 'right' time to perform maintenance actions, so by increasing preventative actions greater reliability would be realised as the condition of assets would never be allowed to degrade significantly [38].

However, the effectiveness of a preventative approach to maintenance is inherently compromised by three factors. Firstly, it relies upon assets presenting consistent mean times between failure (MTBF) characteristics, such that suitable intervals can be identified and implemented. Secondly, a preventative approach will not extract the full life from an asset as a reactive approach will, due to interventions being made regardless of condition. Finally, to implement a comprehensive preventative approach requires significant resource, both in terms of personnel and parts, which may not be available.

Usage-based Maintenance

To address the limitations of time-based preventative approaches the concept of *usage-based maintenance* has emerged, in which preventative interventions are made at intervals dictated by how an asset is used in-service (i.e. the loads it is subjected to). As discussed in section 2.2.1 the rate at which the service life of a mechanical system is consumed will be dictated by its usage, thus if it is possible to understand usage in-service then more appropriate preventative intervals can be defined.

The concept of scheduling maintenance actions based upon actual usage was first explored by the aerospace industry within the scope of health and usage monitoring systems (HUMS). Traditionally, aircraft would be overhauled according to fixed preventative schedules, with intervals defined in terms of flight hours completed. However, as understanding of structural degradation has advanced a direct relationship between in-service loads and fatigue failure in particular has been identified [70]. Accordingly, the traditional time-based intervals implemented by operators on the instruction of manufacturers were often found to be ineffective, leading to a number of catastrophic failures of aircraft, such as the Aloha Airlines Flight 243 disaster. The failure of AA Flight 243 is attributed by most experts to a fatigue failure of the craft's fuselage, accelerated by the typically short nature of flights taken by the craft in comparison to a typical craft of its class, which exposed Flight 243 to far more take-off and landing events per flight hour, accelerating the development of fatigue cracks [71].

To address such deficiencies HUMS enabled the actual loads experienced by craft in-service to be monitored and used to inform maintenance schedules. By monitoring usage operators can not only mitigate for catastrophic failures but conversely extract greater service life from assets with lower than expected usage, where previously static, time-based intervals would demand their overhaul prematurely, as depicted in Figure 3.1.

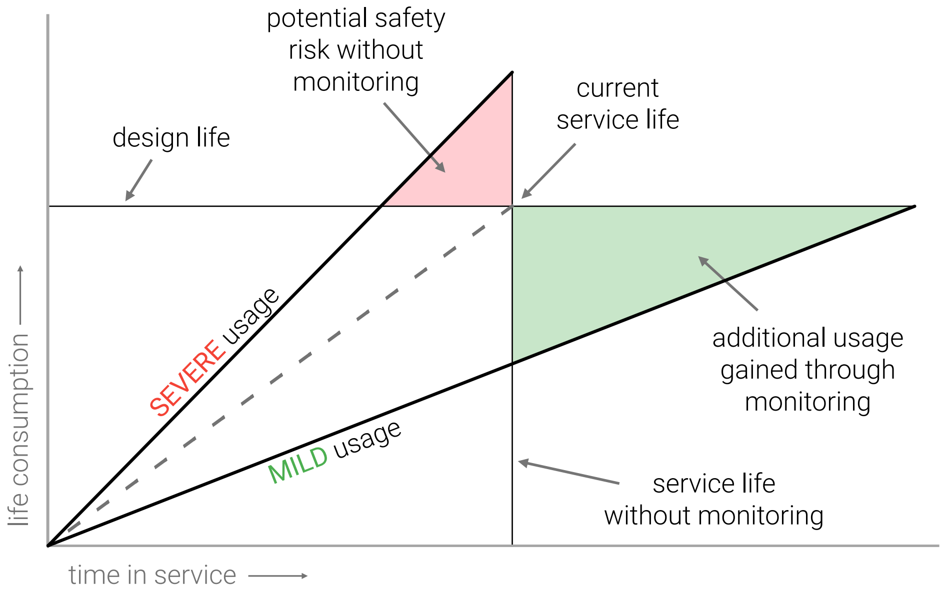

Figure 3.1: Illustration of the potential affordances of system monitoring in terms of increased extraction of life from assets (Adapted from [38]).

In recent years the concept of utilising system usage information to improve maintenance schedules has gained the attention of wider industry, primarily through the work of Tinga [72] who proposes the use of physics-of-failure models in conjunction with measured parameter data to estimate the loads experienced by a component and subsequently usage. For example, to monitor the progression of creep (a known failure mode) within a turbine engine compressor blade firstly induced stress is estimated from a physics-based model which uses measurements of temperature and rotational speed as inputs. Subsequently, induced stress is translated into estimated usage through an empirical damage accumulation model based upon the Norton creep law [72].

However, as recognised by the author, the implementation of such an approach is reliant upon reliable failure model(s) being obtained which describe the relationships between measured parameters, loads and ultimately usage. In the absence of such understanding it is still possible to implement the principles of usage monitoring to improve upon time-based preventative intervals. By selecting appropriate parameters (e.g. operating cycles, intensity levels) the severity of usage can feasibly be observed at a more abstracted level, enabling broad characteristics of operation to be profiled. Over time, with increased operation an operator can develop experience-based models describing the relationship between observed usage profiles and resulting system reliability, support improvements in preventative interval definitions. In this scenario the exact definition of usage will inherently be application-specific and dictated by the mechanisms which drive degradation within a system, as reflected in the loose definition of usage monitoring within the context of structural health monitoring provided by Farrar and Lieven [73]:

> *"the process of acquiring operational loading data from a structure or system, which preferably includes a measure of environmental conditions (e.g. temperature and moisture) and operational variables such as mass or speed."*

Additionally, monitoring the usage of an asset affords manufacturers with an opportunity to implement novel business models such as usage-based pricing or servitization, a trend observed across industry in recent years. Within the aerospace sector servitization models typically constitute a *Power-by-the-Hour*[14] approach to supply, in which rather than selling a physical asset e.g. a turbine engine, an OEM instead supplies a guaranteed provision of service e.g. flight hours. Servitization models often incorporate greater penalties for the OEM if the asset supplied fails to meet its performance requirements, therefore concepts such as usage monitoring are viewed as mechanisms to both mitigate such risk and meet performance obligations at reduced cost [74]–[76]. The extent of service offerings by manufacturers across industry has increased

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[14] Power-by-the-Hour® is actually a registered trademark of Rolls-Royce.

dramatically in recent years in line with a general shift in focus towards more product-service based models. Accordingly, many manufacturers are reporting that after sales services are now as important in terms of overall revenue, if not more than initial sales [77]. Servitization principles are already beginning to penetrate into wider industry, with Continental recently revealing plans for a novel offering [78] within the conveyor sector in which systems are leased to customers within a 'pay-per-tonne' servitized model, relieving the end user from performing maintenance of assets whilst improving reliability.

3.1.3 Predictive

To address the limitations of reactive and preventative approaches to maintenance the concept of *predictive* (PdM) or *on-condition* maintenance[15] was introduced, in which interventions are only made in response to the onset of failure being observed. Commonly considered the 'holy grail' of maintenance a predictive approach can theoretically realise maximum extraction of asset life whilst avoiding the occurrence of functional failure, with an ability to plan interventions in advance. Within a predictive approach to the maintenance of an asset the task is to detect the potential for failure to occur prior to the occurrence of functional failure, a period termed the P-F interval, such that an intervention can be made to prevent functional failure [17] (Figure 3.2).

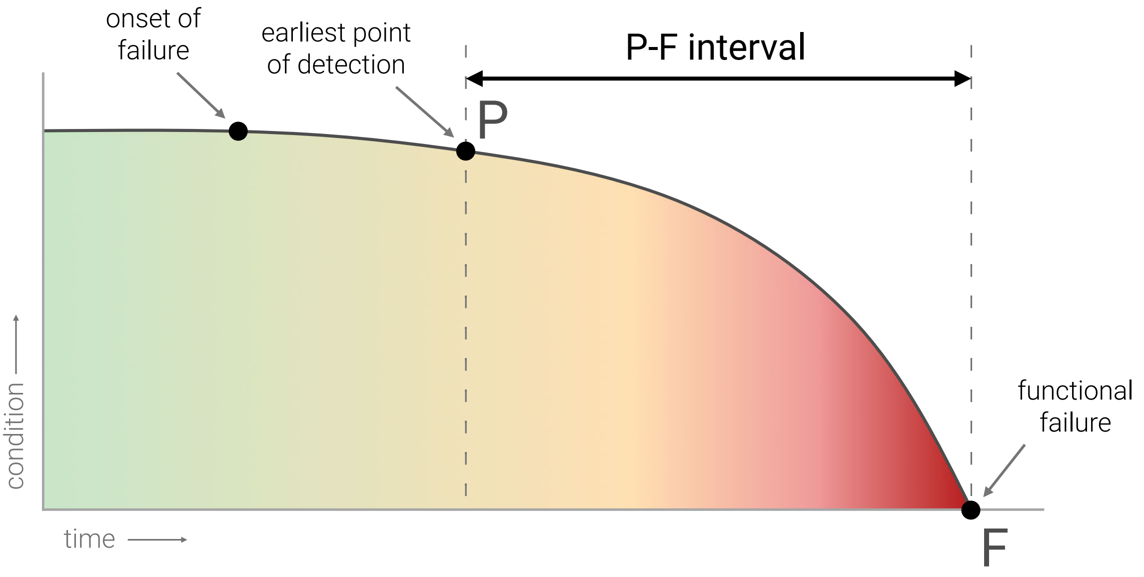

Figure 3.2: The P-F curve of a generic asset (adapted from [74]).

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[15] AKA condition-based maintenance (CBM).

The implementation of PdM is enabled by prognostics, that is, the generation of long term predictions describing the evolution in time of a particular state, with the aim of estimating the remaining useful life (RUL) [79]. Commonly, prognostics is implemented within the scope of prognostics and health management (PHM), an approach to the management of an asset(s), in which information relating to the current condition (i.e. health[16]), as well as predictions of the future condition (i.e. prognostics) of the asset is leveraged to support the preservation of the asset's function, in response to operational demands [80].

Primarily, through the implementation of a predictive approach to maintenance a practitioner is seeking to simultaneously minimise the occurrence of functional failures and maintenance interventions. However, a number of complementary benefits can also be realised such as increased safety[17] and reduced inconvenience[18] [38]. For an in depth analysis of the potential benefits facilitated by PM implementation the reader is directed to Jennions [74].

To date, the majority of condition-based approaches to maintenance have been reported in applications relating to high-value-low-volume assets such as gas turbines or wind turbines, where parts and maintenance costs are high and limited opportunities for interventions exist. Initial efforts within the area of PHM were focused within the Aerospace industry, driven by an assumption that the industry would be able to extract the most value from PHM due to the high costs associated with failure of the low-volume-high-value assets operated [38]. Given the constraints of the Aerospace industry, predictive approaches to maintenance offer an opportunity for operators to demonstrate airworthiness within more cost-effective maintenance schemes.

However, the specific driver for the adoption of PHM will vary across applications, as dictated by the constraints and requirements of each industry. For example, the adoption of PHM within the Joint Strike Fighter (JSF) program was driven by a need to maintain historic levels of safety despite reduced system redundancy[19] whereas within the commercial aerospace sector PHM is

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[16] In this context the term health is used to describe the current state of the asset, with respect to its normal operating state.

[17] Failures are typically of a less catastrophic nature, reducing the potential for harm to personnel upon occurrence.

[18] By reducing the occurrence of catastrophic failures the time required to repair a failure is typically reduced. Furthermore, to a degree, a practitioner has a degree of control over when exactly interventions are made.

[19] The JSF is a single engine configuration, a novel arrangement in contrast to most fighter aircraft produced prior to its conception.

primarily for economic benefit. Commercial airline OEMs and operators typically meet or exceed the safety requirements put upon them by the regulatory authorities so PHM for increased safety is not a prominent driver for commercial operators [81].

Despite many industries indicating aspirations to adopt PHM reports of applications are, to date, few in number, with most effort theoretical in nature and restricted to academic research [82]. Industrial applications have thus far been inhibited by technical issues concerning the accuracy and generality of prognostic algorithms [83], with Peng et. al. [82] suggesting that a general methodology for designing and implementing prognostic solutions is imperative for industrial uptake. Extant algorithms are typically bespoke in nature and thus only valid for specific systems, restricting their applicability in practice. Accordingly, the key challenge for researchers is to develop techniques/algorithms which are able to be applied across fleets of assets without significant additional effort, as recognised by many authors [84]–[86].

Furthermore, even if such technical challenges can be overcome a predictive approach to the maintenance of an asset cannot be considered inherently suitable, but instead is reliant upon the satisfaction of four primary criteria, as defined by Moubray [17]:

1. **A clear potential failure condition can be defined.**
   It must be possible to define objectively the definition between a healthy and failed asset.

2. **The asset presents a reasonably consistent P-F curve.**
   An asset must adhere to known failure characteristics, such that an accurate RUL can be estimated.

3. **The asset can be practically monitored at intervals less than the P-F interval.**
   Either continuous monitoring must be employed or periodic inspections must be conducted at a frequency significantly greater than the typical time taken for an asset's condition to degrade from health to failure[20].

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[20] Regardless of whether an asset is monitored periodically or continuously, manually or through interrogation of acquired parameters, it must also be feasible to assess the condition of an asset against its defined failure characteristics.

4. **The P-F interval is long enough to allow corrective action to be practically taken to prevent failure.**
   The typical period between the onset of failure first being identified and functional failure occurring must be longer than the response time of the maintenance team, given practical constraints and available resource.

Regardless of the technical feasibility of an on-condition approach to an application financial viability cannot be assumed; if the cost of implementing a predictive approach outweighs the savings it can realise then it is unlikely to be attractive to decision makers and budget holders. The task of demonstrating the value in a prognostic system is recognised throughout industry as challenging; often much of the financial benefit of such systems is delivered in the form of cost avoidance (i.e. a reduction in the costs which have to be paid in the future to sustain a system) rather than returning direct cost saving, which typically carries lower perceived value within a commercial context [74]. Further, much of the benefit of a predictive approach to the actual maintenance team is less tangible in nature and more psychological[21], making it a challenge to translate into a viable business case. As commented in ARP6275 [87] *"There are elements that are ultimately unquantifiable or sufficiently intangible which means that their estimation of worth is either based on emotion or "priority" to the specific operator or customer."*

3.2 Maintenance Evolution

The development of first preventative and subsequently predictive approaches was driven by limitations on the effectiveness able to be extracted by operators from reactive and preventative approaches. For example, within a reactive approach a period of unplanned downtime will be incurred every time a failure occurs and within a preventative approach unnecessary interventions can be made and/or functional failures can still feasibly be encountered and thus unplanned downtime incurred.

However, it should be noted that reactive and preventative approaches to the maintenance of an asset are not rendered obsolete by the advent of predictive approaches, as often inferred

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[21] For example, the insight provided by prognostics can make personnel feel more in control of operations, reducing stress and thus supporting better decision making. Similarly, there can be a reputational benefit to an organisation through implementation of advanced technologies such as PdM, creating a perception that the organisation is 'forward thinking' and innovative.

within literature. If, for example, an operator determines that the impact of an asset incurring functional failure is low then a run-to-failure strategy (i.e. reactive) may be most appropriate as it extracts maximum life from an asset and requires the fewest interventions. Similarly, if an asset is known to present very consistent intervals between failure then a scheduled preventative action may be able to extract similar life from an asset when compared to a predictive approach. Thus, it cannot simply be assumed that a predictive approach to the maintenance of an asset will always represent the 'best' approach.

Further, it should also be noted that the approaches are not mutually exclusive; an overall maintenance strategy can incorporate elements of multiple approaches; the most appropriate approach (i.e. that which will best satisfy the maintenance requirements, whether that be reliability, availability or any other metric) may differ across all the assets maintained by an operator. Accordingly, maintenance planning paradigms such as reliability-centred maintenance [17] and variants therein have been developed to support the process of selecting the most appropriate approach to the maintenance of each specific asset. However, when adopting multiple maintenance paradigms, to extract maximum effectiveness an operator must ensure that all are integrated into a single, cohesive approach and not parallel streams [17].

3.3 Characterisation of Current Maintenance Practices

Whilst there exist a number of different approaches to the maintenance of systems the current prevalence of each within actual industrial operations is unclear from literature. Many authors assert that industrial practice is still dominated by reactive and preventative approaches, with predictive yet to find significant adoption [88]–[91]. For example, Siegel et. al. [91] state that the maintenance of general materials handling systems is still overwhelmingly based upon reactive and/or preventative approaches, with only limited implementations of predictive approaches observed. Similarly, Blazej et. al. [92] report that the maintenance of CBSs within Polish mines is still primarily reliant upon manual visual inspection to assess intervention requirements.

To better understand how maintenance of bulk handling CBSs is currently implemented the practices of the Operator were characterised through a series of interviews conducted with members of the maintenance team at one plant. The objectives of interviews were to identify:

1. **Workforce characterisation**
   The composition and credentials of the maintenance team.
2. **Maintenance issues**
   The primary maintenance issues at the plant as perceived by the maintenance team.
3. **Maintenance approach**
   The typical approach taken to maintain CBS assets at the plant.

3.3.1 Research Method

A specific plant was selected by the Operator to be the focus of interviews. This plant was considered internally by the Operator to be both very critical as well as to be facing significant challenges within the context of maintenance effectiveness. The Plant's maintenance team comprises 14 maintenance engineers, with 2 on-site per shift. It should be noted that the Maintenance Manager provides support to all of the Operator's plants not only the subject plant.

In addition to the dedicated maintenance team operations at the Plant are supported by a team of plant technicians. The role of the plant technicians is to supervise the general process, address any transient issues (e.g. clearing blockages) and perform regular cleaning of systems. Due to limitations on their availability plant technicians were not able to participate in the interview process. From these fourteen, four interviews were conducted with personnel fulfilling roles within the hierarchy as shown in Figure 3.3.

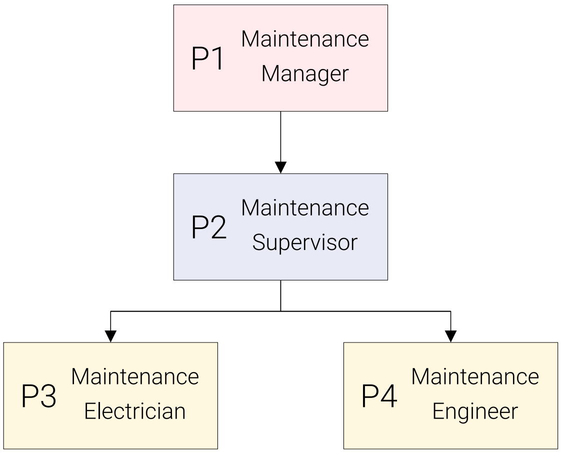

Figure 3.3: Hierarchy of interview participants within the Plant's maintenance team.

Participants were selected based upon availability, however, with the Maintenance Manager ensuring that all levels within the maintenance team hierarchy were represented amongst participants. It is commonly accepted that for such a study to produce valid outputs it is essential that participants are representative of the overall population within which they exist [93].

Ideally a larger section of the team would have been sampled to maximise validity of data, however, constraints on personnel availability prevented this. In addition, to achieve the aim of characterising the maintenance process on site, ensuring quality of data over quantity can be considered a priority, with the concept of saturation as described by Glaser & Strauss [94] relevant.

Interview Procedure

Interviews were conducted on-site by the author one-to-one with selected maintenance personnel, following a consistent protocol as much as possible. Interviews were conducted in a confidential environment and all audio was recorded throughout interviews for subsequent analysis. Prior to commencing interviews participants were asked to sign a consent form, both to ensure participants were made aware of the interview format and expectations upon themselves as participants, as well as to grant permission for captures responses to be used for research purposes. A copy of the interviewee consent form is provided in Appendix C:.

The interview process was semi-structured, an interviewing style in which the researcher poses to interviewees a series of predetermined but open questions. This typically permits the researcher greater control over the narrative of the interview when compared to a structured interview constituting closed questions, with interviewees not being constrained to pre-defined answers to questions posed [95]. Accordingly, a series of high-level questions were developed to frame the interview (Table 3.2), however, the interviewee was allowed to deviate from the specific questions when it was felt to be beneficial to the overall process. As recommended by Gubrium [96] *"Interview questions should help guide an interviewer but not so rigidly that an interviewee is not able to shift footings and perspectives. Interviewers should encourage participants to discuss how they constructed their narrative."* Such sentiments were adhered to throughout the interviewing process.

Table 3.2: Research questions used within semi-structured interviews.

	Question	Explanation	Purpose
1	What is your role, responsibilities and length of service at the company?		To characterise the team
2	What is your experience level with regards to maintenance (service length, qualifications etc)	i.e. what education level do they have	To understand the level of expertise and assess variance within the team
3	What training (if any) does the company provide (initially and ongoing)?	How much does the company value and support training	To assess the operator's investment in maintenance personnel, and the degree to which maintenance approaches are standardised internally
4	What are the objectives of maintenance at the Plant?	Is maintenance just fire fighting to keep operation levels as high as possible? Is cost factored in?	To identify the drivers for maintenance at the Plant
5	Describe the company's approach to maintenance. Do you plan maintenance?	What characterises the maintenance approach, is it reactive, PPM etc.	To assess the mix of reactive, preventative and predictive approaches implemented at the Plant.
6	How are maintenance activities planned, organised, formalised and/or documented on-site?	i.e. is there a formal maintenance plan or is it up to the operators to make it up? If there is then how is it done	To assess the level of planning and documentation of maintenance at the Plant.
7	Name the top 3 issues at the plant in terms of the downtime they incur and for each describe: - how frequently it occurs - what the consequences of it are - how you identify it - how you tackle it - are there SOP for this maintenance action	What are the issues at the Plant that cause the longest stoppages of operation	To identify the most impactful issues at the Plant, as perceived by each interviewee.
8	As per Question 8 but instead in terms of frequency (if different)	What are the issues that occur the most at the Plant	To identify the most common issues at the Plant, as perceived by each interviewee.
9	As per Question 8 but instead in terms of time to correct (if different)	What are the issues that take the longest to fix	To identify the most involved maintenance issues at the Plant, as perceived by each interviewee.
10	Describe the areas of plant that never fail	Which assets are most reliable at the Plant	To compare the interviewee's perception of resilient areas to what would be expected from analysis and literature

Questions comprised three distinct sections, each designed to assess a specific aspect of on-site maintenance activities. The first section sought to characterise the interviewee themselves, including their role and responsibilities. The second section aimed to characterise the Operator's attitude and approach to maintenance from the perspective of the interviewee, including attitudes to training and maintenance planning. The final section aimed to identify specific maintenance issues within the Plant in the context of factors such as incurred downtime and frequency of occurrence, as well as identifying the most reliable assets within the Plant. The questions posed to interviewees represented a combination of positivist (e.g. "What are the objectives of maintenance at the Plant?") and inductive (e.g. "Describe the areas of the Plant that never fail") styles.

Data Processing

Recordings were subsequently evaluated with the support of a Computer Assisted Qualitative Data AnalysiS (CAQDAS) software package, enabling emergent themes in the data to be both highlighted and logged. As suggested by Gibbs [97] recorded audio was coded directed rather than via written transcriptions. This decision was made for two reasons, firstly, the process of written transcription can lead to distortion of data, with the subtleties of human inflection potentially misinterpreted or even lost entirely through the transcription process. Secondly, the process of transcribing audio data to textual format is itself a significantly laborious task, therefore, to accelerate the overall coding process it was omitted.

Initially, all recordings were reviewed in a passive manner, to obtain an informal identification of key themes emerging from interviews. Based upon this initial review of themes a series of high-level codes were defined (Table 3.3), against which each interview recording was subsequently assessed. The coding schema was developed in an iterative manner, following an inductive style and thus evolved in response to the identification of additional themes.

Table 3.3: Summary of codes applied to raw audio datafiles.

ID	Code	ID	Code
1	Interviewee characterisation	4.3	by Time to Repair
1.1	Role and responsibilities	4.3.1	Cause
1.2	Time at company	4.3.2	Consequences
1.3	Time in maintenance	4.3.3	Corrective action
1.4	Training and Qualifications	4.3.4	Frequency
1.4.1	At company	4.3.5	Identification
1.4.2	Externally	4.3.6	Description
2	Maintenance approach	4.4	Most reliable areas
2.1	Documentation	5	General themes
2.2	Organisation	5.1	High priority tasks impacting planning
2.3	Planning	5.2	Dependence upon personnel experience
3	Maintenance objectives	5.2.1	Knowledge of most issue prone areas
4	Plant issues	5.3	Reactive maintenance impact
4.1	by Downtime	5.3.1	Plant has to shutdown to complete action
4.1.1	Cause	5.4	Importance of visual inspection
4.1.2	Consequences	5.5	Impact of ageing assets
4.1.3	Corrective action	5.6	Importance of cleaning
4.1.4	Frequency	5.7	Access issues
4.1.5	Identification	5.8	Importance of maintaining key equipment
4.1.6	Description	6	General frustrations / notable remarks
4.2	by Frequency		
4.2.1	Cause		
4.2.2	Consequences		
4.2.3	Corrective action		
4.2.4	Frequency		
4.2.5	Identification		
4.2.6	Description		

A total of 47 codes were contained within the schema, split across 6 primary categories. The sixth category served as a ‘catch all’, providing a means for coding sentiments considered important but not obviously coherent with any other code(s).

3.3.2 Findings

Using the coding method previously described, a number of clear themes emerged from within raw audio data. Within Table 3.4 a summary of the primary findings is provided, and in this section a description of the workforce characterisation, maintenance approach and maintenance issues identified is presented, supported by relevant extracts from within audio data.

Table 3.4: Key findings identified from interviews conducted with maintenance personnel.

Factors		Description	Examples
Workforce Characterisation	Qualifications	The standard of formal qualifications typically held by employees	“I’ve got NVQ3 in Maintenance and Repair” ”I was at agricultural college for 4 years [where I gained] a BTEC, National Diploma and City and Guilds”
	Training	Evidence of tangible training provided to on appointment and ongoing as well as employee’s perception of company attitudes towards the provision of training	“Initially it’s the usual Health and Safety things mainly” “A lot of H&S courses”, “For the specialist machinery we’ve got they [the company] always try and get you on a course” “They’re pretty open [to funding training]” “There have been a variety of key areas in which we’ve had to put a lot of training into when it comes to H&S… we’re trying to make a standard for [the company]”
	Length of service	The time spent working in the Plant’s maintenance team	“I’ve been here since start-up… at least 5 years“ “I’m coming up to 5 years here” “I’ve been with the company for 7 years” A churn rate of ~20% per annum within the maintenance team was reported
Maintenance Approach	Objectives	Employee perception of the principle objectives of the maintenance approach within the Plant	“Keep the Plant running really… until the scheduled [weekly] shutdown period” “Keep the Plant running and keep it in a condition where it’s easily serviceable” “At this plant it’s just fire-fighting basically” “A top-level objective from a management perspective is plant availability, how long can we have that plant running for… minimal downtime, reduced expenditure to keep costs down”
	Scheduling and Documentation	Overview of the degree to which maintenance is planned and documented within the Plant	“I think some [PPM intervals] came from the manufacturers, others are basically experience… it’s really trial-and-error” “Basically, here it relies on experience... this, this and this have gone. Right, I’d better do this one first then” “Any jobs we do we have to do job sheets for, we put the asset numbers, time it took, date”

	Condition Assessment	Primary methods used within the Plant to identify the onset of undesirable equipment conditions	"Every week he [external belt technician] goes around and surveys all the belts using his knowledge and says 'right, this is what needs doing.' He gives me a list of faults he's found and the importance of them" "Mostly you will pick up [issues] visually with the checks that we do" "They're [plant techs] supposed to walk around, it [issue identification] all depends on how quickly they notice it" "The ones [conveyors] which are less likely to go are the ones they frequent. If they [plant techs] can see it, they notice it starting to go wrong… otherwise it'll purely rely on a PPM [to identify issues]" "It'll trip, sometimes they'll [plant techs] see it [the issue], stop the Plant and clear it but 9 times out of 10 the Plant will come to a halt because it's tripped"
Maintenance Issues	Importance of Cleaning	Evidence of impact of poor cleaning on Plant performance	"The Plant will get a blockage and they'll clear it off, hopefully they'll spot it before it gets too bad, and clean it" "Blockages, lack of cleaning basically, is your biggest cause [of downtime]" "Ingress of dirt and mess, that can cause a lot of damage"
	Impact of Belt Failures	Evidence of the impact of belt failures on Plant availability	"We identified a [belt] split but we couldn't get around to changing it... it split on a night shift and they were down for 6-7 hours"
	Process Linearity	Indications of the limiting effect of process linearity on Plant availability	"If we can divert the waste off of that belt, we'll do that [repair will be scheduled]. If we can't, if it's one of the main feed belts it'd be a plant shutdown… it [the repair] would be done there and then" "Literally every belt gets used… you can't just bypass it [product]"
	Under Resourcing	Demonstrations of under resourcing of maintenance effort	"You have a massive list of PPMs… when the Plant is running you can't get access… you get one day to try and get every job done... you can't win" "They vary the shutdowns so much… some weeks sections are shutdown so you can do 12 hours on each, other months you just get 12 hours a week on it [the Plant], everything else suffers as a consequence" "Because we run so often, we only get an hour of cleaning in the morning… a lot of them [conveyors] are hard to access... you're never going to get them all done"

Workforce Characterisation

Qualifications

Participants all reported to have spent most, if not all, of their working career within the area of maintenance, however, not necessarily exclusively within the waste management industry. Typically, formal qualifications around level 4-5 of the UK Regulated Qualifications Framework [98] were held including BTEC, HND and NVQ level 4.

Length of Service

Service length varied amongst participants, from less than 2 years to over 5. Some participants reported working at the Plant since its inception in 2011. In general, length of service was observed to increase with seniority as may be expected, with both senior employees within the hierarchy reporting to have achieved multiple internal promotions.

However, within the wider maintenance team populous a churn rate of ~20% per annum was reported by senior management, particularly focused within the lower levels of the team. Post completion of interviews, Maintenance Supervisor P2 was reported to have left the Operator.

Training

Due to the nature of the Plant environment significant mandatory health and safety related training is proved to all staff upon commencement of employment, as well as periodic updates. It was reported by P1 that the Operator was "*trying to make a standard*" with regards to health and safety beyond the minimum stipulated by regulations, a standard to which all employees were being brought up to.

Additionally, significant investment in maintenance-specific training was reported, particularly for specialist equipment e.g. shredders and sorters. This training is typically provided by the OEMs, generally off site. For example, it was reported that members of the maintenance team had recently returned from a manufacturer training course held overseas, funded by the Operator.

The Operator's attitude towards supporting the provision of training beyond the core requirements were generally reported as very positive by participants. P4 suggested that "*they always try and get you on a course*" and others suggested additional training, both technical and non-technical, is available to personnel.

Maintenance Approach

Objectives

Primarily participants stated that maintenance activities at the Plant are for the purpose of maximising operational availability, with sentiments such as 'fire-fighting' and 'keeping the Plant going at any cost' expressed. However, the more senior personnel did include consideration of additional factors such as minimising costs, increasing performance and satisfying safety legislations as well.

A general perception that the effectiveness of maintenance within the Plant has improved significantly since inception was reported by a number of participants, with many previously common issues now rarely occurring. It was suggested by the Maintenance Manager that the remaining issues are usage-based 'wear and tear' failures of consumables such as belts and bearings, with the aggressive operational environment and high utilisation being the root cause of these.

Scheduling and Documentation

The maintenance approach at the Plant was described by participants as a combination of reactive and planned preventative maintenance (PPM) elements. Aspirations to increase the degree of PPM actions implemented on site were suggested during interviewing, however, it was indicated that completion even of current schedules was challenging. The maintenance team are provided nominally with 12hrs/week of scheduled downtime however the limitations of this were raised; *"It's a nightmare. You get one day a week in which to get it [PPM] all done, you can't win."*

Additional frustrations around the certainty of this PPM window being available were apparent from participants. Numerous examples of the impact of reactive maintenance on scheduling were provided, wherein the occurrence of a failure within the Plant would result in the PPM window being moved and time lost to completing the reactive repair. *"I've spent 7 hours fixing that, that's 7 hours that comes off the next* [scheduled] *downtime. You won't get a* [scheduled] *downtime window that week because of that 7 hours. Normally we get 12 so you've already been robbed 5 hours."*

Participants reported that the overall maintenance approach at the plant is very much developed in-house using heuristics, supported initially by OEM guidelines. Essentially, intervals for services and inspections are set and then adjusted in response to the observed performance. P4 described the process as *"I check them every* 3 *months and they keep failing, I'd better check them every month."* Generally, schedules are time-in-service-based e.g. a conveyor is serviced at every x operational hours. However, the presence of constraints set by OEMs was indicated by the Maintenance Manager i.e. a specific machine may have to be serviced at certain intervals to retain its warranty.

Despite being a manual data capture process (i.e. paper-based), maintenance planning and actions at the Plant appear to be generally well documented. PPM and reactive jobs scheduled are documented and circulated to the team weekly, and maintenance personnel are required to complete a record of all jobs completed. However, it was reported by some participants that fluctuations in the diligence of maintenance personnel in ensuring proper documentation is completed have been observed at the Plant. As such, the Maintenance Manager did indicate aspirations to introduce a computerised maintenance management system (CMMS) at the Plant.

Participants did not indicate captured maintenance data being used for any purposes other than record keeping; no quantitative analysis of Plant performance is obviously performed at present.

Assessment of Condition

All interviewees reported visual inspection to be the most effective mechanism utilised by maintenance personnel in identifying Plant issues. Issues that are severe enough to stop the Plant (e.g. a motor overload) will be reported to personnel automatically via a control room human-machine interface (HMI) however this is a binary state (i.e. fault or no fault) and no additional diagnostic information to aid the rectification of the issue is provided.

As well as component failure some undesirable process conditions, such as the build-up of product at transfer points (termed 'clumping'), were reported as relying on visual inspection for identification. It was also indicated that such issues can be very difficult to detect due to their transient nature, relying on a person being in the right place at the right time to spot them.

Within the Plant, visual inspection of assets is performed both formally as part of the PPM schedule, as well as informally by plant technicians during their regular duties. However, these informal inspections are not enforced, nor is there a clear and effective mechanism for the reporting of identified issues; verbal communication appears to be the accepted method. Thus, the effectiveness of visual inspection in preventing failures appears limited - *"The ones* [conveyors] *that are less likely to go* [fail] *are the ones they* [plant technicians] *frequent, the ones* *with good access. If they can see it they'll know it's starting to go wrong. A conveyor that's up in the air, you can guarantee the tail drum will go* [fail] *on that."*

This statement also indicates an inherent issue with reliance upon visual inspection for condition identification at the Plant. Within the Plant, access to many areas is severely restricted for safety reasons, with certain areas only accessible during shutdowns. Additionally, physical constraints around assets can restrict access further, resulting in specialist equipment being required such as cherry pickers or scaffolding to gain access. This compromises the ability of personnel to complete visual inspections and thus identify adverse conditions further, with P4 noting that *"when the Plant's running you can't do a lot, you can't get in there and have a good look."*

Maintenance Issues

The Importance of Cleaning

All participants highlighted general blockages of product within conveyors as being amongst the most significant causes of downtime at the Plant. Inadequate cleaning leads to build-up of product on conveyors, often around bearings and motors, which can lead to a multitude of issues such as overheating, ingress of contaminants and mechanical damage.

Not only is adequate cleaning important in preventing direct stoppages, participants indicated that it also has an influence on the occurrence of more severe issues. The secondary effects of blockages can be much more significant if not rectified, for example build-up of product can lead to bearing failure which in turn can damage the shaft, requiring significant effort to repair. It was also suggested that minor component failure can be acceptable if it enables the indication of a potential more severe issue and thus prevention of occurrence.

The identification and clearing of blockages within assets is primarily the responsibility of plant technicians, who are given a cleaning schedule to follow, however, there was suggestion from some participants that these are not always completed and, as such, assets often operate in non-optimal conditions. P3 commented that *"because we run so often, we only get an hour of cleaning in the morning... a lot of them* [conveyors] *are hard to access... you're never going to get them all done."*

Belt Failures

Issues related to conveyor belts were noted by all participants as being significant causes of unplanned downtime at the Plant. These issues were suggested as being unavoidable with cumulative wear a consequence of the Plant environment – *"Because they're rubber they're going to wear out. We predict them* [belt failures] *much better now, we try to repair them before they break."*

The corrective action required in response to belt issues, and thus their impact on availability, is dependent on the severity of the damage incurred. If damage to the belt is small e.g. a hole or gash, then the belt can be patched during scheduled maintenance. However, the completion of such a repair is dependent on both the damage being identified and a judgement call by the maintenance personnel as to the severity. P2 commented that *"if it* [a belt] *has been noticed that it's worn, we'll monitor it and it'll be done* [repaired] *in a maintenance window. If it's worn to an extent that it snaps, where no-one has noticed it* [the damage]*, obviously it would have to be done there and then."*

If a belt completely fails (i.e. is completely severed) it will always incur downtime, and generally will be tackled immediately to ensure the Plant can return to operation as soon as possible. As such it was reported that the Operator has requested an employee of the belt manufacturer be on site at all times, to ensure issues can be tackled immediately. The financial implications of this to the Operator were not reported.

To mitigate against belt failures a weekly check of belts is performed by the belt manufacturer's on-site employee. He assesses the condition of the belts visually and, using his experience, provides the Operator with a list of recommended actions. No objective measure of belt condition was reported to be used by participants.

Some participants reported improvements in the frequency of belt repairs, with it suggested that much less variance in failure periods between belts is now observed as a result of increased experience with operating the Plant. However, others suggested that belt failures were 'random,' with it being possible to either go extended periods without any occurring or equally multiple failures can occur in a short period of time. It was also noted that all participants provided a different answer when asked to estimate the frequency at which belt failures occur, from weekly through to every six months of operation.

In terms of the distribution of belt failures throughout the Plant, it was suggested by the Maintenance Manager that "most of our conveyors are the same and they wear pretty evenly." In contrast, it was suggested by participants P3 and P4 (who are "at the coal face") that specific conveyors can be more problematic. Experience tells them that, for example, more issues can be expected at specific conveyors due to their form (e.g. a right-angle as oppose to a straight conveyor) or their location (e.g. located below other conveyors).

Process Linearity

The issue of linearity within the processes at the Plant was indicated by some participants as being problematic. Due to the configuration of the process, failures in any one section will generally result in the entire process having to stop, and thus unscheduled downtime being incurred. As noted by P4, *"Literally every belt gets used... you can't just bypass it* [product]."

As such, significant maintenance effort is given to the prevention of failures to specific process critical assets. For example, P3 commented on the importance of the shredders and the impact of this on their maintenance - *"That* [shredder] *is the biggest priority. If your shredder goes down, that's it, game over... our welder spends* 12 *hours a week on* [the shredders]*... without that they would be breaking down all the time."* As a result of this effort the shredders are considered to be one of the most reliable areas of the Plant as reported by a number of participants.

Under Resourcing

The inability of the maintenance team to implement planned actions, and the impact on plant availability, were noted throughout the interviewing process. *"You have a massive list of PPMs... when the Plant is running you can't get access... you get one day to try and get every job done... you can't win"* commented P4.

The approach from the Operator with regards to operational capacity appears to be to keep increasing it until it breaks down. Little consideration seems to be given to the impact of this mindset on the ability of the maintenance team to keep the Plant operational. Running at such high levels (continuously for 6.5 days/week) not only overworks the equipment thus increasing the likelihood of failure, but also reduces the time available to the maintenance team to complete PPM actions. As noted by the Maintenance Manager *"ideally we could service everything every week, but that's unrealistic."*

3.3.3 Discussion

From the conducted analysis of interviews, a number of themes relating to existing practice at the Plant and the issues therein can be identified.

Maintenance Characteristics

Based upon the observations made at the subject plant maintenance within the waste management industry (WM) can be seen to be driven primarily by availability. In contrast to the aerospace industry for example, where additional factors such as satisfying performance and safety requirements or innovating within a competitive market are relevant [38], the WM industry view of maintenance appears to one of it as a 'cost centre' or a 'necessary evil'. The supply of waste to process is practically inexhaustible, meaning very high levels of availability of assets is demanded to maximise throughput.

This demand applies limitations on the ability of the on-site maintenance team to realise such levels of availability, both through restricting access to assets to perform inspections and maintenance as well as through accelerating the rate of degradation of assets. By operating assets at maximum (or even above) design capacity the rate at which issues progress from inception to functional failure is increased, resulting in a corresponding increase in maintenance action requirement. However, maintenance resources (i.e. personnel) do not appear to have been increased proportionally.

Significant improvements in the effectiveness of maintenance at the Plant since initial operation were reported by personnel, although this may only be a perception, with no real quantification of improvement provided to support such claims. However, it can reasonably be assumed that effectiveness of maintenance should, within reason, increase over time as personnel gain experience in operating and maintaining the Plant's specific assets.

Accordingly, a desire to implement increased levels of preventative actions on-site was reported by the team, in doing so reducing 'fire-fighting' activities. To that end, efforts to implement planned preventative maintenance actions have been made at the Plant. However, significant challenges to the completion of plans have been encountered, restricted by the availability of both personnel and planned downtime.

Socio-technical Challenges

The existence of socio-technical challenges at the Plant impact upon the ability of the maintenance team to satisfy availability demands. Firstly, much of the maintenance approach implemented is based upon the experience held by key personnel in tacit form. The Operator's ability to achieve existing levels of maintenance effectiveness is therefore reliant upon retaining these persons, making the reported 20% churn rate within the maintenance team a significant concern. Accordingly improving the resilience of the Operator to departures of key personnel through the undertaking of a series of Externalization activities as described by Nonaka [99] may benefit. This process would constitute converting tacit knowledge (i.e. 'know how') as held by maintenance personnel into explicit knowledge (i.e. 'know what') through the production of documentation such as guide and manuals etc.

A secondary effect of a high churn rate within the Plant may be reduced diligence and initiative amongst personnel in the context of identifying and reporting issues observed. Management reported that plant technician roles are typically filled by low-skilled transient workers, often of foreign origin. This is likely to further contribute to communication problems between the plant technicians and the maintenance team, possibly impacting the effectiveness of maintenance.

Similarly, a general feeling of maintenance effectiveness at the Plant being adversely affected by under-resourcing was reported. Members of the maintenance team are facing challenges in completing the volume of actions required, particularly those which are considered non-essential, i.e. preventative actions.

In a broader context a socio-technical issue can be seen to exist around access to the state-of-the-art technology available within other industries. The WM industry is typically slow to take up new technology as reflected in the absence of more sophisticated approaches to maintenance being implemented at the Plant. For example, Reliability-centred Maintenance (RCM) is a relatively mature approach, implemented widely across many industries [100], yet remains unexplored at the Plant.

Similarly, little penetration of 'big data' can be observed within the Plant, in contrast to general industry. Performance data associated with assets was not observed to be significantly utilised by the maintenance team, presumably due to such data not being available, a consequence of the 'agricultural' nature of assets within the Plant. As an example, the revision of PPM intervals was suggested as being a very much manual process, reliant on the judgement of maintenance personnel, not actual operational data. With over 80 conveyors at the Plant plus specialist equipment, there is the potential for inefficacy in the definition of PPM intervals if no formalised process exists to feed back objective performance data.

The agricultural nature of plant equipment is likely a consequence not only of limited visibility of state-of-the-art but also financial constraints; waste processing plants are operating in the face of increasingly demanding legislation, without corresponding increases in financial compensation. Thus, supporting innovation can be expected to perceive a high degree of risk to decision-makers. Additionally, a culture of innovation has not been harboured within the industry historically, restricting both visibility and subsequent penetration of state-of-the-art technologies.

Technical Challenges

In addition to the presence of socio-technical issues, a number of technical issues within the Plant were highlighted as impacting upon maintenance effectiveness. Central to these issues is a reliance upon visual inspection methods for the assessment of condition and identification of emergent issues at the Plant. To conduct visual inspections personnel require physical access to the Plant environment, however, this is severely restricted whilst the Plant is operating, due to health and safety concerns. Thus, as a consequence of the minimal planned downtime implemented at the plant (~12hours/week) the maintenance team are not able to conduct visual inspections at desired instances. Restrictions on access to assets within the Plant also limits visibility of in-service usage patterns; abnormal/abuse loads experienced by systems whilst operating are typically not observed by personnel.

Furthermore, where inspections of assets are undertaken the resulting assessments of condition are at the discretion of maintenance personnel and their experience therein. Little to no evidence of objective measures being employed to assess condition was found. A comprehensive list of instructions to guide inspections is available to personnel to support the conducting of inspections, however, the resulting estimation of condition is still subjective and generally constitutes a binary state e.g. *"belt OK"* or *"belt needs repair/replacement."* Consequently, inefficiencies can be induced: asset failures can occur when the onset of failure is not identified or conversely assets can be maintained too proactively, that is before their useful life is realised, introducing added cost and unnecessary effort.

The most resource-consuming activity at the Plant was found to be the correction of belt issues, both those completed reactively and preventatively. The occurrence of belt issues typically will prevent a conveyor from being operated, which, due to the linearity of the overall process, induces unplanned downtime. Belt issues also carry significant direct costs to the Operator, both in terms of parts costs and effort consumed. Again, the limited ability personnel are permitted in observing assets in operation contributes to the severity of belt issues; precursors to catastrophic belt failure are challenging to identify and significant delays between the occurrence and detection of catastrophic failures are common, resulting in a reliance upon 'good fortune' to identify issues promptly.

The impact of poor cleaning of assets was also identified as a significant contributor to unplanned downtime at the Plant. It is possible that improvements could be realised through optimisation of procedures and increased resource provision. However, ultimately due to the nature of conveyor operation and the characteristics of the materials conveyed regular accumulation of contaminating material is inevitable. The impact of effective cleaning can only reduce this rate, with no cleaning operation able to restore a conveyor to a perfectly clean state. Accordingly, providing an ability for maintenance personnel to gauge the cleanliness of a system without relying on visual inspection may offset the limitations resulting from lack of access to assets.

3.3.4 Summary of Findings

Four semi-structured interviews were conducted with members of the on-site maintenance team located at one of the Operator's plants, to understand how maintenance is implemented and the challenges faced. Through analysis of interview audio key findings relating to the general characteristics of maintenance as implemented were elicited, and the existence of a range of both socio-technical and technical challenges were identified.

The goal of the Plant is to maximise throughput and hence availability of assets is of primary concern. This is reflected in the maintenance approach implemented, where all activities are for the purpose of ensuring the Plant remains operational above all else. A common theme amongst issues faced by the maintenance team in satisfying such demands is an inability for personnel to observe the operation of assets within the Plant. Whilst the maintenance team was found to be both well-trained and motivated, an inherent lack of access to Plant assets restricts their ability to satisfy availability demands. This is further amplified by a general under-resourcing of maintenance personnel on-site, with members of the team unable to keep up with the volume of issues occurring throughout the Plant.

Fundamentally, the approach to and effectiveness of maintenance at the Plant was found to be based upon the experience and expertise of the maintenance team, making the reported levels of personnel churn a significant concern. Personnel aspire to implement more preventative actions on-site, due to an expectation that this will reduce the quantity of reactive actions required, which typically require more involved corrective actions. However, their ability to implement preventative actions is again restricted by limitations on available resource and process downtime, as well as the impact of reactive actions occurring, leading to the 'fire-fighting' culture reported. Enforcing planned downtime to conduct such actions is challenging when the requirement to conduct actions is not obvious i.e. a failure has not already occurred. As such, an 'opportunistic' approach to maintenance actions is commonly implemented at the Plant, with many components thus being replaced without any obvious signs of degradation being identified, incurring unnecessary costs. Access to objective asset condition data may support the decision-making processes of maintenance personnel in this regard, providing a means of assessing the actual usage and condition of assets without relying upon subjective visual inspection methods.

3.4 Implications for Research

Primarily maintenance practices within bulk handling applications appear to constitute a reactive approach supplemented by preventative interventions where possible; given the low safety criticality of these applications run-to-failure practices are able to be employed and opportunistic maintenance is widely practiced. However, moving towards an increase in preventative actions would certainly be of benefit, reducing the occurrence of costly 'fire-fighting' activities. To achieve this maintenance personnel require support in assessing the requirements of systems in-service, to overcome the limitations identified. The implementation of predictive approaches remains mostly unexplored within the bulk handling industries, however, based upon the findings from the research activities conduced their suitability here may be limited. When evaluated against the criteria for the technical feasibility of an on-condition task as discussed in Section 3.1.3 it can be concluded that the characteristics of typical bulk handling applications may inherently render PdM unsuitable. As presented in Table 3.5, only three of the four criterions can be considered satisfiable given the constraints and practices within the Operator's Plant.

Table 3.5: Criteria for feasible implementation of predictive maintenance, assessed against findings from the reported activities.

Criterion #1: *It is possible to define a clear potential failure condition.* NOT SATISFIED
For some failure modes this is trivial/obvious (i.e. belt severed, motor stopped). However, many issues are assessed in a subjective manner (e.g. bearing issues) and actions taken in an opportunistic manner, meaning the specific point of failure is not defined in an objective, consistent manner.
Criterion #2: *The interval between the onset of failure and functional failure is fairly consistent.* NOT SATISFIED
No clear relationship between time in service and component replacements was identified, with significant variability observed due to the wide range of variables contributing to the life of an asset and influence of specific patterns of loading experienced by each conveyor asset.
Criterion #3: *It is practical to monitor the assets at intervals less than the interval between onset and functional failure.* POTENTIALLY SATISFIABLE
With existing practice access to assets is severely limited, restricting the frequency at which inspections can be conducted. However, with the introduction of continuous monitoring of assets reducing such intervals may be possible assuming suitable indicators of asset condition can be identified.
Criterion #4: *The size of the onset to functional failure interval is significant enough to be actionable upon.* NOT SATISFIED
The rate of development of failure modes which directly impact upon the operability of a conveyor (i.e. belt and motor issues) is such that detection of their onset prior to functional failure is infeasible (i.e. events such as overloading due to blockages or rapid-type belt failure), limiting the ability of personnel to act upon theoretical prognostic insights.

Not only are consistent, progressive failure modes present, but a lack of access to assets will likely restrict the ability of a maintenance team to act upon predictive insights. Despite the relative simplicity of CBSs the task of assessing condition is typically complex and influenced by a multitude of factors such as duty, environment, installation and manufacture. As such, the prediction of future condition represents a significant challenge with even nominally identical system likely to realise different operational life due to variance in usage.

In addition, many of the ‘failure modes’ typically reported as the subject of prognostics tasks within literature would not be considered sufficiently impactful to warrant incurring process downtime to correct within the context of a waste processing plant. For example, a common prognostic task reported within literature is that of predicting the remaining useful life of a rolling element based upon the estimated size of a race fault such as spalling or brinelling (e.g.

[101]–[105]). Within the Operator's plants the occurrence of such issues would be considered insignificant due to their negligible impact upon asset operation. A bearing is essentially assumed a consumable component with a low associated cost to replace so there is minimal penalty associated with continuing to operate bearings in such condition. Accordingly, the run-to-failure approach commonly implemented may represent the most appropriate strategy, enabling the maximum life of components to be extracted, which, due to the low cost of replacement COTS parts, may prove more economical than proactive replacements. In contrast to other industries, such as aerospace, this is considered feasible due to the relatively low impact of functional failure in terms of safety concerns and knock-on costs. Fundamentally, even if accurate predictive insights can be generated their potential value is limited, a sentiment echoed by Chanana et. al. [88] who note that "*only a handful of startups understand that predicting failure is of limited use if customers don't know what to do with that information.*"

Chapter 4: The Principles and Practice of Continuous Monitoring

Underpinning many of the concepts discussed in Chapters 2 and 3 is a reliance upon being able to understand how the condition of an asset changes throughout its service life in response to how it is operated, whether this is to support design, operation or maintenance activities. Traditionally, to obtain such information requires maintenance personnel to conduct periodic inspections of an asset, during which human senses are utilised to identify its current state, from which an assessment of its condition can be made. However, given the constraints associated with visual inspection techniques as identified in Chapter 2, increasingly such techniques are being supplemented by (or even entirely replaced by) modern continuous monitoring (CM) techniques. Accordingly, this chapter explores extant literature within the area of CM to identify the current state of maturity of the technology, as well as to what degree it has found adoption throughout industry, particularly applications to conveyor belt systems. Given the potential affordances of the technology the chapter reports a trial implementation of a continuous monitoring system conducted at one of the Operator's plants.

4.1 Monitoring Principles

At a high level the term *health* is used to describe the current condition of an asset relative to its normal condition, where its *condition* refers to the magnitude at that instant of the specific state(s) which can affect its health. For example, the condition of a pump could be defined in terms of the magnitude of debris present within its fluid lubricant; as the magnitude of debris increases the condition of the pump decreases. When debris reaches a specific threshold the condition of the pump is degraded such that health of the pump transitions from *good* to *poor*.

Condition monitoring (CdM) is a non-destructive testing (NDT) technique comprising the continuous evaluation of an asset throughout its service life, typically such that its health can be evaluated [29], [46]. It is the term *continuous* within this definition that differentiates the modern concept of CdM from traditionally practiced periodic NDT techniques such as visual inspection and portable instrument monitoring. However, it is important to recognise a differentiation between the concepts of *condition monitoring* and *continuous monitoring*; the two are not synonymous. The condition of an asset can be monitored in a non-continuous manner and conversely continuously monitoring an asset will not inherently provide insight into its condition. A continuous monitoring system (CMS) utilises various transducers and sensors to acquire continuous streams of data from an asset, typically at a component level, from which insight into the condition of the asset can be gained throughout its service life (Figure 4.1).

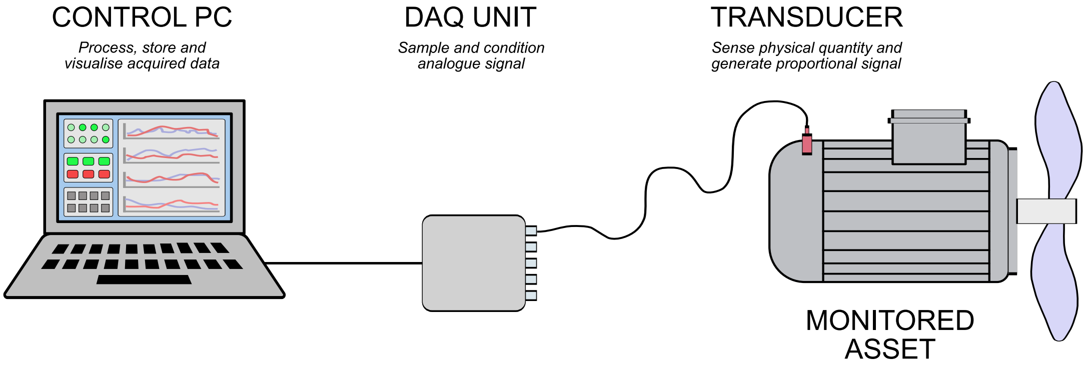

Figure 4.1: Major components of a basic condition monitoring system

Historically the cost of such technology restricted its use to only the highest value or most critical assets, resulting in CM being implemented as a bespoke targeted solution in applications such as the monitoring of:

- **A process critical asset/single-point of-failure**
  e.g. a railway point [106].
- **An asset where a certain level of performance must be assured**
  e.g. the flowrate through a hydroelectric generator [107].
- **An asset which carries a high penalty for lost output**
  e.g. a power station generator [108].

However, in recent years due to advancements in enabling technologies the costs associated with implementing a CMS have fallen dramatically, leading to a proliferation of CM across industry [74].

Through adoption of CM techniques a number of benefits can potentially be realised, primary amongst which is to enable a shift towards condition-based maintenance of assets, as discussed in Chapter 3, Section 3.1.2. In the aerospace industry CM has been leveraged within the scope of integrated vehicle health management (IVHM) to satisfy an emergent demand for online systems capable of providing maintenance decision support in real-time in response to situations which occur [38], [74]. By monitoring key aircraft components in-flight issues are able to be better anticipated and thus maintenance actions better planned, resulting in significant reductions in ‘time on the ground’, a key driver for airlines. Flight 2050: Europe’s Vision for Aviation [109] has specified a number of targets that directly relate to a reduction in time-on-the-ground and it has been suggested that these targets create an “overwhelming necessity” for IVHM [31].

Similarly, CM techniques have been widely adopted to support improvements in wind turbine reliability. Faced with a combination of catastrophic gearbox failures and very high repair costs, particularly in the case of offshore turbines where accessing assets is challenging, CM has provided a clear benefit through advanced warning of impending issues [110]. Not only has this enabled operators to better schedule maintenance actions but also limited the impact of failures which do occur, greatly reducing time-to-repair and parts costs [111], [112].

In contrast, CM techniques have not yet found widespread adoption within the bulk handling industries. Here, in contrast to ‘early-adopter’ industries such as aerospace or automotive a culture of innovation has not been cultivated and instead new technologies have only diffused into the industries once matured elsewhere. Due to the simplistic nature of CBS operations manufacturers are presented with little opportunity to differentiate within the market beyond offering increased throughput or reliability. With designs converging to near identical forms across manufacturers, as discussed in Chapter 2, Section 1, individual manufacturers have had little incentive to invest significantly in novel technologies. In recent years CM technologies have started to be introduced somewhat, with most major manufacturers offering some form of CM solution such as Fenner-Dunlop’s Eagle Eye® [113], Continental’s CONTI® Protect [114] and Phoenix’s PHOENOGUARD® PX system [115], which all provide continuous monitoring of various CBS parameters. However, implementations appear to have thus far been restricted to higher-value bulk handling industries such as mining, where modern systems are incorporating CM techniques to enable remote diagnostics of faults such as shaft unbalance and bearing defects, alerting maintenance personnel automatically and thus reducing the requirement for local inspections [21]. In wider bulk handling applications, due to the longevity of CBSs and the prevalence of single-point-of-failure configuration operators are likely to wait until end-of-life before replacing systems, only at which point the adoption of modern practices may be considered. However, even at this point operators may still be reluctant to adopt new technologies unless a clear demand can be identified, which can be a challenge in itself, and is thus the subject of much research (e.g. [74]). As noted by Lodewijks et. al. [116], *”it’s not* *straightforward to convince procurement personnel at a mine to invest in technology through demonstration of technical capabilities alone."* It may be the case that buy-in for new technology can only be gained through demonstration of a combination of both quantitative and qualitative benefits. For example, it has been suggested that there can be a significant psychological benefit to operators through adoption of CM strategies, facilitating increased confidence in process operation [117]. In the context of CBSs specifically a number of additional benefits to operators may be unlocked through adoption of CM techniques, including:

- **Automatic diagnosis of belt stoppages**
  Diagnosing the root cause of an automated belt trip can be challenging for maintenance personnel in the field. The insight provided by an appropriate CM system could enable necessary actions and spare parts to be selected without requiring an inspection to be conducted, reducing correction times.
- **Improved record keeping**
  A CM system will generate a historian of objective data describing system performance without relying on personnel to manually input data, which can be used to update and improve operation and maintenance [11].
- **Reductions in insurance premiums**
  The increased visibility of operations provided by an appropriate CM system can mitigate for catastrophic operational issues, reducing the risk of damage and injury, as well as lost operation. For example, fire is a significant risk in many CBS applications, particularly waste processing [118] and subsurface mining operations, with claims for fires directly involving CBSs costing an average of $8m per claim [44]. A CBS will literally convey a fire about a plant so if not identified rapidly an entire facility can experience irreparable damage in minutes. By monitoring assets locally issues can be identified without manual intervention.
- **Enable novel revenue models**
  A greater understanding of system usage can permit the implementation of dynamic pricing structures, wherein customers are charged consummate with their actual usage, rather than static time-based structures.
- **Optimisation of system operation**
  Similarly, greater understanding of usage in-service can be leveraged to modify operational patterns such that the mean time between failures (MTBF) of systems can be improved. For

example, loading levels can be monitored and action taken if excessive loads are being experienced frequently.

4.2 State-of-the-Art Practice

As a result, a vast body of literature has been generated around CM concepts, both academic and industrial, comprising applications across a broad spectrum of domains, for which a number of exhaustive review papers have been produced by authors (e.g. [119]–[121]).

In the context of rotating machinery research is most commonly focused around the CM of a key[22] asset in isolation (e.g. [84], [122]–[124]), with the aim of detecting the onset of a specific fault(s). Generally, a *fault* is considered to have occurred when at least one system feature deviates from its acceptable, usual condition [125]. For example, if a gearbox's temperature or a relay's current draw exceeds safe limits then a fault may be considered to have occurred. A fault can ultimately lead to failure if not addressed, however, the occurrence of a fault does not necessarily imply the onset of failure. At the highest level fault diagnostics is concerned with detecting the occurrence of faults, that is, making a binary classification as to whether a fault is present or not. Detection can subsequently be followed by determining where specifically the fault has occurred (*isolation* e.g. tail bearing, motor phase etc.) and what the nature of the fault is (*typing* e.g. cracked rolling element, open circuit etc.).

As summarised for some common applications in Table 4.1, faults targeted for detection are generally linked directly with the physics of operation of an asset and to simplify monitoring often only detection of a single or subset of faults/failure modes are focused on (e.g. [122], [126]).

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[22] In this context a 'key' asset refers generally to either an asset which is process critical or an asset which incurs a high cost penalty when replacement is required, either in part cost or time (or both).

Table 4.1: Primary failure modes of common rotating assets targeted for detection within CM and associated monitored parameters.

Asset Type	Typical Faults	Typically Monitored Parameters	Example
Motor	Air-gap eccentricity, broken bar ends, bearing damage	Rotor vibration, acoustic emission, stator current, electrical discharge	[127]
Pump	Seal failure, shaft misalignment, lubrication escape, bearing damage	Thermal signature, lubrication/particle analysis, shaft vibration	[107]
Gearbox	Shaft corrosion, tooth breakage, bearing damage	Shaft vibration, shaft speed, acoustic emission, lubrication/particle analysis	[128]
Bearing	Lubrication escape, structural failure due to excessive wear, debris in lubrication	Vibration, temperature, shock-pulse method	[102]

Due to their ubiquity throughout industry induction motors in particular have seen much attention, with much research conducted around using CM for the detection of faults such as broken rotor bars, air-gap eccentricity and damaged bearings (e.g. [122], [129], [130]). Similarly, the application of CM to gearboxes for the purpose of fault identification has generated much literature, with authors typically seeking to diagnose the onset of types of tooth damage such as cracking, scuffing and pitting (e.g. [131]–[133]).

Essentially, the process of fault diagnostics constitutes mapping measured parameter data to features associated with known fault types, traditionally a manual task requiring a significant degree of domain-specific expertise [119]. For this purpose, a common approach employed within literature is one based around the utilisation of measured component vibrations in conjunction with advanced signal processing techniques such as spectral kurtosis, cepstrum analysis or wavelet analysis (e.g. [104], [134]). Overall, for fault detection purposes vibration-based monitoring represents the most widespread and mature technique across industry [135]. Here, the task is to separate deterministic components (i.e. those related to the characteristics of known faults) from non-deterministic components (i.e. noise), such that the severity and/or presence of fault frequencies can be identified and thus the presence and possibly severity of faults can be determined (e.g. [136], [137]). Principle challenges in this regard include isolating the effects of faults from effects of changes in system speed and/or load, as well as quantifying the severity of faults (e.g. [131], [138]).

Overall, the area of machine fault diagnostics represents an active and technically sophisticated field. However, the content of recent literature indicates that diminishing returns are being realised, with only small, incremental advancements being presented. Furthermore, a significant disconnect between the academic and industrial state-of-the-art is apparent, with much academic work consigned to only laboratory-based implementation and evaluation only (e.g. [133], [139], [140]).

4.2.1 Continuous Monitoring of Conveyor Belt Systems

Within the context of CBSs specifically existing applications of CM have typically been for the purposes of diagnosing faults in or damage to belts, due to their criticality to operation. Accordingly, much of the wider extant CM literature can be considered applicable to CBSs, however, in addition CBS-specific applications are also represented in literature.

Considering the Manufacturer and the Operator specifically, little CM of systems is currently implemented. Historically, the Manufacturer employed no CM whatsoever; recently developed models of CBS do incorporate a voltage monitoring device interfaced via a digital display, however this data is not logged or accessible remotely and instead exists purely as a diagnostic aid for reactive maintenance personnel to use if call to site. The Operator has a supervisory control and data acquisition (SCADA) system installed within each plant, however, again this data is not logged nor accessible remotely. Furthermore, the SCADA system only provides a binary running state associated with each CBS, delivered at a low sample rate (~1Hz).

Belts

Much effort has been given to the task of detecting the occurrence of wear and tears within a belt, either partial or catastrophic (i.e. total severance across a belt's width). If such conditions can be identified in a timely manner it may be possible to repair the belt and thus minimise disruption to operation, whereas if a torn belt is continued to be operated until catastrophic failure a system will immediately be rendered inoperable, requiring significant resource to correct. A number of different approaches to the task have been pursued, with no consensus reached as to the 'optimal' approach. However, common to all approaches is their focus on the monitoring of gradual-type failures, as discussed in Chapter 3.

Initial efforts in the area were published by Harrison and Brown in the early 1980s at the University of Newcastle, Australia [141], [142] who developed a non-contact method for the detection of corroded and broken cords within a steel-reinforced belt. By exploiting the principle of Faraday's Law of Induction areas of damage or breaks in pre-magnetized cords could be detected by a localised change in induced voltage. Throughout the 1980s and 1990s further methods for NDT of belts in-service were developed, primarily by Australian researchers, driven by demands from the indigenous mining industries, including techniques based upon detection via magnetic reluctance, capacitance and ultrasound [143]. More recently, a significant volume of work has been conducted by Polish researchers into improving upon magnetism-based damage detection methods by enabling damage to be automatically localised in the belt, a process which previously required manual interrogation. Their work, within the scope of the DiagBelt project [144] led by Blazej et. al. [145], has also explored a number of alternatives to magnetism-based techniques, such as vision and thermal imaging, to enable application to fabric carcass belts as well as steel cord belts. Increasingly, vision-based belt monitoring techniques are being reported throughout literature, with a number of Chinese researchers (e.g. [110], [146]) proposing methods in which image processing techniques developed in alternative fields are leveraged to identify surface damage. Such approaches have the advantage of being significantly less intrusive, with overhead cameras able to be installed with minimal complexity, however, the inherent sensitivity to environmental conditions (e.g. lighting changes, airborne particulates, dirt etc.) associated with visual imaging has proven to be problematic, restricting such research to laboratory environments currently.

An alternative approach to the problem is taken by Pang and Lodewijks [147] who propose to modify the design of belts themselves to support increased visibility of their condition in-service. Their approach uses a custom belt within which a magnetic matrix is embedded during manufacture, and a sensor used to detect the position of each element of the matrix whilst in-service. With the nominal position of each element when the belt is in a 'fresh' state known, by measuring any changes in position it is possible to detect the occurrence of different forms of belt deformation, such as elongation and misalignment. Whilst capabilities of the proposed system are theoretically impressive the reliance upon a custom belt is likely to severely restrict the industrial applicability of the system.

Commercially, the Australian company BeltScan Systems represent the market leader in belt monitoring technologies [148], with their Belt Guard® range offering a comprehensive suite of belt monitoring technologies, with systems operating worldwide since the early 1990s. An alternative X-ray based belt monitoring solution is offered by the German company CBG under their CBGuard brand [149], who report having over 300 systems operating in China alone [150]. In this approach a belt is targeted with directed x-rays which penetrate through the thickness of the belt onto a detector unit. By analysing the level of attenuation local variation in belt thickness is able to be inferred and a 'picture' of the belt generated. As such, the system offers operators an alternative to traditional visual inspection techniques for the evaluation of belt condition.

Drive Components

In general, it can be observed that the majority of extant applications of CM for fault detection purposes, both CBS and non-CBS, employ a direct approach to the monitoring task. That is, monitored parameters are associated with the asset in which faults are to be detected e.g. a gearbox's temperature is monitored to identify the occurrence of damage within the gearbox. Few authors have investigated the feasibility of indirect monitoring of faults i.e. inferring the occurrence of a fault in one asset through the monitoring of a second asset. Through such an approach not only can sensor requirements potentially be reduced (i.e. existing monitoring hardware can be exploited) but monitoring complexity can also be reduced (i.e. an easier to access asset can be monitored or a less intrusive sensing method can be employed), both of which contribute to reducing the cost and increasing the reliability of monitoring, particularly attractive for industrial applications.

Efforts in this area have been focused on the use of motor electrical power parameters to identify mechanical issues within coupled assets such as gearboxes and bearings. Such approaches exploit the transmission paths within electromechanical systems through which mechanical vibrations generated in coupled mechanical asset(s) will transmit back to a motor, where they will manifest as modulations in electrical parameters. Frini et. al. [151] propose an approach to the detection of gear damage within a gearbox rigidly coupled to an induction motor through observation of changes in the properties of electrical currents in the motor. Their approach proved sensitive to changes in gear condition as a result of naturally occurring wear, with faults of interest manifesting as visible deformations in geometric patterns. Picot et. al. [152] developed an approach to the detection of slackness in a belt drive system based upon the monitoring of the motor's stator current draw. By injecting a low speed modulation into the motor's speed reference signal transient behaviour is excited in the belt without significantly affecting its operation, from which a diagnostic indicator based upon statistical measures can be used to differentiate healthy from abnormal responses. Similarly, the Artesis system (now part of Bentley Nevada under the AnomAlert brand [153]) offers an industrial solution for the detection of faults in mechanical drivetrains such as rotor imbalance and coupling issues, through monitoring of drive motor electrical power. The system is based upon academic work conducted by Duyar ([154], [155]) on behalf of NASA into fault detection for the Space Shuttle and again is based upon the principle of detecting mechanical faults downstream of an induction motor through monitoring of the motor's electrical power. Synchronous measurements of motor voltage and current draw are first acquired and then measured values are compared against expected values as estimated from a physics-based model of an induction motor system. The residual between the two is then classified against known fault types using a neural network which is trained during the initial few weeks of the system operating.

Whilst the majority of applications of CM to CBSs have been for fault detection purposes, some authors have exploited CM techniques for alternative purposes. However, all such work has been essentially for 'one off' purposes and thus has employed bespoke/custom monitoring setups not designed for the rigours of continuous industrial application, nor has data been used to support in-service decision making. He et. al. [156] propose a novel control strategy to improve the energy efficiency of a CBS, in which the speed of the belt is automatically adjusted in real-time to compensate for the dynamic live load on the belt. Soprana et. al. [157] use a vision-based approach to characterise the material being conveyed by a system in real-time, such that the quality of the material can be verified. CM has also found use within a laboratory environment to enable the characterisation of various aspects of CBS dynamics, typically to improve understanding of rolling resistance, such that improvements to the design of systems can be made. For example, Munzenberger and Wheeler [158] attempted to measure system losses through measurements of dynamic forces within a system's support structure, such that analytic modes of CBS power consumption could be improved. Similarly, Liu et. al. [159] utilised a tactile pressure sensor to measure the dynamic pressure on a loaded belt as caused by material being loaded onto the belt, again as a means to improve analytical models. Building upon this work Ilic and Wheeler [160] used a similar technique to improve understanding of interactions between powdered bulk solids and belts. During tests a tactile pressure sensor was again used to evaluate the distribution of load applied by different materials such as river sand, gravel and coal, from which models were validated, leading to improved methods for the calculation of losses due to bulk solid flexure.

4.3 Implementation Challenges

Throughout literature it is common for the adoption of continuous monitoring to be presented as a panacea, inherently able to realise value in any application. However, despite the potential affordances the implementation of CM is not without its challenges, which can restrict both its suitability and viability to a specific application. The challenges, both commercial and technical in nature, should be considered prior to each implementation to ensure value can be delivered through CM.

4.3.1 Commercial Justification

Ultimately, any implementation of CM will seek to deliver improvements to an operator, whether this be in the form of reduced costs, increased reliability or some other aspect. However, as noted by Tiddens et. al. [90], the cost/benefit associated with the introduction of continuous monitoring is often not well considered prior to implementation, which makes evaluating the success of an implementation difficult. Despite a significant body of work having been dedicated to assessing the value of CM (typically within the context of condition-based maintenance) no consensus has been reached as to how this can be quantified in a general sense. Typically, financial justification for a technical investment can be demonstrated through a simple return on investment (ROI) calculation; by comparing the initial and on-going costs and expected benefits associated with an investment cost savings and impact upon profitability can be understood and a case for the investment made. However, quantifying the benefits associated with a CM implementation is not necessarily trivial; value may be subjective and/or unable to be measured and thus advocates may be forced to seek alternative arguments to obtain buy-in from stakeholders, making the process more challenging [117], [161].

4.3.2 Technical Realisation

A mechanical system possesses a wide range of physical parameters, each representing a form (and quantity therein) of energy, which given the existence of appropriate sensing technology could be monitored. By utilising sensor technology physical quantities can be externalised, enabling parameters to be observed from a remote viewpoint, for example, a temperature transducer may be used to enable the temperature within a nuclear reactor's core to be monitored remotely, or a fuel level sensor may be used to observe the quantity of fuel remaining within an aircraft tank from its cockpit [135]. A monitoring system can be designed to essentially replicate the sensing capabilities of a human or to extend beyond those, enabling 'superhuman' capabilities, limited only by what's achievable with existing technology. Within a typical rotating machine the progression of a single failure will typically be observable through a range of different parameters, with each presenting different sensitivity at different stages in the machine's degradation profile, as dictated by the underlying physical mechanisms each parameter is sensitive to (Figure 4.2).

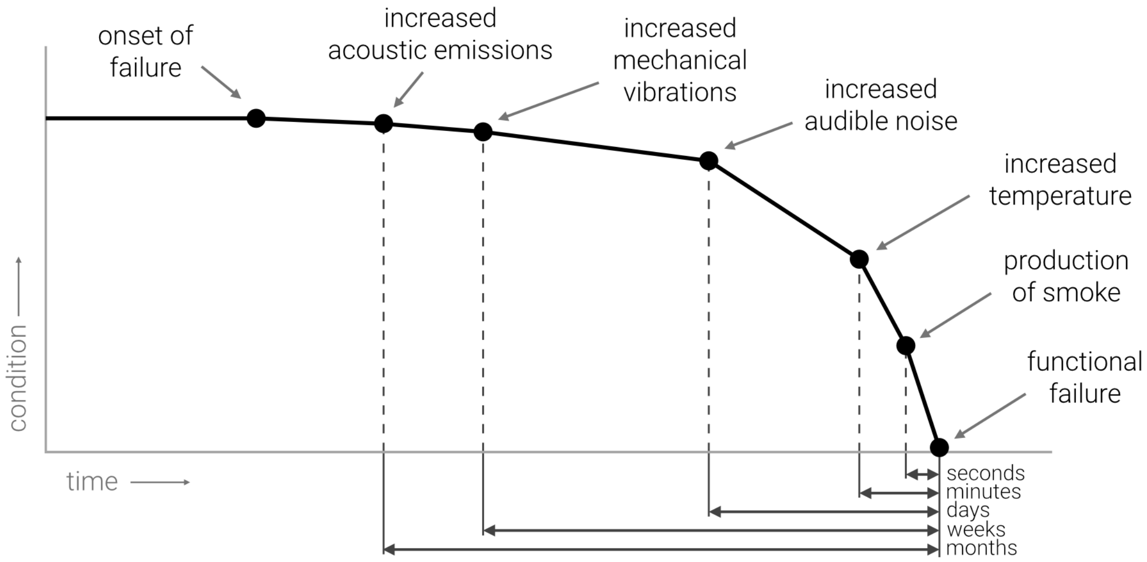

Figure 4.2: The typical development of a mechanical failure and its associated symptoms (adapted from [33]).

For example, the symptoms of a bearing failure will evolve as the failure progresses; As illustrated in Figure 4.2, excessive vibration will be observed before excessive temperature is generated, meaning earlier detection of the failure can potentially be achieved through observing mechanical vibration rather than temperature.

In practice, only a subset of such parameters can be expected to be practically monitorable given the limitations of extant sensor technologies. If within this subset of parameters it is not possible to observe the condition of an asset then fundamentally CM can be considered infeasible for that application. If, however it is assumed possible that the relevant condition of an asset could be inferred from one or more physical parameters then a design choice is presented during the specification of a system. Fundamentally, it is the responsibility of the system designer to identify and select parameters which when monitored will permit observation of the specific conditions of interest; if appropriate parameters are not identified beforehand a monitoring system may not be able to provide maintenance personnel with insightful information and risks becoming a 'white elephant'. Accordingly, the importance of appropriate parameter selection is recognised throughout literature (e.g. [162]–[165]), however, as noted by Heng et al. [166], in practice it is common for authors to give little consideration to the selection process, with parameters selected apparently arbitrarily or due to existing availability (e.g. [110]). As a consequence inappropriate parameters can be selected for monitoring, something which is only evident once a body of data has been able to be collected and analysed with time [165].

Further, within literature the process of monitoring physical parameters is often assumed trivial (e.g. [167], [168]) with a lack of consideration given to practical issues which can be encountered 'in the field'. Parameters which are able to be monitored within a laboratory environment may be unfeasible to monitor within the confines of an industrial environment, where conditions are typically harsher and more varied. Few authors (e.g. [169]) demonstrate consideration of additional factors such as the cost of installing and maintaining monitoring hardware when specifying a system.

4.4 Industrial Monitoring Trial

Whilst the field of continuous monitoring has generated a vast body of work, to date much academic work has focused on the development of technical theory (e.g. signal processing, algorithm development etc.) as applied to test beds within laboratory environments (e.g. [128], [170]–[172]). Whilst such work is of unquestionable value its disconnect from industrial environments may impact upon its ultimate suitability, particularly in bulk handling applications. Therefore, to better understand both typical conditions within an industrial plant as well as the potential utility of continuous component-level data to maintenance personnel a trial implementation was conducted at one of the Operator's plants. This section presents an overview of the monitoring system implemented during the trial, a summary of the findings from completion of the trial and the implications of findings to the overall research programme.

Purpose of Trial

Through the completion of maintenance records analysis (Chapter 2, Section 2.5) and on-site interviews with maintenance personnel (Chapter 3, Section 3.3) a lack of visibility of CBSs within the Plant whilst in-service was identified as a significant limitation of existing maintenance practices. Accordingly, it was proposed to undertake a component-level continuous monitoring trial at the Plant, as a means of assessing the potential value of such data as a supplement to existing visual inspection practices.

Through completion of the trial three primary objectives were to be addressed:

1. **To understand the degree to which changes in CBS operation can be identified through interrogation of continuous component data.**
2. **To assess the feasibility of acquiring continuous component-level data from CBSs across an entire plant, in a reliable manner.**
3. **To appraise the value and usability of continuous component-level data to maintenance personnel as an additional means of assessing the condition of CBSs.**

Within the Plant described in Chapter 3, Section 3.3 a total of four CBSs were selected to be the focus of the trial. The specific systems were selected by the Plant's Maintenance Manager, based upon their high criticality to Plant operations (i.e. product cannot be diverted around and/or the cost of corrective action is significant).

4.4.1 Parameter Selection

To maximise the value of the trial careful consideration was given to the task of selecting parameters to monitor. Primarily, parameters were to be selected based upon their anticipated sensitivity to changes in the health of a CBS. However, in the context of the WM industry additional constraints exist which impact upon sensor selection in terms of what can feasibly and economically be implemented.

For WM applications (and processing industries generally) the nature of the assets (high-volume-low-value) has implications on sensor selection also. Here, the scale of plants combined with the aggressive nature of the environment in which they operate impacts upon the viability of utilising high cost sensors, such as those providing acoustic emission and vibration parameters. For example, if a sensor costs ten times as much as the asset it is monitoring and only enables an average 20% life extension, the financial value of the increased observability it provides will be minimal.

Accordingly, the main criteria for the selection of parameters to monitor during the trial implementation were cost (both initial and ongoing) and sensitivity to system load. Furthermore, as described by Jennions [79] the three primary requirements for a sensor within the context of condition monitoring are: accuracy, stability and lack of interference with the physical quantity being measured, therefore mature technologies were preferred. A review of available technologies for the observing of commonly monitored parameters was undertaken, with support from key references such as [17], [46], [79], [173]. It was subsequently decided that a combination of temperature and electrical current draw parameters would be monitored during the trial, selected for three primary reasons:

1. **Low cost**
   Both parameters can be monitored using establish technologies available 'off the shelf', which can therefore offer reliable acquisition for an acceptable upfront cost. Given the exploratory nature of the trail limited financial resource was available.
2. **Sensitivity to load**
   Both parameters are directly related to the energy being consumed by the component they relate to, with electrical power varying as a function of motor load [174, p. 2013] *and temperature a function of heat generated by frictional losses within components, which will vary with (amongst other factors) mechanical load* [60]. *Whilst the response of temperature to changes in load is an order of magnitude slower than, for example, vibration, as shown in Figure 4.2, it is selected here based upon the utility of temperature as a CM parameter as reported by maintenance personnel in Section 3.3.*
3. **Ease of interpretation**
   Both electrical current and temperature represent physical phenomena which are intuitively understandable, and the occurrence of changes in parameters can be interpreted in a more straightforward manner, due to their relation to mechanical load.

The monitoring of temperature and electrical current draw parameters was in fact already performed at the Plant to a certain extent, however, via manual means. Maintenance personnel reported employing techniques such as using hands to assess the external temperature of gearboxes to gauge condition, and most drive motors at the plant possess built-in overload relays which will stop motors operating if a statically-defined (tuneable by personnel) electrical current draw threshold is exceeded. As such, it was anticipated that introducing continuous monitoring of temperature and electrical current draw would create minimal disruption to existing practices when compared to alternative parameters.

Whilst component temperature and motor electrical current draw were selected for the purposes of the trial it is not to be assumed that this represents the 'optimal' or even only selection based upon the characteristics desired. Within this context there is no single 'right answer'.

The impact of belt issues on plant operation were previously identified as being significant contributors to unplanned downtime at the Plant, however, due to the cost, complexity and limitations of existing COTS technologies direct monitoring of belt parameters was considered to be infeasible within the scope of this trial.

4.4.2 System Setup

The temperature of each conveyor's motor, gearbox and four support bearings were monitored, along with the local ambient temperature, as well as the current drawn by the motor.

The external temperatures of components were monitored via the use of resistance temperature detectors (RTD). RTDs were selected due to their stability over large temperature ranges as can be experienced within the Plant, combined with a robust construction affording high reliability [46]. A single RTD was bonded to the surface of each component using a metalised epoxy resin to provide good mechanical and thermal bonding between sensors and components.

Figure 4.3: An example of an RTD bonded to a bearing.

All the RTD transducer cables associated with a conveyor were connected to a single slave unit located near the motor, from where data was transmitted wirelessly to a master unit located in the control room. To facilitate monitoring of the electrical current drawn by each conveyor belt's motor a Hall effect-based transducer was installed onto a single phase of each motor's supply cables within the Plant Control Room.

All data channels were acquired via a series of signal conditioning hardware located in the control room, where appropriate conditioning and processing was performed such that correctly scaled parameters were produced (°C and Arms for temperature and current draw respectively).

In addition to temperature and current parameters an overall Plant status was able to be monitored, as extracted from an existing SCADA system. All parameters were sampled at a rate of 2Hz and displayed on a human-machine interface (HMI) located within the control room as well as being stored locally for analysis.

4.4.3 Summary of Findings

The monitoring system was commissioned on site at the Plant and a trial period constituting approximately one calendar year of Plant operation was conducted. Throughout the duration of the trial the monitoring system existed in a purely passive state; the system had no degree of control over the operation of the Plant so as to minimise disruption to the overall Plant process. Accordingly, the monitoring system possessed no ability to induce specific operational states or faults, it was only able to observe those which occurred 'naturally'.

Characteristics of Monitored Parameters

Analysis of acquired data shows that, under stead-state conditions, the high temperature measured is that associated with the motor (~28°C above ambient) followed by the gearbox (~18-20°C aa) and the bearings (~3-10°C aa), reflecting the motor's status as the energy supplying component (and thus possessing the most internal energy) within the system (Figure 4.4).

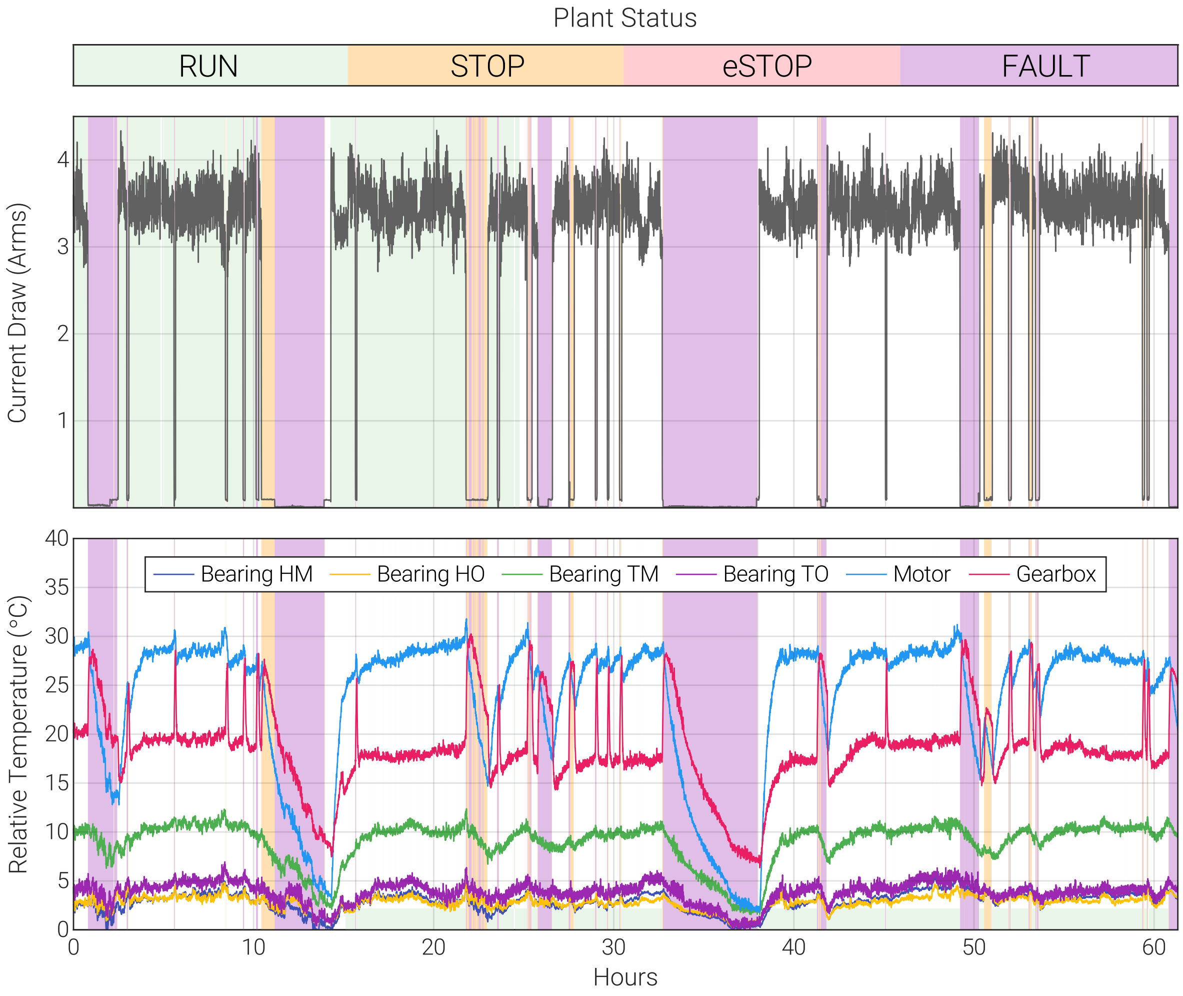

Figure 4.4: Illustrative example of component temperature and motor current draw data as acquired during the monitoring trial. Note, the overall Plant status is also shown.

As seen in Figure 4.4, both temperature and current draw parameters show sensitivity to changes in the overall Plant status, with an obvious correlation between the value of each and the Plant status observed in data. Upon entry of the Plant into a stopped state (Stop, eStop or Fault) the measured value of both temperature and current parameters can be seen to decrease, with contrasting rates of response. As highlighted in Figure 4.5 the measured value of motor current drawn contains a near step change in response to changes in Plant status. In contrast, the response of temperature parameters to the same changes in state occur gradually over a period of hours.

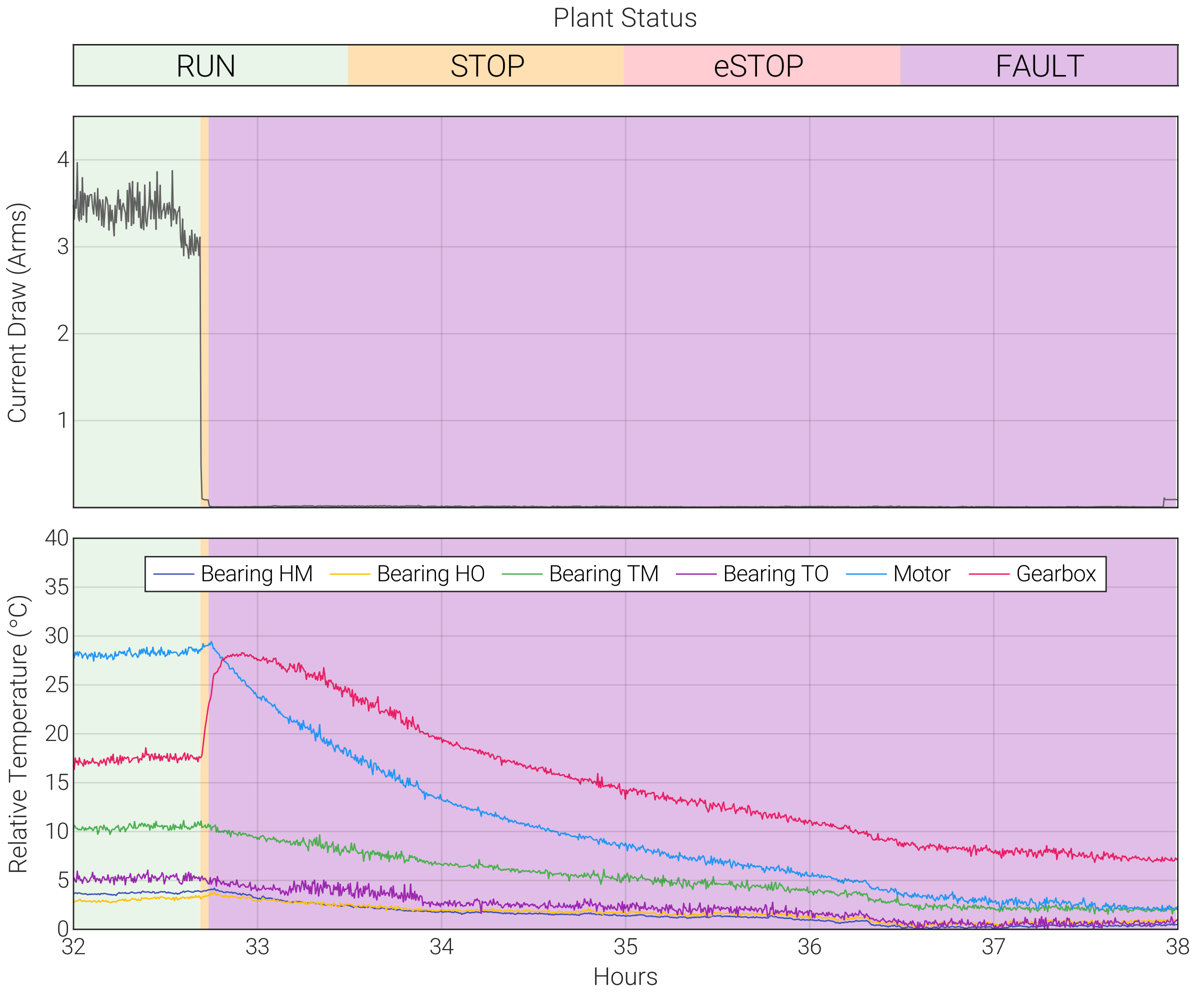

Figure 4.5: An example of a change in Plant status from Run to Stop, highlighting the contrasting response characteristics of motor current draw and component temperatures parameters.

The cause of this behaviour can be explained by differences in the measurement mechanisms employed by temperature and current transducers[23]. The measurement of motor current draw represents a quantification of the rate at which energy is being consumed by the motor. The instantaneous energy consumption of an induction motor is a function of the slip between the rotor and stator, which is itself a function of the mechanical load the rotor is subjected to. When the mechanical load on the rotor changes the energy stored within the magnetic field setup in the rotor-stator air gap changes accordingly. This change is propagated through free space at essentially the speed of light [176], therefore it is only the impedance of the motor which presents tangible resistance to this change, resulting in the motor current draw responding

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[23] A brief description of the relevant mechanisms will be provided here, however, it should be noted that these represent extremely complex concepts for which the reader is directed elsewhere (e.g. [175]) for a more in-depth explanation.

rapidly to dynamic changes in mechanical load. In the case of the trial monitoring system, the order of magnitude of this time delay is far below the sample rate of transducers, therefore, the measured response of the current draw to changes in load constitutes a step function.

In contrast, the measurement of a component's temperature represents a quantification of the amount of internal energy instantaneously stored within the transducer, primarily as conducted to it from its monitored component (in this case). Heat is generated within each component due to the presence of frictional losses, creating a temperature gradient between the heat generation source and the transducer. In accordance with the Zeroth Law of Thermodynamics this gradient tends towards equilibrium, resulting in an equalisation of component and transducer temperatures through conduction over time [177]. However, due to the inherent thermal inertia associated with each component's mass there is a time delay associated with this equalisation process, the order of which is much greater than the equivalent delay associated with motor current draw. Thus, the response to changes in load is far slower in measured temperatures compared to currents drawn.

Changes in measured temperatures in response to changes in load/operation can be observed to follow an approximately first order response [178] with a time constant of ~2 hours. Such behaviour is apparent in response to changes in the Plant's operational state, when transitioning both into and out of a Run state.

An additional effect can be observed within the response of motor and gearbox temperatures as the Plant state changes, with both presenting stable, non-minimum phase characteristics [179] i.e. initially in response to a change in Plant state from Run to Stop the temperature increases before subsequently decaying exponentially, and vice versa.

This behaviour can be considered a consequence of the totally enclosed, fan cooled (TEFC) design of conveyor motors. During operation each motor generates significant heat due to inherent inefficiencies (e.g. bearing losses, Joule heating in windings etc.), causing an increase in the temperature of the motor structure above ambient. In order to cool the motor during operation a fan is rigidly-mounted at the end of the rotor opposite to the output shaft, providing the removal of heat through forced convection. Due to the rigid nature of the fan coupling it provides airflow immediately in response to rotation of the rotor, as well as a converse effect. Thus, the steady-state temperature of the motor represents an equilibrium between two opposing effects; a fast response, non-minimum phase effect which acts to remove heat (i.e. fan action), and a slow response, minimum phase component which acts to add heat (i.e. heating losses).

Sensing and Data Acquisition

Throughout the trial period a number of issues were encountered relating to the reliability and integrity of the monitoring system installed (Table 4.2). The occurrence of these issues impacted upon the validity of collected data, restricting the compilation of a long-term data historian.

The majority of issues encountered related to the monitoring of component temperatures and the inability of RTD transducers to withstand the harsh conditions subjected to within the Plant. At the conclusion of the trial only approximately 60% of installed RTDs remained fully functional.

Table 4.2: Summary of technical issues affecting monitoring hardware experienced during the Industrial Monitoring Trial.

Issue		Description
RTD transducer detached		Bonded transducers becoming detached from their mounting locations on components, due to poor adhesion or mechanical action
RTD transducer failure		Damage to RTD sensor internals rendering output inaccurate
RTD cabling damage	Poor installation	Cabling damaged by escaped product as a result of poor securing during installation
	Nefarious action	Cabling severed or removed by personnel, most likely to gain access
	Accidental	Cabling unintentionally damaged, most likely by power-hose during cleaning
Power loss	Connection removed	Main power feed to DAQ equipment removed by personnel during work completed to other power elements and not promptly reinstalled
	Complete system failure	Entire Plant power supply lost due to external factors

RTD cabling suffered frequent damage, resulting in regular data outages. Accordingly, the most reliable RTD transducers were those attached to motors and gearboxes; due to their proximity to the slave unit they required the least cabling.

Figure 4.6: Examples of relaibility issues encountered during monitoring of component temperatures. A de-bonded RTD (left) and a severed signal cable.

Not only did such issues affect the integrity of data, it also required significant effort form the maintenance team to rectify, further increasing their already significant workload and potentially impacting upon the completion of Plant actions.

In contrast to the issues encountered with monitoring the temperature of components, the monitoring of the electrical current drawn by motors was found to be very reliable, with no outages reported by maintenance personnel. Due to their non-invasive nature, electrical current transducers can be located remotely from the motor itself (i.e. within the control room) isolating them from the harsh Plant environment.

Utility of Data

Informal reports from across the maintenance team suggested that in general personnel were experiencing benefit from access to the data acquired by the trial monitoring system, despite the previously described issues.

Personnel reported the most directly valuable element of the system to be the increased observability of dynamic conveyor load provided by the motor electrical current draw data. All conveyor drive motors at the Plant possess built-in overload relays, which will trip causing the stoppage of the motor when a statically-defined electrical current draw threshold is exceeded. Previously, trip thresholds were adjusted in a heuristic manner; if frequent motor trips were occurring then personnel would increase the trip threshold in order to enable the Plant to continue. However, it may have been the case that an issue had occurred within the motor (e.g.

windings damage) which was causing the increased electrical current draw and thus trips. By increasing the trip threshold such issues could be ignored, potentially resulting in minor issues increasing in severity, ultimately causing more impact in the long-term. Therefore, by having access to measurement of motor electrical current draw continuously the longer-term trends associated with the motor could be observed, allowing issues to be more easily identified, and appropriate trip thresholds to be set.

Conversely, the time lag associated with the response of temperature measurements to transient changes in operation reduced the value of such data in assessing asset loading. The transitory nature of events such as overloading of the belt or abnormal build-up of product result in them not significantly affecting measured temperatures due to the inherent filtering effect of thermal inertia. Through more involved analysis of raw temperature data (e.g. rate of change, outlier analysis etc.) more useable information may be able to be extracted, however, this was not performed by the system and thus would have required maintenance personnel to undertake such interpretation. The absolute temperature of components was valuable in some cases (e.g. assessing gearbox lubricant levels), replacing manual, periodic, however, the temperature of a component does not necessarily represent a direct indication of asset condition in this context, due to the influence of other variables such as ambient temperature and humidity. Therefore, it was reported as being a useful addition but not absolute enough to directly influence maintenance decision making.

4.4.4 Issues Encountered

Whilst the reported trial represents only a limited study from the findings it has produced a number of implications significant to the overall research programme can be identified.

Technical

The data provided by the monitoring system presented a rich source of information, enabling a significant degree of insight to be obtained into asset operation. However, the degree of effort required to acquire data was also found to be significant.

Whilst electrical current draw was simple to observe due to the non-invasive monitoring mechanism (i.e. transducers can be located remotely from the actual conveyor system, at any point along the length of the electrical supply cables) the monitoring mechanism associated with component temperatures reduced its reliability (i.e. transducers must be in physical contact with the component of interest) and contributed to frequent data outages. As such, it can be asserted that the task of data acquisition within such an aggressive environment cannot be assumed trivial, particularly when transducers are to be retrofitted, the impact of asset design upon the design of a data acquisition system must be considered. The design of conveyor belt systems within the Plant appears to be driven primarily by reliability and robustness requirements, with little obvious consideration of design for maintenance or accessibility observed.

During the monitoring trial the implications of such practices were experienced, with poor access compromising both the installation and maintenance of RTD transducers, primarily those located on bearings. Accordingly, greater suitability may be found in non-intrusive thermographic methods of temperature monitoring such as infra-red imaging. Historically, the cost and complexity of such techniques has restricted their applicability for continuous monitoring tasks, however, recent advances in the technology may affect this.

Furthermore, given the observed data acquisition issues the cost of continuous monitoring must be considered as a combination of both initial (purchasing and installation) and on-going (system maintenance) costs, an aspect typically given little consideration within extant literature.

Cultural

The issues encountered during the trial related not only to technical issues but also cultural, impacting upon the degree to which CM data was integrated into maintenance practices at the Plant. Cultural issues such as a lack of trust in new technology, lack of experience in working with new technology and lack of resource available to support the integration of new technology contributed to such limitations.

The implication of cultural issues associated with the introduction of continuous monitoring data into existing maintenance practices are significant for this programme of research. It suggests that data should be provided to personnel in an appropriate form, such that they are able to interpret and subsequently exploit it without significant expertise being required, nor feeling threatened by its presence. Not only are personnel already fully utilised, but also due to the transient nature of the team intimate knowledge of specific assets cannot be assumed.

Therefore, by embedding expertise within technology instead of relying upon it being held by personnel a degree of resilience to such issues may be realised.

4.5 Implications for Research

A review of academic CM literature within the context of general rotating machinery demonstrated the scale and maturity of extant applications. However, to date the majority of applications have constituted bespoke systems targeted at the detection of a subset of application-specific fault types and a significant disparity between the state-of-the-art in academia and industry exists. Furthermore, research appears to be realising diminishing returns in algorithmic performance terms, with most 'low hanging fruit' solutions already exploited. For example, recent advances in the area of vibration-based diagnostics of rotating machinery faults can typically realise only offer minimal improvement in absolute performance against existing literature but instead focus on areas such as ease of implementation or computational efficiency (e.g. [180], [181]).

Within the context of CBSs fault detection activities have primarily targeted belts due to their criticality to operation and associated financial costs. Whilst belt monitoring technology has subsequently achieved significant technical maturity in specific fields its application is still restricted in applicability across fleets of systems due to the cost of purchasing and maintaining associated hardware.

Whilst significant 'buzz' around concepts such as CM and the 'Internet of Things' exists across industry implementations are still in their infancy as operators continue to extend the service life of legacy assets over investment in new equipment. As such, in general, the implementation of such a CM system will require significant investment in hardware, both initially and on-going, therefore, buy-in from procurement personnel will be required, a potentially challenging task. The benefits realised by a CM system can be difficult to quantify with much benefit being found in qualitative benefits, so understanding the value CM may realise prior to implementation is vital.

Through the conducting of an industrial trial the potential value of the insight provided by a suitable CM system was demonstrated, however, the criticality of parameter selection in this respect was highlighted, as reported in extant literature. Based upon the findings from completion of the Industrial Monitoring Trial, to be appropriate for continuous monitoring during CBS operation a parameter must satisfy three requirements:

1. **Financial cost of monitoring**

   Continuous observation of the parameter must represent a feasible financial cost, considering both initial costs of installation and costs associated with the maintenance of sensor hardware.

2. **Technical feasibility of monitoring**

   Similarly, the sensor hardware required to monitor the parameter must be sufficiently robust to the typical operational environments a CBS is subjected to in industrial applications.

3. **Operational insight realised**

   The parameter must show sensitivity to an aspect of CBS health or usage, such that it can provide practitioners with insight into how the operation of the system is affecting its current condition.

To instil confidence in maintenance personnel from the outset and thus ensure their buy-in to a CM system the system itself must demonstrate reliability and accuracy. Furthermore, the process of integrating the insight realised by a CM system within existing maintenance practices must be considered. In this regard the ability to utilise existing data sources or minimising the quantity of data introduced is likely to be critical to realising value from CM by minimising both capex requirements and disruption to existing practices. CM should be delivered as a supplement to existing approaches, certainly in the short-term, so that it is seen as an aid and not a threat or hinderance to personnel.

Chapter 5: Aim and Methodology

As identified in Chapters 2 and 3 restrictions on observability of systems when in operation is contributing to a number of issues faced by both manufacturers and operators of conveyor belt systems within bulk handling applications. CBSs can be operated in diverse ways within a broad spectrum of applications, which has a direct impact upon the ability for manufacturers to appropriately design and specify systems prior to implementation and, once in-service for operators to identify maintenance requirements of systems. Current practice relies upon visual inspection methods to assess the condition of assets in-service and thus identify such requirements, which not only restricts assessments to periodic events but also induces a degree of subjectivity into findings.

Commonly within literature the advent of in-service continuous monitoring of assets is being reported to mitigate for such issues, often as part of a shift (total or partial) towards the implementation of predictive (or on-condition) approaches to maintenance. However, as identified in Chapter 2 the characteristics of CBS operation within bulk handling industries suggests such approaches would not be feasible and/or appropriate given the existence of both technical and socio-technical issues. However, as proposed and explored in Chapters 3 and 4 increasing the observability of systems in operation through the introduction of continuous monitoring could leads to improvements across the design, operation and maintenance of systems. In the design phase data can provide performance feedback to designers to support redesign and specification activities. In the operation phase data can help operators better understand the impact of usage upon condition as well as supporting the detection of impactful fault types and can enable novel offerings from manufacturers such as usage-based pricing. In the maintenance phase data can potentially support the definition of more appropriate preventative intervals based upon actual usage and increase the responsiveness of maintenance teams by providing timely insights. In contrast to predictive concepts, a shift towards a usage-informed preventative approach to the maintenance of systems represents a much less technically challenging undertaking and requires significantly less cultural change to implement.

Table 5.1: Summary of key findings identified within Chapters 2, 3 and 4.

Chapter	Section	Finding
2. The Design and Operation of CBSs.	2.1. Design	- The design of CBSs has converged to a near identical form. - Little feedback of in-service performance is incorporated into design practices.
	2.2. Operation	- Nominally identical CBSs can experience vastly different usage in-service across applications. - The usage of a CBS directly affects its availability. - Two primary issues can compromise the operability of a CBS: belt loss and motor failure.
	2.2.5. Analysis of Maintenance Records	- A small number of issue types constitute the majority of time consumed across plants, primarily related to belt, motors and gearboxes. - Typically, belt issues require the most resource to correct.
3. The Maintenance of CBS.	3.1.1. Maintenance	- Much of industry aspires to implement predictive approaches to maintenance, considering it a ‘golden bullet’. - In practice, reactive and preventative approaches still dominate across industry. - Predictive approaches are not necessarily suitable for application to bulk handling applications.
	3.1.3. Characterisation of Current Maintenance Practices	- Maximising throughput, and thus availability, is the main aim of the Plant. - A predominantly reactive ‘fire fighting’ approach to maintenance is taken. - The approach to and effectiveness of maintenance at the Plant is based upon the experience and expertise of the maintenance team.
4. Principles and Practice of Continuous Monitoring.	4.2. State-of-the-Art Practice	- Continuous monitoring of systems represents a mature and ever-expanding field. - Belts and drive components have been the subject of much research. - Existing solutions are typically invasive and expensive and have thus been restricted in application to only the most critical systems.
	4.3. Challenges	- Understanding the value in continuous monitoring prior to implementation is critical to commercial success. - Sensor selection must be considered carefully to ensure a CMS can provide valuable insight.
	4.4. Industrial Monitoring Trial	- The potential value of CM to practitioners is significant but varies between parameters. - Both technical and socio-technical challenges face the industrial implementation of continuous monitoring at scale in bulk handling applications. - Reliable acquisition of component-level parameters in the field is non-trivial. - The form and integration of CM insights into existing maintenance practices must be carefully considered.

5.1 Research Requirements

Based upon these findings three primary requirements of continuous monitoring for successful application to CBSs can be asserted.

Firstly, CBS parameters appropriate for continuous monitoring of must be identified. As identified in chapter 3 the task of selecting appropriate parameters to monitor is often not well considered or evidenced within literature, which can result in monitoring systems not delivering valuable insights to practitioners. To realise benefits through adoption of CM the data provided must contain appropriate insights into system operation, which cannot be assumed as given. Furthermore, given the aggressive nature of operational environments as encountered during the Industrial Monitoring Trial reported in Chapter 4, Section 4.4, associated monitoring hardware must be robust to industrial conditions. Finally, to make industrial implementation of continuous monitoring at scale viable monitoring hardware must also be financially viable, both in terms of initial purchasing costs as well as costs associated with the installation and maintenance of hardware in the field.

Secondly, trends and relationships between changes in CBS operation and the responses of monitored parameters must be identified. For raw parameters to be translated into actionable insights it is necessary to understand how changes in operation, such as the occurrence of faults and different usage patterns, manifest in the response of monitored parameters, so that the taxonomy of observable (and unobservable) events can be identified.

Thirdly, parameters should be presented in a form which is easily interpretable by practitioners, within the context of their existing practice. Raw parameter data alone does not necessarily provide practitioners with valuable information; it is typically required that data be interrogated to extract actionable insights. Performing such interrogation requires personnel possess both suitable time and expertise, which, as highlighted in Chapter 3 cannot be assumed. Workforces are stretched to capacity and subject to high levels of churn, reducing familiarity with systems. Therefore, the process of interrogating and interpreting parameters should be abstracted from practitioners to minimise effort on their part and provide objective insights. As identified by Maguire et. al. [88] within industry there is real demand for monitoring solutions that are simple and easy to install and utilise, as a step towards innovative practices such as predictive maintenance.

5.2 Aim and Research Questions

Given the identified challenges facing manufacturers and operators of systems and the potential affordances of continuous monitoring the overall aim of this research is:

To create a practical method for observing the operation of a conveyor belt system using continuous monitoring techniques.

To enable evaluation of the primary research aim three research questions (RQs) are explored within this thesis, in accordance with the research requirements identified in Section 5.1:

RQ1: *How could the introduction of continuous monitoring of systems support improvements across the design, operation and maintenance of conveyor belt systems within bulk handling applications given the challenges currently facing manufacturers and operators?*

Primarily, the operation of conveyor belt systems represents an industry-based practice. Accordingly, to enable this research to deliver tangible insight to stakeholders close engagement with industry is vital to ensure the research takes an appropriate form. RQ1, explored in Chapters 2, 3 and 4, seeks to evaluate current practice in the design, operation and maintenance of CBSs within bulk handling applications through interactions with both a manufacturer and operator of systems, such that the key challenges facing industry can be identified. Based upon the nature of these challenges the potential affordances of continuous monitoring can be assessed and requirements therein defined.

RQ2: *How can the operation of a conveyor belt system be most appropriately observed in-service through implementation of continuous monitoring?*

As identified through the investigation of *RQ*1 limitations on the ability of personnel to observe the operation of systems whilst in-service impact upon the availability able to be realised by systems. By introducing continuous monitoring of systems in-service such limitations can potentially be reduced, however, the implementation of continuous monitoring of CBS operation could take many forms. Therefore, *RQ*2 seeks to identify the most appropriate form of monitoring given the technical challenges and operational constraints associated with CBSs in bulk handling applications. Parameters are to be evaluated against three primary criteria: financial cost of monitoring, technical feasibility of monitoring and operational insight realised.

RQ3: *How can the health and usage of a CBS be assessed in an unsupervised manner?*

The rate of degradation of a mechanical system is dictated by the manner in which it is used, meaning the usage a system is subjected to will directly affect its health. Through interrogation of relevant parameter data the usage of a conveyor belt system can potentially be inferred. Similarly, the occurrence of critical fault types can be identified, based upon changes in the characteristics of relevant measured parameters. However, manual interrogation of parameter data requires personnel to both possess a high degree of technical expertise as well as commit a significant effort to the task. Therefore, to mitigate for such constraints an unsupervised approach to the assessment of system usage and identification of critical faults is desirable.

In a general context the term *supervised* describes the action of "overseeing or directing the execution of (a task, activity etc.)" or "to have charge of or responsibility for" [182]. Thus, the term *unsupervised*, as the antonym of *supervised*, can be inferred to imply a task which can be executed without direct oversight. In recent years *unsupervised* has found use within the field of machine learning within the context of *unsupervised learning*, a term describing techniques in which the goal is to "directly infer the properties of a probability density without the help of a supervisor or teacher providing correct answers or degree-of-error for each observation" [183].

In the context of this research *unsupervised* is adopted to describe generally an approach to the production of insights into the health and/or usage of a CBS from raw acquired parameters which requires little to no manual intervention from a human. By satisfying this definition an approach to the production of insights can be independent of the specific experience and expertise of a practitioner and thus more objective and consistent.

Accordingly, based upon interrogation of the parameters identified during investigation of *RQ*2 within *RQ*3 the degree to which the health and usage of a system can be inferred in-service is investigated. Subsequently, using the findings from a body of trials conducted three data descriptors are developed to enable automation of system-level inferencing, supporting fault detection and usage assessment activities whilst reducing effort and expertise requirements placed upon personnel.

5.3 Methodology

This research is positioned far closer to industry than a typical academic body of research and, as such, its purpose is to deliver actionable insights which can deliver tangible value to industrial practitioners. Therefore, it is critical that the challenges facing the specific area of industry relevant to the research are accurately identified at the outset. Accordingly, to support efforts in this task multiple research methods are employed during the problem formulation phase, combining qualitative and quantitative techniques to leverage the benefits of each. A body of statistical analysis is conducted on industrial records to provide objective measures of the typical challenges faced by operators within industry and a series of semi-structured interviews are conducted with industrial practitioners to obtain intangible insight not possible through interrogation of data alone. From these activities, in conjunction with a review of salient literature, the primary research questions are developed.

Given the industry-focused nature of this research during the problem investigation phase a primarily experimentation-based methodology is employed. Experimentation describes a method in which a controlled environment is created to enable causality between independent (i.e. those which are controlled) and dependent (i.e. those which are measured) variables to be assessed and can be conducted in either laboratory-based or in-field environment; a laboratory environment typically affords greater control of variables but at the cost of abstraction from 'real world' conditions [184].

To investigate *RQ*2 a CBS must be comprehensively monitored whilst it is operated within a controlled environment, such that the sensitivity of each monitored parameter to changes in operation can be characterised and a comparison can be made across all. Accordingly, this investigation is most suited to a laboratory-based environment where operational variables can, as much as possible, be controlled across test scenarios. In Chapters 6 and 7 the characteristics of different monitorable CBS parameters are explored through the operation of a bespoke test rig, designed to emulate the dynamics of a CBS. Through tests conducted on the rig a subset of CBS parameters are identified as appropriate and feasible for continuous monitoring at scale beyond a laboratory environment, given the constraints of bulk handling applications.

However, as described, laboratory-based experimentation inherently implies an abstraction from the typical operating conditions of an industrial system such as a CBS. Therefore, to validate the findings from investigation of RQ2 a subsequent body of in-field testing is conducted, as described in Chapters 8 and 9, during which conditions can be considered to more accurately reflect those of a typical industrial application. Through completion of this testing a taxonomy of behaviours is identified, each of which represents an event potentially observable within the response of the reduced set of parameters selected for monitoring.

To convert raw parameters into usage and condition information features must be extracted and classified through signal processing [185]. Accordingly, presented in Chapter 10 is the development of an unsupervised method for translating raw parameters into a series of data descriptors which simplify the interpretation of parameters for practitioners, highlighting key insights within parameter responses which can be used to support decision-making activities across the design, operation and maintenance of systems. In Chapter 11 this method is then evaluated through completion of a short series of industrial trials where the potential utility of the proposed data descriptors is demonstrated through application to two different industrial CBSs provided by the Manufacturer.

Finally, to 'close the loop' on the research work conducted the solution developed is analysed from an industrial implementation perspective, based upon the findings from investigation of *RQs* 1, 2 and 3. The overall structure of the research as composed within this thesis and its relationship to the defined research questions and methodology is presented in Figure 5.1.

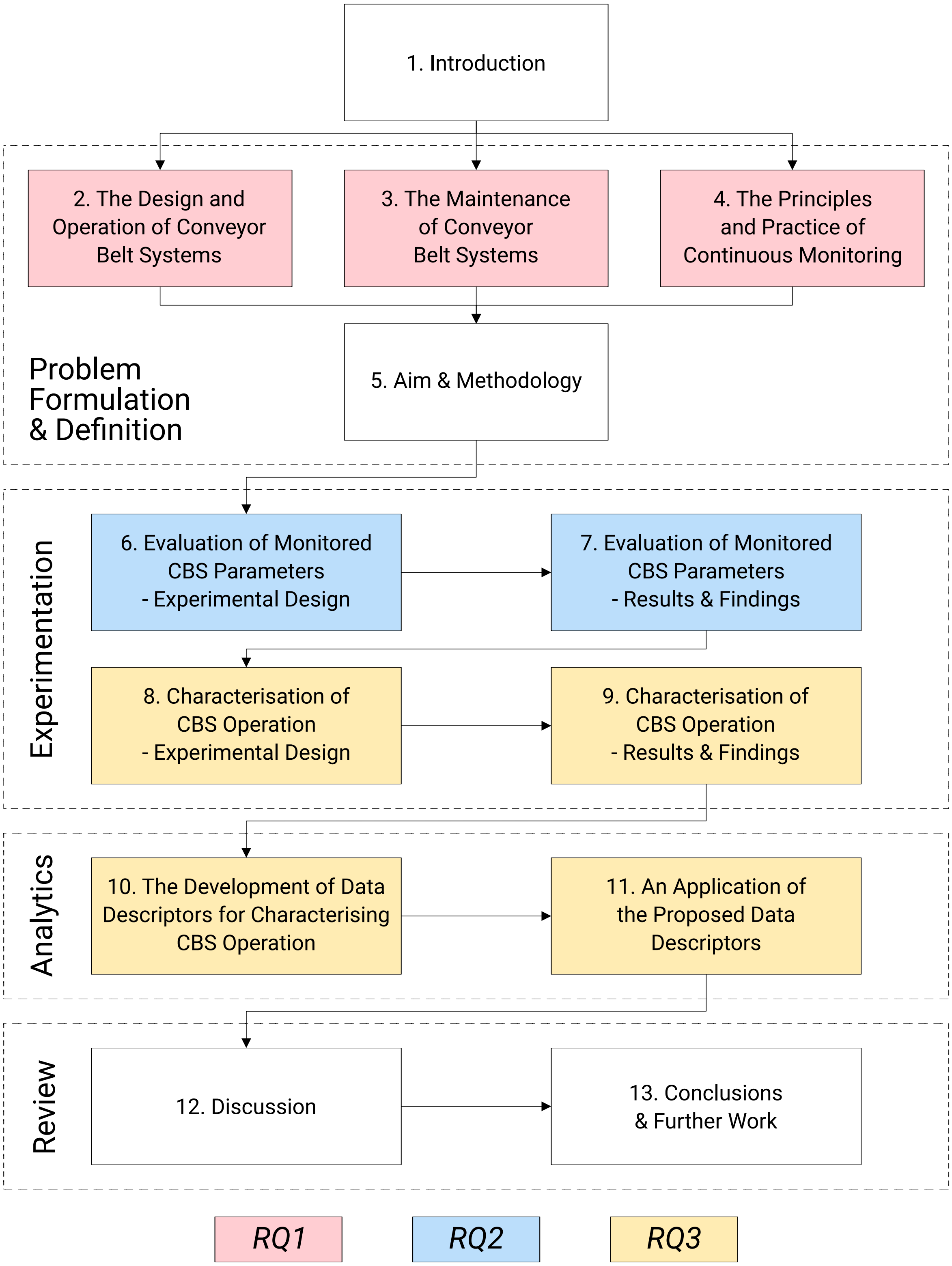

Figure 5.1: Structure of the research as organised in this thesis, mapped against top-level activities and associated Research Questions.

Chapter 6: Evaluation of Monitored CBS Parameters – Experimental Design

Given the previously identified potential affordances of continuous monitoring techniques to bulk handling conveyor belt systems (CBSs), this chapter presents the design of a laboratory-based test rig used to evaluate the characteristics of feasibly monitorable system parameters. The Conveyor Emulation Rig (CER) is designed to emulate the approximate dynamics of a Basic CBS and incorporates a comprehensive continuous monitoring system to provide observability of a wide range of system parameters. Through the control of various CER variables different operational scenarios can be induced and the resulting response of monitored system parameters observed. Whilst ultimately this research seeks to support industrial operators of systems and thus is primarily concerned with application to industrial systems a laboratory-based test rig affords a number of key advantages over in-field testing:

1. **Operational Environment**

   Without the presence of 'day-to-day' operation the exact conditions the rig is subjected to can be controlled without restriction in a repeatable manner. Similarly, the possibility for interruption to day-to-day operations is removed.

2. **Ease of access**

   Restrictions on health and safety are alleviated through minimising of interaction with persons, enabling the rig to be operated and maintained at will. Restrictions on the installation of transducers are similarly alleviated.

3. **Access to resources**

   Locating the rig within an academic environment provides access to a wealth of resources, both equipment and expertise.

The CER was designed to reflect the form of a Basic CBS as described in Chapter 2, Section 2.1, representative of a typical system provided by the Manufacturer, in accordance with the specification defined in Table 6.1.

Table 6.1: Specification of a typical Basic conveyor belt system.

Belt width	Belt Length	Belt speed	Throughput
600mm	3000mm	~1ms^{-1}	100ton/hr

To simplify its design, construction and operation a belt was omitted from the CER and instead the presence of a belt was to be emulated through the application of external loads reflective of those generated by a tensioned belt. In doing so the complexity of the CER could be reduced and thus conditions could be better controlled across test scenarios.

The absence of a belt created an obvious abstraction between the form of the CER and that of a typical CBS, however, given the primary purpose of the CER the degree of mechanical similarity between the two systems was considered sufficient to enable the general characteristics of monitored system parameters to be assessed within the context of the overall research questions.

6.1 CBS Operational Scenarios

To support the selection of parameters to monitor during operation of the CER the scenarios to be investigated were first defined, based upon scenarios typically experienced by a CBS in-service. Scenarios were initially identified through the completion of an FMEA which was subsequently reviewed through discussions with the Manufacturer to confirm the validity of conclusions (Table 6.1).

Table 6.2: Summary of typical CBS operational scenarios and proposed methods of emulation.

Operational Scenario		Description	Emulation
1	Unloaded start-up	A system being started with no product on the belt	Torsional loading of shaft to emulate baseline load on motor
2	Loaded start-up	A system being started with product on the belt	Torsional loading of shaft at increased level to emulate elevated load
3	Continuous loading	A system being loaded with a stream of loose material	Radial and/or torsional loading of shaft to emulate a near constant load
4	Discrete loading	A system being loaded periodically with discrete material	Modulated torsional loading of the shaft to emulate different magnitudes of live load
5	Changes in belt tension	A system being subjected to changes in belt tension	Radial loading of the shaft to emulate a tensioned belt
6	Changes in belt tracking	A system being subjected to off-centre belt tracking	Axial loading of the shaft to emulate thrust load
7	Changes in conveyor inclination	A system's physical inclination being changed	Torsional loading at increased level compared to nominal loads to emulate increased effort
8	Slip between the belt and pulley	A system experiencing slip between the belt and head pulley	Not feasible due to absence of belt within CER
9	Extremes in temperature	A system being subjected to low/high ambient temperature	Not feasible due to limited ability to control environment
10	Extremes in humidity	A system being subjected to low/high ambient humidity	Not feasible due to limited ability to control environment

For each operational scenario a method for emulating the occurrence of each during the operation of the CER was proposed. Based upon the design and operation of the CER three scenarios were considered infeasible to emulate, leaving a total of seven different operational events to be emulated within operation of the CER.

6.2 Parameter Selection

As discussed in Chapter 4, within even the simplest of machines a wide array of feasibly monitorable physical parameters exist, all of which contribute to the overall description of a machine's state at any instance. Within the design of a continuous monitoring system (CMS) it is essential that appropriate parameters are selected to monitor such that the desired conditions/behaviours can be observed. Accordingly, the specification of parameters to monitor within a CMS is a non-trivial activity, an issue recognised within literature [186]. During the Industrial Monitoring Trial reported in Chapter 4 financial and technical constraints restricted the sensor suite able to be implemented, meaning only a limited set of parameters could be monitored on each system. Whilst both motor current draw and external component temperature parameters demonstrated potential value based upon the insight of operation they enabled it cannot be assumed that these represent the most suitable parameters in wider applications. Thus, to address this limitation the CER was to incorporate a more comprehensive sensor suite, enabling the evaluation of other feasibly monitorable parameters against the three requirements identified in Chapter 4:

1. **Financial cost of monitoring**
   What is the financial expense associated with monitoring the specific parameter, both during initial installation as well as on-going maintenance?
2. **Technical feasibility of monitoring**
   Can each parameter be physically monitored given the technical requirements of associated sensor technologies, in a manner robust to the typical environmental conditions experienced in industry?
3. **Operational insight realised**
   What insight into the health and usage of a CBS can be elicited through the monitoring of each parameter?

In this section the process undertaken to identify parameters to monitor within the CER is explained, followed by a high-level description of each parameter and its associated monitoring techniques. In this respect, this is not intended to be an exhaustive or comprehensive guide to each parameter and methods for sensing, for which the reader is instead directed elsewhere to more comprehensive resources such as: *Condition Monitoring of Rotating Electrical Machines* (Tavner) [46], *Vibration=based Condition Monitoring* (Randall) [135], *Rotordynamics* (Muszynska) [187] or *Integrated Vehicle Health Management*: *The Technology* (Jennions) [79].

6.2.1 Selection Process

The initial concept behind the design of a sensor suite for the CER was to emulate the sensing capabilities of a human; sensors within the CER were primarily to monitor the same underlying phenomena but using different methods of transduction. For example, where personnel within the Operator's plants might use touch to assess the temperature of a gearbox within the CER a temperature sensor can be used. In this way the sensing suite can be used to produce a 'virtual' worker, reproducing and extending upon a traditional worker's capabilities whilst mitigating for the issues identified in Chapters 2 and 3, such as limitations on access to plant and resource availability. In replicating rather than deviating significantly from existing practice it was hoped that insights produced from operation of the CER could be more easily interpreted by personnel and thus integrated into existing practice. Furthermore, given the financial and technical constraints of wide scale industrial application established sensor technologies were to be utilised where possible; it is clearly not viable to specify sensor technologies which are more costly than the equipment they are monitoring or the financial penalty associated with unplanned downtime, nor technologies which have yet to demonstrate reliability at scale within non-laboratory conditions.

However, given the prevalence of alternative monitoring techniques such as vibration throughout industry, within the parameter selection process a wider array of potential parameters was considered for monitoring within the CER.

The first step in the parameter selection process was the completion of a failure mode symptoms analysis (FMSA), as specified in ISO13379-1:2012[24], based upon the previously identified operational scenarios defined in Table 6.2.

. This process is essentially a modification of a FMEA process with a focus on the symptoms produced by each failure mode identified and the subsequent selection of the most appropriate detection and monitoring techniques and strategies [188]. Symptoms of each scenario were identified through a combination of first principles analysis and review of extant literature, such as ISO13379-1:2012 itself and *Condition Monitoring of Electrical Machines* (Tavner) [46]. The total number of scenarios potentially identifiable through each symptom was then estimated, enabling symptoms to be ranked by estimated utility (Table 6.3).

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[24] Condition monitoring and diagnostics of machines - Data interpretation and diagnostics techniques - Part 1: General guidelines.

Table 6.3: Physical symptoms associated with feasible CBS failure modes.

Asset	Failure Mode	Root Cause	Symptom																		
			System		Motor							Gearbox						Bearing			
			Δ throughput	Δ pulley speed	Δ current draw	Δ temperature	Δ vibration	Δ torsional load	Δ rotor speed	Δ leakage current	Δ audible noise	Δ oil temperature	Δ oil composition	Δ oil level	Δ vibration	Δ speed	Δ audible noise	Δ temperature	Δ vibration	Δ speed	Δ audible noise
Conveyor System	Reduced throughput	Increased friction due to seized pulley	•	•	•	•		•	•							•					
		Increased friction due to collapsed bearing	•	•	•	•		•	•							•		•	•		
		Conveyor blocked	•	•	•	•		•	•							•					
	No throughput	Belt detached	•		•				•							•		•	•		
		Belt severed	•						•							•					
		Head/tail pulley stuck	•	•	•	•		•	•							•		•			
		Head/tail pulley detached		•	•				•							•		•	•		
		Shaft detached from bearings	•						•			•			•	•		•	•		
		Shaft fractured	•		•			•	•			•			•	•		•	•		
Drive motor	Can't provide required levels	Deterioration of motor insulation				•	•			•											
		Mechanical damage to motor windings			•	•				•											
		Mechanical damage to motor bearing(s)			•	•	•				•										
		Overheating due to fan performance				•	•														
	Can't provide any drive	Catastrophic failure due to coil burnout	•	•	•	•	•	•	•							•					
		Power supply issue	•	•	•	•	•	•	•							•					
Gearbox	Reduced transfer	Gear tooth damage due to debris			•		•						•		•		•		•		
		Gear tooth damage due to corrosion			•								•		•		•		•		
	No transfer	Gears seized due to overheating	•		•	•			•			•				•					
		Gears seized due to lack of lubricant	•		•	•			•			•		•		•	•				
		Output shaft seized due to downstream issue	•		•	•			•			•				•					
Bearing	Reduced rotation	Damaged race due to overheating		•	•				•			•						•	•	•	•
		Damaged race due to overloading	•	•	•			•	•			•						•	•	•	•
		Damaged race due to excessive vibration		•			•								•			•	•	•	•
	No rotation	Collapsed due to age	•	•	•													•	•	•	•
		Collapsed due to seal damage	•	•														•	•	•	•
		Collapsed due to impact	•	•														•	•	•	•
		Seized due to lack of lube	•	•														•	•	•	•
		Seized due to foreign object	•	•														•	•	•	•
	Excessive misalignment	Installation/manufacturing issue			•													•	•		•
		Asymmetric loading			•													•	•		•
		Bent shaft			•		•								•			•	•		•
	Unconstrained axially	Fastening failure																	•		
		Collapsed bearing																•	•	•	
		Total	19	15	22	13	8	8	2	2	18	7	2	1	6	14	3	18	20	9	6

Next, based upon the characteristics of each symptom and a review of extant sensor technologies a list of the sensors which could feasibly be used to detect each of the remaining symptoms was produced. The purchasing cost associated with each technology was approximated to ensure all could feasibly be incorporated into the CER, given the resources available to support the research. In addition, enquiries were made internally with the University of Bristol's Faculty of Engineering to identify any existing hardware which could be utilised within the design of the CER. Although there exists a practical constraint on the acceptable financial costs of each sensor for application to the monitoring of industrial systems, given the exploratory nature of the research programme a decision was made to incorporate as comprehensive a sensor suite as could be produced from both existing resources and bespoke purchases.

Ultimately, a sensor suite was produced comprising eight primary parameter types, distributed across the constituent components of the CER as outlined in Table 6.4.

Table 6.4: Summary of parameters selected for continuous monitoring within the CER and associated cost based upon the specific hardware employed.

Parameter Type	Number of Channels	Subject Components	Approx. cost per channel (£)
Acoustic emission	1	Gearbox	2000
Audible noise	3	Gearbox, Bearing 1, Bearing 2	500
Electrical power consumption	1	Motor	200
Mechanical linear force	2	Radial loading, Axial loading	500
Mechanical torque	1	Braking load	1000
Mechanical vibration	3	Motor, Bearing 1, Bearing 2	1000
Rotational speed	1	Gearbox	100
Temperature	5	Motor, Gearbox, Bearing 1, Bearing 2, Ambient	50

Audible Noise

Where mechanical vibrations are generated within a structure a corresponding pressure wave will be generated at the interface as the atmosphere in which the structure exists is excited[25]. These longitudinal waves emanate from the excitation source (e.g. vibrating structure) through the atmosphere at a speed dictated by the properties of the transmission medium and at a frequency dictated by the oscillation frequency of the source. The audible spectrum of a typical human is in the range ~20-20kHz [189], therefore, if the frequency of a pressure wave falls within this range (and the wave is of sufficient power) then it will be detectable by a human as a sound and can thus be class as audible.

Audible noise is measured through use of some form of microphone, typically based around a piezoelectric element tuned to convert the mechanical vibrations associated with sound pressure into electrical signals. The measurement of audible noise is an established practice so the cost of sensing hardware is relatively low. In comparison to the sensing of parameters such as mechanical vibrations or torque the measurement of audible noise can be done in a non-contact matter, with no mechanical coupling between the sensor and the subject component required. However, this property can also be problematic, presenting a challenge in isolating the source of audible noise; if two audible noise producing components are within measurable distance of a microphone then both excite the microphone's sensing element and thus be measured.

Acoustic Emission

Acoustic emission (AE) describes transient elastic waves which are generated within a material as a result of rapidly released localised stress energy [190]. The occurrence of AE can represent degradation of a material, such as plastic deformation or crack propagation caused by the application of internal or external stresses, typically mechanical or thermal. Alternatively, AEs can result from the interaction of materials in relative motion, such as between sliding surfaces within rotating machinery where surface asperities cause friction. Accordingly, AE has generated much interest due to its ability to detect crack propagation, finding many applications to structural health monitoring (SHM) in particular (e.g. [102], [191]–[193]). Theoretically, AE can be used to detect the onset of material degradation at a much earlier stage than say through observation of mechanical vibrations, further extending its appeal. However, AE monitoring is

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[25] Assuming a transmission medium is present e.g. air

a comparatively immature technology, still restricted to laboratory applications for the most part and as a result associated hardware is still relatively expensive when compared to alternatives such as vibration monitoring. Unlike audible noise waves AE waves are solid-borne[26] and are thus measured using physical detection methods, similar to measurements of mechanical vibrations. Detection of AE events involves the use of piezo-based transducers to convert the mechanical motion of the EPE waves into an electrical signal, however, given that the typical content of AE events is in the frequency range 20k-1MHz transducers are tuned to present sensitivity to these frequencies [135], [194].

Electrical Power Consumption

The electrical power consumption of an induction motor represents the quantity of energy converted from supplied electricity into rotation of the rotor, including any losses incurred. Within the context of a CBS this represents the energy required to maintain rotation of the system's belt as the load on the system varies. At any instant the total power consumed by a motor is equal to the product of the voltage supplied to the motor and the current drawn. While line voltage is typically measured via a direct connection made in series with the motor's supply cables, current draw can be sensed in a non-contact manner via a clamp-on Hall effect-based transducer. In addition, as in the industrial trial reported in Chapter 3, these measurements can be taken remotely from the actual monitored motor at any point along the supply cables, for example from within a control room. This not only significantly reduces installation effort but also means hardware is protected from the aggressive environments associated with system's in operation, improving sensor reliability.

Power monitoring is often undertaken within the scope of motor current signature analysis (MCSA)[27], through which it is theoretically possible to detect the occurrence of a wide range of induction motor faults, both electrical and mechanical in nature, such as rotor eccentricity or shorted windings. By transforming raw time-domain data into the frequency domain characteristics frequencies associated with such known fault types can be identified and thus faults inferred. Accordingly, measurements must be taken at a frequency high enough to fully capture such behaviours within recorded data, typically necessitating a sampling frequency in the range 5-100kHz [174]. In many industrial systems, such as variable frequency drives,

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[26] Technically also fluid-borne, however, detection within a fluid is much more challenging.

[27] Or, more generally electrical signature analysis (ESA).

measurement of power consumption will be available without necessitating any additional hardware, however, the frequency of such measurements is often low (<100Hz). Due to the wide proliferation and maturity of power monitoring associated sensing hardware carries a low purchasing cost in comparison to many other common types of monitoring [46]. Furthermore. many commercial systems are available which operate on such principles such as the Artesis Motor Condition Monitoring System [153] and the Sense monitor [195], reducing the complexity of installation.

Mechanical Force/Torque

In the context of a CBS, loading describes the effect of mechanical forces being applied to the system, typically due to external input. Such loads can be categorised as *primary* loads (i.e. those which result directly from usage of the system) and *secondary* loads (i.e. those which occur regardless of the system's usage e.g. thermal loads due to changes in ambient conditions) [60]. The forces a system is subjected to can be inferred from localised measurement of strain, that is, the physical deformation of a material that results from an applied force[28]. Many different approaches to the measurement of strain exist, however, most commonly a simple strain gauge finds employment, a type of transducer which converts changes in mechanical strain into an electrical signal; when a gauge is subjected to stress its cross-sectional area and length are altered accordingly, causing its electrical resistance to change in a predictable manner. Alternative approaches to the measurement of strain include magneto-elastic or fibreoptic based transducers, however, such approaches are significantly less mature or widespread throughout industry [46].

A strain gauge-based transducer requires must be physically embedded within the mechanical system it is to measure, such that it is subjected to the same loads as the system itself. Accordingly, the measurement of force requires significant installation effort, as well as hardware capable of withstanding both the expected forces and the operational environment. Furthermore, where the torque (i.e. angular force) of a rotating element such as a driveshaft is to be measured some form of slipring or wireless communication method must be used to prevent binding of cables. As a result, direct measurement of force in this manner carries

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[28] Formally, the ratio between the original and extended lengths of a material when subjected to a stress.

significant effort (particularly when performed retrospectively to a system's design) and often financial cost also, depending upon the accuracy and robustness of hardware.

Mechanical Vibration

All bodies possessing mass and elasticity are capable of vibration, that is, the oscillatory motion of a body about a mean position [196]. As such, in practice all mechanical systems experience vibrations of some form during operation, particularly those containing rotating elements. A vibration can be characterised by its amplitude, frequency and phase, each of which is dictated by factors such as the geometry and material properties of a system as well as the excitation forces it is subjected to (e.g. rotational speed) [197]. In many instances the presence of wear or damage within a machine can be identified through changes in the amplitude and/or frequency of specific characteristics vibrations, this principle underpinning the field of vibration-based analysis, where signal processing techniques are used to extract fault indications from noise and other masking components within broadband vibration spectra.

Vibration analysis is often stated as being the most prevalent condition monitoring technique employed across industry, and as such the associated sensor technology is well developed and understood [135]. Typically, vibrations are monitored through direct contact between a transducer and a component to produce an electrical signal proportional to the measured acceleration at that location. Transducers can take a number of forms including induction-based proximity probes, laser vibrometers and velocity transducers, however, most common is the piezo-based accelerometer, used in all but the most specialist of applications [46]. An accelerometer produces an output proportional to the acceleration the transducer experiences, from which quantities such as velocity and position can be derived. A piezo-based accelerometer consists of a piezo crystal sandwiched between a fixed and a floating mass, with the crystal acting as both a spring and damper. As the accelerometer is vibrated the floating mass applies a compressive force to the crystal, the magnitude of which is proportional to the acceleration experienced. This compression in turn causes the generation of a voltage across the crystal, which can subsequently be measured [198]. Good mechanical bonding between the transducer and the monitored component is important to ensure transmission of vibrations with minimal attenuation. A number of options exist for mounting transducers, including magnetic, adhesive and mechanical, with each presenting a trade-off between ease of installation and signal transmission. Thought must also be given to the positioning and orientation of transducers, such that sensitivity to the specific vibrations of interest is maximised; the greater the physical separation between the transducer and the vibration source the more masking of the components of interest there will be within the measured signal [199].

As with measurements of audible noise, vibration monitoring is indiscriminate, however, through the use of signal processing techniques and knowledge of the system it is often possible to isolate known components of interest only. Frequency components of interest are typically in the Kilohertz range, therefore sample rates in the order of 10-50kHz are common, implemented as either a continuous or periodic monitoring task.

With the advent of microelectromechanical systems (MEMS) the cost of vibration hardware has fallen significantly in recent years, with most smartphones now capable of three-axis acceleration measurement. However, the cost of monitoring is essentially a function of the required sensitivity; as the system sample rate is increased so too is the cost of the hardware typically. Further, as vibration monitoring typically requires direct contact with the subject component hardware must be designed to withstand the rigours of operation within proximity to systems.

Rotational Speed

Inherent within the operation of a CBS is the rotation of numerous elements which together produce the continuous movement of the belt. In this context speed refers to the rate at which a component is turning about its axis of rotation, commonly defined in terms of rotations per minute (RPM) or second (rps). Rotation speed can be measured using a number of different contact and non-contact technologies including rotary encoders (typically mechanical or optical), light-based tachometers (laser or infrared) or Hall-effect magnetic wheel transducers. All such methods are based upon the fundamental relationship between speed, distance and time, essentially measuring the time taken to cover a certain angular distance, from which speed is calculated. However, regardless of the specific technology used a speed transducer must typically be located in close proximity to the monitored component, with direct line-of-sight.

Temperature

The temperature of an object describes its potential for heat transfer, whether by conduction, convection or radiation, as a consequence of the heat (i.e. thermal energy) it possesses at any instant [175]. Within the context of condition monitoring temperature finds wide application for the detection of defects or faults in systems, with many such events characterised by an increase in heat generation [200].

Most commonly the local temperature within a system is measured using one of three direct contact techniques: resistance temperature devices (RTDs), thermistors or thermocouples. Each of these techniques involves placing a sensor in direct contact with a component to permit the conducting of heat between the two. An RTD uses a sensing element made of a pure metal such as platinum or copper to produce an output resistance which is proportional to its temperature. A thermistor operates on a similar principle, functioning essentially as a temperature dependent resistor, however, in comparison to an RTD a thermistor represents a simpler (and cheaper) construction and consequently less linear in its output as temperature changes. In contrast, a thermocouple exploits the Seebeck effect to produce a temperature dependent output voltage [175]. All three techniques represent different trade-offs between sensitivity, accuracy, cost and reliability which must be considered on an application-by-application basis.

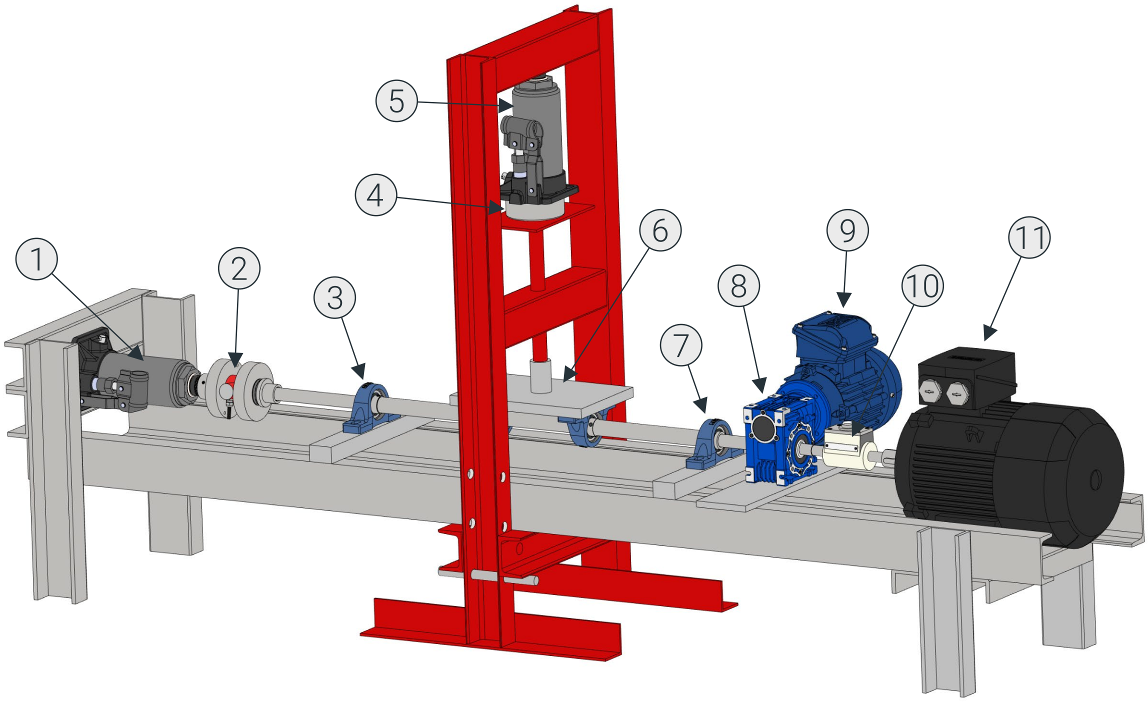
It is also possible to assess the temperature of an object in a non-contact manner using infrared thermographic techniques, where the temperature across a more distributed area is estimated from the thermal radiation emitted by the object. Whilst historically the cost of such technologies restricted their use to only periodic monitoring of particularly high-value or safety-critical applications, in recent years significant reductions in the technology have widened their applicability across industry.

6.3 Mechanical Design

In this section the mechanical structure of the CER is described, including the specification of drivetrain components and design of external loading mechanisms.

6.3.1 Component Specification

To reflect the form of a typical industrial conveyor belt system the drive system for the CER was to comprise an induction motor coupled to a gearbox, driving a main shaft supported by two rolling element bearings.



① Axial loading jack
② Axial load cell
③ Bearing 2
④ Radial load cell
⑤ Radial loading jack
⑥ Radial loading yoke
⑦ Bearing 1
⑧ Gearbox
⑨ Drive motor
⑩ Torsional load cell
⑪ Braking motor

Figure 6.1: Technical illustration of the Conveyor Emulation Rig, with major components labelled.

For each drive element a component was specified for the CER based upon COTS parts availability ensuring a low-cost principle was adhered to ensuring close alignment with industrial systems (Table 6.5).

Table 6.5: Details of CER primary drive components specified.

Component	Quantity	Manufacturer	Part Number	Specification
Drive motor	1	Marelli	MAA71-MB4-B14	0.37kW 4-pole 71 frame B14
Reduction gearbox	1	TEC	FCNDK40	0.37kW 7.5:1 71 frame B14
Ball bearing	2	SKF	SY 20 TF	20mm bore, single row

The primary support structure of the CER was constructed from lengths of mild steel 'c' section, joined using M10 bolted connections, to ensure sufficient tolerance to applied loads whilst permitting reconfiguration and reassembly as required.

Motor

An induction motor was selected to drive the rig, constituting a totally enclosed, fan cooled (TEFC) design, as typical employed throughout industry. A nominal motor power of 0.37kW was selected, a significant downsizing when compared to the typical nominal power (1.5-2.2kW) motor employed within a Basic CBS reflective of the specification defined in Table 6.1.

. This decision was made to reduce the absolute magnitudes required to emulate typical loads experienced by a CBS during operation, for reasons of practicality and operability of the CER. Furthermore, a 3-phase motor was specified; based upon discussions with the Operator 3-phase was indicated as being more commonly employed within fixed plant where 3-phase supplies are available, due to their greater rate of power transfer and ability to self-start [176].

Throughout industry the drive motor of a CBS is typically operated via a fixed-frequency supply, including most systems at the Operator's plant and models offered by the Manufacturer. However, operation via a fixed frequency supply typically limits systems to a (nominally[29]) constant belt rotational speed. Increasingly, the incorporation of variable frequency drives (VFD) within systems is being observed throughout industry, to enable variable speed operation and thus increased flexibility (and potentially efficiency) of operation, as enabled by significant reductions in the cost of such equipment. Accordingly, it was decided that the drive motor within the CER would be driven via a VFD to enable increased flexibility in operation.

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[29] Such operation constitutes an open-loop speed control mechanism, therefore, some variance in dynamic speed will occur in response to changes in motor load.

During operation of the CER the VFD is configured to operate in an open-loop V/f (Volts-per-Hertz) mode i.e. not rotor speed controlled, to reflect the typical direct-on-line connection used within the majority of the Operator's CBSs. Accordingly, during operation the VFD will not attempt to compensate for increased rotor load to maintain a constant speed.

To enable the rig to be stopped in a timely and controlled manner when in operation a category 0[30] emergency stop was installed, in accordance with the recommended practice stated in ISO 13850:2015 (Safety of machinery - Emergency stop function – Principles for design) [201]. When activated the emergency stop causes the disconnection of the motor's electrical supply via a safety relay, resulting in a timely (~0.3s) stoppage of the main shaft's rotation and preventing operation of the motor until the emergency stop is manually reset.

Gearbox

The selected drive motor was coupled to a worm drive gearbox, to both provide a suitable speed reduction, as well as to reflect the form of a Basic CBS. The gearbox is a totally enclosed wet system, provided lubricated for life from original manufacture. A nominal belt speed of ~0.9ms^1 (~90RPM at the head pulley) is common across the Manufacturer's range of systems, therefore, a 15:1 reduction gearbox was specified for the CER, providing a mid-range speed of ~91rpm at the main shaft, with the ability to modulate between 0-182RPM (Table 6.6).

Table 6.6: Permissible range of speeds within the operation of the CER.

Supply Frequency (Hz)	Motor Operating Power (W)	Motor Output Speed (RPM)	Gearbox Nominal Efficiency	Gearbox Operating Power (W)	Gearbox Ratio	Gearbox Output Speed (RPM)
50	370	1370	0.85	314.5	7.5:1	182.67
25	157	685	0.85	133.45	7.5:1	91.33
5	97	137	0.85	82.45	7.5:1	18.27

The ability to vary the speed of the drive motor was desirable to enable the progression rate of developing conditions to be accelerated, a recognised technique throughout monitoring literature [202].

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[30] "Stopping by immediate removal of power to the machine actuators."

Shaft

The primary requirement of the main shaft is to withstand the application of external loads as applied to the CER throughout testing. The most critical mode of loading the shaft must withstand is those loads applied radially, which, if the shaft is not suitably stiff, could cause deflection leading to plastically deformation or even ultimately catastrophic fracturing.

To estimate the deflection (i.e. bending) of a shaft in response to the application of radial load the Conveyor Equipment Manufacturers Association gives the equation [15]:

$$tan\,\alpha = \frac{R\ A\ (B - 2A)}{4E_y I} \tag{6.1}$$

During operation of the CER excessive deflection of the shaft can be considered undesirable, therefore, a nominal permissible limit of 1mm was defined. In accordance with the variable definitions as depicted in Figure 6.2 and values defined in Table 6.7 based upon the geometry of the CER[31] a minimum shaft diameter of approximately 21.2mm is calculated for a permitted deflection of 1mm.

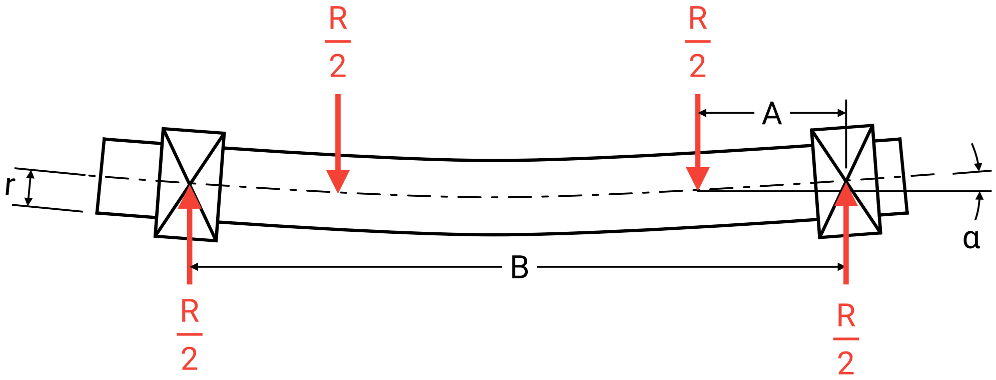

Figure 6.2: Free body diagram of the deflection of a straight shaft [15].

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[31] A distance of 600mm between bearing centres was defined to reflect the most common belt width employed by the Operator and manufactured by the Manufacturer.

Table 6.7: Description of variables used within shaft deflection calculations.

Variable	Description	Units	Value
A	Moment arm between load point and each bearing	Nm	0.15
B	Bearing centres	m	0.6
R	Resultant pulley load based upon 4kN radial load	Nm	600
E_y	Young's modulus	N/m	$200\text{x}10^9$ (for steel)
I	Second moment of area	-	$\frac{\pi}{4}r^4$ (for solid cylinder)
$\tan\alpha$	Angle created between the deflected shaft and its neutral axis	deg	~0.19 (for 1mm deflection)
r	Shaft radius	m	Unknown

Accordingly, a shaft diameter of 25mm was specified to ensure the minimum recommended diameter was exceeded. Within the Manufacturer's range of models a 600mm belt width is typically supported by a 35mm diameter head pulley shaft, therefore, the specification of the CER reflects a slight undersizing, however, this was considered acceptable.

To provide positive location of the inner races of each support bearing on the shaft and thus the transfer of axial (thrust) loads a reducing step was incorporated into the design of the shaft. Based upon the previously described deflection calculation a shaft minor diameter of 20mm was specified and radiuses added at both shaft steps to minimise stress concentrations. The main shaft is coupled to the gearbox output shaft via a flexible coupling to account for manufacturing and assembly tolerances associated with the geometry of the CER structure and to facilitate simple removal of the main shaft support bearings when required. The shaft was manufactured from bright steel, a carbon steel alloy, due to a combination of availability, machinability and resistance to corrosion.

Bearings

Two bearings are used to support the main shaft. Again, to reflect the form of a Basic CBS these are plummer (or pillow) block-style cast iron casings, each housing a single row ball bearing. As dictated by the geometry of the main shaft a bearing bore of 20mm was selected. The SKF YAR-204-TF bearing has a basic load rating of 12.7kN dynamic and 6.55kN static, well above the maximum capabilities of the CER as designed. Within BS 4531:1986 (Specification for portable and mobile troughed belt conveyors) [203] a bearing life of 25k hours is recommended for systems operating up to 16 hours/day. The SKF Bearing Select Tool was used to estimate the life of the SKF YAR-204-TF bearings, which suggested a life of 13.1k hours, given constant operating loads of 2kN radial and axial simultaneously under normal cleanliness conditions. As such conditions (i.e. constant maximum loading) constitute the worse-case scenario such an operational life was considered acceptable. To permit the transfer of torque from the gearbox to the bearings the inner race of each was secured to the main shaft via two grub screws per bearing.

6.3.2 Loading Mechanisms

To enable emulation of the loads typically experienced by a CBS during operation a series of loading mechanisms were incorporated into the design of the CER.

Radial

Through the controlled application of radial load to the main shaft the presence of a tensioned belt could be emulated. As described in Chapter 2 Section 2.1, within a Basic CBS a tensioning force is applied to the belt by adjusting the centre distance between the head and tail pulleys. In doing so the tracking of the belt can be controlled such that the belt runs 'true' along the length of the system. As such, the presence of a tensioned belt within a system will result in the application of a static radial load to all four pulley support bearings (two head, two tail).

To emulate the radial force which would be applied to the main shaft by a belt a 10 tonnes hydraulic bottle jack was employed within the CER (Figure 6.1). The jack was coupled to a steel plate and then positioned between an external steel frame (which is coupled to the main CER structure) and the main shaft such that when the jack's ram extends force is generated between the steel frame and main shaft.

A pair of plummer block bearings were employed to transfer force between the jack and the main shaft so as to minimise the application of torsional load to the main shaft. The jack support bearings were sized with a bore of 25mm (SKF SY 25-TF) to ensure they withstand applied loads and are not fastened to the main shaft to minimise the transfer of axial load.

The extension of the jack's ram (and thus the applied radial force) was manually controlled by pumping the piston via a lever arm. Control of the jack ram's extension is uni-directional; it is possible to extend the ram in a controlled manner but not to retract it. To retract the ram (and thus remove the applied radial force) the pressure within the jack's reservoir can be released manually via a small valve.

A maximum applied radial load of 4kN was specified for the CER. Liu et. al. [159] suggest that for a system of 600mm belt width loaded with 'river sand' the bulk mass load on a 3m section is 115, 156 and 206 kg for 55%, 75% and 100% capacity respectively. In addition, the Manufacturer's most popular mobile system is permitted a load of up to 200kg for a 3m system. Therefore, to be consistent with typical operational loads a minimum of ~2kN of radial load is required. However, to enable the effect of overloading to also be investigated a factor of two is applied, giving 4kN maximum. Additionally, this limit will minimise the possibility of plastic deformation occurring within the main shaft in response to the application of radial load.

Axial

During operation a conveyor pulley shaft can be subjected to axial (or thrust) load due to a range of scenarios such as poor belt tracking or pulleys which are not square or horizontal. To emulate such scenarios the ability to apply axial load to the main shaft is permitted within the CER. This is achieved in a similar manner to the application of radial loading via the use of a generic hydraulic bottle jack. The axial jack is orientated such that its ram is aligned with the axis of the main shaft and the body of the jack is placed between the free end of the main shaft and an external steel structure which is fastened to the main CER structure (Figure 6.1).

As with radial load, the application of axial load is uni-directional and controlled manually by pumping the jack's piston via lever arm. The axial jack is also rated to a lifting mass of 10 tonnes, however, again an upper limit of 4kN is specified to minimise adverse damage. To minimise the generation of torsional load by the action of the axial jack the end of the axial jack's ram is supported by a cylindrical roller thrust bearing. An SKF 81105 TN bearing was specified, due to its compact size and dynamic load rating of 25kN, far exceeding the maximum axial load to be applied by the axial jack.

Torsional

Whilst in operation the loading of material onto the belt is experienced by the drive motor as a counter torque, which acts in opposition to the motion of the motor causing deceleration of the belt. To replicate such loads within the CER a braking motor is used to apply torsional load to the system utilising the principle of direct current injection braking[32]. When DC[33] is supplied to the stator of an induction motor a stationary magnetic field is setup and the synchronous speed of the motor occurs at zero rpm i.e. when there is no relative motion between the stator and rotor. Therefore, if relative motion occurs between the stator and rotor a counter MMF is induced which acts to oppose the direction of motion [176]. Accordingly, by injecting DC into the stator winding of an induction motor a dynamic braking torque can be generated, the magnitude of which is directly proportional to the excitation current [15]. The maximum torque which can be generated by a motor through DC injection is dictated by the motor windings' ability to withstand the drawing of continuous current before incurring damage due to Joule heating.

Within the CER, DC injection braking is facilitated by a second motor, directly coupled to the gearbox output shaft on the opposite side to the main shaft (Figure 6.1). Accordingly, the braking motor must be capable of producing significantly greater output torque when compare to the drive motor. The braking motor employed within the CER is a 4kW 3-phase machine, with a continuous current rating of 9A max. To enable the counter torque generated by the braking motor to be modulated a Manson HCS-3302-USB programmable power supply is employed to provide the source of DC excitation, up to 15A max. The power supply can be commanded remotely via a PC over a serial connection, enabling the generation of dynamic loading patterns (e.g. square, sawtooth) as well as steady-state loads, thus enabling the emulation of both discrete and continuous streams of loaded material.

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[32] Also commonly referred to as dynamic braking.

[33] i.e. an AC waveform with zero real component, thus oscillating at 0Hz.

6.4 Electrical & Electronic Design

In this section the electrical and electronic aspects of the CER are described, which together enable the control of test conditions and continuous monitoring of system parameters, as illustrated in Figure 6.3.

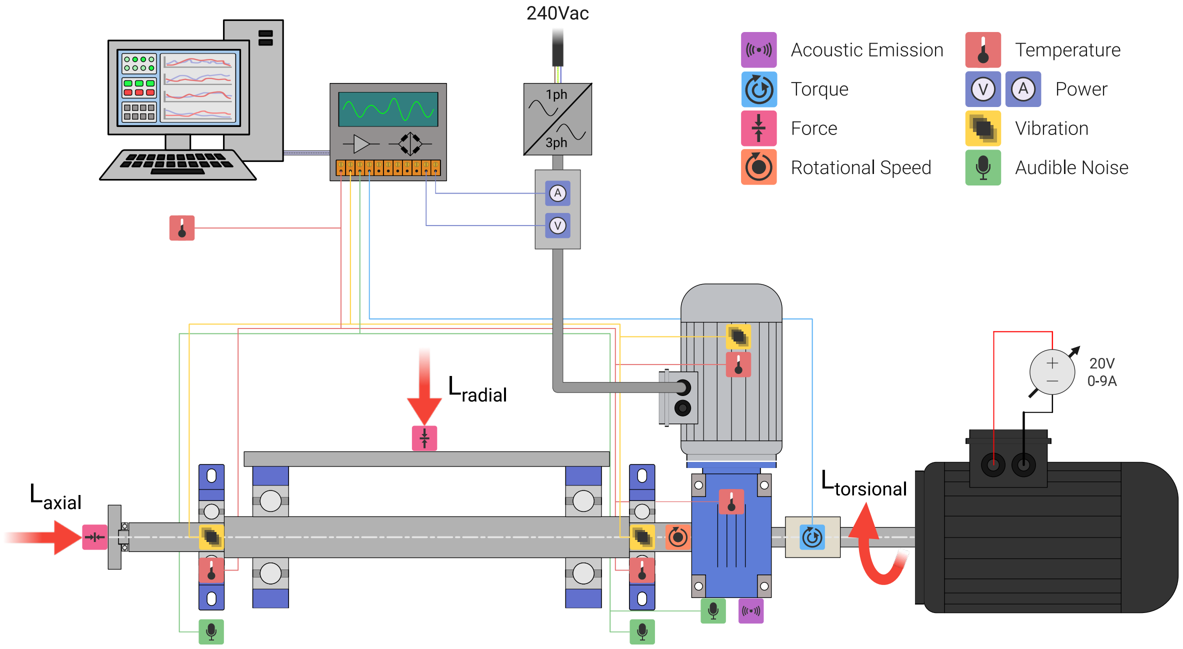


Figure 6.3: Illustration of the major mechanical, electrical and electronic elements within the Conveyor Emulation Rig (CER), highlighting the range of parameters continuously monitored during operation, as well as the external loads able to be applied by the operator.

6.4.1 Control System

Operation of the CER is controlled via a single PC, to which all control and monitoring hardware is interfaced. Via a graphical user interface (GUI) run on the PC a user can both control system inputs to apply specific test conditions and observe the measured response of system outputs.

The GUI, built within the National Instruments LabVIEW environment, facilitates five primary tasks during operation of the CER:

- **Interface with the motor's variable frequency drive.**

  Via a MODBUS TCP connection the VFD can be commanded, enabling the motor to be both started and stopped, as well as the output supply frequency varied within the range 0-50*Hz to* *adjust the motor speed. In addition, operation parameters stored within the VFD such output voltage and current draw are acquired at a rate of* 1*Hz.*

- **Interface with the motor drive emergency stop circuit.**
  The state of the eStop is monitored by the control software to ensure the CER is operated safely and eStop events can be logged.

- **Presentation of current and historical monitored parameter values.**
  All system parameters, both raw and derived, can be viewed, including the magnitude of applied radial and/or axial loads, providing feedback to the user when operating each hydraulic jack.

- **Command of the braking motor's power supply.**
  The power supply to the braking motor can be commanded to generate or remove braking torque. In addition, the torque magnitude can be modulated by adjusting the current draw, either manually or by selecting from a number of pre-programed waveforms such as square or triangle functions.

- **Logging of all system input and output parameters.**
  The GUI offers the user the option to log all monitored system parameters, if desired. Data is stored in the form of National Instruments' proprietary Technical Data Management Streaming (TDMS) file format. All datafiles are stored both locally and synced to the cloud, and a daily backup to a second HDD is made to ensure storage redundancy, and thus mitigate any risk of data loss.

6.4.2 Monitoring System

To enable measurement of each of the parameters selected for monitoring during operation of the CER a CMS responsible for both signal acquisition and conditioning was specified.

Instrumentation

Within the CER monitored parameters can be categorised as either control inputs which dictate the test conditions (e.g. speeds and loads) or system outputs which describe the subsequent response of system elements (e.g. temperatures and vibrations) (Table 6.8).

Table 6.8: Summary of primary control inputs and system outputs by category within the CER

Category	Applicability	Type
Applied load	Radial, axial, braking	Control input
Rotational speed	Gearbox	Control input
Temperature	Motor, gearbox, bearings, ambient	System output
Electrical Power	Motor	System output
Vibration	Motor, bearings	System output
Audible noise	Gearbox, bearings	System output
Acoustic emission	Gearbox	System output

Control Inputs

To ensure the specific conditions created during each test scenario are captured within logged data all relevant control inputs are measured.

The VFD provides an indirect estimate of motor rotor speed based upon the current draw. However, to directly observe the actual instantaneous speed of the main shaft a Hall-effect sensor in conjunction with a magnet wheel is used. The magnet wheel is mounted directly to the gearbox output shaft and thus rotates synchronously with the main shaft. When each magnet passes the Hall-effect sensor the digital output state of the sensor is pulled low creating a pulsetrain with time. Through measurement of each pulse’s period and with the geometry of the magnet wheel known the speed of the main shaft can be calculated. The Hall-effect sensor is interfaced with a NI USB-6211 DAQ unit where it is sampled at a variable rate, in response to observed changes in state.

To capture the loading applied to the CER during each test scenario two compression load cells and an inline torque transducer are used. To measure linear radial and/or axial loads a button style load cell is placed between the base of each hydraulic jack and its support structure. Each cell has a capacity >=10kN and is coupled to a dedicated amplifier to produce a signal measurable by DAQ hardware. To measure torsional load on the main shaft an HBM T5 slip ring torque transducer is installed between the drive gearbox and braking motor, via flexible couplings to minimise induced vibration. All load cell amplifier outputs are interfaced with a NI USB-6211 unit where they are sampled at a rate of 10Hz and logged.

System Outputs

To capture the response of the parameters selected in Section 6.2 during each test scenario the CER incorporates a series of transducers. The instantaneous electrical power consumption of the drive motor is measured through a custom monitoring system, constructed from COTS closed-loop Hall-effect based voltage and current transducers. Transducers are manufactured by LEM and have a measurable range and nominal accuracy of 250Vac RMS and 0.5%, and 5A RMS and 0.9% of full range, for voltage and current measurement respectively. The output of each device is passed through an active analogue filtering stage, where a 2nd order low-pass filter with cut-off frequency of around 300Hz is applied to each channel. This serves to remove any high-frequency harmonics present within the waveforms as a result of the VFD switching action.

The electrical power monitoring system enables two line voltages and two phase currents of the three phase drive motor to be monitored. By selecting appropriate lines and phases to monitor the total instantaneous power consumption of the motor can be calculated without requiring direct measurement of all three line voltages and phase currents, assuming the motor's load is balanced i.e. all line voltages and phase currents sum to zero [204].

The instantaneous power $p(t)$ in an AC circuit is the product of instantaneous voltage $v(t)$ and current $i(t)$ i.e.:

$$p(t) = i(t) \cdot v(t) \tag{6.2}$$

For a three-phase system of designates phases a, b and c this becomes:

$$p_{total}(t) = i_a(t) \cdot v_a(t) + i_b(t) \cdot v_b(t) + i_c(t) \cdot v_c(t) \tag{6.3}$$

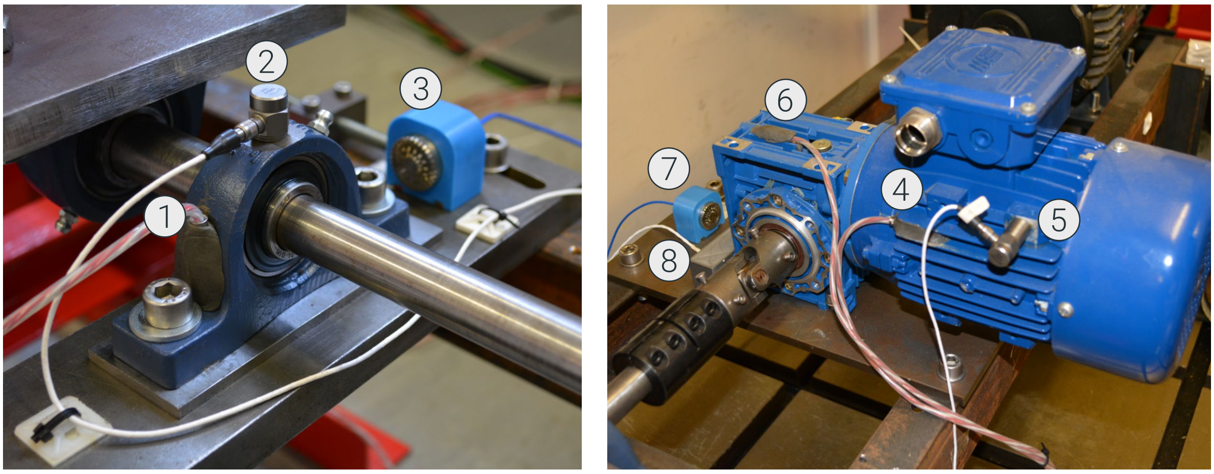
Which, through rearrangement, can be reduced to:

$$p_{total}(t) = -v_{ca}(t) + (i_a(t) + i_b(t)) - v_{ab}(t) \cdot i_b(t) \tag{6.4}$$

Where Vca and Vab are line-to-line voltages.

The output of the electrical power monitoring system is four analogue waveforms, which are then sampled via a National Instruments NI USB-6211 I/O device at a rate of 10kHz. Every second (i.e. 10k samples) the DC component and RMS value of each waveform is calculated along with the instantaneous power consumption according to Equation 6.4. Additionally, every minute a one second segment of each waveform is sampled simultaneously[34] and logged. In accordance with the Nyquist-Shannon Sampling Theorem [205] this will permit all frequency content within the signal up to 5kHz to be preserved, supporting later analysis. A Fast Fourier Transform (FFT) is computed for each segment of data using 262144 points (2^{18}) to provide a frequency resolution of ~0.04Hz. Prior to FFT computation a Hanning window [206] is applied to each segment of data to minimise spectral leakage.

To monitor the temperature of drive components resistance temperature detectors (RTDs) were employed, due to their combination of robustness and linear response over a wide operating range [46], [175]. A single RTD was mounted externally on the motor, gearbox and each support bearing using a metalised epoxy, in accordance with the procedure described in Chapter 4, Section 4.4.2 (Figure 6.4). Each RTD was connected to a COTS signal conditioning unit, from which a calibrated IEEE 754 floating point temperature in the range 0-100°C is output for each channel at a rate of 2Hz.



① Bearing-mounted RTD
② Bearing-mounted accelerometer
③ Bearing microphone
④ Motor-mounted RTD
⑤ Motor-mounted accelerometer
⑥ Gearbox-mounted RTD
⑦ Gearbox/motor microphone
⑧ Gearbox acoustic emission sensor

Figure 6.4: Bearing, motor and gearbox sensor locations.

To monitor the mechanical vibrations of the motor and support bearings three Dytran 32255A1 integrated electronics piezo-electric (IEPE) accelerometers were used. Each accelerometer

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[34] N.b. due to hardware limitations some delay between samples will be unavoidable.

provides a single axis of sensitivity up to 50g max and a frequency response in the range 0-100kHz. Each accelerometer was mechanically fastened via a rigid stud mount as recommended in BS ISO13373-1 [198] for optimal transmission of mechanical vibrations between bodies. In this regard, the flatness of mating surfaces is of prime importance for optimal frequency response, therefore, a planar surface ~10x10mm was required at each mounting location. No such location was present on the motor exterior so an existing threaded hole was used to mount the accelerometer in a horizontal orientation via a machined steel adapter (Figure 6.4).

Similarly, to mount an accelerometer on each bearing an area at the top of each housing was machined flat and a hole drilled and tapped to receive the accelerometer's stud, placing the accelerometer in a vertical orientation. Silicone grease was applied to all mating surfaces to fill any imperfections and thus minimise attenuation of vibrations [207].

All three accelerometers were interfaced with a single National Instruments 9234 DAQ unit and each channel was sampled at 50kHz. Every 30 seconds of CER operation 1 second of continuous data (i.e. 50k samples/channel) is sampled from each channel, and a series of descriptors (Table 6.9) are calculated and stored.

Table 6.9: Waveform descriptors derived from raw time-domain waveforms

Parameter	Definition	Description
Root-mean-square (RMS)	$X_{RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\lvert X_n\rvert^2}$	The value of the square root of the average of the squares of the waveform values.
Peak	$X_{peak} = max\,(X)$	The maximum value within a waveform.
Peak-to-peak	$X_{pk2pk} = \lvert X_{min} - X_{min}\rvert$	The value of the difference between the extrema of a waveform.
Crest Factor	$X_{crest} = \frac{X_{max}}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\lvert X_n\rvert^2}}$	The ratio of the waveform's peak value to RMS value.
Variance	$X_{var} = \frac{1}{N-1}\sum_{i=1}^{N}\lvert X_i - X_{mean}\rvert^2$	The second central moment of a distribution.
Skewness	$X_{skew} = \frac{(X - X_{mean})^3}{{X_{var}}^2}$	The third central moment of a distribution.
Kurtosis	$X_{kurt} = \frac{(X - X_{mean})^4}{{X_{var}}^3}$	The fourth central moment of a distribution.

Definitions taken from [208] *and* [135].

In addition, for every 600 seconds of CER operation 1 second of continuous data (i.e. 50k samples/channel) is sampled from each channel and an FFT is computed, after which both time and frequency-domain waveforms are logged. FFTs are performed using 262144 points (2^{18}) to provide a frequency resolution of ~0.2Hz and again a Hanning window is first applied.

To monitor the audible noise nominally produced by the gearbox and bearings three Bruel & Kjaer type 4117 piezo-electric microphones were used, with a frequency response in the range 4-10kHz. Each microphone was placed in close proximity to the component it was to monitor, however, as previously discussed each microphone will not discriminate against the source of generated noise, resulting in each microphone likely capturing a broad spectrum of noise (Figure 6.4). Each microphone was interfaced with a single NI 9234 where identical sampling, logging, processing and descriptor extraction steps as for acceleration measurements was implemented, except at a sample rate of 10kHz.

Finally, a measurement of acoustic emissions from the gearbox was made using a Physical Acoustics WD wideband differential transducer, with a frequency response of 100-900kHz. The transducer was mounted to the base of the gearbox via a magnetic housing and a layer of silicone grease was again used to improve signal transmission (Figure 6.4). The transducer is interfaced with a NI PCI6251 analog input card via a 20dB gain preamplifier, where an identical sampling, descriptor extraction and logging process as for vibration measurements was implemented, except at a sample rate of 1.25MHz.

Data Storage

If commanded by the test operator via the CER GUI, the control software will log all acquired data. Data is stored in the form of National Instruments's proprietary Technical Data Management Streaming (TDMS) file format. All datafiles are stored both locally and synced into the cloud and a daily backup to a second HDD is made to ensure storage redundancy and thus mitigate any risk of data loss.

6.5 Commissioning

Prior to the commencement of a formal programme of tests a period of commissioning was undertaken to verify the operation of specific aspects of the CER's operation.

6.5.1 Braking Motor Calibration

To assess the ability of the braking motor in generating counter torque a benchtop characterisation exercise was conducted. The braking motor was coupled to a permanent magnet synchronous machine (PMSM) via a calibrated inline torque transducer. The PMSM (operated in closed-loop speed control mode) was then commanded to different speeds in increments of 20rpm and at each speed setpoint the DC supplied to the braking motor was increased from 0-9A in increments of 1A. At each speed and current setpoint the torque generated by the braking motor was measured, enabling a lookup table describing the speed-current-torque relationship associated with the braking motor to be compiled (Figure 6.5).

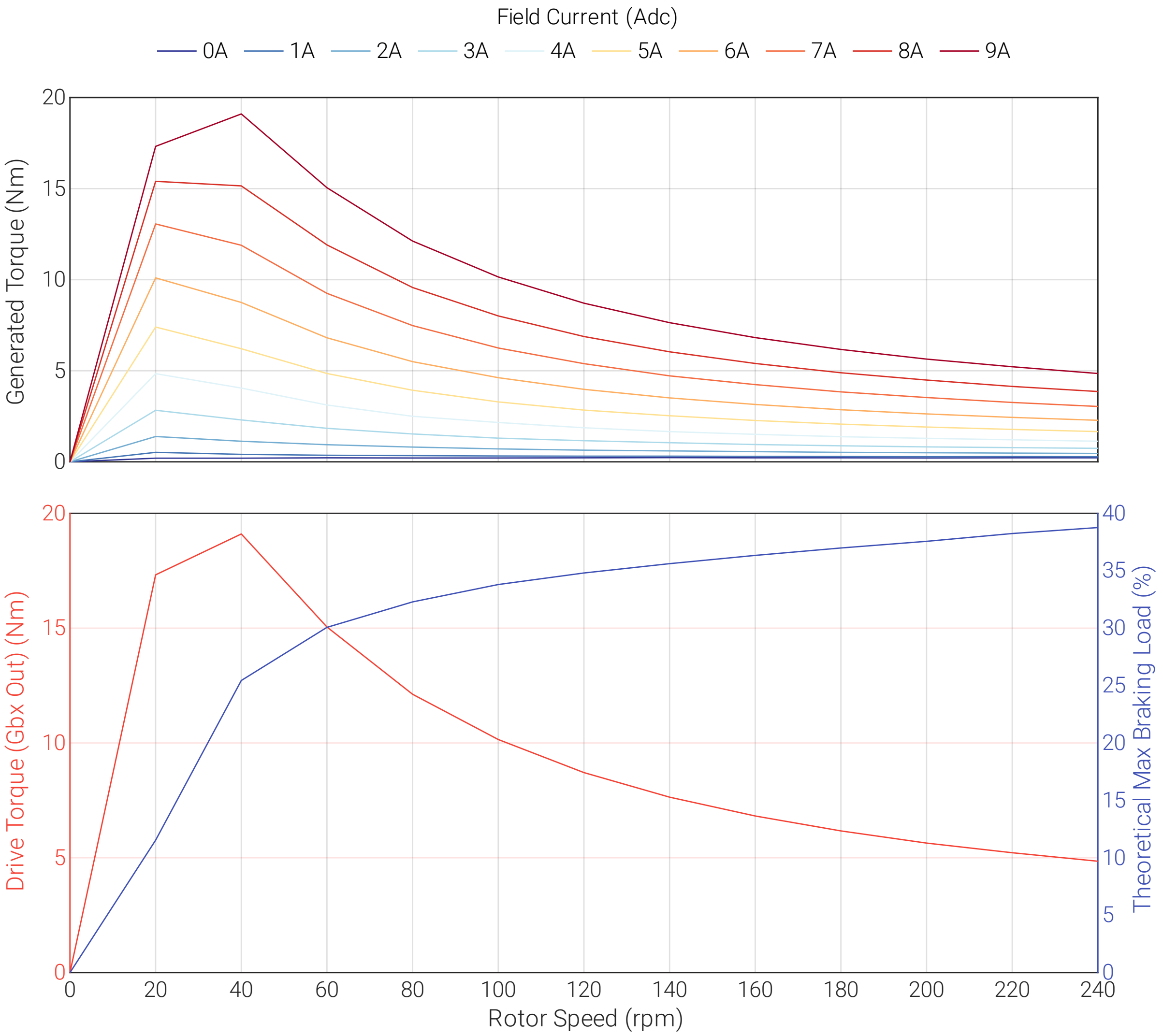

Figure 6.5: Braking motor characterisation data.

It was determined that approximately a 35% braking load could be generated by the braking motor within the speed range of 60-180rpm where the CER is to most commonly be operated, without exceeding the motor's continuous current limit of 9A. Accordingly,

It was expected that that a continuous braking load can be applied to the CER drive motor without incurring damaged to the braking motor, when operated within the described limits.

The rate at which the level of braking load generated can be dynamically varied is dictated by the response time of the power supply to current commands. Through a series of informal tests it was determined that changes in the current setpoint could be made at a frequency no greater than ~0.1s (10Hz).

6.5.2 Load Cell Amplifier Calibration

Calibration of each load cell amplifier was required prior to CER operation to assess the relationship between applied torque and output signal amplitude. To calibrate each linear transducer (radial and axial) and associated amplifier an Instron tensile testing machine was used to apply known magnitudes of force to each transducer[35], from which the resulting amplifier output signal amplitude could be measured. Increments of 1kN up to 10kN max were applied to each cell and the resulting signal amplitude measured using a digital multimeter.

From the measurements taken each amplifier was observed to adhere to an essentially linear relationship between applied load and signal amplitude. Accordingly, for each cell a linear equation was estimated, from which the absolute radial and axial loads applied during CER operation could be determined. The calibration data from each load cell can be found in Appendix E:.

Calibration of the torque transducer and amplifier was achieved through the use of a dedicated calibration rig operated by the Electrical Energy Management Group at the University of Bristol. In a similar manner to the calibration of linear loads a series of known torques were applied to the transducer by a permanent magnet synchronous machine in increments of 1Nm up to 25Nm. Again, a linear relationship was observed, which was used to estimate a linear equation, from which the braking torque applied to the CER motor could be determined.

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[35] The testing machine was Class 0.5 i.e. maximum error of <0.5%.

6.5.3 Motor Power Monitoring Calibration

To assess the accuracy of the power monitoring system a series of calibration tests were conducted in which voltages and currents measured by the system were compared with known supply values. A Bruel & Kjaer BK 4040B function generator was used to generate purely sinusoidal waveforms to excite the power monitoring system and an HP 34401A digital multimeter was used to measure the output of the monitoring system. Accordingly, each channel was found to have a consistent input/output ratio, with an overall error of <0.5% full range. Complete motor power monitoring calibration data can be found in Appendix E:.

6.6 Summary of Chapter

This chapter has presented the design and development of a laboratory-based test rig (termed the CER) constructed to provide a platform for evaluating the characteristics of monitored system parameters. The CER enables the approximate dynamics of a CBS to be emulated within a controlled environment, such that the response of monitored parameters to changes in speed and load can be observed. A comprehensive range of system parameters were selected to be monitored continuously throughout operation of the CER, as identified through a process combining the analysis of CBS operation and a review of extant monitoring technologies as reported within literature. To enable the response of each parameter to changes in CBS operation a series of loading mechanisms were designed to enable the controlled application of axial, radial and/or torsional loads to the CER.

Chapter 7: Evaluation of Monitored CBS Parameters – Results and Findings

Based upon data acquired during operation of the Conveyor Emulation Rig (CER) described in Chapter 6, this chapter evaluates the suitability of each monitored parameter for CBS applications. Through analysis of each category of parameter's response to changes in system speed and the application of mechanical loads a subset of parameters are identified as most suitable for CBS applications.

7.1 Testing Procedure

During the conduction of each test scenario a strict procedure was adhered to, ensuring tests were completed safely, as well as consistently. An overview of the major steps taken during the execution of each test scenario is presented in Figure 7.1.

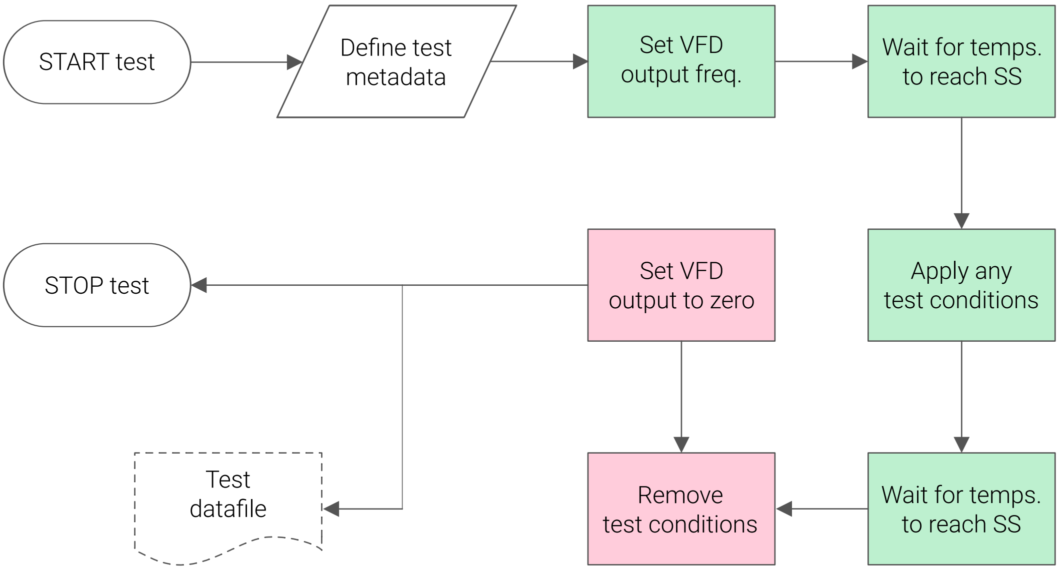

Figure 7.1: Testing procedure adhered to during operation of the CER.

Upon commencement of the CER control GUI the operator was prompted to enter a series of metadata related to the specific scenario implemented such as a test ID and description, as well as the ID associated with each drivetrain component i.e. motor, gearbox and bearings. The GUI also autogenerates a timestamp to associate with the scenario. During the completion of the test scenario the operator is able to input any notable observations via the GUI, which are logged and form part of the scenario's metadata.

The length of each test scenario conducted was dictated by the conditions of the specific scenario; in response to changes in operational conditions (i.e. changes in load or speed) all monitored parameters were allowed to reach steady-state conditions prior to subsequent changes and/or terminating the scenario. A criteria of <1degC of change in a ten minute period was used to define when thermal steady state was reached, in accordance with the recommended practice of the University of Bristol's Electrical Energy Management Group [209] . Each scenario was repeated a total of three times to enable the variance in parameter responses to nominally identical conditions to be assessed. Throughout testing the operator was segregated from the CER by a safety screen to minimise the possibility of injury.

7.2 Test Scenarios Conducted

Based upon the CBS operational scenarios identified in Chapter 5, Section 5.1, six classes of test scenario were conducted on the CER, with each class designed to emulate one or more operational scenario. Accordingly, each class constituted a unique combination of drive speeds and applied radial, axial and/or braking loads, as detailed in Table 7.1.

Table 7.1: An overview of the test scenarios conducted on the CER.

ID	Description	Mode of loading	Loading profile	Rationale	Method
CER_TS_A	Multi speed characterisation	None	NA	Characterise unloaded operation.	Run at 15,30,45Hz sequentially.
CER_TS_B	Radial loading of drive shaft	Radial	Step	Emulate increased belt tension.	Run at 45Hz, apply 1,2,3kN sequentially.
CER_TS_C	Axial loading of drive shaft	Axial	Step	Emulate uneven belt tracking.	Run at 45Hz, apply 1,2,3kN sequentially.
CER_TS_D	Combined radial and axial loading	Radial Axial	Constant, Step	Emulate increasing belt tension with uneven belt tracking.	Run at 45Hz, apply 3kN radial, then apply 2,4,6kN axial sequentially.
CER_TS_E	Torsional loading of drive shaft	Torsional	Step	Emulate increasing levels of product on belt.	Run at 30Hz, apply 3,5,8A power to braking motor sequentially.
CER_TS_F	Torsional loading of drive shaft	Torsional	Cyclic	Emulate typical profile of product being loaded.	Run at 30Hz, apply triangle wave current profile at 3,5,8A peak.

Each scenario was conducted a total of three times to assess the repeatability of parameter responses to each change in operation. In total, conducted tests comprised more than 20 hours of operation, with each scenario generating over 100 directly measured or derived parameters.

7.3 Characteristics of Parameter Responses

In this section a summary of the response of each category of monitored parameter to the conditions implemented during each test scenario is provided. For the purpose of brevity, exhaustive results from each specific scenario conducted are omitted and instead only salient data and findings are presented and discussed.

7.3.1 Motor Electrical Power Consumption

Summary:

- *Presents high sensitivity to changes in rotational speed and torsional load.*
- *Some sensitivity to radial load observed but minimal sensitivity to axial load.*
- *Negligible lag observed between changes in operation and response of motor electrical power consumption.*

In response to an increase in VFD output frequency a corresponding increase in the motor's electrical power consumption (MEPC) is observed with negligible time lag (Figure 7.2). For analysis purposes frequency content was limited to a maximum of 200Hz; spectral content beyond this is not of interest within the context of identifying sensitivity to speed and load. Additionally, beyond ~2kHz MEPC spectra are dominated by components associated with the switching frequency of the VFD (3kHz) and its harmonics and sidebands therein, masking any underlying signals.

Through interrogation of the MEPC frequency content the dominance of the VFD output frequency and its harmonics (primarily second) can be identified within spectra. This behaviour is central to the V/f (volts-per-Hertz) method of induction motor speed control as implemented by the CER VFD, a method commonly employed throughout industry [47], and can be explained through consideration of the fundamental principles of operation associated with an induction motor.

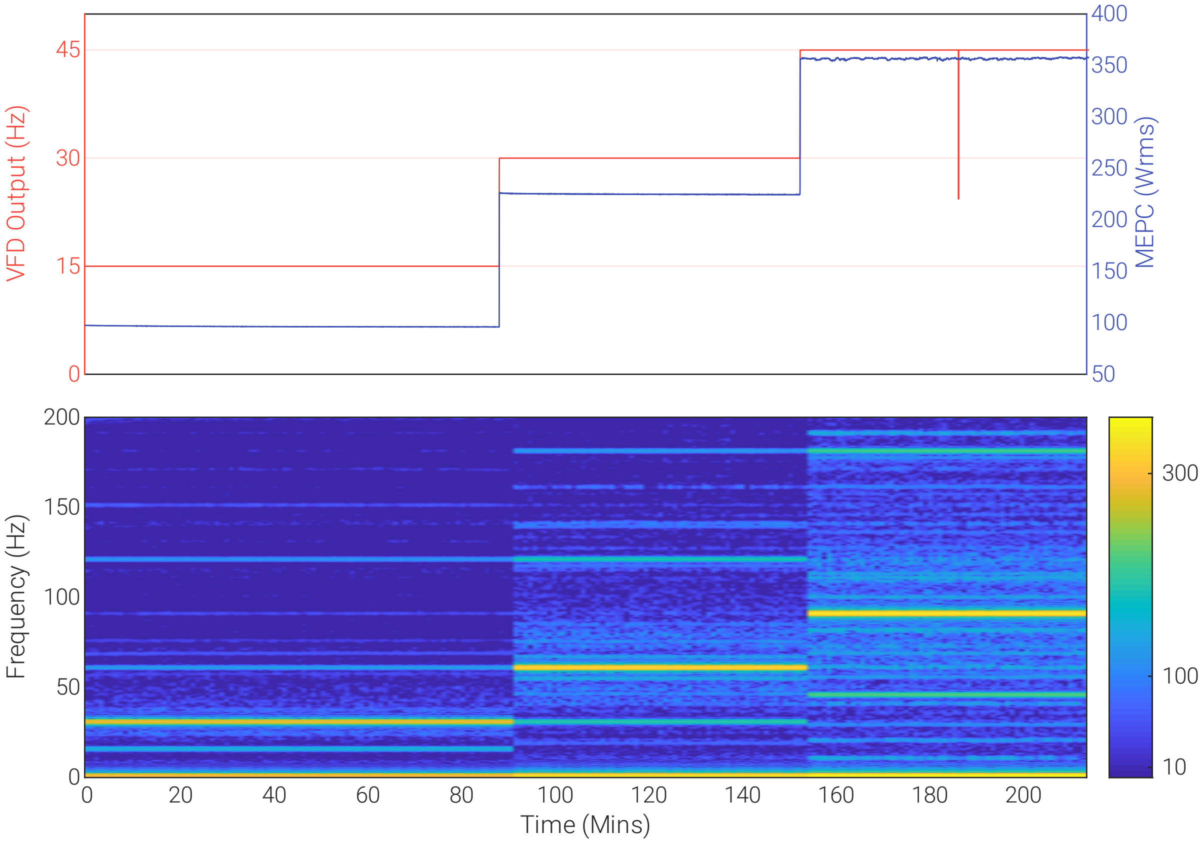

Figure 7.2: Motor electrical power consumption against VFD output frequency, as a function of time (top) and frequency (bottom).

The synchronous speed of an induction motor is dictated by its construction and the alternating frequency of its electrical supply. In a purely sinusoidal voltage waveform[36] the amplitude of the voltage supplied during each cycle is a function of the cyclic frequency (f) in accordance with:

$$v(t) = v_{peak} \cdot sin(\, 2\pi f t \,) \qquad 7.1$$

Accordingly, as the waveform's frequency is increased the speed of rotation of the magnetising flux field generated in the motor's stator-rotor air gap through induction increases synchronously. At synchronous (i.e. no load) speed the motor's rotor is rotating at the same speed as the magnetic flux field in accordance with:

$$N_s = \frac{2\, f_s}{p} \qquad 7.2$$

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[36] The voltage waveform output by the VFD is not purely sinusoidal but instead a quasi-sinusoidal emulation, however, the same theory applies.

Where p relates to the number of magnetic poles within the motor's stator.

Therefore, as the supply frequency is increased so too is the synchronous speed of the rotor. The magnitude of the magnetic flux field generated within the stator-rotor air gap (Bm) is dictated by the supply frequency and applied voltage in accordance with [47]:

$$B_m = k \left(\frac{V}{F}\right) \qquad 7.3$$

Where k is a constant dictated by the construction of the motor.

So, by increasing the supply frequency to the stator the magnitude of the generated magnetic flux field is decreased, for a fixed supply voltage. The action of an alternating voltage waveform flowing within a wire such as the stator winding will induced an emf (E), the magnitude and direction of which are a function of the supply frequency in line with Faraday's Law of Induction and Lenz's Law i.e.:

$$E = -N \cdot \frac{d\phi}{dt} \qquad 7.4$$

Where Φ is the magnetic flux within the created field.

Therefore, as the supply frequency is increased the amplitude of the magnetic flux field generated reduces and thus less emf is induced in the stator winding. The direction of the emf induced in the stator winding is such that it acts to oppose the supply voltage (V), therefore, as the supply frequency is increased the net voltage in the stator winding increases and thus more current (I) can flow in line with Ohm's Law i.e.:

$$I = \frac{V}{R} \qquad 7.5$$

Where R is the resistance of the stator winding.

The total electrical power within the stator winding circuit (P) is described by:

$$P = I^2 R \qquad 7.6$$

Hence, as more current is drawn the overall electrical power consumed by the motor increases. Accordingly, in general the power consumed by an induction motor can be considered to be proportional to its supply frequency[37] [210], providing an explanation for the behaviour observable in Figure 7.2.

When the main shaft is subjected to radial load a small increase of approximately 1W in MEPC is observed at 6kN applied load, compared to unloaded operation (Figure 7.3).

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[37] This statement is not necessarily valid across the entire operating envelope of an induction motor; however, it is broadly reflective of typical behaviour.

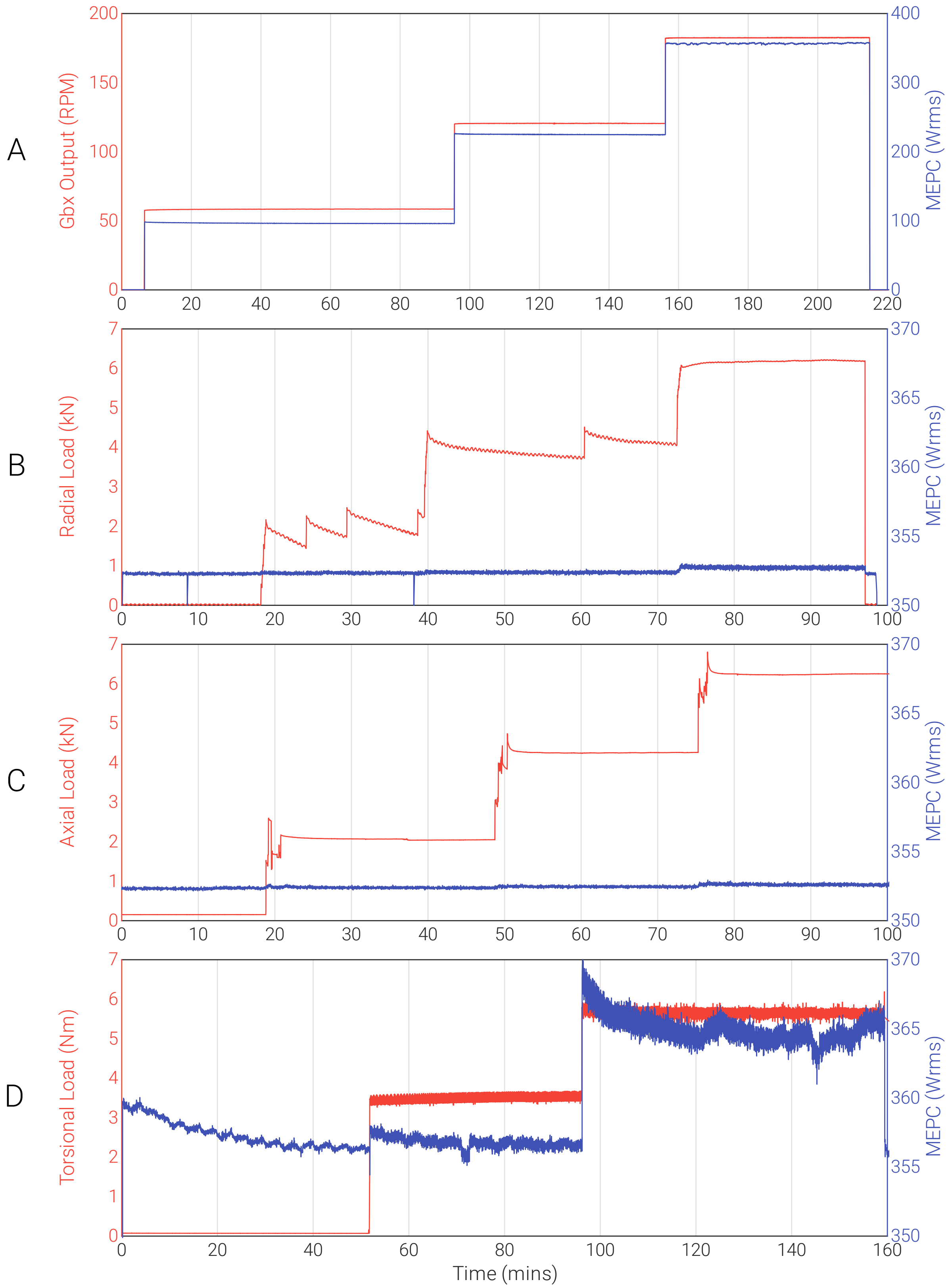

Figure 7.3: Summary of measured CER drive motor electrical power consumption in response to changes in drive speed (A), applied radial load (B), applied axial load (C) and applied torsional load (D).

When radial load is applied to the main shaft it is reacted by the support bearings, causing an increase in contact pressure between the races and the rolling elements (Figure 7.4). In turn this pressure causes an increase in dynamic frictional forces between these mating surfaces increasing Coulomb friction, in accordance with:

$$F_f = \mu F_n \tag{7.7}$$

Where F_f *is the generated frictional force,* μ *is the coefficient of dynamic friction between the bearing surfaces and* F_n *is the normal force between the bearing surfaces (i.e. gravitational force plus radial load).*

This increased frictional force translates into a 'clasping' of the shaft which, via the gearbox, is experienced at the drive motor as an increase in torsional load. Due to the open-loop mode in which the VFD is operated no attempt to compensate for the increased torsional load is made, so its presence causes a reduction in rotor speed, and hence a corresponding increase in MEPC due to the increase in slip.

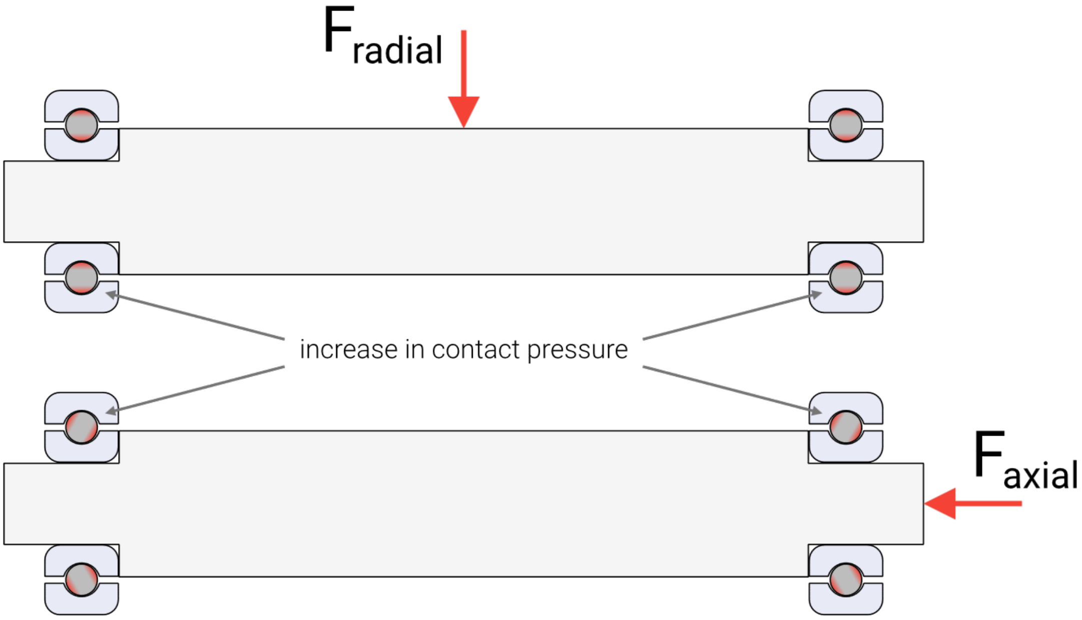

Figure 7.4: Illustration of the transmission paths of applied radial and axial loads through CER support bearings, resulting in increased contact pressure.

A similar MEPC response is observed when axial load is applied to the main shaft, causing an increase of approximately 0.5W from consumption in an unloaded condition (Figure 7.3). Within the CER applied axial loads are supported primarily by Bearing 1 via the stepped profile of the main shaft. This action again generates an increase in contact pressure between the races of Bearing 1 and its rolling elements (Figure 7.4) and thus Coulomb friction as it supports the thrust load, which is also experienced at the motor as an increased torsional load. However, this increase in friction is minimal in comparison to the design load of the bearing so little increase in torsional loading occurs.

The simultaneous application of radial and axial loads to the system can be seen to cause a compounding effect on MEPC, with consumption decreasing with the application of both modes of loading (Figure 7.5).

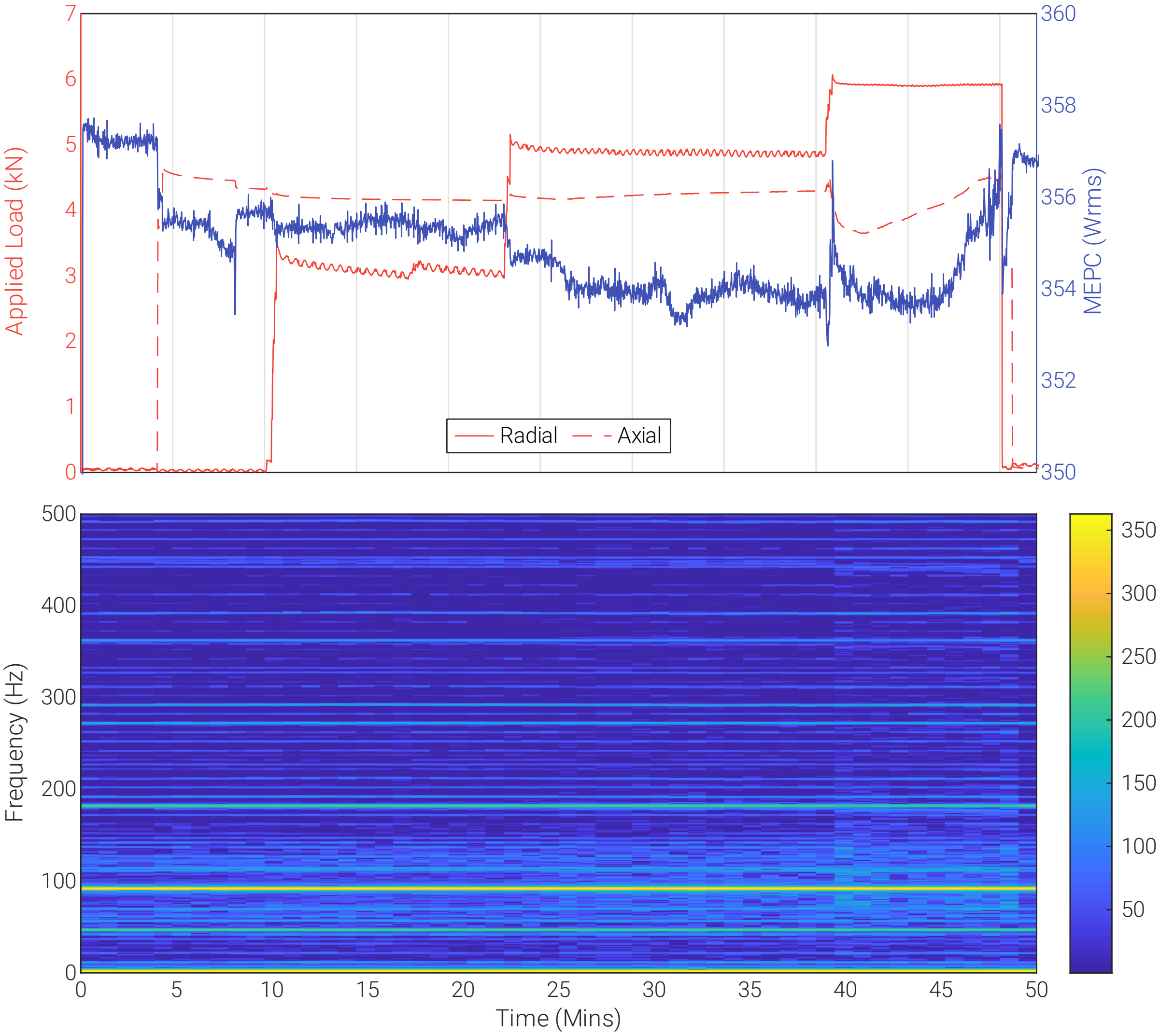

Figure 7.5: Summary of measured CER motor electrical power consumption in response to the simultaneous application of radial and axial loads in both time (top)[38] and frequency domains (bottom).

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[38] The anomalous behaviour observed at the maximum radial load application (i.e. reduction in axial load) can be explained by the deflection of the shaft in response to such levels of loading.

Accordingly, through interrogation of RMS MEPC time-domain data alone it is not possible to discern between the two modes of loading. When the frequency spectra of the MEPC during simultaneous application of loads is interrogated a qualitative change in the spectral content can be observed when subjected to maximum radial (~6kN) and axial (~4kN), however, the characteristic frequencies associated with the rotational speed of the shaft are still dominant within the spectra (Figure 7.5).

A greater increase in MEPC is observed in response to the application of torsional load compared to that associated with applied radial and axial loads, with a maximum increase of ~3% measured in response to ~6Nm of braking torque (Figure 7.3).

In contrast to the application of radial and axial loads, the application of torsional load is reacted directly by the drive motor, with the torque generated by the braking motor acting to oppose that of the drive motor. The presence of this torque creates slip between the rotor and the rotating magnetic flux field generated by the stator in the motor's air gap. Accordingly, due to the relative motion between these two rotating elements the cutting of flux occurs, so causing an emf to be induced in the windings of the stator, in line with Faraday's Law of Induction. As described previously, the effect of the induced emf is to permit more current to flow within the stator winding, thus, as the torsional load on the motor is increased the power consumed by the motor increases accordingly until a balance is reached, preserving the magnetic flux field in the air gap [211].

The measured response of MEPC in response to dynamic changes in torsional load can be seen to present no quantifiable phase delay, with MEPC response remaining apparently synchronous even during load cycles of ~5s period (Figure 7.6).

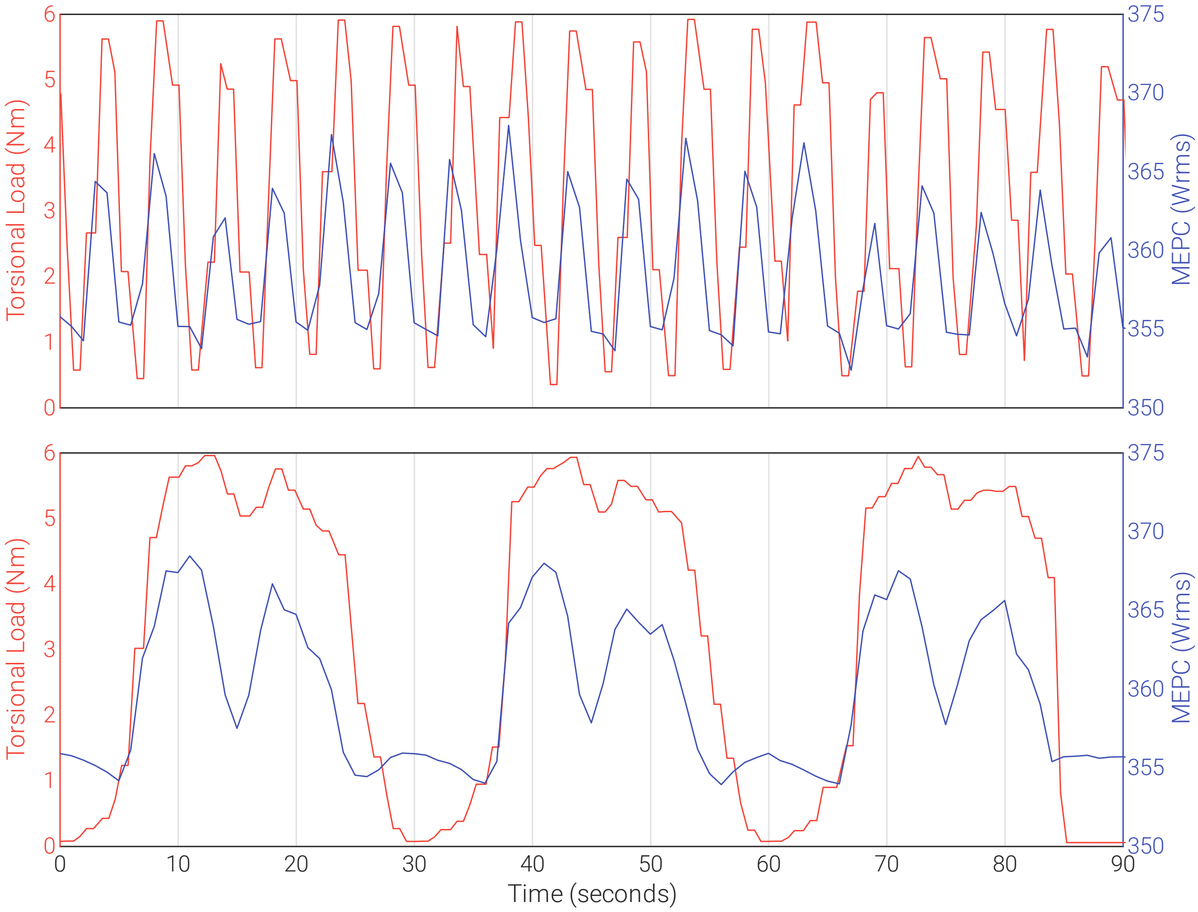

Figure 7.6: Measured MEPC of CER motor in response to dynamic torsional loading profiles of 5s period (top) and 20s period (bottom).

The motor output is coupled to the braking motor output via the gearbox, providing a direct load transfer path and thus negligible mechanical phase delay between the two[39]. Similarly, the change in magnetic field caused by induced slip is propagated through free space at the speed of light [176], so can also be considered negligible, hence a change in torsional load experienced by the gearbox output shaft and the resulting change in MEPC can be considered essentially in phase and hence no time delay is measured.

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[39] Ignoring the effect of backlash within the gearbox, which, due to its worm-drive configuration can be reasonably assumed negligible.

7.3.2 Rotational Speed

Summary:

- *Reduction in system rotational speed observed in response to the application of radial, axial and torsional loads.*
- *No obvious differences in response to each specific mode of loading identifiable.*

In response to the application of radial, axial or torsional load at the magnitudes implemented during tests a reduction in the gearbox output rotational speed is observed (Figure 7.7). Each scenario represents an increase in resistance to the driving motion of the CER motor, and thus, due to the open-loop speed control mode operated by the VFD no attempt to compensate for increased torsional load is made and so the speed of the system decreases accordingly.

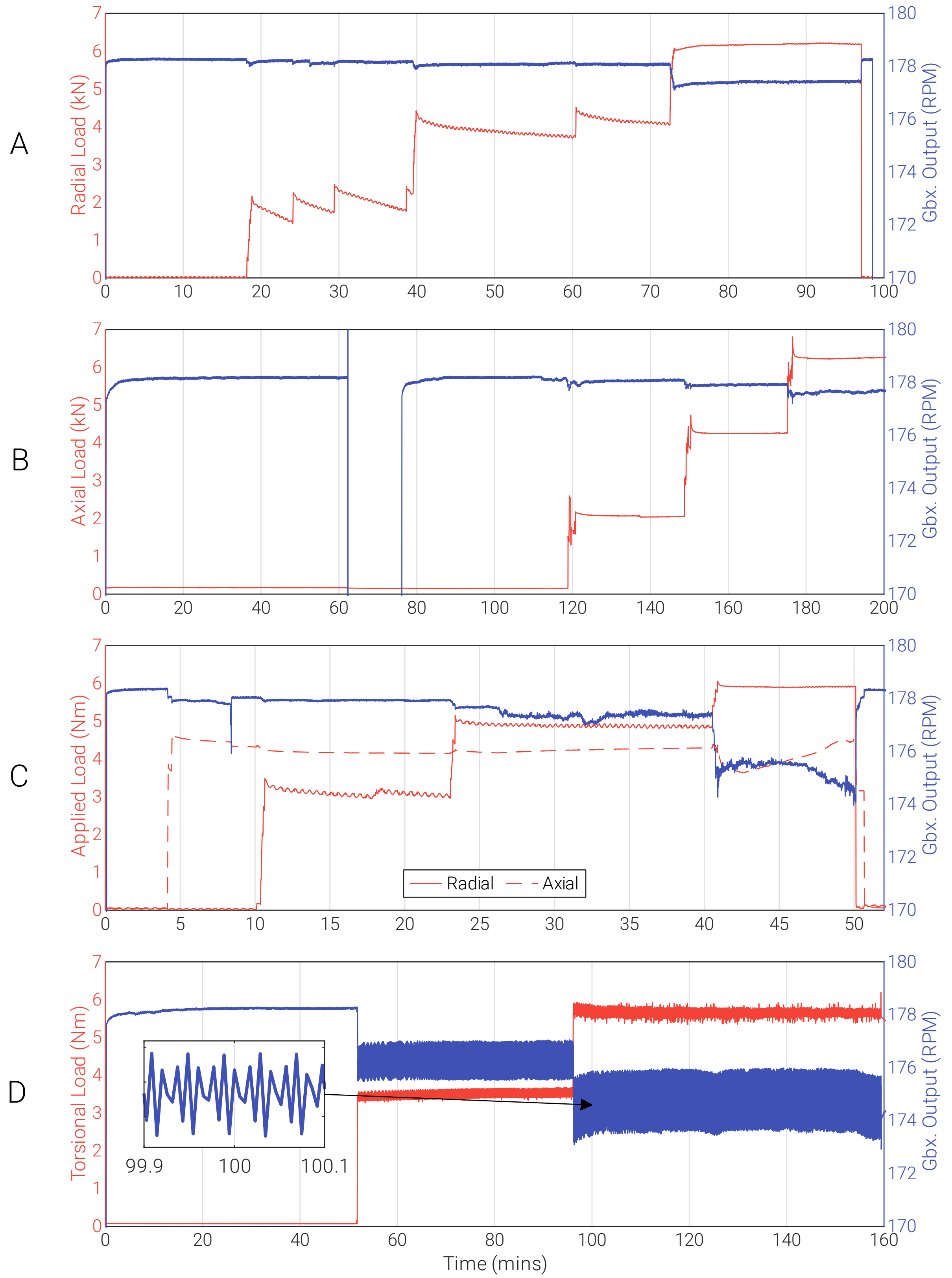

Figure 7.7: Summary of measured CER gearbox output rotational speed in response to the application of radial load (A), axial load (B), radial and axial loads (C), and torsional load(D).

When both radial and axial loads are applied simultaneously a compounding effect on rotational speed can be observed, with a decrease of ~3rpm from nominal operation measured. As such, through observation of the rotational speed of the system alone the specific mode of loading applied cannot unambiguously be determined, with only the magnitude of reduction varying across modes; as shown in Figure 7.7 the application of ~6kN radial or axial load will result in a reduction in gearbox output speed of ~1rpm.

In response to 6Nm of torsional load significant high-frequency oscillation can be observed within the rotational speed of the gearbox output shaft. This behaviour is likely a consequence of limitations on the ability of the braking motor power supply to regulate voltage output under transient loading.

7.3.3 Component Temperatures

Summary:

- *Component temperatures present sensitivity to changes in speed and load, to varying degrees.*
- *No obvious distinction between changes in speed and load observed.*
- *Significant time lag between changes in operating condition and steady-state temperatures being reached.*
- *Little sensitivity to torsional load observed.*

Across all test scenarios the temperature of the CER gearbox was typically the highest (~22°C above ambient) among monitored components, followed by the motor (~20°C a.a.) and then the support bearings (~4°C a.a.) (Figure 7.12). As also observed during the Industrial Monitoring Trial reported in Chapter 3, the measured temperatures of monitored CER components present significant time delay in response to changes in operating conditions, with an extended transient period occurring before steady-state conditions are reached (Figure 7.8). This delay represents the time taken for thermal energy to diffuse through material from the point of generation to point of measurement, and its magnitude is dictated by the thermal resistance of the material.

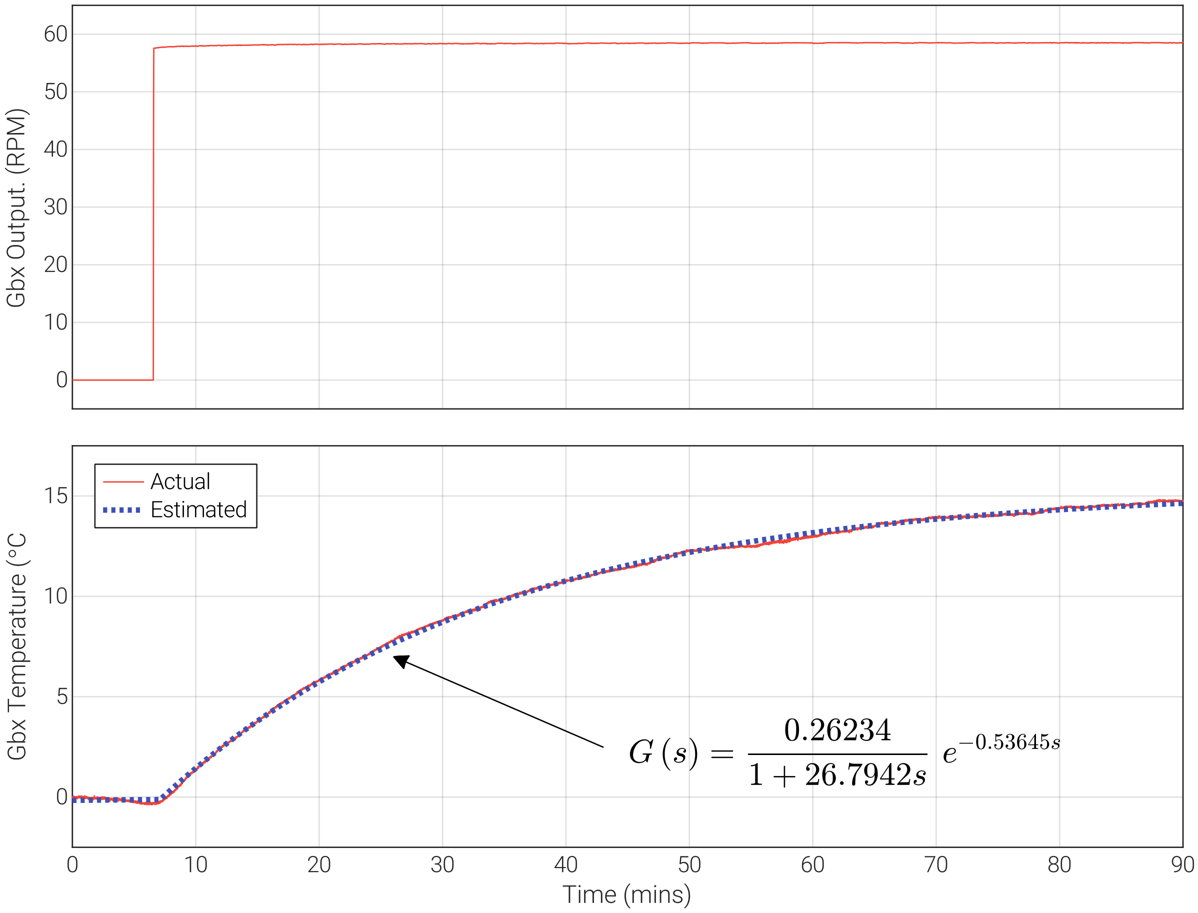

Figure 7.8: Characteristic measured response of CER gearbox temperature to changes in operating speed.

This response is approximately first order in nature, and in the case of the CER gearbox has an estimated time constant of ~27mins (Figure 7.8).

Throughout testing the measured temperature of components is observed to be a function of operating speed (Figure 7.9). The total energy into the CER system is increased with speed (as evidenced by the increased electrical power consumption of the motor), so, due to the various sources of thermal inefficiency associated with each component the absolute quantity of energy converted into thermal energy is increased within each.

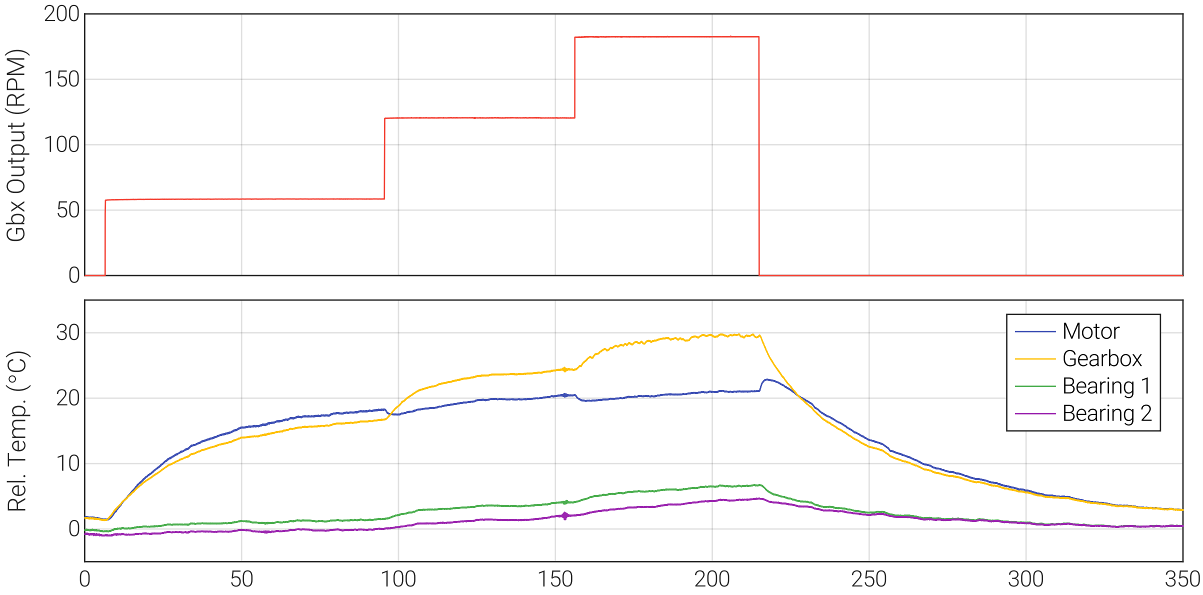

Figure 7.9: Response of component temperatures to changes in gearbox output speed. Note, temperatures are relative to the ambient temperature.

The greater temperatures measured on the CER motor and gearbox are reflective of their function as energy conversion devices, which, due to inherent inefficiencies associated with such processes result in the generation of heat within each component.

Within the gearbox such inefficiencies arise through a range of loss mechanisms such as frictional losses associated with the meshing of gears and viscous losses associated with the movement of lubricant, all of which will act to increase the generation of heat within the gearbox during operation. The gearbox used in the CER has a nominal efficiency of 85%, therefore, at nominal CER operation (i.e. 370W@45Hz) as much as 55.5W of power is lost within the transmission path between the motor and the main shaft. In the case of an induction motor such inefficiencies typically constitute a combination of stator losses (30-50%), rotor losses (20-25%), core losses (20-25%), load losses (5-15%), and friction and windage losses (5-10%) [212].

The measurement of a higher gearbox temperature than motor temperature is likely to be a consequence of the monitoring system setup. As indicated in Figure 7.10 the highest temperature area within the CER drive system was located at the interface of the two components. With respect to this location the motor RTD is at a greater distance and thus represents a more thermally lossy transmission path.

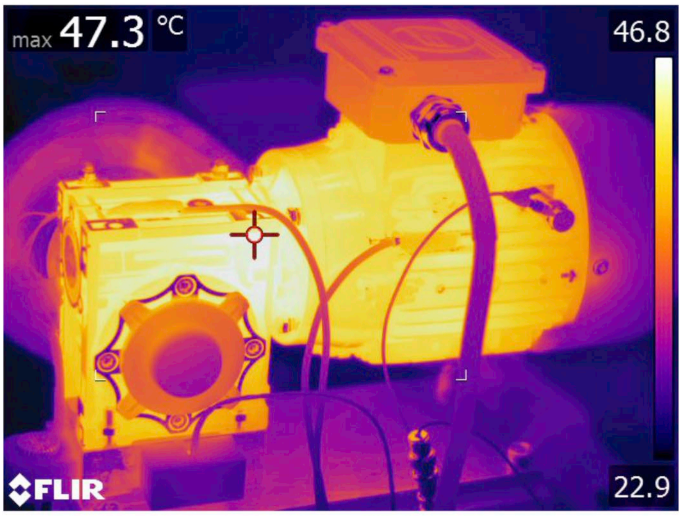

Figure 7.10: Thermal image of CER drive system during unloaded operation at 45Hz.

Within the bearings mechanical inefficiency is incurred through work done to overcome friction between sliding surfaces, almost all of which energy is dissipated in the form of heat at the sliding interface, raising the local temperature above ambient [213]. The work done (and hence energy lost) overcoming friction between two sliding surfaces (E_f) is a function of the frictional force between the two and the sliding distance, therefore the rate at which energy is lost to friction is approximately [214]:

$$E_f = \mu W \frac{ds}{dt} \qquad 7.8$$

Where μ is the coefficient of static friction between the surfaces, W is the compressive load the surfaces are subjected to and ds/dt is the relative velocity between the two surfaces.

Therefore, as the rotational speed of the bearings is increased so too is heat generation and hence measured temperature. In general, Bearing 1 recorded a higher temperature than Bearing 2 during CER operation, possibly due to its proximity to the drive system or due to misalignment with the main shaft setup. Alternatively, this differential may represent random variation in nominally identical components, occurring through differences in lubrication, manufacture, installation etc.

Uniquely, the measured temperature of the drive motor casing was observed to contain a transient effect following changes in CER operational speed wherein initially an inverse response is observed (i.e. an increase in speed results in a decrease in temperature and vice versa) before subsequently the direction of change inverts after a period of time (~2mins) and a direct response is observed until a steady-state temperature is ultimately reached (Figure 7.11).

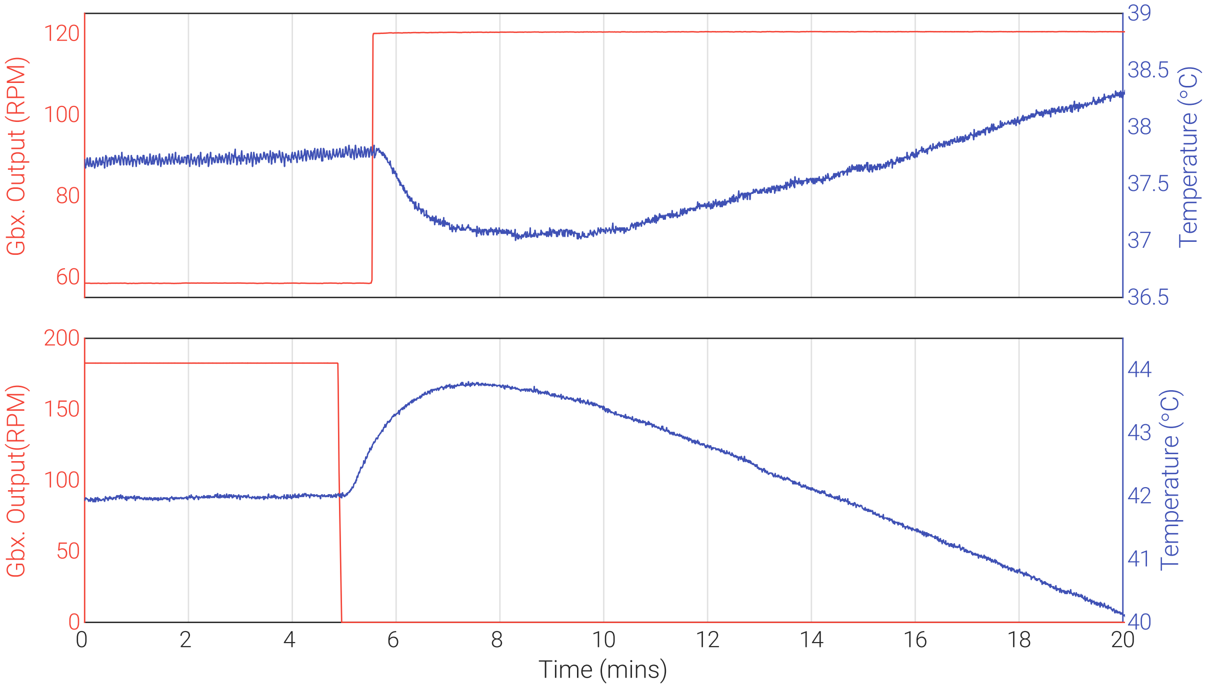

Figure 7.11: Non-minimum phase behaviour observed within the CER motor's measured temperature in response to an increase (top) and decrease (bottom) in operating speed.

Such behaviour is formally described as a stable, non-minimum phase response [215], and its occurrence here can be considered a consequence of the CER drive motor construction. While the CER gearbox is passively cooled, relying upon radiation and natural convection to dissipate heat, the drive motor contains a shaft mounted fan to provide active cooling via forced convection. As the motor fan is rigidly coupled to the rotor it provides an immediate change in airflow through the motor airgap (and thus effective cooling power) in response to changes in operating speed. Therefore, the thermal response of the motor to changes in operating speed can be considered to constitute the summation of a fast-responding component (i.e. fan action) which acts to remove heat from the RTD, and a slow-responding component (i.e. thermal inefficiencies) that acts to add heat to it. Together, these two components result in the counter-intuitive behaviour observed during operation of the CER.

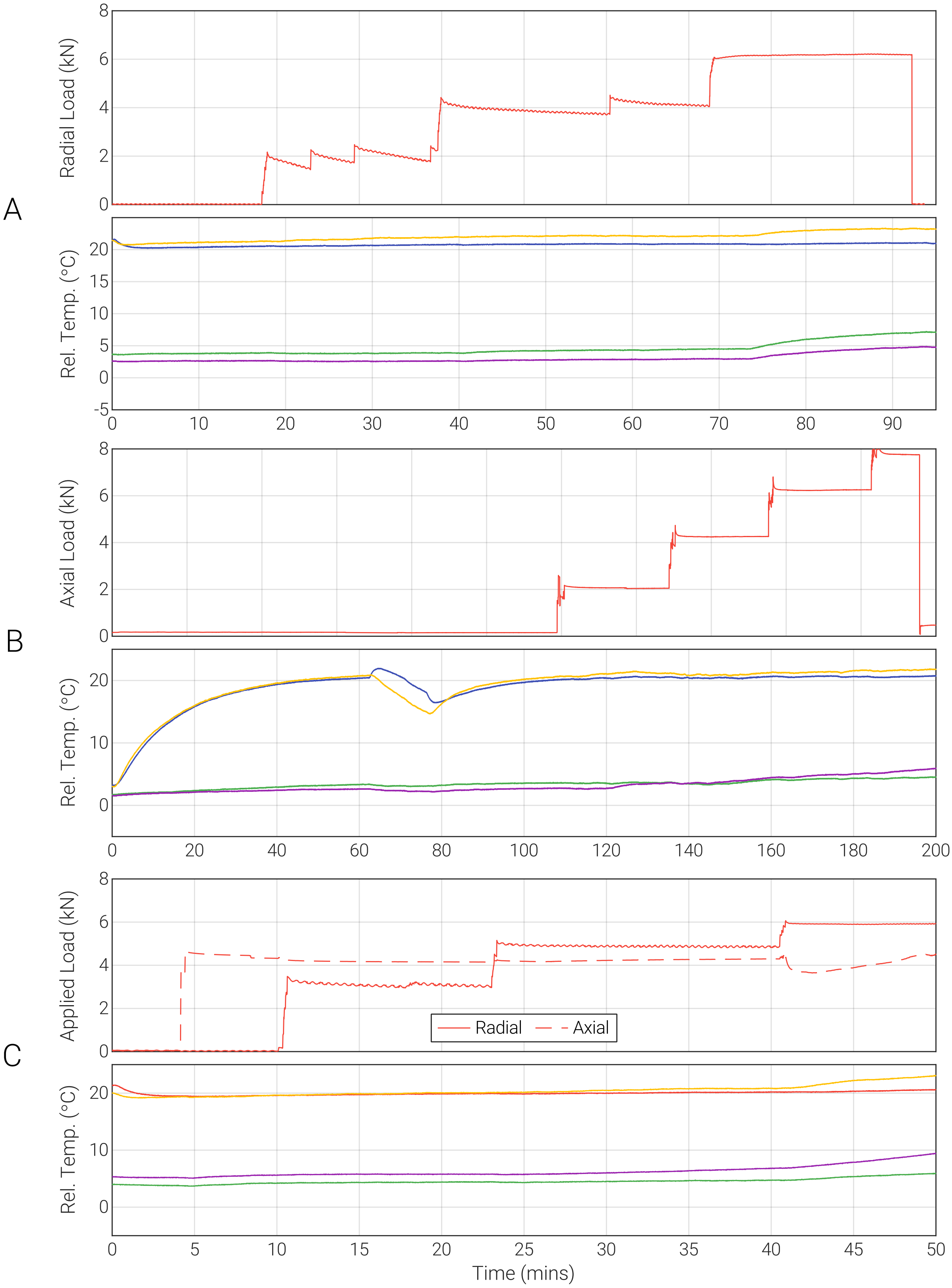

Figure 7.12: Summary of measured CER component temperatures in response to the application of radial load (A), axial load (B) and combined axial and radial load (C).

In response to the application of radial load the measured temperature of all components can be seen to increase, with the greatest relative increase seen in the bearings (~3°C @ 6kN). Primarily radial load is supported by the bearings, with the low frictional torque imposed by rolling element bearings when supporting a shaft minimising the transfer of torsional load to the gearbox and motor, and thus explaining the observed temperature responses.

Similarly, in the presence of 6kN axial load the greatest sensitivity is seen in the response of each bearing as they react the applied load. A greater temperature was measured on Bearing 2 despite Bearing 1 supporting the majority of the applied axial load due to the geometry of the main shaft. This behaviour reflects the occurrence of 'artificial' heating within Bearing 2, as caused by the design of the CER's axial loading mechanism. To minimise the application of torsional load to the main shaft as axial load is applied a needle roller bearing is used. Under load this bearing generates significant heat (~80°C) via the same Coulomb friction mechanism, which, over time, is conducted down the main shaft towards Bearing 2 increasing its temperature (Figure 7.13).

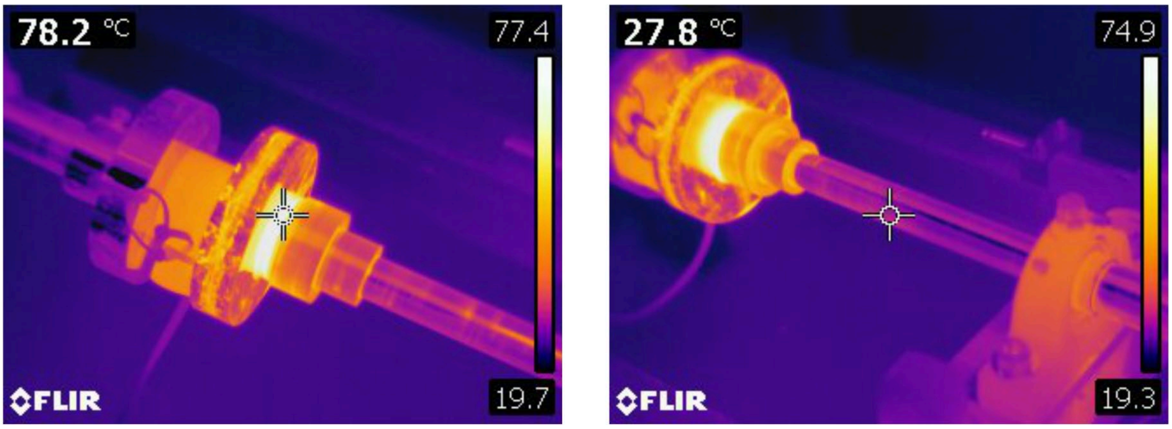

Figure 7.13: Heat generation within CER axial coupling under 6kN axial load at the thrust bearing (left) and shaft (right).

Due to their low rolling resistance the CER bearings generate a minimal frictional moment in opposition to torsional load so present little sensitivity to its application. In contrast, applied torsional load directly opposes the driving force of the motor and gearbox, causing an increase in MEPC as described in Section 7.3.1. The effect of this increased consumption within a thermal context is to cause an increase in heat generated within the motor, primarily due to increased absolute windage losses, and within the gearbox, primarily due to increased frictional losses. As such, both motor and gearbox temperatures can be seen to increase in response to the application of steady-state torsional loading. However, when the applied torsional load is more dynamic in nature minimal sensitivity is observed in the response of both the motor and gearbox temperatures (Figure 7.14).

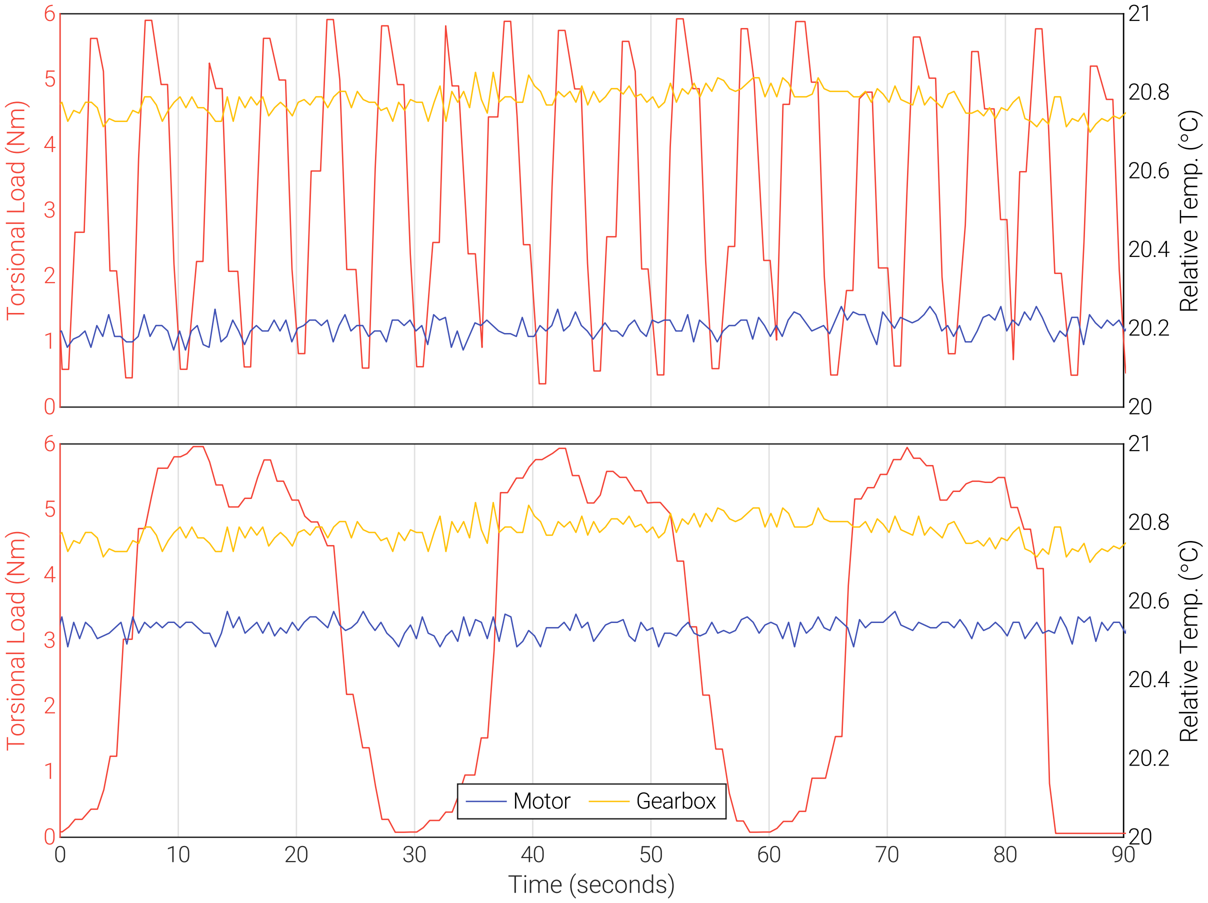

Figure 7.14: Measured temperatures of CER motor and gearbox in response to dynamic torsional loading profiles of 5s period (top) and 20s period (bottom).

Due to the inertia inherent to the thermal mass of the motor and gearbox a filtering effect occurs when fluctuations in torsional load are of an order of magnitude faster than the thermal time constant associated with the measurement of each's temperature, in a manner analogous to the operation of an internal combustion engine's flywheel. Accordingly, as seen in Figure 7.14, there is no obvious correlation between applied braking load and the temperature of the motor and gearbox, with the effect of dynamic variations in load 'smoothed' and thus the true input load profile unable to be observed.

7.3.4 Component Vibration

Summary:

- *Monitored components show sensitivity to changes in operational speed.*
- *Bearings present direct sensitivity to radial loading.*
- *Minimal delay observed between changes in operation and effect on measured responses .*

To minimise the impact of outliers present in recorded data, particularly around speed and load transitions a Hampel filter was applied to time-domain parameters. The Hampel filter identifies outliers based upon their relationship to the median value within a signal; if a sample within the signal exceeds the median by more than three standard deviations then the sample's value is set to the median. Vibration data was acquired at sample rate of 50kHz per period permitting content within the range 1-25kHz to be represented in sampled data i.e. below the Nyquist frequency. However, given the dynamics of the CER, within the context of assessing parameter sensitivity to speed and load the permissible range of frequencies observable can be considered excessive; the highest frequency content associated with the rotation of the CER relates to the speed of the motor[40], which equates to a maximum of ~22Hz[41]. Accordingly, for the purposes of data interrogation only content up to 100Hz was retained.

In response to changes in operation speed all monitored component vibrations show sensitivity, with no measurable delay present within acquired data (Figure 7.15). By increasing the operating speed of the system the total energy input to the CER is increased, a proportion of which is converted into mechanical vibrations primarily due to inherent inertial (i.e. out-of-balance) and frictional forces.

Frictional work is performed at the interface of sliding surfaces due to inherent waviness (global sinusoidal-shaped imperfections in surfaces), an unavoidable facet of even the most high precision manufacturing processes [216]. It has been suggested that unlike most other sounds generated by rolling bearings, the frequency of waviness noise depends on the speed, a characteristic by which waviness noise can hence be distinguished from other types of noise [217].

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[40] N.b. there are likely to be higher frequency components present within vibration spectra associated with phenomena such as torsional modulation induced by the rotor passing over stator slots, however, such content is not of interest here.

[41] 1370rpm at 50Hz supply frequency.

The rate at which mechanical vibrations can travel through a structure from the point of creation to the transducer location is dictated by the material properties of the structure [196]. In the case of solid metal structures and the distances vibrations must travel from source to transducer within the CER such time can be considered negligible. Hence, even given the 50kHz sample rate no measurable delay is observed.

The effect of changes in operational speed on measured acceleration of components is of far lesser magnitude than corresponding responses in temperature. As described in Section 7.3.3 the majority of energy lost through frictional work between sliding surfaces is in the form of heat, with only a minimal quantity converted into mechanical vibrations [213].

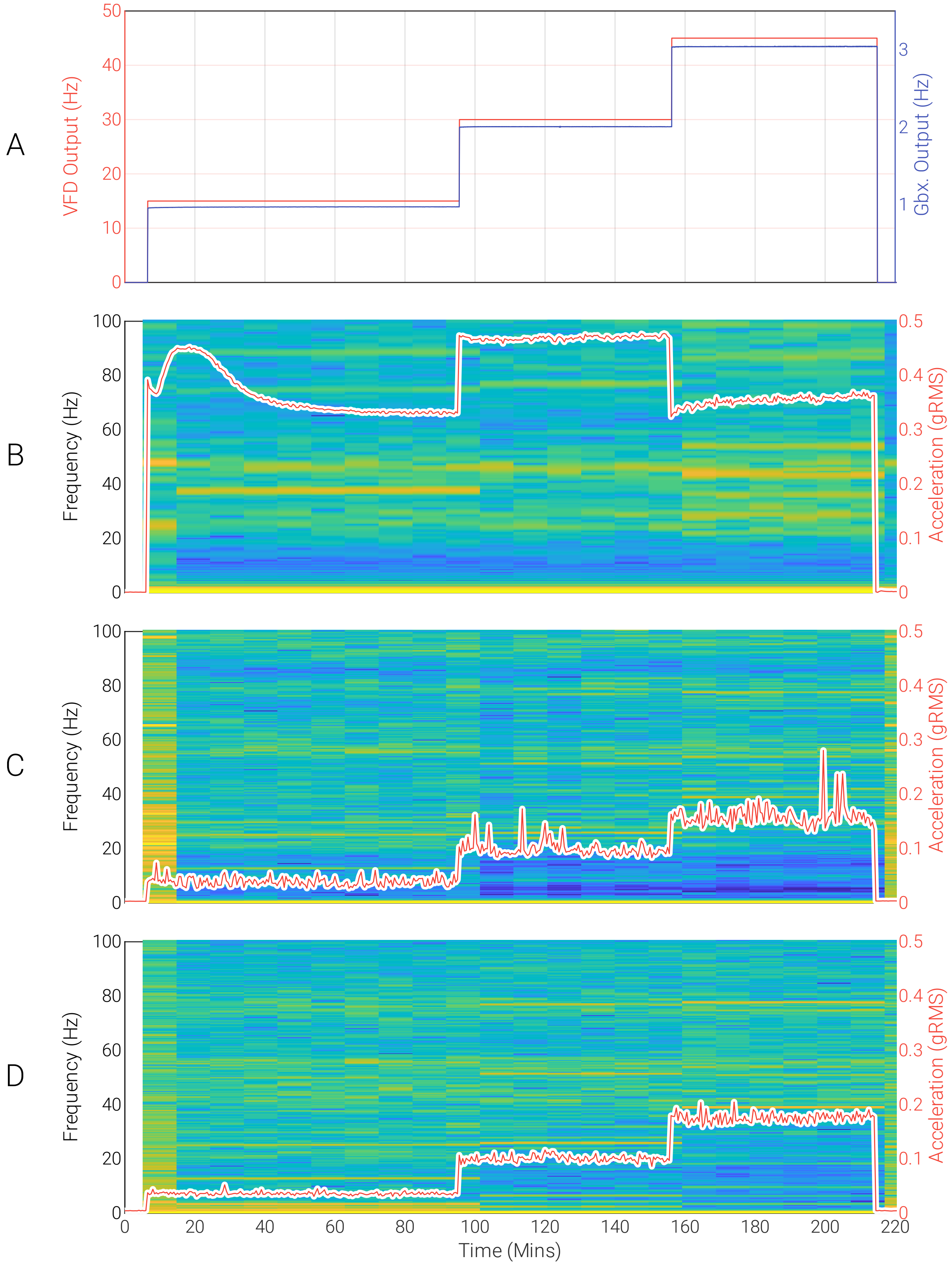

Figure 7.15: Summary of component vibrations (B – Motor, C – Bearing 1, D – Bearing 2) in both time and frequency domains in response to changes in CER speed (A). *Note: the amplitude of each component's spectral content is normalised in the range 0-1.*

Whilst the RMS vibration of each bearing in the time-domain can be seen to increase with increased operating speed, the motor presents non-linear behaviour (Figure 7.15, Plot B). This observation can likely be explained by the mounting configuration of the motor accelerometer; when the spectral content of measured motor acceleration is interrogated significant components within spectra are seen to be relatively constant across all operating speeds. Therefore, it is likely that these spectral components are related to the excitation of structural modes associated with the motor and the accelerometer mount rather than speed effects, accounting for the unusual measured response.

Generally, within component frequency spectra no analytic frequencies are obviously identifiable[42], with an absence of fundamental components associated with the VFD output frequency (15, 30, 45Hz), rotor frequency (7, 15.5, 22Hz), main shaft rotation (~1, 2, 3Hz), mains supply frequency (50Hz) and bearing rolling element passing frequencies (8, 16, 24Hz).

The application of radial load can be seen to induce little effect on the vibration of the motor, due to it not reacting such loads. In contrast, the RMS vibration of both bearings can be seen to increase directly with radial load, however, again the absolute magnitude of increase is small (Figure 7.16).

Such behaviour may be a consequence of increased friction between sliding surfaces generating vibrations of greater amplitude, or alternatively it may result from load-induced changes in bearing geometry. As radial load is applied the inner ring of each bearing is forced to displace relative to the outer ring in the direction of the applied load. As a result of this displacement the rolling elements and cage no longer contact the outer race around its circumference, but instead a gap is created coplanar with the applied force. As the inner race is rotated during operation the rolling elements are force outward radially, which, in the area of the out race-cage gap, results in collision events as elements strike the outer race, generating forced vibrations.

In comparison, no monitored vibrations show significant sensitivity to the application of axial load, with only Bearing 2 showing any degree of correlation between applied axial load and measured acceleration (Figure 7.16). The ability of the selected deep groove roller ball bearings to support axial loads at the magnitudes applied minimises induced out-of-balance vibrations in

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[42] That is not to say that they are absent within spectra, but instead that they are not apparent through basic analysis. Exploitation of more sophisticated signal processing techniques may permit the identification of these weak components.

response; in fact, it could be expected that axial loads would decrease the overall vibration energy of each bearing due to the constraining effect of thrust loading reducing 'looseness' within the structure. It's for this reason that an amount of preload is commonly applied to rotor systems to minimise looseness-induced vibration [135]. Additionally, the axial mode of loading is orthogonal with respect to the measurement axis of each bearing, resulting in minimal sensitivity of each transducer to axial loads.

Accordingly, a combination of simultaneous radial and axial loads can be seen to present broadly comparable response in components as to the application of radial load alone (Figure 7.16).

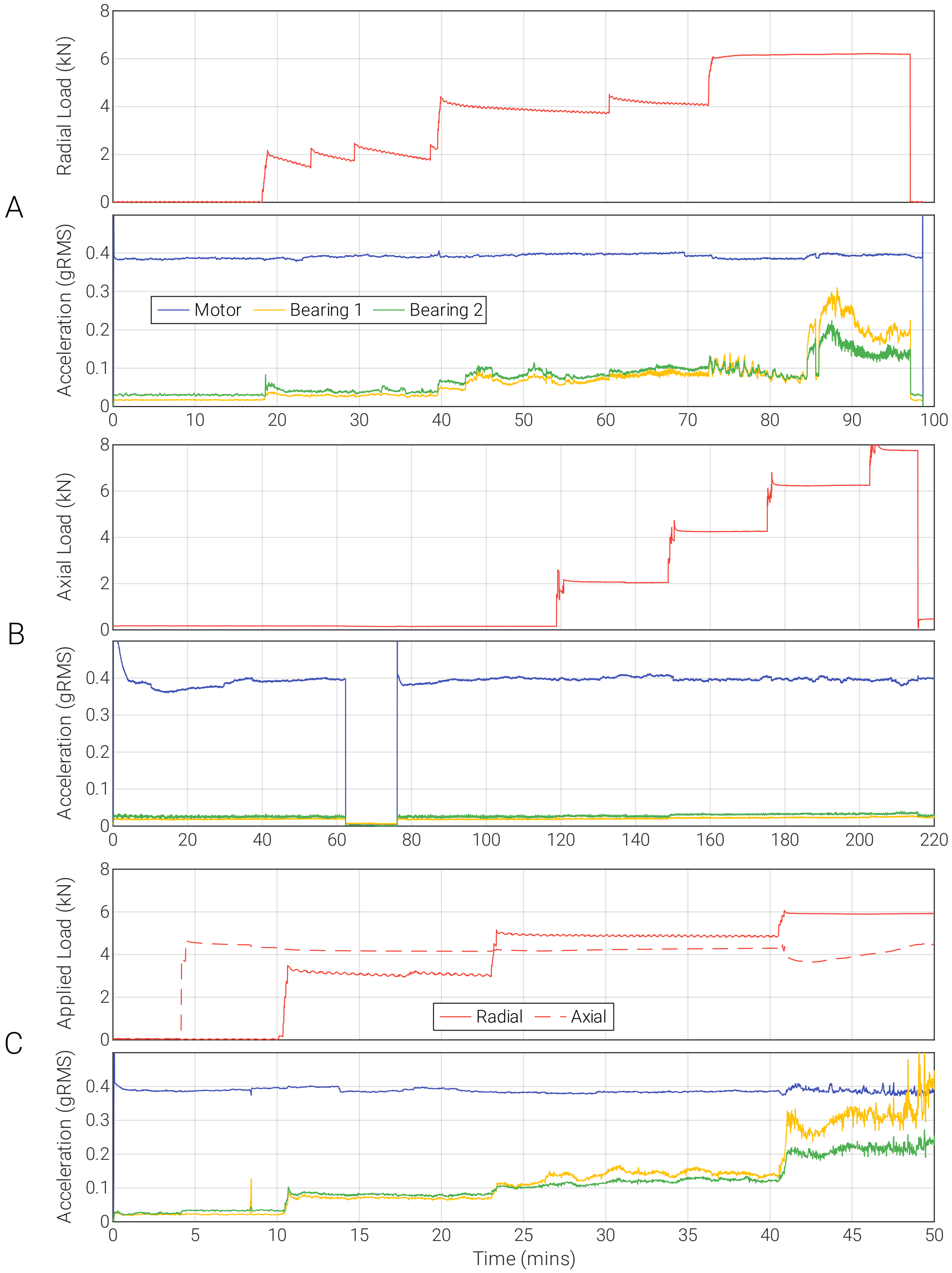

Figure 7.16: Measured time domain accelerations of monitored CER components in response to the application of radial (A), axial (B) and combined radial and axial (C) loads.

The application of torsional load to the system also has minimal effect on monitored vibrations; in response to 6Nm of torsional load the impact upon motor vibration is minimal, and both bearings show only a marginal increase in RMS acceleration (Figure 7.17). The phase lag between changes in torsional load and effects on bearing accelerations is seen to be negligible, with no obvious delay observed, enabling changes in torsional load to be tracked in the response of bearing accelerations. The motor response also shows minimal time lag, however, significant phase delay is present, with modulations in torsional load and motor acceleration presenting antiphase characteristics. Again, this is likely a consequence of the motor transducer mounting, with the cantilever created by the transducer adapter being excited in an antiphase mode.

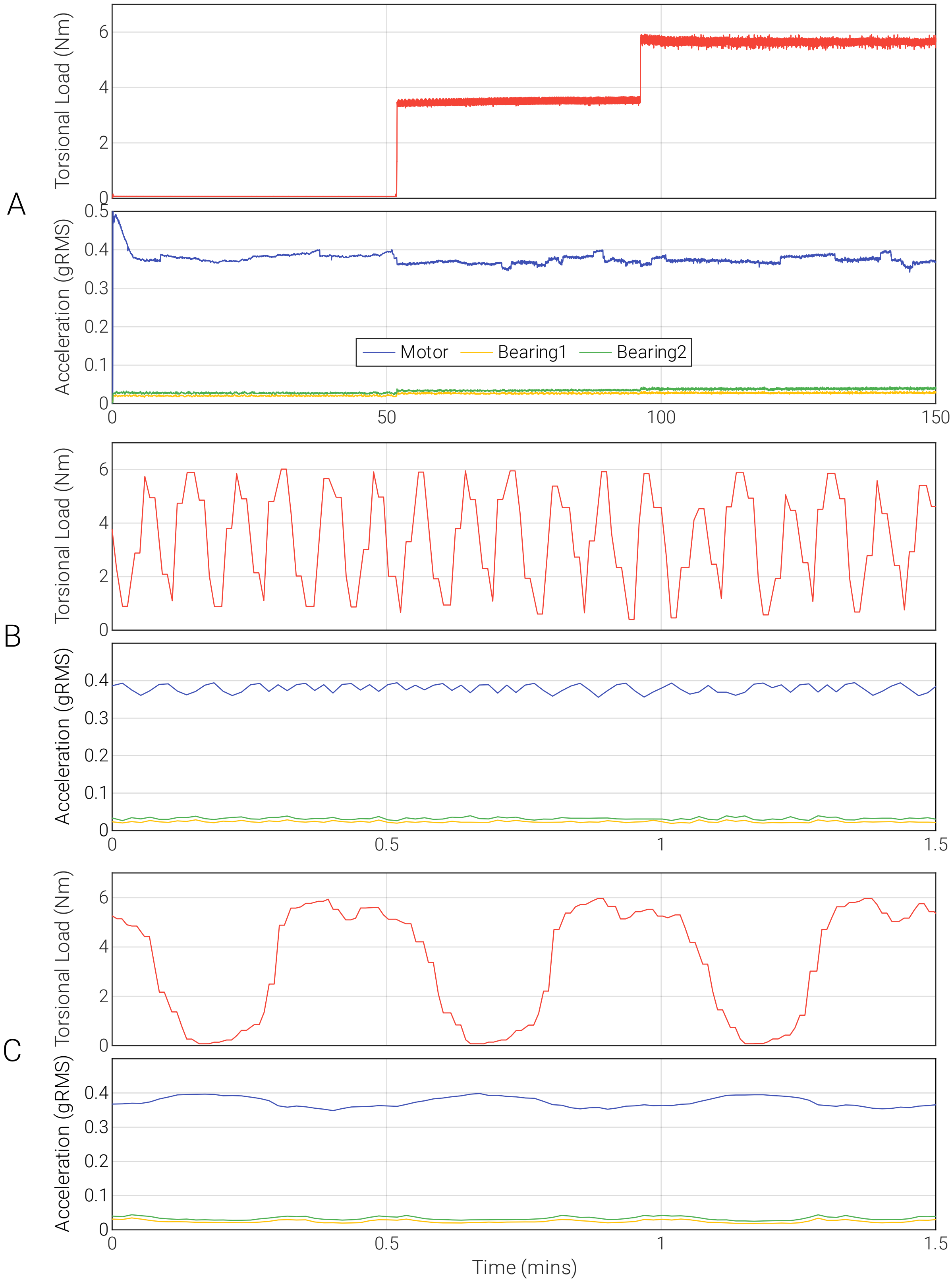

Figure 7.17: Measured acceleration of CER components in response to stepped (A) and cyclic torsional loading profiles of 5s (B) and 20s period (C).

7.3.5 Component Audible Noise

Summary:

- *Observed responses broadly similar to vibration responses.*
- *Direct relationship between operational speed and measured audible noise.*
- *Significant sensitivity to radial load but minimal to axial and torsional.*
- *Negligible time delay between changes in operation and corresponding changes in measured audible noise.*
- *Poor isolation of external sources of noise highlighted.*

As described in Chapter 5, Section 3.2.1. audible noise represents mechanical vibrations caused by pressure waves moving (typically) through air, which fall in the range of 20-20kHz. Accordingly, the audible noise characteristics of the CER can be expected to be broadly similar to the observed characteristics of measured accelerations. Accordingly, in a similar manner to the observed response of mechanical accelerations to changes in CER operating speed the RMS value of all audible noise measurements can be seen to increase with speed (Figure 7.18).

Whilst the gearbox microphone is nominally measuring audible noise generated by the gearbox, given its proximity to the motor inevitably data will include components of noise generated by the motor due to the minimal isolation permitted by the microphones employed. However, the non-linear behaviour observed within motor vibrations in response to changes in speed (Figure 7.15) is not apparent in gearbox audible noise measurements, indicating that, as hypothesised, such behaviour is a consequence of the transducer mounting arrangement.

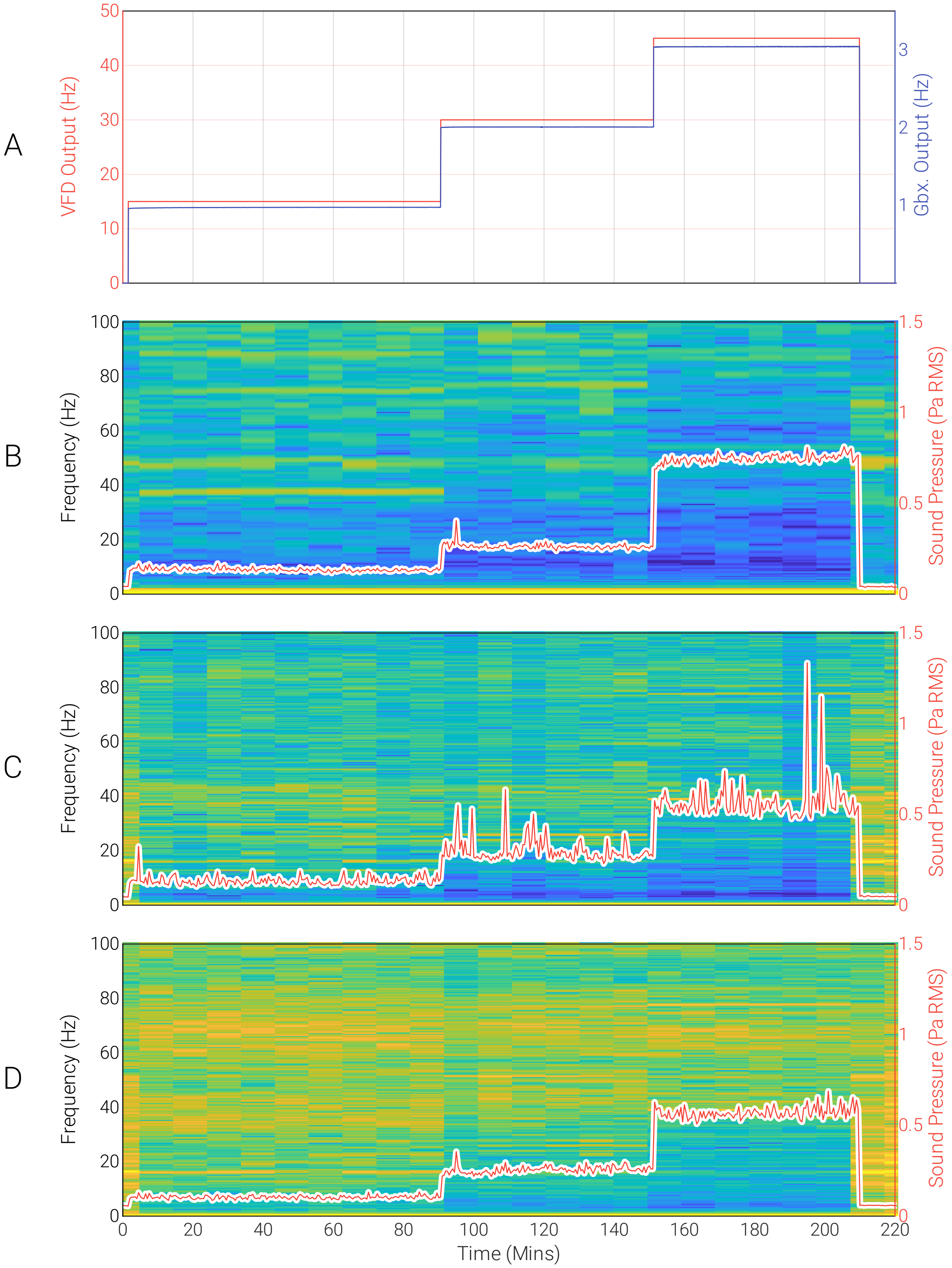

Figure 7.18: Summary of component audible noise (B – Motor, C – Bearing 1, D – Bearing 2) in both time and frequency domains in response to changes in CER speed (A). Note: the amplitude of each component's spectral content is normalised in the range 0-1.

In general, the response of audible noise parameters to the application of radial and axial loads is observed to be similar to those observed of measured component vibrations. A direct relationship was observed between applied radial load and resulting measured RMS audible noise, particularly within the response of support bearings (Figure 7.19). As with equivalent vibration responses, such behaviour reflects the role of the bearings in reacting applied radial loads.

Similarly, and in accordance with observed vibration responses the application of axial loads results in minimal change to measured audible noise. Some sensitivity can be seen in the response of Bearing 1, reflecting its role as the primary reactor of axial loads due to the geometry of the main shaft.

The limited isolation of sources of audible noise permitted by single point measurements is demonstrated within the axial load scenario, where the audible noise measured during the test can be seen to be directly affected by external sources of noise. At ~15mins and ~60mins into the test periods of abnormally high audible noise measurements are present within data, neither of which are reflective of changes in CER operation, but instead due to construction work and a fire alarm activation respectively.

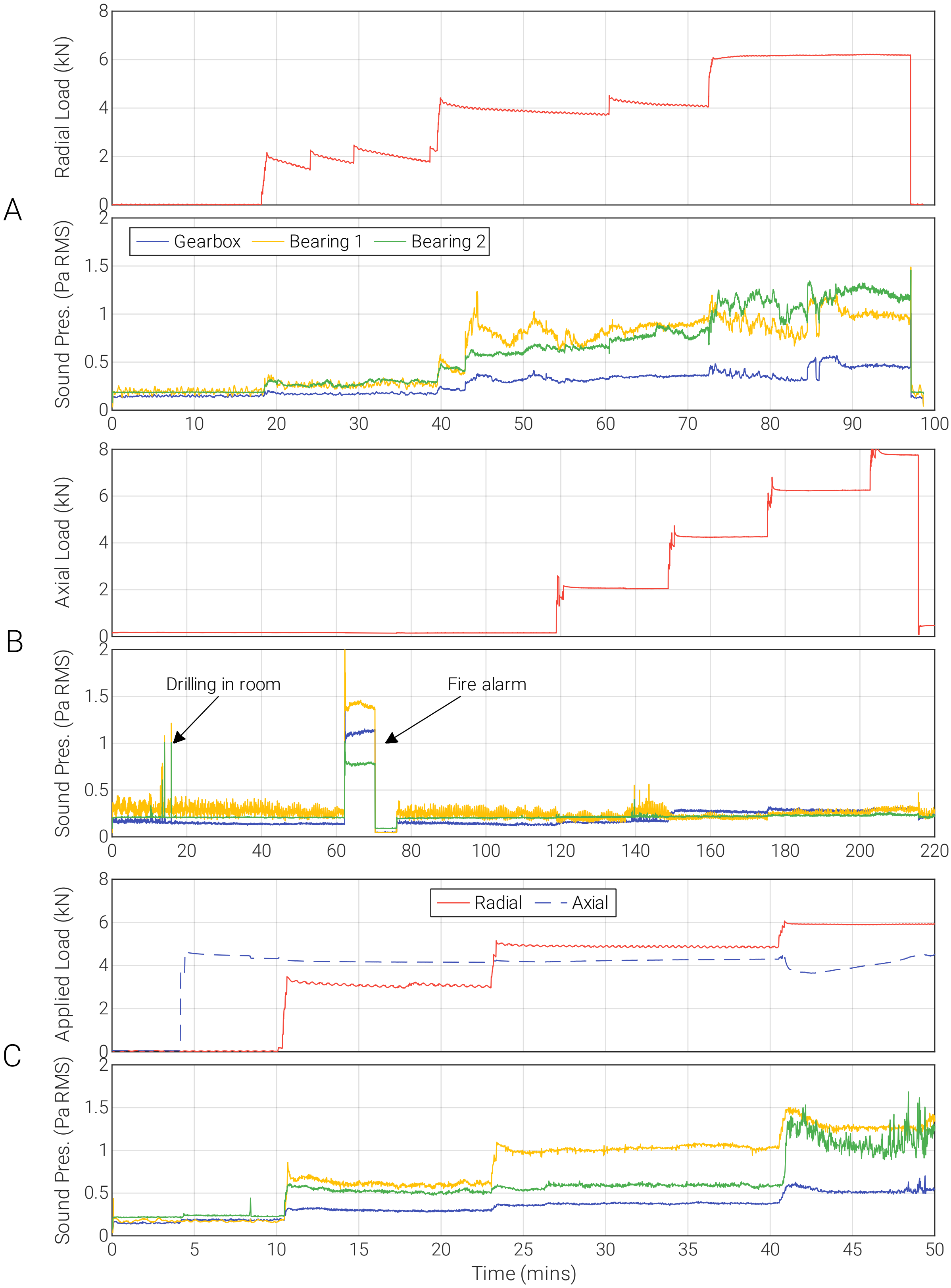

Figure 7.19: Measured audible noise in time domain of monitored CER components in response to the application of radial (A), axial (B) and combined radial and axial (C) loads.

Again, similar to measured vibration observations, little sensitivity to the application of torsional load is seen within audible noise data (Figure 7.20). Only minimal change in CER operational speed occurs in response to the maximum torsional load applied (~6Nm), and, as there is no radial load present, no significant change in the magnitude of noise produced by the system is observed.

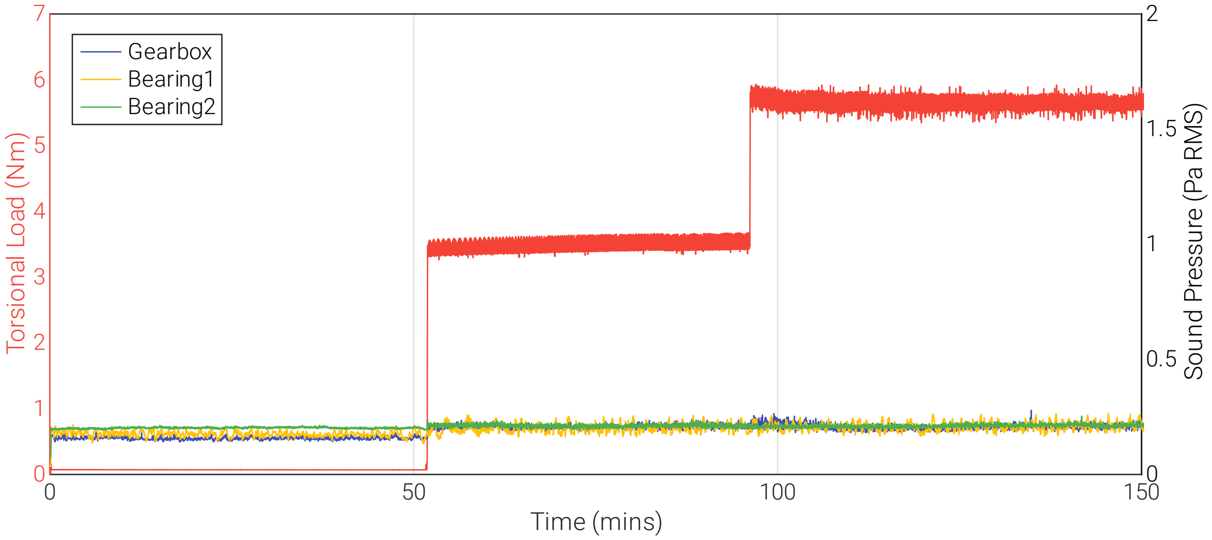

Figure 7.20: Measured sound pressure of CER components in response to stepped torsional loading profiles.

Due to temporary DAQ outages encountered within audible noise measurement no data is available describing the response of audible noise to dynamic changes in torsional load. However, based upon observed responses to static changes, as well as observations of equivalent vibration responses, it can be expected that minimal sensitivity to such events would be observed within audible noise measurements in terms of magnitude. Additionally, minimal time delay would be expected between changes in torsional load and resulting audible noise production.

7.3.6 Gearbox Acoustic Emission

Summary:

- *Overall, behaviour observed comparable to vibration parameters.*
- *Some sensitivity to radial load, minimal to axial.*

An acoustic emission (AE) refers to a transient wave of elastic strain energy generated by the interaction of two bodies which are in relative motion, as a result of surface defects (i.e. asperities) or plastic deformation, for example [197]. Accordingly, the generation of AE waves represents a series of discrete events, with energy typically concentrated within a frequency range of 30k-30MHz. As such, the detection of AE waves constitutes a fundamentally similar mechanism to that associated with the detection of mechanical vibrations, albeit AE transducers are tuned to present sensitivity at much high frequencies.

During operation of the CER and in response to changes in operation speed the RMS acoustic emission measured from the gearbox is observed to respond proportionally, with an increase in operating speed producing a corresponding increase in AE RMS (Figure 7.21).

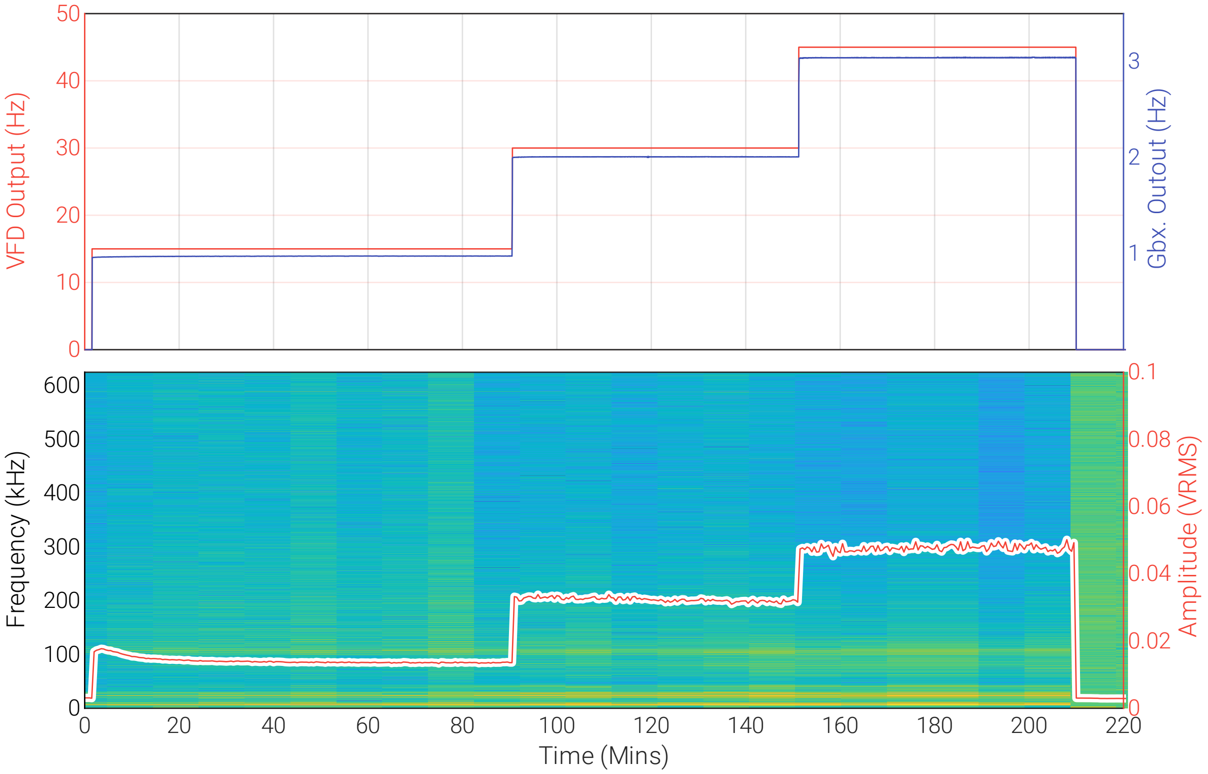

Figure 7.21: CER supply and rotational frequency (top) and corresponding measured gearbox acoustic emissions in both time and frequency domains. Note: amplitude of spectral content is normalised in the range 0-1.

Such observation is reflective of findings reported within literature (e.g. [102], [140], [218]) and can be explained by similar mechanisms to corresponding vibration observations; with increased operational speed the total energy within the CER system is increased, a portion of which is lost through the generation of AE waves as a result of discrete frictional work events at the microscale, the magnitude of which scale with speed. As such energy is contained within high frequency components it is therefore possible that such speed-dependence could be minimised through appropriate filtering.

As observed within the response of gearbox vibration parameters, minimal sensitivity to both radial and axial load is observed within acoustic emission measurements (Figure 7.22). An increase is observed in response to a 6kN radial load, however, significant fluctuation is present within measured data. A small decrease is observed in response to each axial loading step, likely an effect of the reduction in operating speed caused by the application of such load.

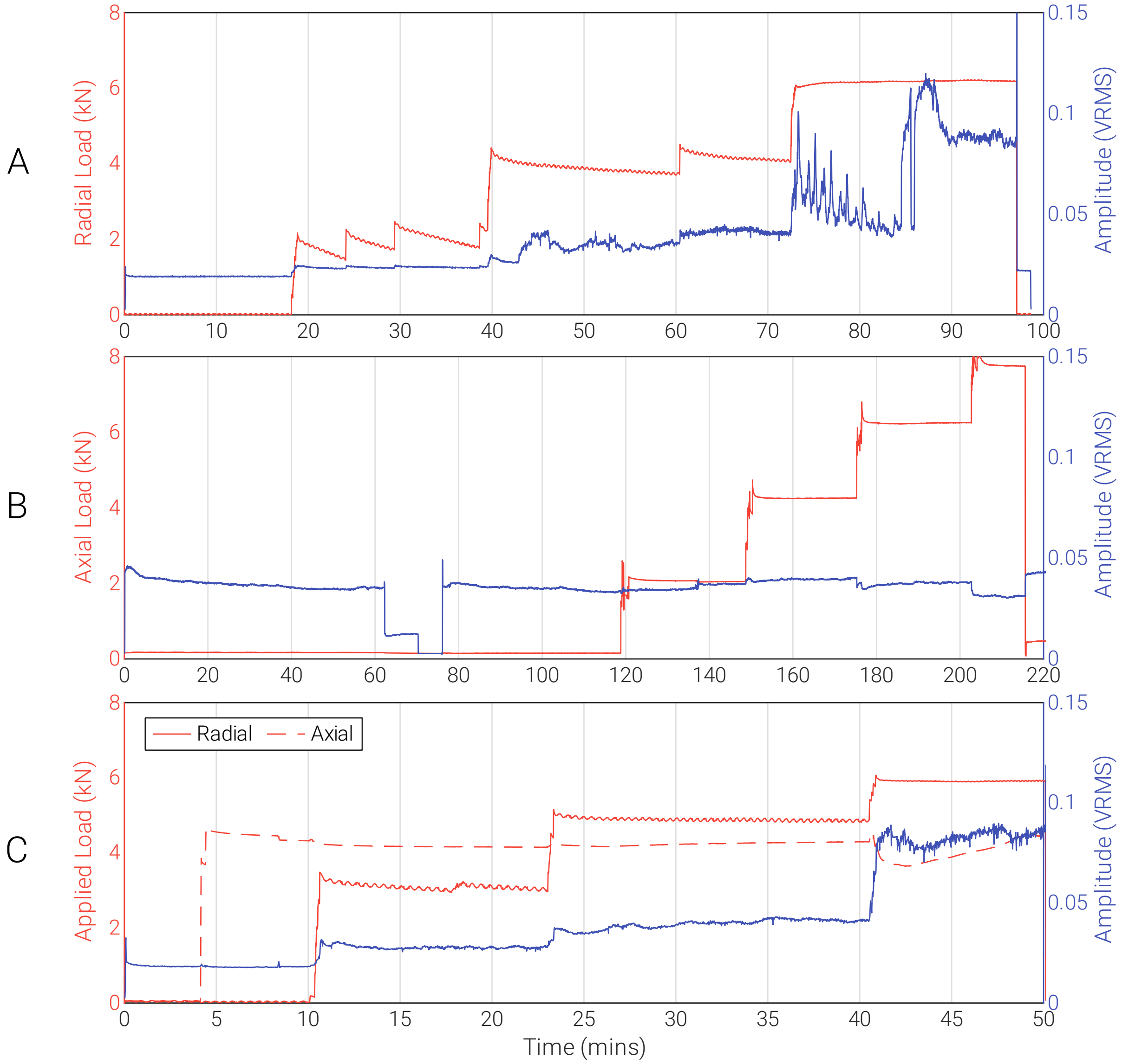

Figure 7.22: Measured gearbox acoustic emissions in time domain in response to the application of radial (top), axial (middle) and combined radial and axial (bottom) loads.

Again, in response to the application of torsional load the behaviour of measured gearbox acoustic emissions can be seen to present comparable characteristics to equivalent vibration responses, with some sensitivity and minimal phase lag observed (Figure 7.23).

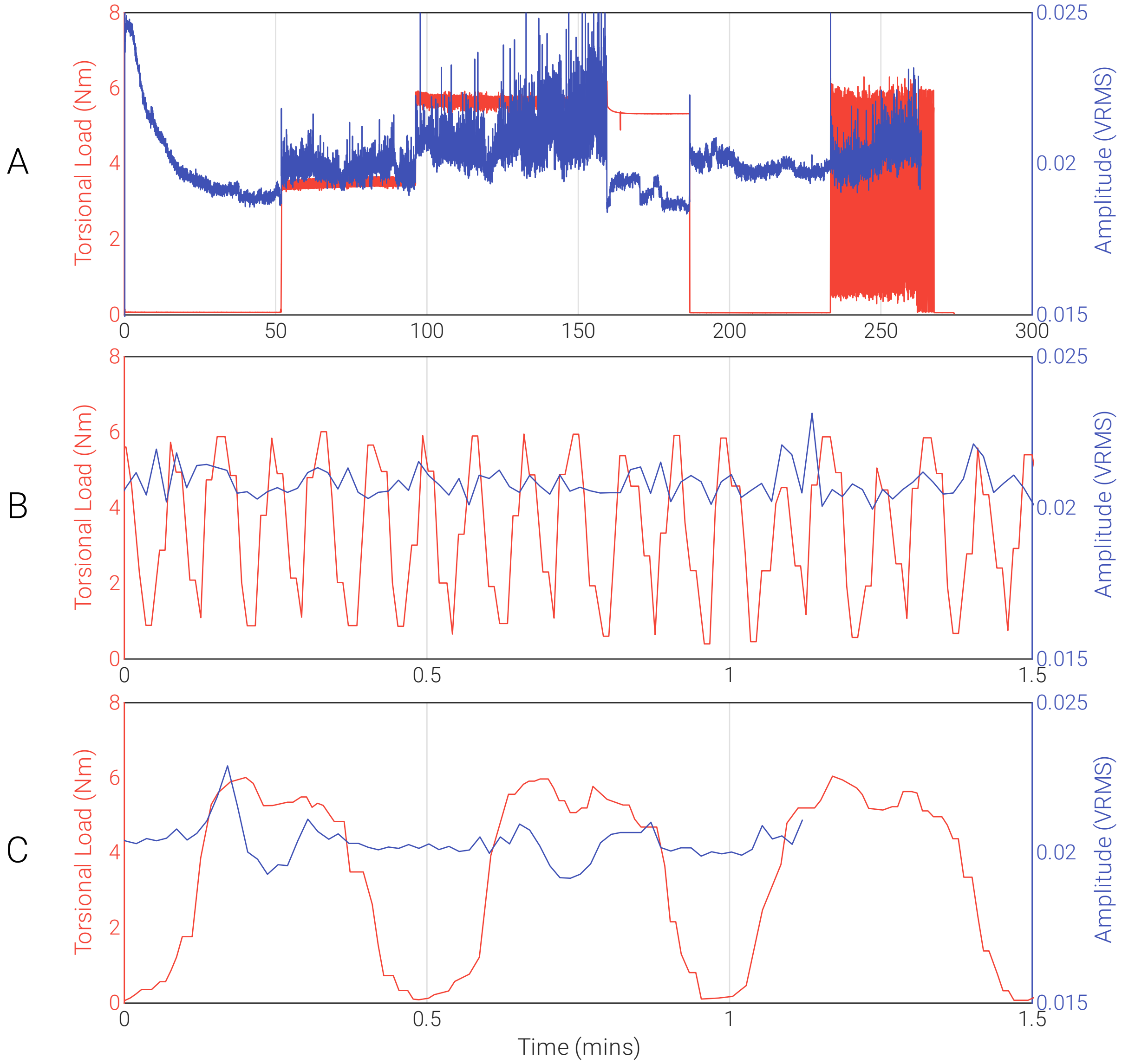

Figure 7.23 Measured acoustic emissions from CER gearbox in response to stepped (top) and cyclic torsional loading profiles of 5s period (middle) and 20s period (bottom).

7.4 Evaluation of Parameters

Through operation of the CER the characteristics of each monitored system parameter in response to different operational scenarios has been established. Based upon the three previously defined requirements of parameters for CBS applications (financial cost of monitoring, technical feasibility of monitoring and operational insight realised) the potential suitability of each can be evaluated (Table 7.2).

Table 7.2: Qualitative assessment of general parameter categories against primary criteria of sensors, based upon observations made during the design and operation of the CER (L – Low, M – Medium, H – High).

Category	Electrical Power	Rotational Speed	Temp.	Vibration	Audible Noise	Acoustic Emission	Mechanical Load
Purchasing cost	M	L	M	H	H	H	M
Installation effort	L	M	M	H	M	H	H
Environmental robustness	H	M	M	L	M	L	M
Sensitivity to speed	M	H	M	M	M	M	M
Sensitivity to radial load	M	M	H	H	H	L	H
Sensitivity to axial load	L	L	M	M	M	L	H
Sensitivity to torsional load	H	M	L	L	L	L	H

The parameter set monitored throughout operation of the CER can be seen to represent wide variation in cost, robustness, and sensitivity, with no single parameter observed to thoroughly satisfy all relevant criteria within the context of the specific scenarios investigated. Given such findings it can be asserted that the process of selecting CBS parameters for continuous monitoring represents a compromise between performance and complexity; increasing the number of sensors employed can provide more comprehensive observation of CBS operation, however, at the expense of increased financial and maintenance requirements.

7.4.1 Purchasing Cost

Based upon the hardware employed within the CER a broad spectrum of upfront cost is associated with each category of monitored parameter. The monitoring of electrical power, rotational speed, temperature and loads represent established industrial techniques which can therefore be monitored for minimal cost. Whilst vibration, audible noise and acoustic emission are seeing increased utilisation throughout literature, due to their typical requirement for much greater sample rates the associated cost of sensing is corresponding high. However, as a consequence of advancements in MEMS technologies associated costs are continually reducing, potentially making such parameters feasible components within a continuous monitoring system in the future.

7.4.2 Installation Effort

The financial cost associated with facilitating the monitoring of physical parameters is not only a function of the initial purchasing costs but also the effort required to install sensing hardware, particularly when installed retrospectively. In this respect, the monitoring of electrical power parameters represents the least effort, with transducers able to be installed remotely from an actual system (e.g. within a control room) and without requiring significant mechanical effort (i.e. able to 'clipped' onto supply cables). In contrast, to realise maximum possible transmission of component vibrations from source to transducer a solid mechanical fastening method is required. Within the CER this involved the drilling and tapping of components, which not only represented significant effort but was also made possible due to the ease of access and disassembly permitted by the CER. In an industrial setting such access could not be guaranteed, potentially restricting the use of accelerometers or resulting in less involved fastening methods such as adhesive coupling, compromising signal transmission.

In between these two extremes lie temperature, audible noise, acoustic emission and loads monitoring. Primarily, the effort associated with monitoring these parameters is contained within the installation of signal and power cabling, which must be installed locally from the transducer location to the signal conditioning hardware. Again, advances in wireless technologies in the future may improve the applicability of these parameters for monitoring within an industrial environment, however, based upon the existing level of maturity of such technology wired solutions remain a necessity, potentially compromising robustness significantly, as evidenced during the Industrial Monitoring Trial (Chapter 3).

7.4.3 Environmental Robustness

Whilst the initial financial cost associated with each category of parameter is dictated by purchasing and installation effort, all parameters can be expected to carry some degree of associated on-going cost, representing any required maintenance. Fundamentally, for a continuous monitoring system to realise financial viability it can be assumed that it must be able to realise greater reliability than the asset(s) it is monitoring.

Due to its laboratory nature the CER was not conducive to an evaluation of the likely robustness of monitoring hardware when subjected to industrial conditions. However, based upon the principles of operation associated with the observation of each categories of parameter some general remarks can be made.

It can be expected that those parameters which require physical contact with a structure in order to sense physical phenomena at a component level will be more susceptible to damage, due to unavoidable exposure to asset operation. For example, as observed during the monitoring trial described in Chapter 3, RTD-based temperature measurement requires a transducer to be bonded directly to the component to be monitored, resulting typically in exposure to fugitive conveyed material as well as pressure washing-based cleaning activities. In contrast, the ability to locate current transducers within a control room minimises their risk of damage during operation and thus increasing the resilience of data.

The effect of such issues can also be expected to be more significant in instances where monitoring hardware is to be retrofitted to a system; where hardware can be designed-in from the outset improvements in robustness can be expected.

In the future, advancements in areas such as non-contact monitoring and wireless power and data transmission may support improvements in environmental robustness of component-level monitoring systems. For example, an interesting line of research is being conducted around non-contact vibration monitoring, based upon digital image processing techniques by Abe Davis and colleagues at Stanford University, USA, which they refer to as 'Visual Vibrometry'[43].

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[43] Their work very much represents early-stage investigations, however, the results are promising and the potential impact throughout SHM in particular significant and thus well worth a read e.g. [219].

7.4.4 Sensitivity to Speed

The monitoring of each category of parameter represents a quantification of some form of energy contained within the CER. Accordingly, all primary parameters were observed to present at least some degree of sensitivity to operational speed, reflected in increased RMS time-domain measurements across parameters. However, at an aggregate level the characteristics of responses to changes in speed were not distinct from equivalent responses to changes in loading. For example, in response to both increased speed and radial load the temperature of bearings was observed to increase at an identical rate, thus preventing the isolation of causality.

Within fixed supply frequency applications (i.e. open-loop speed control) as typically implemented for CBSs the belt speed of a system is nominally constant. However, in practice the instantaneous speed of a system will fluctuate with time in response to the torsional load experienced by the motor. Therefore, it could be assumed that any changes in speed from nominal are caused by changes in torsional load, however, still the exact cause of any fluctuations in speed cannot be isolated e.g. due to increased throughput or due to changes in belt tension.

Utilising advanced signal processing techniques it may be possible to determine instantaneous speed and thus account for any fluctuations, depending upon the category of parameter. For example, the online estimation of induction motor rotor speed from measurements of electrical current is an established technique and is commonly implemented within VFD hardware to provide a 'sensorless' estimation of speed[44]. Similar methods exist for estimation of instantaneous bearing speeds from vibration measurements [135], [220].

7.4.5 Sensitivity to Radial Load

Within a typical CBS the presence of a tensioned belt can be expected to apply a radial load to both the head and tail pulleys, therefore, through observation of instantaneous radial load the presence and state of a system's belt can in principle be inferred. Accordingly, within the context of usage monitoring of a CBS, the ability to observe dynamic radial loading can be considered advantageous as a means of isolating belt effects from throughput effects.

Various degrees of sensitivity to radial loading were observed within monitored CER parameters, with sensitivity dictated by the physical location at which measurements were made

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[44] see [127] for an overview of methods

within the overall CER system. Accordingly, greatest sensitivity to changes in radial load was observed in monitored bearing parameters, with all of bearing temperature, vibration and audible noise responding directly to changes in applied radial load.

Within vibration and audible noise measurements broadly similar responses were observed, with the former having the advantage of greater isolation from external noise, while the latter benefitting from a less involved installation process. Some sensitivity to applied radial load was observed within motor and gearbox related parameters, albeit responses were much more subtle.

7.4.6 Sensitivity to Axial Load

Similarly, a range of sensitivity to applied axial loads was observed within responses of monitored parameters, again driven by the physical location of each component within the overall CER system. Based upon the axial loading configuration implemented the majority of force was reacted by only Bearing 1. Consequently, Bearing 1 parameters demonstrated greatest sensitivity to applied axial loads, with some effect on Bearing 2 parameters also seen but minimal sensitivity observed within motor and gearbox parameters.

However, within the response of parameters which demonstrated sensitivity to both radial and axial loads no obvious differences between the two modes of loading were observed. Accordingly, decoupling the effects of radial and axial loads may prove challenging, particularly within an industrial environment where a greater number of environmental variables can be expected to influence monitored parameters.

7.4.7 Sensitivity to Torsional Load

During operation of a CBS dynamic variation in material throughput can be expected to manifest as fluctuations in torsional load, which are reacted by the drive components. Accordingly, within the context of usage monitoring of CBSs the ability to observe such dynamic effects within monitored parameters can be considered essential, enabling the conditions on the belt to be understood throughout operation.

Again, a spectrum of sensitivity to torsional loads was observed within monitored CER parameters. The most sensitivity was seen within the response of motor and gearbox parameters, reflecting their role in reacting applied torsional loads. The electrical power consumption of the motor presented a direct relationship with applied torsional load, with even the most dynamic modulations in torsional load applied represented within its response. Whilst such loads could in theory be measured directly using an in-line torque transducer indirect inference of mechanical loads via observed changes in MEPC represents a significantly less intrusive and thus robust solution, suitable for application at scale beyond a laboratory environment.

In comparison, whilst the temperature of the motor and gearbox were also observed to respond directly to changes in torsional load, due to the inherent filtering effects of thermal inertia such dynamic changes are not apparent within measured external component temperatures. Torsional loading effects were generally absent within bearing parameter responses as a consequence of the minimal friction moment generated within bearings during operation.

7.5 Experimental Limitations

Whilst operation of the CER has permitted the assessment of parameter responses to changes in operation, there exist inherent limitations which should be understood when considering the suitability of parameters for monitoring, particularly within industrial environments.

Due to the absence of a belt within the CER it was not possible to directly assess the influence of a tensioned belt upon the dynamics of the system and thus the responses of monitored parameters. Whilst the decision to omit a belt provided system simplification and permitted greater control of variables it represents an abstraction from an actual CBS and thus restricted the degree to which the influence of dynamic operation upon parameter responses can be assessed.

Similarly, the CER represents only a single system so the degree to which findings can be considered representative across similar systems can only be speculated. Whilst broadly observed responses can be expected to reflect the characteristics of typical COTS components and thus value in operation of the CER retained, due to inherent variability in manufacturing, handling, installation etc. some subtleties can be expected to exist in practice.

7.6 Implications for Research

Throughout literature and industry a wide range of parameters are selected for continuous monitoring during the operation of various systems. Depending on the particular application the suitability of monitoring each parameter type is likely to vary, with no single parameter ‘optimal’ across all applications. Whilst it is attractive to monitor as many parameters as feasibly possible to maximise insight into system operation, given the existence of technical and financial constraints only a subset of parameters can be monitored in practice. As presented in this chapter, through operation of the CER the suitability of motor electrical power consumption (MEPC) parameters for CBS applications has been identified. In consideration of the three requirements of parameters for suitability in CBS applications, monitoring of MEPC affords the following advantages:

1. **Financial cost of monitoring**

   Hardware for monitoring MEPC is established and mature, and thus parameters can be continuously monitored for a relatively modest cost

2. **Technical feasibility of monitoring**

   MEPC can be monitored remotely from the immediate confines of a CBS, reducing exposure to extremes in environmental conditions as well as the operation of a CBS itself.

3. **Operational insight realised**

   MEPC has demonstrated sensitivity to both changes in speed and mechanical load, even when applied indirectly to a motor. Furthermore, MEPC present an immediate response to changes in operation.

Chapter 8: Characterisation of Conveyor Belt System Operation – Experimental Design

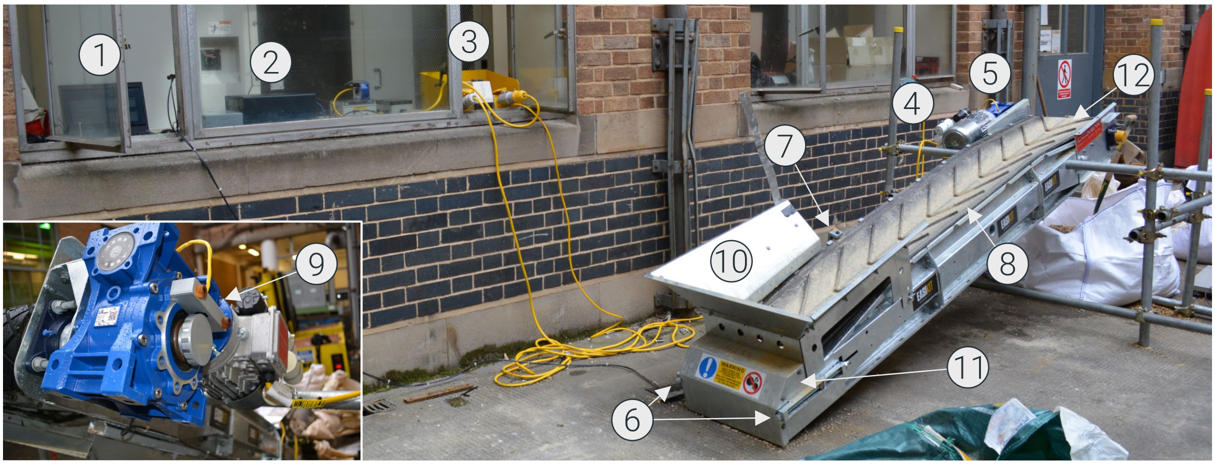
This chapter presents the design of a body of characterisation testing, based around the operation of an industrial conveyor belt system (CBS). Operation of the Conveyor Emulation Rig (CER) as described in Chapter 7 enabled a range of system parameters to be evaluated in the context of their sensitivity to changes in system usage as well as and their feasibility of monitoring within an industrial environment. From this evaluation the suitability of motor electrical power consumption (MEPC) parameters for CBSs monitoring applications was identified. However, given the abstracted form of the CER in comparison to an actual CBS the degree to which the identified characteristics of MEPC parameters in response to different operational scenarios can be considered valid in a wider context remains undetermined.

Accordingly, this chapter reports the experimental design of a series of Conveyor Characterisation Tests (CCTs), undertaken to evaluate the sensitivity of MEPC parameters to different operational scenarios. Primarily, the completion of CCTs served to permit assessment of three aspects:

1. **To assess the feasibility of reliably monitoring MEPC parameters throughout system operation.**
2. **To assess the sensitivity of MEPC parameters to changes in system usage.**
3. **To assess the sensitivity of MEPC parameters to the occurrence of common belt-related faults.**

8.1 Testing Setup

All tests were conducted on a single CBS (herein after referred to as *the System*), provided on loan from the Manufacturer. The System was proved in an 'as new' condition, with all components having previously seen no use, and thus the system was assumed to be in peak health.



① DAQ Control PC
② Power Analyzer
③ Starter Box
④ Drive Motor
⑤ Reduction Gearbox
⑥ Belt Tension Adjustment
⑦ Belt Speed Sensor
⑧ Belt Chevrons
⑨ Shaft Speed Sensor
⑩ Intake Hopper
⑪ Tail Pulley
⑫ Head Pulley

Figure 8.1: Overview of subject CBS and data acquisition system used during CCTs.

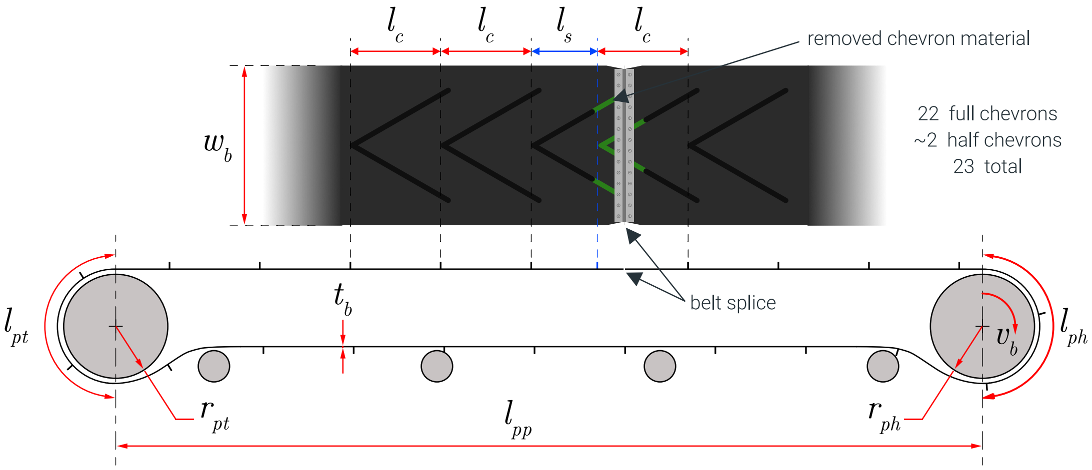
Tests were conducted at the University of Bristol, with the System located outside and all data acquisition hardware within a dry, covered area (Figure 8.1).

8.1.1 Subject Conveyor Belt System

The CBS provided by the Manufacturer is designed to be inherently flexible, with the main support structure comprised of modular elements, enabling a range of lengths and widths of CBS to be configured (Figure 8.2).

Figure 8.2: A typical application of the model of CBS operated during testing (image provided courtesy of the Manufacturer).

The System was configured with a belt width of 450mm and a single 1m section install longitudinally, resulting in an overall length of approximately 3m (Figure 8.3). The overall length of the System can be considered amongst the shortest configurations possible; a short length CBS was required due to the physical constraints of the testing area.



Dimensions		Geometric Relations		Analytical Frequencies
Belt length	$l_b \approx 6.05m$	Belt length	$l_{pt} = 2\pi\left(r_p + 0.5t_b\right)$	Belt fundamental $f_b = \frac{l_b}{v_b} = 7.19s/rev = 0.139Hz$
Belt width	$w_b \approx 0.45m$		$l_b \approx 2\left(l_{bb} + l_{pt}\right)$	
Belt thickness	$t_b \approx 10mm$			
Belt velocity	$v_b \approx 0.9m/s$	Chevron spacing	$l_c = \frac{l_{bt}}{n_c} = \frac{6}{23} = 0.263m$	Chevron fundamental $f_c = \frac{l_c}{v_b} = 0.31s/rev = 3.057Hz$
Chevrons	$n_c \approx 23$			

Figure 8.3: Geometry of the CBS operated during CCTs.

The 450mm wide belt is amongst the most commonly supplied by the Manufacturer, so was selected to ensure testing accurately reflected typical operation. In addition, the belt was specified with a chevron surface pattern, the mid-range option within the choice of three offered by the Manufacturer.

Belts are of a composite construction, created from alternate layers of vulcanised rubber and a woven synthetic membrane, laminated into a single structure. The belt constitutes a single length with ends spliced together using a series of hinged-plate style mechanical fasteners across the width of the belt (Figure 8.4).

Figure 8.4: Hinged-style mechanical fastening of belt ends within the System. Note the removed sections of chevron material on either side of the splice.

The belt is driven by a single-phase induction motor with a rated output power of 2.2kW, via a 15:1 reduction gearbox, both coupled together and located at the head pulley end of the system. The drive motor is a 4-pole machine, with a synchronous speed of 1500rpm, and a nominal operating speed of 1350rpm when supplied by a 50Hz AC waveform. It is a capacitor-start-capacitor-run style machine, which uses a rotor-mounted centrifugal switch to disengage the start capacitor once the rotor has reach approximately 75% of rated speed.

Power to the system is provided from a mains supply, via a 110V step-down, isolating transformer, with the drive motor being controlled manually via a direct-on-line (DoL) starterbox. The supply is of a fixed frequency, hence variable speed operation of the system is not possible.

The Manufacturer states that the System is permitted to operate at angles of inclination up to 40° and should be loaded with individual masses no greater than 30kg. In addition, the geometry of the System results in an analytical belt frequency of ~0.15Hz, and a chevron passing frequency of ~3.45Hz (Figure 8.3).

8.1.2 Data Acquisition

During the execution of CCTs a range of parameters were continuously monitored. Based upon the findings from operation of the CER as described in Chapter 7 and for the purposes of CBS characterisation only motor electrical power consumption (MEPC) and rotational speed parameters were monitored during CCTs.

Feasibly, the torsional load experienced by the drive motor could be inferred from measurements of electrical current draw alone, as implemented during the Industrial Monitoring Trial described in Chapter 4. Current draw can be expected to be more sensitive to torsional vibrations, responding to fluctuations in the rate of cutting of magnetic flux in the motor's air gap in response to changes in rotor speed. In comparison, supply voltage can be expected to be more sensitive to radial and axial vibrations due to their effect on air gap geometry [221]. However, the additional cost and effort associated with also monitoring supply voltage is minimal and the additional observability of CBS operation it permits certainly exceeds such cost (e.g. monitoring of voltage-current phase relationships i.e. power factor) therefore, during CCTs both voltage and power were monitoring simultaneously.

Accordingly, a data acquisition system was designed to enable continuous monitoring of the selected parameters, as summarised in Table 8.1.

Table 8.1: Summary of system parameters monitored continuously throughout Conveyor Characterisation Tests.

Component	Parameter	Units	Acquisition Device	Sample Rate
Motor	Line voltage	Vrms	LEM NORMA 4000	~50Hz
Motor	Current draw	Arms	LEM NORMA 4000	~50Hz
Motor	Active power	Wrms	LEM NORMA 4000	~50Hz
Motor	Apparent power	VArms	LEM NORMA 4000	~50Hz
Motor	Reactive power	VARrms	LEM NORMA 4000	~50Hz
Motor	Power factor	-	LEM NORMA 4000	~50Hz
Gearbox	Output speed	RPM	NI USB6211	Count
Belt	Linear speed	ms^{-1}	NI USB6211	Count

Electrical power parameters were acquired through direct measurements of supply voltage and current draw, sampled continuously throughout testing. Line voltage was monitored via direct connection to the motor power supply lines and current draw via a LEM IT605-S current transducer, both fed into a LEM NORMA 4000 power analyser. Synchronised samples of power quantities were acquired approximately every 20ms (50Hz), where each sample reflected the root-mean-square (RMS) value of that parameter during the previous 20ms period. A 20ms interval was the minimum possible using the LEM NORMAs 4000 unit. Accordingly, fluctuations in power consumption faster than 40ms cannot be accurately represented within measured data, in accordance with the Nyquist-Shannon Sampling Theorem [222]. However, given the magnitude of the analytic frequencies associated with the movement of the belt (Figure 8.3) 50Hz should be sufficient to observe the primary periodic content of interest.

Data samples were acquired by the unit and stored locally, from where they were bulk transferred to the local control PC every 30s. It should be noted that during the transfer period (200ms) the power analyser was unable to simultaneously acquire further samples, hence every 30s a discontinuity of ~200ms can be observed in each acquired power data set.

Similarly, as described in Chapter 5, direct measurement of motor rotor speed is not necessarily required, but instead it can be indirectly inferred from measurements of MEPC through exploitation of advanced signal processing. However, for simplicity and given the one-off nature of the CCT setup it was decided to directly measure both the gearbox output rotational speed and belt linear speed. The rotational speed of the gearbox output shaft was monitored directly using a Honeywell SR3C-A1 non-contact, Hall effect sensor, in conjunction with a bespoke magnet wheel (Figure 8.5).

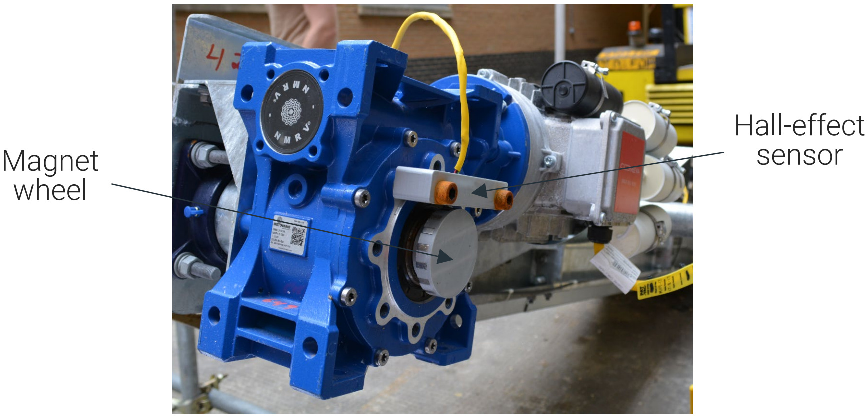


Figure 8.5: Bespoke gearbox output speed monitoring hardware.

The action of a magnet passing the sensor pulls the normally high output of the sensor to a low state, resulting in a binary pulse train being generated as the magnet wheel rotates. This pulse train is then sampled by a National Instruments USB6211 data acquisition device, and using the known geometry of the magnet wheel, translated into a rotational speed in revolutions-per-minute.

The linear speed of the belt was directly monitored using a similar technique, however, instead of a magnet wheel being employed equi-spaced magnetic markers are installed along the length of the belt (Figure 8.6). With the distance between markers known, the linear speed of the belt can be calculated from the time between consecutive pulses.

Figure 8.6: Bespoke belt speed monitoring hardware.

Markers were mechanically fastened to the belt surface, with one marker installed per belt chevron. This resulted in markers being spaced approximately evenly along the length of the belt. However, the presence of a splice in the belt resulted in one marker interval being significantly shorter than all others (Figure 8.3). To ensure accurate values of speed are calculated throughout the belt cycle, during start-up a calibration routine is run within the data acquisition software, in which the relative position of the belt splice within the pulse train is identified, by determining the shortest pulse period per cycle (i.e. 23 marker counts). The speed between the specific markers associated with these pulses can then be calculated using the known, shorter distance, ensuring an accurate measurement.

In addition to the parameters described in Table 8.1, during the conducting of each test scenario video was recorded, to enable subsequent validation of the loads applied during that test. An overall schematic of the setup used during CCTs is presented in Figure 8.7.

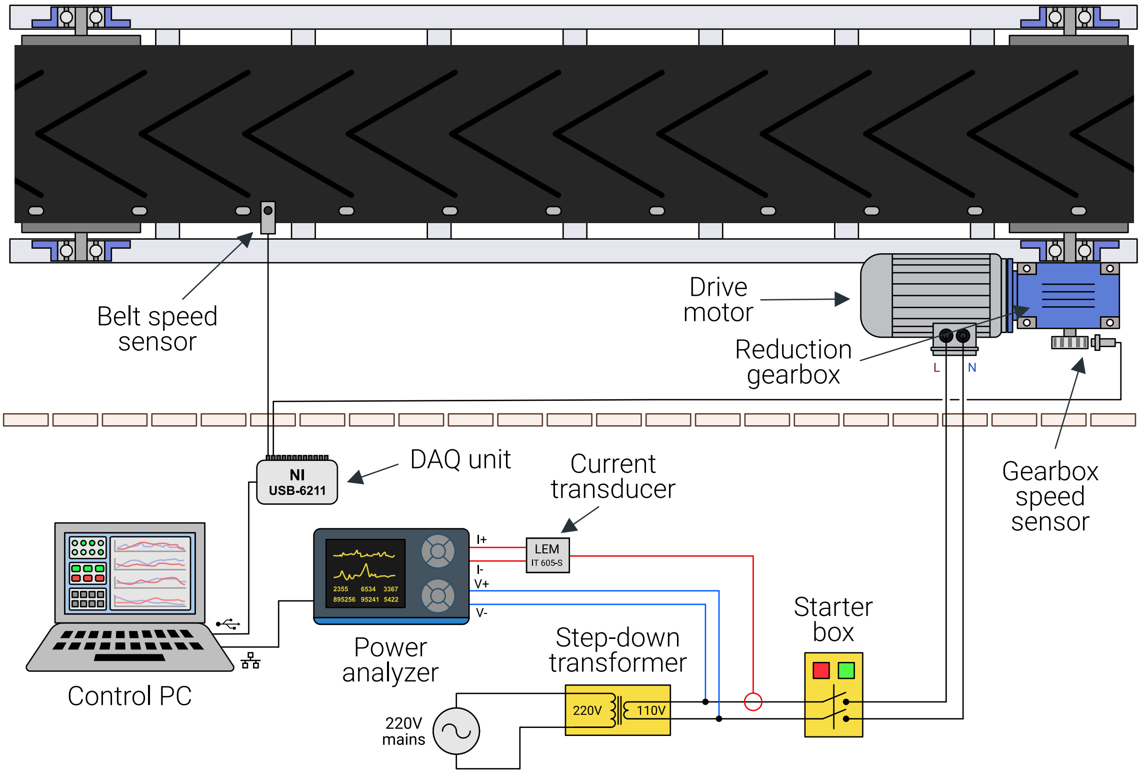


Figure 8.7: Overview of data acquisition setup employed during Conveyor Characterisation Tests.

Acquired data was stored locally, with a separate data folder generated for each test scenario conducted. The National Instruments Technical Data Management Solution (TDMS) file format was utilised for storing acquired data, and a series of scripts were written to enable data to later be imported into MATLAB for post-processing and analysis.

8.2 Operational Scenarios Investigated

A testing schedule was defined, within which tests were split between those designed to investigate the sensitivity of monitored parameters to varying operational conditions and those designed to investigate sensitivity to the presence of specific fault conditions (Table 8.2).

Table 8.2: Overview of test scenarios conducted during CCTs.

Test Group ID	Test Type	Test Scenario	Test Variables					Implementation Details
			Conv. Incline (°)	Load Masses (kg)	Load Height (m)	Loading Freq (s)	Belt Tension (turns)	
CCT.A	Op	Idling baseline	0, 15, 30,	none	N/A	N/A	0	No masses were loaded onto the System during baseline tests
CCT.B	Op	Varying product composition	0	loose, 1, 5, 10, 20, 30	0	1, 2, 3	0	Masses were manually loaded onto the System, therefore, some variance from nominal loading frequencies is expected.
CCT.C	Op	Varying angles of incline	0, 15, 30,	loose, 1, 10, 20, 30	0.3	2	0	A maximum of 30° of incline was investigated due to health and safety limitations, as well as performance limitations associated with a chevroned belt.
CCT.D	Op	Varying loading heights	0	loose, 1, 5, 10, 20, 30	0, 0.3, 0.6	2	0	Masses were dropped from heights as close as possible to the nominal height, using a measurement stick for reference, however, inevitably some variability occurred.
CCT.E	Op	Varying magnitudes of belt tension	0	10	0	2	+1:5 -1:5	Belt tension was adjusted by tightening or loosening both tensioning nuts evenly by the number of turns required.

CCT.F	Fault	Non-centrally tracking belt	0	5, 10, 20	0	2	0	Belt tracking was adjusted by tightening one nut and loosening the other until the belt tracked 'hard over' to one side of the support structure.
CCT.G	Fault	Induced pulley-belt slip	30	10	0	2	0	Water and then vegetable oil (~2l) were introduced to the underside surface of the belt and the System run to allow even dispersion.
CCT.H	Fault	Seeded belt damage	30	10	0	2	0	The belt was slit in increments of 10mm across its width, up to a maximum of 400mm.
CCT.I	Fault	Loss of belt	30	none	N/A	N/A	N/A	The System was run with no belt present.

Scenarios were designed such that the output of the body of testing would provide a comprehensive characterisation, reflective of a typical CBS application. Within each operational test scenario only a single variable was adjusted between tests, in order for the sensitivity of each monitored parameter to that specific variable to be observed.

Live loads were generated as required using masses of various denominations, to reflect a range of typical applications, up to a maximum of 30kg, as stipulated by the Manufacturer within the Operator's Manual. All masses were composed of 'pea' gravel, approximately 10mm in particle size, contained within heavy-duty, woven sacks, which were manually loaded onto the system at a rate and height as required by each specific test scenarios. Within the CEMA Material Classification Code System this material can be considered code 95D27 with an approximate loose bulk density of 90-100lbf/ft^3 (1440-1600kg/m^3) [15], and is reflective of material typically conveyed within construction applications.

Fault scenarios to be investigated during testing were initially identified through interrogation of the FMEA described in Chapter 2, from which an exhaustive list of all possible failure modes was produced. Subsequently, through discussions with the Manufacturer this exhaustive list was reduced to a subset to be investigated during CCTs, based upon their typical likelihood of occurrence.

As identified through the analysis of maintenance records described in Chapter 2 belt issues are typically the most impactful failures within a plant. Through operation of the CER such issues could not be investigated, therefore, during CCTs a number of common belt faults were to be seeded. These included fluctuations in belt tension and alignment, slippage between the belt and pulleys, and progressive belt damage leading to total failure.

8.3 Testing Procedure

During each test scenario a strict procedure was adhered to, ensuring tests were completed safely, as well as consistently. An overview of the eight primary steps taken during the execution of each test scenario is presented in Figure 8.8.

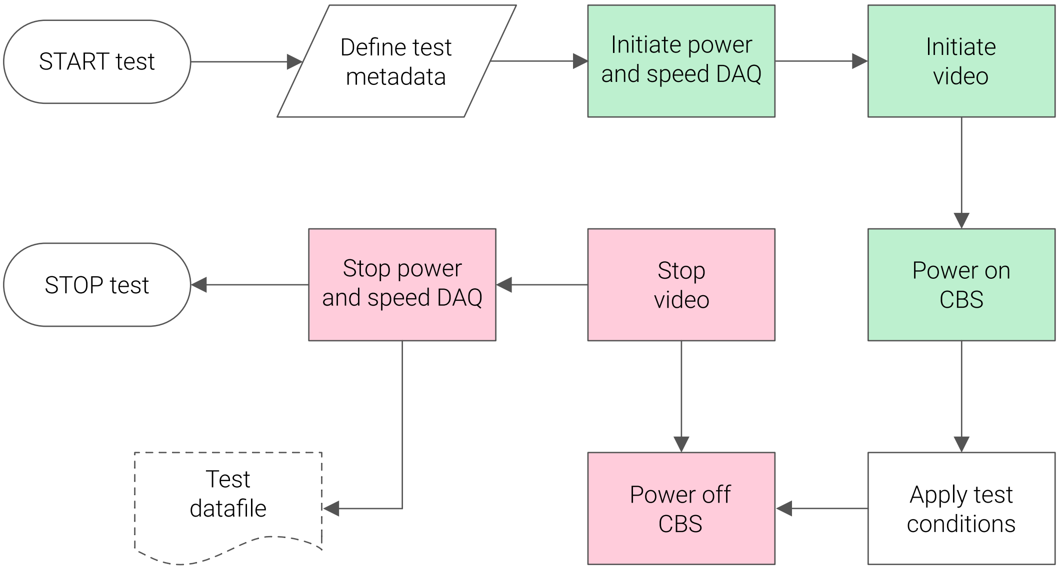


Figure 8.8: Overview of procedure adhered to during the execution of test scenarios.

Prior to the commencement of each test scenario any masses to be used were formed and transferred to the tail end of the System ready for loading, and the system emergency stop was positioned such that it was easily accessible by an operator at all times. Additionally, the video recording equipment was positioned appropriately such that operation of the System could be observed, and the ID of the test to be conducted presented to the camera lens upon test initiation.

Along with the capture of power and speed parameter data a range of metadata associated with each test was captured, including a description of the test, absolute timestamp, and ambient conditions (temperature and weather categorisation), each of which was input by a test operator upon initiation of the data acquisition system.

Once the System was powered on it was allowed to run unloaded for a period of ~5s, to enable the belt speed sensor calibration routine to execute. Once this period had passed and all data acquisition elements were observed to be functioning correctly, the conditions of the specific test could be applied.

When each test was complete the System was powered off using the starterbox, and data acquisition systems were stopped. If any issues were encountered during the execution of a test scenario then the System was immediately stopped using the emergency stop and the test aborted.

8.4 Concluding Remarks

In this chapter the experimental design of a proposed body of testing has been presented, based around the operation of a CBS provided by the Manufacturer. Through operation of the subject CBS the response of motor electrical power consumption (MEPC) parameters to changes in the usage and health of the system are to be assessed. A programme of tests has been developed comprising different operational scenarios, to represent changes in usage (the application of varying live loads) and health (the condition of the System's belt).

Chapter 9: Characterisation of Conveyor Belt System Operation – Results and Findings

Based upon the testing setup and programme of testing described in Chapter 8, in this chapter the results of Conveyor Characterisation Tests (CCTs) are presented and discussed within the context of the demonstrated sensitivity of motor electrical power consumption parameters (MEPC) to changes in conveyor belt system (CBS) operation.

As stated in Chapter 8, the completion of CCTs served to permit assessment of three aspects:

1. **To assess the feasibility of reliably monitoring MEPC parameters throughout the operation of a CBS.**
2. **To assess the sensitivity of MEPC parameters to changes in CBS usage.**
3. **To assess the sensitivity of MEPC parameters to the occurrence of common belt-related faults**.

9.1 Results

In this section a summary of the findings from across all 61 unique test scenarios conducted is presented. N.b. for purposes of brevity, motor electrical power consumption is presented and considered primarily in terms of apparent power consumption only, that is, the product of the RMS voltage and RMS current as calculated consecutively every 0.02s, in accordance with the sample rate of the DAQ system (50Hz). Furthermore, in many instances MEPC is presented as mean-adjusted, that is, the difference between instantaneous MEPC and idling MEPC, to minimise steady-state effects and thus aid comparison of transient effects. Additionally, a low pass first order Butterworth filter is applied to acquired MEPC data to minimise the presence of measurement noise within data. It should be noted that, as an inevitable consequence of this filtering stage the amplitudes of transients spikes in MEPC are modified in comparison to their 'true' values. Finally, all presented frequency spectra are calculated from periods when the CBS was idling (i.e. with no live load present).

9.1.1 CCT.A Idling

Summary:

- *Transient in power consumption observed at start-up.*
- *No significant longer-term effects observed in data.*
- *Frequency-spectrum content during idling shows peaks associated with belt and chevron passing frequencies and their harmonics.*
- *Measurements present good signal-to-noise ratio, with noise presenting white characteristics.*

CCT.A scenarios involved conducting a long duration test (~10mins) at each inclination, with no live load applied to the belt. These tests served two purposes; firstly, the long duration enabled the System to warm up to steady-state running temperatures before tests were commenced, enabling the presence of any longer-term effects to be observed. Secondly, the tests enabled unloaded System operation to be characterised, providing a baseline against which subsequent scenarios could be compared.

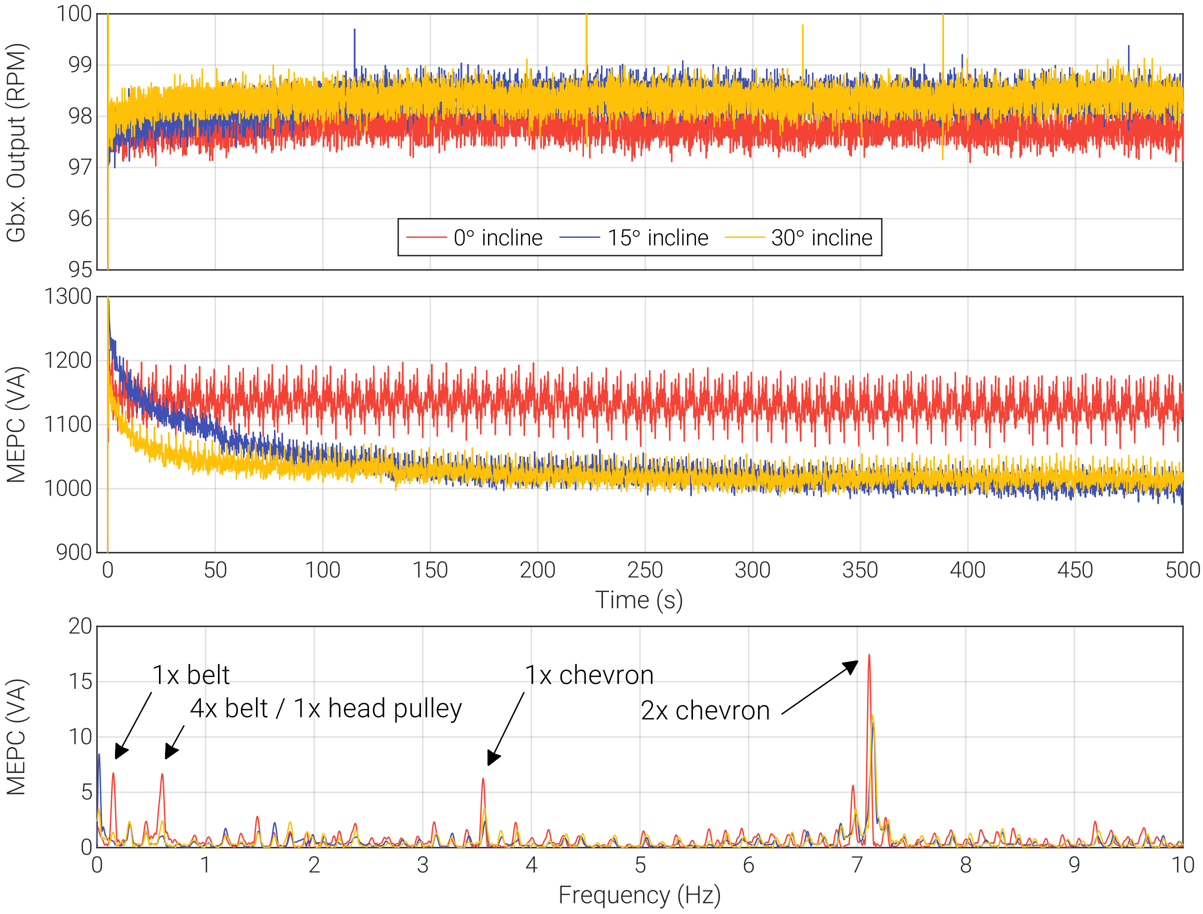


Figure 9.1: CCT.A Idling time and frequency domain characterisation data.

Time-domain data from these test shows no significant long-term effects to be present in either power or speed data. However, during the first ~100s of the 15° and 30° scenarios a gradual decrease in MEPC of ~100VA is observed, likely a consequence of thermal build-up within the motor windings and stator, in turn causing an increase in resistance and thus reduction in current flow (Figure 9.1).

Between the inclines a different magnitude of power consumption during idling can be observed, with consumption inversely proportional to incline. The behaviour observed can most likely be explained by the order of completion of tests. All tests at each incline were completed consecutively, thus, between the completion of each individual test within CCT.A the belt tension was changed. Efforts were made to ensure that the belt tension was returned to nominal for subsequent tests, however in practice this proved challenging, with no feedback available to support resetting.

Frequency-domain data shows no significant differences between tests, with correlation observed between the most prominent components in each spectra (Figure 9.1). The most significant periodic component within motor power consumption data is located at around 7.2Hz, approximately equal to the second harmonic of the belt chevron passing frequency, as illustrated in Figure 8.3. Additional significant peaks are present at the belt passing frequency (0.15Hz) and its harmonics, as well as the rotational frequency of the head pulley (0.61Hz)[45]. The presence of significant components at the chevron passing frequency and first harmonic are likely a consequence of chevrons being restricted at certain points around the travel of the belt, possibly where they contact the two support idlers on the underside of the System, as evidenced by the greater amplitude of the 2x component. When chevrons are dynamically restricted a corresponding fluctuation in motor current draw can be expected due to the transient change in torsional load.

The power factor of an electrical component describes the ratio between the amount of *real power* absorbed by the electrical load associated with the component to the *apparent power* flowing in the circuit, where *real power* refers to the instantaneous product of voltage and current and *apparent power* refers to the product of the average current and average voltage in the circuit [223]. When the System's power factor is analysed transient characteristics can be seen to occur

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[45] It may also be the case that the tail pulley frequency is identical to that of the head pulley, however, as the two are not rigidly coupled it cannot necessarily be assumed that they are always rotating synchronously.

during start-up of the motor, however, once the System has reached idling speed, the power factor remains approximately constant (Figure 9.2).

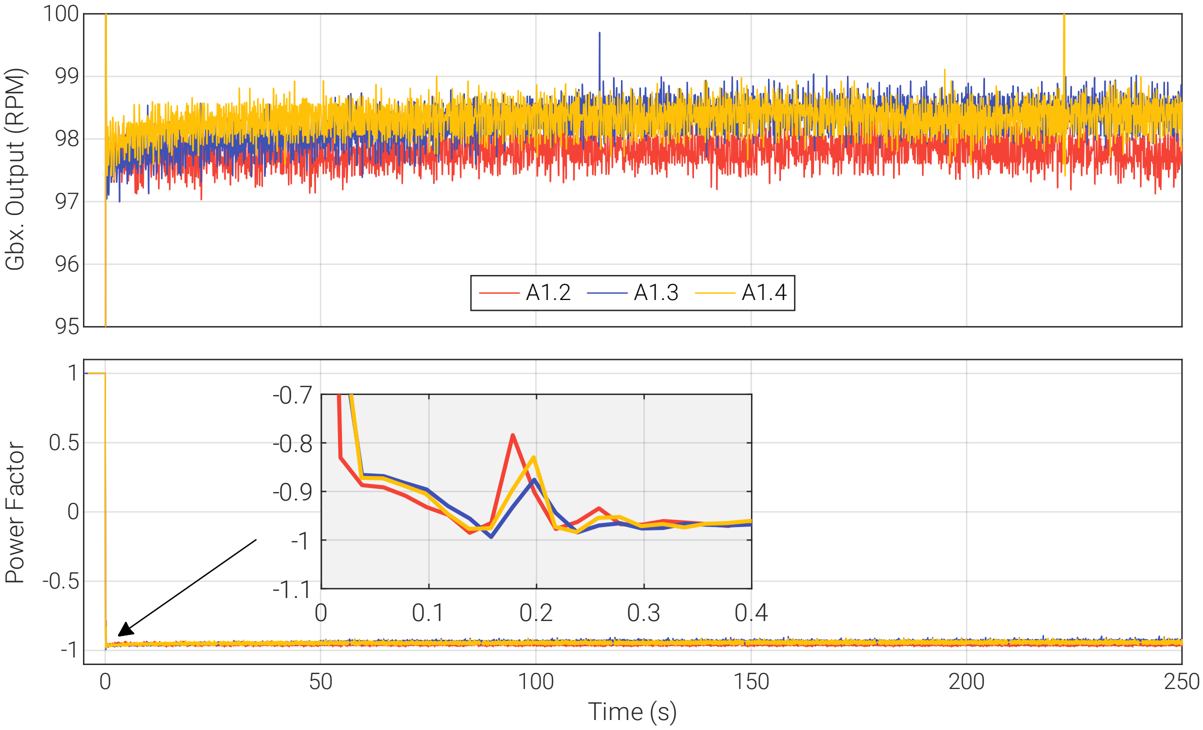


Figure 9.2: Power factor fluctuations at start-up during CCT.A test scenarios.

This behaviour is a consequence of the motor's nonlinear impedance, which is a function of rotor speed. After an initial change in power factor as the motor is connected to the power supply a secondary fluctuation is also observed around 20ms later, as highlighted in Figure 9.2. This transient is likely caused by the opening of the start winding centrifugal switch as the rotor reaches operational speed, which will affect the motor's overall impedance.

Time series data is seen to contain a degree of noise within measurements, an unavoidable facet of the data acquisition process. To determine the nature and significance of measurement noise its characteristics can be explored through calculation of the signal-to-noise ratio (SNR) associated with measured data. The SNR of a signal is defined as the ration of power between a 'true' signal and its associated corrupting noise [224] i.e.:

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{9.1}$$

Where the components are measured across an identical impedance the SNR can be calculated from the square of the amplitude ratio i.e.:

$$SNR = \frac{P_{signal}}{P_{noise}} = \left(\frac{A_{signal}}{A_{noise}}\right)^2 \qquad 9.2$$

Where each amplitude is calculated from the root-mean-square (RMS) of each signal i.e.:

$$x_{RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|x_n|^2} \qquad 9.3$$

Where x_{RMS} *represents an input signal and N represents the number of samples in the signal.*

Typically, for convenience a signal's SNR is expressed in decibels (dB) i.e.:

$$SNR = 10\,log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \qquad 9.4$$

The acceptable lower limit on SNR will vary across applications, however, typically a SNR above 3dB is considered the low threshold on acceptability [225]. To determine the power of each component the 'true' signal and the corrupting noise must be separated. This can be achieved by applying a low pass filter to the measured time series to remove high frequency noise. This is realised here using a 2nd order discrete Butterworth filter of the form [226]:

$$H(\omega) = \frac{1}{\sqrt{1 + \omega^{2n}}} \qquad 9.5$$

Where n is the filter order (in this case 2) and ω is the cut-off frequency of the filter, which is set to 2Hz, based upon a maximum loading speed of once per second.

A Butterworth filter is selected due to its flat passband response and smooth roll-off characteristics. The filter is implemented as a zero-phase operation by applying it to both forward and reversed versions of the input time series, resulting in no phase shift in the output signal but a doubling of the order. The output of the filter can then be subtracted from the input time series to produce a residual signal which represents an estimate of measurement noise. A section of CCT data from a baseline characterisation test (A1.3) is used as an input to the filter as it represents steady-state operation of the system (i.e. no live load).

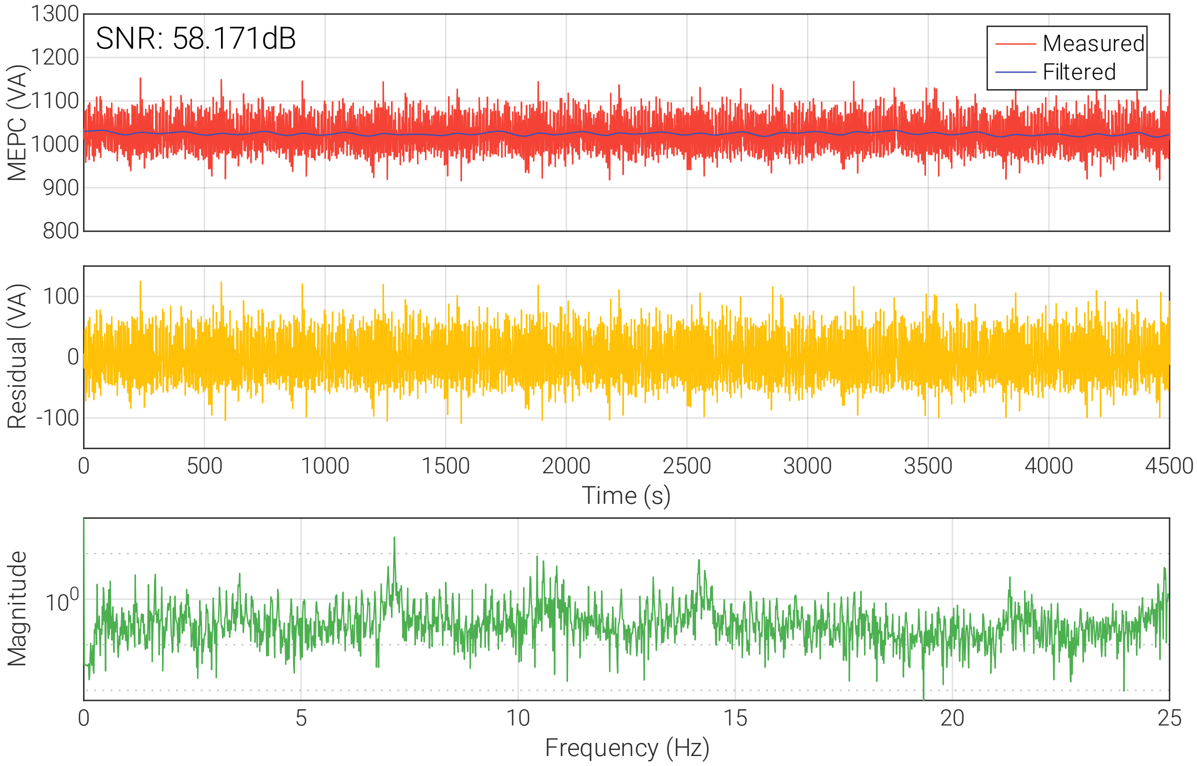


Figure 9.3: Characterisation of measurements noise contained within acquired data. Measured and low pass filtered MEPC (top), the residual between the two (middle) and the frequency content of the residual (bottom).

As shown in Figure 9.3 noise contained within measured data is approximately flat across the frequency spectrum, suggesting it is white in nature, with an associated SNR of ~58dB.

9.1.2 CCT.B Product Composition

Summary:

- *Loading a discrete mass onto the belt induces a transient increase in MEPC.*
- *The duration of each transient is relatively independent of the amount of mass loaded*
- *Each discrete mass can be identified down to a loading frequency of at least* 0.5*s.*
- *Statistical moments, particularly variance, skewness and kurtosis are increased when the mean mass loaded is increased.*
- *Stream of loose material has little effect on MEPC.*

CCT.B scenarios were concerned with identifying the effect of loading different quantities of mass at different frequencies on the power consumption and rotational speed of the drive motor. Discrete masses of denomination 1, 5, 10, 20 and 30kg, as well as a continuous stream, were used, and for each denomination loading frequencies of approximately 1, 2 and 3 seconds were implemented. All tests within the series were conducted at 0° inclination.

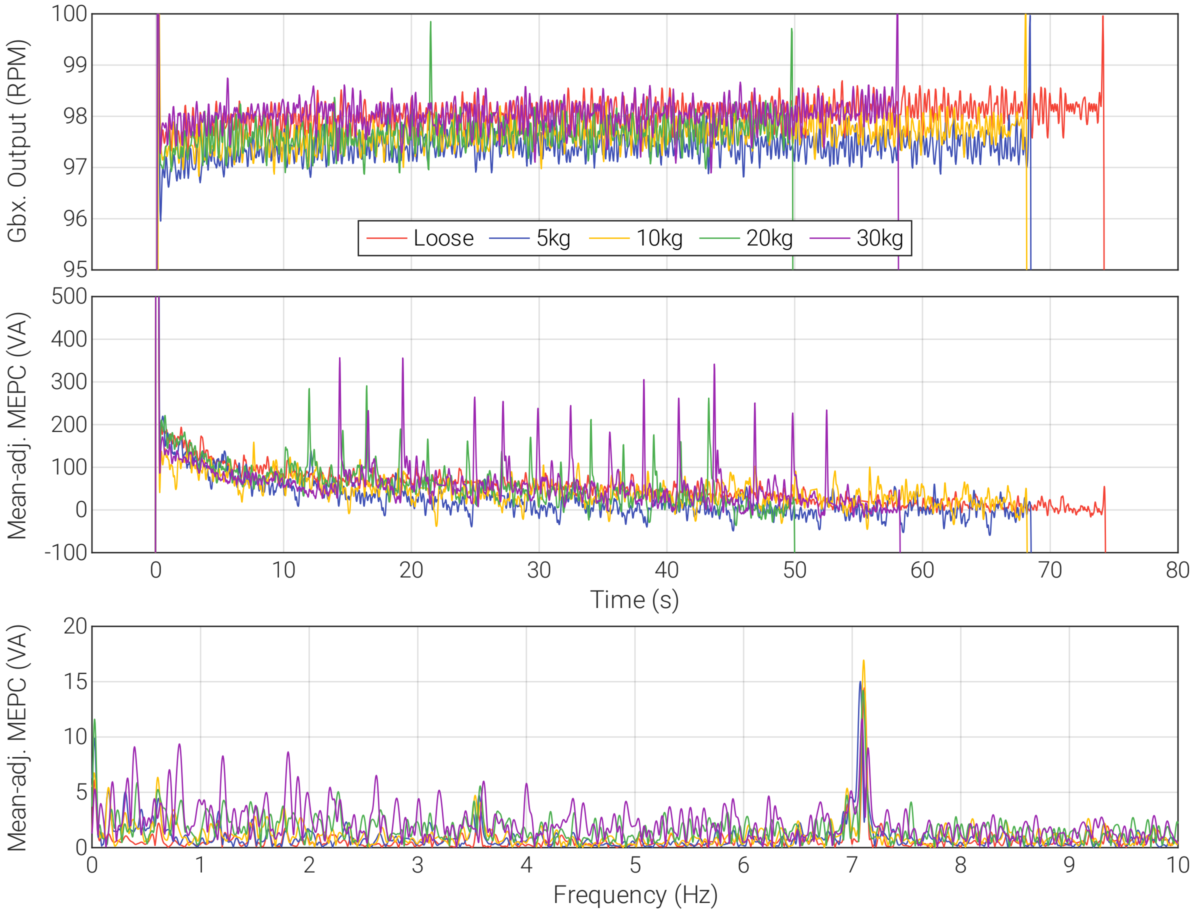


Figure 9.4: CCT.B Product Composition time and frequency domain characterisation data – 30kg (x15) masses loaded.

CCT.B time domain data shows that as each discrete mass is loaded onto the surface of the belt a corresponding spike in MEPC can be observed, with the magnitude of the spike a function of the quantity of mass loaded (Figure 9.4). Such behaviour can be explained by the mechanics of the system; at the point at which a mass is loaded onto the belt it has zero velocity in the direction of belt travel. As a result, the inertia of the added mass is felt by the drive motor as an increase in torsional load and thus a transient increase in slip is generated. As described in Chapter 7, the occurrence of increased slip will cause a transient reduction in apparent stator impedance and thus permit an increase in current draw. Accordingly, the overall power consumption of the motor is increased until slip returns to a steady-state condition, resulting in the observed spike in MEPC. The magnitude of the spike induced is dictated by the degree of transient increase in slip which is induced, which can be considered a direct function of the quantity of mass loaded.

The mechanics of mass loading are also reflected in the gearbox output shaft rotational speed, where a corresponding negative spike in speed can be observed with each mass loaded, indicating a period of deceleration and subsequent acceleration of the belt in response to the additional load.

A gradient within each MEPC spike measured (as opposed to an instantaneous step change) can be observed. This can be considered to be a consequence of the inductance of the drive motor, which limits the rate at which the polarity of the magnetic flux field within the motor's air gap can change, and thus the rate at which current drawn by the motor can change.

Additionally, as the process of acquiring digital data from the system has a finite sample rate associated with it there is a limitation on the frequency of changes (i.e. bandwidth) that can be captured within the acquired data. In accordance with the Nyquist-Shannon Sampling Theorem [227], any dynamic effects faster than half the rate at which the signal is sampled will not be able to be captured within the recorded data, and instead some distortion of the 'true' signal (i.e. aliasing) may be induced.

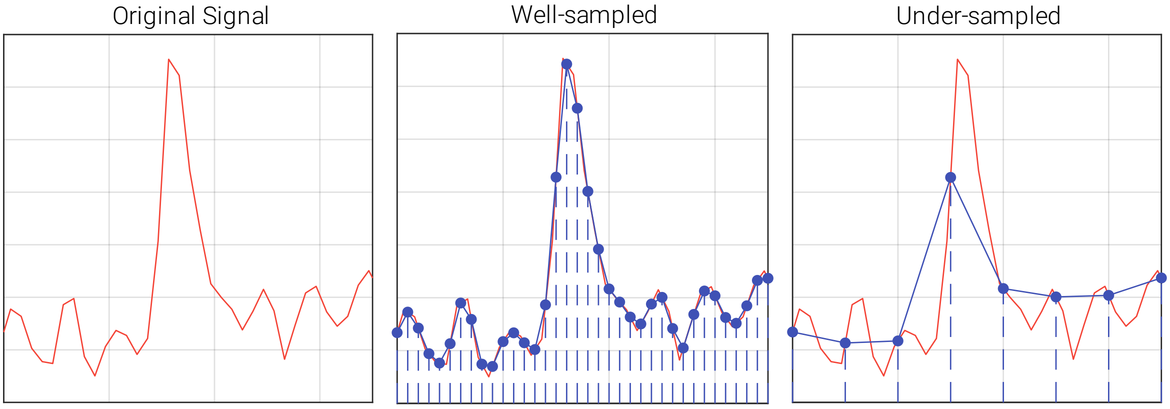


Figure 9.5: Example of effect of sampling rate on reproduction of 'true' signals within measurements, highlighting the potential clipping of spikes (r).

This phenomenon could result in the characteristics of the transients (spikes) in power consumption induced in response to the loading of masses onto the belt not being accurately captured within acquired data, for example, the amplitude of transients as recorded may be lower than their true amplitude, as demonstrated in Figure 9.5.

Across all CCT.B test scenarios the duration of each spike induced in response to the loading of a mass onto the belt appears to be consistent, with a duration of ~0.08s measured in all tests, suggesting the duration is independent of the quantity of mass loaded (Figure 9.6).

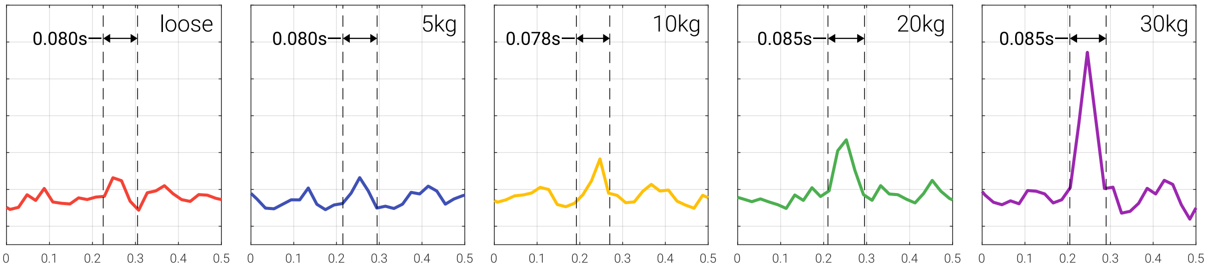


Figure 9.6: Comparison of induced spike duration across different loaded mass quantities.

Such observation may be explained by limitations imposed by the rate at which electrical parameters were sampled. As illustrated in Figure 9.5, a minimum measurable transient duration will be imposed, dictated by the sample rate employed. In the case of electrical power measurements during CCTs the 50Hz sample rate will result in any transients shorter than 0.02s in duration will be captured as a transient of duration 0.02s, regardless of amplitude, as illustrated in Figure 9.7.

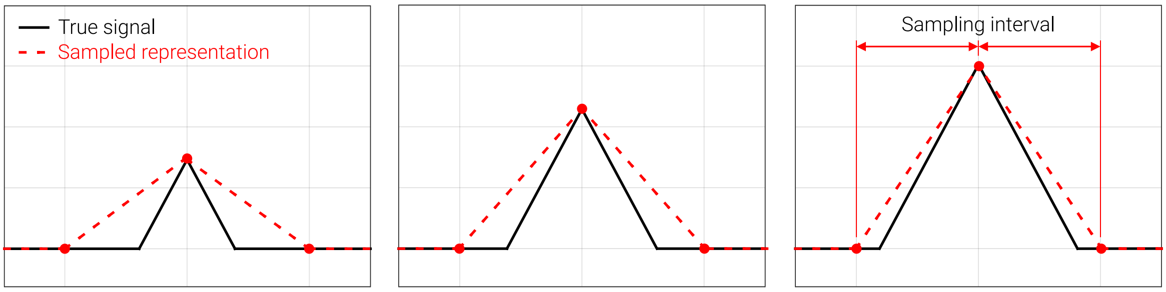


Figure 9.7: Illustration of the potential effect of discretisation on the measured durations of MEPC transients as caused by sample rate limitations.

However, given the durations of transients measured during CCTs $(\sim 0.08\text{s})$ the discretisation effect imposed by the implemented sampling rate would not be expected to dominate. Alternatively, such behaviour may be a consequence of the electromechanical properties of the machine; as the quantity of loaded mass is increased the degree of slip induced within the motor increases accordingly, in doing so inducing a greater EMF and current draw.

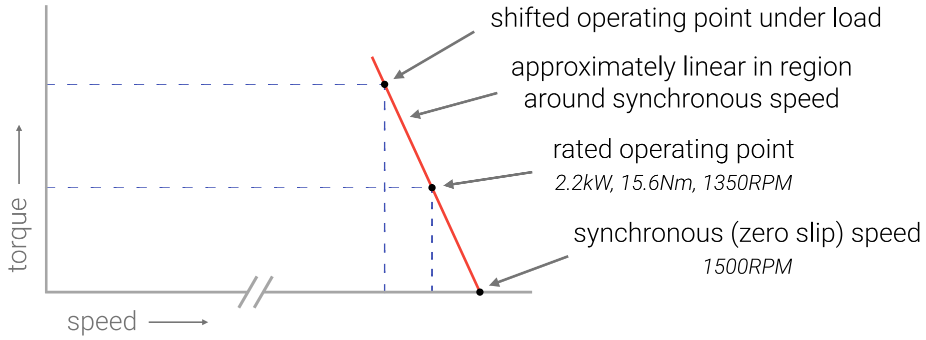


Figure 9.8: Approximate torque-speed characteristics of an induction motor at low slip.

As depicted in Figure 9.8, the decelerating effect of loading mass onto the belt causes a shift in the motor's operating point, which will result in a disproportionally greater increase in produce torque, due to the characteristics of a typical induction motor. Given the low impedance of an induction motor, the greater the magnitude of mechanical loading experienced is, the greater the rate of change of torque production is. Thus, as the quantity of mass is increased the rate of change of torque produced increases, so transient durations remain approximately constant.

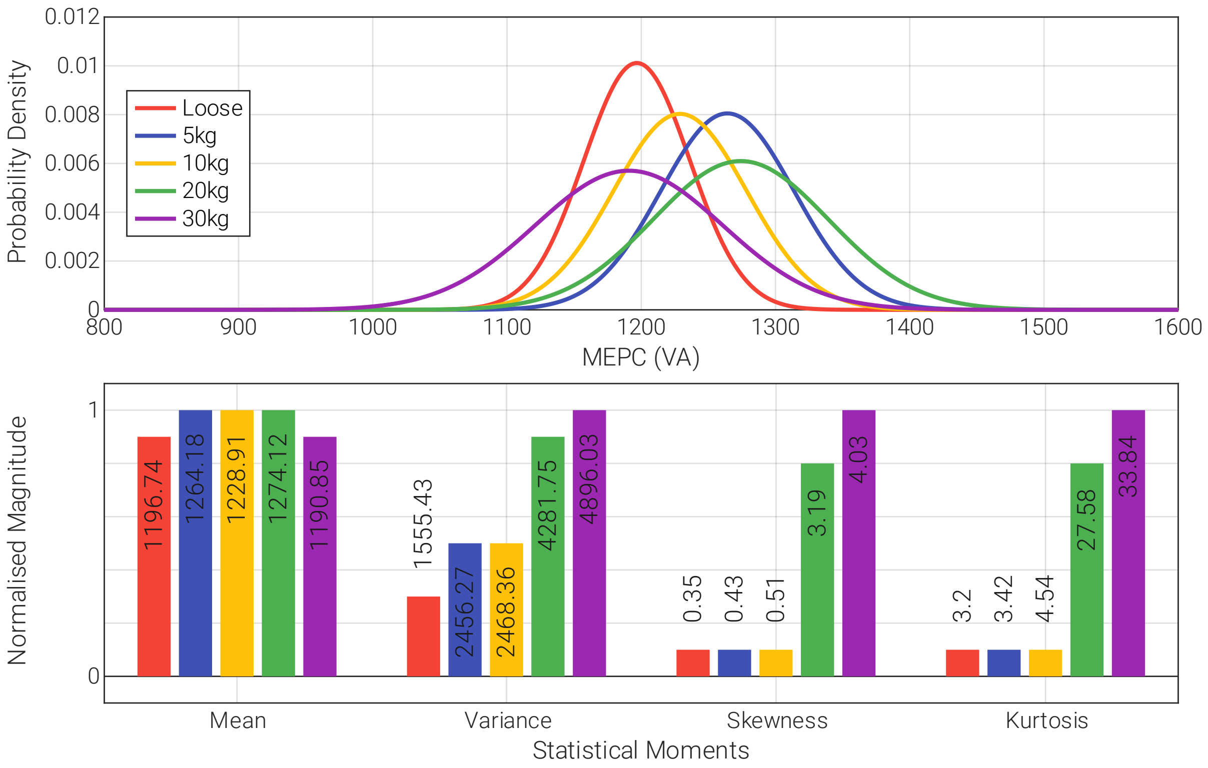


Figure 9.9: CCT.B Product composition characterisation data statistical moments.

When the statistical distribution of each test within the CCT.B series is considered a clear increase in the variance, skewness and kurtosis of each with increasing mass denominations is observed (Figure 9.9). Variance, a measure of the spread of values within a distribution, is increased with mass as a result of the load masses effectively disrupting how closely data points are grouped around the mean power consumption. The effect increases with the magnitude of the mass loaded, as the significance of the increase in power caused by the mass, relative to the idling power consumption, increases. Skewness, a measure of the symmetry of a distribution, is increased with mass, as the added mass results in an increase in power consumption, resulting in more data points above the mean power consumption being recorded. Kurtosis, a measure of the presence of outliers within a distribution, is increased as the load mass magnitude is increased, with the loading of identical masses adding a narrow group of data points to each distribution, far from the mean, thus making the positive tail of the distribution more significant.

During CCT.B tests the effect of varying the loading frequency of applied masses was also investigated. As the frequency at which masses are loaded onto the belt is increased, the period between spikes reduces accordingly (Figure 9.10), however, even at the fastest loading frequency implemented during tests (~1s) it is still possible to identify the application of each mass.

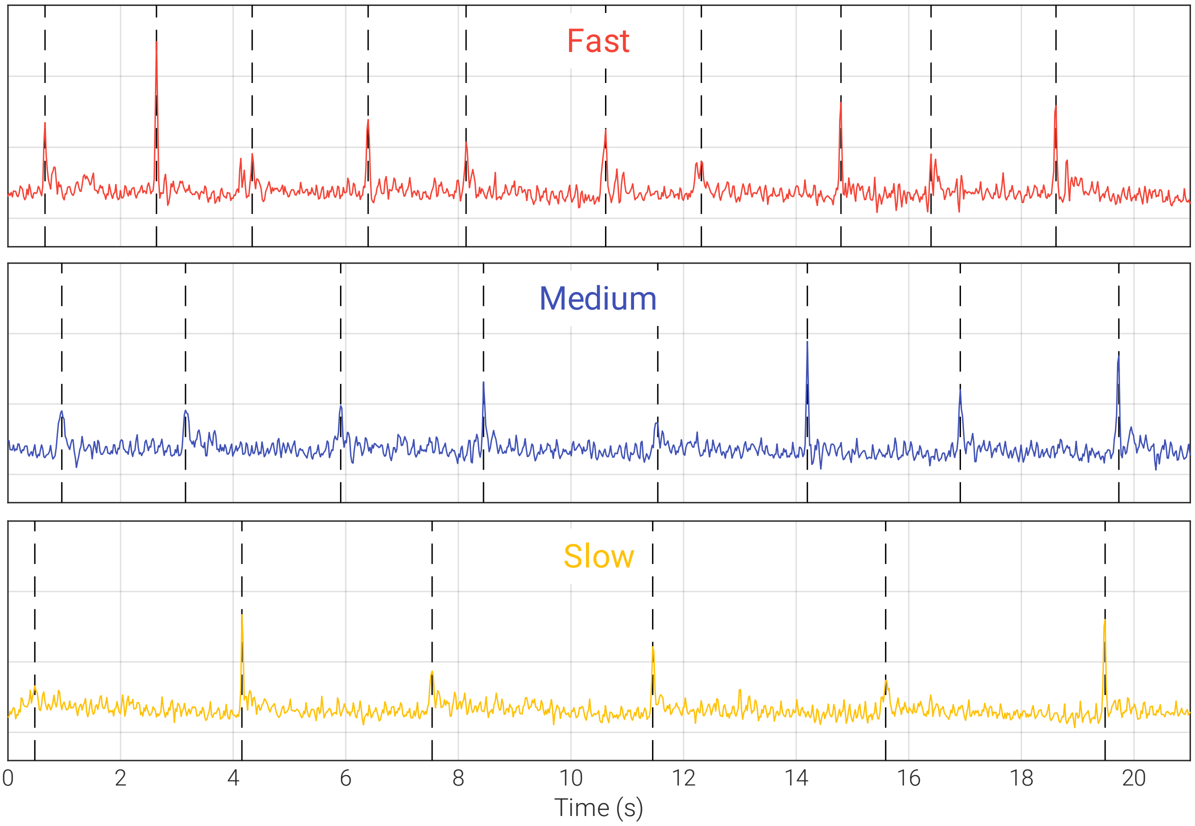


Figure 9.10: Illustration of spikes induced in MEPC by live loads as a function of the loading frequency across CCT.B test series.

It can be considered that a 1s loading frequency represents the fastest rate likely to be achieved by manual means when the material being conveyed is of a discrete nature (i.e. 'lumps' as opposed to loose material). Accordingly, the sample rate implemented during CCTs can be considered sufficient to capture such events within measured data.

In comparison to the loading of discrete mass, in response to continuous stream of material no such transients are present within measured data, but instead a steady-state increase in power consumption is observed (Figure 9.11).

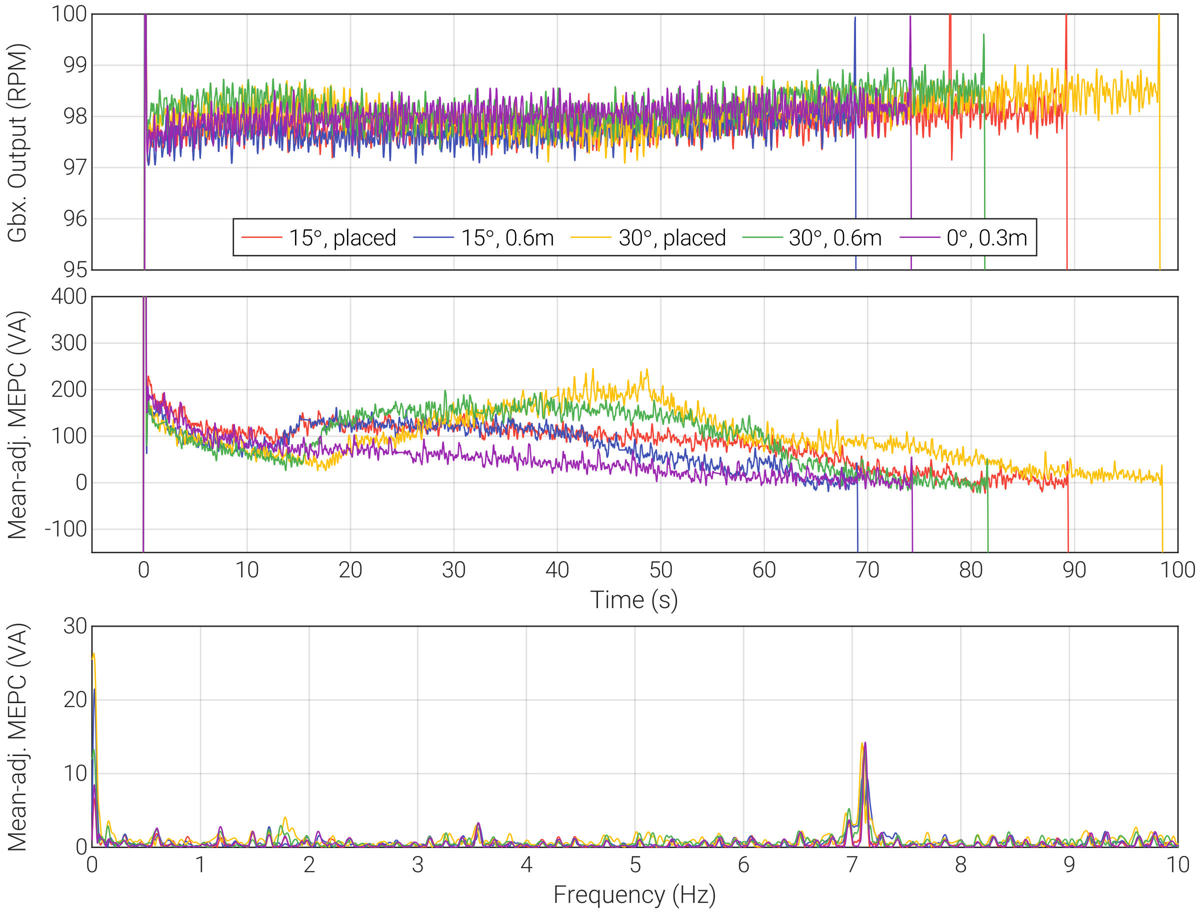


Figure 9.11: Time and frequency domain characterisation data associated with each loose stream test scenario.

The magnitude of this increase is small in comparison to the idling consumption of the motor, with a maximum increase of ~200VA observed across all loose stream tests. Whilst the overall mass conveyed by the System during loose scenarios was significant (~800kg) this material was conveyed over a period of~50s, resulting in a flowrate of ~16kg/s. As the material is loose in nature, the magnitude of the instantaneous load it applies to the belt is reduced in comparison to an equivalent 16kg, where, conversely the effect of the entire mass is experienced instantaneously by the motor. Consequently, the torsional load experienced by the motor in response to loose material is less significant and so the effect on MEPC is minimal.

9.1.3 CCT.C Inclination

Summary:

- *Changing the inclination of the System has no effect on MEPC whilst idling.*
- *Increased inclination does not affect the magnitude of spike induced when a mass is loaded.*
- *Steady-state MEPC whilst conveying a mass does increase as inclination increases.*

CCT.C scenarios involved varying the System's inclination to enable the sensitivity of monitored parameters to changes in the physical configuration of the System to be observed. Inclines of 0°, 15° and 30° were investigated, with safety concerns over operating beyond 30° dictating the upper limit. Additionally, the ability of a chevroned belt to effectively convey product reduces significantly beyond 30°; even at 30° difficulty in conveying masses observed, with masses showing a tendency to tumble on the belt, rather than be conveyed along its length.

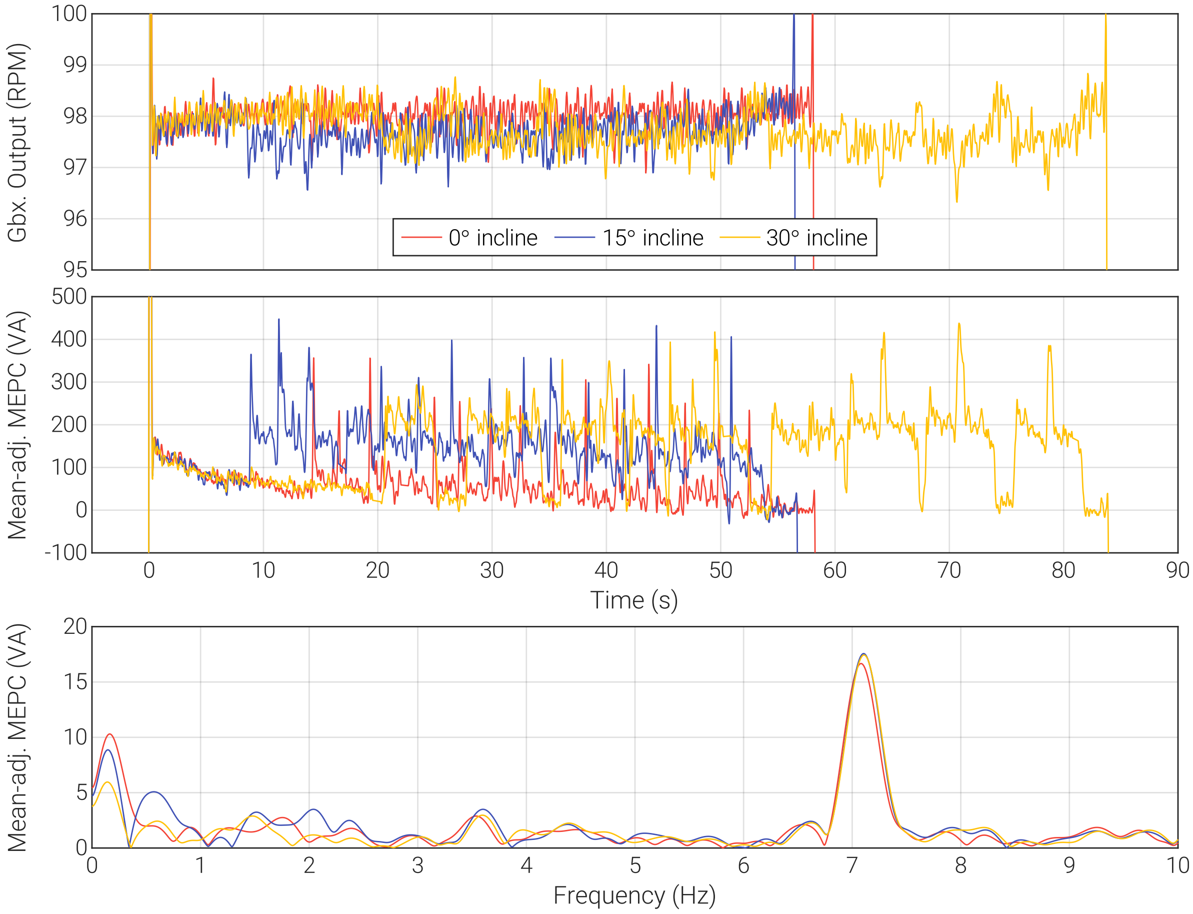


Figure 9.12: CCT.C Inclination time and frequency domain characterisation data – 30kg (x15) masses loaded.

Time-domain data from CCT.C test scenarios demonstrates similar characteristics as CCT.B tests, with a discrete spike in power consumption observed in response to each mass loaded onto the belt. The magnitude of the spike induced appears to be unaffected by the System's angle of inclination; as seen in Figure 9.12, when differences in idling consumption are accounted for, the mean magnitude of spikes induced by 30kg masses stays relatively constant across all inclinations, with mean amplitudes of ~510VA, ~670VA and ~414VA above mean idling consumption observed for 0°, 15° and 30° inclination respectively.

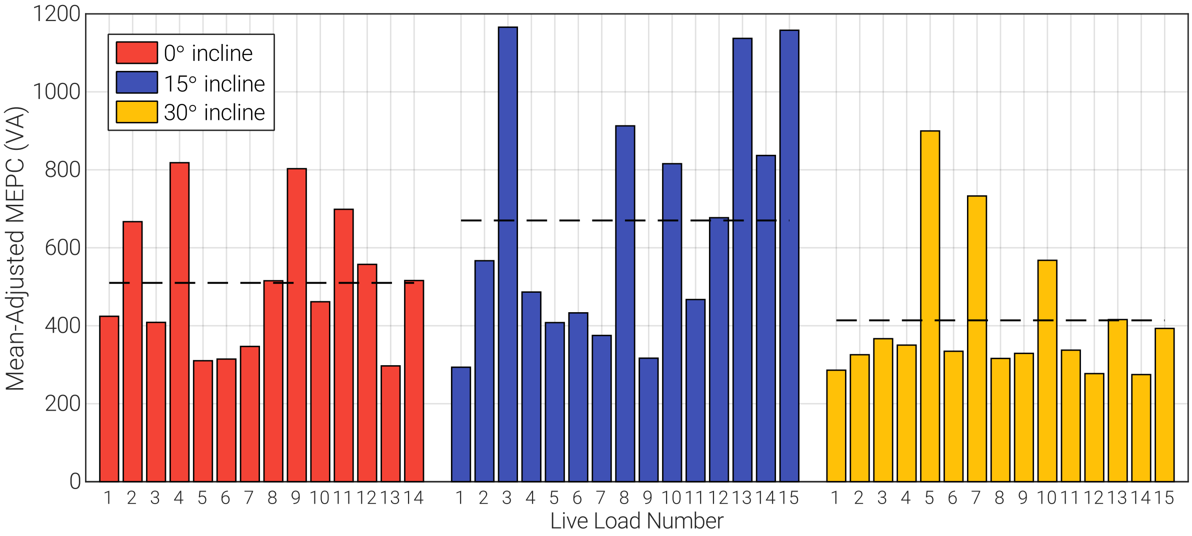


Figure 9.13: Comparison of mean spike magnitude induced in response to application of 30kg masses, as a function of inclination. N.b. the mean of each test scenario is indicated by a dashed line.

Such an observation is consistent with the mechanics of the system as described in Section 9.1.2; the power consumption associated with the spike induced in response to a loaded mass represents the energy required to accelerate the stationary mass up to the nominal belt speed and is thus relatively independent of the System's inclination. Significant variance in the actual magnitude of each spike induced is seen at each inclination, likely a consequence of natural variance in the height at which masses were loaded from. Masses were loaded onto the belt manually, with only a datum indicating the 0.3m and 0.6m nominal heights from which masses should be released. As the quantity of mass loaded increased so too did the required physical exertion, likely resulting in the average loading height in practice deviating more as the live load denomination increased.

However, during the period between the end of the loading transient and the mass exiting the end of the System, the RMS power consumption of the motor can be seen to increase with System inclination. This behaviour is highlighted in Figure 9.14, and corresponds to *Period* 3.

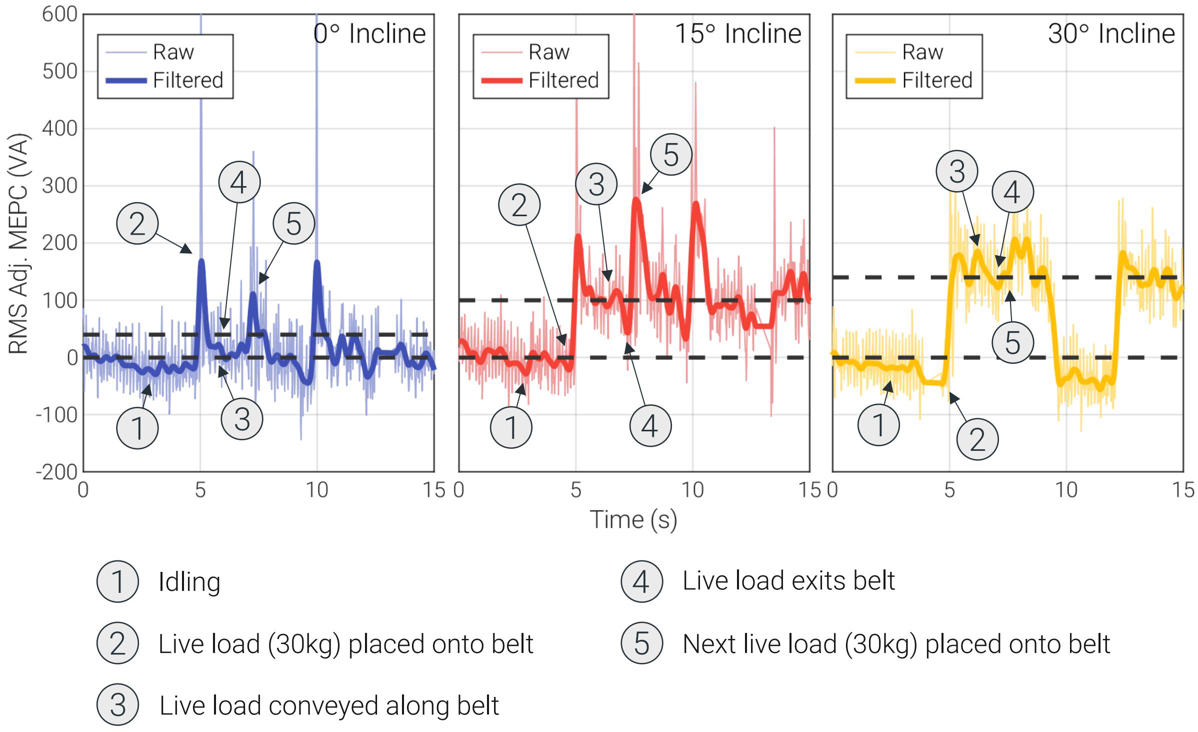


Figure 9.14: The effect of changes in System inclination on the MEPC when loaded with 30kg masses.

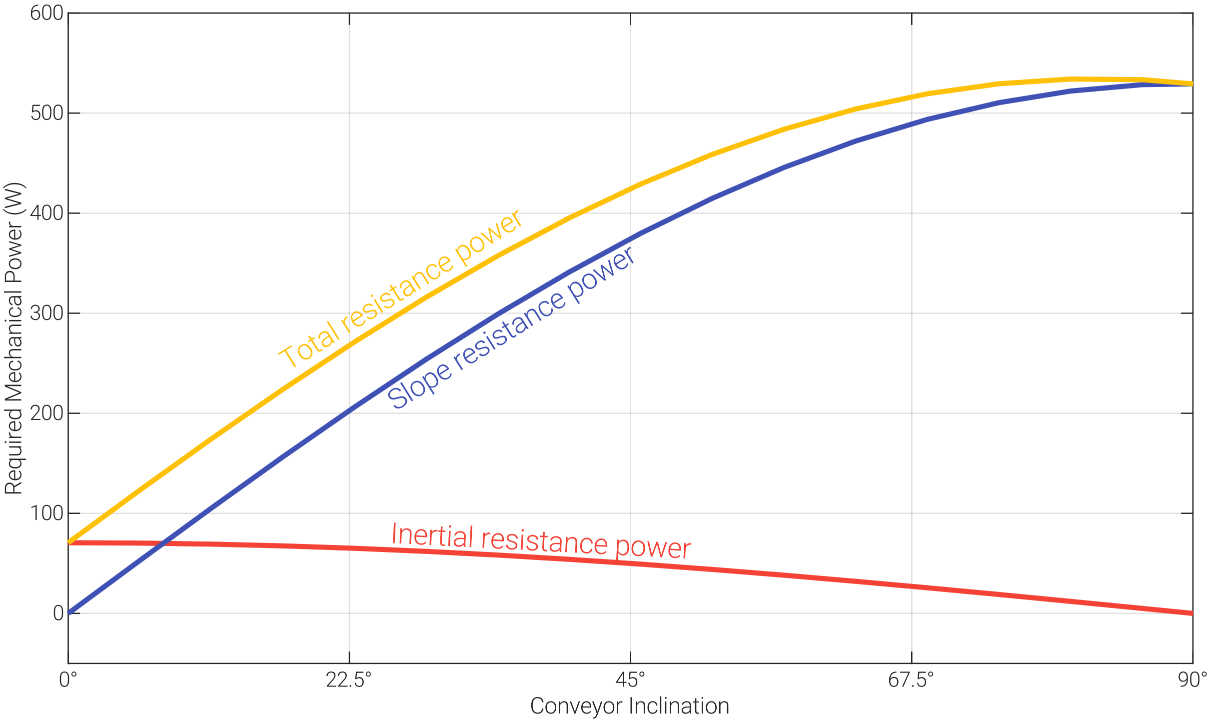
It can be seen from Figure 9.14 how during *Period* 3 within each test scenario MEPC is around ~50VA greater than idling at 0° inclination, ~100VA greater at 15° inclination and ~140VA greater at 30° inclination. Once each mass has exited the System (*Period* 4) and thus the belt is subjected to no live load, the System's MEPC can be seen to return to its idling level.

Again, such observations can be explained by the mechanics of a CBS; when the system is idling (i.e. no live load) the tension forces in both the top and bottom surfaces of the belt are equal and thus the mass the motor must raise (i.e. the top side of the belt) is balanced by an equal mass being lowered (i.e. the bottom side of the belt). Accordingly, the only effort required by the motor is that needed to overcome friction within the system, and thus the power consumed whilst idling is essentially independent of system inclination, as seen in Figure 9.12.

However, when a live load is added the tension in the upper side of the belt will exceed that in the return side and thus the motor is required to raise additional mass which is not counterbalanced by corresponding lowering mass. Accordingly, the power consumed by the motor whilst conveying this additional mass (i.e. *Period* 3) is increased.

Such mechanics are comparable to those associated with a typical vertical elevator in which a counterweight is employed to balance the load within the elevator, reducing the work required to be performed by the drive motor.

The observation that the magnitude of the increase in MEPC during *Period* 3 is a function of system inclination reflects the increased work done against gravity in raising live loads, which can be examined analytically using a simplified[46] model of a CBS, based upon that described in ISO5048:1989 [51], to demonstrate the relative effect of different angles of inclination on the mechanical power requirement of a CBS.



$$F_{inertial} = l_{conv} \cdot \mu \cdot g \cdot (2m_{belt} + m_{load})\ cos\theta\ , \quad F_{slope} = l_{conv} \cdot g \cdot m_{load}\ sin\theta\ , \quad P_{mech} = (F_{inertial} + F_{slope})\ v_{conv}$$

where : $l_{conv} = 2m,\ v_{conv} = 0.9ms^{-1},\ \mu = 0.04,\ m_{belt} = 10kgm^{-1},\ m_{load} = 30kgm^{-1},\ g = 9.81ms^{-2}$

Figure 9.15: Simplified model of the power required to move a point mass along the length of a CBS, as a function of inclination.

From Figure 9.15 it can be seen how, in this simplified model, the entirety of the work done by a flat CBS will be to counter inertial resistance of the mass on its belt, as well as the belt

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[46] The model is simplified such that only those terms which are incline-dependent are included

itself, whereas for a completely vertical CBS the entirely of power consumed will be required to counter slope resistance, with the proportions of each transitioning for inclines between.

Accordingly, given the slope resistance is both a function of mass and vertical height, for the same inclination the magnitude of the increase in power consumption whilst conveying is affected only by the quantity of mass loaded. Similarly, for the same quantity of mass loaded the magnitude of the increase in power consumption whilst conveying is affected only by the angle of inclination.

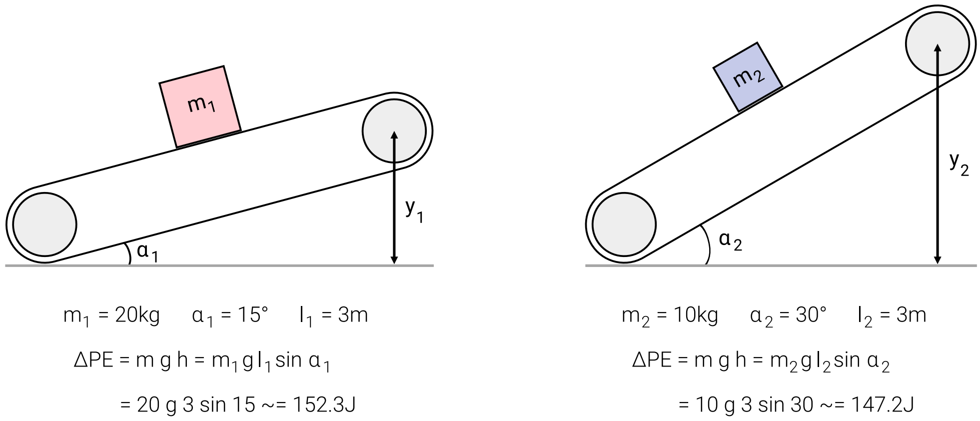

Figure 9.16: Illustrative example of potential equivalence between a change in CBS inclination or quantity of mass loaded in terms of required energy.

The equivalence between mass and height on total energy required to convey can be examined through a simple example; as illustrated in Figure 9.16 the change in potential energy associated with a 15° increase in system inclination can be seen to be approximately equivalent to an increase in mass of 10kg. Accordingly, decoupling changes in each variable through observation of MEPC only can be considered infeasible.

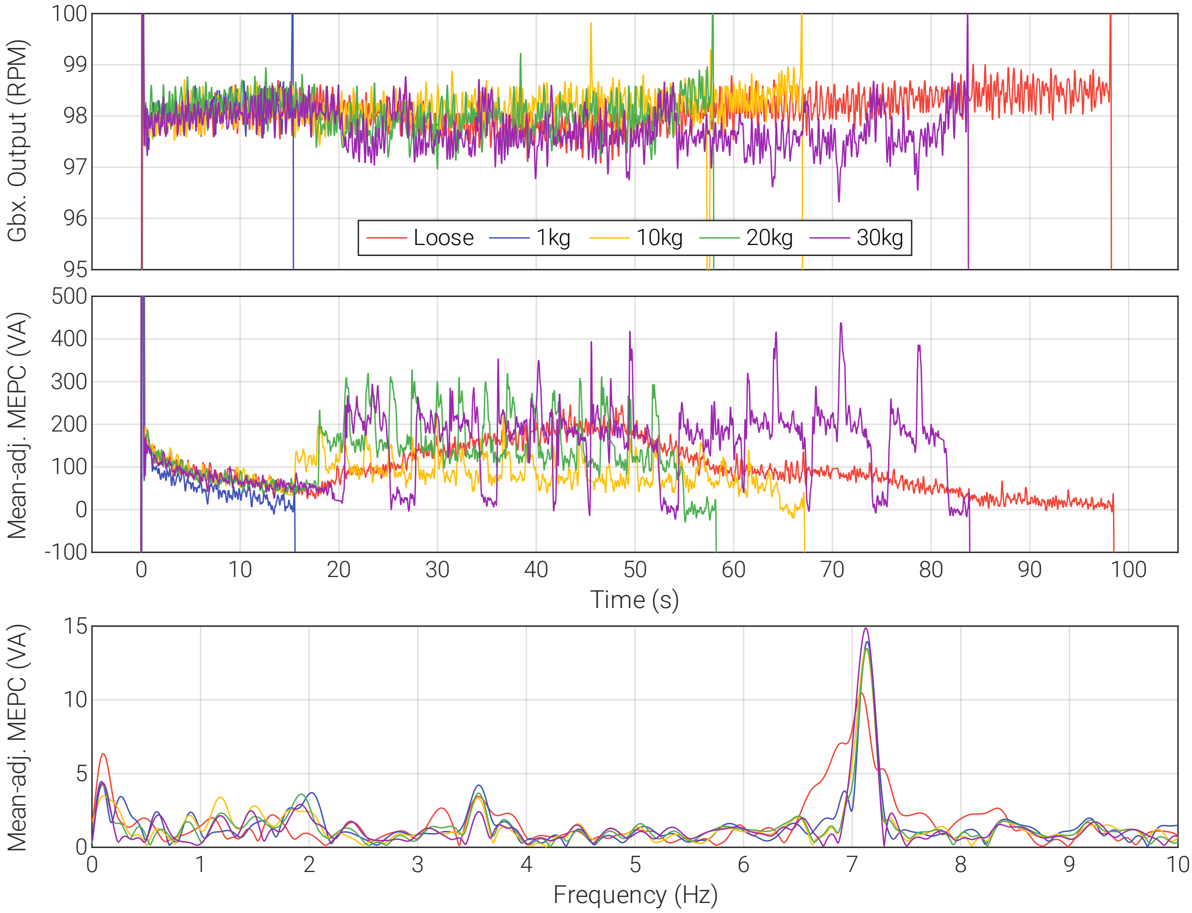

Figure 9.17: CCT.C Inclined System time and frequency domain characterisation data – increasing denominations of mass at constant 30° inclination.

As seen in Figure 9.17, for a constant System incline the magnitude of the increase observed during period C is greatest in response to the loading of 30kg masses.

9.1.4 CCT.D Loading Height

Summary:

- *Magnitude of spike induced by loaded mass increases with increasing loading height.*
- *Broadband frequency content masks analytical frequencies.*

CCT.D scenarios were conducted to investigate the effect of changes in loading height on MEPC characteristics. The time-domain data shown in Figure 9.18 indicates that the magnitude of the spike induced by a mass being loaded onto the belt surface is directly related to the height from which it is dropped.

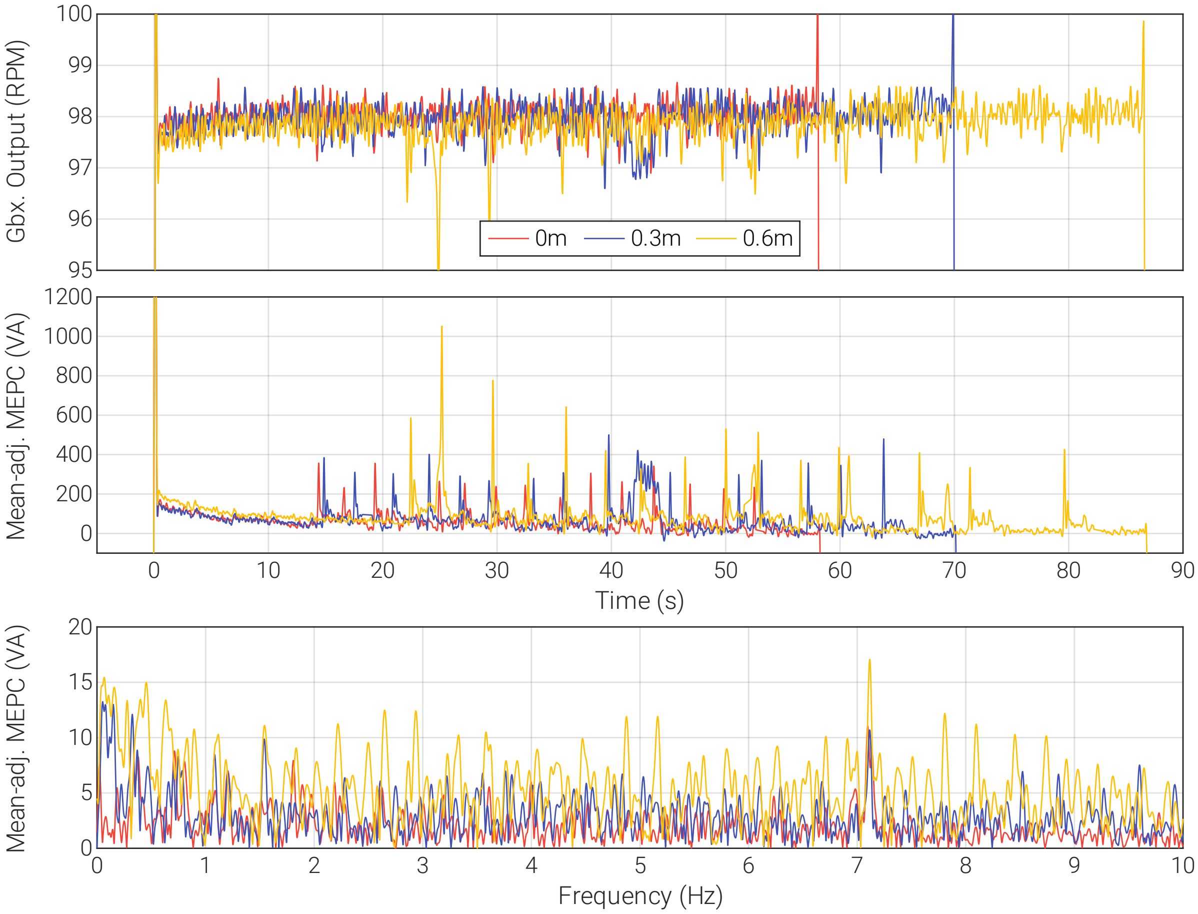

Figure 9.18: CCT.D Loading Height time and frequency domain characterisation data – 30kg (x15) masses loaded.

The potential energy associated with a mass before release is a function of its height from the ground, therefore, once released the kinetic energy (and thus velocity in a vertical direction) it generates will be directly affected by its release height. A greater velocity will result in a mass having greater momentum, so, when the mass comes into contact with the belt it will apply a greater force to the belt, resulting in an increased compression force between the belt and its supporting members (i.e. support structure and rollers), and thus a transient increase in Coulomb friction.

This increase in friction will be felt by the drive motor as an increased torsional load, hence inducing an increased power draw. The deflection in the belt may also cause a transient increase in dragging, further loading the drive motor. Both of these mechanisms act to decelerate the belt for a period, until the motor is able to accelerate back up to nominal operating speed, as demonstrated in the characteristics of the gearbox output speed shown within Figure 9.18. Accordingly, in contrast to CCT.C test scenarios, the average magnitude of spikes induced by loaded masses during CCT.D tests does increase as the test variable, loading height, is increased (Figure 9.19).

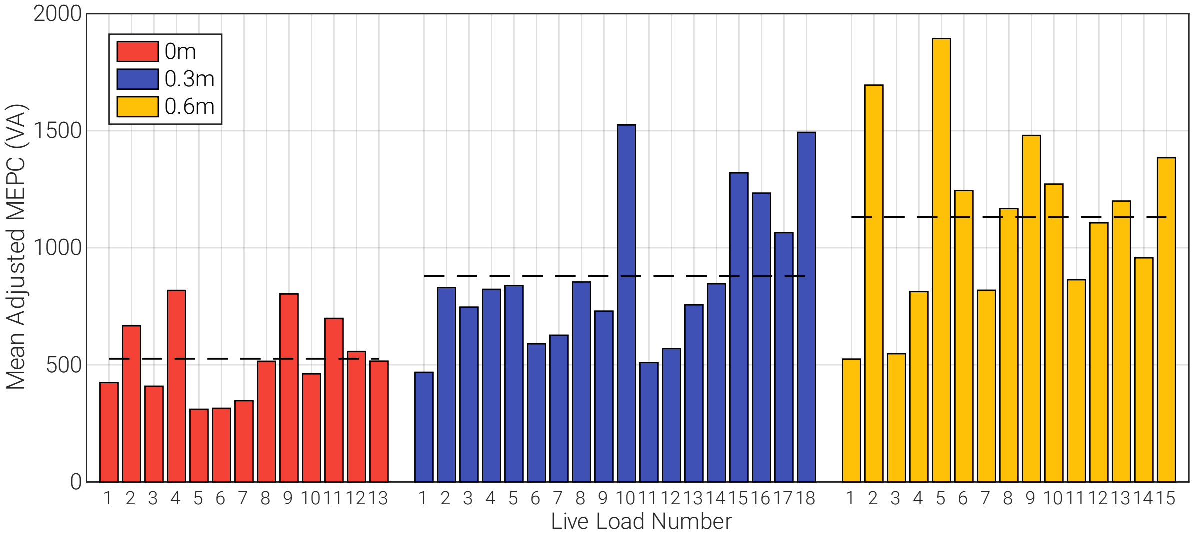

Figure 9.19: Comparison of mean spike magnitude induced in response to application of 30kg masses, as a function of loading height.

Significant variance in the magnitude of each spike induced around the mean can also be observed at each drop height (Figure 9.19); As with CCT.C scenarios this observation is likely a consequence of the experimental procedure implemented.

Frequency-domain data from CCT.D tests indicate that as loading height is increased, an increase in the magnitude of broadband noise throughout the power spectrum is induced, which result in the analytical system frequencies previously identified being concealed (Figure 9.18). Such behaviour is likely caused by the physical impact of live loads exciting various vibratory modes within the System's support structure, the magnitude of which increases as the loading height is increased.

9.1.5 CCT.E Belt Tension

Summary:

- *An increase in the longitudinal tension of the belt induces a corresponding increase in mean MEPC when idling.*
- *Analytical frequencies modulated as a result of longitudinal deformation of the belt.*

CCT.E scenarios involved modulating the longitudinal tension of the belt, to both increase and decrease the tension. Within the System the tension within the belt is altered by adjusting the centre distance of the head and tail pulleys, via a near and farside tensioning screw, both located at the tail end of the System.

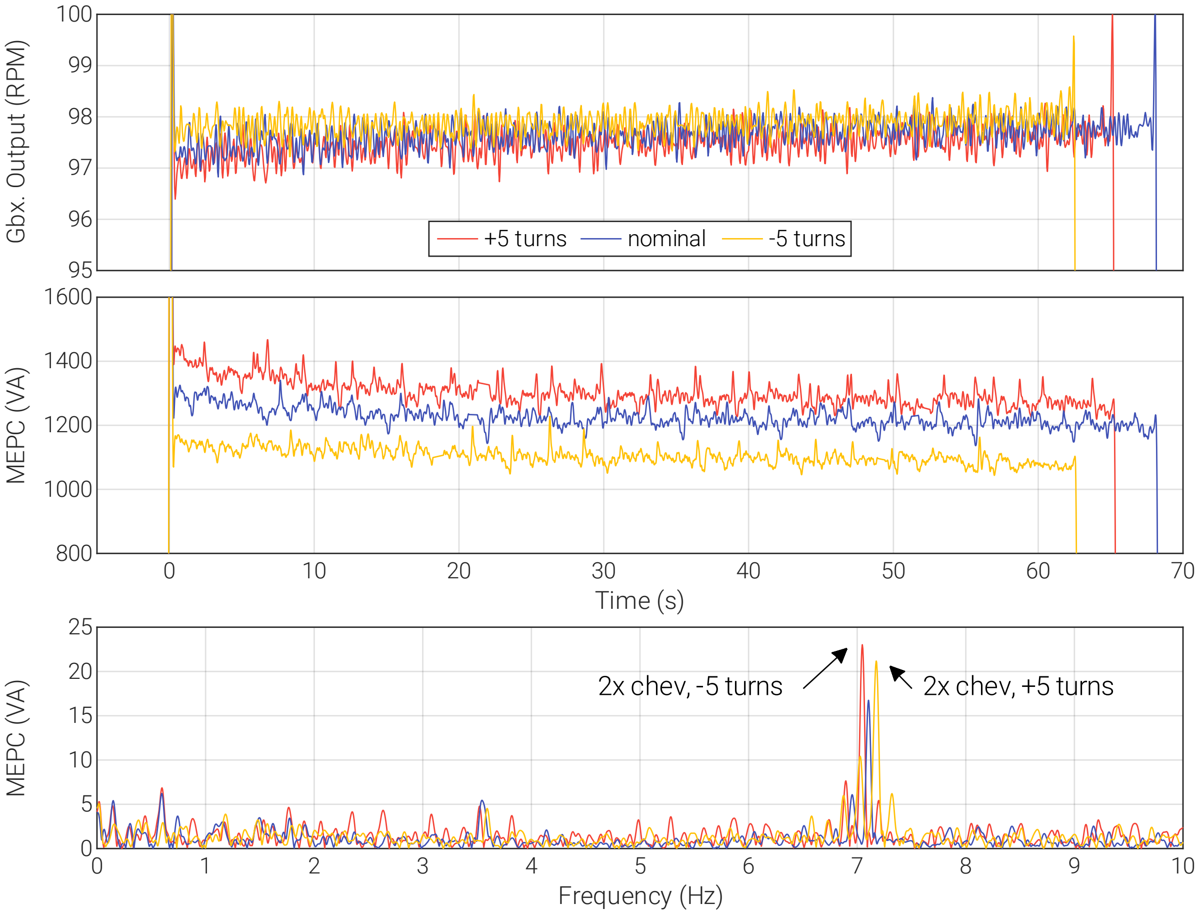

Figure 9.20: CCT.E Belt Tension variation time and frequency domain characterisation data – 30kg (x15) masses loaded.

From Figure 9.20 the effect of changes in belt tension on idling power consumption can be observed, with consumption increasing as tension is increased, and decreasing as tension is decreased, varying by ~100VA in each direction from nominal idling consumption.

By increasing the centre distance of the pulleys, the total distance that the belt must travel to complete a revolution of the system is increased, and thus the belt must deform along its length to account for this. Due to the properties of the belting material, this deformation is predominantly elastic, so as it lengthens it applies a compressive force between the two pulleys, which in turn results in the gearbox output shaft experiencing a radial load[47]. The presence of this load on the gearbox output shaft causes an increase in frictional losses within the gearbox, due to the increases contact pressure between mating surfaces, which the drive motor feels as an increased torsional load, and hence idling power consumption is increased. This loss mechanism could be validated by observing the temperature of the gearbox; the energy associated with these additional losses will primarily manifest as thermal energy[48] as a result of the increased friction.

The change in belt length can be observed within the frequency-domain spectrum of the motor power consumption, where the exact frequency of the chevron passing fundamental and first harmonic alters in response to changes in belt tension (Figure 9.20). When tension is either increased or decreased by 5 turns the specific frequency of the first harmonic of the chevron passing frequency is modulated by ~0.05Hz (20ms) in either direction from its nominal frequency of ~7.1Hz. This behaviour reflects the slight change in chevron spacing caused by the elastic deformation of the belt. When tension is increased the spacing of chevrons increases and so the frequency at which they pass is correspondingly decreased, due to the fixed speed operation of the drive system.

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[47] Such loading is commonly referred to as an overhung load.

[48] Thermal losses are likely to be the dominant loss mechanism, however there will be additional losses incurred, such as acoustic and mechanical vibration [213].

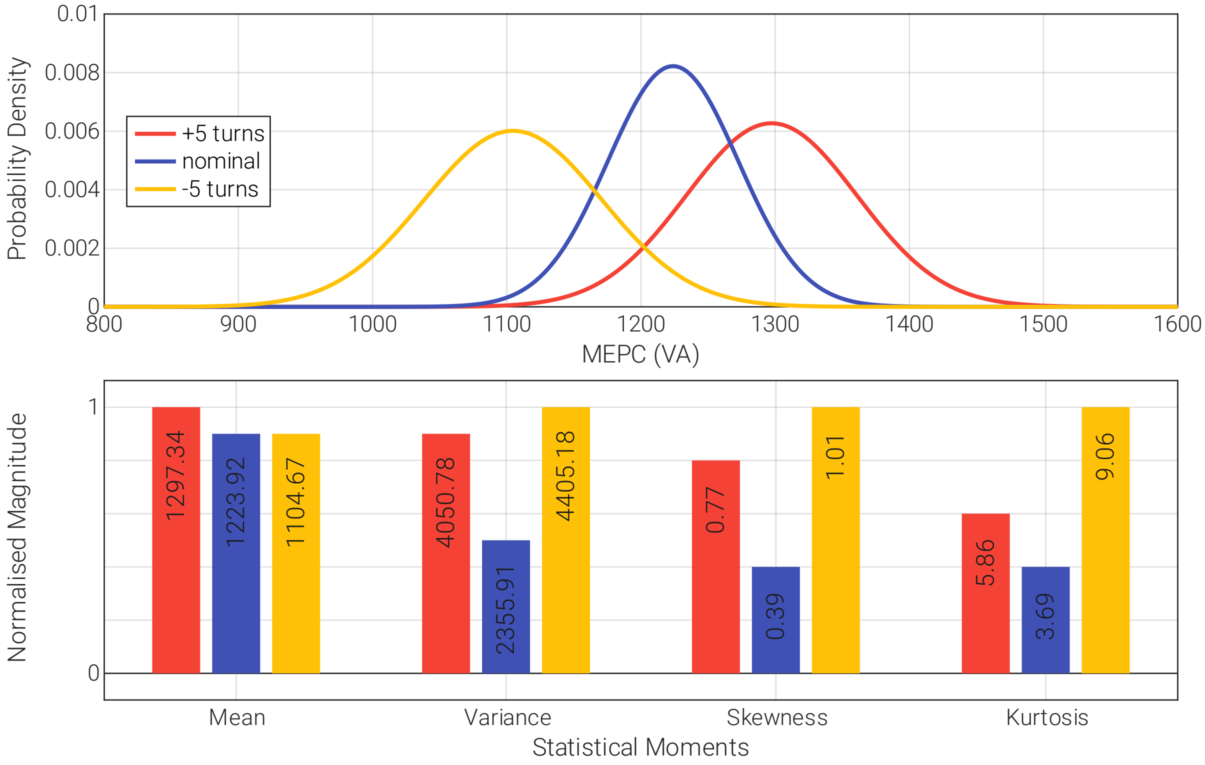

Figure 9.21: CCT.E Belt Tension characterisation data statistical moments.

Whilst idling power consumption can be seen to change in response to the applied belt tension, the associated statistical moments are relatively unaffected (Figure 9.21), suggesting that the relative magnitude of the belt tension can be directly inferred from the idling power consumption alone.

Similarly, the power factor of the drive motor remains broadly constant as the tension in the belt varies (Figure 9.22), suggesting that the variation in MEPC during idling as the tension in the belt is change reflects primarily a change in active power consumption.

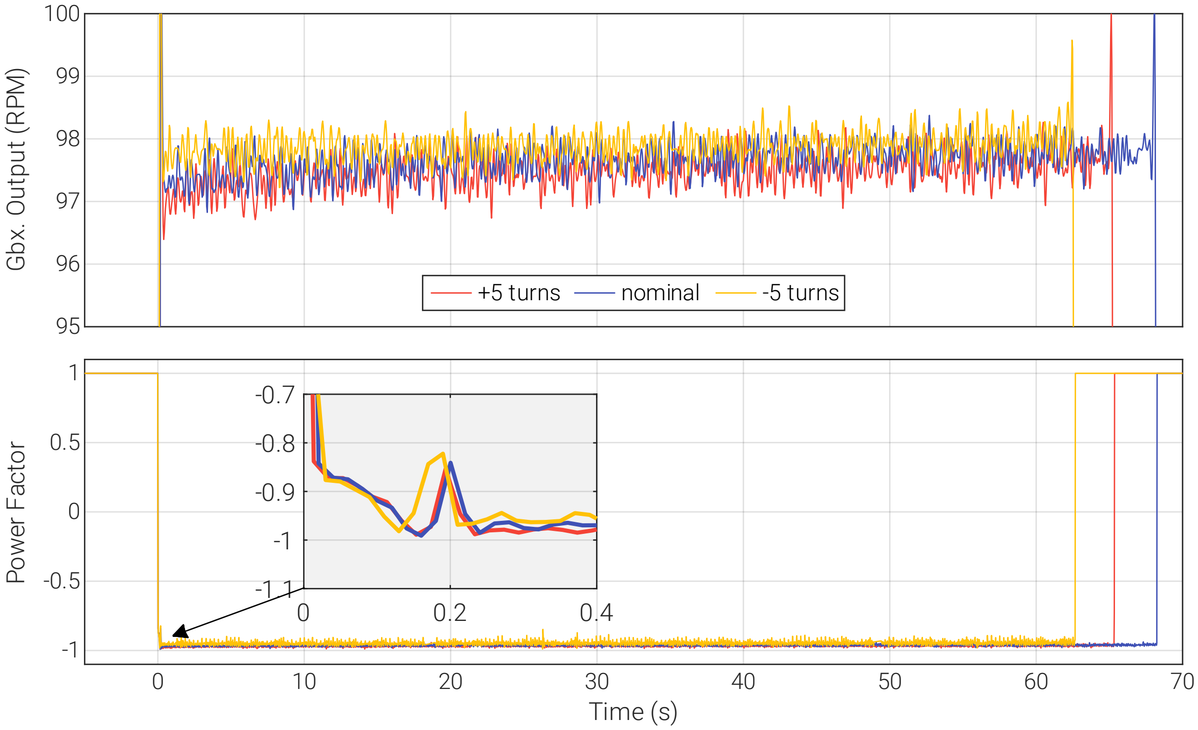

Figure 9.22: Power factor fluctuations throughout CCT.E extrema test scenarios.

9.1.6 CCT.F Belt Tracking

Summary:

- *MEPC whilst Idling is increased with the belt tracking hard-over.*
- *Periodic components are induced as a result of contact between the belt and System support structure.*

During CCT.F the lateral tracking of the belt was adjusted such that it did not track centrally across the width of the belt, but instead was hard-over to one side. Within the System the tracking of the belt is controlled via the manipulation of the two tensioning screws located at the tail end of the System, as seen in Figure 8.1. By adjusting these in opposite directions the belt can be driven such that it tracks consistently to one side of the central line, as shown in Figure 9.23. When the belt is tracking hard over to one side mechanical drag is induced where the belt contacts with the support structure, primarily at the tail end of the system.

Figure 9.23: Belt tracking centred (l) and off-centred (r) at the head end of the System during CCT.F test scenarios.

This scenario can be considered the most extreme case of off-centred tracking possible, and, whilst it would be expected to rarely occur in a system operating under supervision, for an unsupervised system such a condition could feasibly develop and remain uncorrected for a significant period of operation.

Additional mechanical drag is experienced by the motor as an increase in torsional load, reflecting the energy required to overcome the increase sliding friction within the System. As presented in Figure 9.24, both a reduction in gearbox output speed and increase in MEPC can be observed for an off-centre belt compared to a true tracking belt.

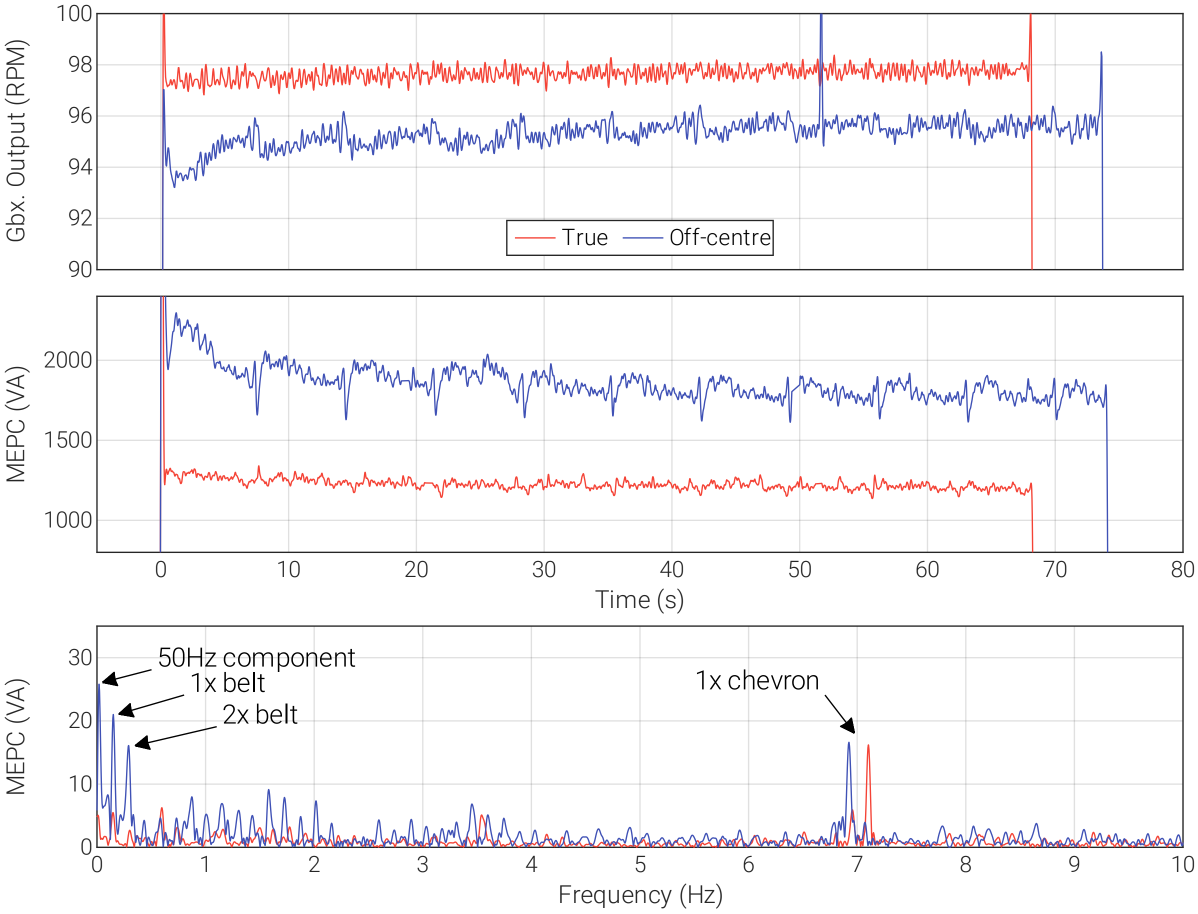

Figure 9.24: CCT.F Belt Tracking time and frequency domain characterisation data – 10kg (x20) masses loaded.

In additional to an overall increase in MEPC when idling, the presence of a clear, low frequency periodic component can be observed. When the time-domain data is transformed to the frequency-domain this periodic behaviour can be seen to have a fundamental frequency of ~0.15Hz, which is associated with the rotational period of the belt. This periodicity therefore likely reflects the motion of the belt being restricted at specific points around its cycle, where it comes into contact with the support structure.

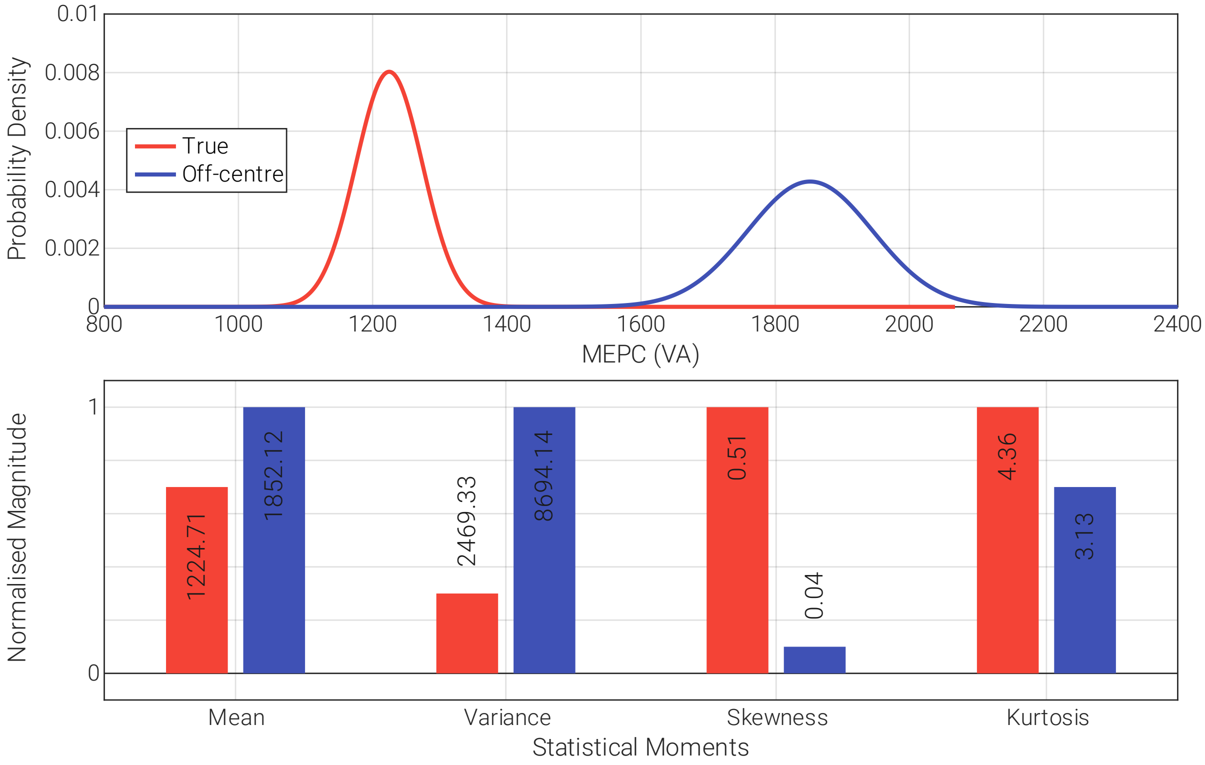

Figure 9.25: CCT.F Belt Tracking characterisation data statistical moments.

The statistical moments associated with CCT.F test scenarios show an increase in mean and variance as the belt tracks off-centre, reflecting the presence of the induced belt frequency components, as well as a reduction in both skewness and kurtosis.

9.1.7 CCT.G Belt Slip

Summary:

- *Water and oil introduced to underside of belt surface to induce slip between the drive pulley and belt.*
- *Presence of water found to have minimal impact upon operation of the System.*
- *Presence of oil induced small degree of slip and resulted in a slight reduction in idling consumption.*

CCT.G test scenarios sought to assess the sensitivity of monitored system parameters to the presence of relative motion (i.e. slip) between the System's belt and drive pulley. The occurrence of slip between a belt and pulley can cause catastrophic damage to either or even both components, and as such, many industrial systems employ dedicated equipment to detect the occurrence of such slippage during CBS operation [15]. However, this not only adds cost to a system but complexity too, therefore, the potential for detecting the occurrence of slippage via MEPC measurements was of particular interest to the Manufacturer. Within the System all power to the belt is transferred from the gearbox output shaft to the belt via the head roller pulley, where rubber-to-rubber contact is made. The degree to which power can be transferred from the pulley to the belt is a function of the friction between the two surfaces, in line with:

$$F_{max} = \mu_s F_n \tag{9.6}$$

Where F_{max} is the maximum frictional force, μ_s is a coefficient of static friction and F_n is the normal force between mating surfaces.

The normal force is a function of the longitudinal tension in the belt, as defined by the centre distance of the two pulleys. If this is assumed constant, then the proportion of power which can be transferred from the gearbox output shaft to the belt is dictated only by the coefficient of friction between the two surfaces.

If $\mu_s = 1$ (i.e. zero slip) then there is no relative motion between the two surfaces and thus no power loss. If $\mu_s = 0$ (i.e. zero force) then no power is able to be transferred from the pulley to the belt, and thus the belt will remain stationary. Therefore, by affecting the coefficient of friction between the surfaces, the degree of slip can be varied. Within CCT.G test scenarios this was achieved by introducing lubricating liquids to the underside of the belt surface, via an access hole within the support structure.

Two lubricating liquids were used; water and a generic vegetable oil, a proxy for a typical lubricant that might be used on sliding surfaces within a rotating machine. The operation of partially submerged CBSs was reported by the Manufacturer, as well as contamination of belt surfaces by lubricating fluids such as gearbox oil, therefore, whilst severe in nature, the conditions implemented during test scenarios represent potential industrial conditions.

From Figure 9.26 it can be seen that the presence of water on the underside of the belt had negligible effect on the degree of slip between the belt and head pulley, whereas the presence of oil induced a ~0.03ms^{-1} differential between the speed of each.

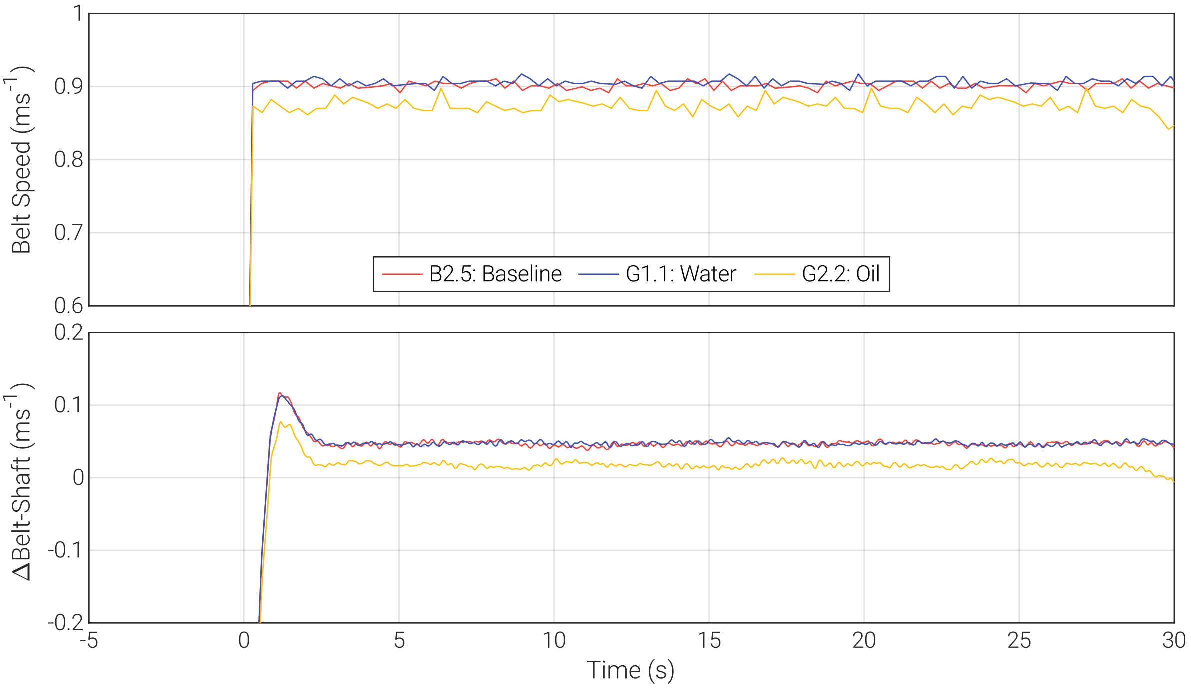

Figure 9.26: Speed differential between gearbox output shaft and belt surface measured during CCT.G test scenarios.

However, the effect of this differential on the power consumption of the drive motor is minimal, with a reduction in consumption of ~30VA for water and ~70VA for oil (Figure 9.27).

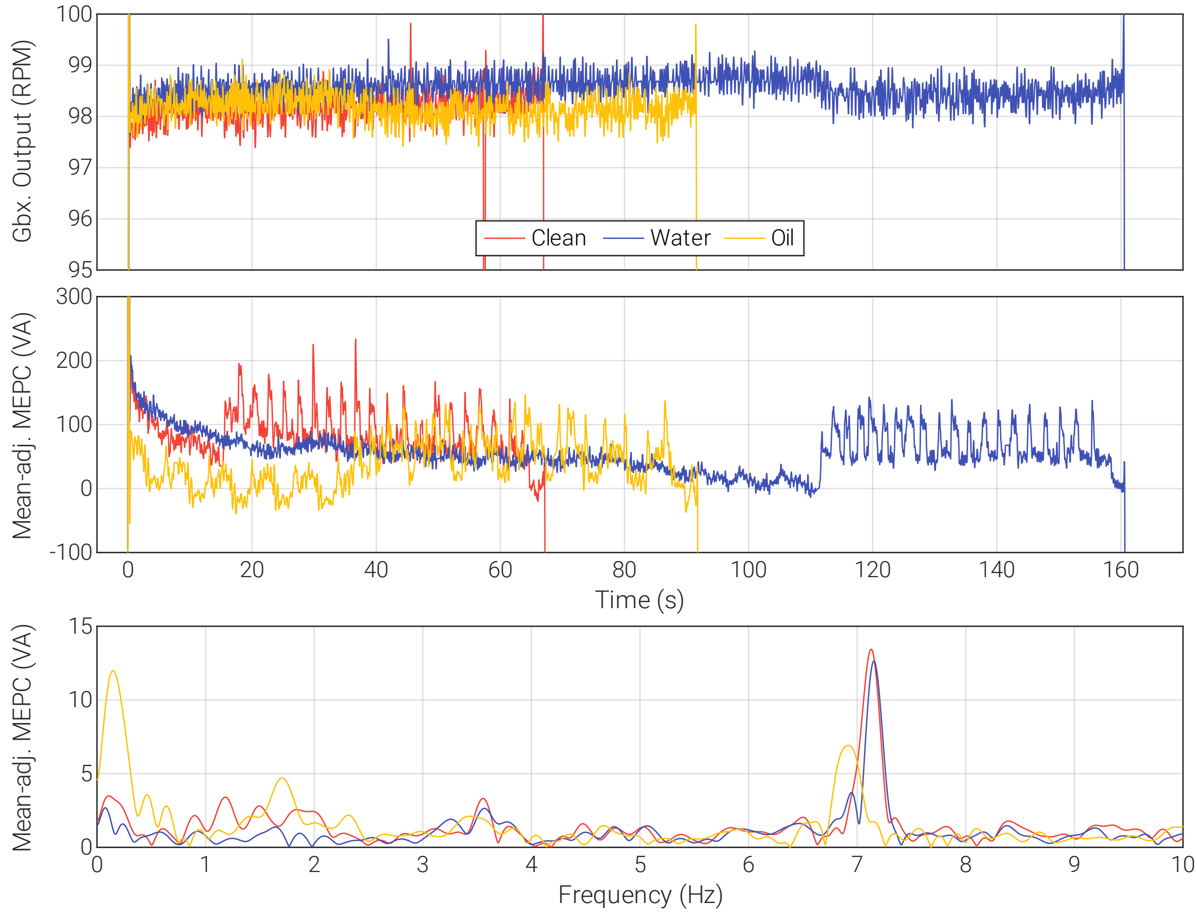

Figure 9.27: CCT.G Belt Slip time and frequency domain characterisation data – 10kg (x20) masses loaded.

Similarly, little impact upon the frequency content of the time-domain data can be seen, with each test scenario showing similar spectra. A reduction in the magnitude of the belt chevron frequency component (~7Hz) can be observed, possibly a result of the lubricating effect of the oil, reducing friction between the support rollers on the return side of the system and the belt chevrons.

The seeded introduction of such a quantity of lubricating oil directly onto the underside of a belt can be considered the most severe slippage conditions feasible to occur within a system, yet the resulting response upon system operation can be seen to be minimal. Accordingly, it can be concluded that the risk of belt slippage impacting upon normal operation of a system can be considered to be minimal.

9.1.8 CCT.H Belt Damage

Summary:

- *Slit seeded across width of belt and manually progressed up to* 400*mm maximum.*
- *Quasi-sinusoidal signature induced in time series data, with amplitude related to slit width.*
- *Period of signature consistent with belt frequency.*
- *Duration of start-up spike reduced with increasing damage severity.*

The most severe fault feasibly encounter by a CBS is the loss of its belt. Such an occurrence will render the entire system inoperable and will typically require significant time and personnel resource to rectify. There are two possible ways in which a system's belt can be lost; either the belt can track off the pulleys or the belt can be severed across its width.

To investigate the effect of the second of these scenarios on monitored system parameters the CCT.H test scenarios involved artificially damaging the belt by manually creating a slit across its width. Damage to a belt can manifest in a number of forms, such as discrete holes, lateral slits at the centre or edge, or longitudinal slits, which can effectively turn one belt into two. Furthermore, damage can be caused by a number of mechanisms, including the action of a foreign body (either directly slicing a belt or through being trapped between the belt and a pulley, for example), the failure of a mechanical splice or due to contact between the belt and the support structure. Within literature few reliable reports describing the mechanisms of belt-related failure and their propensity across applications exists[49]. In lieu of such resources and through discussions with the Manufacturer it was decided that belt damage would be seeded by initiating a single slit laterally across the width of the belt, starting at one edge. Such damage was reported as being particularly common on belts connected using a mechanical splice, where failure of the splice at one edge can propagate across the entire width of a belt until total failure. Alternatively, the action of conveyed material (typically in the case of hard rock) trapped between the belt and the side supporting structure causing such a slice was also reported by the Manufacturer as being a common failure mechanism.

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[49] There exists some literature in which rates of belt-related failures are presented, however, such literature overwhelmingly fails to report the specific mechanism of each failure (e.g. [228]).

Figure 9.28: The progression of seeded belt damage. Clockwise from top left: 10cm, 20cm, 30cm, 40cm.

As a result of its composite structure the belting material demonstrated very good fracture toughness. Therefore, to permit timely completion of test scenarios it was required that the slit, once initially seeded in the belt, be manually progressed across the width of the belt, as opposed to it progressing unassisted. Between each test scenario the slit was incremented in width by 10mm, up to a maximum of 400mm (~90% of the total width), and then run unloaded for ~60s (Figure 9.28).

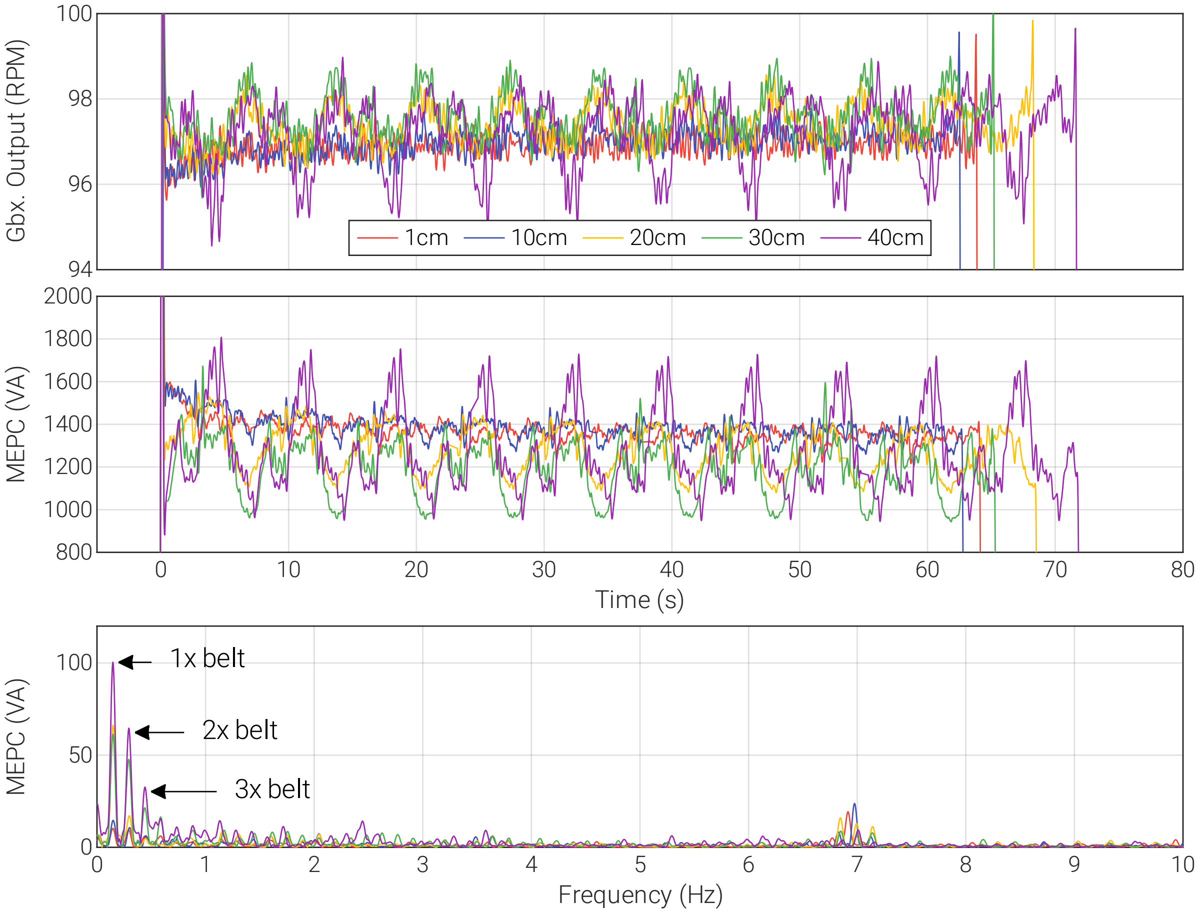

Figure 9.29: CCT.H Belt Slit time and frequency domain characterisation data.

The introduction of a slit into the belt can be seen to produce a quasi-sinusoidal fluctuating component within the overall motor power consumption (Figure 9.29), with an apparently constant period. When the frequency content of the data is analysed the period of these fluctuations can be seen to be consistent with the belt fundamental frequency and its harmonics, with significant peaks present at 1x (~0.15Hz/~6.6s), 2x (~0.3Hz/~3.33s) and 3x (~0.45Hz/~2.22s). The amplitude of each of these can also be seen to increase as the width of the slit increases, to a maximum of around 100VA at the belt fundamental with a 40cm slit present, approximately 5x greater than the amplitude of the chevron frequency component. Such behaviour is reflected in the statistical moments associated with each level of damage severity, particularly the variance, which can be seen to increase directly in response to increasing severity (Figure 9.30).

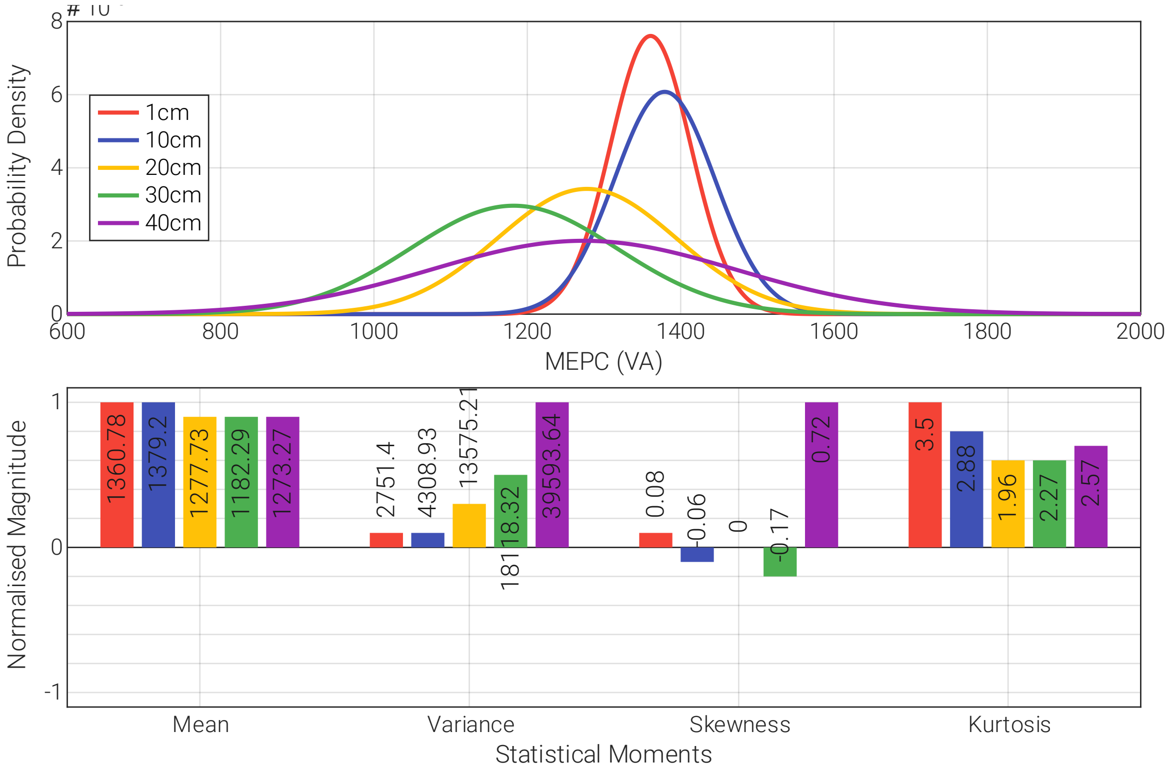

Figure 9.30: CCT.H Statistical moments of seeded belt damage characterisation data.

A possible explanation for this behaviour is that it is a result of the failed portion of the belt width folding (either backwards or under itself) and/or catching on elements of the support structure, such as the return rollers and hopper unit, as shown in Figure 9.31.

Figure 9.31: Examples of loose belt material folding backwards (l) and under itself (r) as a result of seeded lateral damage.

This action causes an increase in mechanical drag, which causes the belt to decelerate and increases the torque load on the drive motor. In response to this the drive motor consumes more power in order to overcome the drag, and thus maintain the speed of the belt. Once the belt has been accelerated and thus returned to nominal operating speed, the power consumed by the motor falls, resulting in the quasi-sinusoidal response seen in Figure 9.29.

Alternatively, such observation may be a result of a localised reduction in the longitudinal stiffness of the belt at the location of the damage. As the belt is driven by the motor it is forced to bend around both the head and tail pulleys. At the location of the slit the effective width of the belt is reduced, and thus less force is required to drive the belt over the pulley and thus less electrical power is consumed.

To more closely examine the characteristics of the observed periodic fluctuation the time-synchronous average (TSA) of each scenario's time-domain signal can be computed. The TSA of a periodic signal is computed by first splitting the continuous time series data into a series of segments where each segment corresponds to one period of the signal[50]. Then the element-wise average of all segments is computed to produce a single period signal, the amplitude of which is the mean of all segments at each point, as illustrated in Figure 9.32.

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[50] Typically, this is based upon the output of a once-per-rev tachometer signal – for CCT data, given the number of magnets on the gearbox speed sensor wheel and the approx. belt length are known, each belt rotation can be inferred from the binary output of the gearbox Hall effect sensor.

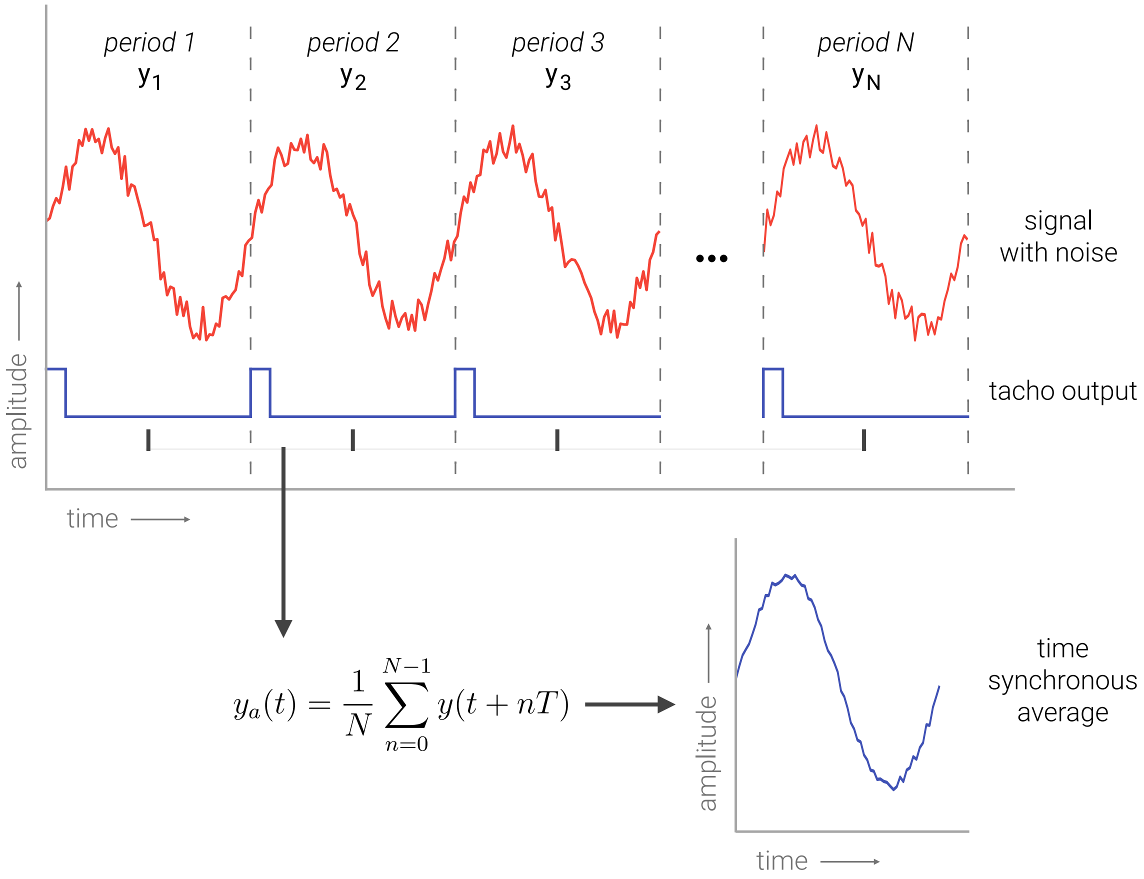

Figure 9.32: Graphical illustration of the time synchronous averaging (TSA) procedure.

Formally, this operation is defined as:

$$y_a(t) = \frac{1}{N}\sum_{n=0}^{N-1} y\left(t + nT\right) \qquad 9.7$$

Which essentially corresponds to a convolution of the original time-domain signal $y_a(t)$ with a pulsetrain of N delta functions displaced by integer multiples of the signal's periodic time T [135]. Through computation of the TSA the influence of background noise within a signal can be reduced, and the periodic fluctuation within a signal can be viewed as a function of its cyclic position.

When the TSA is computed for each belt slit scenario the presence of two distinct peaks in power consumption over each belt cycle are apparent, particularly within the 40cm scenario (Figure 9.33), further supporting the theory that the belt becomes restricted at specific points in its rotation.

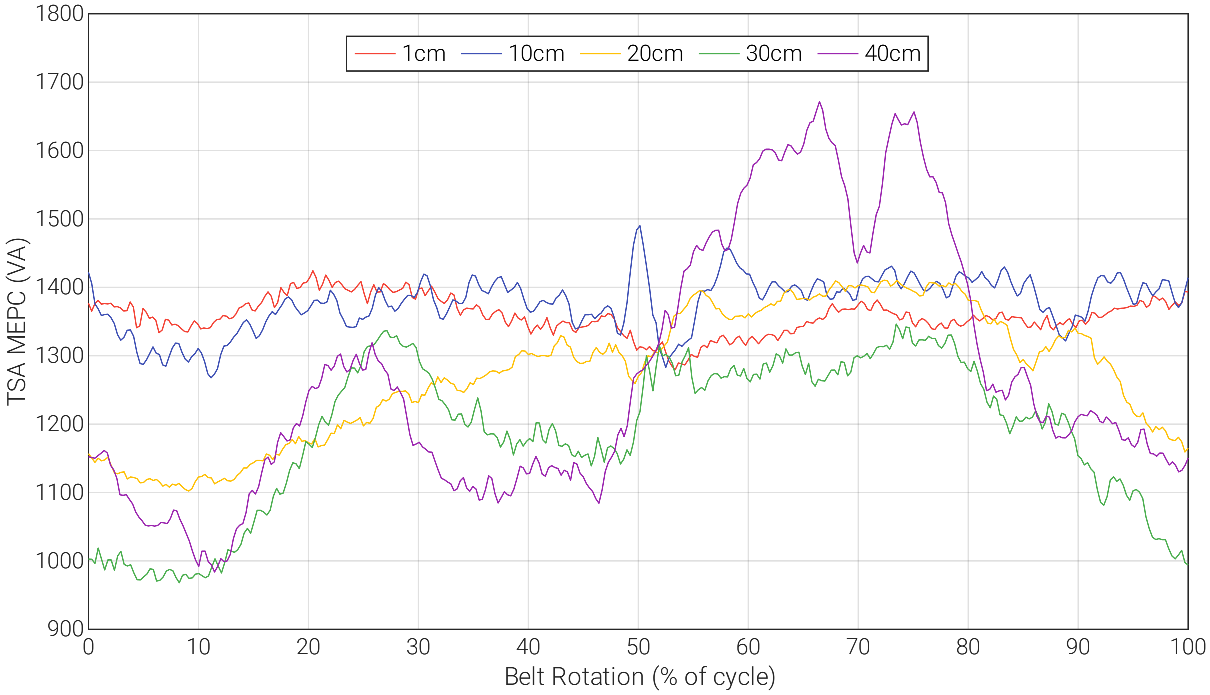

Figure 9.33: Time synchronous average computed at each magnitude of belt damage.

The presence of damage within the belt can be observed to result in a marginal reduction in the start-up transient duration, with the start-up transient associated with an intact belt lasting ~30ms longer than that associated with a 40cm slit damaged belt (Figure 9.34).

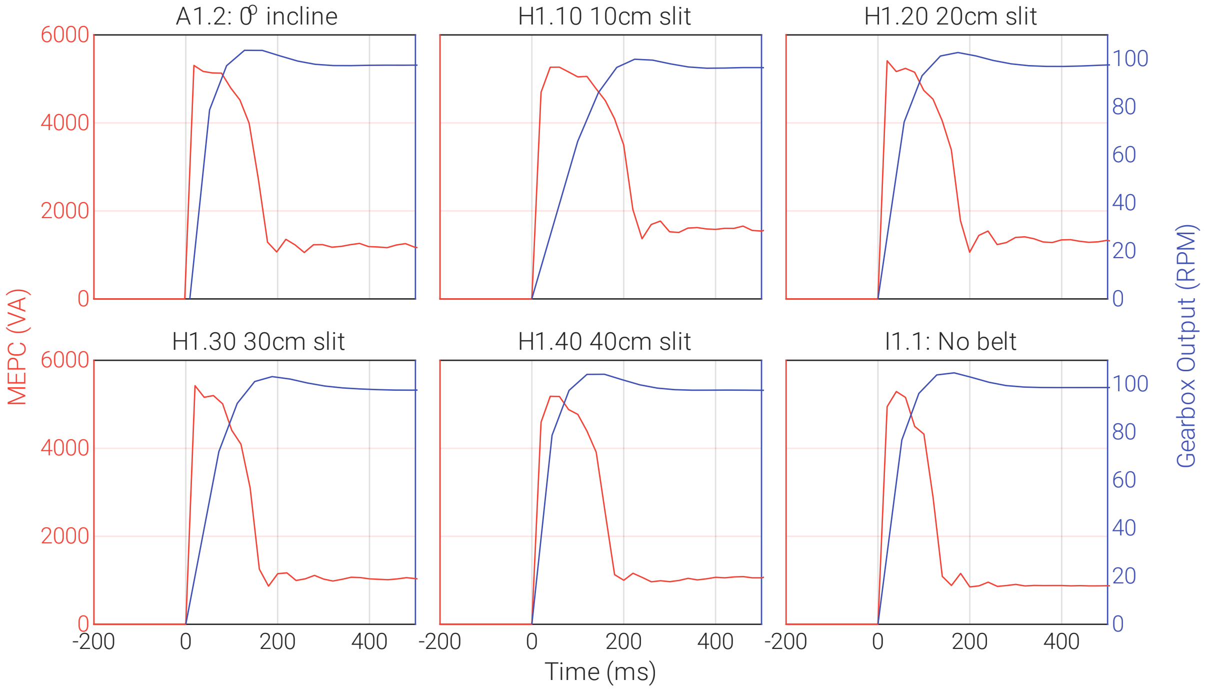

Figure 9.34: Comparison of start-up transient characteristics as the severity of belt damage is increased.

However, as only a single test was conducted at each slit width the magnitude of variance in start-up transient duration across multiple runs of the same test cannot be assessed, and it may be that the variance observed is purely random in nature.

9.1.9 CCT.I Belt Absence

Summary:

- *Removal of belt from system causes reduction in idling MEPC.*
- *Magnitude of start-up spike unaffected but duration reduced.*
- *Steady-state reduction in motor power factor.*

The final test conducted, CCT.I, involved operating the System without a belt present, to characterise such operation. As discussed in Section 0, feasibly a system can run its belt off completely if good tracking is not maintained and appropriate corrective action is not taken.

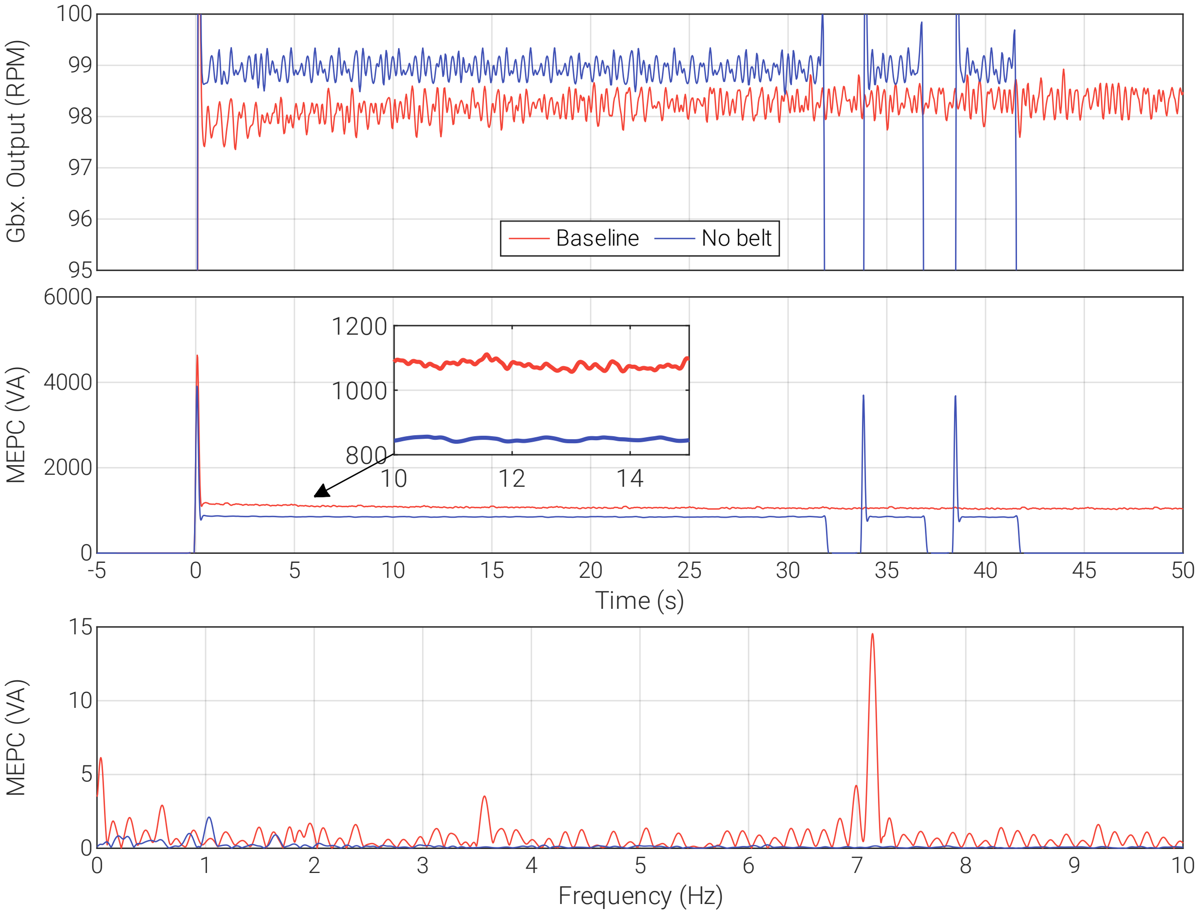

Figure 9.35: CCT.I Belt Absence time and frequency domain characterisation data.

When operating the system with no belt present a clear reduction in idling power of ~240VA can be observed compared to a healthy idling system (Figure 9.35). As with CCT.H, such behaviour is likely a result of reduced mechanical load on the drive motor due to the presence of damage within the belt structure. This effect is increased with no belt present, as the system is no longer having to drive the tail pulley at all.

Additionally, the time-domain data shown in Figure 9.35 shows a significant reduction in noise compared to previous test scenarios. This observation is also reflected in the frequency content of the data, where the spectrum shows minimal broadband noise, as well as the absence of significant peaks at the belt and chevron analytical frequencies, as previously observed.

During the execution of the CCT.I test scenario the system was power cycled a number of times in order for the characteristics of a beltless system's start-up transient to be observed. When compared to baseline idling test scenarios a beltless system start-up transient can be seen to be of a similar magnitude, around 5200VA (Figure 9.36).

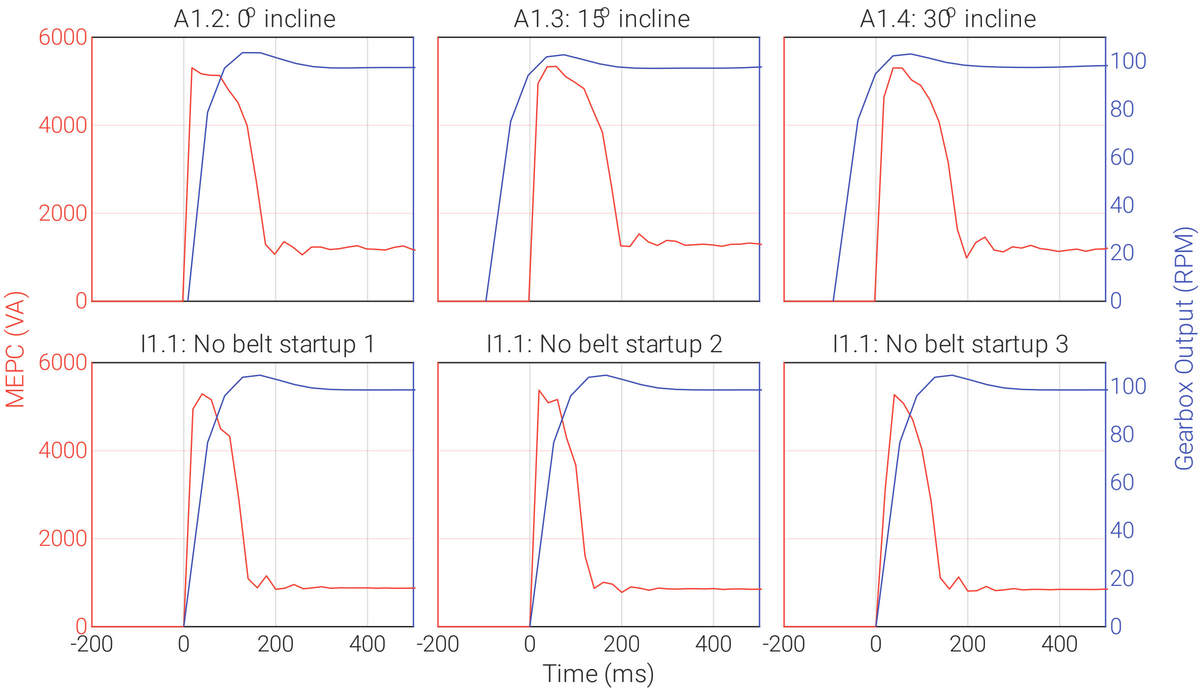

Figure 9.36: Comparison of start-up transient characteristics with a belt installed and without.

However, the duration of the transient can be seen to reduce slightly across all three beltless start-ups, where it lasts for ~150ms compared to ~190ms for a healthy system. This is again likely a result of the system no longer having to accelerate both the belt and the tail pulley, without which system inertia is lowered, and thus greater acceleration can be achieved.

The power factor during beltless system idling is reduced when compared to a belted system, with a value of around -0.98 seen, compared to -0.94 previously (Figure 9.37). As previously stated, this behaviour is a reflection of the reduced mechanical load on the system; with a reduced torque load on the drive motor present, the degree of slip created within the motor is reduced, the counter EMF generated by the motor is reduced and thus the power factor remains closer to unity.

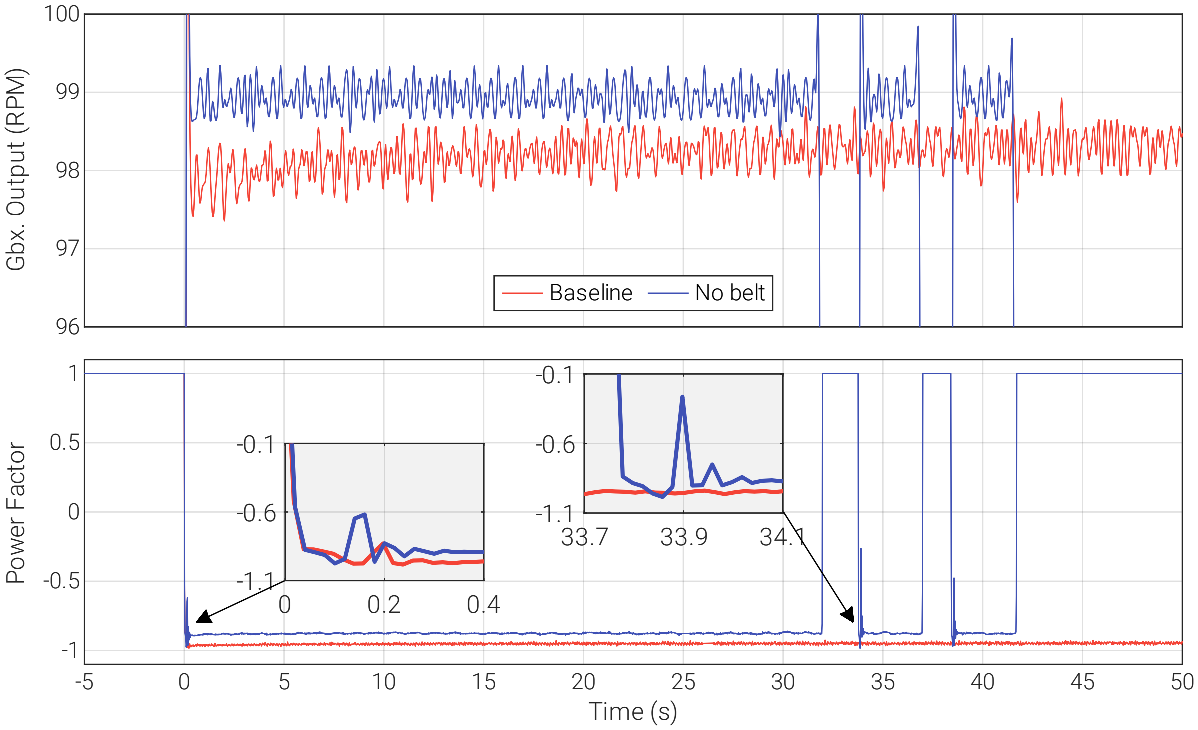

Figure 9.37: Power factor fluctuations throughout CCT.I test scenario start-ups.

When the power factor during a beltless start-up is considered, some oscillation before a steady-state level is reached can be observed (Figure 9.37), however, this behaviour appears to be present in both healthy and damaged belt systems, as indicated in Figure 9.2. Given the change in mechanical load induced by the removal of the belt an increase in the magnitude and/or duration of these oscillations could be expected; the presence of the belt and tail pulley introduce increased inertia into the system, which is likely to have a damping effect on the system dynamics, thus potentially reducing such oscillations. The lack of evidence of such behaviour during CCT.I may be a result of the small sample size or limitations of the data acquisition system, or, alternatively, expectations of such behaviour may be invalid.

9.2 Summary of Findings

Based upon the conducted test scenarios, a number of key findings can be drawn, relating to the response of monitored parameters to the conditions imposed by each scenario. These are summarised in Table 9.1.

Table 9.1: Summary of key findings from the CCT test scenarios conducted.

Test Group ID	Test Type	Test Scenario	Observations
CCT.A	Usage	Idling baseline	- A transient peak ~5x idling MEPC observed at every start-up, ~100-200ms in duration. - No obvious long-term temperature effects present. - Components associated with belt (~0.15Hz) and chevron (~3.5Hz) passing frequencies clearly identifiable within frequency spectrum of MEPC.
CCT.B	Usage	Varying product composition	- The action of loading a mass onto the surface of the belt induces a transient increase in MEPC (spike), the magnitude of which is a function of the quantity of mass loaded. - Such spikes range from ~50VA (5kg) to ~500VA (30kg) in magnitude but all are ~0.08s in duration. - While a mass is being conveyed along the length of the belt MEPC is increased compared to when idling. - Discrete masses can be discerned even when loaded at a frequency of 1 second.
CCT.C	Usage	Varying angles of incline	- Changing the System's angle of inclination does not appear to affect the magnitude of mass-induced spikes. - MEPC whilst conveying a mass increases by ~150VA as the System's angle of inclination is increased to 30°.
CCT.D	Usage	Varying loading heights	- Spikes induced by loaded increase in magnitude as loading height increases, to a maximum of ~1500VA in response to 30kg dropped from 3m. - Broadband noise is within MEPC as mass loading height is increased, masking previously identifiable analytical frequencies associated with the belt.
CCT.E	Usage	Varying magnitudes of belt tension	- Increasing the tension in the belt by 5 turns causes an increase in idling MEPC of ~100VA. - The analytic frequencies associated with the belt are modulated accordingly to reflect the change in belt length.
CCT.F	Fault	Non-centrally tracking belt	- With a belt tracking 'hard over' to one side idling MEPC is increased. - Some fluctuation in MEPC occurs throughout the belt's rotation as a result of mechanical drag caused by the belt catching the support structure at certain points.

CCT.G	Fault	Induced pulley-belt slip	- The presence of water on the underside of the belt has a negligible effect on MEPC and belt speed. - The presence of oil induces a measurable degree of slip between the head pulley and belt, resulting in a reduction in idling MEPC.
CCT.H	Fault	Seeded belt damage	- Damage seeded across the width of the belt induces a periodic fluctuation in MEPC when idling, in accordance with the rotation of the belt. - The amplitude of this fluctuation increases as the severity of the damage seeded is increased to a maximum of ~800VA peak-to-peak at 40cm.
CCT.I	Fault	Loss of belt	- When the belt was absent idling MEPC reduced by ~20%. - The magnitude of the start-up of transient was unaffected but the duration reduced by ~0.1s.

9.3 Discussion

Given the characteristics of monitored parameters as observed during CCTs an assessment of the potential operational insight obtainable through the interrogation of motor electrical power consumption parameters is now presented. In particular, the observability of four specific aspects of CBS operation are considered: start-up events, idling operation, the effect of live load and changes in belt conditions.

9.3.1 Start-up Events

In response to each start-up of the System from standstill a transient increase in MEPC was observed, the magnitude of which is approximately 5x greater than the subsequent consumption once idling. This transient is termed *inrush current* and, in the case of an induction motor, represents two effects; Firstly, upon start-up a quantity of energy is required to setup and be stored in the magnetic field within the stator-rotor airgap. Secondly, at zero rotor speed (i.e. standstill) slip is at a maximum, therefore, maximum counter EMF is induced and thus the apparent resistance of the stator winding is low. Accordingly, at this point high current is permitted to flow within the stator winding, termed the *locked rotor current* (Figure 9.38). As the rotor speeds up slip reduces accordingly and thus the current drawn by the motor reduces quickly, until a steady-state operating point is reached and current draw remains constant.

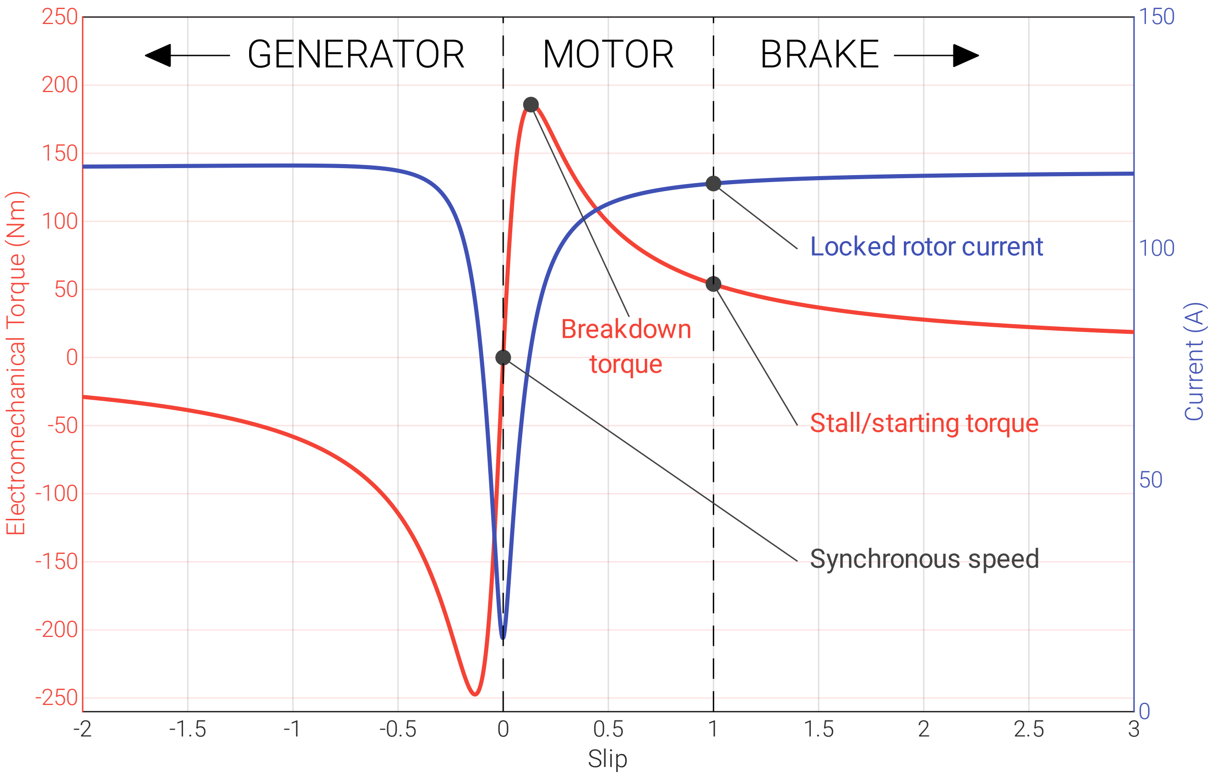

Figure 9.38: Torque and current draw characteristics of a typical induction machine across its operating speed.

It should be noted that the presence of such transient characteristics at start-up are likely a facet of the direct-on-line mode of starting. To limit the current drawn by an induction motor during start-up it is common for some form of 'soft start' device to be used to reduce heating effects within the motor and, particularly in the case of larger motors (>10kW) to reduce the impact upon the supply line as the motor is connected onto it. Accordingly, the characteristic spike in consumption observed during each CCT scenario cannot necessarily be assumed to occur in all applications.

Whilst a start-up transient in MEPC was observed across all test scenarios, the exact magnitude of each transient's peak presented a significant degree of variation, with a range of ~1400VA from the largest to smallest (±7% about the mean) (Figure 9.39).

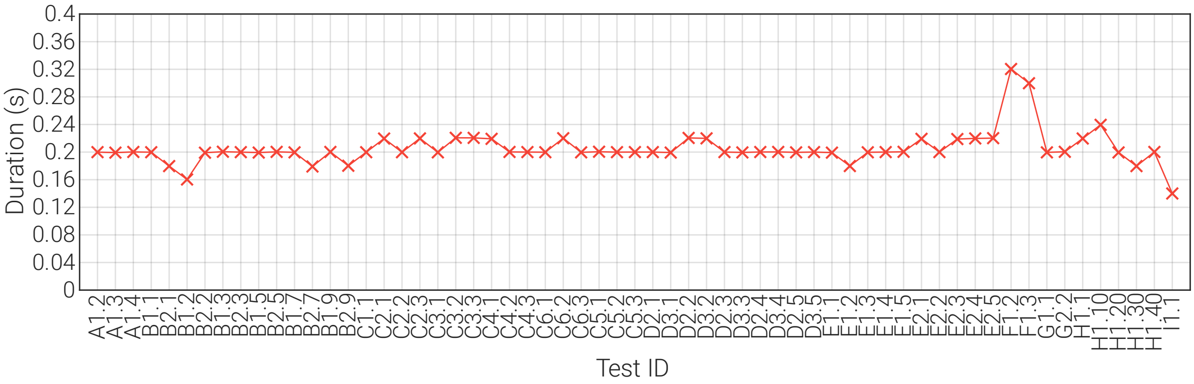

Figure 9.39: Approximate duration of each start-up transient across all CCT scenarios.

However, no obvious correlation between the magnitude of each transient and the state of the System was identified, and instead it is likely that such variance is induced by two primary factors. Firstly, the magnitude of the inrush current drawn by the motor as it is started up is a function of the supply waveform's voltage at that instant [176]. If the supply voltage is at the peak of its cycle the motor will draw minimum inrush current. In contrast, if the voltage is at a zero-crossing point[51] then maximum inrush current will be drawn by the motor. Each time the motor is started up the probability of the supply voltage being at any point in its cycle can be considered to be uniformly distributed, therefore, it can be expected that significant variation in inrush current will occur.

Secondly, inherent sources of inaccuracy are associated with the data acquisition process, which will contribute to differences between measured and 'true' data. Due to the imperfect nature of the practical data acquisition process inevitably a degree of noise will exist within measured data, which, if Gaussian in nature, will result in a normally distributed variance about true values. Additionally, as previously discussed in Section 9.1.2, the limitations of the data acquisition system's sampling rate may imply a discretisation error, resulting in recorded responses not necessarily accurately representing each transient's 'true' characteristics.

In addition to significant variation in magnitude a degree of variation in the duration of each start-up transient was observed across test scenarios, with the shortest transient lasting only 150ms and the longest 320ms, as seen in Figure 9.39.

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[51] i.e. at the mid-point between a transition to negative from positive, or vice versa.

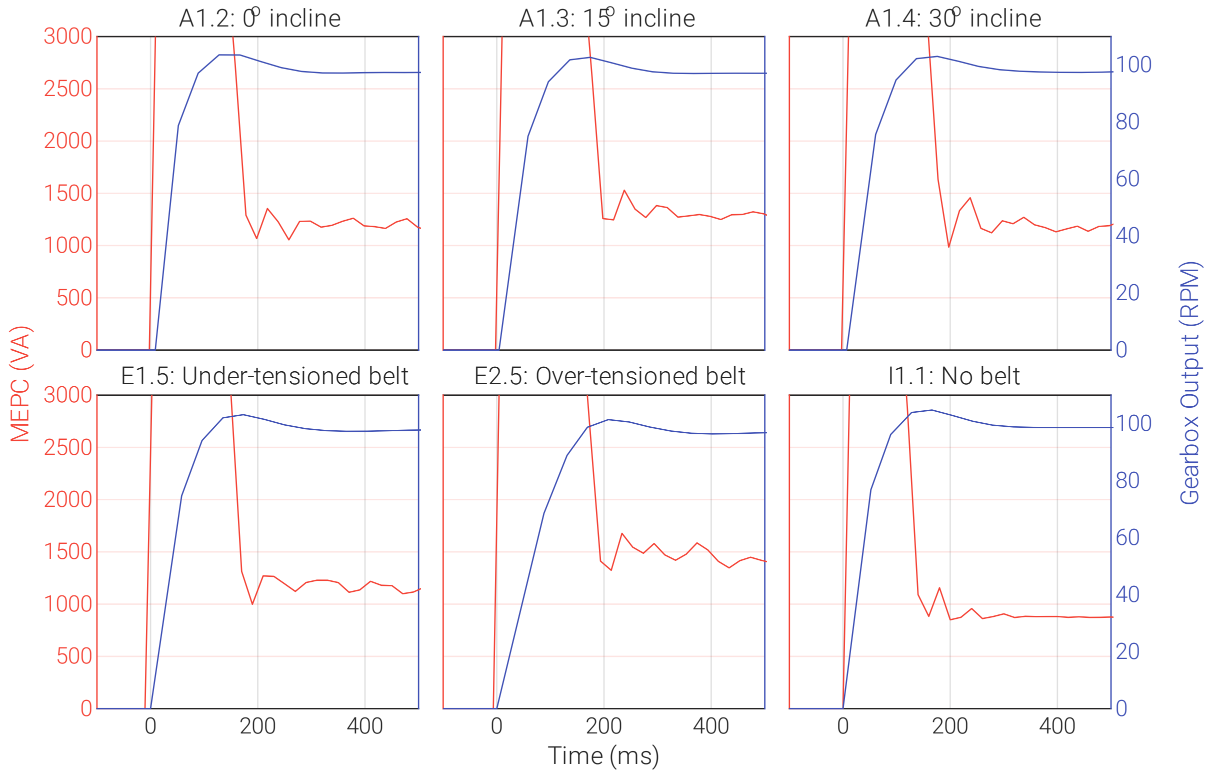

Figure 9.40: Comparison of start-up transient characteristics in response to changes in various operational conditions.

As highlighted in Figure 9.40, in response to changes in inclination little impact on the duration of the start-up transient can be observed, with the transient associated with each incline increment lasting ~200ms. The effect of an increase in inclination on motor load is minimal; adjusting the System's angle of inclination requires work to be done to the system to affect this change[52], however, once the adjustment has been made the only energy required to be input into the system once running is that which is required to drive the belt around the system, the net magnitude of which is essentially unchanged compared to a flat system.

In contrast, modifying the tension in the belt can be seen to directly affect the duration of the start-up transient, with a -5 turns reduction in tension reducing the start-up transient duration by ~20ms, and conversely, a +5 turns increase in tension increasing the duration by ~20ms. As belt tension is reduced the radial load experienced by the gearbox reduces correspondingly and thus gearbox losses are reduced. In turn, the motor thus experiences a reduced torsional load and is therefore able to accelerate the pulleys and belt up to running speed faster, with the converse being true as the tension is increased.

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[52] i.e. to physically raise the CBS support structure and belt.

With no belt present at all, the duration of the start-up transient is reduced even further to ~150ms, ~50ms shorter than normal operation. When the belt is removed from the System no acceleration of the belt and tail pulley is performed, therefore there is less rotational inertia for the drive motor to overcome, and hence it is able to accelerate up to running speed even faster. No test scenarios were conducted in which the System was loaded (i.e. with live load on the belt) prior to start up to minimise potential for damage to be caused to the drive motor. However, it could be expected that in such a scenario the duration of the start-up transient would be increased due to the additional inertia associated with added mass.

9.3.2 Idling Behaviour

Across the test scenarios implemented a range of factors can be seen to affect the MEPC measured whilst the System was idling, all of which relate to changes in the state of the belt, including its tension and tracking, as well as the occurrence of slippage and damage. The presence of oil caused a reduction in idling consumption of ~50VA, whereas increasing the tension in the belt (~200VA), inducing poor belt tracking (~700VA) and seeding a 40cm lateral slit (~100VA) all caused an increase in idling consumption (Figure 9.41).

Of these, changes in tension and slippage were observed to affect the mean consumption whilst idling, whereas changes in tracking and damage were observed to affect the mean consumption as well as inducing a periodic component at the frequency of the belt's rotation, causing an additional increase in variance (Figure 9.41).

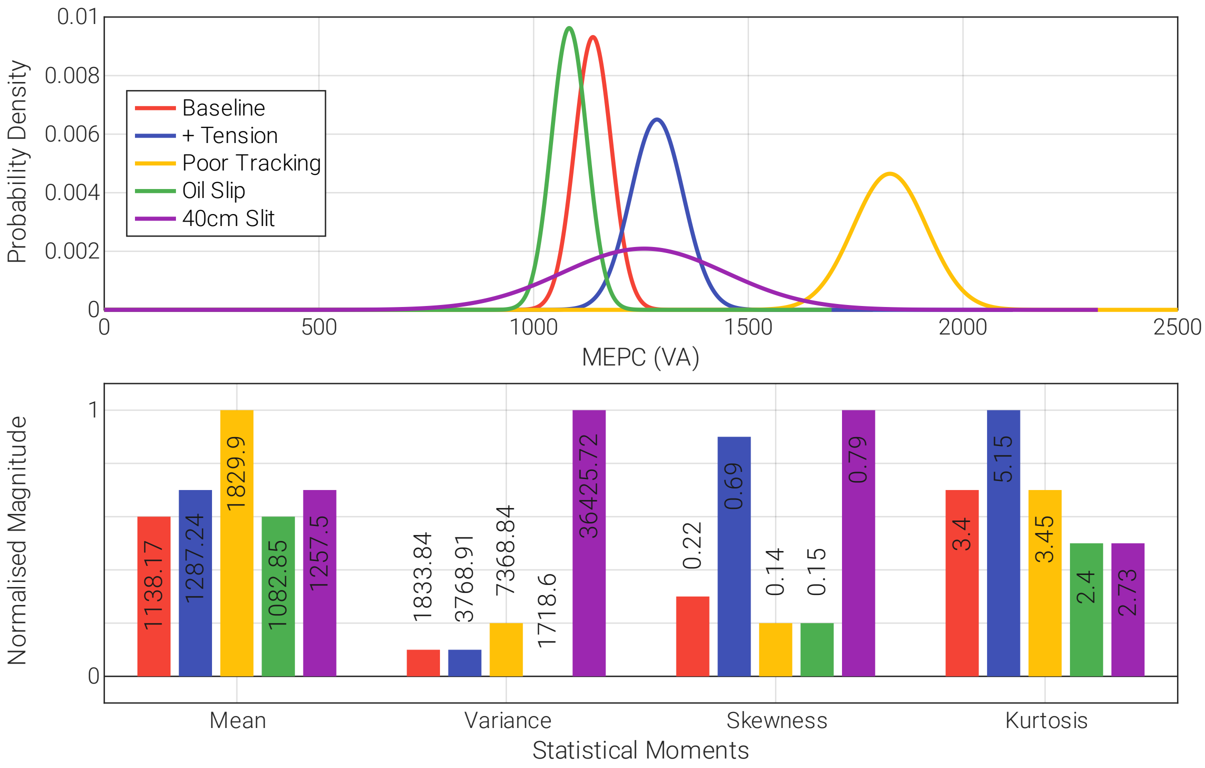

Figure 9.41: Statistical moments associated with factors affecting MEPC whilst idling.

Each condition represents a change in system state which could potentially impact upon the overall operability of the System, therefore, the ability to detect them upon occurrence from changes in MEPC can be considered advantageous. As discussed in Section 0 the likelihood of significant belt slippage occurring within a system can be considered minimal, therefore, its potential impact can reasonably be ignored. Given this, it can be proposed that through observation of changes in the measured variance whilst idling the occurrence of such changes in belt state could be detected.

In addition, the demonstrated sensitivity of idling MEPC to changes in belt tension, both increased and decreased, affords an opportunity to provide operators with in-service feedback on the instantaneous tension of the belt. Typically, the tension in a CBS's belt is set manually by an operator and adjusted such that tracking of the belt is maintained, both during initial setup as well as in-service, as required. During such a procedure poor tracking or the presence of damage to a belt will be clearly visible to the operator, however, in contrast a system can operate with a wide range of belt tension whilst presenting no ostensible change in operation. Accordingly, systems can easily be setup with suboptimal belt tension, the consequences of which can potentially include reduced belt life, the inducing of slippage and/or accelerated deterioration of drive components [229]. Additionally, if a belt is excessively tensioned it will place a greater torsional load on the drive motor, causing an increase in power consumption for the same nominal belt speed and thus financial cost. Based upon the difference in power consumption between maximum and minimum tension during testing (approximately 100VA) an additional cost of ~£45/year could be incurred by each CBSs in practice, based upon a system operating 12 hours per day for 300 days per year[53].

Therefore, the provision of belt tension feedback to operators provides an opportunity to improve the tension setting process and thus reduce overall operating costs. Such feedback could be provided through direct means (i.e. measurement of force), however, the addition of required hardware represents significant additional cost and complexity to a system, therefore the ability to infer qualitative changes in tension indirectly through observation of MEPC characteristics alone represents an attractive proposition, particularly within an industrial context.

9.3.3 Live Load Effects

Throughout tests the application of live load to the belt was seen to cause an increase in drive motor electrical power consumption compared to idling operation, reflecting the increased torsional load experienced by the motor. Where the live load applied was of a discrete nature (i.e. 'lumps' of material) a transient was induced in the measured MEPC, reflecting the work required to be done by the motor in accelerating the loaded mass up to belt speed.

The magnitude of each transient induced within MEPC by a discrete live load was seen to not be significantly affected by the inclination of the System or the loading frequency, but instead only by the quantity of mass and the loading height (Figure 9.43). Such behaviour could be expected based upon the fundamental mechanics of mass being loaded onto the system; by increasing the mass or the loading height the total embodied gravitational potential energy of a discrete load is increased prior to release. However, an equivalence was observed between the effect on MEPC of increasing the quantity of mass loaded or the loading height (Figure 9.42), with it not possible to obviously decouple each effect.

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[53] Based upon a cost of £0.125/kWh, as charged by British Gas (correct of January 2020).

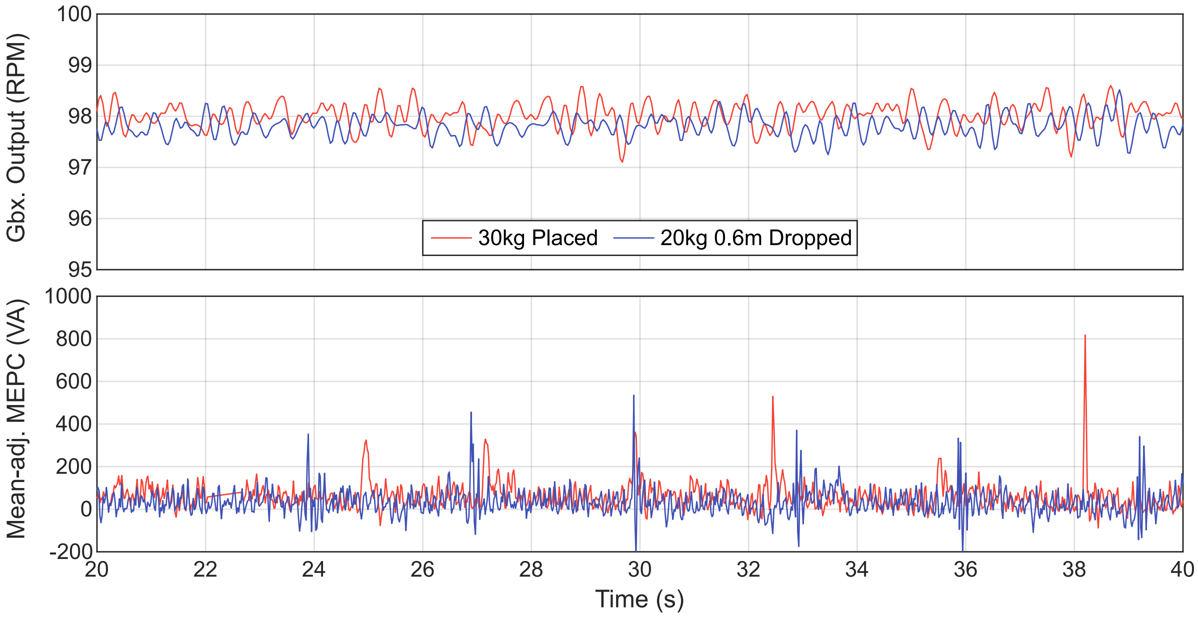

Figure 9.42: Example of equivalence in induced transient characteristics between heavier placed mases and lighter dropped masses.

Accordingly, it can be asserted that quantifying the total mass throughput of a system from observations of MEPC only is not feasible. However, within the context of assessing CBS usage it may actually be that assessing work done by a CBS is of greater interest rather than mass alone, with degradation driven by not only the total mass conveyed but also the manner in which mass is loaded. Given the work done by a CBS is performed solely by the motor the sensitivity of MEPC to the torsional load experienced by the motor enables such usage to be observed in-service. Furthermore, as the duration of each transient induced was observed to be unaffected by the quantity of mass loaded throughout tests, it can be asserted that live loads of a discrete nature can potentially be characterised through determination of only a single parameter; the magnitude above idling consumption of the transient induced. This parameter will be sensitive to both changes in loading height and quantity of mass and will be directly related to the transient increase in torsional load experienced by the drive motor in response to the loading of material, thus enabling total work done by the motor to be tracked over time.

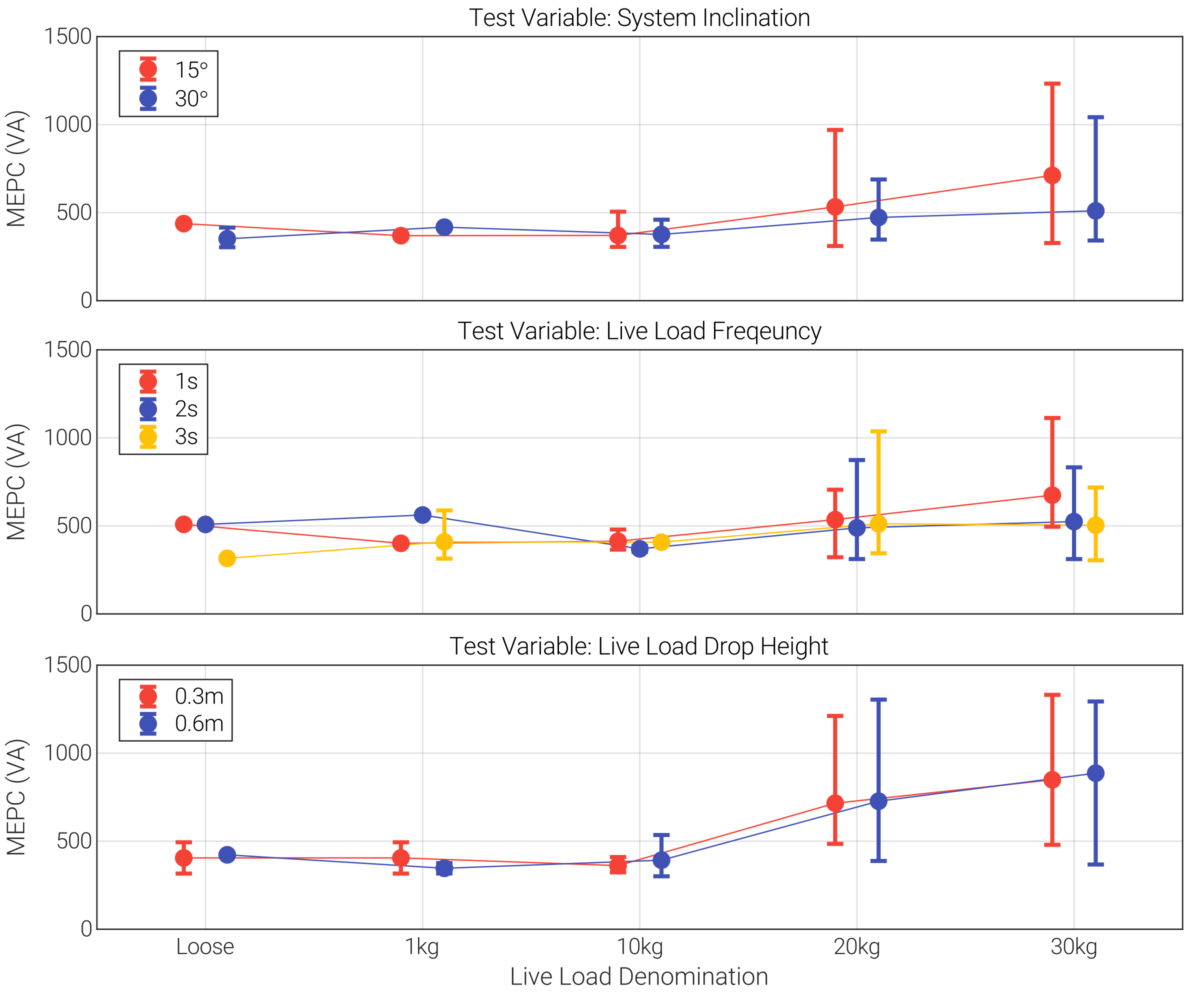

Figure 9.43: Comparison of variance in magnitude of MEPC spikes induced by live loads across CCT scenarios.

Greater variance in the exact magnitude of transients induced by live load was observed as the quantity of mass was increased. Such behaviour is likely to be a consequence of the experimental method; as the mass denomination increased the physical demand on the operator increased accordingly, making heavier masses more difficult to manoeuvre and thus load consistently. However, manual handling of live loads is common within industrial applications therefore the characteristics observed can be considered to reflect typical behaviour.

Despite the relatively low sample rate of MEPC measurements the characteristics of each individual transient were able to be observed, even at a 1s loading frequency. Where a CBS is manually loaded a rate of once-per-second can be considered the fastest practical given the limits of humans. Material loaded faster than once-per-second can be classed as a continuous stream i.e. a loose material load.

In response to the loading of a continuous stream of loose material an absence of such transients was observed, with instead the uninterrupted nature of loaded material inducing only a steady-state increase in power consumption. The absence of an initial spike in consumption reflects the loose nature of the material as loaded; within the overall stream each individual particle possess only minimal mass and thus momentum, so, when it contact the belt it causes only a negligible deceleration of the belt and thus transient increase in torsional load on the motor.

Across the five loose material tests this was only ~100-160VA irrespective of the system's inclination, comparable to the increase in steady-state power consumption observed whilst conveying a 30kg mass, as described in Section 0. Such similarity suggests the torsional load experienced by the motor in response to each event is roughly equivalent, which can be confirmed by examining the characteristics of the continuous stream implemented; a quantity of ~1000kg of material was conveyed during each continuous stream test scenario, which as indicated in Figure 9.44 discharged in ~60s at an approximate material flowrate of 16.7kg/s. Given a belt speed of ~0.9m/s and an exposed belt length of ~2.5m a steady-state load of ~42kg can be deduced, comparable to the 30kg discrete mass scenarios, for which the steady-state increase in MEPC whilst conveying was ~50-140VA.

Accordingly, given there are additional factors which have been observed to affect the idling consumption of the System, such as changes in belt tension as discussed in Section 9.3.2, isolating changes in each factor from observation of MEPC and speed only may not be feasible. Restricting measurements to such a minimal parameter set will inevitably impose such limitations; potentially differentiation could be achieved through observation of additional parameters such as mechanical vibrations.

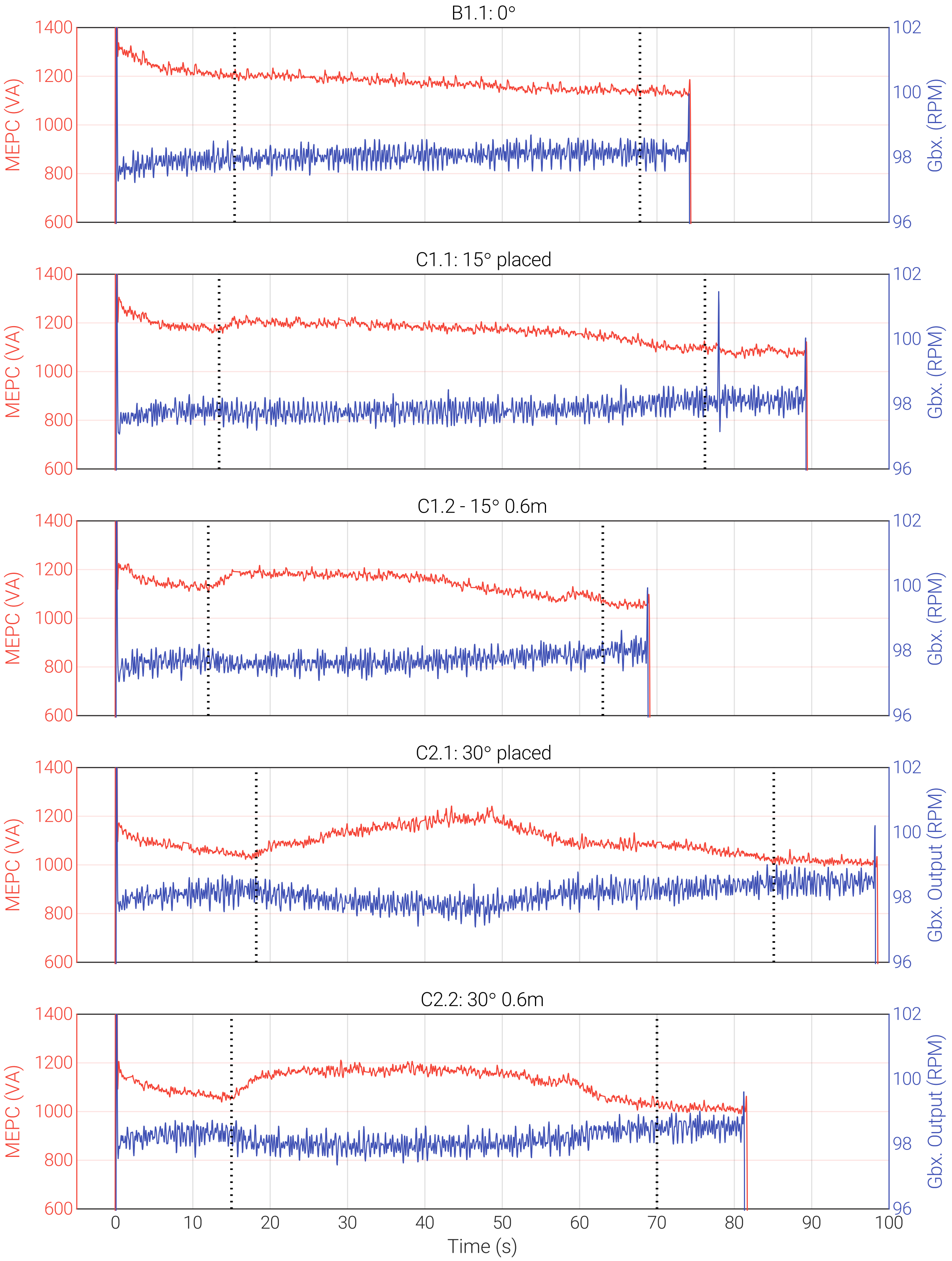

Figure 9.44: Time domain characterisation data associated with each continuous stream of loose material test scenario. Note that the approximate start and end point of each stream is indicated by the dashed black lines.

9.3.4 Belt Conditions

As identified in Chapters 2 and 3, preserving the condition of a CBS's belt is critical to maintaining overall operability. Therefore, the potential to infer changes in the state of a belt indirectly via observation of MEPC alone represents an attractive proposition. Data acquired during the completion of CCTs demonstrates the feasibility of such a concept, with MEPC parameters exhibiting sensitivity to changes in belt tracking, tension and integrity, as summarised in Table 9.1,

Changes in the longitudinal tension of the belt directly affected idling consumption by ~100VA when tension was either increased or decrease by 5 turns from nominal, with the specific frequency of the belt chevron component correspondingly modulated by ~0.05Hz (20ms). The occurrence of poor belt tracking was similarly seen to induce a significant increase in the duration of the start-up transient (~0.1s) as well as the idling consumption (~700VA). Furthermore, a significant increase (~20VA) in the magnitude of the belt passing frequency component was observed, likely representing the occurrence of mechanical drag between the belt and system structure. In response to the seeding of transverse damage within the belt, a reduction of ~100VA in idling consumption was observed, reflecting the reduced tension force. In addition, a series of periodic components were induced, with significant peaks present at the belt passing frequency (~0.15Hz) and its harmonics. The duration of the start-up transient was also seen to reduce by ~40ms as the magnitude of damage was increased to 40cm, with a further reduction of ~50ms observed when the belt was no longer present, reflecting the reduced rotational inertia experienced by the drive motor.

However, due to the inherent indirect nature of inferencing via observations of MEPC and speed the fidelity of information which can be inferred is potentially limited, with differentiating between the occurrence of each condition not trivial. Whilst it is possible to identify qualitative differences via manual interrogation extracting consistent quantitative differentiators from the CCT dataset which can be considered valid in the general case may require further data and/or more involved signal processing.

9.3.5 Reliability of Monitoring

As found during operation of the CER and reported throughout literature MEPC was able to be reliably monitored throughout the completion of CCTs, with no data outages incurred and minimal post-processing of data required prior to interrogation.

In comparison, the monitoring of system speed and in particular that of the belt, was found to be far more challenging. Whilst the hardware required to measure MEPC can be located remotely from the belt and thus live loads, in order to monitor the speed of the belt via the selected technique hardware was required to be located directly on the belt, making it vulnerable to damage caused by the loading of material.

Primarily, direct monitoring of belt speed was implemented during CCTs to enable an assessment of slippage between the drive pulley and belt to be made; as little evidence of such occurrence was identified during tests it is unlikely that direct monitoring of belt speed will be implemented beyond CCTs, therefore, the issues encountered can be considered to have minimal impact to the overall research. However, if direct monitoring of belt speed were to be implemented subsequently issues encountered could be addressed through either redesign of the specific hardware setup to minimise exposure to live loads or through the utilisation of an alternative monitoring technique where such issues may be less significant, such as vision-based speed monitoring.

9.3.6 Experimental Limitations

Whilst completion of the CCTs as described has provided insight into the characteristics of monitored parameters in response to typical operational scenarios, a number of factors exists which limit the degree to which findings can be considered applicable in a more general context:

- **Single subject system**
  During the completion of CCTs the operation of only a single CBS was characterised, preventing assessment of inter-system variance. Different systems are likely to present different responses, which may affect the applicability of CCT findings.
- **System condition**
  The System was provided in an 'as new' condition i.e. it had seen no previous service. Accordingly, the degree to which observed behaviours can be expected to persist with increased usage remains unknown.

- **Power supply characteristics**

  The System was powered by a stable mains supply, whereas in-service a CBS is commonly supplied by a portable generator, which will likely impact upon the MEPC characteristics.

- **Belt characteristics**

  During CCTs the system was operated with only single belt, preventing assessment of the impact of different belts, both of the same and alternative forms (e.g. flat, cleated) on monitored parameters.

- **Isolated changes**

  To enable the specific effect of changes in each operational variable on monitored parameters to be observed each was changed in isolation, thus, combined effects were not able to be observed (for example, simultaneous changes in belt tension and system inclination) and thus an assessment of the resulting impact upon inferencing ability made.

9.4 Implications for Research

Through completion of Conveyor Characterisation Tests (CCTs) the sensitivity of motor electrical power consumption parameters to changes in CBS operation, related to aspects of system health and usage, was assessed. Through a process of manual interrogation of measured data, the feasibility of indirectly inferring changes in the operational state of a CBS through monitoring of the drive motor only was demonstrated. As illustrated in Figure 9.45, analysis of MEPC can potentially afford significant observability of CBS operation, related to the characteristics of changes in the state of a belt (health) and the application of live loads (usage).

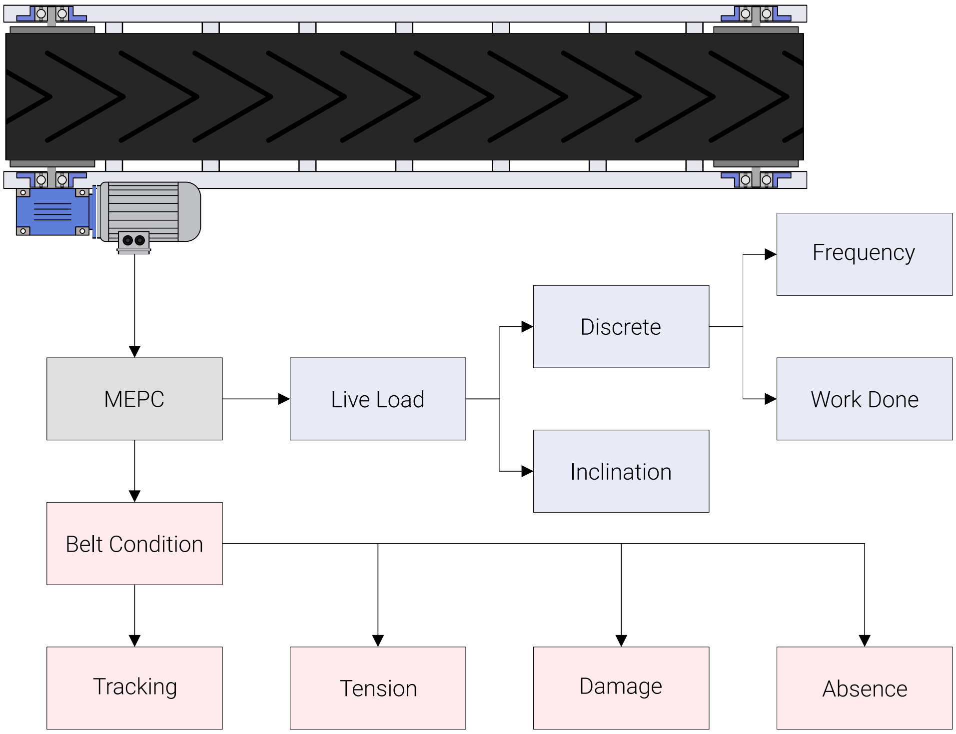

Figure 9.45: Taxonomy of aspects of CBS health and usage potentially inferable through interrogation of MEPC, based upon observations from CCTs.

For the specific CBS operated, changes in inclination and belt conditions were able to be identified through fluctuations in the apparent power consumption of the System's drive motor. Additionally, the loading of discrete masses onto the belt could be detected, and the work done in conveying discrete live loads could be assessed. However, an equivalence in the effect of changes in loading height and quantity of live load prevented isolation of changes in each variable. Furthermore, when live loads were loose in nature their effect on MEPC was too subtle to confidently identify.

The occurrence of most changes in belt state were observed to induce detectable changes in the response of MEPC parameters, suggesting such events can feasibly be identified through indirect means. However, throughout tests only a negligible of belt slippage could be induced, indicating such events are not likely to impact CBS operation in practice.

Furthermore, test demonstrated that MEPC parameters can be monitored reliably outside of laboratory conditions, corroborating reports in literature, suggesting that continuous monitoring of MEPC parameters in CBS applications is achievable and without incurring significant financial cost, both during initial installation and on-going maintenance.

Chapter 10: The Development of Data Descriptors for Characterising CBS Operation

As identified in Chapter 2 the ability of industrial practitioners to conduct essential visual inspections of conveyor belt systems is compromised by physical limitations in accessing systems, restricting assessments to periodic completion only. Furthermore, when inspections are able to be conducted a degree of subjectivity inherent to the inspection process impacts validity and thus value. Such issues can potentially be mitigated through the utilisation of continuous monitoring of systems; as demonstrated in Chapters 5 and 6 through interrogation of low cost, non-intrusively monitored parameters specific elements of a CBS's health and usage can be inferred, providing a source of objective, actionable insights for practitioners to leverage. However, the process of translating raw measured parameters into such insights places a significant effort and expertise requirement upon personnel, which cannot be assumed, given the characteristics of bulk handling applications as identified in Chapters 2, 3 and 4.

Accordingly, in this chapter the development of three numeric indictors is presented, each of which provides a means for translating raw motor electrical power consumption (MEPC) parameters into such objective, actionable insights in an unsupervised/automated manner. Indicators are referred to in this context as *data descriptors*, and, in line with the definition provided in BS ISO 13372-2012[54], represent measures derived from raw data, processed parameters or external observations, which provide insight into specific aspects of a system's operation. Data descriptors can serve to identify the occurrence of a specific fault type (health) or alternatively quantify a specific aspect of a system's usage, conceptually similar in nature to the Figures of Merit proposed by Stewart [230] to support the diagnostics of helicopter faults. For example, the accumulation of debris within a valve could be estimated from changes in flowrate as an indicator of a fault within the valve or the number of take-off and landing events experienced by an aircraft could be derived from measured altitude and airspeed time series data to produce a descriptor related to the craft's usage in-service. The provision of data descriptors serves to supplement rather than replace the existing practice of personnel, providing

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[54] As defined in ISO 13372:2012 (Condition monitoring and diagnostics of machines - Vocabulary) the term *descriptor* refers to a *"data item derived from raw or processed parameters or external observations"* [29].

additional insight into the operation of a CBS which can be used to support activities across the design, operation and maintenance of systems.

10.1 Health and Usage of Systems

In-service the health of a CBSs is directly influenced by its usage; the more a system is used the faster its health will degrade as a consequence of usage-induced loads driving failure/wear mechanisms, which will ultimately lead to the occurrence of faults. For example, an aircraft engine fan blade will not likely fail if left idle, however, when subjected to repeated loading cycles the likelihood of fatigue failure increases. Within a single system the onset of multiple failure modes can occur simultaneously, each driven by a specific type of loading, thus the usage of the system can be considered in different manners as dictated by each application. Accordingly, in the same way that a single phenomenon can often be observed within the response of multiple parameters, the usage of a system can be considered from multiple perspectives.

Typically, the perspective selected is likely to be linked to a specific failure mechanism of interest, however, it could also be dictated by external factors (e.g. to demonstrate compliance with health and safety legislation). However, given that, in practice, each failure mode will represent a specific likelihood and impact, the criticality and thus significance of each will vary. Accordingly, it can be asserted that certain perspectives of a system's usage will be more relevant than others. For example, consider the different perspectives from which the usage of an automobile can be considered, as posed by Tinga et. al. [231]:

"for a car tire the number of driven kilometers is a more relevant usage parameter than driving hours and much more relevant than calendar time (unless the car is not used at all and ageing of the rubber finally leads to rupture of the tire)."

Thus, it could be concluded that driven hours represents the most relevant usage parameter for an automobile. However, if the vehicle were to be operated predominately within a coastal environment then structural failure due to corrosion may be a more likely failure mode and thus ambient conditions may be a more relevant perspective on system usage. Similarly, the concept of severity is an important property of usage; a system's resilience to usage may present non-linear characteristics, meaning the effect of severe usage is far more significant than low usage. Again, considering the example of an automobile, its high-level usage could be observed through its mileage whilst its usage severity dictated by the rate of change of speed (i.e. acceleration) experienced whilst covering that distance. In the context of a CBS this would be analogous to the total mass conveyed (usage) and the temporal distribution of that mass (usage severity).

Accordingly, to identify the most appropriate definition of a system's usage requires an understanding of the relationship between how a system is operated and the resulting effect upon the system's health. As presented in Table 10.1, based upon observations made during the completion of each body of testing within this research programme a number of hypotheses relating to characteristic indicators of various CBS failure modes can be elicited.

Table 10.1: Summary of data hypotheses compiled from observations across testing activities.

ID	Hypothesis	Level	Rationale
S.1	Localised belt damage (i.e. slit at specific location) will manifest as a modulation in the torsional load on the drive motor, the frequency of which will be related to the geometry of the conveyor.	System	Point damage will result in periodic effects at 2x belt frequency most likely, as there are two pulleys over which any damage present must pass.
S.2	Wear (and hence life) of the belt (i.e. before functional failure) is a function of the tensioning force applied to the belt by the support pulleys.	System	Greater tension in the belt is likely to result in plastic deformation of belt, and thus thinning over time, ultimately leading to complete failure.
S.3	Power consumed by the drive motor during idling is a function of the tensioning force applied by the head and tail pulleys to the belt.	System	Belt friction is a function of the normal force between the belt and pulleys, angle of wrap, and the frictional coefficient, therefore by increasing the normal force more frictional force is generated and thus an increased load is seen by the drive motor. Additionally, thermal loss from bearings is likely to increase with belt tension due to the increase in static load on the bearings, resulting in an increase in power consumption..
S.4	The idling power consumed by the drive motor is a function of the angle of inclination of the conveyor.	System	As the angle of the conveyor is increased, it is required to do more work to transfer the same material vertically as well as horizontally, thus more power must be consumed.
S.5	Product dropped onto the surface of the belt will induce a transient spike in motor power consumption, the magnitude of which will be a function of the drop height.	System	Greater drop height results in greater kinetic energy associated with product, and thus greater impact force onto the belt, in turn generating an increased frictional force between the belt and support surface, requiring more power to move the same load.
S.6	The magnitude of the power consumed by the driving motor above idling consumption is a function of the mass of product on the belt.	System	More mass on the belt requires more energy to move it, and thus more power. Also, more mass increases friction between the belt and support rollers/surfaces, thus the drive motor will experience more load.
S.7	The occurrence of rubbing between the belt and conveyor structure will cause an increase in the power consumed by the drive motor.	System	A belt rubbing on the support structure of the conveyor will cause frictional force to be generated, in turn increasing the load experienced by the motor.

S.8	The occurrence of relative slip between the belt and drive pulley will result in a reduction in the torsional load experienced by the drive motor.	System	The introduction of fluids onto the belt underside can be expected to have a lubricating effect on the contact surfaces, resulting in a reduction in friction. This in turn will cause the contact force between the belt and pulley to be reduced, and thus the load on the motor will reduce also
M.1	The presence of a fault within the drive motor will result in the complete inoperability of the conveyor system.	Motor	Typically issues encountered with motors, such as damaged/degraded capacitors or centrifugal switches, will not result in reduced performance as the degradation increases in magnitude, but instead will, at a certain point, completely impede the function of the motor.
M.2	The operable life of the drive motor is a function of the number of transient load spikes experienced by the motor, and their intensity.	Motor	Spikes in load over a certain threshold will result in significant short-term high current draw, which in turn is likely to cause irreversible damage to motor windings/capacitors/insulation.
M.3	The temperature of the motor above ambient is a function of the torsional load experienced by it.	Motor	Additional load on the gearbox will be passed through to the motor, which will likely increase in temperature, with the greater load requiring greater power consumption, and thus more thermal losses.
M.4	The temperature of the motor above ambient is a function of the insulation around the motor.	Motor	The drive motor is cooled via a combination of forced convection and conduction, therefore an increase in insulation around the motor (i.e. dirt build-up) will reduce the ability of the motor to dissipate heat and thus the temperature will increase.
G.1	The temperature above ambient of the gearbox is a function of the quantity of oil within the gearbox.	Gearbox	The presence of oil within the gearbox provides lubrication to gear tooth contacts, reducing friction and thus heat generation.
G.2	The temperature above ambient of the gearbox is a function of the torsional load on the gearbox.	Gearbox	Whilst an increase in torsional load may not necessarily increase the quantity of heat generated by the gearbox, it will likely increase heat generated by the drive motor, and as the two are directly coupled will likely result in the gearbox temperature increasing.
G.3	The temperature of the gearbox above ambient is directly influenced by the integrity of the insulation around the motor.	Gearbox	The gearbox is passively cooled via conduction/convection, therefore it relies on clear airspace being present around the gearbox casing in order to regulate its temperature
G.4	The presence of gear tooth damage within the gearbox will manifest as a modulation in its output torque/speed. Where the modulation frequency is a function of the gear geometry and the rotational speed of the gear.	Gearbox	Tooth damage (e.g. a broken tooth) will result in a transient drop in output torque once per rev.
B.1	The occurrence of a seized/partially seized pulley bearing will result in the drive motor experiencing an increased torsional load.	Bearing	A seized bearing will result in an increase in rolling resistance, and thus a greater load will be seen by the drive motor.
B.2	The occurrence of a collapsed pulley bearing will result in the drive motor experiencing an increased torsional load.	Bearing	A collapsed bearing is likely to present more rolling resistance than an intact bearing, hence the drive motor will see a greater torsional load.
B.3	The occurrence of damage to either race of a pulley bearing will generate additional vibration during rotation of the bearing, the amplitude and frequency of will be related to the bearing geometry, rotational speed and damage characteristics.	Bearing	Distributed damage is likely to produce broadband vibrations, whereas localised damage is likely to produce excitation at specific frequencies.

Together, these hypotheses represent a taxonomy of behaviours potentially observable during the operation of a CBS, each of which could be considered to contribute to the overall description of a specific system's usage. In practice, to utilise the knowledge of each relationship in-service requires that appropriate data be available. For example, to conduct analysis of a bearing's mechanical vibrations requires the monitoring of a parameter sensitive to such phenomena. Accordingly, it can be asserted that the degree to which inferences about a system's health and usage can be made is dictated by data availability.

As identified within Chapters 6 and 8 the suitability of MEPC parameters for in-service continuous monitoring of CBSs has been established. This therefore places restriction on data availability and thus the range of data hypotheses which can potentially be exploited. Consequently, given the previously identified impact of motor and belt issues to manufacturers and operators, the development of three specific descriptors is proposed, each of which provides a means for quantifying an aspect of a CBS's health or usage:

- **Start-up Classification**

  An estimation of the time taken for a system to reach operational speed once started up, used as an indicator of suboptimal belt scenarios such as over-tensioning (health).

- **Exceedance Analysis**

  A quantification of the quantity and magnitude of torsional load experienced by a system's drive motor as caused by the addition of live load onto a system's belt (usage)

- **Belt Damage Severity**

  A means to identify the presence of lateral damage to a system's belt, and quantification therein (health).

In the following sections a series of methods for deriving each data descriptor from raw MEPC parameters are proposed (Figure 10.1), from which an aggregated method for characterising the operation of a CBS in-service is produced.

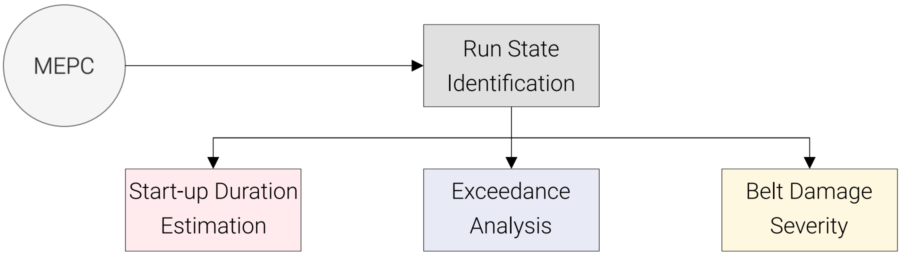

Figure 10.1: Proposed taxonomy of data descriptors derivable from MEPC parameters.

10.2 System Run State Identification

Each of the three proposed data descriptors are based upon analysing the characteristics of a CBS whilst in-service. Therefore, to derive each data descriptor it is first necessary to identify when a CBS is in operation and when it is stationary. Under normal circumstances (i.e. a fault-free motor) when a CBS is powered off no electrical current should flow within the motor and thus zero MEPC should be measured. In contrast, when a CBS is powered on a non-zero consumption of power should be measured. Accordingly, changes in the running state of a CBS can be inferred from changes in the running state of a motor i.e. transitioning from stopped to running and vice versa, reducing the running state of a CBS to a binary classification.

As depicted in Figure 10.2 transitions in the running state of a motor can be identified through a simple state machine, wherein a start-up is identified as the transition from a low state (i.e. powered off) to a high state (i.e. powered on), based upon the magnitude of MEPC.

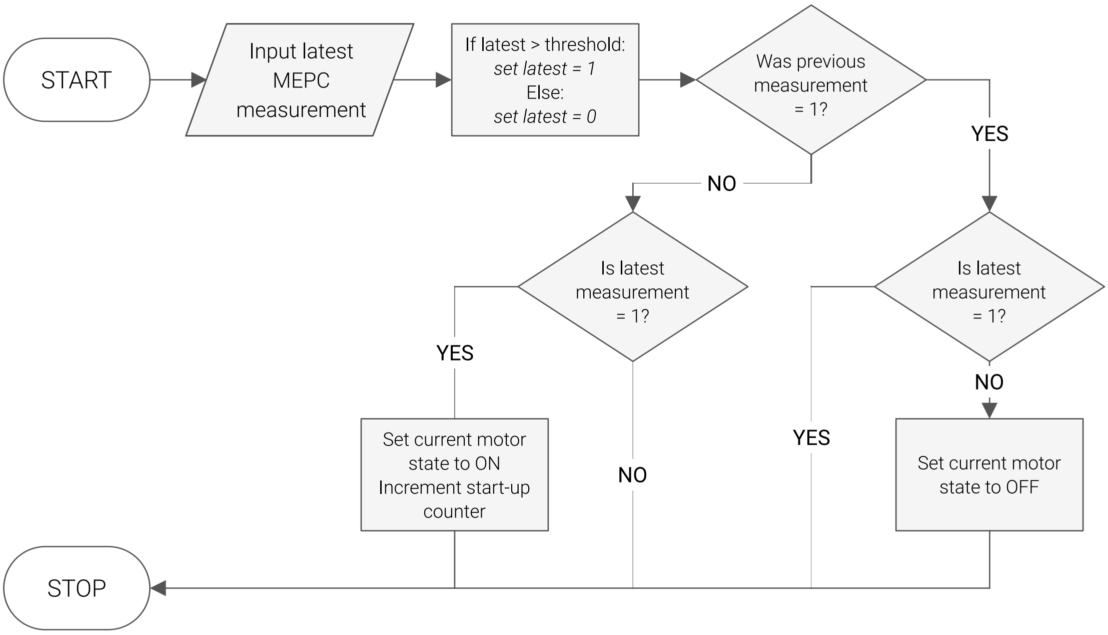

Figure 10.2: Logical flow of the proposed algorithm for identifying the running state of a CBS from MEPC.

When applied to a sample test scenario this state tracking algorithm demonstrates robust performance and an ability to track the total number of start-ups observed, as depicted for scenario I1.1 in Figure 10.3. Given the signal-to-noise ratio of data acquired during CCTs accurate tracking of the system's running state can be achieved without an initial filtering stage, however, if data was corrupted more significantly with noise then some form of low-pass filtering could be implemented on raw data prior to processing with the tracking algorithm.

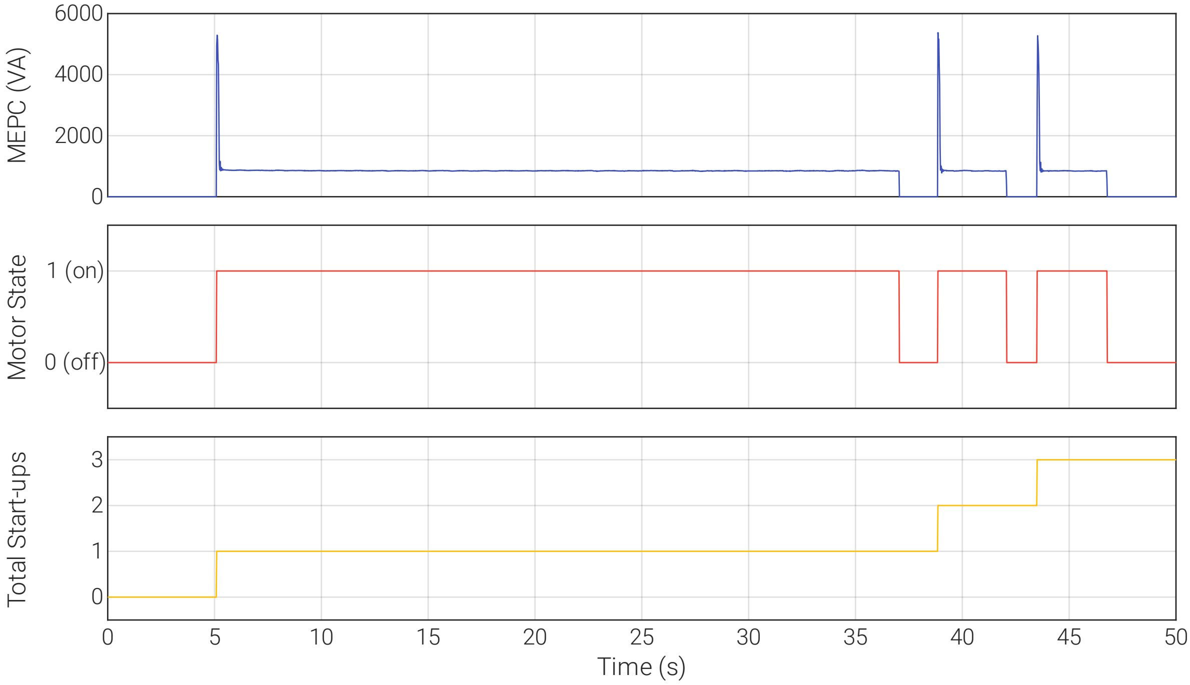

Figure 10.3: Classification of motor running state during the I1.1 test scenario using the proposed algorithm.

The ability to detect and log start-up events also enables a number of secondary descriptors to be derived, such as *total running time*, *number of periods of operation* and *average operational period length*, as shown in Table 10.2. Such descriptors will be impacted by the specific manner in which a system is used and thus may provide valuable insight to practitioners.

Table 10.2: Examples of secondary parameters able to be derived from analysis of MEPC transitions.

TS	# Start-ups	Run Time (s)		Duty	TS	# Start-ups	Run Time (s)		Duty
		Total	Mean				Total	Mean	
A1.2	1	912.3	912.3	0.98	D2.1	1	91.0	91.0	0.61
A1.3	1	497.4	497.4	0.92	D3.1	1	83.2	83.2	0.69
A1.4	1	632.8	632.8	0.96	D2.2	1	70.1	70.1	0.58
B1.1	1	88.1	88.1	0.42	D3.2	1	88.9	88.9	0.74

10.3 Start-up Duration Estimation

As identified during the completion of CCTs the specific characteristics of start-up transients can provide insight into the state of a CBS, such as the relative tension in the belt or the presence of damage to the belt. During each CCT scenario, upon powering on from standstill a transient increase in the power consumption of the drive motor between 3-5 times greater than idling consumption was observed, primarily representing the additional energy required to overcome the mechanical inertia of the system and thus accelerate it to operational speed. Accordingly, a system is typically subjected to peak forces upon start-up, which in turn translates into peak stress within the belt. The cyclic nature of such loading may contribute to accelerated shortening of belt life due to fatigue, resulting in belt failure despite an absence of loads well below a belt's ultimate tensile stress (UTS) potentially in as few as 1000 cycles [60]. Quantifying the significance of start-ups on the realised life of a belt is challenging; many factors contribute to the life of a belt beyond purely its cyclic loading and decoupling these factors is practically infeasible even if theoretically possible. However, given the underlying understand of fatigue mechanisms it can reasonably be asserted that increasing understanding of start-up/life relationships is of interest to practitioners.

Accordingly, there exists potential to infer information about the health of a system's belt by understanding the specific characteristics of start-up transients in-service. Therefore, in this section the development of an unsupervised (i.e. without manual interrogation) method for estimating the duration of CBS start-up events is presented.

Drawing from traditional transient response analysis methods, the broad characteristics of a start-up transient can be encapsulated by four components:

- **Rise time:** *The time taken to reach peak consumption from the point of the motor being powered on.*
- **Peak consumption:** *The magnitude of peak consumption observed during a start-up event.*
- **Transient duration:** T*he total time between the motor being powered on and the point at which the transient has settled (i.e. steady-state conditions are reached).*
- **Idling consumption:** *The magnitude of power consumption once the transient has settled and steady-state conditions are reached.*

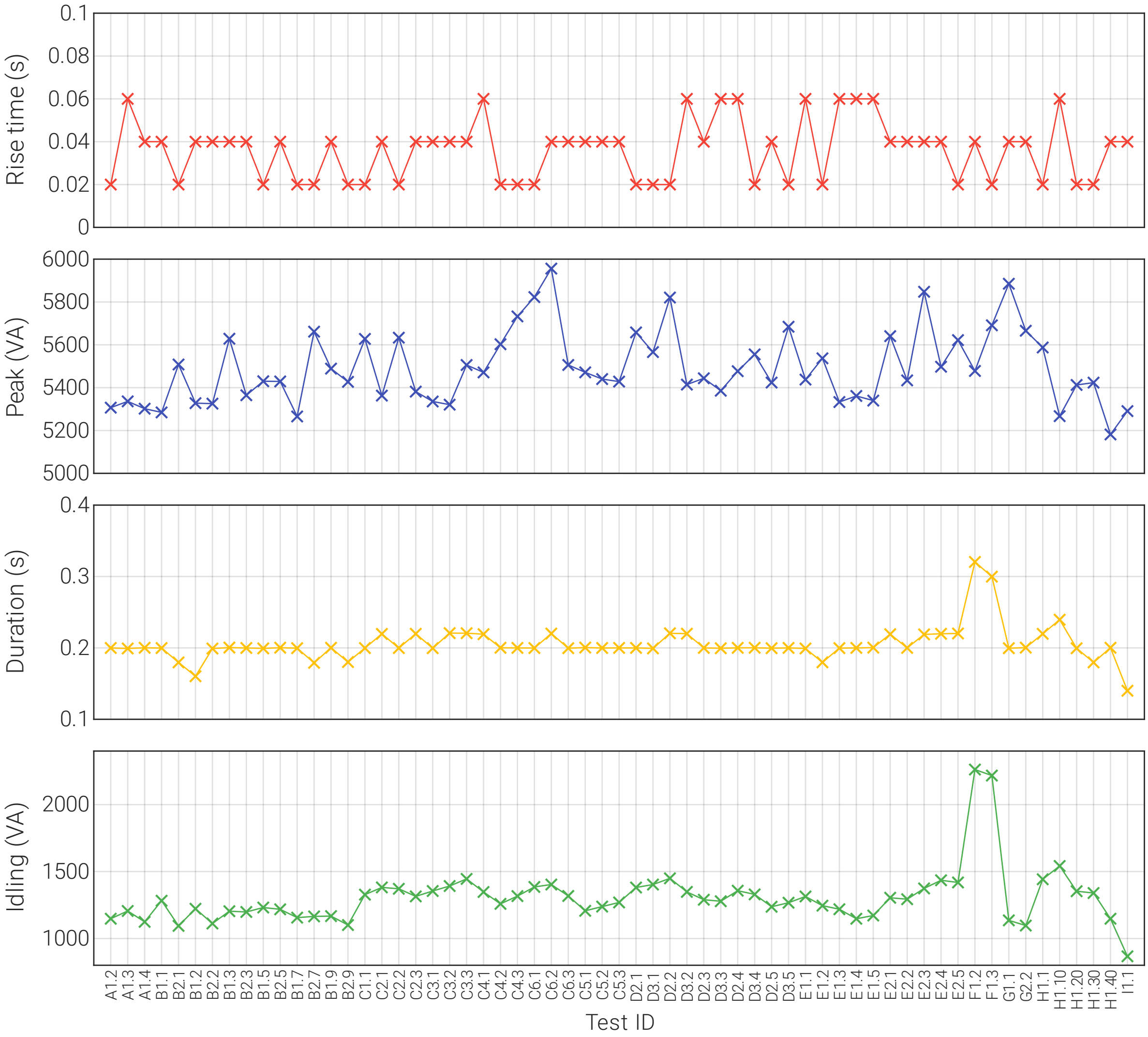

Figure 10.4: CCTs start-up transients decomposed into characteristic variables

When each start-up is decomposed into each component it can be seen that peak consumption and rise time present no apparent correlation with changes in belt state (Figure 10.4). In contrast, both the duration of transients and the idling consumption are affected; when tracking is poor or tension is increased both increase correspondingly whereas when tension is decreased or the belt is damaged or removed a subtle reduction is observed. Therefore, by analysing how these variables change in-service practitioners can be alerted to abnormal conditions, triggering investigative action. It should be noted that although changes in start-up duration and/or idling consumption can be used to infer abnormal operation it is unlikely that they will be sufficient to diagnose the type of fault(s) present; multiple abnormal scenarios could present in an equivalent manner. For example, it would not be possible to differentiate between a scenario in which an over-tensioned belt was started up with no live load present on the belt and a scenario in which an appropriately tensioned belt was started up with live load present on the belt.

As duration and idling consumption present apparent sensitivity to the same conditions no additional insight can be obtained from analysis of both, therefore it is proposed to track only the duration of start-up transients. The duration of a start-up event is selected due to its predictable localisation in time; by definition, a start-up transient will always occur immediately following a system being powered on.

The task of estimating the duration of start-up transients involves estimating the time which elapses between a CBS's motor being powered on and a steady-state level of power consumption being reached. As depicted in Figure 10.5 a start-up event can be separated into three distinct stages: an initial stage where the system is stationary and no consumption is recorded (*Stage* 1: Off), a second state where a spike in power consumption is observed as the motor comes up to operational speed (*Stage* 2: Transient) and a final stage where the motor is idling and an approximately constant consumption of power is observed (*Stage* 3: Idling).

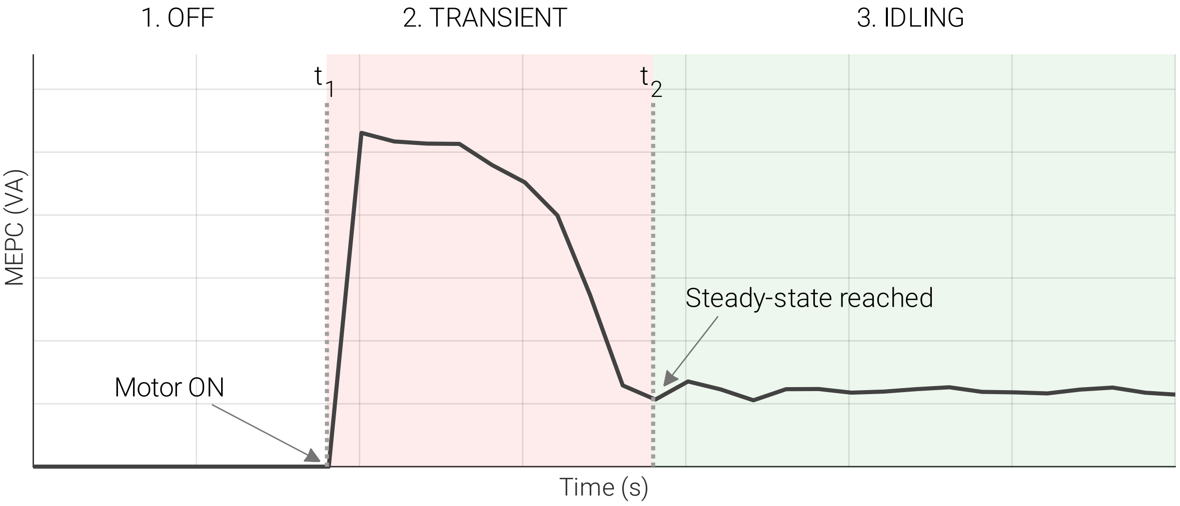

Figure 10.5: Illustration of a start-up event decomposed into steady-state and transient stages.

The task of analysing time series data to characterise transient characteristics possesses similarities with a number of wider signal processing tasks. For example, non-intrusive load monitoring (NILM) seeks to disaggregate the total energy consumption of a premise (e.g. a factory or domestic household) as measured by a single sensor[55] into the consumption of each

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[55] It is this aspect which makes it *non-intrusive* as opposed to an *intrusive* approach, in which each appliance has a dedicated sensor.

individual appliance (e.g. a kettle or washing machine) to provide increased insight [232]. Accordingly, NILM requires the analysis of transient signals to identify the particular signatures associated with each appliance, for which a wide range of algorithmic approaches have been developed.

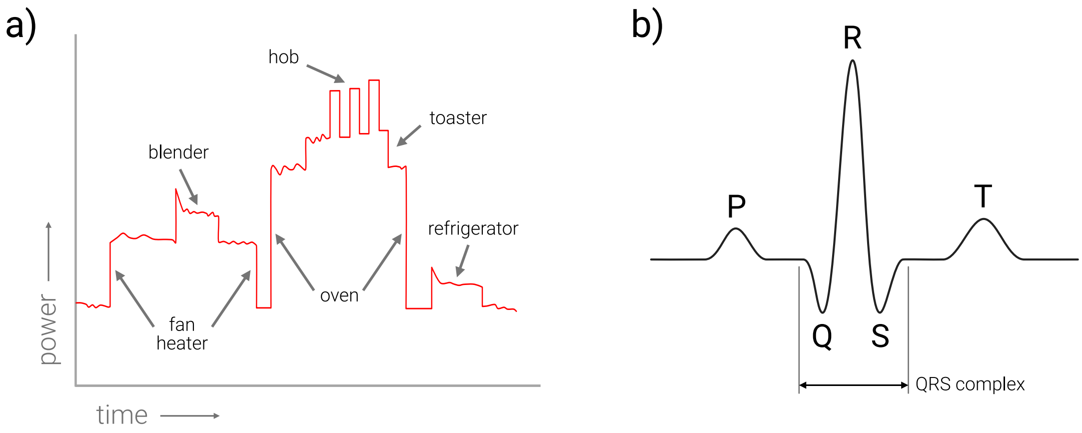

Figure 10.6: Illustration of the basic principle of NILM (a) and the QRS complex present within ECG signals (b).

Similarly, during an echocardiogram (ECG) specific behaviours of interest contained within inherently transient heartbeat signals must be identified and characterised. Traditionally, such analysis required the expertise of a highly trained medical professional to interpret the characteristics of an individual's QRS complex[56] and identify any abnormalities. However, to support practitioners, increasingly automated approaches to this task are being employed such as the widely used Pan-Tompkins algorithm, which employs a series of successive filtering and thresholding stages to extract QRS components [233]. Accordingly, there exists a significant body of literature which can be leveraged in the development of an approach to the estimation of start-up transient durations, four of which are presented in this section.

To provide a baseline against which each method could be evaluated firstly the duration of the start-up transient associated with each CCT scenario was estimated through manual interrogation of raw times series data (Figure 10.4). As depicted in Figure 10.5, the start point of a transient was defined as the first non-zero value recorded (t_1) and the end point was defined as the first point at which power consumption was considered to have reached a steady-state value (t_2). This definition thus induced an element of subjectivity into the estimation of start-up durations, however, as manual estimations only served to provide a baseline for

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[56] The QRS complex refers to a series of markers present within a typical human heartbeat.

comparison, as long as a consistent approach was taken across all scenarios then the effect of subjectivity was considered to be inconsequential.

For each CCT scenario the first 100 samples (2s) of data after the CBS was initially powered on were extracted to isolate start-up events. Given the 50Hz sample rate of acquired data start-up durations can be estimated down to a resolution of 0.02s (20ms).

10.3.1 Moving Range Method

As depicted in Figure 10.5, a start-up event consists of three distinct stages: an initial stage (1) prior to a system being powered on during which no power is consumed, a transient stage (2) during which consumption rises quickly to a peak and then drops and an idling stage (3) where steady-state conditions are reach and an approximately constant, non-zero consumption of power is observed. Accordingly, MEPC can be considered essentially stationary[57] during Stage 1 and Stage 3 and non-stationary during Stage 2, presenting a means to differentiate between the stages and thus estimate the duration of start-up transients. By observing the magnitude of the range between a number of consecutive values the changepoints within a time series of data can be accentuated, from which the start-up duration can feasibly be estimated; this is the principle exploited within the Moving Range method.

To implement the Moving Range method first the 3-point range (i.e. absolute difference between maximum and minimum values) is calculated across successive points within each time series i.e.:

$$y_{range}(n) = \left| max\left(x(n-1), x(n), x(n+1) \right) - min\left(x(n-1), x(n), x(n+1) \right) \right| \qquad 10.1$$

Where $y_{range}(n)$ represents the 3-point moving range at time n of the input time series x.

Next, the two most prominent peaks within the calculated moving range series are identified using a peak detection algorithm[58] and the timestamp associated with each is extracted, as depicted in Figure 10.7. Finally, the duration of the start-up transient can be estimated from the absolute difference between the extracted timestamps.

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[57] I.e. its statistical descriptors (mean, variance etc.) are approximately constant.

[58] The MATLAB *findpeaks* algorithm is employed in this instance, however any peak detection algorithm could be employed for this task.

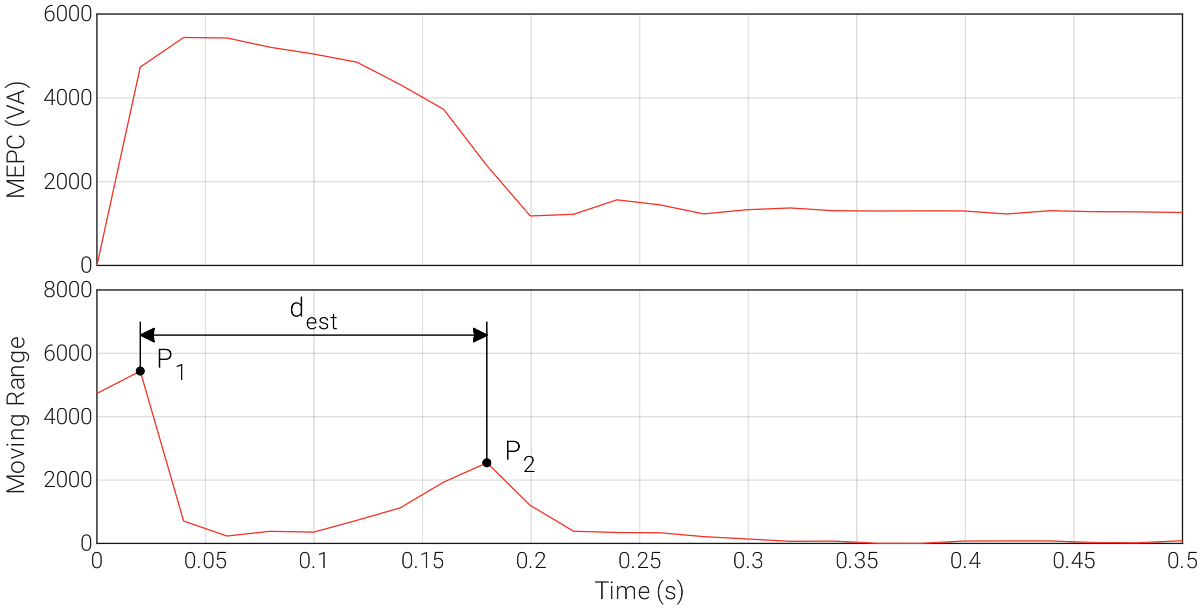

Figure 10.7: Illustration of the principle of the Moving Range method. Raw MEPC data (top) and its 3-value moving range (bottom), highlighting the dominant peaks P_1 and P_2 from which a duration is estimated (d_{est}).

When applied to the CCT scenarios the Moving Range method can be seen to produce good correlation with manual estimates of duration, with the impact of changes in belt tracking, for example, able to be identified (Figure 10.8).

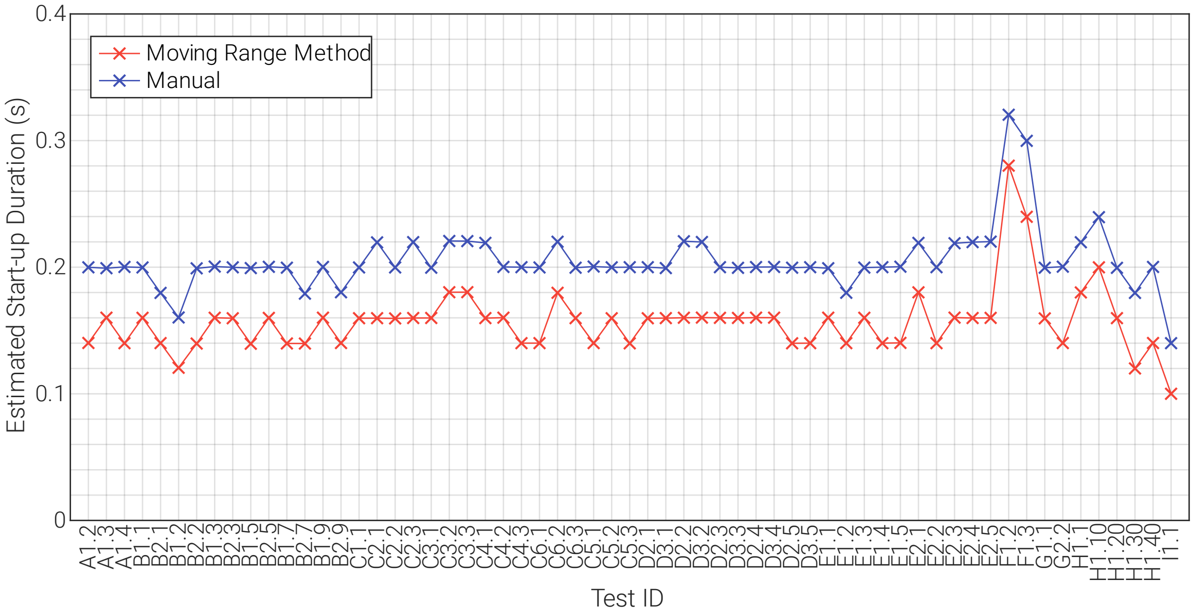

Figure 10.8: Duration of start-up transients as estimated by Moving Range method compared with manual estimates.

10.3.2 Differentiator Method

A similar approach to the Moving Range method is proposed by Lindahl et. al. [234] as a means for identifying load state changes within shipboard generators, within the scope of NILM. To both identify the occurrence of a generator coming online and subsequently quantify the duration of the resulting transient increase in electrical power consumption they develop a multi-step approach based upon analysing the rate-of-change of power consumption during start-up as a means to identify the transitions between transient and stead-state stages, as depicted in Figure 10.9.

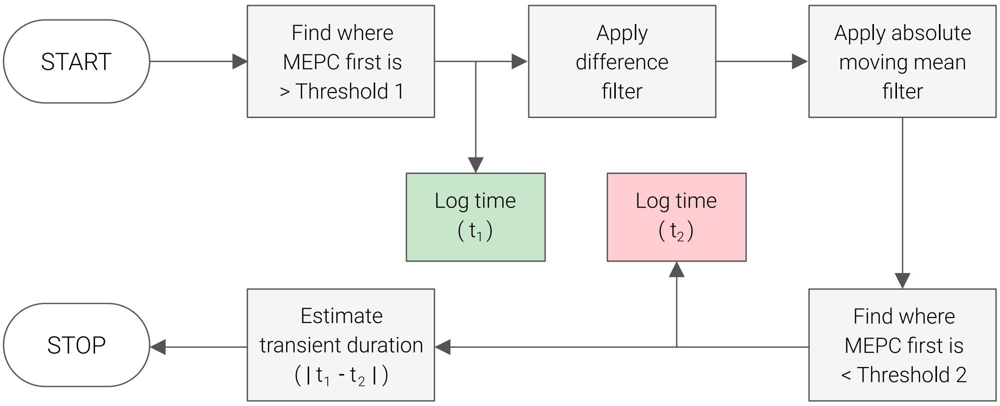

Figure 10.9: Logical flow of the Lindahl Method for trasient duration estimation.

Firstly, a step detector is used to identify the occurrence of a start-up, based upon comparison of electrical power consumption against a static threshold, set to 10VA. Next, a difference filter is applied to the time series, of the form:

$$y(n) = x(n) - x(n-1) \qquad 10.2$$

Where $y(n)$ *represents the filter output and* $x(n)$ *represents the original time series.*

Following this a 3-value moving mean filter is applied and the absolute value of the output taken, in accordance with:

$$y^{*}(n) = \left| \frac{1}{3} \left[y(n-1) + y(n) + y(n+1) \right] \right| \qquad 10.3$$

Where $y^{*}(n)$ *represents the 3-value moving mean and* $y(n)$ *represents the output of the difference filter.*

The endpoint of the start-up transient is then defined as the first time at which the value of y* falls below a pre-defined static threshold, in this instance defined as 200VA, based upon typical idling consumption. When implemented across CCT scenarios the Differentiator method produces significant under-estimates of start-up durations when compared to baseline values as well as presenting little sensitivity to changes in belt conditions, as shown in Figure 10.10.

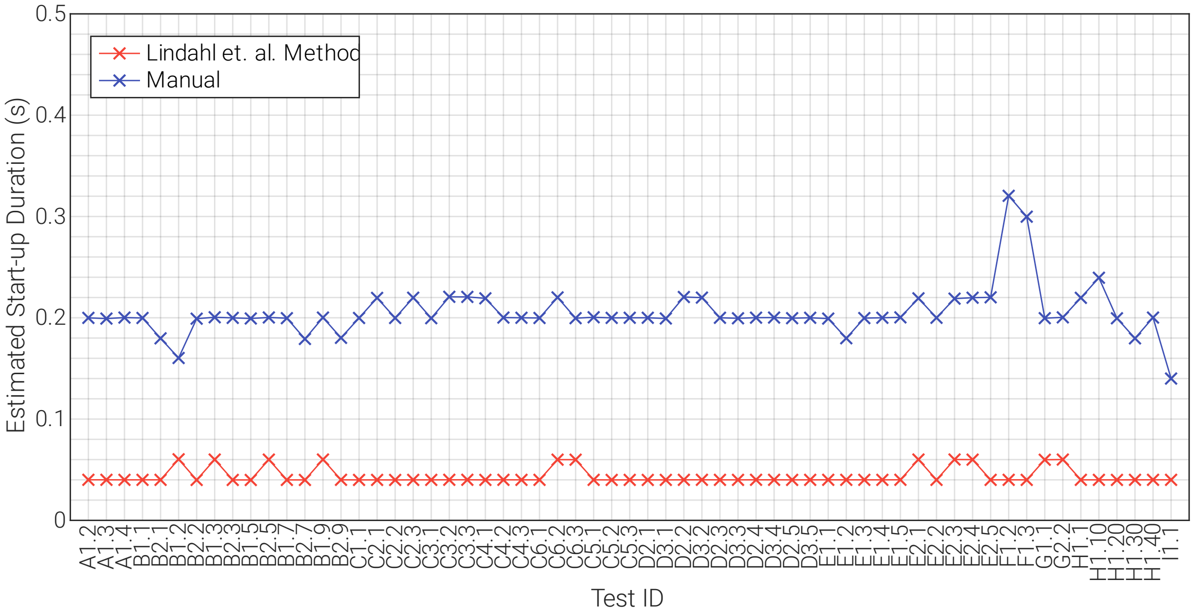

Figure 10.10: Duration of start-up transients as estimated by Lindahl method compared with manual estimates.

As illustrated in Figure 10.11 when applied to CCT data the Differentiator method as implemented by Lindahl et. al. generates two significant peaks within the time series, each associated with a transition between states and thus the distance between which is approximately equal to the start-up duration. However, between the peaks the value of the processed signal falls to near zero, meaning the signal falls below the second threshold prior to the second peak and thus an inaccurate estimate of the start-up up duration is produced. The poor performance of this approach can be attributed to fundamental differences in the characteristics of CCT start-up transients when compared to the form of transient analysed by Lindahl et. al., which are characterised by a step increase to a peak value of consumption, followed by an approximately exponential decay until eventually steady-state conditions are reached.

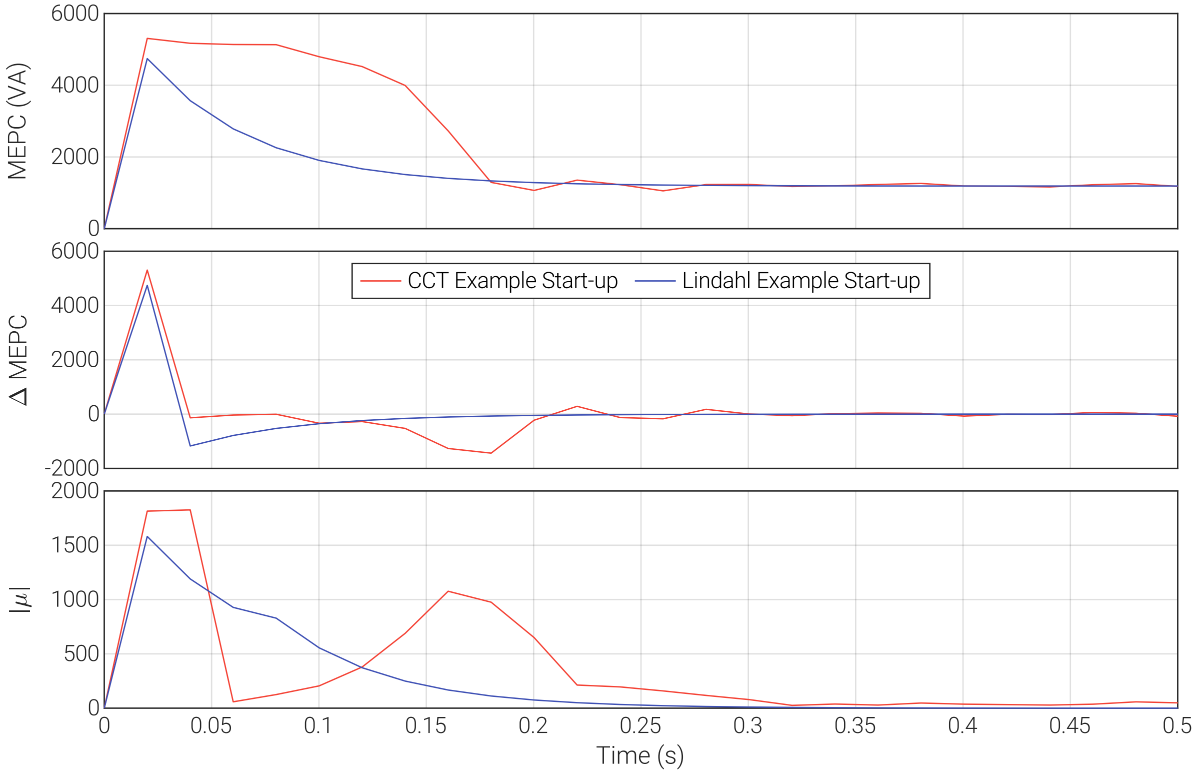

Figure 10.11: Comparison of the form of CCT start-up events and the form of transients analysed by Lindahl et. al. Note the presence of a double peak within the CCT transient.

To account for this difference the method implemented by Lindahl et. al. can be modified such that the second threshold is only activated after two distinct peaks have been identified in the filter output (y^*). Peaks are detected using a simple peak detection algorithm[59] with the constraint that only peaks above 200VA be included and the second peak is defined as the peak following the highest amplitude peak. When this Differentiator Method is applied to CCT data much improved duration estimates are produced, and the effect of changes in tension are able to be clearly identified (Figure 10.12).

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[59] Again, *findpeaks* is employed for this task.

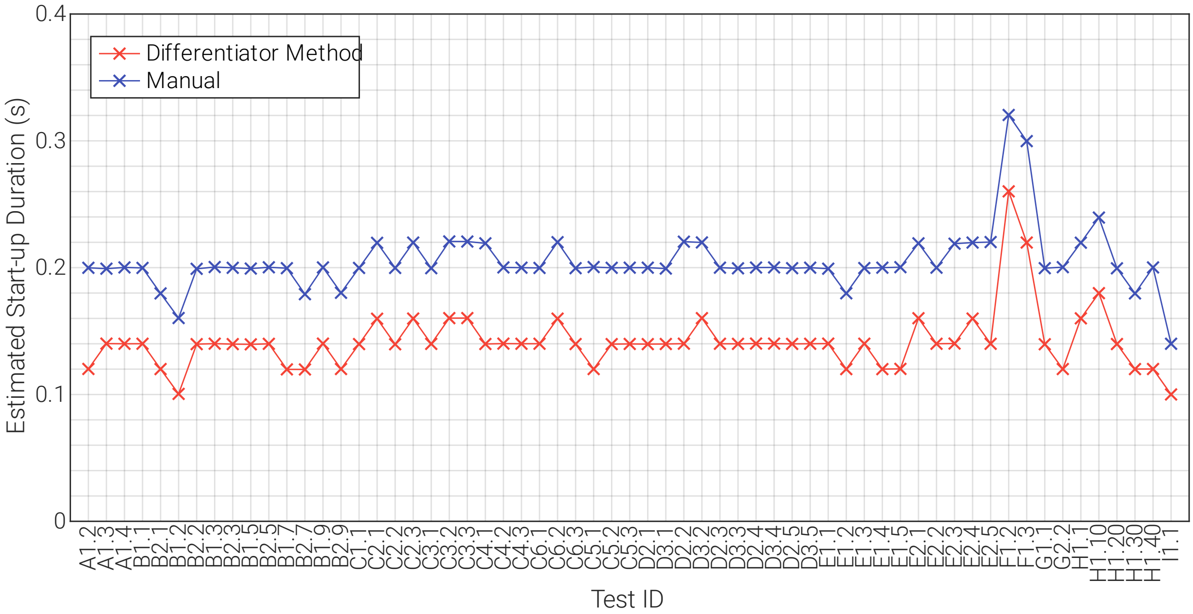

Figure 10.12: Duration of start-up transients as estimated by the Differentiator method compared with manual estimates.

As with the Moving Range method the Differentiator method produces significant under-estimates of durations compared to manual values consistently across test scenarios. However, good correlation with the general characteristics of manual estimates can be seen.

10.3.3 Wavelet Energy Method

A wavelet is a wave-like function which is localised in time, that is, it possesses the characteristics of having finite energy (i.e. beginning and ending with zero amplitude) as well as having zero mean (i.e. an integral of zero). Accordingly, a wavelet function can take many different forms, commonly used examples of which are depicted in Figure 10.13. A wavelet function has two properties which can be manipulated; either the wavelet can be moved in time relative to a signal (location) or it can be stretched or shrunk in time (scale).

Wavelets have found wide application to the analysis of time series data where, unlike traditional Fourier analysis, they provide a means for analysing a signal simultaneously in both frequency *and* time, most notably within the JPEG 2000 image standard for the lossy compression of images [235]. This makes the wavelet particularly suited to the analysis of non-stationary signals (i.e. non-sinusoidal) which exhibit transient characteristics. Whereas Fourier analysis decomposes a signal into a series of purely sinusoidal waveforms of various frequencies[60], in

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[60] And therein makes an assumption that the signal is composed of only imaginary components i.e. pure sinusoids.

wavelet analysis a signal is decomposed into timed-shifted and scaled versions of the specific wavelet used (referred to as the *mother* wavelet), as illustrated in Figure 10.13.

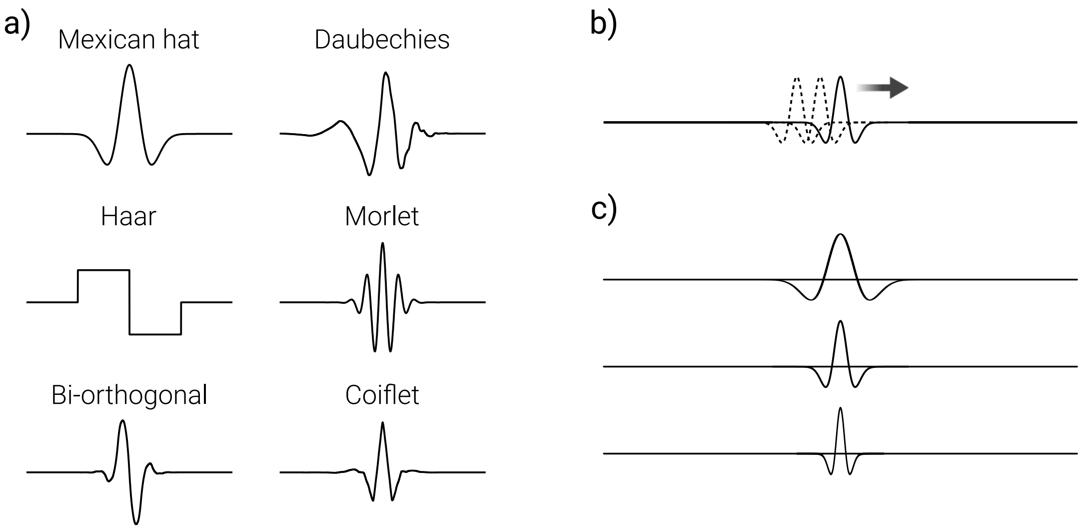

Figure 10.13: Some commonly employed mother wavelets (a) and the concept of location (b) and scale (c) (adapted from [235]).

The continuous wavelet transform (CWT) is defined mathematically as the convolution of a signal with a specific wavelet function i.e. [236]:

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^* \left(\frac{t-b}{a}\right) dt \qquad 10.4$$

Where $x(t)$ is the input signal, $\Psi^*(t)$ is the complex conjugate of a mother wavelet, a is a scale parameter and b a location parameter.

Essentially, when performing a wavelet transform the input signal is convolved with scaled versions of the mother wavelet and at locations where the two strongly correlate the output of the transform will be correspondingly significant, as illustrated in Figure 10.14.

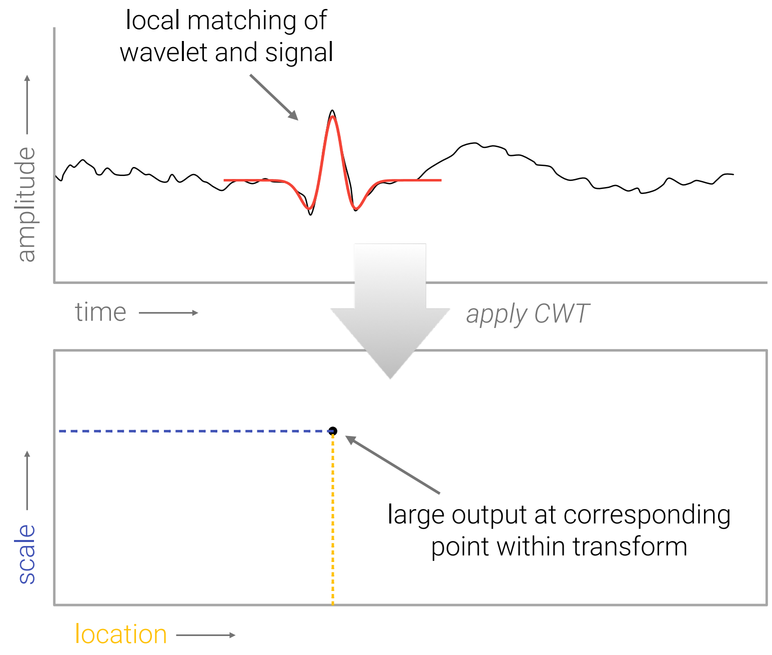

Figure 10.14: Graphical depiction of the basic operating principle of the wavelet transform (adapted from [235]).

Accordingly, given the sensitivity of the wavelet transform to transient characteristics potentially it can be used to estimate the duration of start-up events. In this context wavelets have already found employment, with Daviu et. al. [237] developing two different methods based upon the Discrete Wavelet Transform (DWT) for the analysis of induction motor start-up events to detect the presence of broken rotor bars.

For the purpose of analysing start-up transients a Haar mother wavelet is selected. The Haar wavelet is essentially a square wave with an amplitude which alternates between zero and one, formally described by:

$$\psi(t) = \begin{cases} 1 & 0 \leq t < \frac{1}{2} \\ -1 & \frac{1}{2} \leq t < 1 \\ 0 & otherwise \end{cases} \tag{10.5}$$

and its scaling function by:

$$\varphi(t) = \begin{cases} 1 & 0 \leq t < 1 \\ 0 & otherwise \end{cases} \tag{10.6}$$

As such the Haar wavelet is a non-continuous function which is therefore not differentiable. However, this property makes it particularly suited to the detection of sudden transitions within signals, such as start-up transients due to its instantaneous transition between states.

To implement the wavelet transform for the estimation of start-up transients first a DWT is applied to each start-up, using a Haar mother wavelet[61]. A DWT represents a specific implementation of a CWT (as described by Equation 10.4) wherein the scaling (a) and location (b) parameters are discretely sampled, typically in accordance with a dyadic grid (i.e. logarithmic power-of-two) in an operation termed *dyadic decimation*[62] [239]. The DWT is then performed by passing the input signal simultaneously through a pair of low and high pass filters[63] designed around the Haar mother wavelet, bifurcating the input signal into a low pass (termed *approximate*) and high pass (termed *detailed*) representation of the signal. This filtering stage can then be repeated on each representation within a filter bank arrangement of the form depicted in Figure 10.15 to increase the frequency resolution of each representation.

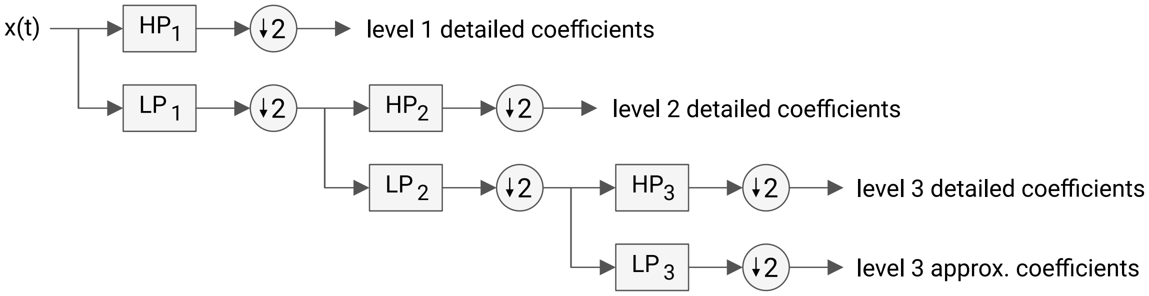

Figure 10.15: Filter bank arrangement of the DWT, showing three levels of decomposition.

Because half of the frequency content of the original signal has been removed in each representation each is downsampled by a factor of two before the next stage of filtering, in accordance with the Nyquist-Shannon Sampling Theorem [238]. This filtering process can be successively applied until the point where fewer samples remain in the lowest level's representation of the signal than there are in the mother wavelet; the maximum level of decomposition possible can thus be determined by:

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[61] A summary of the DWT process is included here, however for an exhaustive overview the reader is directed to [236] or [238], both seminal works in the area.

[62] This essentially equates to downsampling by an integer factor of 2.

[63] These are designed such that they oppose each other so that when the output of each is summed together the original signal is reproduced. A filter of this form is termed a *Conjugate Mirror filter* and is fundamental to the design of the DWT [238].

$$d_{max} = log_2(N) \qquad 10.7$$

Where D_{max} *is the maximum level of decomposition possible for an input signal of length N.*

The output of the DWT at each decomposition level is therefore a vector containing detailed coefficients associated with that level (high-pass representations), plus a single vector at the final decomposition level containing approximate coefficients (low-pass representation), an example of which is presented in Figure 10.16.

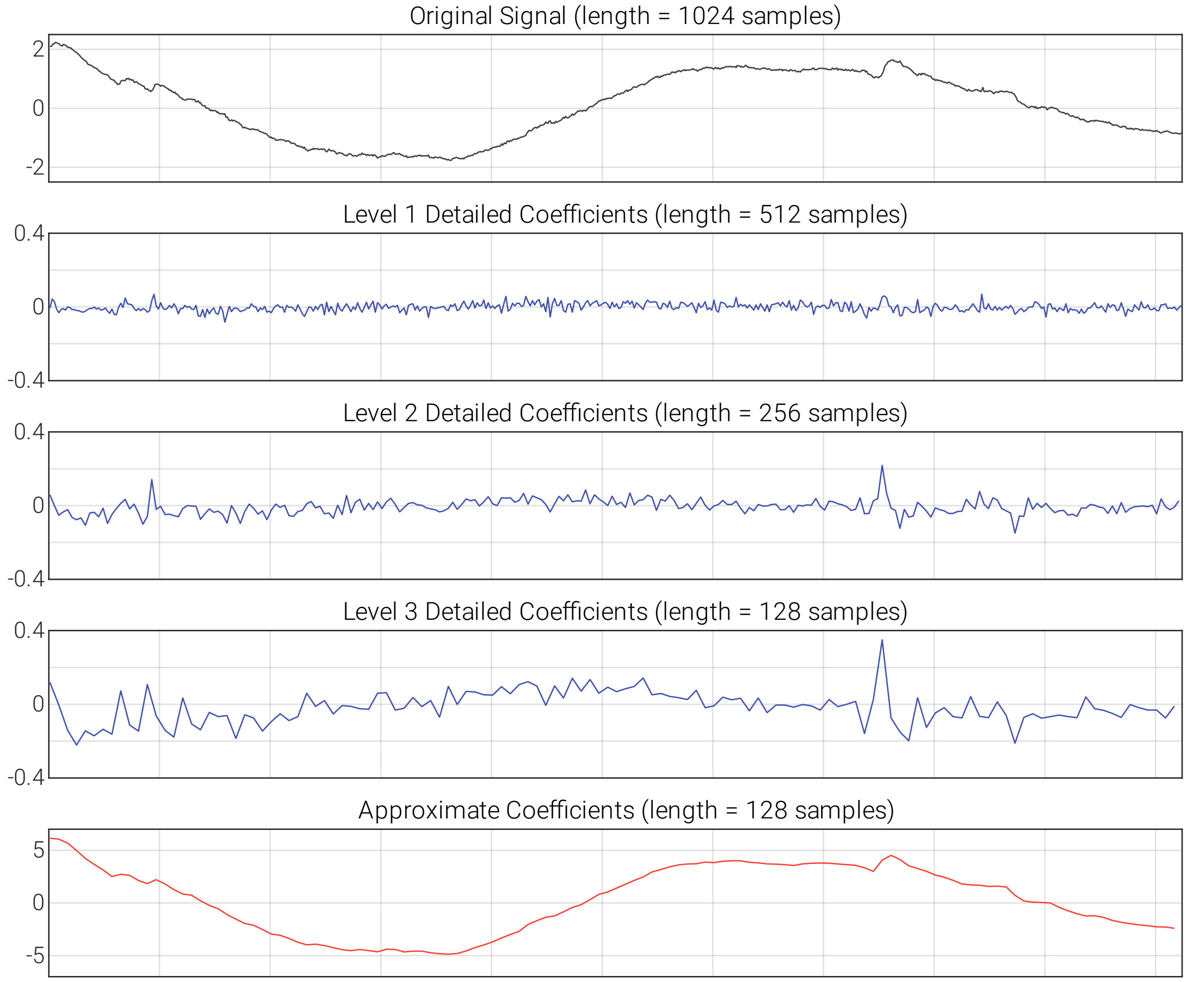

Figure 10.16: Example of the typical DWT process showing the decomposition of a signal into approximate and detailed coefficients. Note the trade-off between time and frequency resolution.

As the level of decomposition is increased the frequency content within the signal narrows and thus frequency resolution increases; in contrast, as half the samples are lost from the signal at each level the time resolution decreases correspondingly [235], as illustrated in Figure 10.16.

For the purposes of analysing start-up transients a DWT is performed on a segment of 64[64] samples taken from the first non-zero consumption value, in accordance with the dyadic requirement of the DWT. Given the length of input signals a maximum of 6 levels of decomposition can be performed, in accordance with Equation 10.7, resulting in each level containing frequency content approximately in accordance with the bands presented in Table 10.3.

Table 10.3: DWT decomposition levels and associated frequency bands for 50Hz sampled segments of length 64.

Level	Frequency band (Hz)	Samples
1	25 - 12.5	32
2	12.5 - 6.75	16
3	6.75 – 3.375	8
4	3.375 – 1.6875	4
5	1.6875 – 0	2

However, it should be noted that, in practice these bands provide only an approximation of the content contained within each; in practice a degree of leakage across levels will occur. The DWT has the property that the energy[65] contained within the input signal is preserved at each decomposition level within the transform [235]. Accordingly, once the DWT has been performed on the original signal the energy contained within each level can be calculated as the square of the sum of all absolute values within each detailed coefficient vector i.e.:

$$E_{l\_n} = \left(\left|d_{l\_n}\right|\right)^2 = \left(\left|d_{l\_n1} + d_{l\_n2} + \cdots d_{l\_np}\right|\right)^2 \qquad 10.8$$

Where E_{l_n} *represents the energy at level n,* d_{l_n} *represents the detailed coefficient vector at level n and* d_{l_np} *represents element* p *within that vector.*

Thus, for each start-up transient a five element vector of energies can be produced, where each element corresponds to the proportion of the total signal energy contained within that level.

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[64] Based upon the 50Hz sample rate and a maximum observed start-up duration of ~0.4s 64 samples should be sufficient.

[65] In this context the term 'energy' refers to the integral of the squared magnitude of a signal [227].

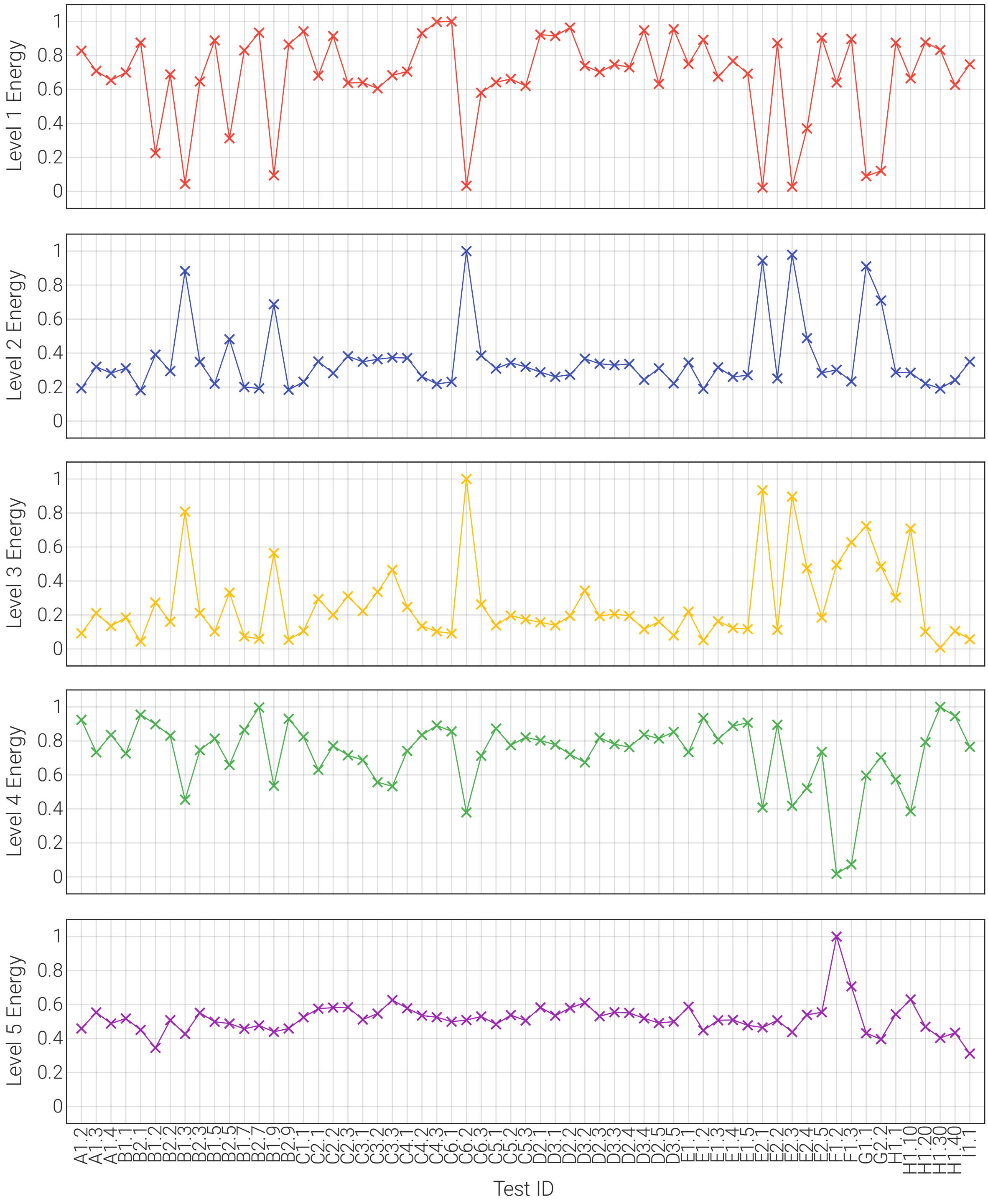

Figure 10.17: Energy by level contained within Haar DWT of each CCT start-up event. N.b. the energy at each level is normalised in the range 0-1.

When the energy at each level within the DWT representation of each start-up is interrogated a correlation between the signal energy at scale 5 and the relative duration of the start-up can be identified (Figure 10.17). As indicated in the analytic frequency bands associated with each level of the decomposition (Table 10.3), based upon an input signal length of 64 samples, at the fifth level only 2 samples remain in the output, reflecting the low pass filtering action of the DWT. With only two samples the representation of the original signal at the fifth level essentially constitutes a straight line between the first and last elements within the input signal, as illustrated in Figure 10.18.

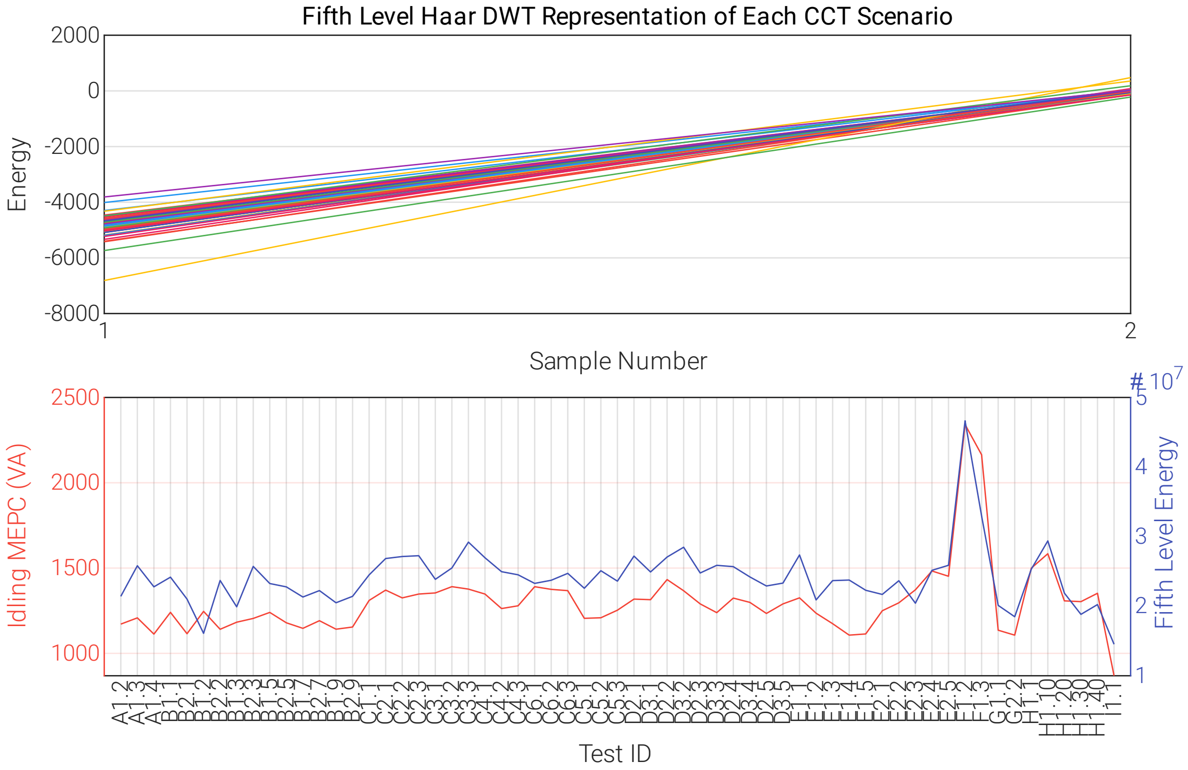

Figure 10.18: Fifth level representation of each CCT scenario (top) and comparison of fifth level energy and idling MEPC (bottom).

Accordingly, it is likely that the apparent sensitivity of the fifth level to the duration of start-ups is actually a sensitivity to the idling consumption of the System, which, as shown in Figure 10.18, also presented sensitivity to changes in belt health during CCTs. Furthermore, as seen in Figure 10.19, the absolute duration of each start-up is not able to be estimated directly from the magnitude of the fifth level energy.

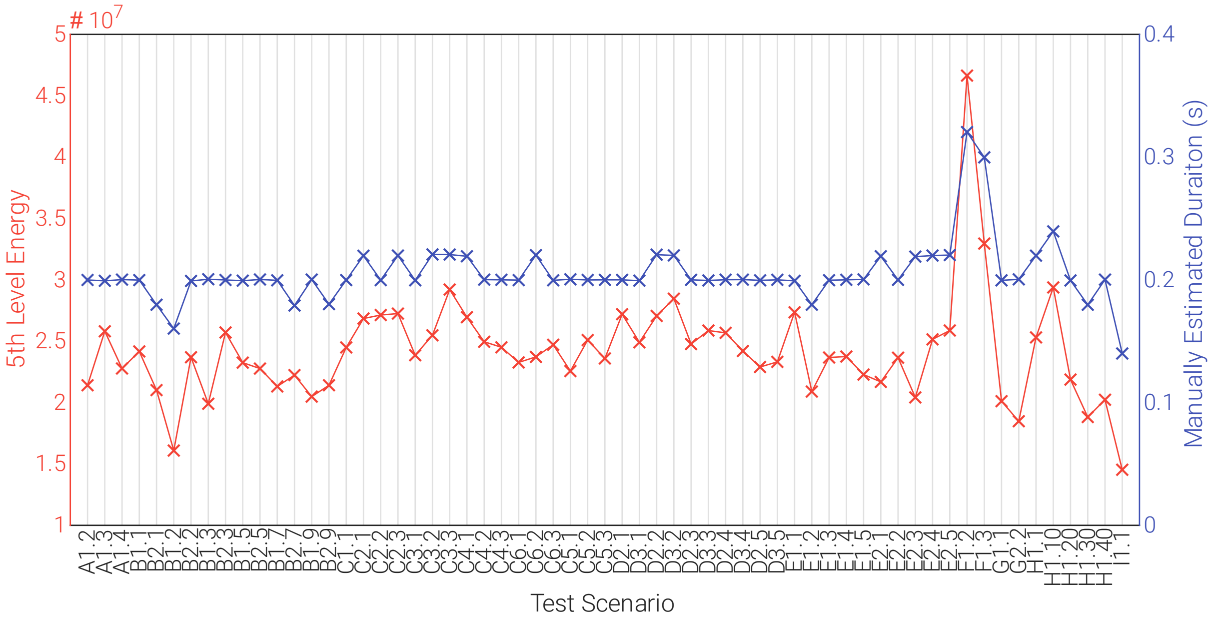

Figure 10.19: Comparison of motor start-up durations during CCT scenarios based upon manual estimations and the value of the fifth level energy of the Haar-based DWT.

In practice, an ability to detect relative changes in start-up duration is likely to be as valuable as estimating the absolute duration of each start-up. However, to translate wavelet energy into an absolute estimate of start-up duration a scaling factor can be applied to each estimate. The scaling factor can be calculated as the mean of the absolute difference between each start-up's manually estimated and level 5 Haar wavelet signal energy i.e.:

$$\alpha = \frac{\sum(|t_{man} - t_{Haar}|)}{n_{start-ups}} \qquad 10.9$$

Where t_{man} *represents a vector containing the manually estimated duration of each start-up,* t_{Haar} *represents a vector containing Haar DWT-based estimates of duration and* $n_{start\text{-}ups}$ *is the total number of scenarios.*

When this scaling factor is applied to each estimate close correlation between manually and wavelet-based estimated durations is produced, as presented in Figure 10.20.

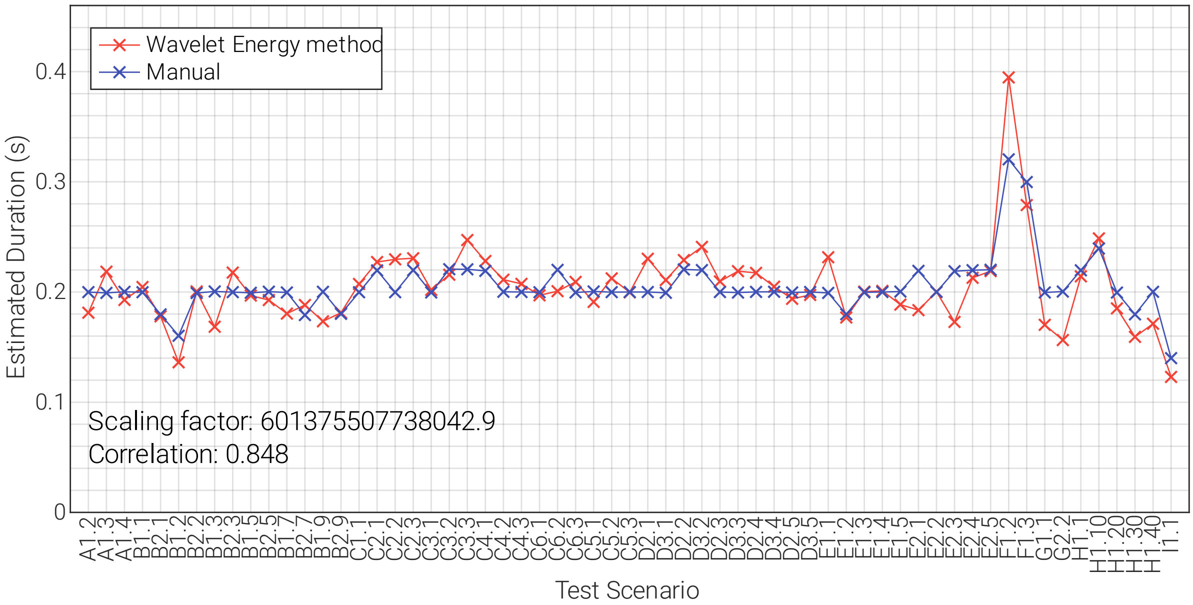

Figure 10.20: Duration of start-up transients as estimated by Wavelet Energy method compared with manual estimates.

10.3.4 Template Correlation Method

This method is inspired by the Matched filter, an optimal technique for detecting a signal of known shape in the presence of additive noise. The Matched filter is a widely used technique within radar applications, where it enables the signal-to-noise ratio of received signals to be maximised by passing only the energy associated with signals of the form originally emitted [240]. Essentially, the Matched filter seeks to identify the presence of a deterministic signal (i.e. one of known characteristics) which is corrupted by white[66], Gaussian[67] noise by performing a cross-correlation between a noisy input signal and a time-delayed version of a template signal, enabling (most of) the noise to be removed from the signal. Mathematically this operation is equivalent to a convolution between the input signal and a time-reversed conjugated version of the template signal [68] and thus the impulse response of the matched filter $g_a(t)$ to the input signal corrupted by noise $s*(t)$ is given by [241]:

$$g_a(t) = k \cdot s^*(t_0 - t) \qquad 10.10$$

where k represents a filter gain and t_0 represents a time delay parameter.

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[66] i.e. of uniform power across all frequencies contained within the signal.

[67] i.e. normally distributed in the time-domain, with zero mean.

[68] See [240] for an exhaustive proof.

Given an input signal $x(t)$ of the form:

$$x(t) = s(t) + n(t) \tag{10.11}$$

where $n(t)$ represents a corrupting white Gaussian noise component.

The output signal of the Matched filter $y(t)$ then becomes:

$$y(t) = x(t) * g_a(t) = \int_{-\infty}^{\infty} x(t) g_a(t - t_0) dt \tag{10.12}$$

i.e. the cross-correlation between the input signal and time-shifted versions of the template signal, producing an output signal such as in the example presented in Figure 10.21.

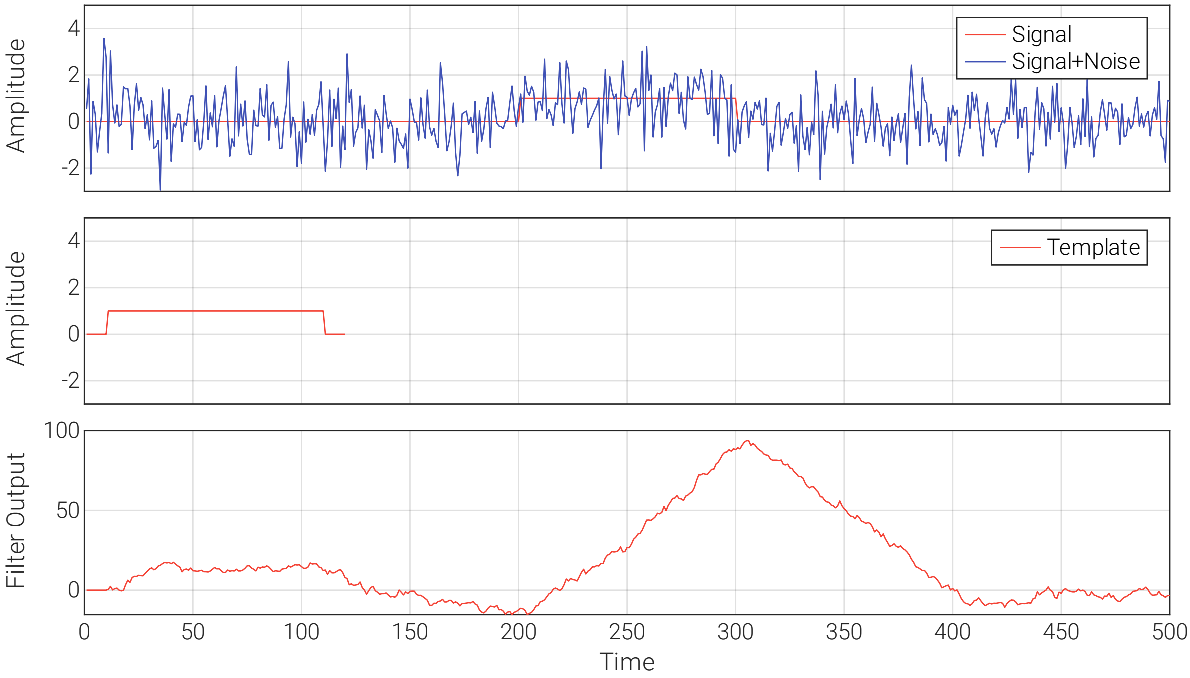

Figure 10.21: An example Matched filter implementation. An input signal corrupted by white, Gaussian noise (top), the associated signal template (middle) and the filter output (bottom) indicating the presence of a match.

Accordingly, the principles of Match filtering can potentially be leveraged to estimate the duration of start-up transients. In this scenario the characteristics of the input signal (i.e. start-up transients) are well understood and varying in only one respect across test scenarios (i.e. duration). Therefore, by constructing a series of template signals of different widths (each representing a different duration) and calculating the correlation between each template signal and the input signal the template signal closest to the input signal can be identified and thus the start-up duration estimated. As only the duration of start-ups is expected to change across scenarios template signals can be simplified to square waves of varying duty, as illustrated in Figure 10.22.

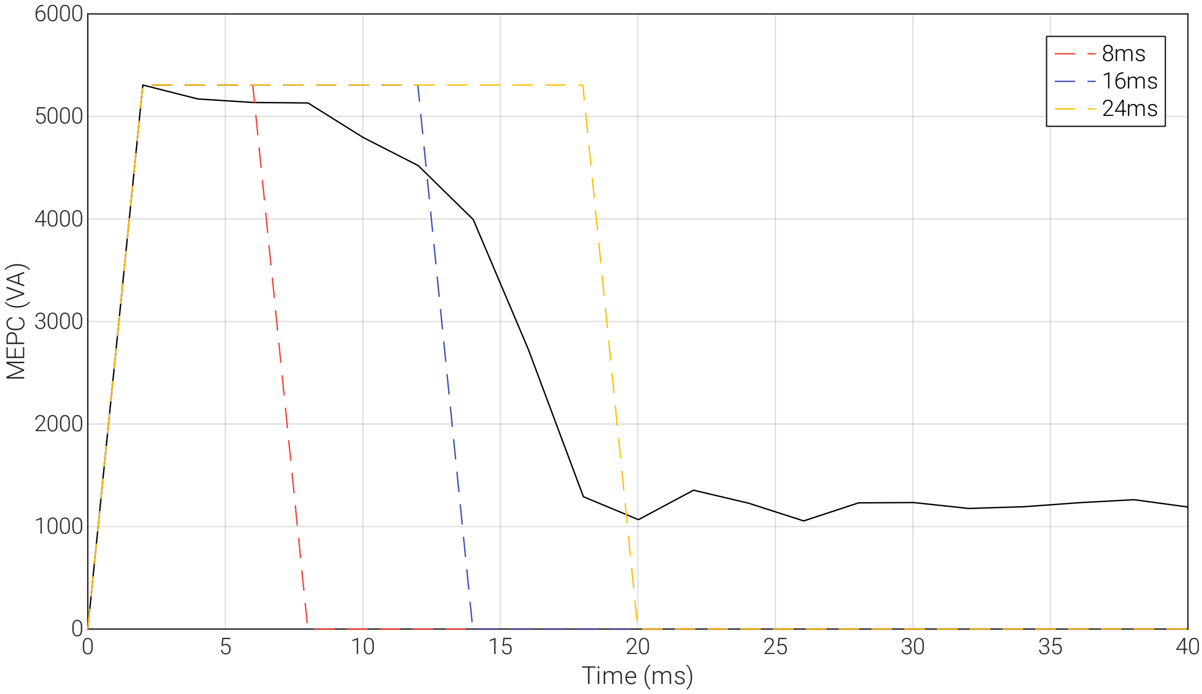

Figure 10.22: Illustration of the principle of the Template Correlation method. A start-up duration of 16ms is estimated based upon it representing the closest correlation between the input signal and each template.

Unlike in a Matched filter, the expected location of maximum correlation is invariant across scenarios (i.e. the start-up event always begins at the same location within each signal, it is only the point at which the start-up ends which varies across signals) therefore, the cross-correlation at this specific location only (i.e. when the signals are aligned) can be extracted by taking only the maximum correlation coefficient i.e.:

$$y_{xcorr}(n) = max(x \star t_a) = max\left(\overline{x} * t_a\right) = max\left(\sum_{-\infty}^{\infty} \overline{x}(-d)\ t_a(n-d)\right) \qquad 10.13$$

Where $\star$ *represents a cross-correlation operation,* $*$ *represents a convolution operation,* $\overline{x}$ *represents the complex conjugate*[69] *of a start-up transient time series and* $t_a(n\text{-}d)$ *represents a delayed version of a specific template signal.*

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[69] As the input signals are non-complex the conjugate is purely a time-reversed version of the original signal.

This calculation can be performed for each template signal defined and the duration of the transient estimated by identifying the template signal which produces maximum correlation with the start-up signal.

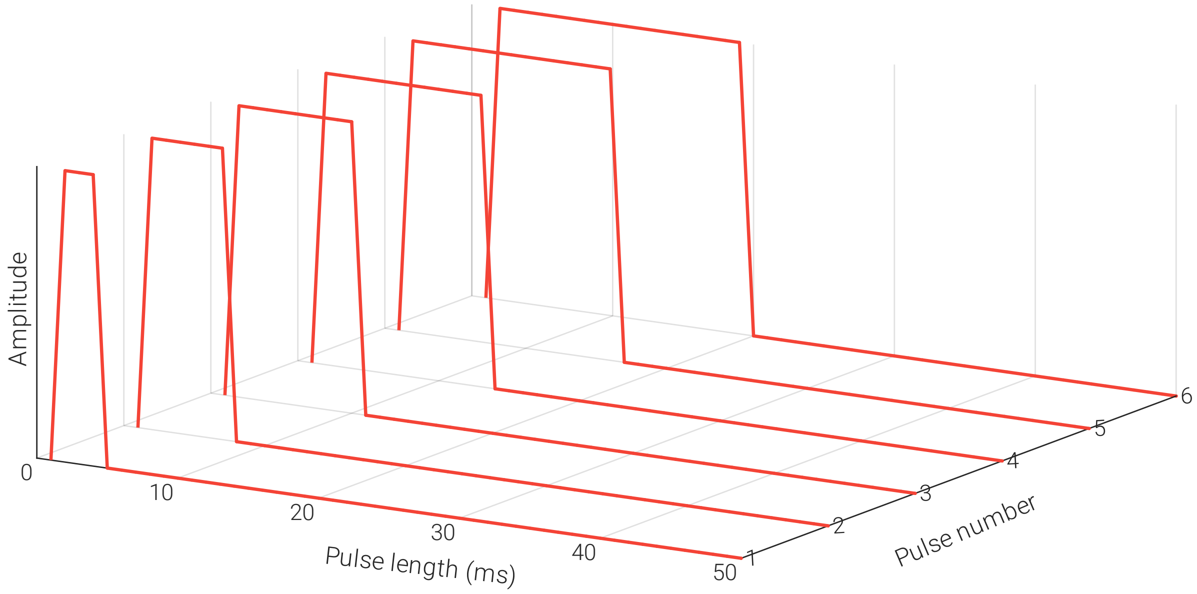

Figure 10.23: Examples of reference pulses as used within the Template method.

When applied to CCT scenarios, as observed with previous methods, overall the Template method underestimates the duration of start-ups in comparison to manual estimates (Figure 10.24). Again, however, sensitivity to changes in the belt state can be identified within estimated durations, with off-tracking belt scenarios particularly emphasised.

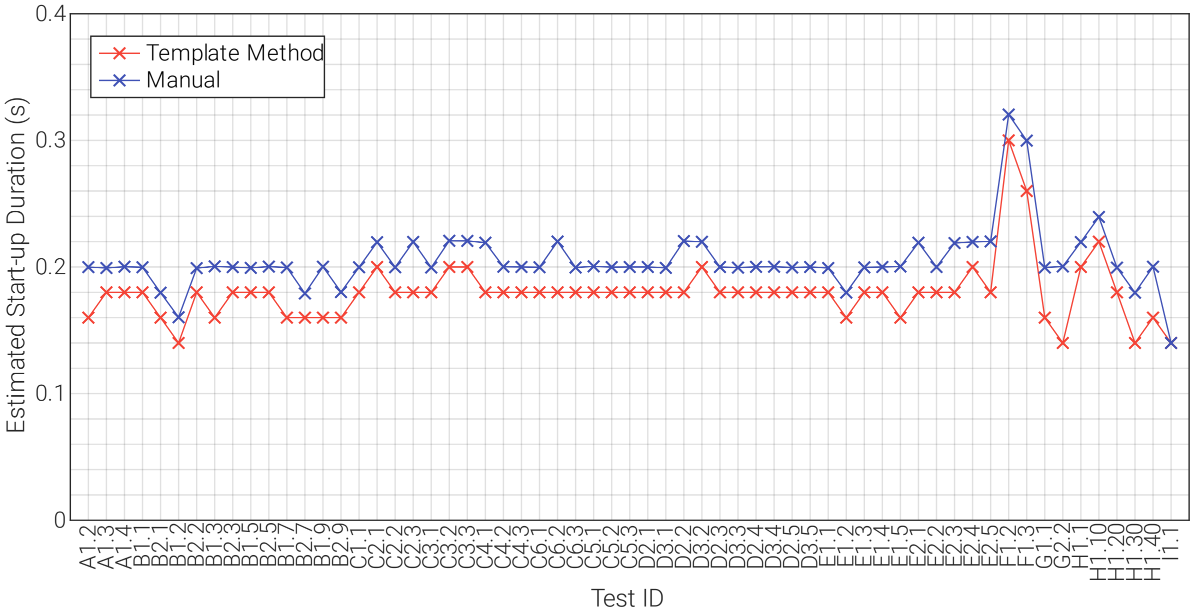

Figure 10.24: Duration of start-up transients as estimated by Template method compared with manual estimates.

As described the Template method implements a ‘brute force’ approach to identification of the most correlated template (i.e. calculating the correlation of all defined templates), potentially incurring unnecessary computation. To improve upon this some form of search algorithm such as Simulated Annealing or a Genetic Algorithm could be employed to reduce computation. However, as the analysis of start-up events is not expected to run in real-time the additional computation associated with a brute force approach is likely acceptable.

10.3.5 Evaluation of Proposed Methods

Each of the developed methods demonstrate sensitivity to changes in start-up transient duration. As shown in Figure 10.25, all methods produce a mean error of less than 0.06ms (3 samples) across all CCT scenarios in comparison to manual estimates.

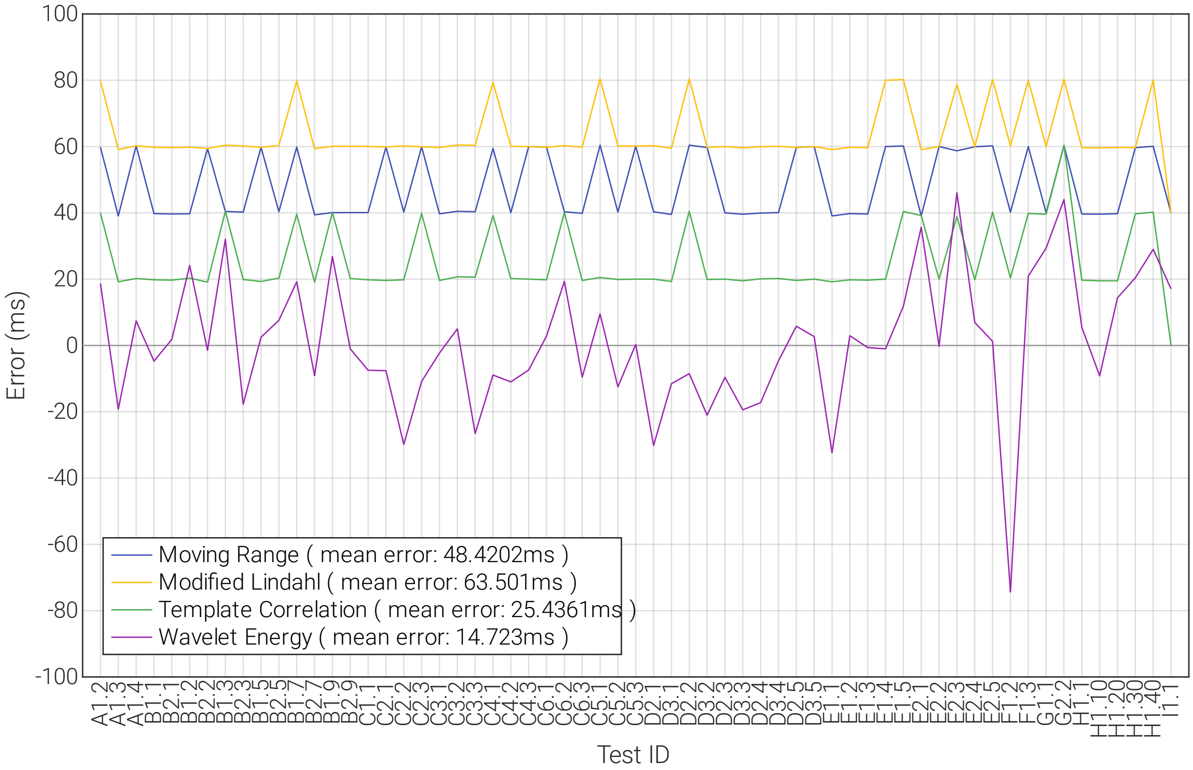

Figure 10.25: Comparison of error across CCT scenarios between manually and each method’s estimated start-up duration.

Overall, the Wavelet Energy method produces the lowest mean error across all scenarios (~15ms), followed by the Template Correlation method (~25ms), the Moving Range method (~48ms) and the Modified Lindahl method (~64ms), which is to be expected given the method incorporates a scaling factor designed explicitly to minimise error with manual estimates.

However, in contrast to the other three methods, significant variance is present within the error produced by Wavelet Energy, as seen in Figure 10.25.

Given the comparable performance demonstrated by each method the selection of which to employ for the task is dictated primarily by their ease of implementation. All methods have been developed for acausal application, that is, to be implemented on collected data as a post-processing task to provide sights. Accordingly, this will induce a delay between the occurrence of start-ups and the estimation of their duration, however, given that all methods require minimal computational effort such delay will likely be insignificant i.e. an order of <2s post start-up. Of the four methods the Differentiator Method requires the definition of two static thresholds and the Wavelet Energy method requires scaling of estimates to produce absolute durations, both of which will require initial and on-going manual effort to determine appropriate values for each application. The Moving Range Method requires no such manual definitions, however, to produce accurate estimates it relies upon an assumption that the second most prominent peak within data will correspond with the transition to Stage 3. In contrast, the Template Correlation Method can be implemented for any application without prior effort or knowledge of the specific CBS's characteristics, therefore, it represents a suitable approach for the estimation of start-up transients of the form observed during CCTs.

10.4 Exceedance Analysis

As identified in Chapters 2 and 3, manufacturers and operators are currently afforded limited visibility of how systems are being used in-service, restricting their ability to understand patterns of usage across systems. As discussed in Section 10.1 the concept of a system's usage is application-specific; in the context of CBSs one means by which a system's usage can be described is based upon the characteristics of its material throughput (i.e. live load). During the completion of CCTs an increase in MEPC was observed in response to the presence of live loads on the belt. As described in Chapter 8 when live loads were discrete in nature (i.e. 'lumps') a corresponding spike (i.e. localised in time) in power consumption was generated as each mass was loaded onto the System's belt, the magnitude of which was a function of the loading height, quantity of mass loaded and the System's inclination. Together, the individual effect of each factor combines to produce a single external load to the system, which, in the case of the belt, must be reacted by the drive motor in order to preserve belt speed. The more frequent and severe these loads are the more work the system must do and thus it can be asserted more usage. Accordingly, by analysing the characteristics of a system's MEPC over time the loads it has been subjected to can be understood and thus differences in usage patterns across systems can be inferred.

The analysis of a system's live load throughput can thus be considered a form of Operational Loads Monitoring (OLM), the principles of which involve taking measurements of the loads (internal or external and either direct or indirect measurements) a system is subjected to whilst in operation and using these to understand system degradation, typically with a view to estimating life consumption. OLM found initial application during the early 1980s within the aerospace sector as part of a general safety initiative to reduce the unacceptably high accident rate associated with helicopter craft [38]. Within the scope of HUMS, monitoring systems were introduced to enable a craft's flight profile to be characterised and loading cycles to be counted, from which the progression of fatigue damage in particular could be estimated, based upon previously identified relationships between loading cycles and fatigue related failure modes. To count the number of loading cycles experienced by a component a number of techniques were developed based around the concept of categorising exceedances of loads above predefined thresholds into bands, enabling time series data to be transformed into objective descriptions of flight profiles.

The basic principles of exceedance analysis for cycle counting can be exploited for the purpose of characterising in-service CBS loads. In a manner similar to the characterisation of a specific aircraft's flight profile, CBS usage can be characterised through analysis of transient events within MEPC as generated by the loading of mass, as a proxy for the mechanical loads it is subjected to and thus its live load throughput. MEPC cannot be considered an exact indicator of live load throughput; as seen during CCTs other factors can induce changes in MEPC, such as poor belt tracking or damage to the belt. However, ultimately all such events result in additional stressing of the drive motor which will impact upon its condition, so contribute to a system's usage.

This section summarises a multi-step process for the detection and characterisation of transients within MEPC, based upon the principles of exceedance analysis. The overall process is illustrated in Figure 10.26, output from which is a measured termed Total Weighted Exceedances.

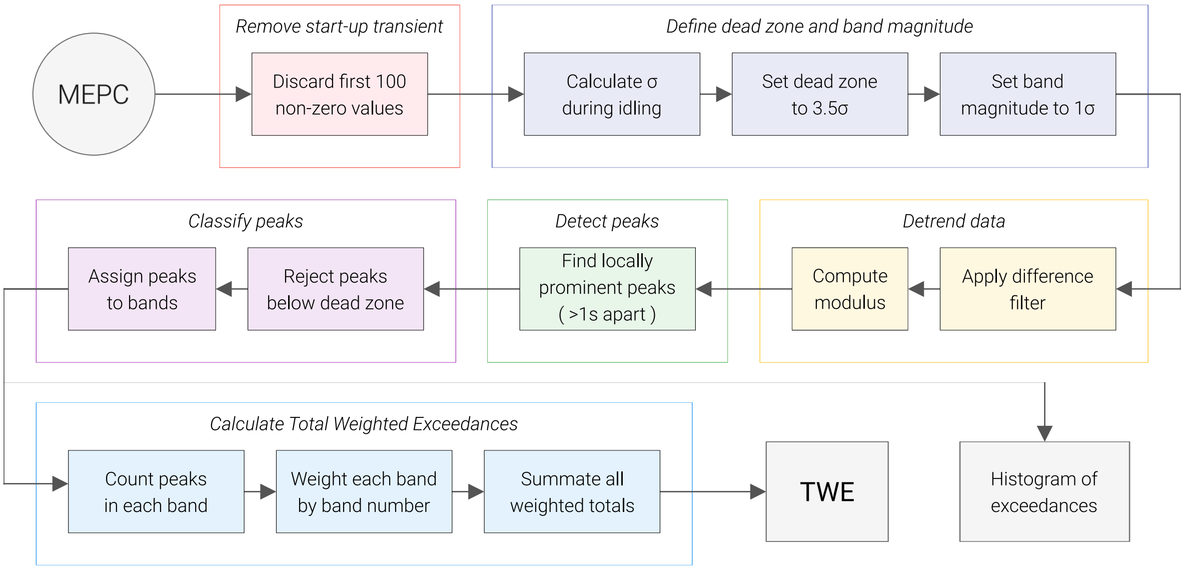

Figure 10.26: Major steps within the process for deriving Total Weighted Exceedances.

The process comprises six main steps and is again designed for acausal implementation (i.e. the process is applied retrospectively to segments of time series data post measurement, as opposed to operating in real-time, point by point). Firstly, to remove transient behaviour associated with start-up events (which are analysed independently, as described in Section 0) the initial second of operation post start-up is removed from each time series. Next, to remove variation in idling consumption across systems and scenarios a detrending step is implemented, in which the absolute difference between samples is computed, as illustrated in Figure 10.27. A prefiltering step to remove broadband noise induced by the measurement process is not included as any such filtering would impact the magnitude of transients, obscuring their 'true' impact upon MEPC.

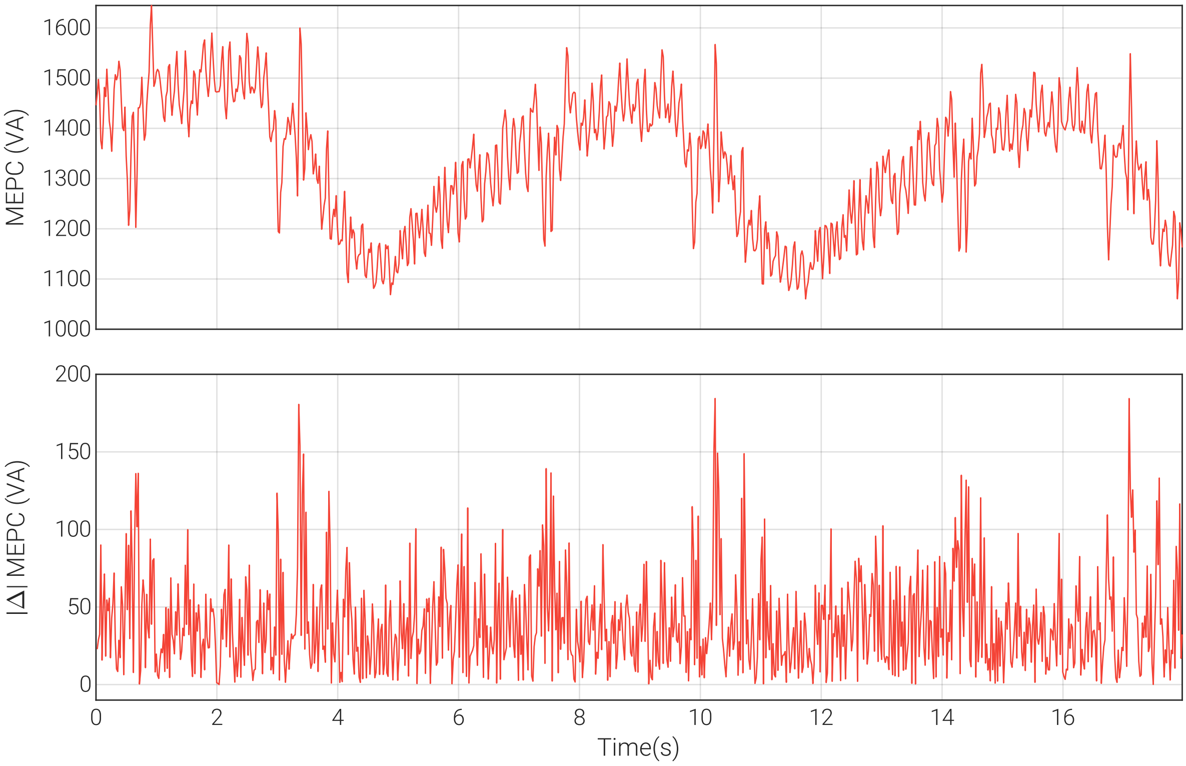

Figure 10.27: Illustrative example of the effect of taking the absolute difference of a signal. Note the detrending effect produced.

Next, peaks present within processed time series data are detected, where a peak is defined as a locally prominent maxima within data, where prominence refers to the significance of a peak relative to peaks in close proximity. As illustrated in Figure 10.28 the local prominence criterion prevents peaks in close temporal proximity from being counted. As observed during CCTs the loading of a discrete mass could induce a number of closely spaced local peaks in MEPC, however, given practical constraints it can be asserted that peaks associated with the loading of discrete masses will not occur faster than ~1Hz. Therefore, through appropriate definition of the proximity threshold (d_{min} in Figure 10.28) it can be ensured that a single mass will only be counted once.

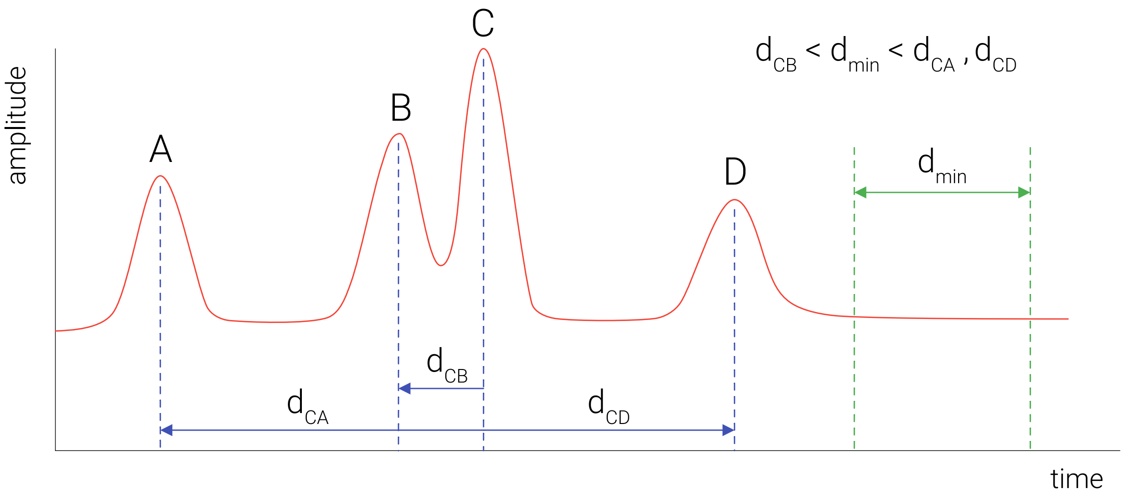

Figure 10.28: Illustration of the concept of a peak's prominence. Peak C is the global maximum so is counted. Of peaks A, B and D only A and D are further away than the minimum proximity defined (d_{min}) so A and D are counted but not B.

The task of detecting peaks within time series data is generic and as such can be achieved through any number of different algorithms[70]. For this application the MATLAB *findpeaks*[71] algorithm is used, which will identify local maxima, defined as any data point which is greater than its two neighbouring data points.

Once all peaks which satisfy the local prominence criterion have been detected each peak is categorised into one of a range of predefined bands of exceedance, based upon its amplitude. However, given the presence of electrical noise within measured data it cannot be assumed that all identified peaks represent transient increases in mechanical load on the drive motor. Therefore, to prevent measurement noise from being captured within exceedance banding analysis a *dead zone* is applied, which essentially defines a minimum amplitude which peaks must exceed to be counted. The amplitude of the dead zone must be defined appropriately, such that noise-induced peaks are excluded without 'true' peaks being excluded. In Chapter 6 measurement noise was analysed and found to be approximately white in nature and of constant amplitude; this knowledge can be exploited to set an appropriate dead zone. Using the concept of *the rule of three sigma* and the known standard deviation (σ) of typical measurement noise a dead zone can be defined statistically.

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[70] This (https://stackoverflow.com/questions/22583391/peak-signal-detection-in-realtime-timeseries-data) Stack Overflow question provides a good discussion on various methods for peak detection.

[71] See https://uk.mathworks.com/help/signal/ref/findpeaks.html for an overview of the *findpeaks* algorithm.

Table 10.4: Expected rate of exceedance of measurement noise based upon an assumed Gaussian noise distribution and 50Hz sample rate. (μ: population mean, **σ**: standard deviation about mean).

Range	% samples within	Samples between exceedances	Time between exceedances (hrs)
μ	68.27	3	0.0000167
μ + 1.5σ	86.64	7	0.0000389
μ + 2σ	95.45	22	0.000122
μ + 2.5σ	98.76	81	0.000450
μ + 3σ	99.73	370	0.00206
μ + 3.5σ	99.95	2149	0.0119
μ + 4σ	99.99	15787	0.0877
μ + 4.5σ	99.9993	147160	0.818
μ + 5σ	99.99994	1744278	9.690
μ + 5.5σ	99.999996	26330254	146.279
μ + 6σ	99.9999998	506797346	2,815.541

As presented in Table 10.4, were a dead zone of three sigma to be used a noise-induced exceedance could be expected only every ~7.4s (0.00206hrs), which is clearly unacceptable. In contrast, doubling the dead zone to six sigma would reduce the expected frequency of erroneous peaks to once every ~117 days, however, at the likely cost of excluding 'true' peaks. A trade-off between rate of false positives and false negatives, therefore, a value of 4.5 sigma is selected, offering good sensitivity whilst an expected error of just under once per hour.

Beyond the dead zone a series of equi-spaced bands of exceedance are defined, with each band also 4.5 sigma in amplitude (~147VA) and a total of twelve[72]. The selection of band size and total number of bands is somewhat arbitrary; a greater number of bands will obviously provide greater granularity of categorisation but at the cost of complexity of interpretation. To count peaks a number of different variants of specific cycle count definitions are used, as defined in the 'Standard Practices for Cycle Counting in Fatigue Analysis' produced by ASTM International [242]. For this application a modified version of the *peak counting* variant is selected; as the

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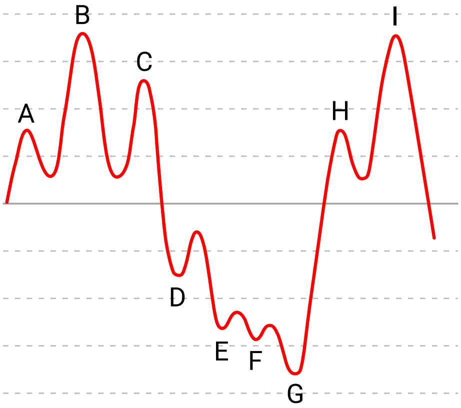
[72] The maximum band is defined to extend to infinity to ensure peaks of any theoretical amplitude are counted.

absolute difference of samples has already been computed only positive peaks need be counted (or, in fact, will be present within data).



Band	Counts
+4	0
+3	2
+2	1
+1	2
-1	1
-2	2
-3	1
-4	0

Figure 10.29: Definition of a counted peak within the Peak Counting Method, as defined by ASTM International within 'Standard Practices for Cycle Counting in Fatigue Analysis' [242].

Once all peaks have been counted into appropriate bands the breakdown of a system's loading during that period can be analysed, as presented in Figure 10.30 for the example of scenario D2.3 and Figure 10.31 for scenario D2.4.

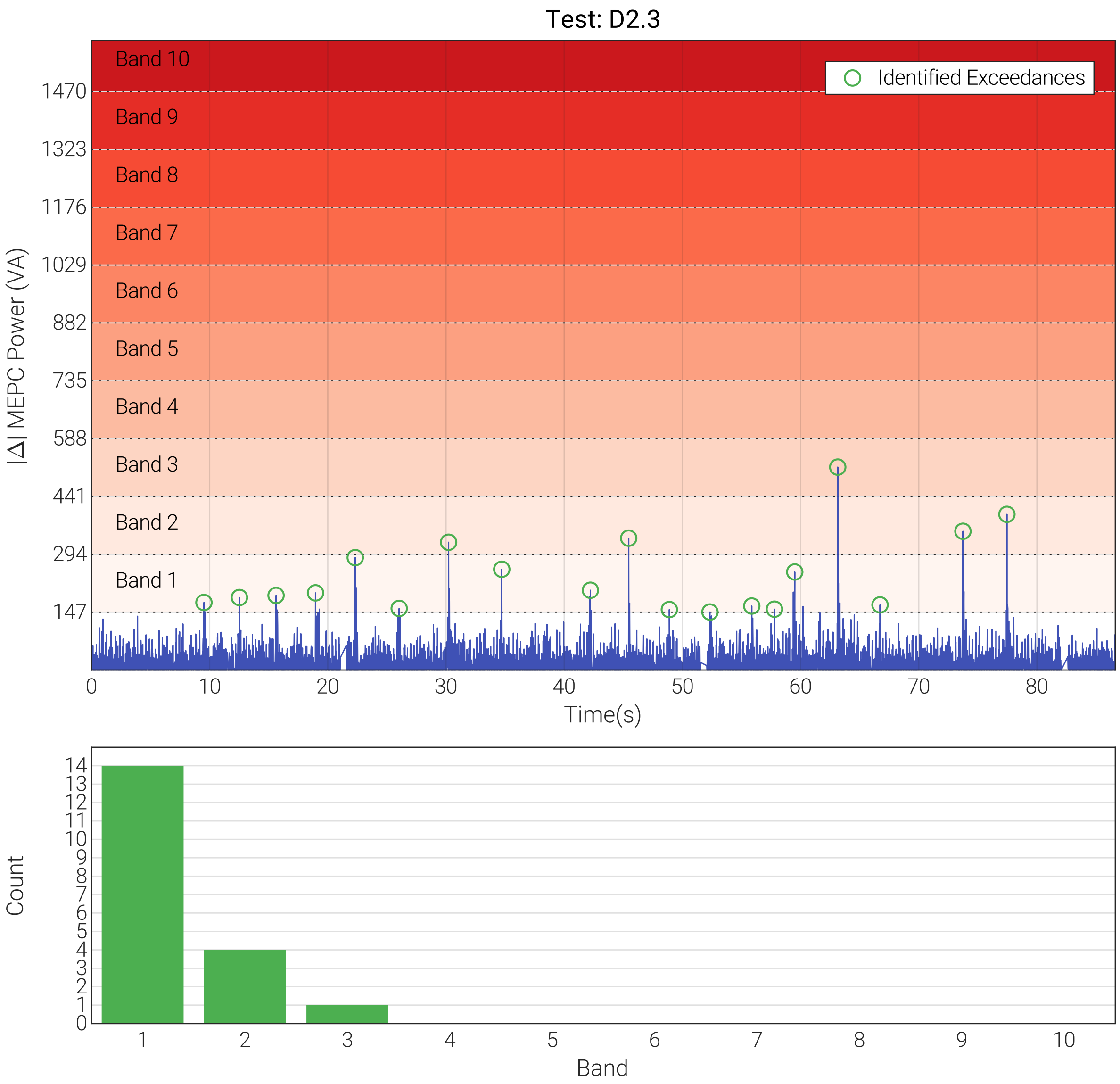


Figure 10.30: Exceedance banding method as applied to test scenario D2.3.

During D2.3 (Figure 10.29) a total of twenty 10kg masses were placed onto the System, however, when analysed using the exceedance banding method only 19 exceedances are counted. Due to the quantity of mass and loading height the transient torsional load transferred to the motor is not significant and so not all live load-induced peaks fail to exceed the dead zone. It should also be noted that due to the limitations associated with the DAQ system employed as described in Chapter 6 some live loads may have coincided with periods when data was being transferred and so cannot be identified within measured data. Overall, throughput during D2.3 is estimated as being minimal, with no exceedances above Band 3, in which there is only one. In contrast, analysis of scenario D3.4 (x15 20kg masses from 0.3m height) reveals that 15 exceedances are identified, in accordance with the 15 live loads applied during the test (Figure 10.31).

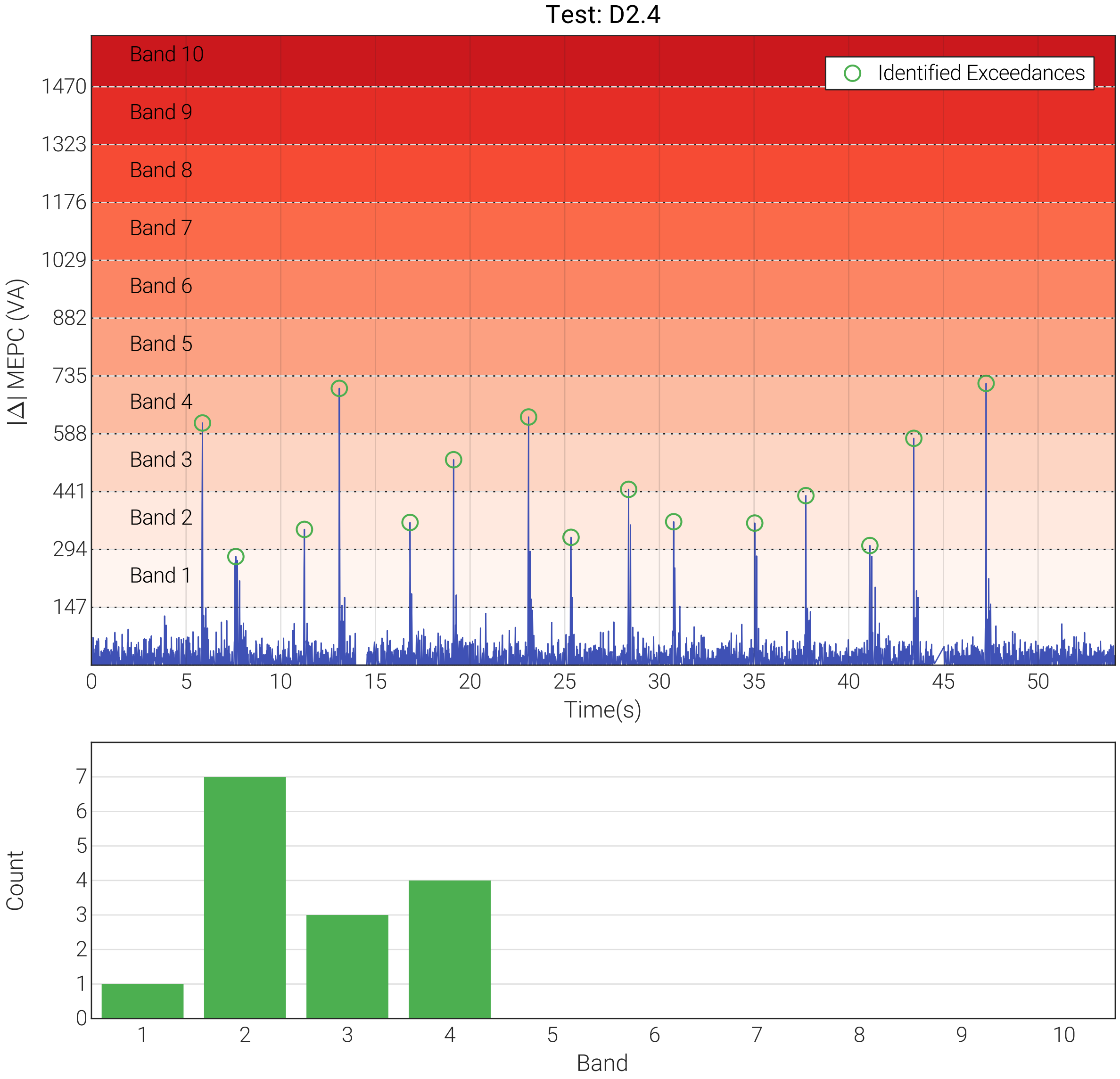


Figure 10.31: Exceedance banding method as applied to test scenario D2.4.

The relative energy associated with 20kg masses from 0.3m is clearly far greater than that of 10kg placed masses, resulting in a much more significant braking force being experienced by the drive motor, as reflected by the specific bands within which counted peaks fall.

To further simplify interpretation, the output of exceedance banding analysis can be converted into a single descriptor. Most simply, the total number of exceedances can be considered buy summing the count within each band i.e.:

$$c_{total} = c_1 + c_2 + \cdots + c_n \qquad 10.14$$

Where c_n *represents the count in band n, and n equals the total number of bands.*

However, this approach obfuscates the magnitude of each exceedance by treating all counts as equally impactful. To compensate for the magnitude of each exceedance a weighing factor can be applied to each count, for example, equal to the band number i.e.:

$$l_{total} = (1 \cdot c_1) + (2 \cdot c_2) \cdots + (n \cdot c_n) \qquad 10.15$$

This adjustment will produce a descriptor (termed Total Weighted Exceedances (TWE)) which is sensitive to the actual magnitude of exceedances and can therefore be considered a proxy for the total torsional load experience by a drive motor. However, it should be noted that many different forms of weighting could be implemented if more appropriate, such as non-linear weighting (e.g. exponential, quadratic). When linear weighing of the form described in Equation 10.15 is applied across all CCT scenarios variable correlation between the total actual mass throughput and the linearly weighted total exceedances can be observed (Figure 10.32).

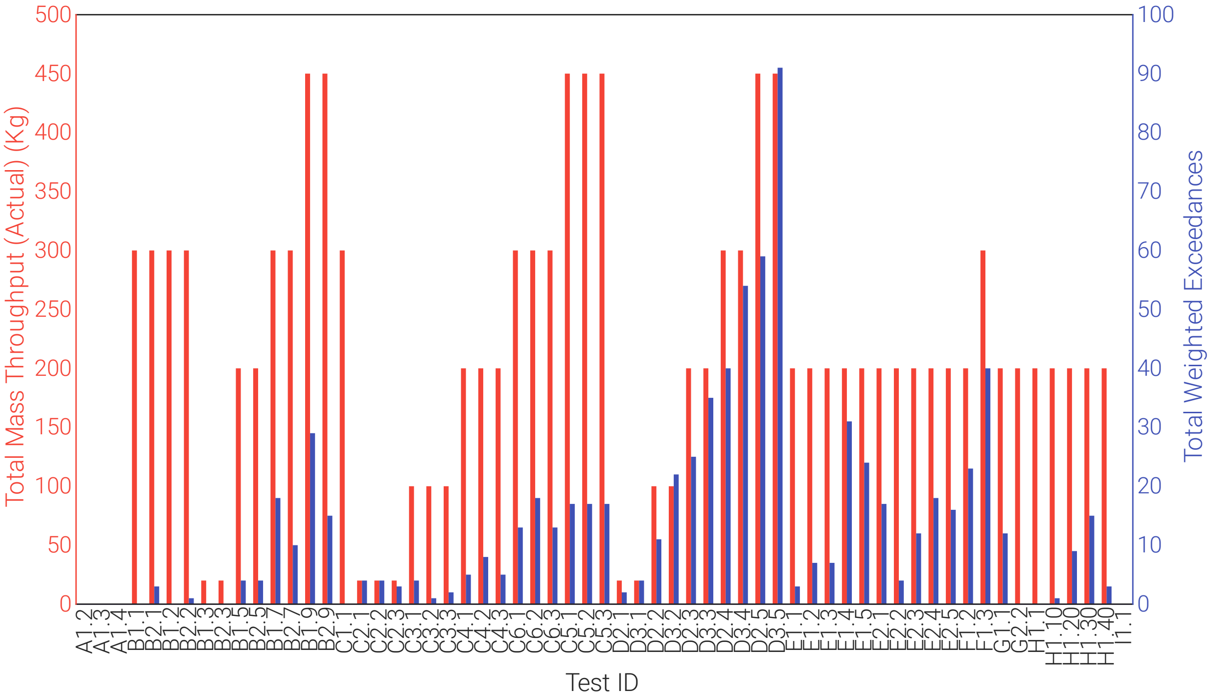


Figure 10.32: Exceedance band method applied across all CCT scenarios, showing the comparison between actual mass throughput (total) and output of exceedance banding analysis using weighted total.

For example, during D scenarios (varying load height) good correlation is observed, suggesting good sensitivity of the TWE to torsional motor load. However, in other scenarios (e.g. B1.1, B2.2) a large discrepancy exists between actual total mass throughput and TWE; in these such scenarios whilst the total mass throughput is significant the rate of braking power generated is minimal due to the low rate of material loading. To account for this behaviour, it is more appropriate to compare TWE to the approximate potential energy associated with each discrete mass loaded during each test i.e.:

$$E_{in} = m\ g\ h \tag{10.16}$$

Where m refers to the quantity of mass loaded, g is the Gravitational Constant and h refers to the height from which the mass was loaded[73].

When TWE is then plotted against the approximate relative energy associated with each live load mass $\left(E_{liveLoad}\right)$ a much closer correlation is seen (Figure 10.33).

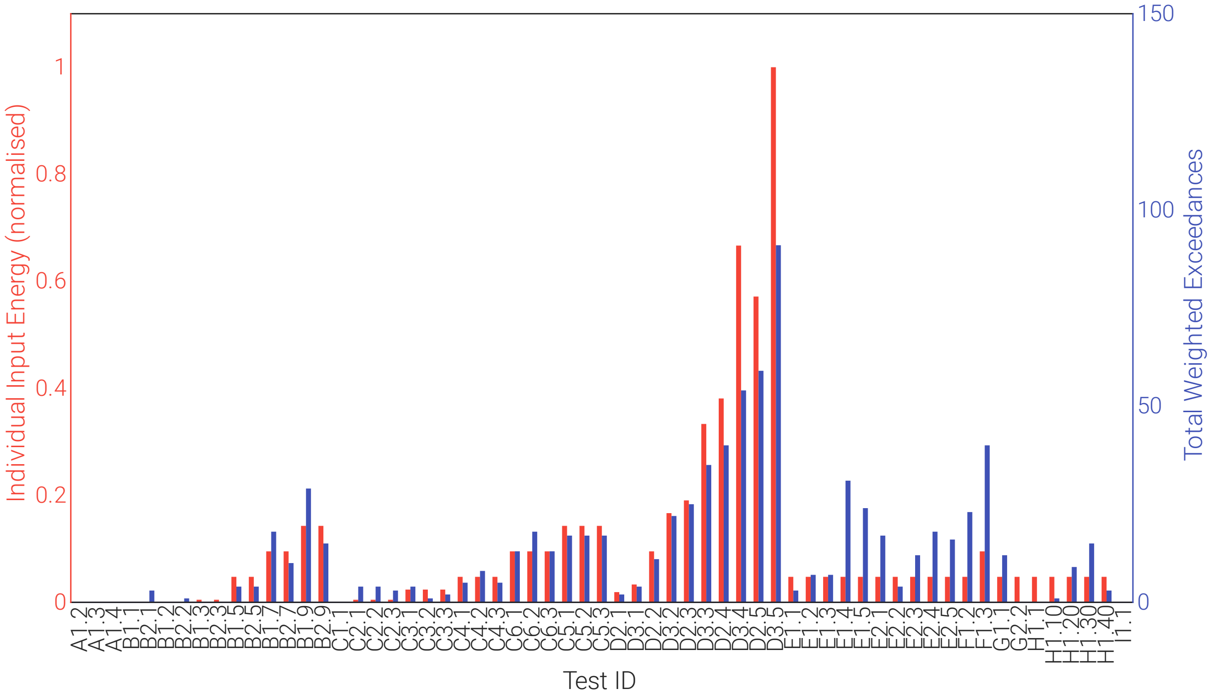


Figure 10.33: Exceedance band method applied across all CCT scenarios, showing the comparison between approx. energy associated with each discrete live load and total weighted exceedances.

The combined effect of increases in live load quantity and loading height can be seen across tests C and D. However, as expected, smaller quantities of live load as well as continuous streams of material are not captured within TWE.

TWE as a descriptor can then be considered as a cumulative measure, as presented in Figure 10.33, or, to account for the actual time which each system is operated the TWE can be

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[73] N.b. to avoid multiplication by zero a baseline value of 1m is added to each nominal loading height, reflecting the approximate height of the system's belt from the ground during tests

normalised by periods of operation (e.g. minutes or hours) and presented as the rate per period, as shown in Figure 10.34.

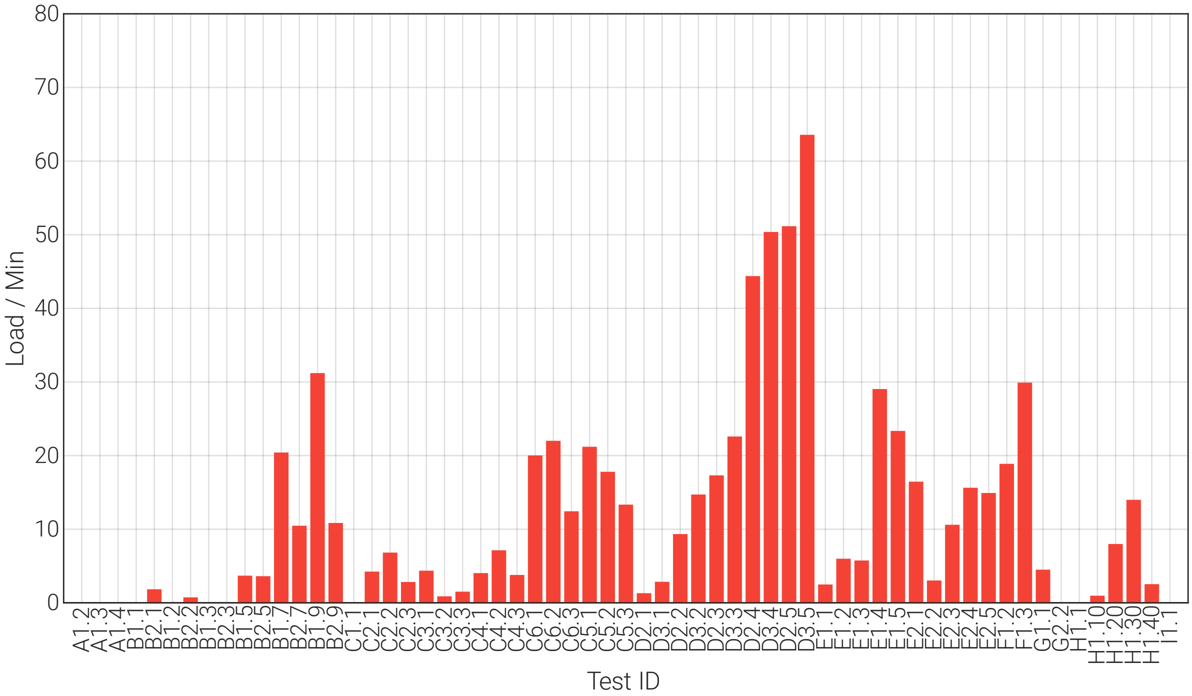


Figure 10.34: Total Weighted Exceedances across all CCT scenarios, normalised by running time.

This adjustment permits the relative intensity of usage to be compared across different systems, regardless of actual operating time. Through this descriptor the usage profile of each specific system can be assessed, whether this be across systems within a facility, as per the Operator or across distributed systems leased to customers, as per the Manufacturer. In the case of CCT data, a conversion to units per time does not provide significant additional insight as generally CCTs were all of similar duration, however, in the general case such conversion may provide value.

To further simplify the interpretation of TWE the concept of Functional Usage Profiles (FUPs) as proposed by Tinga et. al. [231] can be utilised, in which the usage of a system is classified into a limited number of profiles. Together these profiles are defined such that they reflect only the essential variation in operational usage experience by a system, without needing to accurately understand relevant mechanisms of failure. A relative rate of degradation is then specified for each profile, such that it is only necessary to track the relative occurrence of each usage profile to estimate the appropriate preventative interval. For example, the authors present the case of a military helicopter, for which three FUPs are defined based upon flight hours conducted in saline areas (0%, 0-25% and 25-100%). Using historical data combined with a known phenomenological model describing the effects of saline air on corrosion a degradation rate is defined for each profile and an associated inspection interval. The authors propose three methods for identifying usage profiles and associated degradation rates; expert opinion, phenomenological models and field data, however, they suggest that the most appropriate choice will likely be application-specific and thus it is difficult to provide generic guidelines.

The concept of FUPs can be adopted to further simplify the interpretation of TWE, by converting the magnitude of TWE into a higher-level usage categorisation, for example, light, medium and heavy duty periods of operation. A simple implementation of the FUP concept can be achieved by applying a thresholding process to the time-normalised magnitude of TWE to produce a times-series of categorise system usage (Figure 10.35).

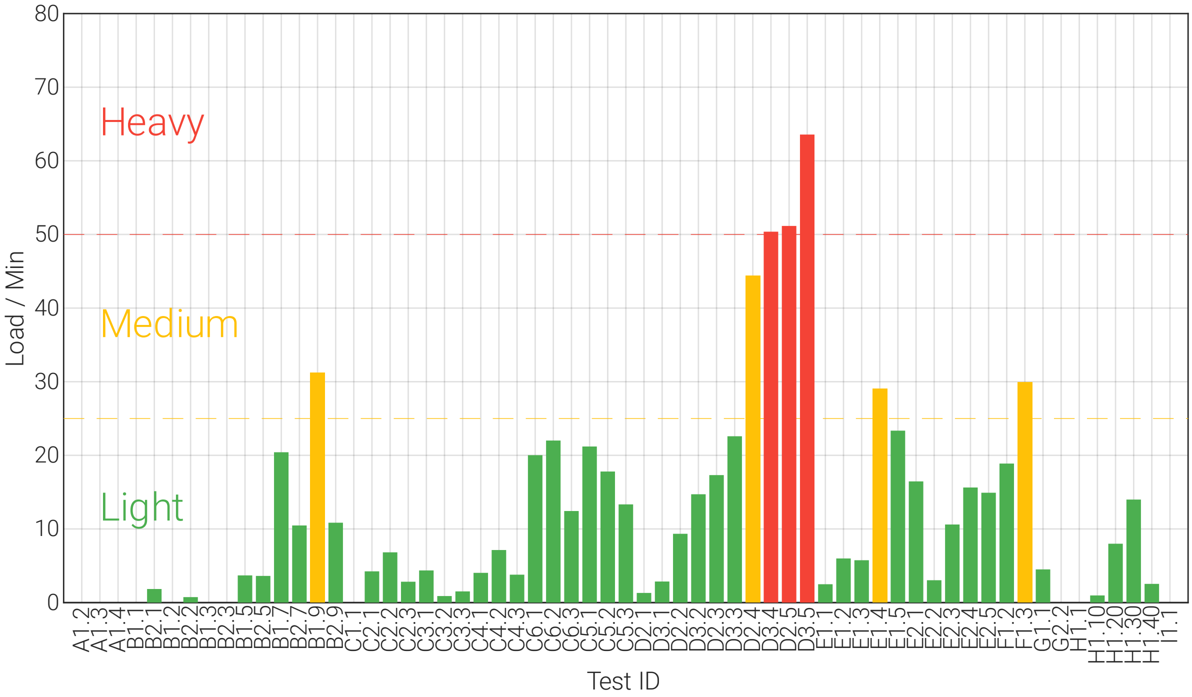


Figure 10.35: Total Weighted Exceedances across all CCT scenarios, normalised by running time coloured by duty.

Clearly, the categorisation produced is dictated by the specific thresholds defined; For this application, values of 25 for medium duty and 50 for heavy duty have been applied to demonstrate the concept, in practice some work would be required to understand the most appropriate thresholds, in a manner similar to the selection of preventative intervals. The key advantage of TWE however is its ability to isolate the effect of variance in usage across different CBSs from the effect of variation in absolute (or even relative) time in operation.

10.5 Belt Damage Severity

As described in Section 10.1, within data acquired during the completion of CCTs it is possible to identify the presence of lateral damage to the System's belt through specific changes in MEPC. As seen in Figure 9.29, when the severity of belt damage increased a corresponding increase in the amplitude of the frequency component associated with the rotational period of the belt (and its harmonics) was observed.

Given the previously identified impact of belt issues to operators and manufacturers, through both direct (parts and labour) and indirect (lost operation) costs, an ability to identify the occurrence of belt damage automatically and through non-invasive means is potentially of significant value. Accordingly, in this section the development of a data descriptor sensitive to belt damage of the form seeded during CCTs is presented.

During CCTs a total of 41 belt damage scenarios were conducted, with each representing an increase in damage magnitude from an undamaged belt through to 400mm of lateral damage, in 10mm increments. During the development of a belt damage data descriptor test scenarios are segmented into a development dataset containing scenarios corresponding to 0, 100, 200, 300 and 400mm damage magnitudes and a validation dataset containing all scenarios containing other magnitudes of damage.

As with start-up transients the characteristics of the artefacts induced within MEPC by the presence of lateral belt damage are not entirely stationary and are therefore well suited to wavelet-based analysis. Using the principle of the Wavelet Energy method presented in Section 10.3.3 the MEPC associated with various magnitudes of damage can be decomposed into the energy contained within each decomposition level, in accordance with the high-level logical flow illustrated in Figure 10.36.

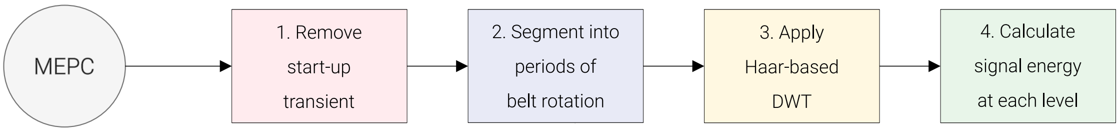


Figure 10.36: High-level logical flow of the proposed belt damage data descriptor.

Each scenario within the development dataset is first subdivided into lengths of data approximately equal to one revolution of the belt (approx. 6.8s), based upon the measured instantaneous speed. To comply with the dyadic condition imposed by the DWT segments are rounded up to 512 samples long (padded equally on either end), resulting in adjacent segments partially overlapping, as illustrated in Figure 10.37.

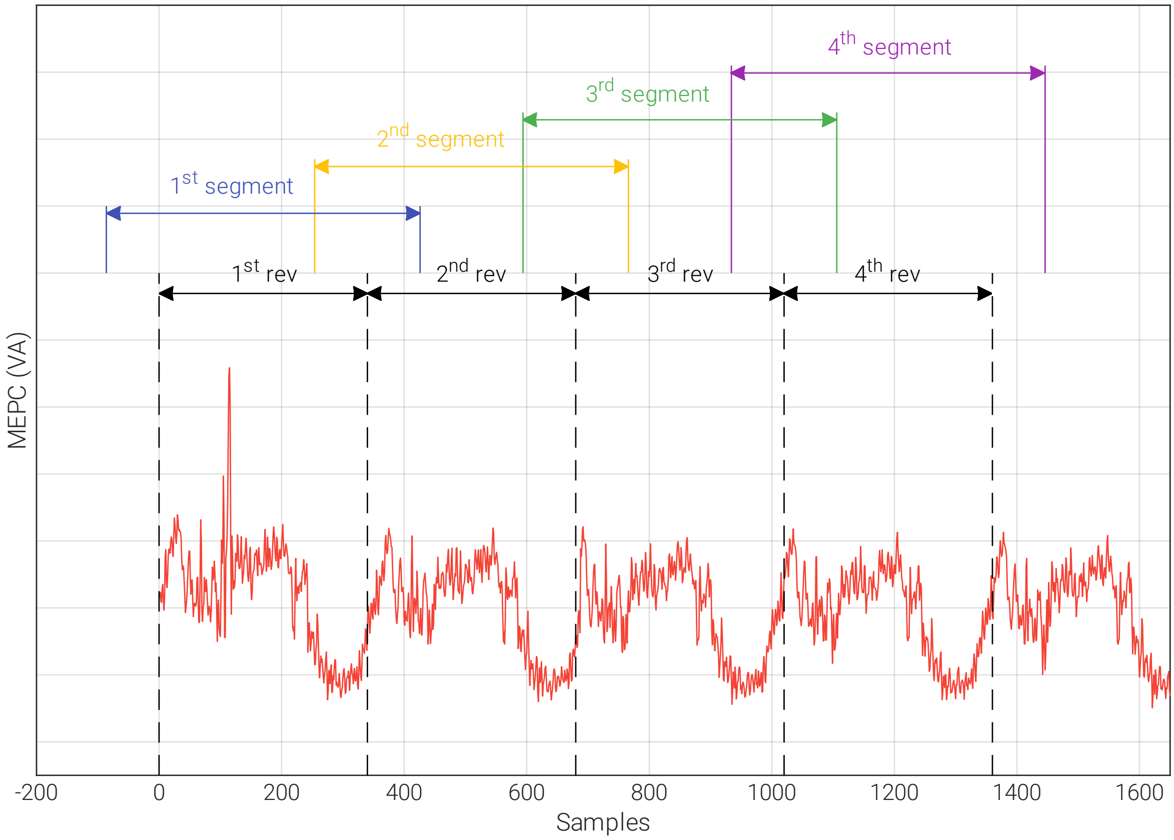


Figure 10.37: Signal segmentation procedure employed within belt damage detection method.

Next, a DWT is performed on each segment in turn, again using a Haar mother wavelet, decomposing to five levels, based upon a segment length of 512 samples. As the input time series data is still sampled at 50Hz fundamentally the highest frequency content contained within the signal cannot change and thus each level corresponds to content in accordance with the approximate bands presented in Table 10.5.

Table 10.5: DWT decomposition levels and associated frequency bands for 50Hz sampled segments of length 512.

Level	Frequency band (Hz)	Samples
1	25 - 12.5	256
2	12.5 - 6.75	128
3	6.75 – 3.375	64
4	3.375 – 1.6875	32
5	1.6875 – 0	16

Again, it should be noted that the analytic frequency bands only represent approximations; as with any real filtering process an inevitable degree of non-ideal behaviour will occur, in this case resulting in some overlap between the actual frequency content contained within each band. When the energy at each level is compared across scenarios an apparent sensitivity of the fifth level energy to the severity of belt damage present can be identified (Figure 10.38).

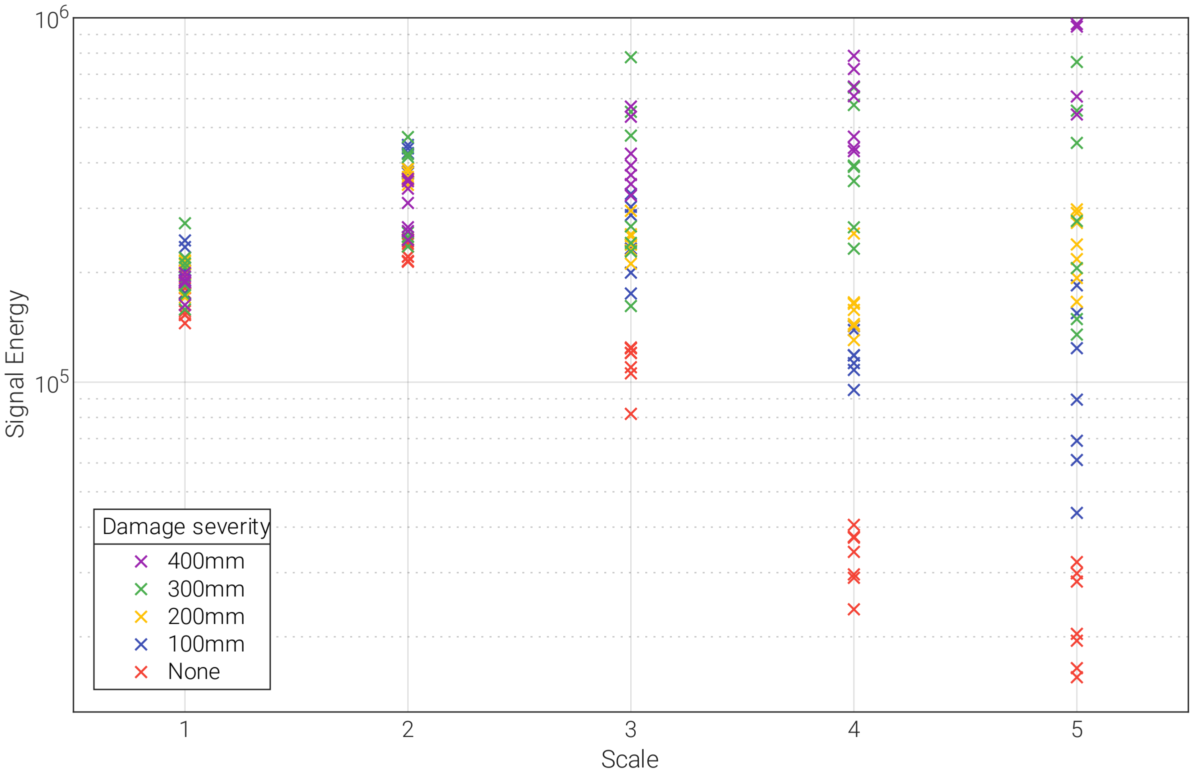


Figure 10.38: Energy by level contained within DWT using Haar mother wavelet when applied to scenarios of increasing slit width. N.b. each scenario is segmented into periods approximately equal to one belt revolution.

The energy with the fifth level of the transform represents all content at a frequency below ~1.6Hz, with any content faster than this attenuated by the transform, in accordance with approximate bands presented in Table 10.5. Therefore, it is likely that a significant proportion of the remaining energy is associated with the passing frequency of the belt (~0.15Hz) and its harmonics, thus, in comparison to lower levels, it presents sensitivity to changes in the rotation of the belt specifically, such as those induced by the occurrence of lateral damage.

When the fifth level energy is examined across all scenarios within both the development and validation datasets this relationship is seen to present consistently, suggesting it can potentially be used to indicate the presence of damage to a system's belt (Figure 10.39).

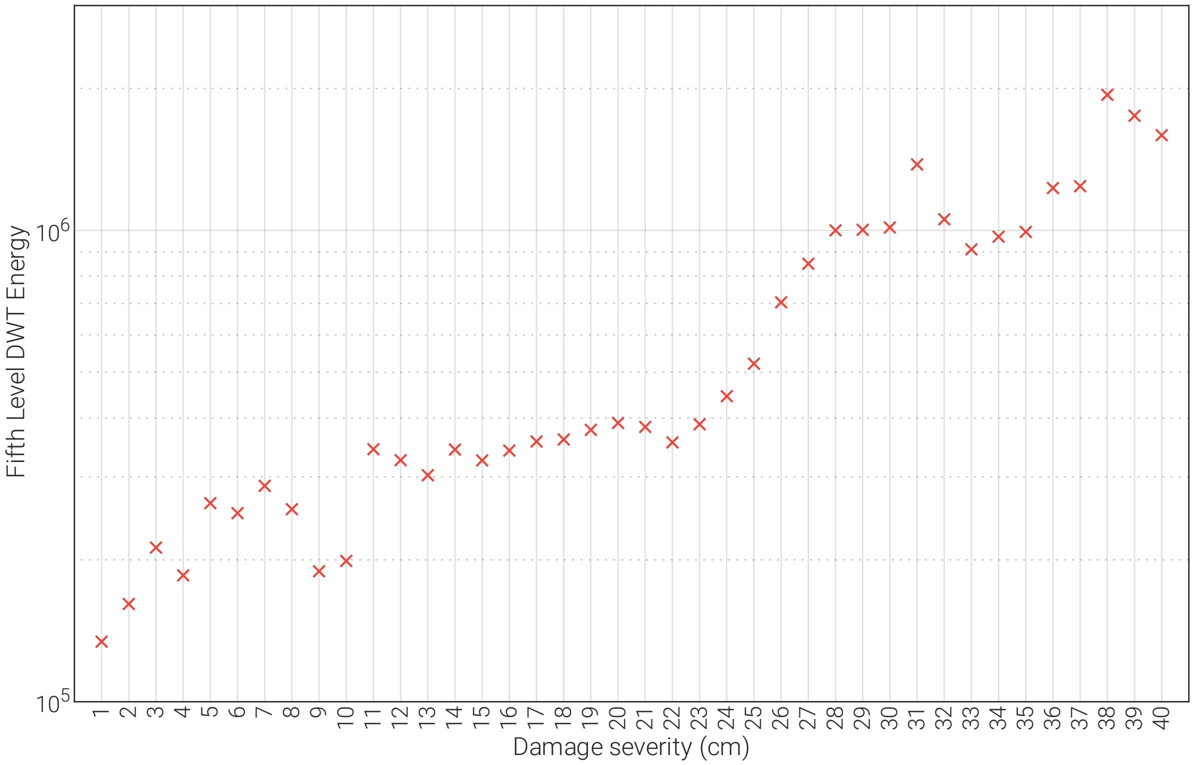


Figure 10.39: Fifth level energy contained within DWT using Haar mother wavelet when applied to all belt slit scenarios.

As observed during the estimation of start-up transient the scale of the indicator bears no direct relationship with the magnitude of belt damage present in absolute terms. However, again a relative indication of potential damage being present can be used to inform personnel and trigger an inspection, through which the actual condition of the belt can be assessed.

To improve the interpretability of the indicator a normalisation step (for example, in the range 0-1) could be applied, based upon characterisation of a system's operation when healthy to provide a baseline for each specific system.

10.6 Refined Overall Method

An overall method for characterising aspects of a CBS's operation in-service through analysis of motor electrical power consumption (MEPC) data has been proposed, as illustrated in Figure 10.40. The method is composed of three data descriptors, each of which provides a quantification of a specific aspect of a CBS's health or usage from changes in MEPC characteristics.

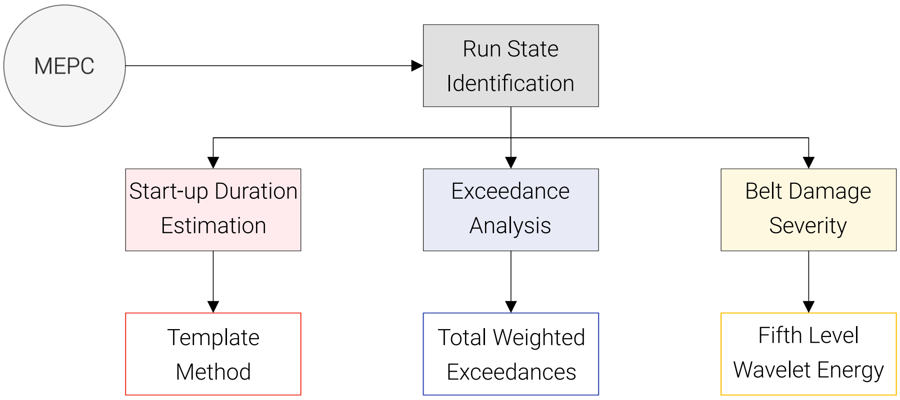


Figure 10.40: Refined taxonomy of proposed data descriptors and methods selected for their derivation from MEPC parameters.

For each data descriptor proposed a method for deriving the descriptor from MEPC parameters has been developed, transforming raw data into actionable insights without requiring manual effort in-service. In their proposed form, all three data descriptors can be derived from raw MEPC parameters without requiring any additional information describing the specific CBS to which the data relates, based upon reasonable assumptions concerning the operational characteristics of a generic CBS.

Chapter 11: An Application of the Proposed Data Descriptors

To demonstrate the application and potential utility of the data descriptors proposed in Chapter 10, a series of tests were conducted on two conveyor belt systems (CBSs) provided by the Manufacturer. Completion of tests served two purposes: to assess the variance in MEPC characteristics across different CBSs and to assess the transferability of the proposed data descriptors (and their methods of production) to the operation of a generic CBS. In this regard, the CBSs operated during tests not only represented two physically distinct systems, but two distinct models of CBS produced by the Manufacturer, enabling assessment of the proposed data descriptors in terms of their ability to produce valid insights when applied to systems containing distinct differences in their physical design. Via these two complementary objectives this chapter provides an application of the proposed method and considers future refinements to improve its industrial value.

11.1 Testing Setup

During testing two CBS were operated; one (herein after referred to as *System* 1) of a nominally identical form to the CBSs operated during the Conveyor Characterisation Tests (CCTs) described in Chapters 7 and 8 (herein after referred to as *System* 0), and a second (herein after referred to as *System* 2) representing a newly developed model offered by the Manufacturer.

Figure 11.1: Overview of subject CBSs operated during tests. System 1 (l) and System 2 (r). Note: the hopper of System 2 is not present at this instant.

A number of notable differences exist between the design of the two systems, including:

- **Motor specification:** *System 1 has a nominal power of 2.2kW and System 2 1.5kW.*
- **Motor configuration:** *The motor of System 1 is located externally, whereas the motor of System 2 is located internally between the pulleys.*
- **Drive system:** *The gearbox output of System 1 is rigidly coupled to the head pulley while the output of System 2's gearbox drives the head pulley via a 1:1 sprocket drive.*
- **Belt cover surface:** *System 1 has a chevroned belt and System 2 a cleated belt.*
- **Belt join:** *The belt of System 1 is joined using a mechanical splice whereas System 2's belt is vulcanised to produce a seamless join.*

In addition, the two systems possess differing geometry, with the analytic frequencies associated with each modulated accordingly (Table 11.1).

Table 11.1: Geometry and analytic frequencies of System 1 and System 2.

System	Dimension						Analytic Frequencies	
	Belt length (m)	Belt width (m)	Belt thickness (mm)	No. Belt patterns	Belt velocity (ms^{-1})	Pulley diameter (m)	Belt fund. (Hz)	Pattern fund. (Hz)
1	6.052	0.45	10	22	0.84	0.52	0.139	3.057
2	7.972	0.45	10	17	0.77	0.54	0.096	1.631

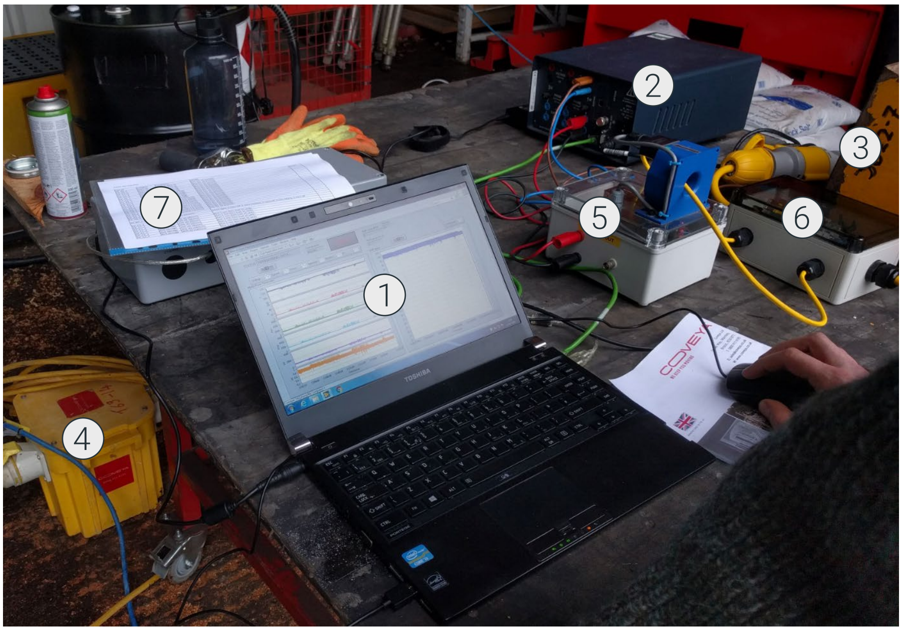
Throughout testing motor electrical power consumption (MEPC) and gearbox output speed parameters were continuously monitored using the data acquisition setup developed for Conveyor Characterisation Tests (CCTs) and described in Chapter 8.

However, direct measurement of belt speed was omitted to simplify testing. Direct measurement of gearbox output speed was included to provide a means for validating changes in the response of MEPC parameters. As summarised in Table 11.2, a total of seven CBS parameters were monitored and recorded continuously throughout testing of each system.

Table 11.2: Summary of system parameters monitored continuously throughout tests.

Component	Parameter	Units	Acquisition Device	Sample Rate
Motor	Line voltage	Vrms	LEM NORMA 4000	~50Hz
Motor	Current draw	Arms	LEM NORMA 4000	~50Hz
Motor	Active power	Wrms	LEM NORMA 4000	~50Hz
Motor	Apparent power	VArms	LEM NORMA 4000	~50Hz
Motor	Reactive power	VARrms	LEM NORMA 4000	~50Hz
Motor	Power factor	-	LEM NORMA 4000	~50Hz
Gearbox	Output speed	RPM	NI USB6211	Count

The testing procedure described in Chapter 8 was employed, however, the recording of video was omitted, to simplify testing. All tests were conducted at the Manufacturer's premises, with each CBS located outside and all data acquisition hardware within a covered location to protect from inclement weather[74], as shown in Figure 11.2.



① DAQ control PC
② Power analyser
③ Starter box
④ Power transformer
⑤ Current transducer
⑥ Voltage connection
⑦ Speed DAQ

Figure 11.2: Overview of data acquisition hardware employed during tests.

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[74] It rained a lot in south west England during winter 2019/20…

11.2 Testing Programme

In comparison to CCTs a condensed series of test scenarios were conducted. Tests were divided into three categories (A, B and C), each of which served to enable evaluation of a specific data descriptor (Table 11.3). The first category involved start-up events subject to different conditions, the second category represented fluctuations in usage and the third category involved the progressive seeding of belt damage.

Table 11.3: Summary of testing programme implemented on each system.

Test ID	Quantity	Category	Type	Details
A1	5	Start-up	Normal	Baseline test.
A2	5	Start-up	Loaded	Five sacks (~100kg) placed upon belt prior to starting.
A3	5	Start-up	Over-tension	Tension increased from nominal by five turns (~10mm increase in pulley centres).
A4	5	Start-up	Under-tension	Tension decreased from nominal by five turns (~10mm decrease in pulley centres).
A5	5	Start-up	No belt	Belt removed completely from system
B1	1	Usage		Random usage scenario emulated. ~2 mins idling, ~5 mins loading, ~2 mins idling, ~5 mins loading, ~2 mins idling, ~2 mins loading.
C1	5	Belt damage	Slit 1	For System 1 = 90mm. For System 2 = 45mm. Idle for ~50s followed by the loading of five sacks.
C2	5	Belt damage	Slit 2	For System 1 = 180mm. For System 2 = 90mm. Idle for ~50s followed by the loading of five sacks.
C3	5	Belt damage	Slit 3	For System 1 = 270mm. For System 2 = 135mm. Idle for ~50s followed by the loading of five sacks.
C4	5	Belt damage	Slit 4	For System 1 not conducted. For System 2 = 180mm. Idle for ~50s followed by the loading of five sacks.
C5	5	Belt damage	Slit 5	For System 1 not conducted. For System 2 = 225mm. Idle for ~50s followed by the loading of five sacks.

The general programme of tests shown in Table 11.3 was conducted sequentially on each system, however, some specific details varied between each system, such as the increments of belt damage seeded.

Throughout testing the inclination of each system was unchanged, approximately 10° and 13° for System 1 and System 2 respectively. Where live loads were applied to systems, sacks of pea gravel (~10mm diameter) in approximately 20kg denominations were used. Live loads were not loaded from any specific height to emulate a degree of variance typical of manual loading applications.

11.3 Results

Overall, a total of 92 test scenarios were conducted across both systems. In this section a summary of the findings from across tests is presented, in the context of the data descriptors proposed in Chapter 10.

11.3.1 System 1

During normal idling of System 1, MEPC is seen to be approximately equivalent (~1200VA) to that of System 0 (Figure 11.3), despite the previously used status of System 1 in comparison to the unused status of System 0. This suggest that, as indicated during the completion of the motor analysis reported in Chapter 2, the design of drive motors is robust to typical operational environments and usage patterns.

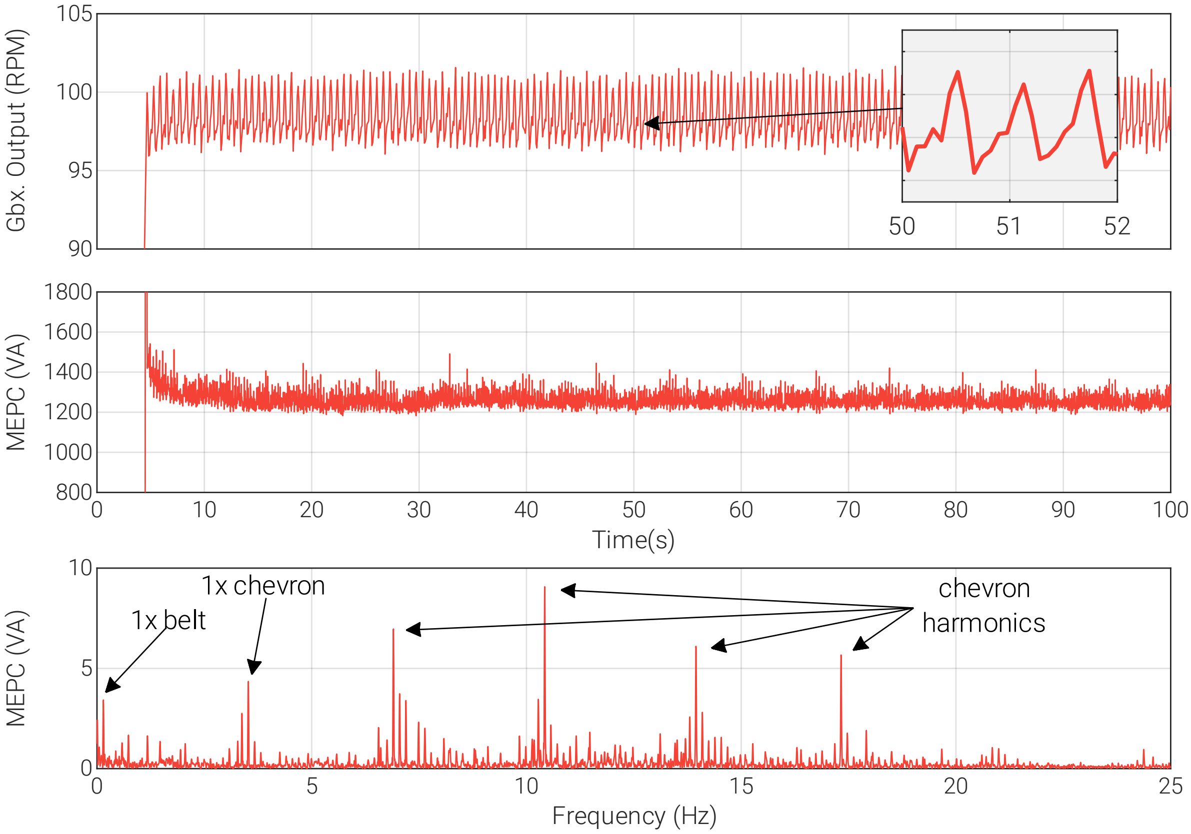

Figure 11.3: Characterisation of System 1 during normal, idling operation.

The effect of removing the belt from System 1 was a reduction in MEPC of ~200VA, as shown in Figure 11.4, a reflection of the reduced torsional load experienced by the drive motor without a tensioned belt present.

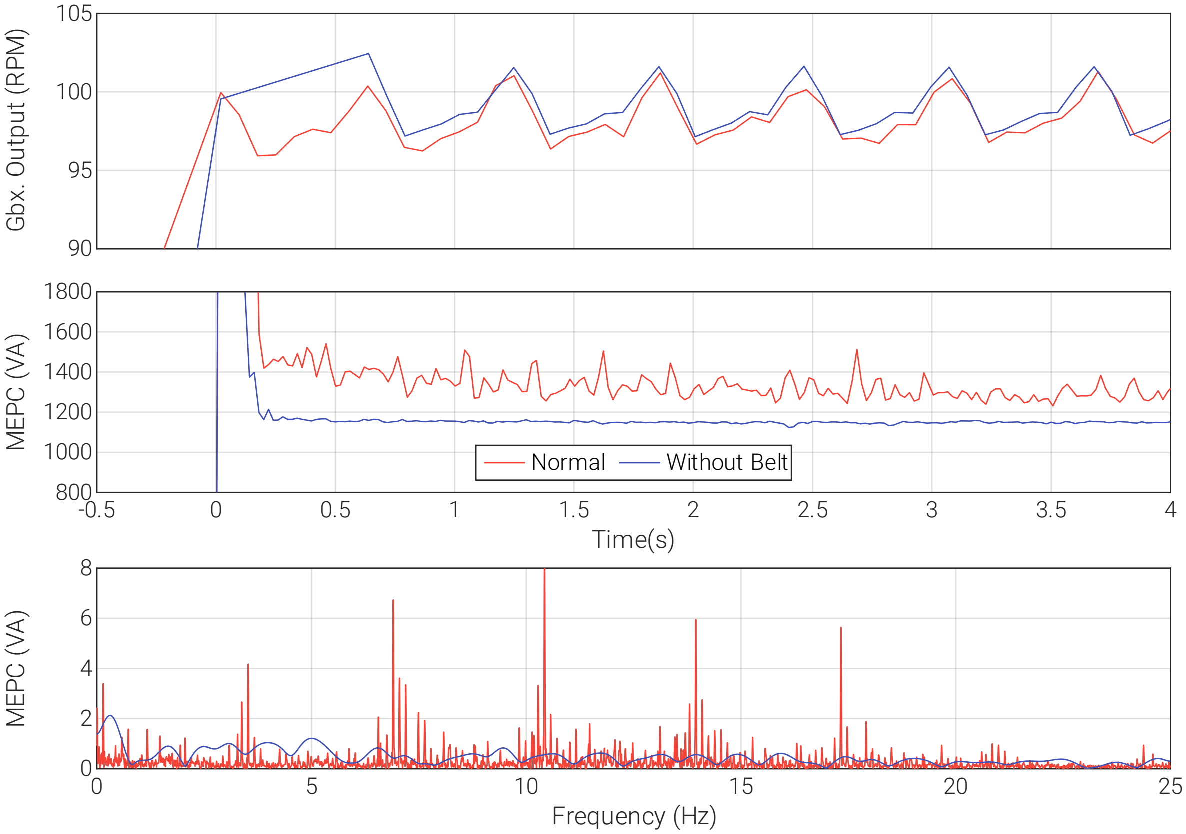

Figure 11.4: Characterisation of System 1 operating with and without a belt.

A significant periodic (~1.6Hz) fluctuation can be identified within the gearbox output speed when idling. As seen in Figure 11.4, the speed fluctuation persists even in the absence of a belt, suggesting it is generated by the motor itself rather than induced by the conveyor structure. In addition, significant spectral peaks are present within MEPC data, located at the approximate analytic frequencies associated with the rotational period of the belt and the chevrons, and their associated harmonics. However, in contrast to fluctuations in speed, when the belt is removed these peaks are no longer present with MEPC data, confirming the rotation of the belt to be their source of excitation.

Descriptor 1

To enable evaluation of the Template method for start-up duration estimation first the duration of each start-up was manually estimated. Across all System 1 scenarios, similar start-up behaviour to that previously observed during CCTs can be seen. In general, increasing the load on the motor (by loaded the belt or increasing belt tension) causes an increase in duration and conversely decreasing the load on the belt (by reducing belt tension or removing the belt) causes a reduction in duration (Figure 11.5).

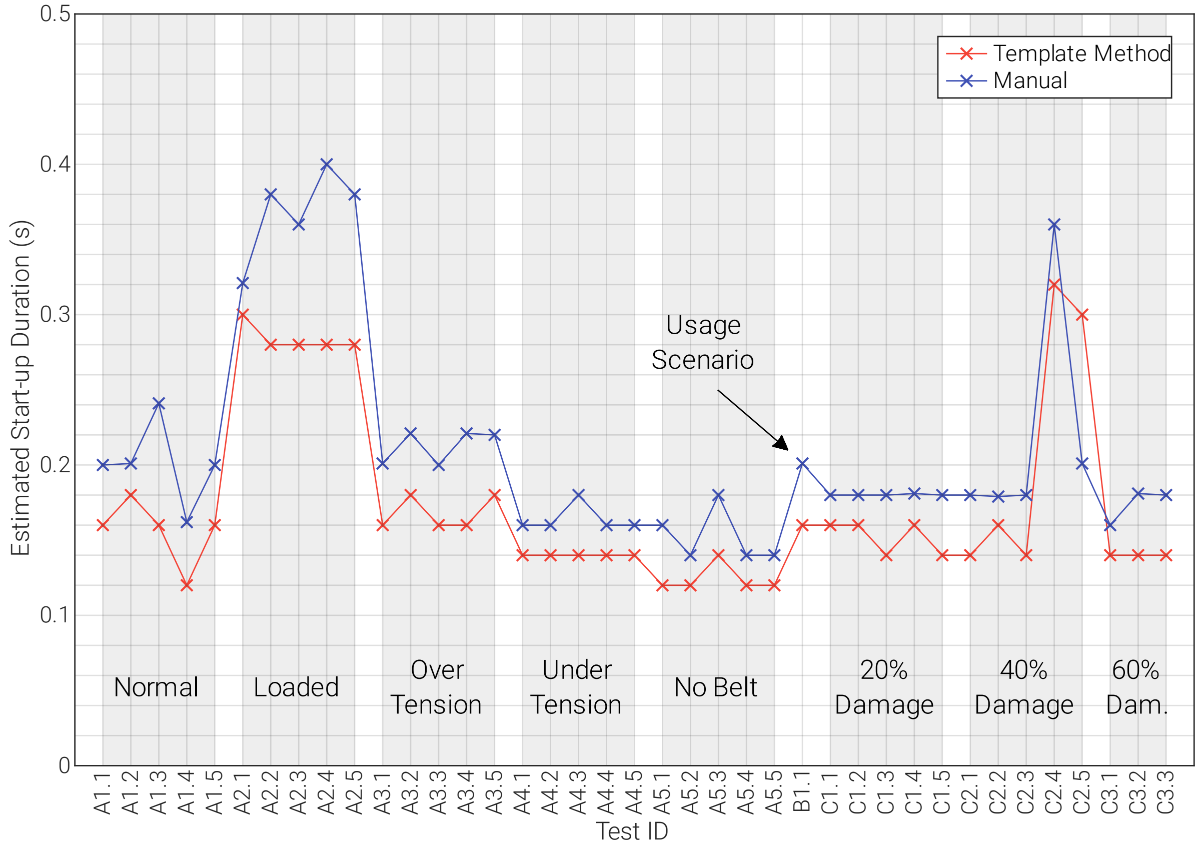

Figure 11.5: Variance in the start-up duration of System 1 across conducted scenarios, based upon Template Method and manual estimates.

A change of ~50ms in start-up duration is induced in response to adjusting between minimum and maximum belt tension, similar in magnitude to that observed during CCTs. Where severe belt damage is present, greater variance in duration is seen. This is likely a consequence of the motor experiencing increased torsional load when the loose section of cut belt became trapped within the support structure. When significant belt damage was present the belt was observed to fold back upon itself as it contacted the hopper skirts; if System 1 was started with the belt in such a state the motor will experience greater resistance to motion in a similar manner to starting with live load on the belt.

Overall, the Template method is seen to produce an under-estimate of duration compared to manual estimates, with a mean error of 42.3ms across all tests. However, general behaviours are represented as well within Template method estimates as they are with manual estimates, with a maximum error on any one scenario of only 120ms (A2.5 and C2.5).

Descriptor 2

To provide an illustration of the potential utility of Total Weighted Exceedances (TWE) as an indicator of live load throughput a typical usage scenario was conducted, encompassing periods of idling and periods of more severe usage. No formal loading pattern was implemented; a loose schedule of two minutes idling followed by 5 minutes of loading, repeated twice, followed by a final 45s period, was adhered to, at which point physical fatigue overwhelmed! All loads were discrete in nature, composed of ~20kg sacks of gravel, loaded manually via the hopper from an approximate height above the top belt surface of ~0.3m during the first loading period, ~0.6m during the second and randomly during the third.

The principles of exceedance analysis can be applied to the System 1 usage scenario, using a dead zone and bands of 4.5σ, equal to ~147VA, as determined in Chapter 10, Section 10.4. The dead zone value represents the standard deviation (σ) of MEPC calculated during idling operation of System 1. When applied to the System 1 usage scenario a total of 57 exceedances are identified, contained within Bands 1, 2 and 3 (Figure 11.6).

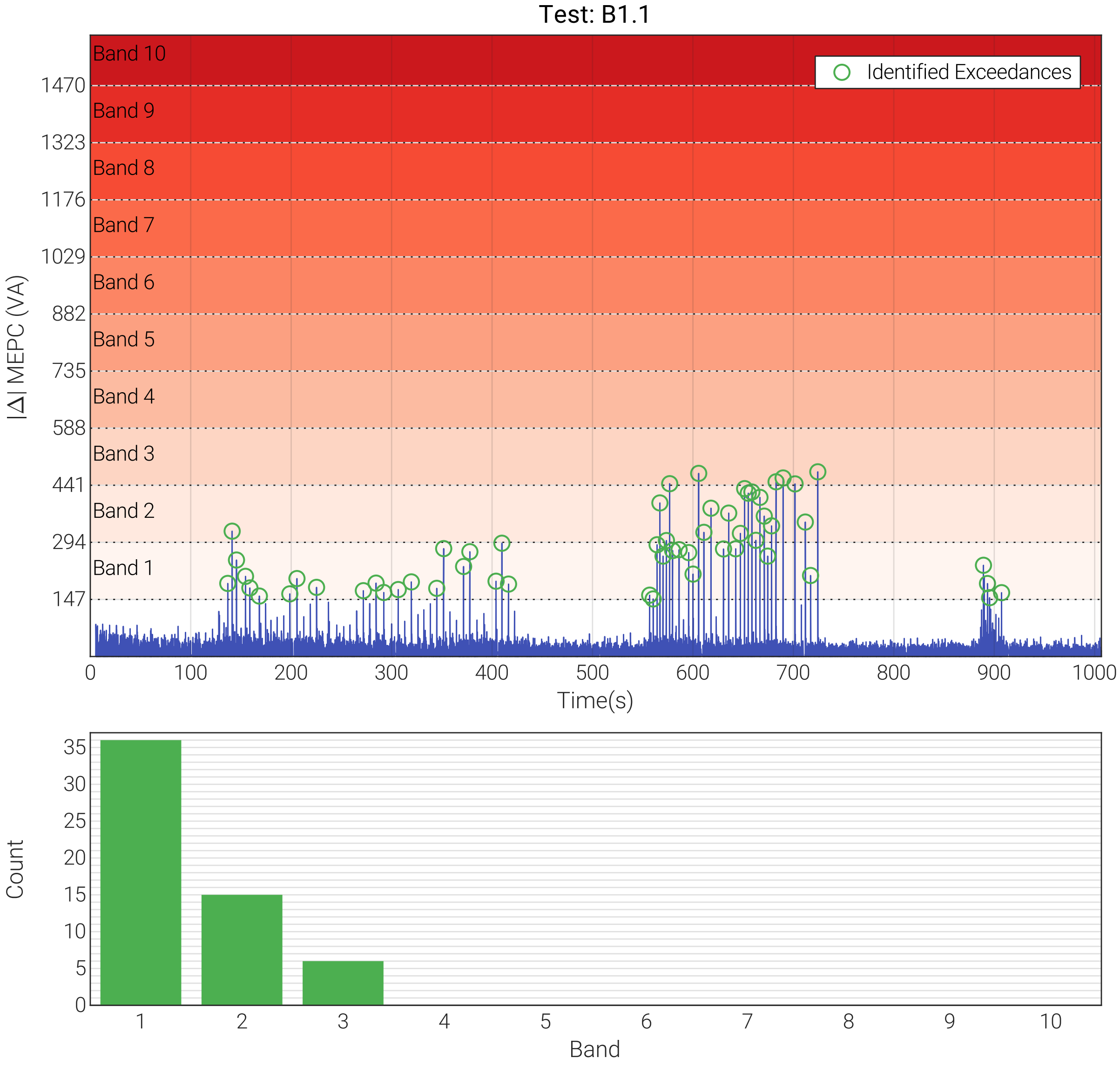

Figure 11.6: Exceedance analysis as applied to System 1's usage scenario.

When the output of the exceedance analysis is examined it is seen that all peaks detected occurred approximately during actual periods of usage (~120s-420s, ~540s-740s and 880s-925s), with the average magnitude of peaks increasing between the first and second period, reflecting the increase in loading height. Furthermore, when banded peaks are converted to TWE a clear distinction between periods of idling and loading can be identified (Figure 11.7).

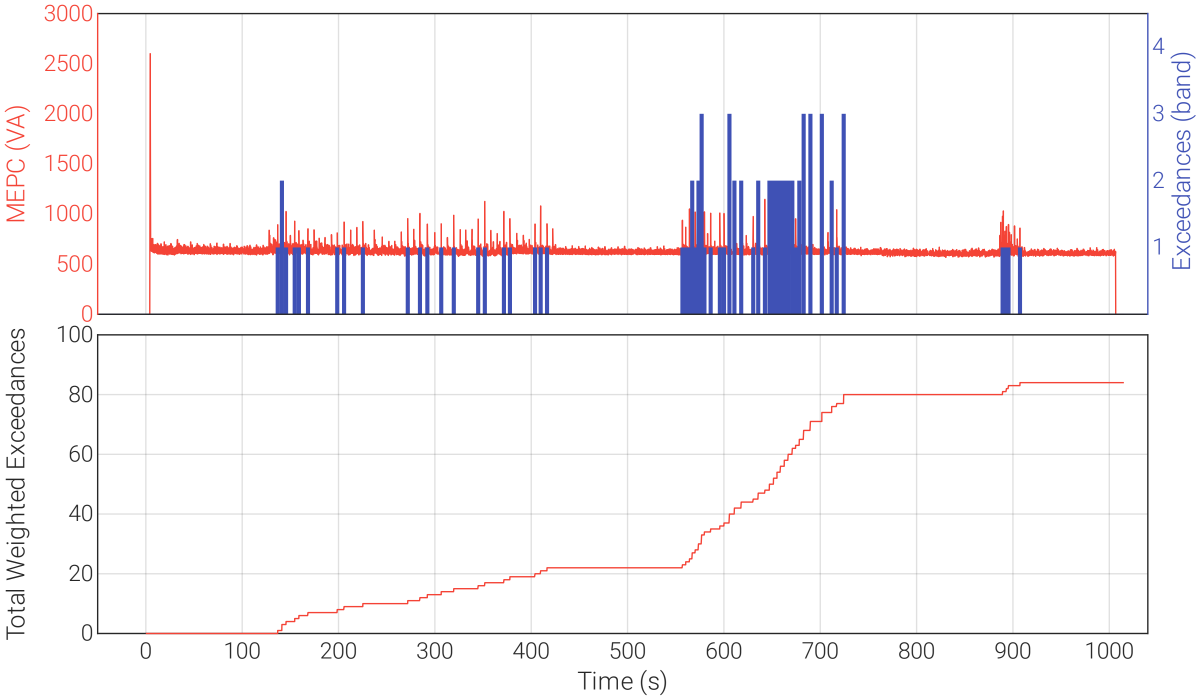

Figure 11.7: Exceedances by band and cumulative TWE as applied to the System 1 usage scenario.

An overall TWE of ~84 is calculated across the entirety of the scenario, divided between three distinct periods of loading, with the location of each correlating with an actual period of loading.

Descriptor 3

To assess the sensitivity of the belt damage data descriptor proposed in Chapter 10, Section 10.5, a series of test were conducted with progressively more severe damage present within the belt. An identical form of damage to that seeded during CCTs was seeded to the belt of System 1, however, for concision fewer and greater increments of damage severity (90mm or 20% of total belt width) were seeded. Three severities of damage were seeded, up to 270mm total width, at which point tests were terminated due to the belt stalling.

Figure 11.8: Depiction of the maximum severity of belt damage seeded to System 1 (l) and an example of loose belt material catching on hopper skirting (r).

As shown in Figure 11.8, at a severity of 270mm the belt tended to catch on the support structure, in particularly as it passed the hopper assembly, causing a temporary or permanent loss of belt drive. Furthermore, when such conditions occurred a number of times the power supply transformer thermal breaker was activated, causing a loss of motor drive, thus, no further belt damage tests were conducted. Testing comprised of running System 1 idle for ~50s, after which five 20kg sacks were individually loaded onto the belt.

After applying the DWT-based procedure described in Chapter 9, Section 10.5 to raw MEPC data from each damaged belt scenario again a clear correlation between the fifth level energy and the severity of damage present can be observed (Figure 11.9).

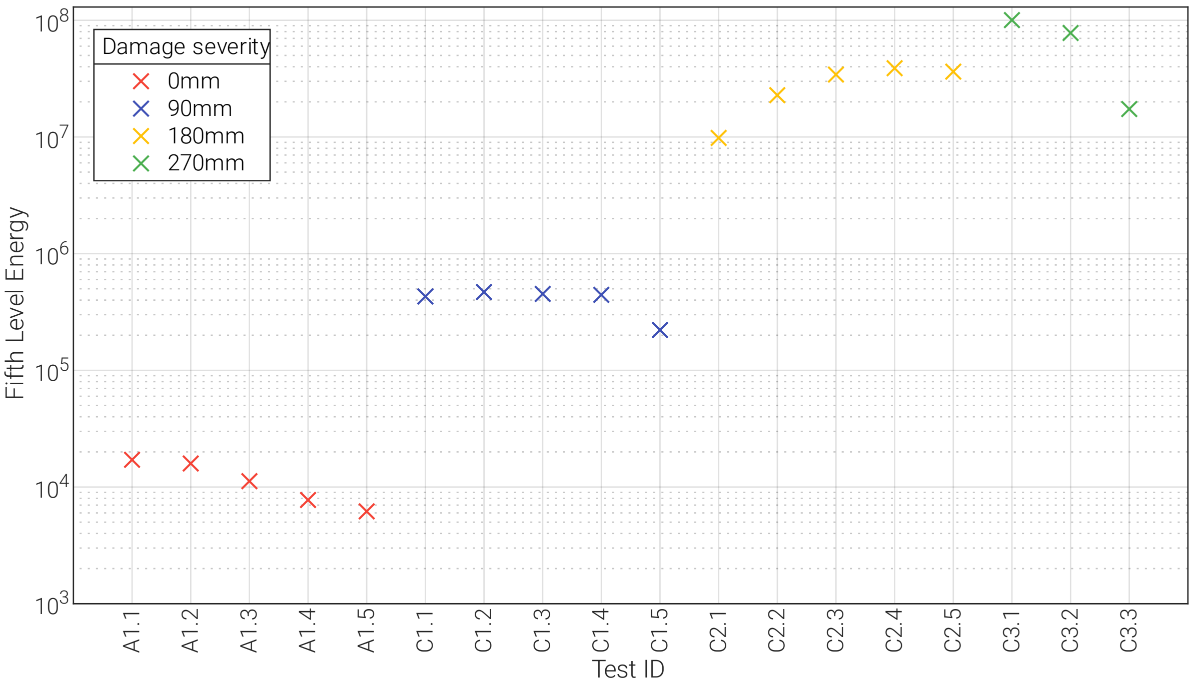

Figure 11.9: Fifth level DWT energy across each System 1 damaged belt test scenario.

At each severity a reasonably consistent value presents across repeated tests and as severity is increased an overall direct relationship between the proposed damage indicator and the actual severity of damage present can be identified.

11.3.2 System 2

As shown in Figure 11.10, During normal idling of System 2, MEPC is seen to be significantly greater (~700VA) than for System 1 (Figure 11.3). Given the significant differences in the design of each system such disparity in MEPC is not necessarily unexpected.

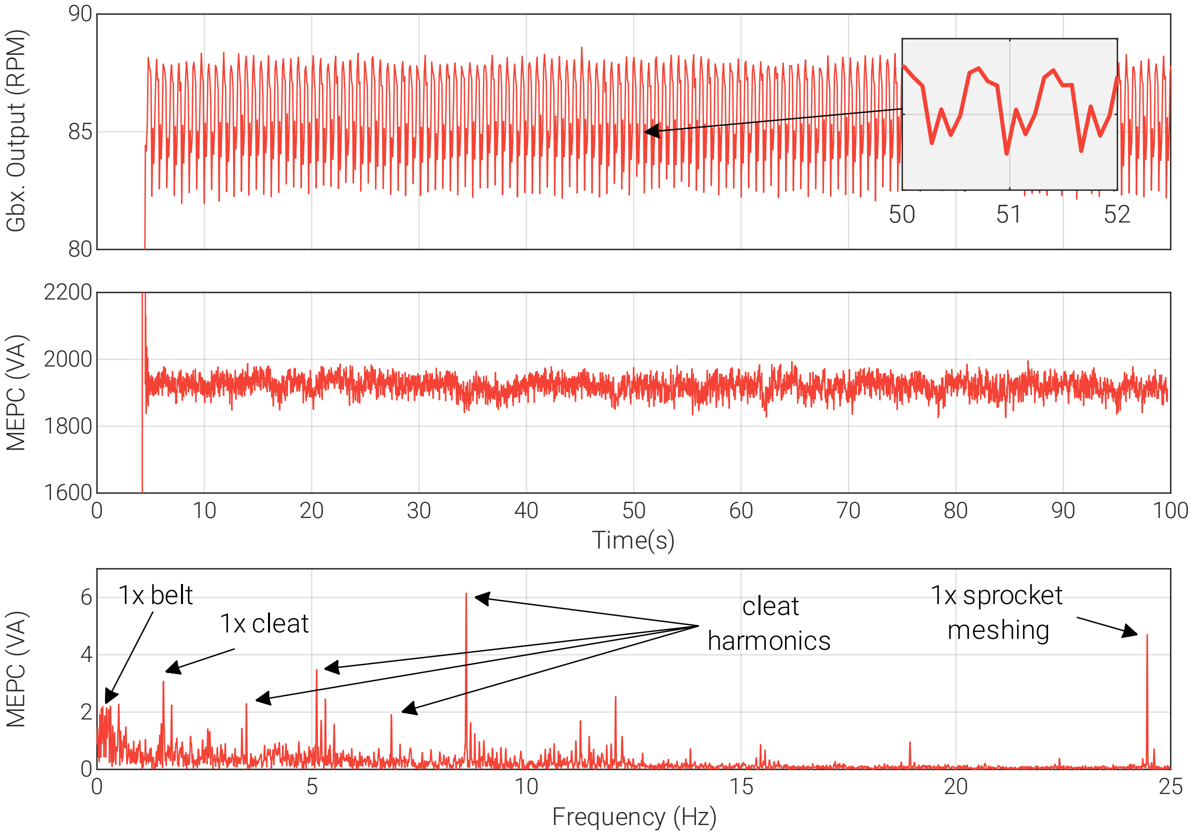

Figure 11.10: Characterisation of System 2 during normal, idling operation.

Similar to System 1, System 2 presents a periodic fluctuation in gearbox output speed (~1.4Hz) even when idling, the frequency of which is close to the passing frequency of belt cleats (~1.57Hz). When System 2's belt is removed this speed fluctuation persists, again suggesting it is generated by the motor itself, rather than excited by the rotation of the belt.

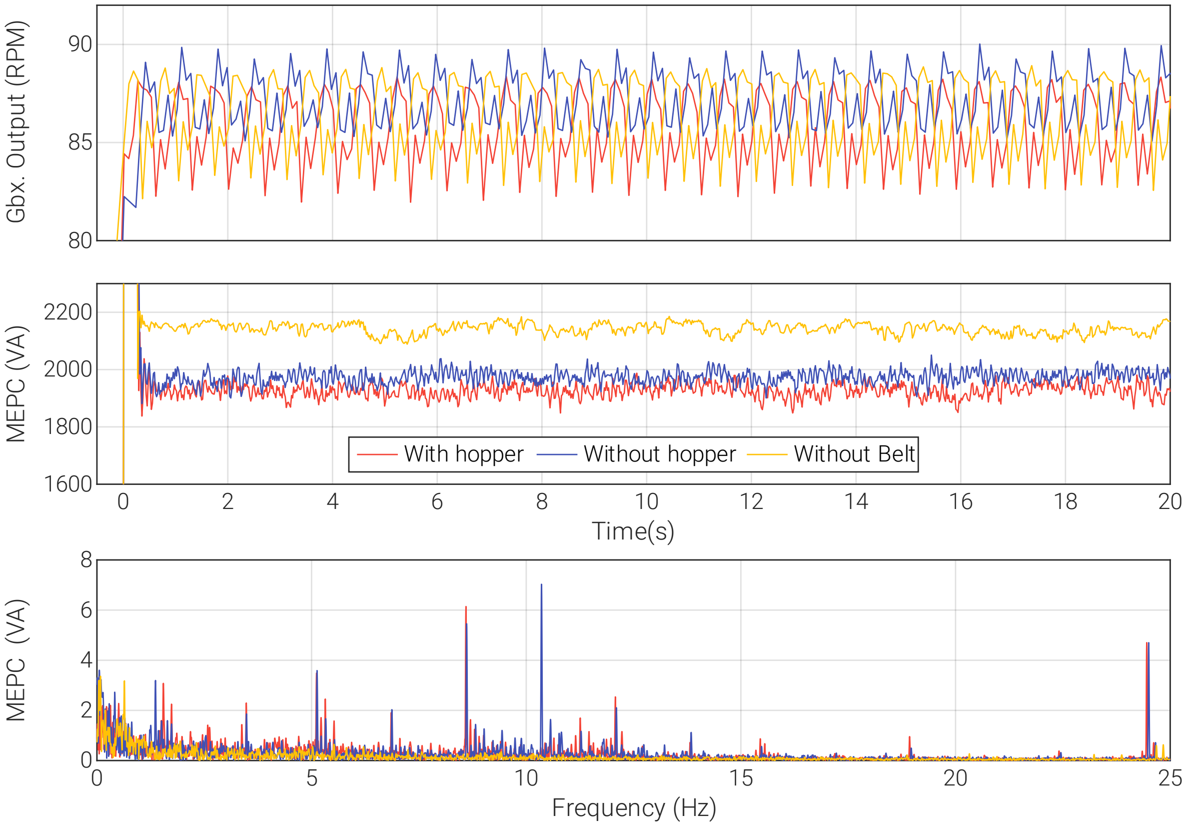

Figure 11.11: Characterisation of System 1 during normal idling operation, without a hopper present and without a belt present.

However, inexplicably MEPC is seen to increase significantly (~200VA) when the belt is removed, with no corresponding change in speed observed. This behaviour is inconsistent with previous observations, as well as not obviously explainable from a physics of operation perspective. Similarly, when System 1's hopper assembly is removed a slight increase in MEPC is observed, however, in this case gearbox speed is increased slightly, causing an increase in power consumed. The presence of the hopper causes significant mechanical drag, produced by the rubber skirting contacting the belt surface, thus, when it is removed sliding friction is reduced and consequently MEPC.

Descriptor 1

In accordance with previous testing regimes and to enable evaluation of the Template method for start-up duration estimation, the duration of all System 2 scenarios was first estimated manually. In contrast to System 1, the duration of System 2 start-ups demonstrates much less sensitivity to changes in load, with only loaded start-ups presenting significant deviation (~100-200ms) from normal (Figure 11.12).

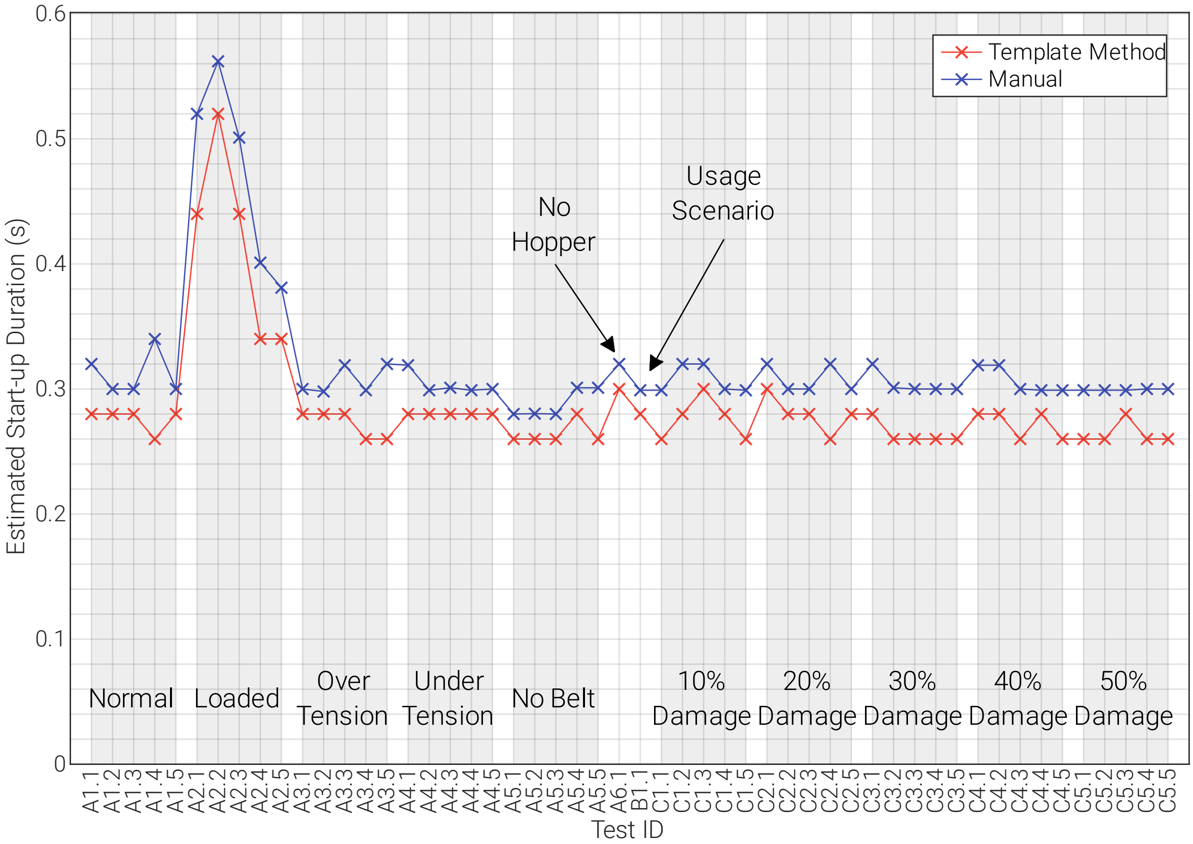

Figure 11.12: Variance in the start-up duration of System 2 across conducted scenarios, based upon Template Method and manual estimates.

Changes in belt tension have little effect on start-up duration and the removal of the belt caused only a small (~10ms) reduction in duration. Across all belt damage scenarios, start-up duration remained practically constant, with the wide variance observed during equivalent System 1 scenarios not present.

Overall, as seen for System 1 the Template method produced underestimates of the duration of System 2 start-ups compared to manual estimates, with a mean error of 34.1ms across all scenarios. However, and as with System 1, estimates present good sensitivity to actual changes in duration, with the increased duration of loaded scenarios in particular clearly identifiable and a maximum error on any one scenario of only 80ms (A1.4).

Descriptor 2

To assess the utility of TWE when applied to a different model of CBS a typical usage scenario was also conducted on System 2, following a similar loading schedule to that implemented on System 1. When an identical exceedance analysis is applied to System 2's usage scenario a total of 37 exceedances are identified, exclusively contained within Bands 1 and 2, other than one exceedance within Band 4 (Figure 11.13).

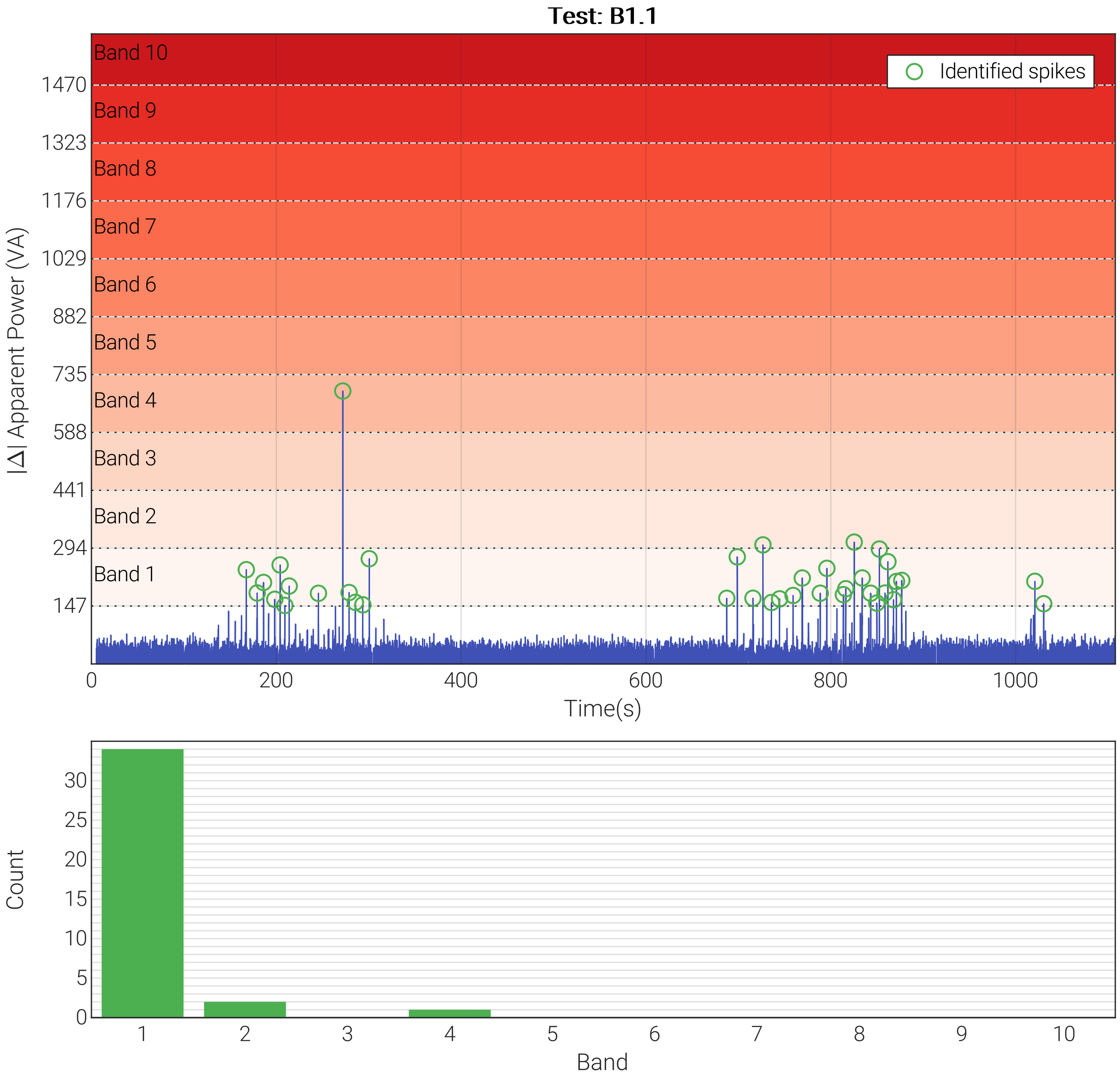

Figure 11.13: Exceedance analysis as applied to System 2's usage scenario.

Overall, exceedances are far less significant in magnitude than observed for System 1, however, the three distinct periods of actual loading can still be identified within exceedance analysis. Furthermore, a number of identifiable spikes within System 2 MEPC are seen to not exceed the dead zone and are thus not registered within analysis. Accordingly, when the previously defined dead zone is implemented the overall TWE of System 2 is only 42 (Figure 11.14).

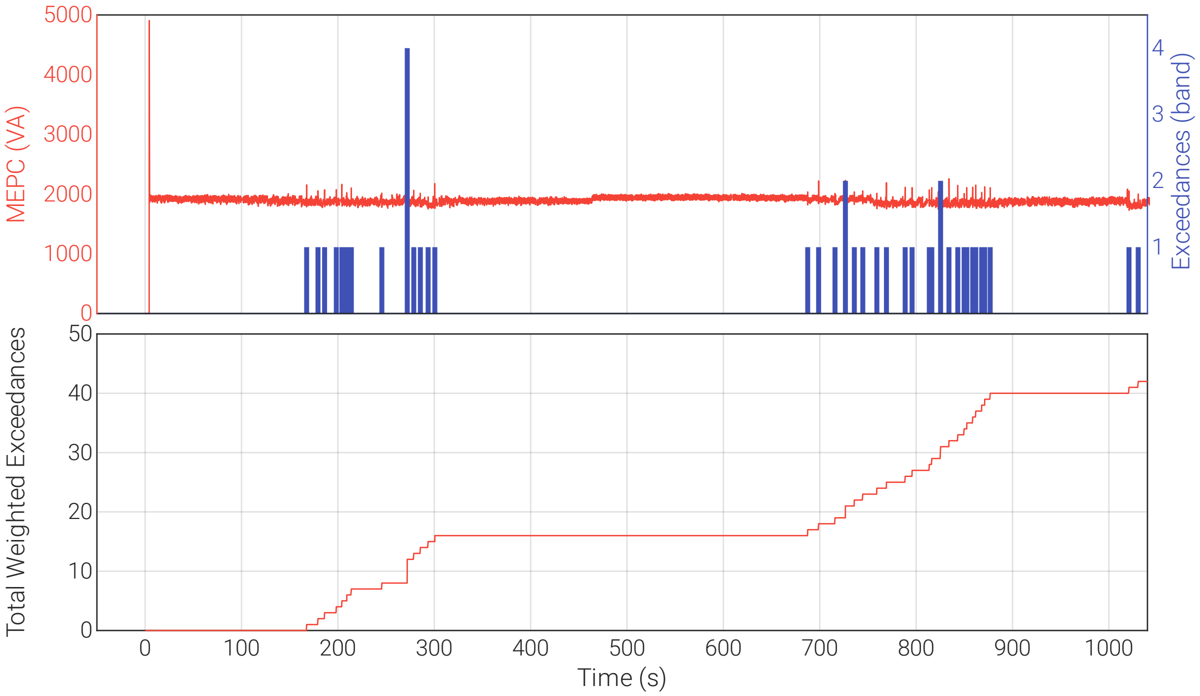

Figure 11.14: Exceedances by band and cumulative TWE as applied to the System 2 usage scenario.

This observation may be a consequence of differences in the load carrying capacity of each system, as a product of their design. For example, the presence of a belt-supporting bed with System 2 may reduce the impact of dropped masses, causing less deformation of the belt and thus torsional load transferred to the motor. Accordingly, given the differences in design between the two models it may be necessary to tailor the dead zone and band width used within the calculation of TWE across models to increase the utility of output. For example, if the dead zone is reduced to 100 the TWE of System 2 increases to 64 as more exceedances are registered (Figure 11.15).

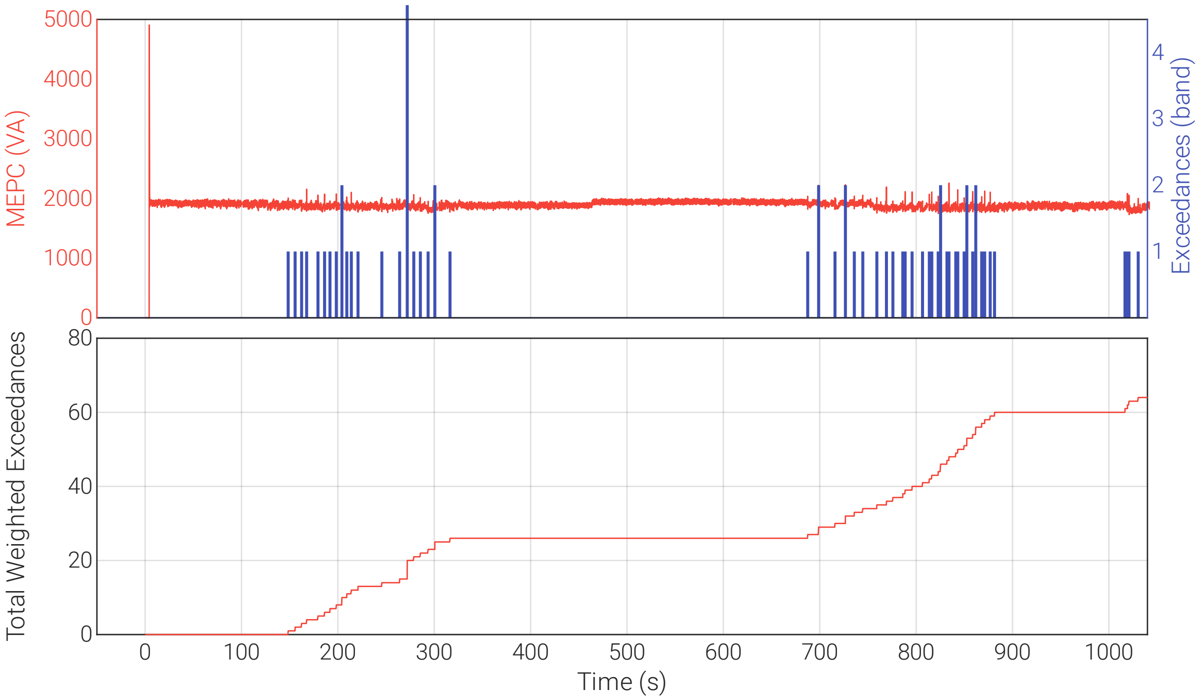

Figure 11.15: Exceedances by band and cumulative TWE as applied to the System 2 usage scenario using a modified dead zone of 100.

Descriptor 3

As implemented on System 1, a series of test were conducted on System 2 in the presence of lateral belt damage, progressively seeded across the width of the belt. As belt damage had not previously been seeded to the model of CBS represented by System 2 smaller increments (45mm/10% of total belt width) were seeded between each series of tests, up to a maximum of 270mm. At this point tests were terminated due to the loose sections of belt becoming trapped between the conveyor structure and belt bed, as shown in Figure 11.16.

Figure 11.16: Deformation of System 2's belt as a result of lateral damage, folding under (l) and becoming trapped underneath the bed (r).

Similar to System 1, at a severity of 270mm the loose sections of belt had a tendency to catch on elements of the conveyor structure, in particular around the hopper and underside of the belt, resulting in the belt ultimately locking solidly in place, preventing any further rotation. Furthermore, the asymmetric nature of the damage seeded caused a degree of lateral belt deviation about its rotational period, however, the rails of the conveyor structure typically ensured the belt retracked centrally and prevented belt loss.

After applying the DWT-based procedure to raw MEPC data from each System 2 damaged belt test, a general correlation between the fifth level energy and the severity of damage present can again be observed, however correlation is less strong compared to System 1 (Figure 11.17).

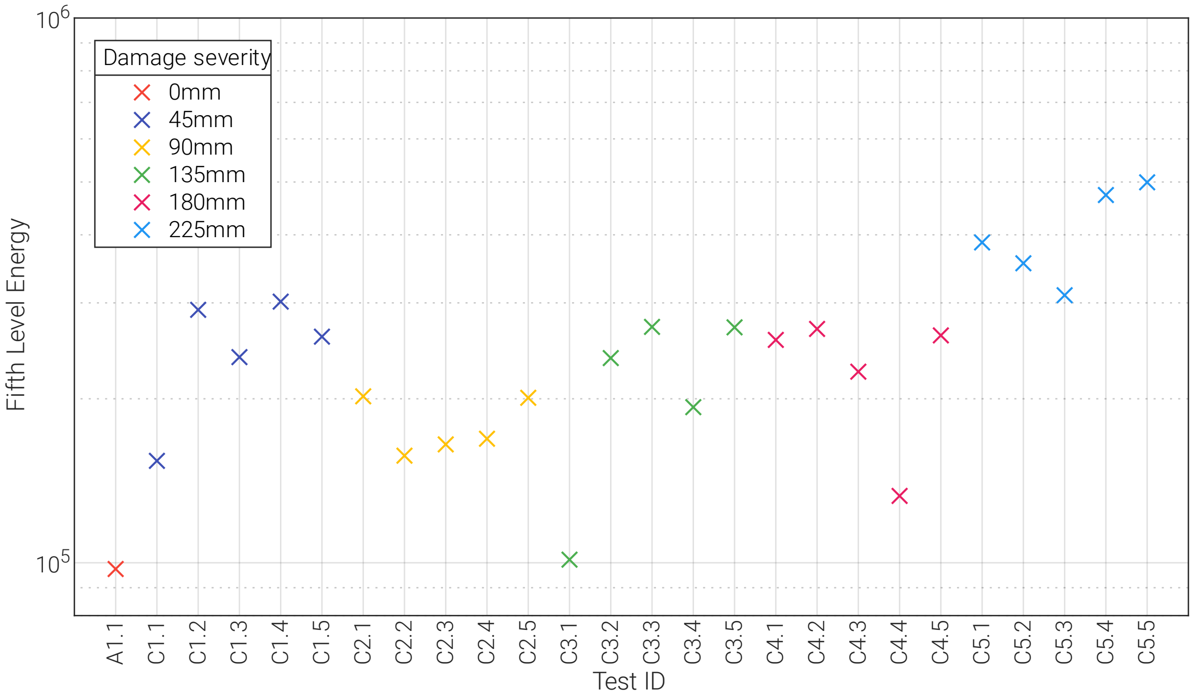

Figure 11.17: Fifth level DWT energy across each System 2 damaged belt test scenario.

In comparison to System 1, the variance across tests at each severity of damage is much greater, however overall a general increase in the magnitude of the indicator still occurs with increasing severity. A difference in the magnitude of the indicator at each severity between systems can also be identified, with all severities of System 2 concentrated around 1-5x10^5, which equates to a damage severity of 90mm for System 1.

11.4 Comparison of Systems

The first objective of the conducted tests was to assess the variance which presents across nominally identical CBSs. in this regard, two specific comparisons can be made: firstly, between two nominally identical CBSs (System 0 and System 1) and between two CBSs representing different models offered by the Manufacturer (System 1 and System 2).

11.4.1 System 0 and System 1

When idling the MEPC and speed of System 1 was seen to be comparable to that of System 0, with both consuming around 1200VA, with a gearbox output speed of ~98RPM. However, a significant periodic fluctuation in the speed of System 1 was observed which was absent within the MEPC frequency content of System 0.

Between System 0 and System 1 the duration of start-ups under normal conditions was similar (~200ms) as well as the effect of a 5 turn change in tension (~+/-20ms). During loaded start-up scenarios the duration of System 1 start-ups (~360ms) exceeded the duration of all System 0 test scenarios, however, no equivalent scenario was conducted during CCTs, preventing a direct comparison.

During the usage scenario implemented on System 1 exceedances were seen to present similar magnitude to previous observations from System 0, Within System 0 scenarios as presented in Chapter 10 the D2.4 test scenario (20kg live loads loaded from 0.3m) represents the most directly comparable conditions to those implemented on System 1; when the characteristics of exceedances within each scenario are compared a similar grouping is seen, with exceedances in each scenario primarily registering within Bands 1 to 3.

Finally, the presence of lateral belt damage within the belt of System 1 induced similar behaviour as previously observed for System 0. The belts of both systems tended to fold over at the slit location, causing the belt to get trapped within the supporting structure, particularly as the severity of damage was increased, ultimately curbing the motion of the belt. When the frequency content of System 1 MEPC data is examined an increase in the magnitude of the belt fundamental component can be identified in System 1, as previously observed for System 0 (Figure 11.18).

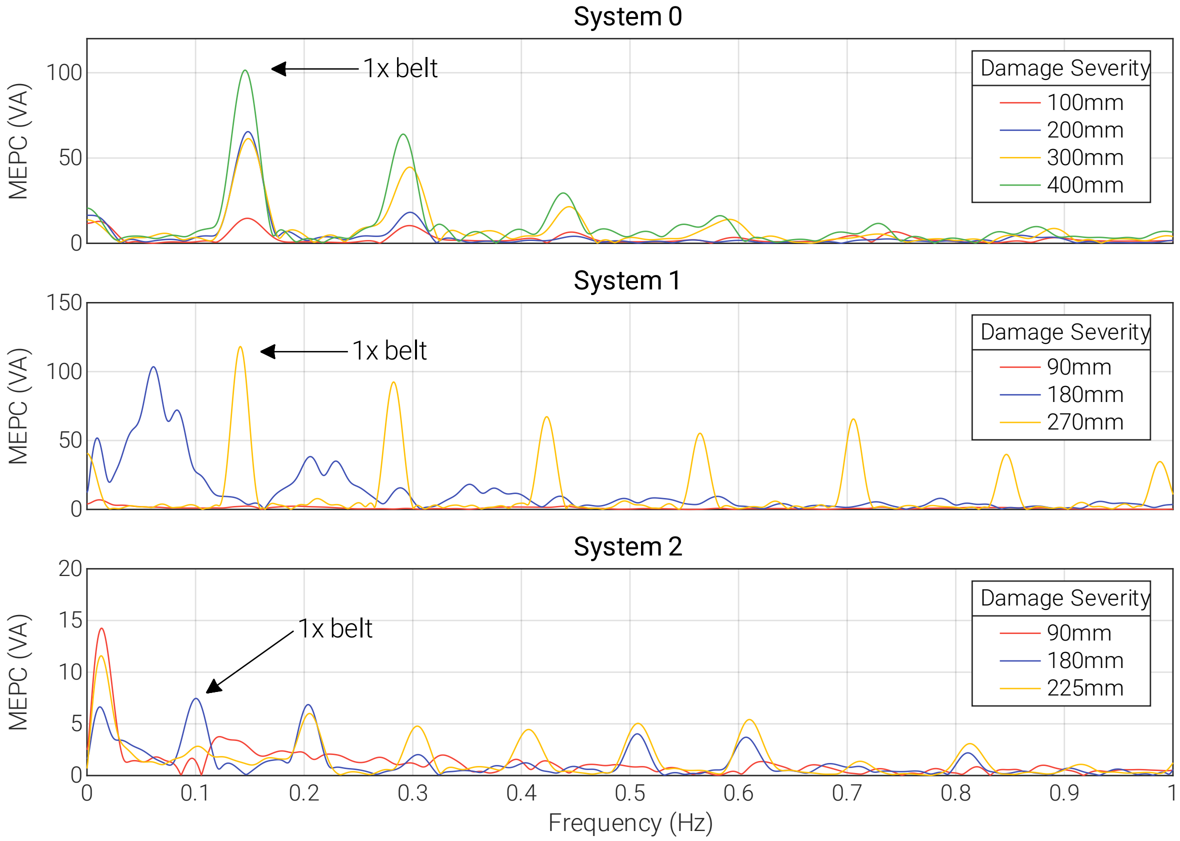

Figure 11.18: The effect of a damaged belt within measured MEPC for System 0 (top), System 1 (middle) and System 2 (bottom).

Similarly, within the spectral content of System 2 an increase in the magnitude of low (<1Hz) component is seen, however the most prominent amongst these (~0.015Hz) does not obviously relate to any analytic frequency.

11.4.2 System 1 and System 2

The second comparison of operation to consider is that of System1 and System 2, representing different models of CBS produced by the Manufacturer. When considered directly, the MEPC characteristics of System 1 and System 2 were seen to be largely comparable throughout test, however, a number of differences in specific aspects of each's operation can be identified.

During idling the MEPC of System 2 was approximately 600Va greater than for System 1, an observation which may be a consequence of design differences between the two models of CBS. In comparison to System 1 the design of System 2 may result in an increase in rolling resistance and thus torsional load on the drive motor; System 2's belt runs on a solid bed, which will induce sliding friction and its head pulley is driven via a chain drive, which will incur inefficiency. Further, given that the nominal tension of belts within models of CBS produced by the Manufacturer is not regulated there is the possibility that the nominal tension of System 2's belt exceeded that of System 1, again inducing additional torsional load on the drive motor. Finally, the motor within System 2 was of only 1.5kW nominal power, in comparison to 2.2kW for System 1, suggesting the motor of System 2 may be undersized for typical applications.

As with System 1, during idling the speed of System 2 was observed to fluctuate, the effect of which was significant enough to be audible. Fluctuations were seen to also persist in the absence of a belt, suggesting the motor itself was the source as opposed to the action of chevrons or cleats contacting support structures. Each system employs a single-phase capacitor-start-capacitor induction motor, in which a second electrical phase is created through the use of appropriately specified capacitors. However, due to inaccuracies in the specification[75] and manufacture of capacitors the relative phase angle between the original supply and the generated phase will inevitably deviate from exactly 90°, resulting in torque production not being uniform about the period of the rotor and thus speed fluctuating.

Overall, start-up durations of System 2 were typically around twice that of System 1 across conducted tests, again indicating System 2 must overcome greater mechanical inertia, possibly caused by the interaction of the belt and supporting bed. In addition, the duration of System 2 start-ups was generally unaffected by changes in system state, with only loaded start-ups producing a significant change in duration. When the response characteristics of each system are examined a notable difference in transient MEPC whilst starting can be identified, with System 2 presenting a distinct second peak in consumption (Figure 11.19).

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[75] The capacitance required to produce an exactly orthogonal second phase will vary during operation as a function of motor load.

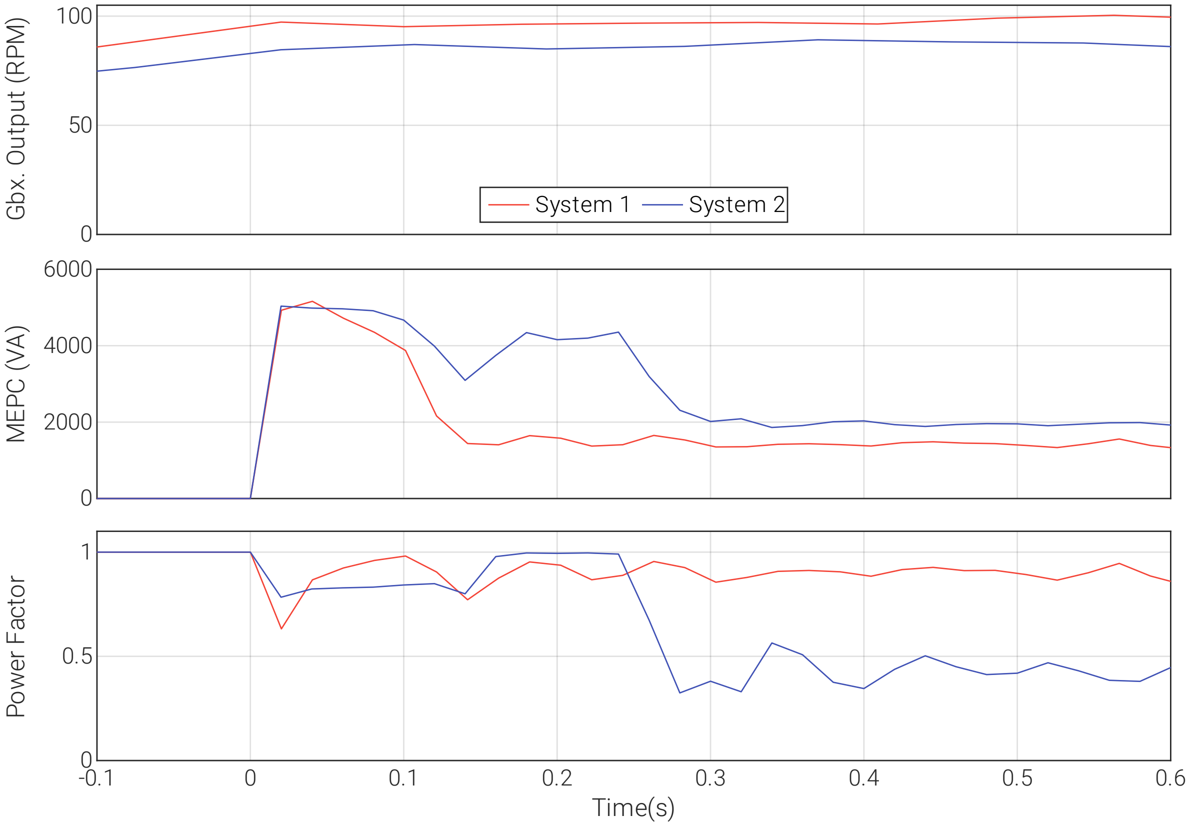


Figure 11.19: Comparison of MEPC between System 1 and System 2 during start-up.

This behaviour is likely induced by the action of the start winding centrifugal switch; as the motor approaches operational speed the switch disconnects the start capacitor, causing a change in inductance and thus torque production, indicated by the step change in power factor at ~0.14s in Figure 11.19. However, regardless of this difference in start-up characteristics, the Template Method was still able to effectively detect changes in the duration of start-ups across conducted tests.

Between the usage scenarios implemented across systems broadly similar responses were observed, however, overall the magnitude of spikes induced within the MEPC of System 2 were reduced in comparison to those of System 1.

Finally, the effect of lateral belt damage to System 2 was seen to be similar to that of System 1, with the belt no longer able to be driven by the motor once damage reached 270mm. An increase in the magnitude of belt rotation related frequency components can also be seen (Figure 11.18), as previously observed for both System 0 and 1, albeit with the specific frequencies shifted based upon the difference in geometry across Systems 0 and 1, and System 2.

The interaction of systems and the resulting effect on the MEPC of each was also observed during tests, as a consequence of non-ideal power supply characteristics. At the testing site only a single power supply outlet was available, meaning systems could not be electrically isolated from each other. To assess the potential impact of both systems operating in series from a single power supply an investigative test was conducted. As shown in Figure 11.20, when both systems are in operation MEPC is reduced as a consequence of sagging line voltage.

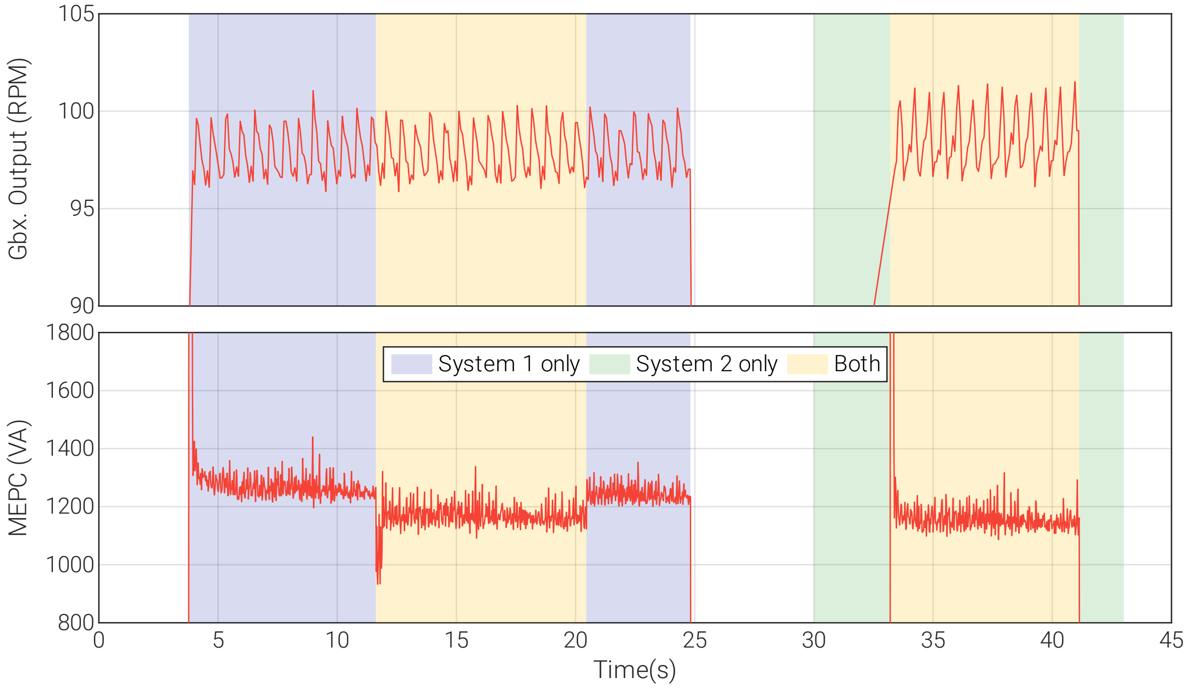


Figure 11.20: The impact of operating both systems simultaneously from a single power supply.

Thus, to eliminate any such effects and thus not obfuscate other behaviours of interest only one system was ever powered on during completion of the main testing programme. Given the Manufacturer advocates customers operating multiple systems from a single supply if necessary, with systems connected together in series (AKA *daisy chaining*), this effect is noteworthy and may affect operation in extreme applications. In fact, the new model of CBS offered by the Manufacturer (as represented by System 2) includes a display unit providing measured line voltage in real-time to enable customer to identify when significant voltage sag is present.

11.5 Comparison of Data Descriptors

The second objective of the conducted tests was to demonstrate an application of the proposed data descriptors to a system of equivalent design (System 1) and a system of differing design (System 2) to that of System 0.

11.5.1 Descriptor 1

When applied to start-up events from both systems the Template Method demonstrated good performance and strong correlation with manual estimates, with an average error of only 42.3ms and 34.1ms was produced across System 1 and System 2 scenarios respectively. As previously observed during application to System 0 data (as described in Chapter 10), Template Method estimates of duration were, however, consistently lower than manual estimates, although a similar level of sensitivity to changes was demonstrated across tests, with a maximum error of only 80ms and 120ms produced across System 1 and System2 scenarios respectively.

11.5.2 Descriptor 2

Using the dead zone and band size previously identified in Chapter 10 (147VA) the TWE resulting from each system's usage scenario was derived. For System 1 a TWE of 84 was produced, comprising of exceedances distributed between Bands 1, 2 and 3 while for System 2 a TWE of only 42 was produced, with exceedances almost exclusively within Band 1.

Accordingly, and given that the two scenarios represent approximately similar usage between systems, the dead zone for System 2 was reduced to 100 to enable live loads previously not registered as exceedances to be captured within TWE, resulting in TWE increasing to 64. Consequently, this suggest that, if applied at scale across systems it may be necessary to modify the dead zone implemented within the production of TWE across different models of CBS, such that a more directly comparable (and thus actionable) measure of usage is provided to practitioners through TWE.

11.5.3 Descriptor 3

Across both systems the proposed belt damage data descriptor demonstrated an increase in magnitude as the severity of damage present increased. Sensitivity to damage was present in the data descriptor regardless of the application of live loads to each system, despite the absence of such loads within the data from System 0 used to develop the descriptor, demonstrating the benefits of wavelet-based analysis over traditional Fourier analysis for the analysis of non-stationary signals.

The correlation between the damage severity of System 2 and the data descriptor was not as strong as that for System1, however, clear distinction between the binary healthy and damaged states was still present. As such, the observed sensitivity of the belt damage data descriptor across both systems suggests that it could potentially be successfully applied to industrial CBSs in conjunction with only a simple static threshold to differentiate between healthy and damage belts.

11.6 Summary of Findings and Implications

The completion of this body of tests served to investigate two primary aspects of CBS operation: firstly, to understand the generalisability of previous observations of CBS operation and secondly to assess the insight realised by the proposed data descriptors when applied to alternative CBSs, both of equivalent and differing design.

Between Systems 1 and 2, the broad characteristics of MEPC were similar across the three categories of test conducted and corroborated previous observations of System 0's operation. Some subtle differences were identified within MEPC characteristics, particularly between systems of differing design, however, overall data acquired during tests presented no obvious contradictions to previous observations.

Similarly, all three of the proposed data descriptors were able to be successfully applied to MEPC from each system, some variance in the significance of the insights produced and thus the effectiveness of each descriptor's method of derivation for a general application was observed. In particular, it was suggested that, for application across different designs of CBS the specific dead zone implemented within the derivation of TWE may require adjusting. Furthermore, the potential effects of electrical interaction between CBSs on specific MEPC characteristics (and thus data descriptors) was identified.

Overall, the completion of this body of tests has demonstrated the potential utility of the proposed data descriptors to manufacturers and operators of CBSs in scaled applications, with each able to provide observability of an aspect of CBS operation in-service.

Chapter 12: **Discussion**

This programme of research was initiated to provide a platform through which the potential suitability of continuous monitoring (CM) techniques to bulk handling conveyor belt systems (CBSs) could be explored, serving to bridge the gap between academia and industry.

The potential benefits realised through adoption of CM of systems are vast and well understood, however, it cannot be assumed that these benefits will be realisable across all applications. Implementation of CM is likely to represent a significant undertaking to operators and manufacturers of CBSs, both financially and culturally, therefore, it is essential that the potential value able to be realised through its adoption is understood, as well as the most appropriate form of monitoring. Accordingly, the primary aim of this research programme was:

To create a practical method for observing the operation of a conveyor belt system using continuous monitoring techniques.

As defined in Chapter 5 this aim was to be addressed through the exploration of three research questions. In this chapter a discussion of the findings against each research question is given and the limitations and implications of these findings is considered within the context of their industrial exploitation.

12.1 Research Question 1

How could the introduction of continuous monitoring of systems support improvements across the design, operation and maintenance of conveyor belt systems within bulk handling applications, given the challenges currently facing manufacturers and operators?

Exploration of Research Question 1 sought to identify and understand the issues currently facing both manufacturers and operators of CBSs in bulk handling applications, such that the suitability and potentially value therein of continuous monitoring of such systems could be assessed. To support exploration of RQ1 a number of primary research activities were conducted in conjunction with both the Manufacturer and Operator, through which current practice across the design, operation and maintenance of systems was characterised. Whilst a Basic CBS represents a reliable, robust system adapted to withstand the rigours of extreme and varied operational environments operability-compromising issues still impact upon their realisable availability, the primary requirement of a Basic system.

The findings of these activities demonstrated that the range of issues which can potentially afflict a system in-service is broad; nominally similar systems can be subjected to diverse operating conditions and usage patterns across applications, causing a significant variance in reliability and thus maintenance requirement. However, in practice, only a limited subset of potential issues will actually compromise the operability of a system and thus its realised availability; through a combination of failure mode and effect analysis (FMEA) and analysis of maintenance records produced by the Operator those issues causing the loss of a belt or a motor's driving force were identified as most impactful. Maintenance records indicated that whilst such issues do not occur frequently, when they do a system will typically be rendered inoperable and thus will require immediate corrective action. In contrast, the occurrence of many other types of issue is considered acceptable within reason and will thus only be corrected when an opportunity presents, such as in conjunction with another corrective action. Such practice is distinct from many other industries and is permitted here due to a combination of minimal parts and secondary costs as well as an absence of safety criticality.

Accordingly, run-to-failure is common in many bulk handling applications, as highlighted through the completion of on-site interviews with members of the Operator's maintenance team (Chapter 3, Section 3.3). Interviewees indicated system availability as being the primary driver of operations on site; systems must be managed to maximise their ability to operate. To support this requirement, a primarily reactive approach to maintenance is implemented based upon identifying issues through visual inspection. Such practices were commonly described as 'fire fighting', with personnel indicating a lack of resource availability impacting upon their ability to satisfy availability demands. Aspirations to shift towards a more preventative approach to maintenance were reported, driven by the perception that such an approach could reduce unplanned downtime and thus increase availability. However, two fundamental issues were identified as preventing such a shift. Firstly, the ability to plan actions ahead of time is severely impacted by the frequent occurrence of essential reactive actions relating to belts and motors. When such issues occur they must be addressed immediately in order to restore the operability of systems, consuming vast personnel resources and taking priority over preplanned inspections and actions. Secondly, significant variance in the realised mean time between failure (MTBF) of nominally similar systems within the plant made the definition of appropriate preventative maintenance intervals challenging.

Together these activities highlighted a need to improve the resilience of operators of systems to failures of belts and motors specifically. Accordingly, a body of analysis was conducted on a limited sample of previously operated CBS motors to understand both their construction and assess the impact of operation on their condition (Chapter 2, Section 2.2.4). Overall, motors were found to be in generally good condition, however, despite the small sample size some potential signs of degradation were identified, primarily relating to the accumulation of corrosion to contacts and mechanical damage to capacitors. These observations provided an indication of the aggressive operational environments that systems are subjected to, a point emphasised by the Manufacturer during discussions and fuelled a desire to better understand how each system is actually being used 'in the field.'

A general theme common to the issues identified concerns the limitations imposed by a reliance upon visual inspection techniques. Commonly referred to as 'walking the belt', a visual inspection of a CBS will comprise personnel moving between each individual CBS in turn, inspecting the operation of each, performing minor adjustments or cleaning activities where required and noting any more significant conditions or problems for later attention [243]. Whilst a visual inspection can provide valuable insight into the state of systems their efficacy is compromised by a number of issues, as recognised throughout literature (Chapter 2, Section 2.2.2). Inherently, a visual inspection requires that personnel are permitted close proximity to systems, something which is often restricted; discussions with the Manufacturer revealed that systems are frequently operated remotely from maintenance personnel. Similarly, at the Operator's plant many systems are located in areas which are unable to be accessed whilst in operation due to health and safety concerns. Additionally, even where access is permitted the effectiveness of inspections is limited by physical human capabilities; there is an upper limit on what can be identified with the naked eye as well as scope for errors in inspections cause by unintended human negligence. Given the identified high levels of personnel churn reported by the Operator as well as the leasing dominated structure employed by the Manufacturer personnel will not necessarily have sufficient expertise or familiarity with systems to be able to effectively conduct assessments, limiting their value. Further, even if issues can be identified by personnel a subjective decision must be made as to their significance, creating potential for inconsistency across a maintenance team.

When the collective findings across these activities are considered the potential value from adoption of CM techniques is apparent, primarily as a means for mitigating the limitations of visual inspection techniques. Through appropriate implementation of CM periodic visual inspections can be supplemented by continuous assessments of systems, reducing demands upon personnel, removing subjectivity and circumventing physical restrictions. As demonstrated during the industrial monitoring trial documented in Chapter 4 practitioners were able to extract key insights from even relatively basic monitoring delivered in an ad hoc manner, utilising it to modify existing practice with minimal direction.

In this respect, the concept of supplementing existing practice with CM serves to create 'virtual personnel', essentially increasing the capacity of a maintenance team without increasing personnel numbers. Furthermore, the addition of sensors can feasibly enable an extension upon human capabilities, allowing for an increased fidelity of operational insights. However, the existence of potential value in CM is predicated upon an assumption that the insight obtained through the conduction of a visual inspection can both be obtained/replicated through analysis of feasibly monitorable system parameters as well as actioned upon by maintenance personnel.

A common driver for the adoption of CM seen throughout literature is to enable a shift towards a predictive approach to the maintenance of systems. However, based upon the characteristics of typical bulk handling operations as identified through this research the implementation of such practices to these industries remains far off, restricted by both technical feasibility and readiness of the industries. As summarised by Chanana et. al. [88]:

> *"PdM [predictive maintenance] is still mostly in experimental stages though, and the pace of technology innovation continues to outpace actual industry deployments... the bottom line is that many companies still employ preventive, scheduled-based maintenance and are only just moving to remote condition monitoring. Moving to higher value forms of preventive and prescriptive maintenance is further out."*

As previously discussed in Chapter 4, only one of the four criteria defined by Moubray [17] for feasible implementation of a predictive approach to the maintenance of an asset can be satisfied (Chapter 3, Table 3.5). Accordingly, it is contested that adoption of PdM is not feasible nor suitable for application to bulk handling CBSs; failures are often difficult to define and their progression not well understood, with wide variance in MTBF observed historically, with the rate of progression of critical failures often far exceeds the practical response time of a maintenance team. The development of validated prognostic models, essential to the implementation of predictive strategies, is recognised as a technically complex task throughout literature, yet to see widespread adoption.

Industrial practitioners are seeking solutions which can support an eventually shift towards more sophisticated practices such as PdM to realise the potential benefits without creating significant disruption to existing practice. In this respect the concept of usage monitoring as an enabler of usage-based maintenance (UBM) was identified within literature, as a means of supporting a shift away from a primarily reactive-based approach towards an evidenced preventative approach.

As discussed by Tinga [60], the effectiveness of traditional time-based preventative approaches is restricted by uncertainty in the characteristics of damage evolution within components. In this context variance in the MTBF of nominally similar assets is induced by the combined effects of variance in factors across the manufacture, installation, operation and maintenance of each component. Thus, by understanding the usage of a system one source of uncertainty in MTBF can be minimised and so more appropriate preventative intervals can be defined. Accordingly, a shift towards UBM serves to normalise against the effect of different usage patterns, in doing so reducing uncertainty and thus improve the effectiveness of preventative intervals.

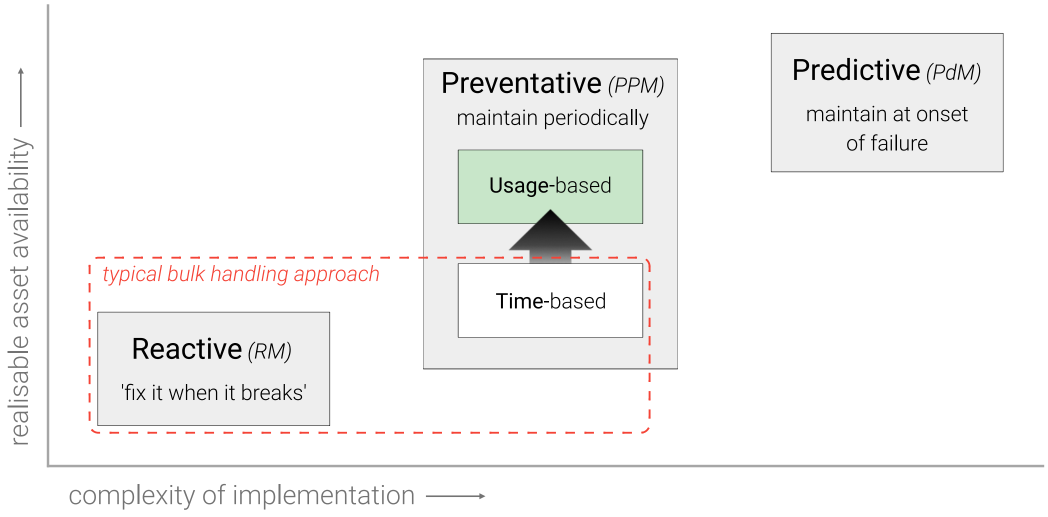


Figure 12.1: Maintenance taxonomy, highlighting the location of usage-based maintenace.

As depicted in Figure 12.1, UBM represents a maintenance paradigm shift towards PdM to support increased effectiveness with less induced complexity; implementation of UBM represents only a small modification to traditional preventative practices and can thus be expected to face fewer challenges to successful implementation. However, whilst implementation of UBM does not require detailed knowledge of the P-F interval associated with individual components it does rely upon the existence of a relationship between usage and realised life and an ability to identify this relationship therein.

A further key benefit of CM adoption is to enable the automatic detection of faults, again reducing reliance upon visual inspections as well as mitigating for their limitations. Not only can CM be used to identify faults in a timelier manner but potentially such data can extend beyond the capabilities of human senses, enabling the detection of fault types not feasible via manual means. For example, through a review of salient literature a number of applications of CM techniques to CBSs for fault detection purposes was identified, most commonly focussing on the identification of degradation to belts. Such techniques can permit the identification of degradation whilst systems are in operation, enabling the continuous assessment of condition. Since the 1970s numerous techniques have been developed for the direct monitoring of belts involving the installation of bespoke, costly hardware. However, such technologies, whilst having demonstrated clear value in many applications remain financially unviable for many bulk handling applications.

Whilst the introduction of CM to bulk handling CBSs has the potential to support improvements the existence of a number of potential challenges associated with its successful implementation were identified which should be considered. Fundamentally, to provide valuable insight monitored parameters must present sensitivity to the specific phenomena of interest. However, as observed through the completion of an industrial monitoring trial within a waste processing facility sensor selection is influenced by addition factors, both technical and socio-technical in nature. Accordingly, the issue of sensor selection was identified as of critical importance in realising value in a CM system, further reinforced through a review of salient literature presented in Chapter 5.

From a technical perspective, sensors must be able to realise high reliability such that data is provided in perpetuity; During the completion of the industrial monitoring trial the nature of the environment within the plant was seen to be highly aggressive, consequently the task of data acquisition is non-trivial with high levels of robustness an essential requirement of sensors. If frequent monitoring outages are encountered the degree to which practitioners can integrate CM insights into practice will be severely compromised; CM is unlikely to realise value if it requires more maintenance than the system it is monitoring! Accordingly, the cost of maintaining a monitoring system must be factored into the value proposition.

Based upon the collective findings from exploration of RQ1 three requirements of system parameters to be suitable for continuous monitoring were defined:

1. **Cost of monitoring**

   What is the financial expense associated with monitoring the specific parameter, both during initial installation as well as on-going maintenance?

2. **Technical feasibility of monitoring**

   Can each parameter be physical monitored given the technical requirements of associated sensor technologies, in a manner robust to the typical environmental conditions experienced in industry?

3. **Operational insight realised**

   What insight into the usage and health of a CBS can be obtained through the monitoring of each parameter?

It is asserted that unless a system parameter is able to satisfy these requirements it will be unlikely to realise value within an industrial setting.

The existence of socio-technical issues was also identified during completion of the industrial monitoring trial, relating to two key aspects: how to integrate CM into existing practice and how to minimise resistance from personnel. As identified through interviews with onsite personnel, systems are operating in many instances at or even beyond their designed capacity levels, therefore, it is essential that the introduction of a new technology minimises disruption to operation in the short term. It was suggested that to mitigate for such issues CM data should be presented to personnel in such a form that minimises the effort and expertise required to interpret and thus utilise it. The existence of such cultural issues when introducing disruptive maintenance technologies is increasingly reported within literature and throughout industry [244], suggesting that despite the limited scope of the trial its findings may be reflective of wider industry, not just the specific plant. Certainly a more comprehensive series of trials would be required in order to confirm such sentiment, however inherently consideration of human-technology interactions must be made, as echoed by the example of 'Old Fred' given by Bond [40]:

"Consider Old Fred, a seasoned maintenance professional whose experience and intuition have served his company well for decades in the absence of self-monitoring equipment. A tablet-wielding greenhorn can seem like a threat to Old Fred, who is correct that his vast knowledge and instincts cannot be replaced entirely by software and sensors."

Accordingly, in order to mitigate for such issues it is suggested that buy-in from Old Fred should be obtained from the outset, through education and involvement:

"Get his buy-in, because he can be a strong proponent or strong opponent. Old Fred will soon learn that new technology helps him turn weeks or months of putting his hand on something until it's too hot to touch into a much simpler process. Meanwhile, the new guys shadowing him can learn how data relates physically to the equipment. It's the same thing Fred used to do manually, but now he has the data to back it up. You can tell a manager motors have been getting hotter, but you can't spend big bucks to rebuild equipment just because Fred said so. But you can take that old wisdom and combine it with connected tools to provide Fred with more tricks while validating his knowledge."

As such, if performed correctly, the introduction of monitoring technology should represent not a hinderance or threat to Old Fred, but instead support improvements in his effectiveness and decision-making process. Failure to provide sufficient levels of skilled personnel to support the introduction of a new monitoring system can result in it "creating more problems than it solves [11]."

It was thus asserted that data should be presented to practitioners in an appropriate form, such that it is able to be interrogated and interpreted without requiring significant effort or expertise. In doing so it can be seen as a supplement to existing practices rather than a replacement, thus reducing negative perceptions. Ultimately, a monitoring system can only ever provide information to personnel; it will (for the foreseeable future) remain the responsibility of personnel to act upon this information and perform physical interventions, a sentiment which certainly must be emphasised to practitioners.

Summary of findings:

- *The design of CBSs has converged to a common form across industry, utilising low cost COTS parts where possible.*
- *In-service, practitioners are reliant upon visual inspection to assess the condition of assets, which applies inherent limitations on the availability and validity of condition data.*
- *The most impactful issues experienced by CBSs are belt and motor related.*
- *Predominantly, reactive maintenance approaches are being implemented within bulk handling applications, with aspirations to move towards more preventative-based approaches.*
- *The implementation of predictive maintenance approaches to CBS is not necessarily appropriate.*

12.2 Research Question 2

How can the operation of a conveyor belt system be most appropriately observed in-service through implementation of continuous monitoring?

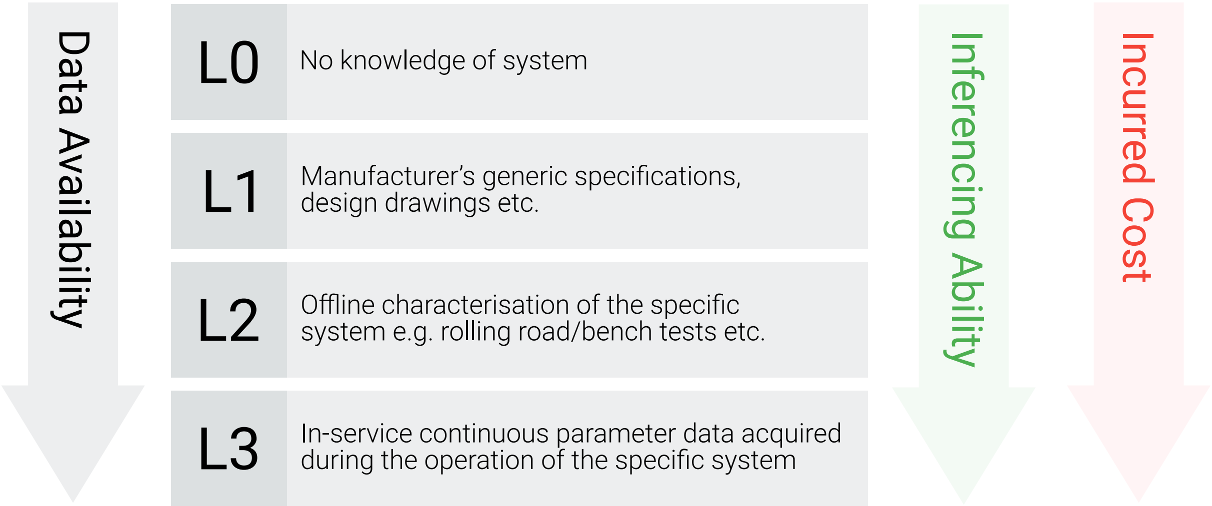
Exploration of RQ1 demonstrated the potential suitability of continuous monitoring techniques when applied to bulk handling CBSs, as a means for supplementing existing visual inspection-based practices. However, in this respect the realisation of value from continuous monitoring is predicated upon an assumption that the information obtained during a typical visual inspection can be replicated by an appropriately specified monitoring system. Accordingly, Research Question Two sought to identify the most appropriate form of continuous monitoring for application to a bulk handling CBSs, considered both the insight of information provided as well as the feasibility of monitoring within an industrial environment, both technically and financially, in line with the requirements defined during exploration of RQ1.

To evaluate the characteristics of feasibly monitorable system parameters a series of laboratory and industrial trials were undertaken. Firstly, as reported in Chapter 5 an industrial monitoring trial was conducted at one of the Operator's plants to evaluate the insight into CBS operation possible through interrogation of temperature and electrical current parameters. Furthermore, the industrial trial served enabled the characterisation of typical operational environment, establishing the severely and diversity of conditions to which monitoring hardware must withstand in practice. Subsequently, to characterise the sensitivity of a wider complement of parameters to varying operational scenarios a bespoke test rig (CER) was designed and constructed, as reported in Chapter 6. Finally, the findings of operation of the CER (Chapter 7) were fed into a body of testing conducted around the operation of an industrial CBS provided by the Manufacturer, where the sensitivity of monitored parameters to both live loads and changes in belt state was observed (Chapters 8 and 9).

Together, findings from these activities demonstrated that there is no single viable solution to the selection of appropriate parameters to monitor; in many scenarios a single event or phenomena can be observed or inferred within the response of multiple parameters (Table 7.2). For example, the mechanical loading a bearing is subjected to affects both its temperature and vibration characteristics (amongst others) thus either or both could be used to observe such loading in-service.

As such, it is common for sensors to be employed in a complementary manner, exploiting the advantages of each; for example, within an offshore wind turbine typically vibration and oil debris monitoring are used in conjunction to identify tooth wear within gearboxes [110].

The application of continuous monitoring to a system can be realised in many different forms, influenced by the requirements of that specific implementation, which will impact upon the *form* and *extent* of data available describing that system's operation. In this context *form* refers to the type and frequency of data available and *extent* refers to the proportion of the system to which available data relates, which together describe the system's *data availability*. In practice, available data can be provided at one of four distinct levels, as depicted in Figure 12.2.



L0	No knowledge of system
L1	Manufacturer's generic specifications, design drawings etc.
L2	Offline characterisation of the specific system e.g. rolling road/bench tests etc.
L3	In-service continuous parameter data acquired during the operation of the specific system

Figure 12.2: The influence of data availability on inferencing ability and incurred cost as related to a single system.

Through operation of the CER it was identified that increasing availability can increase the fidelity of inference possible, permitting greater insights into different aspects such as system health and usage. For example, the temperature of the CER's gearbox was observed to increase in response to both increases in rotational speed and applied torsional load; thus, through observation of only either parameter the cause of a temperature increase cannot be determined. Increasing the level of data availability, either through form or extent, can potentially enable not only the binary detection of events but additionally their isolation and typing.

In this respect, based upon the combined data availability of the CER and during CCTs a number of hypotheses relating to CBS events potentially inferable through interrogation of specific parameters (or combinations therein) were made (Table 10.1).

Given the influence of data availability upon inferencing ability intuition might suggest that when designing a continuous monitoring implementation maximising data availability should be the design goal. However, as data availability is increased typically so too is the cost incurred in making that data available. Fundamentally, the cost incurred as data availability is increased comprises three elements:

- **Financial overhead**

  R*epresenting the cost of purchasing, installing and maintaining monitoring hardware, as well as training personnel*

- **Physical complexity**

  R*epresenting the effort associated with increasing data availability including increased points of failure associated with monitoring hardware.*

- **Data interpretability**

  R*epresenting the overhead associated with analysing and interpreting data and the risk of creating 'information overload.'*

Thus, there exists a trade-off between inferencing ability and incurred cost and so, in practice, within each monitoring implementation only a subset of all feasibly monitorable parameters can be made available. Furthermore, increasing the fidelity of insight possible may not necessarily be appropriate within the context of bulk handling CBS operations. As identified in RQ1 typically in-service maintenance actions involve the replacement of components rather than repair; Systems are mostly composed of simple COTS components which represent little financial cost to replace, thus rendering repair work unviable. Therefore, increasing data availability to permit increased fidelity of insights such as fault isolation and typing is not likely to represent a good value proposition given the associated cost incurred. Although it is feasible to observe each of the data hypotheses it is not appropriate to do so as the associated cost of data availability exceeds the value of the collective insight realised.

Instead, the findings from this research suggest that continuous monitoring of motor electrical power consumption (MEPC) alone represents the most appropriate form and extent of monitoring for bulk handling CBSs. During the industrial monitoring trial access to current draw measurements enabled personnel to understand motor loads in real-time, such that trip threshold could more appropriately be defined and flow-related issues could be identified. Through operation of the CER MEPC parameters demonstrated sensitivity to different modes of mechanical loading without any perceptible time delay. Further evaluation during the completion of CCTs demonstrated that within the context of an actual industrial CBS not only did MEPC parameters demonstrate sensitivity to mechanical loading downstream of the drive motor as generated by live loads but also to changes in the state of the belt.

Throughout all trials the measurement of MEPC was straightforward, reliable and produced an excellent signal-to-noise ratio. When assessed against the primary requirements of a sensor within the context of condition monitoring as defined by Jennions [79] the measurement of MEPC demonstrated accuracy and stability without interfering with the operation of the system. Overall, when assessed against the three previously defined requirements the suitability of MEPC to this application is evident:

1. **Cost of monitoring**

   The monitoring of MEPC parameters is possible using well-established COTS hardware. Furthermore, within each system only one component is directly monitored, reducing installation and maintenance costs.

2. **Technical feasibility of monitoring**

   Due to its non-intrusive nature monitoring hardware can be located remotely from the main CBS area, avoiding potential contamination and/or damage which could occur through typical system operation.

3. Operational insight realised

MEPC can provide direct insight into the dynamic operation of a system's drive motor, as well as conditions downstream including insight into the state of a system's belt.

MEPC provides a means for inferring the mechanical loading a motor is subjected to, as generated by the physical load connected to its output. In this respect the response of MEPC to changes in operation is intuitive to interpret by personnel familiar with the dynamics of rotating machines, as evidenced by personnel utilising current draw data without any specific direction or training during the Industrial Monitoring Trail.

Alternatively, the mechanical torque experienced by the drive motor could be measured directly using a torque transducer of the form included within the design of the CER. However, in comparison with the measurement of MEPC direct measurement of mechanical torque is significantly more challenging. The purchasing cost of a torque transducer is an order of magnitude greater, installation is far more involved, particularly when retrofitted and the transducer must be located directly at the measurement point, leaving it vulnerable to aggressive operational environments, particularly of concern outside of a laboratory environment. As such, the low cost and non-invasive characteristics of MEPC are particularly advantageous.

Similarly, during trials measurements of component temperatures also demonstrated sensitivity to changes in mechanical loading, suggesting suitability to this application. The measurement of temperature is a well-established and widely implemented practice across industrial, however, a number of specific issues restrict its suitability here. Firstly, the slow response of temperature measurements to changes in load limit the dynamic content able to be observed within acquired data. Further, as the temperature of a component can be affected by any source of thermal energy it is a challenge to isolate effects; it is often ambiguous as to the root cause of a change in temperature. Finally, as demonstrated during trials, traditional direct contact thermometry techniques require significant effort to install and maintain, particularly across a fleet of systems, resulting in poor data reliability within aggressive operation environments. Given this limitation, during operation of the CER preliminary investigations into the suitability of thermography-based temperature measurement were conducted. Whilst historically thermographic technologies were prohibitively expensive for most applications, recent reductions have made such technology accessible more widely, which given the non-invasive nature has potential to mitigate for the limitations of thermometric techniques.

Another significant advantage of MEPC measurement is the sensitivity to changes in belt state observed during completion of CCTs. Not only can measurements be used to evaluate live loads but also changes in aspects such as belt tension and damage. Analysis of MEPC thus provides an opportunity to provide personnel with a remote diagnostics capability, serving to alert to potential issues which occur to trigger further investigation. This is of particular potential benefit to the Manufacturer for whom all systems are operated remotely; an ability to inform reactive maintenance personnel with potential reasons for issues prior to arriving onsite could greatly reduce time to correct issues as well as even removing the need for physical site visits.

Summary of findings:

- *The degree to which the operation of a CBS can be observed through the interrogation of continuously monitored parameters is directly affected by data availability.*
- *In many instances a single phenomenon can be observed simultaneously within the response of multiple parameters.*
- *Overall, for this application, motor electrical power consumption (MEPC) was identified as the most appropriate parameter to monitor, given the characteristics of industrial environments.*
- *MEPC demonstrates sensitivity to changes in torsional load (as a proxy for usage) and changes in belt states such as tension and integrity (as a proxy for health).*

12.3 Research Question 3

How can the health and usage of a CBS be assessed in an unsupervised manner?

As demonstrated through the exploration of RQ2, significant insights into the operation of a CBS can potentially be obtained through interrogation of continuously monitored parameters. However, to obtain such insights from raw parameter data requires significant effort and expertise on the part of personnel which, as identified during exploration of RQ1 cannot be assumed available in practice. Therefore, exploration of Research Question 3 sought to develop a method for translating raw parameters into actionable insights, in doing so compensating for potential limitations relating to effort and expertise resources. Additional benefit in such an approach can also be found in reducing vulnerability to personnel churn, an issue also identified in RQ1; by automating the process of analysing acquired data reliance upon tacit knowledge held by personnel is transformed into utilisation of embedded explicit knowledge in a process termed Externalisation [99]. Furthermore, by embedding analysis within an objective system the subjectivity inherent to human practices is removed, ensuring a consistent and traceable process is implemented every time and thus increasing generalisability of outputs across systems.

Accordingly, in Chapter 10 three data descriptor were proposed along with a method for their production, each of which provides quantification of a specific characteristic of CBS operation relating to its health and/or usage, based upon analysis of the response of MEPC parameters.

The first descriptor proposed was the duration of start-up transients as an indicator of mechanical load. Based upon observations during testing such transients were identified as presenting sensitivity to both changes in belt state (i.e. damage or incorrect tension) and/or the presence of live load on a belt during start-up. Both such scenarios subject a drive motor to excessive torsional load increasing severity of usage and are therefore undesirable. The provision of observability of start-up durations affords practitioners with a number of potential benefits, primary related to managing the state of belts. Based upon existing designs the belts of most Basic CBSs are tensioned in an open-loop manner, either via manual adjustment as with the Manufacturer's systems or via some form of take-up device. The optimal belt tension is likely to vary throughout a system's operational life in response to changes in ambient conditions as well as plastic deformation of the belt. If tension is too low then a belt can track off and conversely if tension is too great then the belt is subjected to unnecessary stress, potentially shortening its life. Existing tensioning systems rely upon either manual adjustment by an operator (or in the case of gravity weight take-up systems an assumption of the typical operational load on the system[76]) to set belt tension, a process which requires significant time and expertise. Neither system will thus necessarily result in appropriate tension being set at all times, therefore, providing practitioners with a means for assessing belt tension in real-time via estimated start-up durations could significantly improve system operation.

The second descriptor proposed was Total Weighted Exceedances (TWE) as means for quantifying the frequency and magnitude of transient loads experienced by a drive motor from analysis of MEPC. TWE as a descriptor provides a means for practitioners to understand the throughput of a system in a manner not feasible or practical via manual means; as identified through interviews with the maintenance team, the Operator lacks sufficient resource to comprehensively observe systems in operation, as well as being constrained by health and safety concerns. Even considering a hypothetical situation in which an operator was able to provide dedicated personnel to directly supervise and analyse the operation of each CBS the output of analysis would still be inherently subjective. In this respect TWE can provide an objective quantification of each system's throughput, supporting the implementation of practices such as usage-based maintenance and pricing, extreme loads analysis, and system-level comparative analysis.

The fidelity of insight represented within TWE is limited by the sensitivity of MEPC, thus it is not possible to understand exact conditions downstream of a motor through TWE alone. For example, as observed during CCTs (Chapter 8) it is not possible to differentiate between a heavy mass placed onto a belt and a light mass dropped onto a belt from height[77]. However, regardless of the specific source of loads all are experienced in an identical manner by the drive motor so can, from a motor usage perspective, be considered equivalent. Conversely, it may be that some elements of belt usage are not well captured within TWE; for example, if loading height has a disproportional effect compared to mass.

As discussed in Section 12.1, variance in the MTBF of nominally similar CBSs is caused by the combined effect of variance in multiple factors, including usage. In this respect TWE can provide greater insight into the operation of systems, translating raw MEPC data into contextualised

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[76] More sophisticated take-up systems able to compensate for changes in belt length and load are available, however, these are typically prohibitively expensive for application to Basic CBSs.

[77] Similarly, a constant stream of material was not able to easily be identified through MEPC alone. However, this represents a light usage scenario so can likely be omitted without significance.

information and thus enabling the effect of variance in usage to be removed as a factor contributing to variance in MTBF. However, whilst the magnitude of TWE provides an indication of a system's usage the subsequent relationship between each system's usage and its maintenance requirement must still be determined. For example, in the case of the Operator the existing maintenance requirement of CBS assets can be quantified from records, however, the corresponding MEPC of each system over that period is not captured. In the absence of such information it is not possible to deduce the true relevance of TWE as a usage indicator. Identifying such relationships is a challenge common to all usage-based maintenance applications and accordingly is increasingly recognised throughout literature. The concept of Function Usage Profiles (FUPs) was proposed as a mechanism for reducing the information contained within TWE and thus simplifying its interpretation. Whilst to implement FUP concepts still requires an understanding of the relationship between each FUP and its impact upon MTBF to enable appropriate thresholds and degradation rates to be defined, it is anticipated that reducing usage insights to discrete profiles will simplify the interpretation of MEPC. Initially, in the absence of phenomenological models or field data industrial implementation of FUPs it is necessary to utilise expert opinion to define the thresholds associated with each profile, which can then be updated with use as understanding is increased in a heuristic manner.

The third descriptor proposed provides a means for identifying specific forms of damage to a system's belt. Given the diverse applications in which CBSs can find operation the specific forms of damage which feasibly will afflict belts will likely be similarly diverse; thinning of a belt can cause a reduction in force carrying capacity leading to failure, material loss through mechanical abrasion or corrosive substances can lead to physical loss of belts or catastrophic damage can occur due to the slicing action of foreign objects, amongst many other potential failure modes. As the proposed descriptor was developed from data relating to the failure of only three belts and representing one failure mode the degree to which the descriptor will present sensitivity to wider belt failures is not comprehensively understood; to assess the broader sensitivity of the descriptor will certainly require the completion of a more extensive body of tests. For example, the typical rate of progression of a lateral belt failure when occurring 'naturally' as opposed to seeded is not known, therefore, the potential utility of the descriptor cannot be understood; as with any prognostic technique if the rate of progression of failure is faster than the typical response time of personnel then the descriptor may be of limited value. However, given the high fracture toughness demonstrated by composite belts typically used within CBSs it can be assumed that lateral failures will progress gradually, suggesting corrective interventions will be feasible. In a more general sense, the proposed method for detecting belt damage as presented in Chapter 10 can be expected to present sensitivity to periodic components below a frequency of ~1.6Hz; thus, in application to a generic CBS it may be necessary to adjust the specific decomposition level selected, if the geometry and/or belt speed of a CBS results in belt rotation components exceeding 1.6Hz.

Together, it is posited that through utilisation of the proposed descriptors insight into specific aspects of a CBS's health and usage can be obtained, serving as a means to increase observability of systems in operation to supplement existing visual inspection methods. Furthermore, access to the insight provided by data descriptors creates an opportunity to perform fleet-wide analytics across systems. For example, by comparing exceedances between sequential CBSs irregularities in material throughput can be inferred, indicative of issues such as blockages or belt loss.

Exploration of RQ3 sought to develop specifically an unsupervised means for assessing the health and/or usage of a CBS, such that assessments represent objective and consistent insights across systems, as well as minimising effort and expertise requirements to reapply across similar systems initially, as well as ongoing on the part of practitioners when interpreting insights.

To satisfy this requirement the methods developed for the production of each data descriptor were based upon phenomenological principles, that is, explainable relationships between changes in system state and MEPC. As presented in Chapter 10, to estimate the duration of start-up transients the Template Method was selected amongst similarly performing candidate methods due to its lack of reliance upon knowledge of each specific system to produce accurate estimations. Similarly, a method for estimating a system's Total Weighted Exceedances was developed which, in theory, required no knowledge of that system. However, subsequently, as described in Section 11.3.2, it was determined that some degree of deadzone tuning across classes of CBS may be required in practice. Finally, a method for identifying lateral belt damage was developed using wavelets, based upon exploiting the specific effects of such damage on MEPC as observed across tests, which again was directly applicable across similar systems.

By exploiting such relationships over, for example, 'black box' methods as commonly found in artificial intelligence applications, both the interpretation of insights and the application of descriptors to generic CBSs is anticipated to be simplified. However, given the small sample size of systems investigated thus far, ultimately, degree to which the proposed descriptors are suitable for mass implementation and can thus comprehensively be considered unsupervised in nature must be proved 'in the field.'

To demonstrate the potential utility of the proposed data descriptors a short series of trials were conducted, based around the operation of two different models of CBS produced by the Manufacturer (Chapter 11). Using MEPC data acquired during tests and the method for deriving each data descriptor developed within Chapter 9 the operation of each CBS was analysed, producing accurate insight into specific aspects of each's health and usage.

In addition to supporting systems in-service descriptors can potentially find value across the lifecycle, feeding into design activities where appropriate; for example, the specification of drive motors can be informed by understanding in-service loads obtained through analysis of TWE.

Summary of findings:

4. *Through observation of MEPC potentially a range of insights can be obtained in-service, relating to both the health and usage of a CBS.*
5. *The process of interrogating raw parameter data can be simplified through translation into appropriate data descriptors.*
6. *Three descriptors relating to specific aspects of CBS health and usage were proposed.*
7. *For each descriptor an analytic method of production was developed, based upon phenomenological principles, thus suitable for application to a generic CBS.*
8. *The applicability of the proposed data descriptors to a generic CBS was demonstrated through the completion of a short series of industrial trials.*

12.4 Limitations

Throughout the completion of this programme of research a number of limitations have been encountered, the potential impact of which should be considered. Primarily, limitations identified relate to two specific aspects of the conducted research: the ubiquity of the identified challenges facing the Manufacturer and Operator across wider bulk handling applications and the generality of empirical findings from testing activities.

12.4.1 Generality of Requirements

The methodology presented within this research programme has been developed such that it addresses the specific challenges facing the Manufacturer and Operator as identified through the primary research activities described in Chapters 2, 3 and 4. Bulk handling is a primarily industry-led field with thus little literature in existence describing both current practice as well as challenges faced. Thus, whilst there is no obvious suggestion that the findings of this research are unique to these organisations, based upon such a narrow study it remains a challenge to comprehensively understand the general applicability of findings. For example, interviews were only conducted with maintenance personnel at one of the Operator's plants; whilst the Operator gave no indication of this plant being unique the practices and challenges identified may not necessarily be present in other organisations. Furthermore, as with any qualitative data collection method the objectivity of findings must always be considered. The findings reported may only represent the opinion/perspective of those specific personnel and not the actual characteristics of the plant.

To address this limitation would require greater and sustained interactions with wider bulk handling manufacturers and operators to establish commonalities in both current practice and challenges faced, such that the potential value of the conducted research beyond utilisation by the Manufacturer and the Operator can be better understood.

12.4.2 Experimental Design and Implementation

Similarly, the degree to which technical findings of this research can be considered valid for a generic CBS beyond the specific applications presented within this thesis is not fully understood. CBSs represent a high volume asset, therefore, for research findings to be truly valuable they must be broadly applicable to similar systems without requiring significant effort for each application. The methods presented within this thesis have been developed based upon a combination of empirical and theoretical relationships identified within data acquired from a limited number of systems and encompassing a non-exhaustive combination of all possible operational variables. For example, no emulation of extremes in environment such as moisture, temperature and salinity were investigated during testing. Whilst the relationships identified within MEPC responses are for the most part explainable based upon the underlying mechanics of a CBS the degree to which these relationships will be apparent in a general application is a challenge to understand. For example, the impact of variance in aspects such as sources of power (VFD, portable generator etc.) or type of belt (flat, cleated etc.) has not been evaluated, and only a limited number of belt failures have been seeded and monitored, potentially limiting the extent to which findings can validly be extrapolated. Ultimately, given the number of potential operational variables associated with the operation of a CBS it is not possible to ever absolutely validate findings in a general sense. Furthermore, given the practical constraints of the research programme it was necessary to limit the exploration space to enable a tractable investigation. However, increasing the body of CBS characterisation data will only ever improve the value of the research, enabling greater confidence in findings and conclusions.

Overall, an experimentation-based methodology was employed to support exploration of research questions, keeping research as closely aligned to actual industrial practice as possible, such that findings could more directly be exploitable by industry. However, pursuing such an approach imposes practical limitations on the conducting of research; conducting physical experimentation involves significant resource, both time and financial, dictating the rate at which research can progress. Alternatively, a simulation-based approach (or elements therein) could have been utilised, for example, to enable a far more rapid rate of research development, unhindered by lead times, logistics and legislation, although, potentially at the cost of industrial alignment.

Similarly, to support industrial implementation of the proposed data descriptors explainable approaches to their generation have been preferred where possible, that is, methods based upon physical relationships which are the result of understood phenomena. In recent years machine learning (ML) and artificial intelligence (AI) techniques based upon data-driven approaches have seen widespread utilisation across signal processing literature, including the areas of diagnostics and prognostics of rotating machinery [245]. Historically, data-driven approaches have suffered from an inherent lack of transparency of their functioning; most data-driven approaches are ‘black box’ in nature, rendering their inner workings essentially invisible to a human and practically uninterpretable. Whilst recent literature has sought to resolve such limitations through increasing the ‘explainability’[78] of data-driven approaches significant obfuscation is still overwhelmingly present, resulting in a disconnect between algorithms and users. Therefore, by pursuing a phenomenological approach within this research it is hoped that the meaning of descriptors can more simply be conveyed to practitioners and thus an intuition for the characteristics of each descriptor can be fostered. Given the findings from exploration of RQ1 it is likely critical to the successful implementation of descriptors that practitioners are able to comprehensive understand the insight provided by each descriptor.

12.5 Industrial Implications

This programme of research was initiated to support industrial practitioners in addressing existing operational challenges, in particular those faced by the Manufacturer and the Operator. Based upon the research findings a number of means through which each organisation could realise value through the adoption of CM practices can be identified, as well as potentially wider organisations. A key issue identified as common to both organisations is the impact of a limited ability to observe the operation of CBSs in-service. In this respect the potential value of MEPC parameters and the proposed data descriptors is significant.

For the Manufacturer, access to data descriptors during design activities can support the specification of motors in particular. By understanding exactly the loads experienced by systems in-service more informed specifications for new applications can be made, ensuring motors operate efficiently, reducing operating costs and potentially extending functional life. In operation, data descriptors can support diagnostic activities; CBSs are operated remotely from the Manufacturer so through interrogation of data descriptors potential issues can be highlighted and the time spent on site by reactive maintenance personnel reduced. Similarly, data descriptors can be used to ensure belt tension is set appropriately throughout the service life of a CBS, enabling changes in length due to belt deformation or environmental conditions to be accounted for.

Currently, the belt tensioning procedure implemented by the Manufacturer (both during initial assembly and as recommended to customers) is entirely open-loop and based upon ‘feel’;

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[78] So called ‘explainable AI’ or XAI.

personnel will tighten a belt until obvious slack is removed and sufficient tension is present such that the belt moves without obvious slipping. Accordingly, the ability to provide personnel with objective feedback describing actual belt tension based upon MEPC presents an opportunity to prevent belts from over-tensioning, both during initial assembly and in-service, in doing so directly reducing energy costs (potentially as much as £45 per year per CBS, as described in Chapter 9). Further, data descriptors can enable a novel commercial offering; usage-based pricing. By observing exactly how each system is being used the Manufacturer can implement a pricing structure in which heavy users are penalised and light users are rewarded, reflecting the relationship between usage severity and maintenance effort.

For the Operator, access to CBSs in operation is challenging, both due to limited resources and health and safety concerns. Accordingly, access to data descriptors can enable personnel to understand better the state of CBSs throughout a plant from a single location at any instant. In doing so issues such as belt damage or incorrect tension can be identified earlier and corrective actions can be targeted appropriately across systems. Furthermore, over time personnel can develop an understanding of the relationship between each CBS's usage and resulting maintenance requirement, such that more effective preventative intervals can be defined.

To realise such benefits requires that research findings be translated into an implementable industrial solution. Throughout methods have been developed with consideration of industrial implementation; the selection of MEPC represents a feasibly monitorable parameter at scale. Utilising COTS hardware such as that utilised during the Industrial Monitoring Trial (IMT) reported in Chapter 4 the per CBS cost of monitoring is in the region of £250, however, for a permanent installation at scale this cost can certainly be reduced. Furthermore, given MEPC hardware doesn't require direct contact with a CBS's motor the cost of installation and maintenance is not likely to be significant. As mentioned in Chapter 4 the Manufacturer has designed in a voltage monitoring system within newer CBS models, thus suggesting extending capabilities to include power measurement is relatively simple. During initial trials storing data locally and manually offloading periodically for review is likely to be most appropriate, essentially constituting a 'soft launch'. In doing so data can be collected in the background without affecting existing operation and used to tune the implementation of data descriptors/fix hardware and software bugs. In the long term, a shift towards automatic wireless transfer of data to a central system may be appropriate, particularly in the case of the Manufacturer where CBSs are distributed over a large geographic area, enabling data across a fleet of CBS to be compiled an analysed aggregately, either at a remote location or locally, within a control room, for example. In doing so data can be distilled into an autogenerated report format, further simplifying the interpretation of data.

Similarly, given the existence of potential socio-technical challenges associated within the adoption of CM as identified during the IMT (Chapter 4) it is important to consider how the insight provided by the provision of data descriptors can be integrated into existing practices. Despite the potential affordances of such insights ultimately the actual state of systems must be confirmed by personnel; data descriptors should most appropriately be considered as supplements to existing practice, rather than a replacement for. The insight provided by data descriptors falls into two categories: that which is actionable upon in the short term and that which supports longer term analysis. Essentially data descriptors can be used to can flag up the potential occurrence of specific issues or can provide a means for tracking the operation of system over time in an objective manner. The first (start-up duration) and third (belt damage) descriptors are actionable in the short term, triggering inspections to verify indicated conditions. In contrast, the utility of the second descriptor (TWE) is realised over longer timescales, enabling the relationships between CBSs usage and its resulting health and maintenance requirement to be identified.

However, within the scope of this research programme the general applicability of each descriptor when applied to a generic CBS has not be substantially confirmed; to a degree, descriptors have been developed in an inductive manner. As such, an expanded body of testing will be required to assess wider validity, within the scope of a lateral and longitudinal study. A lateral study will enable the variance across similar CBSs and the impact of this on the validity of descriptors to be assessed more comprehensively, whereas a longitudinal study will permit observation of key events such as belt and motor failure. In practice, these events often evolve gradually over extended periods of operation, necessitating a long duration study to enable their characterisation from a MEPC perspective. Such a trial will likely constitute an expansion of the IMT, however, incorporating the lessons learned through the completion of the research programme.

Finally, an importance aspect of industrial implementation is understating how the value of research can be assessed/measured. As discussed in Chapters 2 and 3, primarily the performance of a CBS is dictated by the availability it realises, therefore, the value of this research programme to industry will ultimately be demonstrated through improvements in availability. Whilst availability is a simplistic concept it cannot be assumed that it is accurately measured in practice; to measure availability requires that the operational state of each CBS is logged continuously, which , particularly in the case of the Manufacturer where systems are operated by customers and are subjected to varying demands (i.e. a system may not be running because there is no demands for it rather than because it is inoperable) may not be trivial. As such, demonstrating improvement in CBS availability as a result of the adoption of data descriptors may also not be trivial. Furthermore, the 'softer' secondary benefits associated with adoption, such as resilience to personnel churn, are similarly likely to be challenging. Each organisation must decide whether data descriptors represent a potential value proposition for their application. Ultimately, however the value in data descriptors is defined this must be explicitly identified prior to implementation and agreed upon by all parties.

Chapter 13: Conclusions and Further Work

In the broadest sense the continuous monitoring of a system comprises continuous acquisition and processing of information and data that indicates the state of that system over time. In recent years adoption of continuous monitoring has been increasing across industry, supported by advances in the technology and reductions in the cost of monitoring systems. However, thus far adoption has predominantly been restricted to applications within higher-value industries, such as aerospace and energy production, with little penetration into traditionally less innovative industries, such as waste management and construction. Accordingly, this programme of research was initiated to understand how the adoption of continuous monitoring techniques may support manufacturers and operators of bulk handling conveyor belt systems (CBSs) across the design, operation and maintenance of systems. In doing so the programme of research sought to address the aim:

To create a practical method for observing the operation of a conveyor belt system using continuous monitoring techniques.

In addressing the aim three Research Questions were defined, through exploration of which a clear opportunity for continuous monitoring to provide value to practitioners was identified and a method for characterising the operation of bulk handling conveyor belt systems in-service was developed.

13.1 Summary of Thesis

Firstly, in **Chapter 2** the design and operation of a Basic CBS was explored through a review of extant literature, as well as interactions with both the Manufacturer and Operator. Through an industry corroborated failure mode and effect analysis and the analysis of maintenance records from across the Operator's plants the most impactful issues facing a CBS were identified as those relating to belts and motors. Furthermore, a reliance upon visual inspection to identify CBS issues in-service was identified as contributing towards reduced availability of systems.

In **Chapter 3** existing approaches to the maintenance of systems across industry were examined, again through a combination of literature review and industrial studies. Interviews were conducted with maintenance personnel at one of the Operator's plants, revealing a predominantly reactive approach to the maintenance of systems is currently implemented, supported by preventative elements. The impact of a lack of visibility of systems when in operation was highlighted as contributing to limitations on the effectiveness of existing maintenance practices, exacerbated by personnel churn and health and safety restrictions. The concept of predictive maintenance was discussed, however, ultimately such an approach was demonstrated to not necessarily be suitable for application to CBSs due to the low cost of replacement parts, a limited ability of personnel to act upon theoretical insights as well as a lack of understanding of the failure characteristics of CBSs components in practice.

Next, in **Chapter 4**, the principles of continuous monitoring were discussed, and current practice as reported in extant literature was examined. A significant body of research within the areas of belt and motor monitoring was identified and reviewed, and a number of challenges associated with the specification and implementation were discussed. To evaluate the potential utility of continuous monitoring in CBS applications a short industrial trial was conducted at one of the Operator's plants, through the completion of which the existence of a number of technical and socio-technical issues were recognised. Based upon the findings of this chapter three requirements of continuous monitoring to be appropriate for application to CBSs were defined, relating to the cost, feasibility and insight realised through monitoring.

Bringing together the findings from Chapters 2, 3 and 4, in **Chapter 5** the aim of the programme of research was defined, along with three research questions to support the addressing of the aim. Primarily, the three research questions sought to understand the current challenges facing manufacturers and operators of CBSs (RQ1), identify the most suitable parameters for continuous monitoring in such applications (RQ2), and evaluate the potential insight obtainable through these parameters as well as how such insight can be provided to practitioners without requiring manual interrogation of raw parameters (RQ3). Accordingly, a methodology for exploration of the research questions was proposed, based primarily around a series of experimental studies, to maximise the industrial applicability of any research findings.

The first of these experimental studies involved the design and operation of a bespoke test rig, as presented in **Chapters 6 and** 7. The Conveyor Emulation Rig (CER) enabled the characteristics of a range of continuously monitored system parameters to be evaluated whilst different operational scenarios were emulated within a controlled environment. Findings from the body of test scenarios conducted indicated the suitability of motor electrical power consumption (MEPC) parameters for CBS applications, due to their low cost, non-invasive method of monitoring and sensitivity to changes in drive motor torsional load.

Based upon the findings from operation of the CER, in **Chapters 8 and 9** a subsequent body of Conveyor Characterisation Tests (CCTs) were conducted using a CBS provided by the Manufacturer, to evaluate the potential insight into CBS operation obtainable through analysis of MEPC parameters. A series of test scenarios were implemented, which comprised scenarios representing different usage patterns and scenarios during which common belt-related faults were seeded. Acquired data suggested that it is possible to infer significant insight into the characteristics of live loads from the response of MEPC parameters, as well as to identify changes in belt state, including tension, tracking and the occurrence of lateral damage.

Using the findings of CCTs an unsupervised method for characterising the operation of a CBS in-service was developed in **Chapter 10**, comprising the derivation of three data descriptors from raw MEPC parameters, each of which relates to an aspect of a CBS's health or usage. A method for deriving each data descriptor was developed such that manual input from personnel is not required, enabling the interrogation of data descriptors in-service without placing additional demands upon personnel.

Subsequently, in **Chapter 11** application of the proposed data descriptors was demonstrated through the completion of a series of trials, during which two models of CBS offered by the Manufacturer were operated. Through these trials the variance in MEPC characteristics as well as the applicability of the proposed data descriptors across similar CBSs was assessed. It was established that the proposed data descriptors can be feasibly applied to a generic CBS without requiring significant effort or modification of the developed methods.

Finally, in **Chapter 12** the conducted programme of research was evaluated against the Research Questions defined in Chapter 5, and the potential limitations of the implemented methodology were considered. In addition, the industrial implications of the proposed method for characterising CBS operation in-service were discussed, in particular in the context of the Manufacturer and the Operator specifically.

Overall, the aim of this programme of research has been satisfied through the development of an unsupervised method for characterising the operation of a CBS in-service, based upon the continuous monitoring of drive motor electrical power consumption. Collectively, the research presented within this thesis is considered to constitute an enabling body of work, upon which further research streams can build. As illustrated in **Figure 13.1**, within this thesis the completion of Task 1 and 2 have been described, providing a foundation for the validation of each aspect of Task 3 beyond the scope of this thesis.

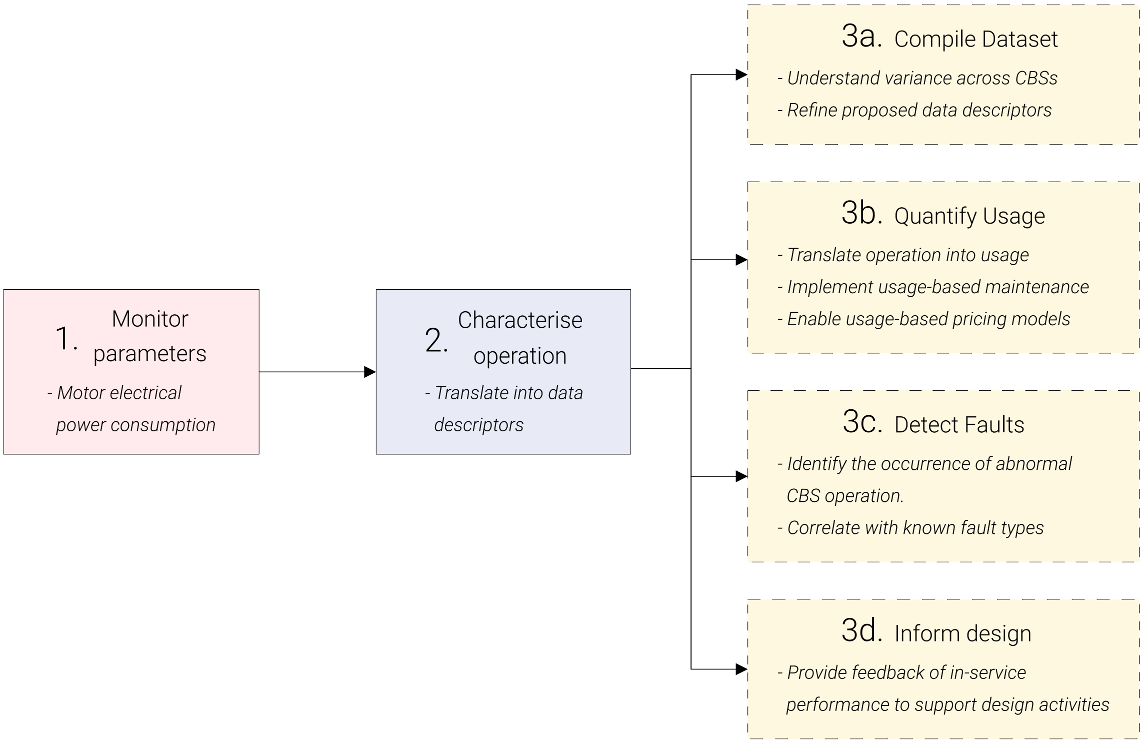

Figure 13.1: Taxonomy of high-level tasks within the overall programme of research, indicating those presented within this thesis (1 and 2) and those enabled for further exploration (3).

13.2 Summary of Research Findings

Through exploration of the three research questions defined in Chapter 5, a number of key findings have emerged:

13.2.1 Research Question 1

- *The design of CBSs has converged to a common form across industry, utilising low cost COTS parts where possible.*
- *In-service, practitioners are reliant upon visual inspection to assess the condition of assets, which applies inherent limitations on the availability and validity of condition data.*
- *The most impactful issues experienced by CBSs are belt and motor related.*
- *Predominantly, reactive maintenance approaches are being implemented within bulk handling applications, with aspirations to move towards more preventative-based approaches.*
- *The implementation of predictive maintenance approaches to CBS is not necessarily appropriate.*

13.2.2 Research Question 2

- *The degree to which the operation of a CBS can be observed through the interrogation of continuously monitored parameters is directly affected by data availability.*
- *In many instances a single phenomenon can be observed simultaneously within the response of multiple parameters.*
- *Overall, for this application, motor electrical power consumption (MEPC) was identified as the most appropriate parameter to monitor, given the characteristics of industrial environments.*
- *MEPC demonstrates sensitivity to changes in torsional load (as a proxy for usage) and changes in belt states such as tension and integrity (as a proxy for health).*

13.2.3 Research Question 3

- *Through observation of MEPC potentially a range of insights can be obtained in-service, relating to both the health and usage of a CBS.*
- *The process of interrogating raw parameter data can be simplified through translation into appropriate data descriptors.*
- *Three descriptors relating to specific aspects of CBS health and usage were proposed.*

- *For each descriptor an analytic method of production was developed, based upon phenomenological principles, thus suitable for application to a generic CBS.*
- *The applicability of the proposed data descriptors to a generic CBS was demonstrated through the completion of a short series of industrial trials.*

13.3 Contributions to Knowledge

As previously stated, the overall contribution of this research is an unsupervised method for characterising the operation of a conveyor belt system in-service through the monitoring and processing of motor electrical power consumption parameters. However, in addition, it is contested that a number of significant sub-contributions to knowledge of interest to both researchers and practitioners have been produced, primarily within three areas:

1. **Characterisation of current practice and challenges within bulk handling CBS applications (RQ1).**

    a. *Characterised current maintenance practices through semi-structured interviews with an industrial maintenance team.*
    b. *Assessed the potential failure modes of a CBS through an industrially corroborated failure mode and effect analysis.*
    c. *Through analysis of an industrial operator's maintenance records identified belt and motor issues as most impactful for a CBS.*
    d. *Identified existence of potential socio-technical issues facing the adoption of new technologies within industrial operations.*

2. **Evaluation of CBS parameters (RQ2).**

    a. *Developed a physical testbed to assess the relative sensitivity of various CBS parameters to changes in health and usage.*
    b. *Determined the effect of various modes of loading on range of monitored system parameters.*
    c. *Assessed the feasibility of monitoring of various monitored parameters within the context of industrial application.*

d. *Identified the suitability of MEPC parameters for continuous monitoring in CBS applications.*
e. *Identified the feasibility of inferring mechanical changes from the response of MEPC parameters.*

3. **Data processing methods (RQ3).**

a. *Identification of suitable data descriptors relating to the heath and usage of a CBS.*
b. *Development of an unsupervised method to estimate the duration of motor start-up transients from MEPC parameters.*
c. *Development of an unsupervised method to evaluate CBS usage based upon exceedances within MEPC parameters.*
d. *Development of an unsupervised method to identify and quantify the presence of lateral damage within a CBS's belt from changes in MEPC parameters.*

13.4 Further Work

Based upon the extent and findings of this programme of research in this section the future direction of the research is discussed, in addition to a number of tangential areas suggested as worthy of further investigation by other researchers.

Firstly, the practical value of the proposed data descriptors to industrial practitioners can be more extensively explored. Within the scope of this thesis data descriptors were not integrated within day-to-day operations at either the Manufacturer or Operator, but instead only within the context of controlled trials. To better understand the value and most appropriate form of delivery of the proposed data descriptors such activities are necessary.

Furthermore, the developed method has only be applied to Basic conveyor belt systems, however, there is the potential for application of the method to alternative forms of CBS, or even alternative systems altogether. In theory, the principles of MEPC monitoring can be applied to any system containing electric motors, opening up the possibility of applying this research in a wider context. Across industry a number of potential candidates for reapplication of the principles of MEPC-based data descriptors exist, such as centrifugal pumps and blowers, ubiquitous throughout many industrial operations.

The methods developed for the derivation of each data descriptor, as presented in Chapter 10, are based upon phenomenological principles to simplify interpretability and generalisability across CBSs. Increasingly the utilisation of artificial intelligence and machine learning techniques are being reported across industry, primarily for data classification tasks, where they have demonstrated an ability to produce insights from vast datasets not feasible to interrogate via manual means. Historically, such techniques have suffered from a lack of visibility of their functioning, abstracting practitioners from their internal 'black boxes', however, given recent advances in both the explainability and Implementability of techniques their potential suitability as methods for the derivation of alternative data descriptors is certainly worthy of future exploration.

During exploration of RQ1 belt-related issues were identified as the most impactful to the operability of a CBS. Within this programme of research no significant effort has been given to increasing understand of the mechanisms associated with belt failures. Within literature there exists few reports describing the specific characteristics of CBSs belt failures. As implemented within this research, typically seeded failures are used to generate failure data for reasons of practicality; within industrial operations many modes of belt failure can be expected to develop over extended periods, perhaps weeks or even months. Increasing understanding of the specific mechanism of belt failure as they evolve over time would potentially enable the identification of precursors to failure, from which appropriate data descriptors may be developed.

Similarly, within this programme of research the direct monitoring of belts to detect the onset and/or occurrence of failure has also not been explored. Whilst technologies for this task exist within industry, at present their cost restricts their application to only the most critical CBSs. Given the impact of belt failures on the operability of CBSs, the development of a technology capable of providing an indication of changes in belt condition which can feasibly be implemented at scale across a diversity of operational environments would certainly be of interest to industrial practitioners.

References

[1] D. Clénet, ‘Optimising Energy Efficiency of Conveyors’, Schneider Electric, Paris, 2010.

[2] J. Bond, ‘Conveyor systems market to post steady growth until 2020’, *Mod. Mater. Handl.*, vol. 70, no. 4, pp. 10–10, Apr. 2015.

[3] Conveyor Equipment Manufacturers Association, ‘Conveyor Equipment Manufacturers Association (CEMA) Semi-Annual Press Release’, Naples, Florida, Press Release, Apr. 2019. [Online]. Available: https://cemanet.org/cema-semi-annual-press-release-march-2019/.

[4] C. R. Woodcock and J. S. Mason, *Bulk Solids Handling*: *An Introduction to the Practice and Technology*. Springer Netherlands, 1987.

[5] K. T. Higgins, ‘More than Point A to Point B’, *Food Processing* (00156523), vol. 75, no. 5, pp. 70–76, May 2014.

[6] L. K. Rogers, ‘Food and Beverage: Keeping up with the SKUs’, *Modern Materials Handling*, p. 35, Jul. 2012.

[7] N. Boysen, D. Briskorn, S. Fedtke, and M. Schmickerath, ‘Automated sortation conveyors: A survey from an operational research perspective’, *Eur. J. Oper. Res.*, vol. 276, no. 3, pp. 796–815, Aug. 2019, doi: 10.1016/j.ejor.2018.08.014.

[8] A. Goolsbee and P. J. Klenow, ‘Internet Rising, Prices Falling: Measuring Inflation in a World of E-Commerce’, Social Science Research Network, Rochester, NY, SSRN Scholarly Paper ID 3191099, Jun. 2018. Accessed: Jan. 14, 2020. [Online]. Available: https://papers.ssrn.com/abstract=3191099.

[9] G. Lodewijks, ‘Energy efficient use of belt conveyors in baggage handling systems’, in *Proceedings of* 2012 *9th IEEE International Conference on Networking, Sensing and Control*, Apr. 2012, pp. 97–102, doi: 10.1109/ICNSC.2012.6204898.

[10] Markets and Markets, ‘Conveyor System Market by Industry, Type and Region – 2025’, Jan. 2019. https://www.marketsandmarkets.com/Market-Reports/conveyor-systems-market-31314058.html (accessed Jan. 13, 2020).

[11] Mining World, ‘Conveyor monitoring and maintenance: If you only plan to fix equipment when it breaks, you’re going to be very busy’, *Min. World*, vol. 14, no. 4, pp. 30–32, Aug. 2017.

[12] ‘Bulking Up: Conveyor system technology evolves to meet the changing bulk materials handling needs of the industry’, *Engineering & Mining Journal*, vol. 214, no. 10, pp. 82–86, Oct. 2013.

[13] P. M. McGuire, *Conveyors : Application, Selection, and Integration*. CRC Press, 2009.

[14] Coveya Ltd., ‘How can a hired conveyor save me money?’, Sep. 19, 2018. https://www.coveya.co.ukarticles/85-how-can-a-hired-conveyor-save-me-money (accessed Jan. 13, 2020).

[15] Conveyor Equipment Manufacturers Association, *Belt Conveyors for Bulk Materials*, Sixth. Naples, Florida: Conveyor Equipment Manufacturers Association, 2005.

[16] V. Pavlova, ‘The Amazon Effect: How Amazon Is Disrupting European E-commerce’, *Forbes*, Sep. 02, 2019. https://www.forbes.com/sites/victoriapavlova/2019/02/09/the-amazon-effect-how-amazon-is-disrupting-european-e-commerce/ (accessed Jan. 13, 2020).

[17] J. Moubray, *Reliability-centered Maintenance* 2.1 (*2nd Edition*), 2nd ed. Oxford: Butterworth-Heinemann, 1999.

[18] T. Schools, ‘Condition Monitoring of Critical Mining Conveyors’, *Engineering and Mining Journal*, vol. 216, no. 3, p. 50, 2015.

[19] G. Paton, ‘Heathrow chaos forces fliers to leave bags behind’, *The Times*, Jun. 16, 2017.

[20] A. Winning, ‘South Africa’s Eskom resumes power cuts after Medupi fault’, *Reuters*, Jan. 04, 2020.

[21] R. T. Swinderman, A. D. Marti, L. J. Goldebeck, D. Marshall, and M. G. Strebel, *Foundations - The practical resource for cleaner, safer, more productive dust & material control*. Martin Engineering, 2009.

[22] E. Isokangas, ‘Delivering a Step Change in Operating Costs’, *Can. Min. J.*, vol. 138, no. 3, pp. 27–28, Apr. 2017.

[23] Office for National Statistics, ‘Construction statistics, Great Britain: 2017’, *Office for National Statistics*.

https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/articles/constructionstatistics/number192018edition (accessed Jan. 13, 2020).

[24] Ricardo-AEA and The Chartered Institute of Waste Management, 'Waste on the Front Line – Challenges and Innovations', The Chartered Institute of Waste Management, 2014.

[25] Ofgem, 'About the Climate Change Levy exemption', *Ofgem*, Jul. 22, 2016. https://www.ofgem.gov.uk/environmental-programmes/about-climate-change-levy-exemption (accessed Jan. 13, 2020).

[26] D. Evans, 'How the Next Evolution of the Internet Is Changing Everything', Cisco Internet Business Solutions Group, White Paper, 2011.

[27] E. Maguire, 'The Intelligent Edge: Opportunity and IoT Innovation', White Paper, 2018.

[28] A. Gilchrist, *Industry* 4.0: *The Industrial Internet of Things*, 1st edition. Apress, 2016.

[29] British Standards Institution, 'Condition monitoring and diagnostics of machines - Vocabulary', International Standard BS ISO13372:2012, 2012. [Online]. Available: https://www.iso.org/standard/52256.html.

[30] European Commission, 'Flightpath 2050: Europe's Vision for Aviation', 2011. doi: 10.2777/50266.

[31] I. K. Jennions, 'The Developing Field of Integrated Vehicle Health Management', *J. Aerosp. Sci. Technol.*, vol. 65, no. 1A, pp. 69–78, 2013.

[32] J. Igba, K. Alemzadeh, K. Henningsen, and C. Durugbo, 'Effect of preventive maintenance intervals on reliability and maintenance costs of wind turbine gearboxes', *Wind Energy*, vol. 18, no. September 2014, pp. 2013–2024, 2015, doi: 10.1002/we.

[33] P. Tchakoua, R. Wamkeue, M. Ouhrouche, F. Slaoui-Hasnaoui, T. A. Tameghe, and G. Ekemb, 'Wind Turbine Condition Monitoring: State-of-the-Art Review, New Trends, and Future Challenges', *Energies*, vol. 7, no. 4, pp. 2595–2630, Apr. 2014, doi: 10.3390/en7042595.

[34] IAEA, 'Application of Reliability Centred Maintenance to Optimize Operation and Maintenance in Nuclear Power Plants', 2007. doi: 978-92-0-105008-3.

[35] J. Smith, 'Intelligent Infrastructure: Network Rail's Strategy for RCM', 2011, no. November.

[36] D. J. Pedregal, F. P. García, and F. Schmid, 'RCM2 predictive maintenance of railway systems based on unobserved components models', *Reliab. Eng. Syst. Saf.*, vol. 83, no. 1, pp. 103–110, Jan. 2004, doi: 10.1016/j.ress.2003.09.020.

[37] F. P. García Márquez, F. Schmid, and J. C. Collado, 'A reliability centered approach to remote condition monitoring. A railway points case study', *Reliab. Eng. Syst. Saf.*, vol. 80, no. 1, pp. 33–40, 2003.

[38] I. K. Jennions, *Integrated Vehicle Health Management: Perspectives on an Emerging Field*. SAE International, 2011.

[39] O. Freeman Gebler, B. Hicks, A. Harrison, M. Barker, and P. Stirling, 'Towards the Implementation of a Predictive Maintenance Strategy : Lessons Learned from a Case Study within a Waste Processing Plant', in *European Conference of the Prognostics and Health Management Society* 2016, 2016, pp. 1–17.

[40] J. Bond, 'CONVEYORS: A Method to the Maintenance', *Mod. Mater. Handl.*, vol. 74, no. 1, pp. 44–51, Jan. 2019.

[41] B. Trebilcock, 'Conveyor technology: Are you thinking differently?', *Mod. Mater. Handl.*, vol. 88, no. 4, pp. 24–29, Apr. 2013.

[42] Department for Environment, Food and Rural Affairs, 'Mechanical Biological Treatment of Municipal Solid Waste', DEFRA, PB13890, 2012. Accessed: Feb. 19, 2109. [Online]. Available: https://www.gov.uk/government/publications/mechanical-biological-treatment-of-municipal-solid-waste.

[43] British Standards Institution, 'Maintenance - Maintenance terminology', Technical standard BS EN 13306:2017, 2017.

[44] S. Brouwers, 'Playing with Fire?', *Coal International*, vol. 262, no. 2, pp. 50–53, Apr. 03, 2014.

[45] Dunlop-Enerka, *Conveyor Belt Technique: Designa and Calculation*. 1994.

[46] P. Tavner, L. Ran, J. Penman, and H. Sedding, *Condition Monitoring of Rotating Electrical Machines*, 2nd ed. The Institute of Engineering and Technology, 2008.

[47] A. Hughes and W. Drury, *Electric Motors and Drives: Fundamentals, Types and Applications*. Elsevier Science, 2013.

[48] E. D. Yardley and L. R. Stace, *Belt Conveying of Minerals*. Woodhead Publishing, 2008.

[49] P. Sen, *Principles of Electric Machines and Power Electronics*. 2013.

[50] British Standards Institution, 'Light conveyor belts - Part 1: Principal characteristics and applications', Technical standard BS EN ISO 21183-1-2006, 2006.

[51] International Organization for Standardization, 'Continuous mechanical handling equipment - Belt conveyors with carrying idlers - Calculation of operating power and tensile belt forces', Technical standard ISO 5048:1989, 1989.

[52] British Standards Institution, 'Rolling bearings - Dynamic load ratings and rating life', Technical standard BS ISO 281:2007, 2007.

[53] SKF Group, *SKF Bearing Maintenance Handbook*. 2010.

[54] A. Starr, B. Al-najjar, K. Holmberg, E. Jantunen, J. Bellew, and A. Albarbar, 'Maintenance Today and Future Trends', in *E-maintenance*, London: Springer London, 2010, pp. 5–37.

[55] R. A. Carter, 'Taming the Terrain', *Eng. Min. J.*, vol. 217, no. 10, pp. 44–46, Oct. 2016.

[56] M. Loyola, 'Big data in building design: a review', *J. Inf. Technol. Constr. ITcon*, vol. 23, no. 13, pp. 259–284, Nov. 2018.

[57] P. Bernstein, 'Future of Design: Big Data Changes Everything', *Redshift by Autodesk*, Jun. 11, 2014. https://www.autodesk.com/redshift/future-of-design-big-data-changes-everything/ (accessed Feb. 19, 2020).

[58] Tesla Automotive, 'Tesla Autopilot: The Future of Driving'. https://www.tesla.com/autopilot (accessed Feb. 19, 2020).

[59] J. Gertner, 'Behind GE's Vision For The Industrial Internet Of Things', *Fast Company*, Jun. 18, 2014. https://www.fastcompany.com/3031272/can-jeff-immelt-really-make-the-world-1-better (accessed Feb. 19, 2020).

[60] T. Tinga, *Principles of Loads and Failure Mechanisms: Applications in Maintenance, Reliability and Design*. London ; New York: Springer, 2013.

[61] IEEE, 'IEEE Guide for Induction Machinery Maintenance Testing and Failure Analysis', IEEE, International Standard IEE Std. 1415-2006, 2006. Accessed: Feb. 07, 2019. [Online]. Available: http://ieeexplore.ieee.org/document/4197458/.

[62] Federal Aviation Authority, 'Visual Inspection for Aircraft', Federal Aviation Authority, Advisory Circular AC 43-204, 1997. [Online]. Available:

https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentid/22597.

[63] T. Ruff, P. Coleman, and L. Martini, 'Machine-related injuries in the US mining industry and priorities for safety research', *Int. J. Inj. Contr. Saf. Promot.*, vol. 18, no. 1, pp. 11–20, Mar. 2011, doi: 10.1080/17457300.2010.487154.

[64] R. K. Mobley, *An Introduction to Predictive Maintenance*, 2nd ed. Amsterdam ; New York: Butterworth-Heinemann, 2002.

[65] British Standards Institution, 'Failure modes and effects analysis (FMEA and FMECA)', Technical standard BS EN IEC 60812:2018, 2018.

[66] L. Hoggan, 'Proper Conveyor Belt Maintenance Prevents Downtime', *C&D World*, vol. 6, no. 3, pp. 28–31, Jun. 05, 2013.

[67] IEEE, 'IEEE Std. 43-2013: Recommended Practice for Testing Insulation Resistance of Electric Machinery', *IEEE Std* 43-2013 *Revis. IEEE Std* 43-2000, pp. 1–37, Mar. 2014, doi: 10.1109/IEEESTD.2014.6754111.

[68] B. S. Dhillon, *Engineering Maintenance*: *A Modern Approach*. CRC Press, 2002.

[69] R. A. Carter, 'Maintaining the Pace', *Eng. Min. J.*, vol. 220, no. 5, pp. 32–35, May 2019.

[70] G. Gunther, 'Loads Monitoring and Hums', Sofia, Bulgaria, 2000, p. 17.

[71] National Transportation Safety Board Bureau of Accident and Investigation, 'Aircraft Accident Report - Aloha Airlines Flight 243', Washington D.C., NTSB/AAR-89/03. Accessed: Sep. 09, 2019. [Online]. Available: https://www.ntsb.gov/investigations/AccidentReports/Pages/AAR8903.aspx.

[72] T. Tinga, 'Application of physical failure models to enable usage and load based maintenance', *Reliab. Eng. Syst. Saf.*, vol. 95, no. 10, pp. 1061–1075, 2010, doi: 10.1016/j.ress.2010.04.015.

[73] C. R. Farrar and N. A. J. Lieven, 'Damage prognosis: The future of structural health monitoring', *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.*, vol. 365, no. 1851, pp. 623–632, 2007, doi: 10.1098/rsta.2006.1927.

[74] I. K. Jennions, *Integrated Vehicle Health Management*: *Business Case Theory and Practice*. SAE International, 2012.

[75] G. Lay, *Servitization in Industry*. Heidelberg: Springer International Publishing, 2014.

[76] O. Benedettini, T. S. Baines, H. W. Lightfoot, and R. M. Greenough, 'State-of-the-Art in Integrated Vehicle Health Management', *J. Aerosp. Eng.*, vol. 223, no. 157, 2009, doi: 10.1243/09544100JAERO446.

[77] I. Fan, R. Verma, I. Jennions, and A. Dubicka, 'A Business Analysis Methodology for Integrated Equipment Health Management in High Value Assets', London, UK, 2011, pp. 1–8, doi: 10.1049/cp.2011.0572.

[78] Continental, 'The Business Model of the Future: Conveyor Belts: Lease, Don't Buy', *Continental*. https://www.continental.com/en/press/press-releases/conveyor-belts-lease-127640 (accessed Sep. 04, 2018).

[79] I. K. Jennions, *Integrated Vehicle Health Management: The Technology*. SAE International, 2013.

[80] J. Bird, 'Introduction to Prognostics and Health Management', presented at the PHM Fundamentals Short Course, Bilbao, Spain, 2016.

[81] SAE International, 'ARP6275: Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System'. SAE International, 2014.

[82] Y. Peng, M. Dong, and M. J. Zuo, 'Current status of machine prognostics in condition-based maintenance: a review', *Int. J. Adv. Manuf. Technol.*, vol. 50, no. 1–4, pp. 297–313, 2010, doi: 10.1007/s00170-009-2482-0.

[83] H.-J. Marais, G. van Schoor, and K. R. Uren, 'Energy-based fault detection for an autothermal reformer', 11*th IFAC Symp. Dyn. Control Process Syst. Biosyst.*, vol. 49, no. 7, pp. 353–358, 2016, doi: 10.1016/j.ifacol.2016.07.325.

[84] G. Niu, B. S. Yang, and M. Pecht, 'Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance', *Reliab. Eng. Syst. Saf.*, vol. 95, no. 7, pp. 786–796, Jul. 2010, doi: 10.1016/j.ress.2010.02.016.

[85] R. Walker, S. Perinpanayagam, and I. K. Jennions, 'Rotordynamic Faults: Recent Advances in Diagnosis and Prognosis', *Int. J. Rotating Mach.*, vol. 2013, p. 12, 2013.

[86] J. Lee, F. Wu, W. Zhao, M. Ghaffari, L. Liao, and D. Siegel, 'Prognostics and health management design for rotary machinery systems - Reviews, methodology and applications', *Mech. Syst. Signal Process.*, vol. 42, no. 1–2, pp. 314–334, 2014, doi: 10.1016/j.ymssp.2013.06.004.

[87] SAE International, *ARP6275: Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System*. SAE International, 2014.

[88] D. Chanana, E. Maguire, L. Mazzei, and A. Cresto, 'Realizing the Opportunity in Predictive Maintenance Analytics', Momenta Partners, White Paper, 2017.

[89] R. Blazej, L. Jurdziak, and W. Kawalec, 'Operational Safety of Steel-Cord Conveyor Belts Under Non-stationary Loadings', in *Advances in Condition Monitoring of Machinery in Non-Stationary Operations. Applied Condition Monitoring*, 2016, vol. 4, pp. 535–544, doi: 10.1007/978-3-319-20463-5_36.

[90] W. W. Tiddens, T. Tinga, A. J. J. Braaksma, and O. Brouwer, 'The business case for condition-based maintenance: a hybrid (non-) financial approach', presented at the European Safety and Reliability Conference, ESREL 2017, 2017, doi: 10.1201/9781315210469-107.

[91] D. Siegel, H. D. Ardakani, J. Lee, Y. S. Chang, and J. Lee, 'A review of predictive monitoring approaches and algorithms for material handling systems', *Int. J. Adv. Logist.*, vol. 3, no. 3, pp. 87–99, 2014, doi: 10.1080/2287108X.2014.985775.

[92] R. Błażej, L. Jurdziak, and W. Kawalec, 'Condition Monitoring of Conveyor Belts as a Tool for Proper Selection of Their Replacement Time', in *Advances in Condition Monitoring of Machinery in Non-Stationary Operations. Applied Condition Monitoring*, 2016, vol. 4, pp. 484–487, doi: 10.1007/978-3-319-20463-5_37.

[93] G. Albuam and A. N. Oppenheim, 'Questionnaire Design, Interviewing and Attitude Measurement', *J. Mark. Res.*, vol. 30, no. 3, p. 393, 1993, doi: 10.2307/3172892.

[94] B. G. Glaser and A. L. Strauss, *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Chicago: Aldine Publishing Company, 1967.

[95] L. M. Given, Ed., 'Semi-Structured Interview', in *The Sage Encyclopaedia of Qualitative Research Methods*, Los Angeles, California: Sage Publications, 2008.

[96] J. F. Gubrium, *The SAGE Handbook of Interview Research: The Complexity of the Craft*. Sage Publications Inc, 2012.

[97] G. R. Gibbs, *Analyzing Qualitative Data*. 1 Oliver's Yard, 55 City Road, London England EC1Y 1SP United Kingdom: SAGE Publications, Ltd, 2007.

[98] The Department for Education, 'What Qualification Levels Mean', *GOV.UK*. https://www.gov.uk/what-different-qualification-levels-mean/list-of-qualification-levels (accessed Feb. 19, 2020).

[99] I. Nonaka, 'A Dynamic Theory of Organizational Knowledge Creation', vol. 5, no. 1, pp. 14–37, 1994, doi: 10.1287/orsc.5.1.14.

[100] J. T. Selvik and T. Aven, *A framework for reliability and risk centered maintenance*, vol. 96. 2011, pp. 324–331.

[101] S. A. Aye and C. J. H. Thiart, 'A Review of Slow Speed Bearing Diagnostics and Prognostics', vol. 6, no. 10, pp. 726–739, 2014.

[102] A. M. Al-ghamd and D. Mba, 'A comparative experimental study on the use of acoustic emission and vibration analysis for bearing defect identification and estimation of defect size', *Mech. Syst. Signal Process.*, vol. 20, pp. 1537–1571, 2006, doi: 10.1016/j.ymssp.2004.10.013.

[103] A. Bellini *et al.*, 'Diagnosis of bearing faults in induction machines by vibration or current signals: A critical comparison', *IEEE Trans. Ind. Appl.*, vol. 46, no. 4, pp. 1350–1359, 2010, doi: 10.1109/TIA.2010.2049623.

[104] N. Bessous *et al.*, 'Diagnosis of bearing defects in induction motors using discrete wavelet transform', *Int. J. Syst. Assur. Eng. Manag.*, 2016, doi: 10.1007/s13198-016-0459-6.

[105] I. El-Thalji and E. Jantunen, 'A descriptive model of wear evolution in rolling bearings', *Eng. Fail. Anal.*, vol. 45, pp. 204–224, Oct. 2014, doi: 10.1016/j.engfailanal.2014.06.004.

[106] F. B. Zhou, M. D. Duta, M. P. Henry, S. Baker, and C. Burton, 'Remote condition monitoring for railway point machine', in *ASME/IEEE Joint Railroad Conference*, Apr. 2002, pp. 103–108, doi: 10.1109/RRCON.2002.1000101.

[107] S. P. Berge, B. F. Lund, and R. Ugarelli, 'Condition Monitoring for Early Failure Detection. Frognerparken Pumping Station as Case Study', *Procedia Eng.*, vol. 70, no. 1877, pp. 162–171, 2014, doi: 10.1016/j.proeng.2014.02.019.

[108] A. Prabhakaran and C. R. Jagga, 'Condition monitoring of steam turbine-generator through contamination analysis of used lubricating oil', *Tribol. Int.*, vol. 32, no. 3, pp. 145–152, Mar. 1999, doi: 10.1016/S0301-679X(99)00028-6.

[109] European Commission, 'Flightpath 2050: Europe's Vision for Aviation', 2011.

[110] W. Yang *et al.*, 'Wind turbine condition monitoring: technical and commercial challenges', *Wind Energy*, vol. 17, no. April 2013, pp. 673–693, 2014, doi: 10.1002/we.

[111] F. P. García Márquez, A. M. Tobias, J. M. Pinar Pérez, and M. Papaelias, 'Condition monitoring of wind turbines: Techniques and methods', *Renew. Energy*, vol. 46, pp. 169–178, 2012, doi: 10.1016/j.renene.2012.03.003.

[112] D. McMillan and G. W. Ault, 'Quantification of Condition Monitoring Benefit for Offshore Wind Turbines', *Wind Eng.*, vol. 31, no. 4, pp. 267–285, 2007.

[113] Fenner Dunlop, 'Eagle Eye® Belt Monitoring & Rip Detection'. https://www.fennerdunlop.com.au/conveyor-products/conveyor-diagnostic/eagle-eye-belt-monitoring-rip-detection (accessed Feb. 07, 2020).

[114] Continental, 'Belt Monitoring Systems: CONTI® Protect'. https://www.continental-industry.com/en/Solutions/Conveyor-Belt-Systems/Conveyor-Services/Belt-Monitoring/Products/Product-Range/Belt-Monitoring-Systems (accessed Feb. 07, 2020).

[115] Phoenix Conveyor Belt Systems, 'PHOENOGUARD® PX'. https://www.phoenix-conveyorbelts.com/pages/products/protection-systems/phoenoguard-px/phoenoguard-px_en.html (accessed Feb. 07, 2020).

[116] G. Lodewijks, W. Li, Y. Pang, and X. Jiang, 'An Application of the IoT in Belt Conveyor Systems', in *Internet and Distributed Computing Systems. IDCS* 2016, 2016, vol. 9258, pp. 340–351, doi: 10.1007/978-3-319-45940-0_31.

[117] P. A. Scarf, 'A Framework for Condition Monitoring and Condition Based Maintenance', *Qual. Technol. Quant. Manag.*, vol. 4, no. 2, pp. 301–312, 2007.

[118] O. Balch, 'The troubling fire record of UK recycling plants', *The Guardian*, Jul. 06, 2017.

[119] A. K. S. S. Jardine, D. Lin, and D. Banjevic, 'A review on machinery diagnostics and prognostics implementing condition-based maintenance', *Mech. Syst. Signal Process.*, vol. 20, no. 7, pp. 1483–1510, Oct. 2006, doi: 10.1016/j.ymssp.2005.09.012.

[120] Z. Hameed, Y. S. Hong, Y. M. Cho, S. H. Ahn, and C. K. Song, 'Condition monitoring and fault detection of wind turbines and related algorithms: A review', *Renew. Sustain. Energy Rev.*, vol. 13, no. 1, pp. 1–39, 2009, doi: 10.1016/j.rser.2007.05.008.

[121] E. P. Carden and P. Fanning, 'Vibration Based Condition Monitoring: A Review', *Struct. Health Monit.*, vol. 3, no. 4, pp. 355–377, Dec. 2004, doi: 10.1177/1475921704047500.

[122] S. Bakhri, N. Ertugrul, and W. L. Soong, 'Investigation And Development of A Real-Time On-Site Condition Monitoring System for Induction Motors', in *Australasian Universities Power Engineering Conference*, Perth, 2007, pp. 9–12.

[123] M. Irfan, N. Saad, R. Ibrahim, and V. S. Asirvad, 'Development of an Intelligent Condition Monitoring System for AC Induction Motors using PLC', in *IEEE Business Engineering and Industrial Applications Colloquium*, 2013, pp. 789–794.

[124] W. Bartelmus and R. Zimroz, 'A new feature for monitoring the condition of gearboxes in non-stationary operating conditions', *Mech. Syst. Signal Process.*, vol. 23, no. 5, pp. 1528–1534, 2009, doi: 10.1016/j.ymssp.2009.01.014.

[125] R. Isermann, *Fault-Diagnosis Applications*: *Model-based Condition Monitoring*: *Actuators, Drives, Machinery, Plants, Sensors, and fault-Tolerant Systems*. Berlin: Springer, 2011.

[126] R. B. Walker, R. Vayanat, S. Perinpanayagam, and I. K. Jennions, 'Unbalance localization through machine nonlinearities using an artificial neural network approach', *Mech. Mach. Theory*, vol. 75, pp. 54–66, 2014, doi: 10.1016/j.mechmachtheory.2014.01.006.

[127] S. Nandi, H. A. Toliyat, and X. Li, 'Condition Monitoring and Fault Diagnosis of Electrical Motors—A Review', *IEEE Trans. Energy Convers.*, vol. 20, no. 4, pp. 719–729, Dec. 2005, doi: 10.1109/TEC.2005.847955.

[128] M. Baqqar, M. Ahmed, and F. Gu, 'Data mining for gearbox condition monitoring', in *The* 17*th International Conference on Automation and Computing*, 2011, no. September, pp. 138–142.

[129] W. T. Thomson and M. Fenger, 'Current signature analysis to detect induction motor faults', *IEEE Ind. Appl. Mag.*, vol. 7, no. 4, pp. 26–34, 2001, doi: 10.1109/2943.930988.

[130] W. J. Bradley, M. K. Ebrahimi, and M. Ehsani, 'A General Approach for Current-Based Condition Monitoring of Induction Motors', *J. Dyn. Syst. Meas. Control*, vol. 136, no. 4, p. 041024, 2014, doi: 10.1115/1.4026874.

[131] I. Bravo-Imaz, H. Davari Ardakani, Z. Liu, A. García-Arribas, A. Arnaiz, and J. Lee, 'Motor current signature analysis for gearbox condition monitoring under transient speeds using wavelet analysis and dual-level time synchronous averaging', *Mech. Syst. Signal Process.*, vol. 94, pp. 73–84, 2017, doi: 10.1016/j.ymssp.2017.02.011.

[132] J. Igba, K. Alemzadeh, C. Durugbo, E. T. Eiriksson, and E. Thor, ‘Analysing RMS and peak values of vibration signals for condition monitoring of wind turbine gearboxes’, *Renew. Energy*, vol. 91, pp. 90–106, 2016, doi: 10.1016/j.renene.2016.01.006.

[133] S. Schmidt, P. S. Heyns, and J. P. D. Villiers, ‘A novelty detection diagnostic methodology for gearboxes operating under fluctuating operating conditions using probabilistic techniques’, *Mech. Syst. Signal Process.*, vol. 100, pp. 152–166, 2018, doi: 10.1016/j.ymssp.2017.07.032.

[134] Z. Li and S. Ganeriwala, ‘Rotating Machinery Faulty Diagnosis Techniques – Envelope and Cepstrum Analyses’, Spectraquest, Technical note, 2006.

[135] R. B. Randall, *Vibration-based Condition Monitoring -Industrial, Aerospace and Automotive Applications*, First. Wiley, 2011.

[136] R. B. Randall and J. Antoni, ‘Rolling element bearing diagnostics-A tutorial’, *Mech. Syst. Signal Process.*, vol. 25, no. 2, pp. 485–520, 2011, doi: 10.1016/j.ymssp.2010.07.017.

[137] P. Bo *et al.*, ‘Distributed bearing fault diagnosis based on vibration analysis’, *Mech. Syst. Signal Process.*, vol. 67, pp. 521–532, 2015, doi: 10.1016/j.ymssp.2015.06.007.

[138] C. Ruiz-Cárcel, V. H. Jaramillo, D. Mba, J. R. Ottewill, and Y. Cao, ‘Combination of process and vibration data for improved condition monitoring of industrial systems working under variable operating conditions’, *Mech. Syst. Signal Process.*, vol. 66–67, pp. 699–714, 2016, doi: 10.1016/j.ymssp.2015.05.018.

[139] A. D. Nembhard, J. K. Sinha, A. J. Pinkerton, and K. Elbhbah, ‘Combined vibration and thermal analysis for the condition monitoring of rotating machinery’, *Struct. Health Monit.*, vol. 13, no. 3, pp. 281–295, 2014, doi: 10.1177/1475921714522843.

[140] C. K. Tan, P. Irving, and D. Mba, ‘A comparative experimental study on the diagnostic and prognostic capabilities of acoustics emission, vibration and spectrometric oil analysis for spur gears’, *Mech. Syst. Signal Process.*, vol. 21, no. 1, pp. 208–233, Jan. 2007, doi: 10.1016/j.ymssp.2005.09.015.

[141] A. Harrison and B. C. Brown, ‘Monitoring System for Steel-Reinforced Conveyor Belts’, *J. Eng. Ind.*, vol. 108, no. 2, pp. 148–153, May 1986, doi: 10.1115/1.3187050.

[142] A. Harrison, ‘A magnetic transducer for testing steel-cord deterioration in high-tensile strength conveyor belts’, *NDT Int.*, vol. 18, no. 3, pp. 133–138, Jun. 1985, doi: 10.1016/0308-9126(85)90197-X.

[143] A. R. Harrison, 'Review of Conveyor Belt Monitoring Research in Australia', presented at the 10th Powder and Bulk Solids Conference, Rosemont, Ill, 1987.

[144] Wroclaw University of Science and Technology, 'DiagBelt'. http://diagbelt.pwr.edu.pl/index.php/en/ (accessed Feb. 07, 2020).

[145] R. Błażej, L. Jurdziak, T. Kozłowski, and A. Kirjanów, 'The use of magnetic sensors in monitoring the condition of the core in steel cord conveyor belts – Tests of the measuring probe and the design of the DiagBelt system', *Measurement*, vol. 123, pp. 48–53, Jul. 2018, doi: 10.1016/j.measurement.2018.03.051.

[146] C. Hou, T. Qiao, H. Zhang, Y. Pang, and X. Xiong, 'Multispectral visual detection method for conveyor belt longitudinal tear', *Measurement*, vol. 143, pp. 246–257, Sep. 2019, doi: 10.1016/j.measurement.2019.05.010.

[147] Y. Pang and G. Lodewijks, 'A novel embedded conductive detection system for intelligent conveyor belt monitoring', 2006 *IEEE Int. Conf. Serv. Oper. Logist. Inform. SOLI* 2006, pp. 803–808, 2006, doi: 10.1109/SOLI.2006.235556.

[148] Beltscan Systems, 'Belt Guard'. http://www.beltscan.com/ (accessed Feb. 07, 2020).

[149] Conveyor Belt Gateway, 'CBGuard - The Ultimate Conveyor Belt Monitoring System'. http://www.cbguard.info/ (accessed Feb. 07, 2020).

[150] A. Lopez-Pacheco, 'Unnecessary interruptions: Improved material handling the product of smarter modelling, design and monitoring', *The Canadian Institute of Mining, Metallurgy and Petroleum Magazine*, Jul. 24, 2018. https://magazine.cim.org/en/technology/unnecessary-interruptions-conveyor-belt-solutions-en/ (accessed Feb. 07, 2020).

[151] M. Frini, A. Soualhi, and M. El Badaoui, 'Gear faults diagnosis based on the geometric indicators of electrical signals in three-phase induction motors', *Mech. Mach. Theory*, vol. 138, pp. 1–15, Aug. 2019, doi: 10.1016/j.mechmachtheory.2019.03.030.

[152] A. Picot, E. Fournier, J. Régnier, M. TientcheuYamdeu, J. Andréjak, and P. Maussion, 'Statistic-Based Method to Monitor Belt Transmission Looseness Through Motor Phase Currents', *IEEE Trans. Ind. Inform.*, vol. 13, no. 3, pp. 1332–1340, Jun. 2017, doi: 10.1109/TII.2017.2661317.

[153] Bentley Nevada, 'AnomAlert'. https://www.bakerhughesds.com/bently-nevada/online-condition-monitoring/anomalert-motor-monitoring (accessed Feb. 07, 2020).

[154] A. Duyar and W. Merrill, ‘Fault Diagnosis for the Space Shuttle Main Engine’, *J. Guid. Control Dyn.*, vol. 15, no. 2, pp. 384–389, 1992.

[155] F. M. Atay, T. Durakbasa, and A. Duyar, ‘A Novel Method for Fault Detection in Electrical Motors’, *Sound & Vibration*, vol. 35, no. 2, p. 26, 2001.

[156] D. He, Y. Pang, and G. Lodewijks, ‘Green operations of belt conveyors by means of speed control’, *Appl. Energy*, vol. 188, pp. 330–341, 2017, doi: 10.1016/j.apenergy.2016.12.017.

[157] M. Soprana, A. C. Santomaso, and P. Facco, ‘Artificial vision system for the online characterization of the particle size distribution of bulk materials on conveyor belts’, in *Computer Aided Chemical Engineering*, Jan. 2018, vol. 43, pp. 1667–1672, doi: 10.1016/B978-0-444-64235-6.50290-4.

[158] P. Munzenberger and C. Wheeler, ‘Laboratory measurement of the indentation rolling resistance of conveyor belts’, *Measurement*, vol. 94, pp. 909–918, Dec. 2016, doi: 10.1016/j.measurement.2016.08.030.

[159] X. Liu, Y. Pang, G. Lodewijks, C. A. Wheeler, and B. Beh, ‘Assessment of the dynamic pressure measurement on a loaded conveyor belt using a tactile pressure sensor’, *XXI Int. Conf. Mater. Handl. Constr. Logist. MHCL*, no. May, 2015.

[160] D. Ilic and C. Wheeler, ‘Measurement and simulation of the bulk solid load on a conveyor belt during transportation’, *Powder Technol.*, vol. 307, pp. 190–202, 2017, doi: 10.1016/j.powtec.2016.11.020.

[161] A. Davies, Ed., *Handbook of Condition Monitoring: Techniques and Methodology*. Springer Netherlands, 1998.

[162] B. Al-Najjar, ‘On establishing cost-effective condition-based maintenance’, *J. Qual. Maint. Eng.*, vol. 18, no. 4, pp. 401–416, 2012, doi: 10.1108/13552511211281561.

[163] M. Brahimi and M. Leouatni, ‘Development of A Prognostics and Health Management System for the Railway Infrastructure – Review and Methodology’, in *Prognostics and System Health Management Conference (PHM-Chengdu)*, 2016, pp. 1–8, doi: 10.1109/PHM.2016.7819783.

[164] M. C. Carnero, ‘Fuzzy Multicriteria Model for Selection of Vibration Technology’, *Shock Vib.*, vol. 2016, 2016, doi: https://doi.org/10.1155/2016/6723605.

[165] W. W. Tiddens, A. J. J. Braaksma, and T. Tinga, 'The Adoption of Prognostic Technologies in Maintenance Decision Making: A Multiple Case Study', *Procedia CIRP*, vol. 38, pp. 171–176, 2015, doi: 10.1016/j.procir.2015.08.028.

[166] A. Heng, S. Zhang, A. C. C. Tan, and J. Mathew, 'Rotating machinery prognostics: State of the art, challenges and opportunities', *Mech. Syst. Signal Process.*, vol. 23, no. 3, pp. 724–739, Apr. 2009, doi: 10.1016/j.ymssp.2008.06.009.

[167] A. D. Nembhard and J. K. Sinha, 'Development of a generic rotating machinery fault diagnosis approach insensitive to machine speed and support type', *J. Sound Vib.*, vol. 337, pp. 321–341, 2015, doi: 10.1016/j.jsv.2014.10.033.

[168] S. Teja, K. Kjell, G. R. Hamid, and R. Karimi, 'Towards farm-level health management of offshore wind farms for maintenance improvements', pp. 1557–1567, 2016, doi: 10.1007/s00170-015-7616-y.

[169] S. Cheng, M. H. Azarian, and M. G. Pecht, 'Sensor systems for prognostics and health management', *Sensors*, vol. 10, no. 6, pp. 5774–5797, 2010, doi: 10.3390/s100605774.

[170] T. Sreenuch, a. Tsourdos, and I. K. Jennions, 'Distributed embedded condition monitoring systems based on OSA-CBM standard', *Comput. Stand. Interfaces*, vol. 35, no. 2, pp. 238–246, Feb. 2013, doi: 10.1016/j.csi.2012.10.002.

[171] M. Irfan, N. Saad, R. Ibrahim, and V. S. Asirvad, 'Development of an Intelligent Condition Monitoring System for AC Induction Motors using PLC', in *IEEE Business Engineeering and Industrial Applications Colloqium*, 2013, pp. 789–794.

[172] J. Liu, W. Wang, and F. Golnaraghi, 'An Enhanced Diagnostic Scheme for Bearing Condition Monitoring', vol. 59, no. 2, pp. 309–321, 2010.

[173] British Standards Institution, 'Condition monitoring and diagnostics of machines - General guidelines', British Standards Institution, Technical standard BS ISO 17359:2011, 2011.

[174] British Standards Institution, 'Condition Monitoring and Diagnostics of Machine Systems - Electrical Signature Analysis of Three-Phase Induction Motors', Technical standard BS ISO 20958:2013, 2013.

[175] R. L. Rusby, 'Introduction to Temperature Measurement', National Physical Laboratory, 2015. [Online]. Available: http://www.npl.co.uk/content/ConPublication/6874.

[176] P. L. Alger, *Induction Machines: Their Behaviour and Uses*, 2nd ed. New York: Gordon and Breach, 1971.

[177] C. J. Adkins, *Equilibrium Thermodynamics*. Cambridge University Press, 1983.

[178] R. W. Lewis, K. N. Seetharamu, and P. Nithiarasu, *Fundamentals of the Finite Element Method for Heat and Fluid Flow*. John Wiley & Sons, Ltd, 2005.

[179] R. C. Dorf and R. H. Bishop, *Modern Control Systems*. Pearson Prentice Hall, 2011.

[180] L. Barbini, A. P. Ompusunggu, A. J. Hillis, J. L. du Bois, and A. Bartic, 'Phase editing as a signal pre-processing step for automated bearing fault detection', *Mech. Syst. Signal Process.*, vol. 91, pp. 407–421, Jul. 2017, doi: 10.1016/j.ymssp.2016.12.004.

[181] A. Moshrefzadeh and A. Fasana, 'The Autogram: An effective approach for selecting the optimal demodulation band in rolling element bearings diagnosis', *Mech. Syst. Signal Process.*, vol. 105, pp. 294–318, May 2018, doi: 10.1016/j.ymssp.2017.12.009.

[182] 'supervise, v.', *OED Online*. Oxford University Press, Accessed: Aug. 28, 2020. [Online]. Available: https://www.oed.com/view/Entry/194556.

[183] T. Hastie, R. Tibshirani, and J. Friedman, 'Unsupervised Learning', in *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*, T. Hastie, R. Tibshirani, and J. Friedman, Eds. New York, NY: Springer, 2009, pp. 485–585.

[184] D. V. Thiel, *Research Methods for Engineers*. Cambridge University Press, 2014.

[185] K. Worden, C. R. Farrar, G. Manson, and G. Park, 'The Fundamental Axioms of Structural Health Monitoring', *Proc. R. Soc. Math. Phys. Eng. Sci.*, vol. 463, no. 2082, pp. 1639–1664, 2007, doi: 10.1098/rspa.2007.1834.

[186] J. Braaksma and W. Tiddens, 'Selecting Suitable Candidates for Predictive Maintenance', *Int. J. Progn. Health Manag.*, vol. 9, no. May, p. 14, 2018.

[187] A. Muszynska, *Rotordynamics*. CRC Press, 2005.

[188] British Standards Institution, 'Condition monitoring and diagnostics of machines - Data interpretation and diagnostics techniques: Part 1: General guidelines', Technical standard BS ISO 13379-1:2012, 2012.

[189] T. Rossing, *Springer Handbook of Acoustics*. New York, NY: Springer New York, 2007.

[190] A. M. Al-ghamd and D. Mba, 'A comparative experimental study on the use of acoustic emission and vibration analysis for bearing defect identification and estimation of defect

size', *Mech. Syst. Signal Process.*, vol. 20, pp. 1537–1571, 2006, doi: 10.1016/j.ymssp.2004.10.013.

[191] W. Caesarendra *et al.*, 'Acoustic emission-based condition monitoring methods: Review and application for low speed slew bearing', *Mech. Syst. Signal Process.*, vol. 72–73, pp. 134–159, 2015, doi: 10.1016/j.ymssp.2015.10.020.

[192] A. Choudhury and N. Tandon, 'Application of acoustic emission technique for the detection of defects in rolling element bearings', *Tribol. Internaational*, vol. 33, pp. 39–45, 2000.

[193] S. A. Aye, P. S. Heyns, and C. J. H. Thiart, 'Seeded damage detection on self-aligning ball bearings with acoustic emission', *Cond. Monit. Mach. Non-Station. Oper.*, pp. 1–7, 2012.

[194] British Standards Institution, 'Condition monitoring and diagnostics of machines - Acoustic emission', British Standards Institution, Technical standard BS ISO 22096:2007, 2007.

[195] Sense, 'The Sense Home Energy Monitor'. https://sense.com/ (accessed Feb. 09, 2020).

[196] W. T. Thomson and M. D. Dahleh, *Theory of Vibrations with Applications*, Fifth. Upper Saddle River, New Jersey: Prentice Hall, 1998.

[197] R. Halmshaw, *Non-Destructive Testing*, Second. Arnold, 1991.

[198] British Standards Institution, 'Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 1: General procedures', Technical standard BS ISO 13373-1:2002, 2002.

[199] British Standards Institution, 'Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 9: Diagnostic techniques for electric motors', Technical standard BS ISO 13373-9, 2015.

[200] R. Bogue, 'Sensors for condition monitoring: a review of technologies and applications', *Sens. Rev.*, vol. 33, no. 4, pp. 295–299, Sep. 2013, doi: 10.1108/SR-05-2013-675.

[201] British Standards Institution, 'Safety of Machinery. Emergency Stop Function. Principles for Design', Technical standard BS ISO 13850-2015.

[202] O. F. Eker, F. Camci, and I. K. Jennions, 'Major Challenges in Prognostics : Study on Benchmarking Prognostics Datasets', in *European Conference of Prognostics and Health Management Society*, 2012, pp. 1–8.

[203] British Standards Institution, ‘Portable and mobile troughed belt conveyors’, Technical standard BS 4531:1986, 1986.

[204] B. Lu, T. G. Habetler, and R. G. Harley, ‘A nonintrusive and in-service motor-efficiency estimation method using air-gap torque with considerations of condition monitoring’, *IEEE Trans. Ind. Appl.*, vol. 44, no. 6, pp. 1666–1674, 2008, doi: 10.1109/TIA.2008.2006297.

[205] S. J. Orfanidis, *Introduction to Signal Processing*. Englewood Cliffs, N.J: Prentice Hall, 1996.

[206] National Instruments, ‘Understanding FFTs and Windowing’, White Paper, 2019. [Online]. Available: http://www.ni.com/en-gb/innovations/white-papers/06/understanding-ffts-and-windowing.html.

[207] P. Theobald, B. Zeqiri, and J. Avison, ‘Couplants and their Influence on AE Sensor Sensitivity’, *J. Acoust. Emiss.*, vol. 26, pp. 91–97, 2008.

[208] IEEE Instrumentation and Measurement Society, ‘IEEE Standard for Transitions, Pulses, and Related Waveforms’, vol. 181, no. September. IEEE, New York, 2011, doi: 10.1109/IEEESTD.2011.6016198.

[209] P. H. Mellor, D. Roberts, and D. R. Turner, ‘Lumped parameter thermal model for electrical machines of TEFC design’, *IEE Proc. B - Electr. Power Appl.*, vol. 138, no. 5, pp. 205–218, Sep. 1991, doi: 10.1049/ip-b.1991.0025.

[210] C. A. Gross, *Electric Machines*. CRC Press, 2007.

[211] M. G. Say, *Alternating Current Machines*, 5th ed.. London: Pitman, 1983.

[212] British Standards Institution, ‘Rotating electrical machines. Selection of energy-efficient motors including variable speed applications. Application guide’, Technical specification DD CLC-TS 60034-31-2011, 2011.

[213] E. Rabinowicz, *Friction and Wear of Materials*. Wiley, 1965.

[214] I. Hutchings and P. Shipway, *Tribology*: *Friction and Wear of Engineering Materials*. Butterworth-Heinemann, 2017.

[215] J. R. Leigh, *Control Theory*. IET Digital Library, 2004.

[216] S. P. Harsha, ‘Rolling Bearing Vibrations—The Effects of Surface Waviness and Radial Internal Clearance’, *Int. J. Comput. Methods Eng. Sci. Mech.*, vol. 7, no. 2, pp. 91–111, Apr. 2006, doi: 10.1080/155022891010015.

[217] T. Momono and B. Noda, 'Sound and Vibration in Rolling Bearings', *NSK Tech. J. Motion Control*, vol. 6, p. 9, 1999.

[218] D. Mba, 'Acoustic Emissions and Monitoring Bearing Health', *Tribol. Trans.*, vol. 46, no. 3, pp. 447–451, 2003.

[219] A. Davis, J. G. Chen, O. Buyukozturk, F. Durand, and D. L. James, 'Structural Health Monitoring from the Window Seat of a Passenger Airplane', *Struct. Health Monit.* 2017, vol. 0, 2017, doi: 10.12783/shm2017/14234.

[220] C. Peeters *et al.*, 'Review and comparison of tacholess instantaneous speed estimation methods on experimental vibration data', *Mech. Syst. Signal Process.*, vol. 129, pp. 407–436, Aug. 2019, doi: 10.1016/j.ymssp.2019.02.031.

[221] J. P. Barton and S. J. Watson, 'Analysis of electrical power data for condition monitoring of a small wind turbine', *IET Renew. Power Gener.*, vol. 7, no. 4, pp. 341–349, Jul. 2013, doi: 10.1049/iet-rpg.2012.0326.

[222] S. W. Smith, *Digital Signal Processing: A Practical Guide for Engineers and Scientists*. Amsterdam ; Boston: Newnes, 2003.

[223] G. McPherson, *An Introduction to Electrical Machines and Transformers*, 1st ed. John Wiley & Sons, Inc, 1981.

[224] F. R. Connor, *Noise*, 2nd ed. London: Edward Arnold, 1982.

[225] A. Whalen, *Detection of Signals in Noise*, Second. 1995.

[226] S. Winder, *Analog and Digital Filter Design*, Second. 2002.

[227] D. G. Manolakis and V. K. Ingle, *Applied Digital Signal Processing: Theory and Practice*, First. New York, NY: Cambridge University Press, 2011.

[228] R. Zimroz and R. Król, 'Failure Analysis of Belt Conveyor Systems for Condition Monitoring Purposes', *Min. Sci.*, vol. 128, no. 36, pp. 255–270, Sep. 2015.

[229] C. Mitchell, 'Slash High Costs from Low Profile Conveyors', *Mater. Handl. Logist.*, vol. 66, no. 10, pp. 37–39, Oct. 2011.

[230] R. M. Stewart, 'Some Useful Data Analysis Techniques for Gearbox Diagnostics', Institute of Sound and Vibration Research, Southampton, UK, Paper #18, 1977.

[231] T. Tinga, J. Ph. C. Wubben, W. W. Tiddens, J. C. Wortmann, and G. J. C. Gaalman, 'Dynamic Maintenance based on Functional Usage Profiles', *J. Qual. Maint. Eng.*, Jul. 2019.

[232] G. W. Hart, 'Nonintrusive appliance load monitoring', *Proc. IEEE*, vol. 80, no. 12, pp. 1870–1891, Dec. 1992, doi: 10.1109/5.192069.

[233] J. Pan and W. J. Tompkins, 'A Real-Time QRS Detection Algorithm', *IEEE Trans. Biomed. Eng.*, vol. BME-32, no. 3, pp. 230–236, Mar. 1985, doi: 10.1109/TBME.1985.325532.

[234] P. Lindahl, D. Green, G. Bredariol, A. Aboulian, J. Donnal, and S. Leeb, 'Shipboard Fault Detection Through Nonintrusive Load Monitoring: A Case Study', *IEEE Sens. J.*, vol. 18, no. 21, pp. 8986–8995, Sep. 2018, doi: 10.1109/JSEN.2018.2869115.

[235] P. S. Addison, *The illustrated wavelet transform handbook: introductory theory and applications in science, engineering, medicine and finance*, Second edition. Boca Raton, FL: CRC Press, Taylor & Francis Group, 2017.

[236] I. Daubechies, *Ten Lectures on Wavelets*. Society for Industrial and Applied Mathematics, 1992.

[237] J. Antonino-Daviu, M. Riera-Guasp, J. Roger-Folch, F. Martínez-Giménez, and A. Peris, 'Application and optimization of the discrete wavelet transform for the detection of broken rotor bars in induction machines', *Appl. Comput. Harmon. Anal.*, vol. 21, no. 2, pp. 268–279, Sep. 2006, doi: 10.1016/j.acha.2005.12.003.

[238] S. Mallat, *A Wavelet Tour of Signal Processing*, Second. Academic Press, 1999.

[239] G. Nason, *Wavelet Methods in Statistics with R*. New York: Springer-Verlag, 2008.

[240] J. Eaves and E. Reedy, *Principles of Modern Radar*, First. New York, NY: Van Nostrand Reinhold Company, 1987.

[241] A. Quinquis, *Digital Signal Processing using MATLAB®*. John Wiley & Sons, Ltd, 2008.

[242] ASTM International, 'Standard Practices for Cycle Counting in Fatigue Analysis', ASTM International, International Standard E1049-85, 2017. [Online]. Available: https://doi.org/10.1520/E1049-85R17.

[243] R. T. Swinderman, A. D. Marti, L. J. Goldebeck, D. Marshall, and M. G. Strebel, *Foundations - The practical resource for cleaner, safer, more productive dust & material control*. Martin Engineering, 2009.

[244] B. J. Hicks and J. Matthews, 'The barriers to realising sustainable process improvement: A root cause analysis of paradigms for manufacturing systems improvement.', *Int. J. Comput. Integr. Manuf.*, vol. 23, no. 7, pp. 585–602, 2010, doi: 10.1080/0951192X.2010.485754.

[245] R. Liu, B. Yang, E. Zio, and X. Chen, 'Artificial intelligence for fault diagnosis of rotating machinery: A review', *Mech. Syst. Signal Process.*, vol. 108, pp. 33–47, Aug. 2018, doi: 10.1016/j.ymssp.2018.02.016.

Appendices

Appendix A: Results of In-service CBS Motor Analysis

Table A.1: Exhaustive results from testing of previously in-service CBS motors.

IEEE Std 1415-2006 Section	Test Details		Target	M1	M2	M3
N/A	Motor information		N/A	CSCR 2.2kW 110Vac 50Hz 1350rpm S1 (continuous)	CSCR 2.2kW 110Vac 50Hz 1350rpm S1 (continuous)	CSCR 2.2kW 110Vac 50Hz 1390rpm S1 (continuous)
4.2.2.5	External condition	Visual inspection	N/A	Some cosmetic damage present, otherwise acceptable	Significant dirt present, but otherwise acceptable	Generally, quite dirty. Number of dents present, but acceptable
4.3.25	Shaft rotation		seized = 1, free rotation = 5	4.5	5	5
4.3.12	Earth continuity		<0.5Ω	0.2	0.2	0.2
4.2.2.5	Condition of terminals		N/A	Good	Good	Good
4.3.40	Windings resistance	Continuity	Pass/Fail	Pass	Pass	Pass
		V2-W2	Within 3-5% of mean	2.5	1.4	1.4
		V2-V1/W1		0.4	0.4	0.4
		W1-W2		1.1	1.1	1.2
4.3.1	Insulation resistance	V2-Earth	>1MΩ	0	165	152
		V1/W1-Earth		0	165	151
		W2-Earth		0	190	150
4.2.2.5	Condition of capacitors	Visual Inspection	N/A	Small dent present in R1, otherwise acceptable	Significant dirt on run caps but acceptable. Start cap appears to have suffered damage to casing.	R1 heavily dented. Start capacitor appears to have been replaced
4.3.5	Measured capacitance	Run 1	Within capacitor's rated tolerance	51.2	59.9	0.003
		Run 2		50.1	60.2	52.7
		Run 3		50.2	60.7	53.1
		Start		196.3	256.9	190.6
4.2.2.5	Fan condition	Visual Inspection	N/A	Fully intact	Fully intact	Fully intact
4.2.2.5	Condition of centrifugal switch	Visual Inspection	N/A	Slight corrosion present but functional	Significant corrosion present, resistance to movement, however, still appears functional	Good condition, perfectly functional
4.2.2.4	Condition of bearings	Visual Inspection	N/A	Clean and turn smoothly	Clean and turn smoothly	Clean and turn smoothly
4.2.2.1 4.2.2.2	Condition of stator and rotor	Visual Inspection	N/A	Reasonable, minor scratches on rotor	No obvious damage, however, significant corrosion present on both	Uneven wear along length of rotor, more wear at output end

Appendix B: Exhaustive Maintenance Record Categories

Table B.1: Overview of condensed metadata fields post data cleaning.

Name	Description	Permissible Values	Source Field(s)	Notes
Job ID	A unique identifier associated with each job completed	N/A	N/A	Unchanged
Date	The day during which the job was conducted	N/A	N/A	Unchanged
Site	The site at which the job was conducted	A, B, C, D	N/A	Unchanged
Asset ID	A unique identifier associated with the asset being maintained	N/A	N/A	Unchanged
Personnel	The number of personnel who conducted the job	1-4	Personnel 1, Personnel 2, Personnel 3	Specific names of personnel removed, leaving only the quantity
Time Taken	An estimate of the time, in hours, taken to complete the action	N/A	N/A	Unchanged. 0.5hr resolution
Issue	A high-level categorisation of the primary reason for the completion of the entry	79 categories (see X)	Description of Breakdown, Additional Comments	
Component	A high-level categorisation of the primary component which has been maintained	13 categories (see X)	Description of Breakdown, Additional Comments	
Action	A high-level categorisation of the form of action completed by the personnel	56 categories (see X)	Description of Repair, Additional Comments	*Other* category used for entries where the action completed is dissimilar to any other action category.

Table B.2: High-level issue categories.

Issue Categories
'Bearing collapsed', 'Bearing collapsed; Head drum misaligned', 'Bearing damaged', 'Bearing loose; Gearbox overheating', 'Bearing noisy', 'Bearing worn', 'Belt catching', 'Belt damaged', 'Belt misaligned', 'Belt worn', 'Blockage', 'Blockage; Motor tripping', 'Collapsed bearing', 'Electrical issue', 'Filler missing', 'Gearbox damaged', 'Gearbox leaking', 'Gearbox seized', 'Grease line damaged', 'Grease line issue', 'Guards damaged', 'Guards required', 'Handrails required', 'Head drum damaged', 'Head drum misaligned', 'Head drum seized; Gearbox damaged', 'Head drum worn', 'Head drum worn; Tail drum worn; Belt worn', 'Hopper plate damaged', 'Inspection requested', 'Issue observed', 'Issue observed; Bearing noisy', 'Issue observed; Rollers seized', 'Loud gearbox', 'Miscellaneous', 'Motor damaged', 'Motor damaged; Head drum damaged', 'Motor failed', 'Motor faulty', 'Motor leaking', 'Motor tripped', 'Motor tripping', 'Motor tripping; belt misaligned', 'Motor vibrating', 'Preventative action', 'Preventative check', 'Preventative upgrade', 'Product buildup', 'Product escaping', 'Roller missing', 'Roller noisy', 'Roller seized', 'Rollers damaged', 'Rollers seized', 'Rollers worn', 'Scraper damaged', 'Scraper misaligned', 'Scraper missing', 'Scraper worn', 'Seals worn', 'Shaft bent', 'Shaft worn', 'Shaft worn; sprocket worn; bearing worn', 'Skirting damaged', 'Skirting missing', 'Skirting worn', 'Slats damaged', 'Slats incorrect', 'Slats missing', 'Structure damaged', 'Structure worn', 'System inoperable', 'Tail drum damaged', 'Tail drum misaligned', 'Tail drum worn', 'Torque arm damaged', 'Unspecified', 'Wear plate worn', 'Wear strips worn'
Notes
The *Issue* field will reflect to the primary issue associated with each record, however, there may be multiple issues present e.g. collapsed bearing and worn pulley. The *Unspecified* category is used for any issues where an obvious rationale for the issue is absent, e.g. *'gearbox replaced as needs replacing.'* The *Miscellaneous* category is used for issues which do not obviously fall into any other category, typically when they're considered one-off events. These issues only relate to non-essential conveyor components i.e. not motors, gearboxes, bearings, rollers or belts.

Table B.3: High-level component categories.

Component Categories
'Bearing', 'Belt', 'Gearbox', 'Head drum', 'Motor', 'Motor & gearbox', 'Multiple', 'Other', 'Rollers', 'Slats', 'Structure', 'System', 'Tail drum'
Notes
The *Other* category is used for records where the primary component is either not obvious, or, the record doesn't fit into any existing categories. The *Multiple* category is used for records in which interventions were made to more than one primary component.

Table B.4: High-level action categories.

Action Categories
'Bearing adjusted', 'Bearing repaired', 'Bearing replaced', 'Belt and drums replaced', 'Belt repaired', 'Belt replaced', 'Belt retracked', 'Blockage cleared', 'Cleaned and retracked', 'Cleaning', 'Cleaning and other', 'Complete drive replacement', 'Drums and bearings replaced', 'Electrical repair', 'Filler installed', 'Filler moved', 'Gearbox cleaned', 'Gearbox refilled', 'Gearbox repaired', 'Gearbox replaced', 'Grease line repaired', 'Guards repaired', 'Head drum adjusted', 'Head drum realigned', 'Head drum repaired', 'Head drum replaced', 'Inspection', 'Monitor', 'Motor and gearbox replaced', 'Motor repaired', 'Other', 'Roller

freed', 'Roller repaired', 'Roller replaced', 'Rollers repaired', 'Rollers replaced', 'Rollers replaced and cleaning', 'Scraper adjusted', 'Scraper repaired', 'Scraper replaced', 'Seals repaired', 'Shaft repaired', 'Shaft replaced', 'Skirting replaced', 'Slats replaced', 'Structural adjustment', 'Structural upgrade', 'Structure adjusted', 'Structure repaired', 'System replaced', 'System upgraded', 'Tail drum realigned', 'Tail drum repaired', 'Tail drum replaced', 'Torque arm replaced', 'Wear strips replaced'
Notes
The *Other* category is used for records where the action completed does not obviously fall into any other Action category. The *Belt retracked* category incorporates all belt retensioning actions, whether these be a standalone action e.g. the belt has wandered over to one side whilst operating so requires retensioning to correct, or as a sub-action within a top-level action e.g. post a belt replacement, or when a belt has had to be removed as part of a roller replacement, for example. The *Cleaning* category constitutes a range of activities such as clearing product which has built up, clearing tape from rotating elements etc.

Appendix C: Interview Consent Form

Characterising Maintenance

Overview

This study by the University of Bristol aims to understand the approach to maintenance throughout industry in the UK. Through a series of interviews with maintenance operatives within the waste processing industry the research will explore how maintenance is both planned and implemented as well as trying to determine how effective it is.

This study will characterise the behaviour of maintenance personnel through a series of interviews with industry operatives with a view to determining the potential value to operatives that could be realised by providing prognostic insight into the future condition of assets.

The research will form part of a doctoral thesis and the findings may also be published in academic conferences and journals.

Requirements of participants

The interview will last between 10-30 minutes and will take place in a relaxed environment. A voice recording of the interview will be made, which will later be transcribed for analysis. The researcher asks that the participants will turn off any portable communications equipment and avoid disturbances from colleagues during the meetings. The participant is free to decline to answer any question and may request that anything said is removed from the records of the interview.

Confidentiality

All findings will be reported anonymously, though a categorisation of the sector, organisational type, professional role and project values will be stated for context. The author is happy to acknowledge individuals or organisations in publications, though the ultimate decision rests with the participant. Any outputs submitted for publication can be made available for review before submission, any reasonable requests for amendment will be accommodated.

Contact and queries

Researcher:	Research supervisor:
Owen Gebler	(for comments or complaints)
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07783719702	ben.hicks@bristol.ac.uk

Consent to take part in research

	Please tick
I have been informed of and understand the purposes of the study.	
I have been given an opportunity to ask questions.	
I understand I can withdraw at any time without prejudice.	
Any information which might potentially identify me will not be used in published material.	
I agree to participate in the study as outlined to me.	

Name Signature Date

Appendix D: CBS Failure Mode and Effect Analysis

Tabel D.1: Failure mode and effect analysis of complete CBS.

Asset		Function		Functional Failure		Failure Mode			Failure Effect	
						Level 1	Level 2	Level 3	*What happens when it fails?*	*What action is required in response?*
CBS belt system	A	To transport the required volume of product along the CBS length at a minimum rate	1	Unable to transport product at required rate	i	Increased friction in system	Return (passive) roller seized	Material trapped in roller	Product throughput will decrease. Increased loading on drive components likely to lead to increased rate of wear.	Removal of material from roller. Inspection of condition
								Lack of lubrication		Lubricate roller
								Contamination		Clean or replace
								Other		Replacement of seized roller
							Head/Tail bearing collapsed	See *Bearing* sheet	Product throughput will decrease/stop. Increased load on motor/gearbox likely. Potentially damage to shaft.	Replacement of bearing and potentially shaft
					ii	CBS blocked	Overload of product		Motor load will spike and trip, CBS stops. CBS will have to be restarted fully loaded.	Manual removal of product blocking the CBS. Reset of motor. Inspection of CBS prior to restart.
							Oversized material			
					iii	Gearbox reduced output	See *gearbox* sheet		Less product through process, material likely to 'back up' in system. Increased rate of wear on components	Investigation into root cause required prior to decision
					iv	Motor reduced output	See *motor* sheet			
			2	Unable to transport any product	i	Belt detached	Shaft fractured		CBS will not be able to move product however drive to CBS will not necessarily stop and thus damage could be incurred. Product likely to spill out of CBS and backlog created potentially	Product will have to be removed from the CBS before the belt can be reattached. Investigation into the root cause and subsequent damage to other components will be required and potentially replacement of these.
							Bearing detached	Assembly error		
								Excessive vibration		
							Poor track			
					ii	Belt severed	Severed by product			Belt replacement.
					iii	Head/tail roller detached				Reattach roller.
						No drive to head roller	Gearbox issue	See *Gearbox* sheet		
					iv		Motor issue	See *Motor* sheet		
					v	Shaft detached from bearings				Reattach shaft.
						Shaft fractured				Replacement of shaft required likely and potentially bearings also as a knock on.
					vi	Head/tail roller stuck	Bearing collapsed	See *Bearing* sheet	Increased friction and thus potentially increased heat production and wear to components.	Replacement of bearing likely.
					vii		Bearing seized	See *Bearing* sheet		
	B	To support and contain product along the length of the CBS system	3	Product not all contained within extents of CBS	i	CBS overloaded			Product spillage from CBS. Motor likely to trip.	Clear belt and restart.
					ii	Side skirts not fitted			Product spillage from CBS. Motor likely to trip.	Fit side skirts if desired.
					iii	Side skirts worn				Replace side skirts.
					iv	Side skirts damaged				

Table D.2: Failure mode and effect analysis of drive motor.

Asset	Function		Functional Failure		Failure Mode				Failure Effect	
						Level 1	Level 2	Level 3	*What happens when it fails?*	*What action is required in response?*
Drive motor	A	To provide mechanical power to the CBS drive end shaft under a loaded motor condition at the required speed and torque, when a voltage is applied.	1	Unable to provide the required output torque and speed magnitude.	i	Deterioration of motor insulation	Potential short circuiting of coils	Burnout of coils	Motor efficiency likely to reduce, potentially stalling CBS if load is significant enough. Overall process impacted - reduced throughput. Temperature increase within motor housing likely as insulation fails.	May be able to be repaired or may require complete unit replacement.
					ii	Mechanical damage to motor windings	Cyclic fatigue loading resulting from intermittent use	Overheating and damage to windings		Likely replacement will be required.
							Corrosion build-up due to water ingress	Damage to windings		
							Damage caused by rotor asymmetry - cracked bars			
					iii	Mechanical damage to motor bearing(s)	Overloaded		Excessive vibration likely, potentially leading to severe shaft misalignment.	Depending on level of damage incurred, either relubrication or replacement of bearing and potentially shaft.
							Lubricant displaced			
					iv	Overheating motor due to fan performance	Fan performance reduced	Fan outlet blocked	Motor housing internal temperature likely to rise potentially inducing one of the failure modes above (I,ii,iii).	Clearing of blockage from outlet by operator.
								Blade damaged		Replacement of fan and potentially motor dependent upon damage incurred.
							Fan not operational	Fan blocked		Clearing of blockage from fan blade by operator.
								All blades damaged		Replacement of fan and potentially motor dependent upon damage incurred.
			2	Unable to provide any output power.	i	Catastrophic unit failure	As *A.1.i*		No torque provided by motor - CBS not operational.	Replacement or repair of motor.
					ii	Power supply failure	Mains supply issue			Investigation and subsequent repair.
							Inverter issue			Repair or replacement of inverter.
							Connection failure	Connector disconnected		Reconnection of connector.
								Connector cable severed		Cable repair or replacement.
								Connector corroded		Connector repair or replacement.
					iii	Fire	External factors		Potentially fire is conveyed along process. Motor thermal trip should eventually halt drive.	Put out the fire. Replace motor and any other damaged components.
							Combustion of conveyed material			
							Combustion of grease			

Appendix E: Calibration Data

Figure E.1: Axial load cell amplifier calibration data.

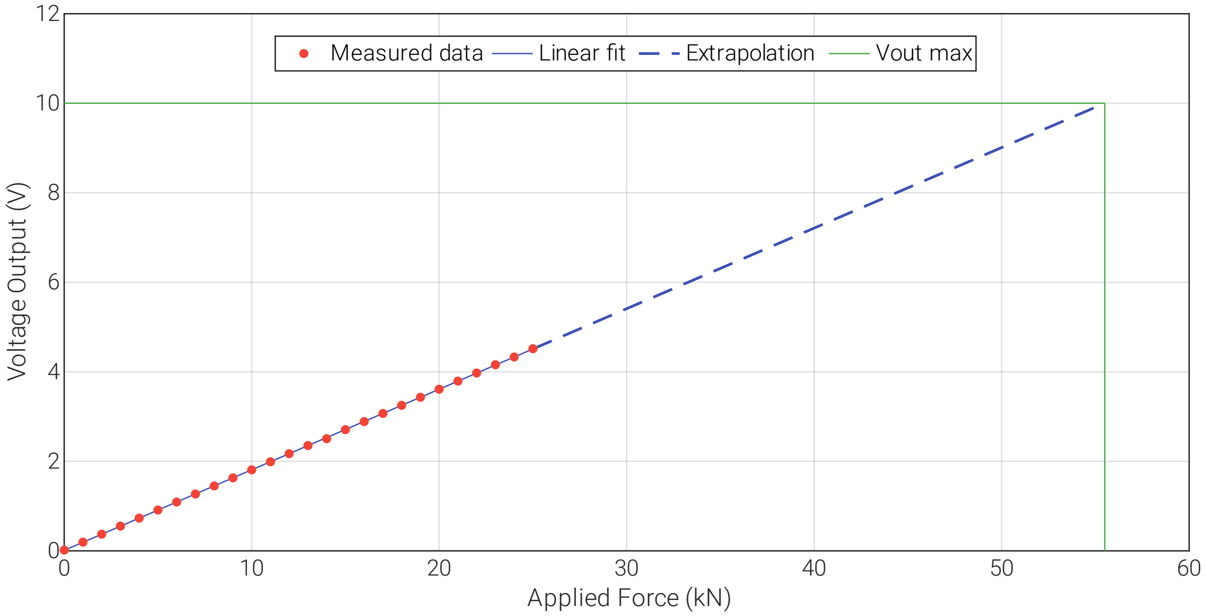

Figure E.2: Radial load cell amplifier calibration data.

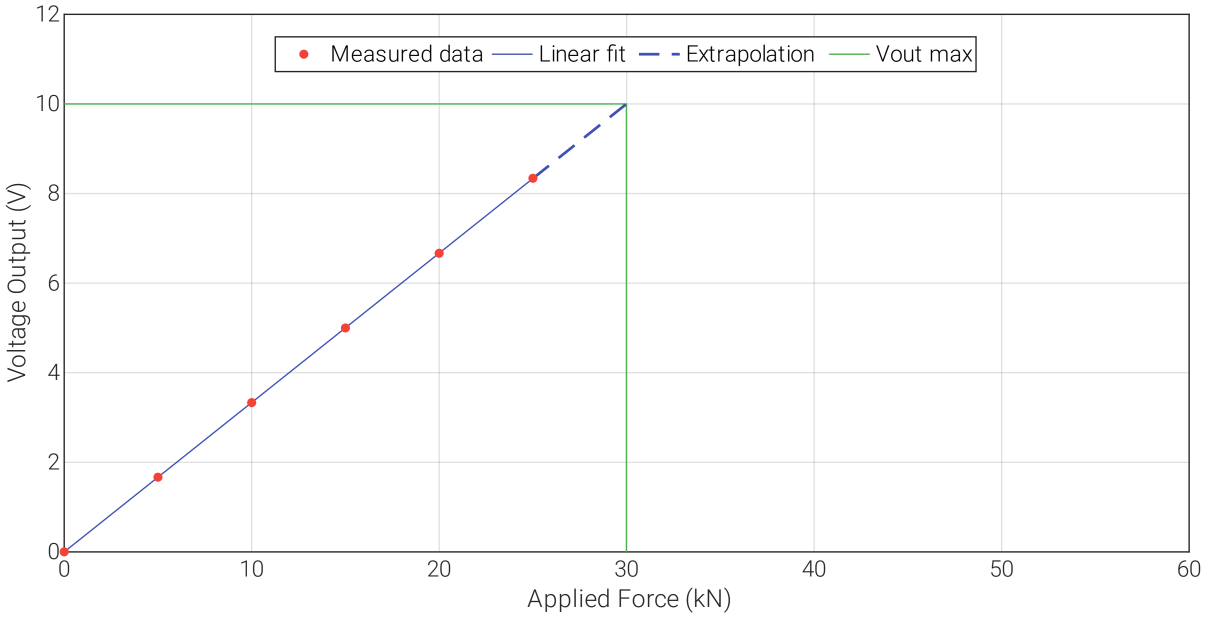

Table E.1: Summary of CER electrical power monitoring system calibration data.

Channel	Supply Input (RMS)	Measured Output (V RMS)	Ratio
V1	231.7	1.638	2.5053
V1	135.15 V	0.956	2.5053
V2	231.0 V	1.623	2.5027
V2	135.16 V	0.950	2.5027
I1	1.000 A	0.493	2.5031
I1	0.500 A	0.244	2.5031
I1	3.56 A	1.765	2.5031
I2	1.000 A	0.496	2.5062
I2	0.500 A	0.246	2.5062
I2	3.56 A	1.778	2.5062