Condition Monitoring of Diesel Engines

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Abstract

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Reliability of emergency Diesel generator systems, or indeed any Diesel engines in a wide range of fields is critical. Traditional maintenance procedures for these engines follow time based or statistical based methods. Due to the wide variety of uses of Diesel engines it is not possible for these forms of maintenance to be as effective as condition based monitoring. Condition based monitoring holds many advantages over traditional maintenance methods. It allows for the earlier detection and diagnosis of a fault and allows for planned maintenance work avoiding costly and unexpected downtime. It also reduces the overall maintenance costs as parts need only be replaced when they are worn or faulty, not based on a time schedule.

The ability to unobtrusively monitor the engines also has many advantages including reduced sensor cost and negating the need to tamper permanently with the engine. Acoustic monitoring has been identified as the most prominent and effective way in which to achieve this goal. As such, extensive experimentation was carried out on both large and small Diesel engines over a wide range of speeds, loads and faults and the data was then analysed. The data was first investigated statistically and then processed using Independent Component Analysis after the statistical results were found to be poor.

A program was written for the automatic comparison of the collected data and the results presented in this thesis show that ICA and acoustic emissions have the ability to aid in engine fault detection and diagnosis. The results have shown to be reliable, consistent and able to distinguish when the engine is healthy or faulty.

> *The automobile engine will come, and then I will consider my life's work complete…*
>
> Rudolf Diesel

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Declaration

Candidate Name: David John Moore

Faculty: Engineering and Physical Sciences

Thesis Title: Condition Monitoring of Diesel Engines

Declaration to be completed by the candidate:

I declare that no portion of this work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Signed:

Date: 12th September 2013

Copyright Statement

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I am also especially thankful to Mr. Fengshou Gu for his guidance and help academically and his friendship throughout the initial years studies. My thanks also extend to the other students in the research group and specifically my SIG, Reliability, Availabilty and Maintenance and Safety. I am particularly grateful to Peter Charles who I have worked alongside for the duration of my PhD studies for his patience, help and support throughout.

I would also like to thank my supervisor Dr Iain Dupere for picking up where Professor Andrew Ball left off. For providing me with a great deal of support through difficult times and always being available to talk to. His help and guidance has been invaluable in the completion of my PhD.

This research work has been supported by Power Systems Services Ltd. I would like to thank Mr Craig Arnold and Ian Tatlock of PS^2 for their help and funding for this work.

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Last and always, special thanks extend to my family: my mother, Shirley Jackson and my father, Philip Jackson, for their support.

The Author

David Moore graduated with a **M.Eng (Hons)** in Aerospace Engineering from The University of Manchester, United Kingdom in 2005.

In July 2005 he was accepted as a research student in the Extreme Loading and Design research group in the Health Monitoring and Through Life Support special interest group. His research was centred on the condition monitoring of Diesel engines, spending a lot of time investigating various aspects, electrical, vibration and acoustical monitoring. Through his investigations and the guidance of many years of research from colleagues within his research group David started on an ambitious piece of research to investigate the non-intrusive acoustical monitoring of Diesel engines regardless of size or environment. This work goes on to be presented within this thesis.

Whilst continuing his research, David has been working within the oil and gas industry for Schlumberger Oilfield Services as a Wireline Field Engineer and now more recently for Royal Dutch Shell as a Completions and Well Intervention Engineer.

Publications

Journal Papers

1. J. Jiang, F. Gu, **D. J. Moore**, A. D. Ball and K. Liu. (2007) *'An Investigation Into the Fault Detection of Machines Based on Acoustic Array Systems'*. Submitted to the *Journal of Sound & Vibration.*

2. J. Jiang, F. Gu, R. Gennish, **D. J. Moore**, G. Harris and A.D. Ball. (2007). *'Monitoring of Diesel Engine Combustions Based on the Acoustic Source Characterisation of the Exhaust System'*. p. 1465-1480, 22 (2008), *Mechanical Systems & Signal Processing* Journal

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Part I

Motivation

Chapter 1

Introduction

1.1 Research Background and Motivation

All types of machinery require some form of maintenance schedule. Without one, equipment will eventually fail and either need to be replaced or will have to be taken offline for costly repairs. Traditionally, maintenance is carried out based on the time, or the number of cycles the machinery has been through. Components are replaced or maintained on this schedule. These schedules are followed, but increasingly, instead of replacing components they are inspected and not replaced if it is deemed they are still sound. Whilst many components will outlast the suggested replacement time, modern financial constraints have meant that a higher degree of risk is being taken to keep machines running for longer with the least amount of maintenance and downtime. This method is prone to human error and is based heavily on risk, leading to potentially catastrophic failures, prolonged and unplanned downtime and potential for greater maintenance and repair costs when failure occurs. An alternative approach is to use condition monitoring to allow maintenance to be carried out when it is actually required for the specific components. This has the following major advantages:

- Reduced Costs
- Reduced Downtime
- Greater Flexibility

- Increased Safety

The research reported in this thesis considers the benefits of condition monitoring with particular reference to Diesel engines. In addition, the possible faults, type of measurement and signal processing are assessed and applied to two different Diesel engines using both acoustic and electrical signals. Condition monitoring offers improvements over traditional time and cycle based maintenance methods. A good maintenance strategy can significantly reduce maintenance costs and prolong the life of machinery. Condition monitoring aims to take maintenance that extra step by allowing the maintenance engineer to see a fault developing much further ahead than would be possible with visual or aural inspections. Even oil samples, which maybe contaminated with metallic shards due to wear, present issues at a more advanced stage. This offers an alternative to time or cycle based maintenance and is potentially more efficient, lowering the potential of unplanned downtime.

There is a large dependence in today's world on large Diesel engines whether they power boats, trains, factories or even for important backup emergency Diesel generator systems. The necessary technology and mindset of modern business requires that the business can operate when needed and that computer equipment is suitably protected against blackout. The importance of backup systems, therefore, cannot be underestimated and hence the maintenance of these engines must be meticulous. When called upon, these engines must start and must take load, businesses and lives could depend on it. Therefore lack of preventative maintenance cannot be justified.

This research has been sponsored by an industrial company, Power Systems Services Ltd (PS^2). PS^2 is an industry leading company providing high quality engineered integration of power systems. Due to the nature of their work and the clients they provide services too, advances in the way they operate and to the techniques they use are required to maintain their market lead. Combining the knowledge of the Through Life Research Group with that of PS^2, a solution is to be sought to maximise information gained from the sites they work upon allowing them to better advise their clients whilst maintaining the minimum amount of disruption.

1.2 Why Maintenance?

It is the author's experience through his time on many industrial sites, which include the world's leading Diesel engine manufacturer and many major financial companies in the London business district, that monitoring and regular maintenance of machinery and engines is met with a great deal of resistance. It is seen as time consuming, and a cost that can be cut to attain budget target levels. Many maintenance managers are constrained by tight budgets imposed upon them and will often double (or triple) the time between inspections to lower overall costs. However, maintenance carried out correctly both in terms of time and thoroughness, allows the optimal and safe running of equipment, both key factors in reducing costs. A minor fault can start to reduce the life of machinery by inducing secondary more serious faults which have the potential to cause serious economic loss due to unplanned downtime, or worse, injury or death.

Given the large investments companies make in machines, versus the high return in profit they make, it is in their interest to avoid unplanned losses of these machines. The early detection and diagnosis of a fault is essential, as it is possible for the maintenance engineer to schedule the maintenance and potential downtime. This minimises production and economical loss and will also lower labour and parts cost [1,2].

Machinery failure has been responsible for the loss of life and an impact upon the environment both on minor and large scales as demonstrated in table 1.1. In addition a report by CNN [3] of serious oil industry disasters within the last 20 years (1981-2001), gave a figure of 552 deaths, which is approximately 27 deaths per year in a single industry sector. All except one of which, could have been prevented by better maintenance practice.

1.2.1 Reliability of Diesel Engines

Diesel engines are compression ignition engines. This means that the correct and efficient usage of these engines relies on the proper control of the airflow and fuel injection into the cylinder. The Diesel engine can be split down into many subsystems,

Year	Location	Causes	Effects
1980	North Sea (UK)	Oil Rig Capsize	123 killed
1984	Bhopal (India)	Toxic Release	2700 Killed and 10 times as many injured
1984	San Juan Ixhuatepec (Mexico City)	LPG Explosion	500 killed
1986	Chernobyl (USSR)	Nuclear Reactor Fire	31 killed and 135,000 evacuated
1988	North Sea (UK)	Oil Rig Explosion	167 killed
1989	USSR	Gas Pipe Explosion	500 killed

Table 1.1: Major Disasters from 1980 - 1989 Due to Poor Maintenance [4]

all of which can suffer potential problems that could affect the running of the engine. A Diesel engine has many moving parts, both large and small which operate in a wide range of conditions and loads. Determining the reliability of a Diesel engine is an inherently difficult task as they have a wide range of applications. A car Diesel engine will have different reliability to that of a Diesel engine running 24 hours a day, 365 days a year in a manufacturing plant. This will mean that comparing a typical large Diesel engine to a black start large Diesel engine, which is an engine that only runs in emergency situations, will be difficult.

In comparative terms, Diesel engines are thought of to be more reliable than their petrol counterparts; this is due to several factors. Diesel engines do not need to burn as much fuel to produce the same power as a petrol engine but they tend to be constructed more substantially to take the added stresses of higher compression ratios and the shock loading of the combustion. The lack of electrical ignition system also makes the Diesel engine more reliable, a benefit for black run engines.

1.2.2 Emergency Diesel Generator Systems

Emergency Diesel generator systems (EDGS) are critical components in a system that is designed to provide operation 24 hours a day, 365 days a year. In other words, they are key components in systems that at all costs must not be interrupted. When mains power drops, emergency systems must start and be on full load within a specified time (usually 30 seconds) [5]. This means they are critical to the environment in which they are located and they can be called upon at anytime to run and run intensely even after years of no use (except maintenance runs). In fact, these engines have accrued most of their running time due to maintenance.

EDGS are made up of several components, a black start Diesel engine, generator, electrical controls, auxiliary subsystems and the engine support subsystems. The engine subsystems are as follows:

- **Fuel Storage and Transfer**. Includes all the pipes, tanks and pumps.
- **Cooling System**. Includes all the heat exchangers, valves, pumps and piping.
- **Engine Starting**. Includes instrumentation and control subsystems, batteries or air compressors, engine cranking devices and filters and valves up to the engine.
- **Engine Lubrication**. Includes piping and pumps, filters with all its associated auxiliary systems to provide heated and clean lubrication oil to the engine.
- **Combustion Air Intake and Exhaust**. Includes filters, silencers, support structures, ducts to and from any turbochargers and provides the engine with a clean supply of air whilst removing the exhaust gases from it to the atmosphere.

The engine is the largest and most complex of these components, with the most potential issues. It is also the first major component in the electrical generation system, without it the generator is useless. Usually EDGS are installed to work in parallel, to have redundancy. Each installation is a separate entity and only operates in a system at the electrical output where various electronic control units control each engine to produce a steady and equal output. Any engine not producing a steady or reliable output is dropped from the system by the control units.

The following sections will cite specific examples of situations where emergency Diesel generator systems are implemented and how important these generator systems are to PS^2 clients. Some of the data has been censored for confidentiality reasons.

Information Technology

Businesses are heavily dependent on their electricity supply for operation of its staff through business hours but also to maintain IT systems every hour of the year. A recent study by the Department of Trade and Industry (DTI) produced some significant figures [6]:

- 98% of UK businesses have an internet connection.
- 81% of companies have a website.

These figures demonstrate the high reliance upon IT. The companies who have a website will rely on that site to have as higher uptime as possible. In addition, digitizing of data has taken off in a big way in the last few years. Many companies now have a number of servers (Exchange E-Mail, File Sharing) to maintain. Loss of these IT services could cause serious operational issues during office hours and loss of trade and reputation for any business conducted via the web. Add to these costs, the cost of hardware damage that could follow from equipment losing power, data loss for the same reason and systems not coming back online after a power shut down. PS^2 has many clients in the banking sector as well as clients that provide coverage to large events viewed by millions around the world, it is therefore vital for both financial and reputational reasons that these systems function correctly when needed.

Banking

There is a heavy reliance on IT in the banking sector. Banks today are on a global scale, their information needs to be accessible all day every day and from any location in the world. Their automatic teller machines (ATM's), internet banking, client information and transfers all rely on electricity. To put it into perspective, according to the Australian Banking Association the total assets of banks operating in Australia was $1.98 trillion at the end of 2007 and the American Bankers Association was reporting assets of $11.860 trillion at the end of 2006 [7].

Investment banking sectors need to have high availability to ensure trading never ceases, an interruption to trading could be disastrous. With the increased threat of terrorism banking corporations have taken huge steps to ensure data redundancy, so that it is never lost, but also to maintain uptime should one system go down. They have also moved towards self sufficient running of their buildings should a terrorist attack damage power supplies in the financial districts. Any disruption to the banking sector could cost millions of pounds of loss per hour.

Live TV Broadcasting

With the ever-increasing lifestyle dependent upon electricity, TV sales and viewing has skyrocketed. According to the Consumer Electronics Association colour TV sets up until 1999 were in 98% of all US homes, making it as prolific as the radio. Major sporting events, including both major international competitions and domestic competitions, such as premiership football, are televised worldwide and attract millions of viewers. The reputation of the broadcaster is at stake as well as the sponsorship money of any large companies that maybe sponsoring the event or the broadcaster. As such EDGS are on standby to provide power should the mains supply be interrupted.

Power Stations

EDGS are critical in power stations, especially nuclear ones to maintain monitoring and cooling systems in the event of mains failure. Loss of power in a nuclear power plant could cause a massive disaster. There have been various examples of ‘close calls’, but one such prominent example occurred at the Vogtle Electric Generating Plant Unit 1 in 1990 [8] when all AC power was lost including that from the EDGS. This led to a dangerous rise in the reactor coolant system. A typical nuclear power plant has two or more independent EDGS installed [9]. In the case of Vogtle, one of their two units was disassembled for maintenance when the other failed, a serious incident even if the outcome was not as bad as it potentially could have been.

Other Situations

Hospitals are obvious candidates for EDGS. If all power were to be lost there could be a loss of life, indeed, on August 15th 1990 one New York hospital had lost power then lost its backup generator completely rendering its life support systems useless for over an hour [10]. This demonstrates that even in the western world power can be interrupted, but these interruptions are more prolific in the eastern hemisphere and Africa. PS^2 has an African office that supports a number of mining operations who rely on EDGS since the power from the national grid is, at best, intermittent.

1.2.3 Reliability of Black Start Engines

Unlike normal Diesel engines, black run Diesel engines do not run constantly. The critical task for these engines is they start and can take load. The potential fault areas can be catagorised as shown in Figure 1.1.

Figure 1.1: Three Fault Stages of a Black Start Engine

Due to the strain on these engines, the ‘start up’ and ‘on load’ stages are the most critical. Black start engines must be able to complete these stages otherwise they have failed in their task.

Published research on black start engine reliability is scarce, this research therefore takes an industrial tact with its direction of focus. The sponsoring company maintain hundreds of black start engines and other generator systems and keep records of faults, failures and causes for every site they maintain. Their records and expertise therefore provide the best source of fault and failure information for this type of engine [5].

The majority of failures for black start engines and the associated power generation system are their failure to start when required. A common cause is the use of an incorrect battery when the user does not want to invest in the correct battery, or because their correct batteries are in a very poor condition. These issues already have solutions. The main issue is when the customer is using the correct battery and it is in a good condition but the engine is still not starting. Monitoring of the battery condition and the load placed on it at startup, could provide an array of information about potential faults that may hinder engine startup in the future. Batteries are PS^2's main reason for EDGS failing to start, therefore, a preliminary investigation was carried out into how battery current was affected in an engine that had a fault compared to that of a healthy one. Appendix E presents this preliminary investigation and is an important and unique avenue of investigation based upon battery current draw during cranking or startup. Whilst it has no bearing on acoustic condition monitoring it has potential as a technique used in the overall condition monitoring toolset. Indeed, from the initial results there is potential for this technique to be used upon startup to locate the potential issue or fault to a particular cylinder.

If the engine starts successfully, then the main concern is the loading phase. Combustion parameters and the valves that control this are critical to the engines ability to make and maintain the required power output. If there are faulty valves, incorrect valve timings, issues with the injector or its timing then the engine may not take load successfully, or more likely, may take load but not be stable enough to run in a generator group. PS^2 engineers have detailed that injector issues and fuel supply systems are their next major issue, mainly causing the engine to run less stably than the others causing it to be dropped from the set, thus, rendering it useless to the task. These issues, as well as cylinder issues, such as cylinder liner wearing, ring wear or poor lubrication and valve issues in general make up the majority of issues and maintenance work they perform on clients sites.

There is a need to load engines to conduct testing. This is done via a 'load bank', which is simply a large electrical resistor. With many of these sites being in a basement or at the top of a building and normally in the centre of London there is obvious preference for testing without load banks. Vibration and acoustic measurements combined with instantaneous angular speed (IAS) data could provide information for PS^2 without the need to load test. This would give the company the advantage of being able to reliably inform the customer, with evidence, that they need to load test. Customers tend to decline load banking, as a test can cost up to £10,000 a day (location dependant). This would improve the companies reputation as they often have customers complaining when the engine fails, which could have been resolved had they accepted a load bank test.

1.3 Why Condition Monitoring?

Condition monitoring represents the advanced monitoring of a machine to allow predictive maintenance and thus the ability to detect an incipient fault before it causes an identifiable issue. The early detection of a fault has many advantages, a major advantage being able to detect a fault before the primary fault leads to a secondary one. This has economic advantages both in terms of time and costs. Condition monitoring allows maintenance downtime to be scheduled, this prevents sudden downtime, reduces production downtime costs as well as reducing the risks of injury and death. It can also be used to estimate how long a machine can continue to operate in its current state, or if the machine could be operated differently to avoid downtime, if it is not an option. The other major advantage to condition monitoring is knowing the exact condition of the machine and not having to adhere to a manufacturers estimated maintenance schedule. For example, a manufacturer may recommend replacing a part every 1000 running hours. Condition monitoring gives the engineer the power to say it needs replacing sooner, as it poses a risk of failure, or it doesn't need replacing as it is in a perfectly good condition. This removes the statistical based estimations and replaces it with actual knowledge based on the condition of the machine.

There have been examples, such as the "Three Mile Island" incident, where condition monitoring has failed and has caused an accident. This was due to the system providing incorrect information to the operators causing them to take incorrect actions. It is, therefore, incredibly important that a condition monitoring technique is robust enough to avoid such issues.

There has been rapid advances in condition monitoring techniques to improve the maintenance of Diesel engines but these techniques have largely remained on small Diesel engines. Although little work has been carried out so far on the transferal of these techniques to large Diesels they should, in theory, be transferable or modifiable for large Diesels. The condition monitoring of these engines has always been carried out on engines that run for continuous periods of time and on a regular basis. Engines such as these progress through their lifetime and follow regular manufacturer prescribed maintenance schedules. A traditionally-run Diesel engine and its components also tend to follow the 'Bathtub Curve', a general example of the failure rate of components throughout their lifetime.

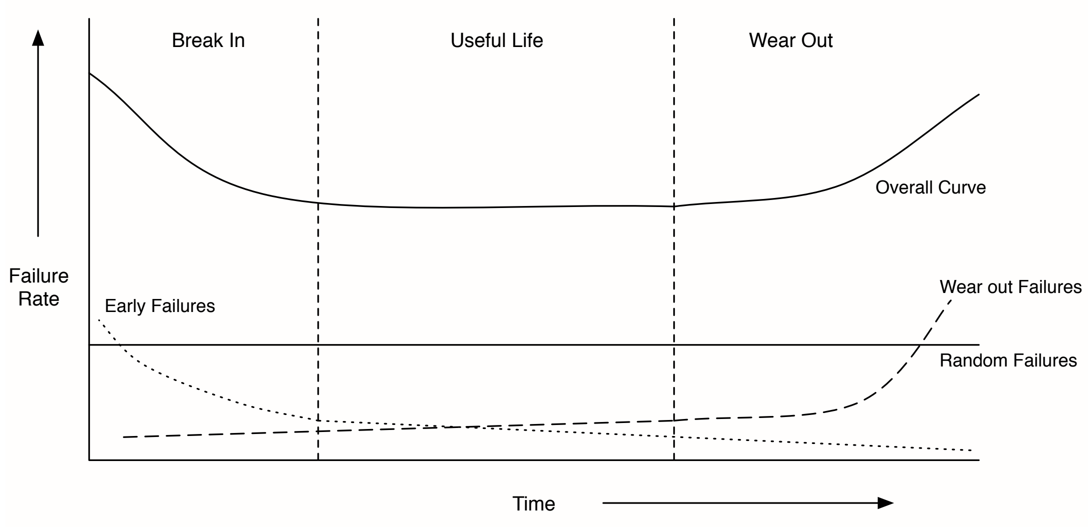

Figure 1.2: Bathtub Curve

'Bathtub Curves' were always typically associated with electronic equipment, indeed, the top curve in figure 1.2 would be the popular electronic component failure curve. The curve is made up from three component parts. The early portion of the curve demonstrates the 'infant mortality' of a component, it has failed sooner than it was designed to. The middle section shows the useful life of the component where the failure rate within this section is essentially random but at a constant rate. The later section shows the wear-out of the component, this section is past the designed life of the component and failure rate is increased within this portion.

Figure 1.2 depicts the life cycle we would expect from a normally run engine and its components. This research is concerned with emergency Diesel generators which are only running when there is an emergency. When they do run they run extremely hard, sometimes for short periods sometimes for long periods, never on a predictable basis. This stopping and starting and heavy loading increases the incidence of premature wear and random failures making condition monitoring all the more important for these sets of engines. In other words, we cannot predict or even presume on how components may fail. Condition monitoring is, therefore, particularly important for these engines as they do not follow the manufacturers recommended time based schedule for maintenance.

The current level of predictive maintenance technology is still in its relative infancy as the prediction of faults from the relatively low level signals produced from a very early underlying incipient fault is still relatively hard.

1.3.1 What Effects Can Condition Monitoring Have?

There are numerous examples worldwide where condition monitoring has proven successful, none more so than the energy industry. Whether its a renewable source or oil and gas, the energy industry requires a high degree of uptime where downtime is costly to the operator. The wind turbine industry is one such energy sector where condition monitoring has really taken off. It was found in the period from 2000 - 2002 that there was a high prevalence in damage to the gear systems. This lead some of the insurance companies to change their terms and conditions so that the energy companies had to change the drivetrain sections of the turbines regularly [1]. This is putting the maintenance back in the realms of time based not condition based. This way of maintaining equipment is not cost effective as mechanical parts that maybe perfectly sound are being replaced. The solution, therefore, was to monitor the load characteristics on the rotors as well as the vibration data from the drivetrain system. This allows engineers to accurately estimate the remaining life of components as well as monitor their 'health' realtime. A good example of this was the early detection and resolution to a damaged bearing. The condition monitoring system had detected a rise in vibration, these vibrations exceeded the threshold and an alarm was sent out to the monitoring centre who dispatched an engineer (figure 1.3).

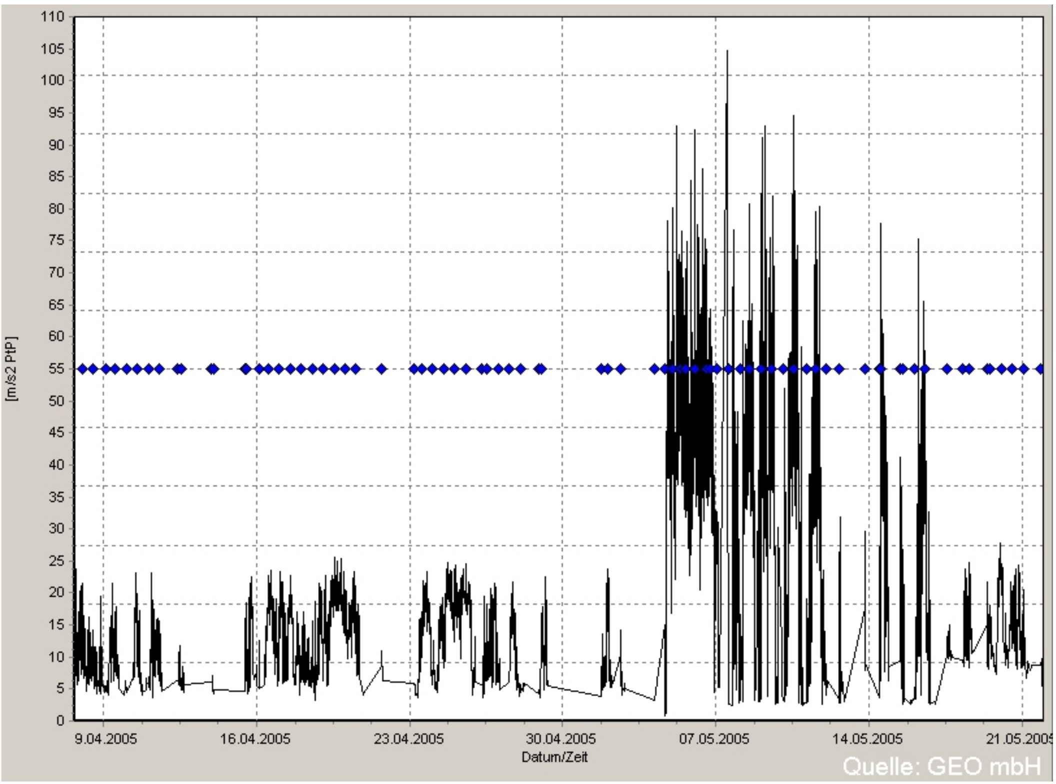

Figure 1.3: Rapidly Increased Vibration Signature on a Wind Turbine Bearing Housing [1]

The engineer analysed the frequency data shown in figure 1.4 and from this was able to pinpoint the damage to the cage for the high-speed output shaft bearing on the generator side bearing [1]. When the cage was inspected it was found to have cracked. The bearing was replaced within two days at a cost of €5,500. As the World Wind Energy Association (WWEA) identified, had this turbine not been monitored and this had occurred between two maintenance visits then the shaft could have displaced itself and worn out the gear teeth. The cost of a replacement gearbox is in the region of €105,000, not including fitting and labour.

WWEA provide another example where damage to a tooth ring on the gearbox had been detected. Not only was the fault detected but specialists were consulted and it was deemed safe to allow the turbine to run. This allowed the operator to plan when they were going to carry out the maintenance. The total cost of this maintenance was €13,500, providing a saving for the cost of a new gearbox as well as providing the flexibility to carry out the maintenance when appropriate.

Condition monitoring has now been in active service in the wind turbine industry

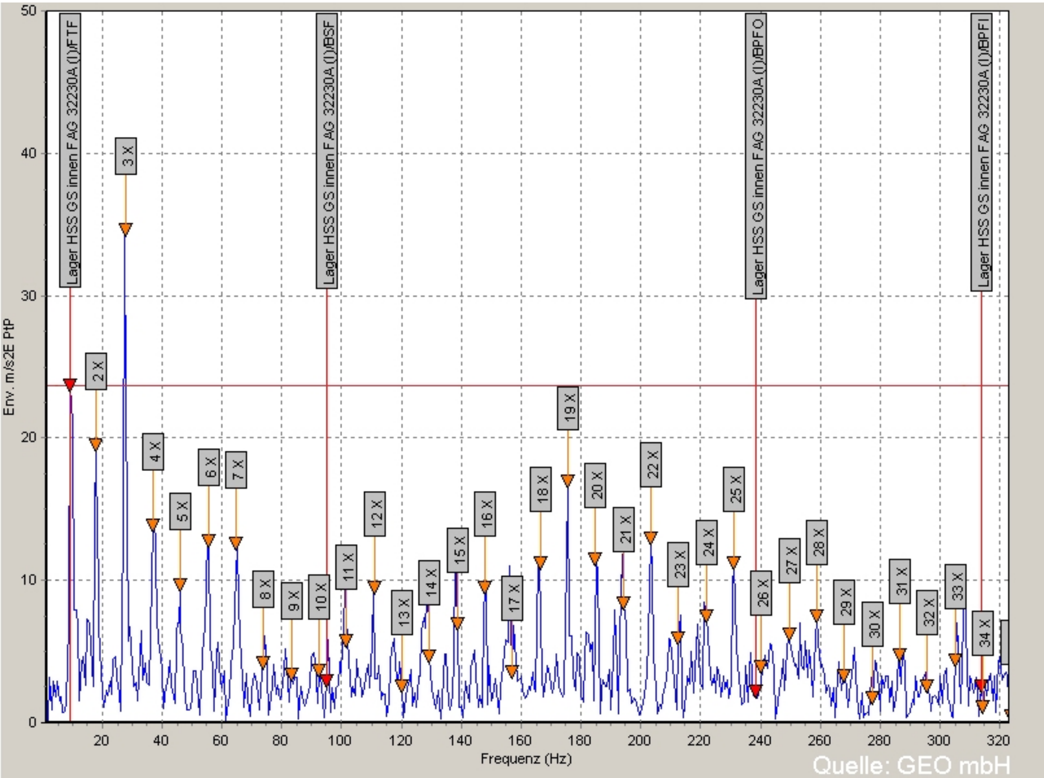

Figure 1.4: Frequency Information From the Vibration Data on a Wind Turbine Bearing Housing [1]

for many years and these systems have provided other benefits besides minimising downtime due to failures. These have included, better rates and terms from the insurance companies, historical data recording allowing for warranty claims with the turbine manufacturer and also having an onsite copy of the service life incase the manufacturer goes bust or the service agreement expires.

The oil and gas industry is also a big consumer of condition monitoring techniques. Condition monitoring is used offshore on platforms as well as sub-sea in pump systems. Multiphase pump (MPP) systems are used to pump heavy crude oil as well as its derivatives from deserts, jungles, offshore, sub-sea and other environments [2]. A market leader for these pumps is Bornemann Pumps, they recognise the importance of condition monitoring to the point where they actively retro fit their MPP systems to perform condition monitoring. Their condition monitoring system allows full online monitoring, where the monitoring starts from day one. For example, during the pump commissioning, which allows experts where ever they are in the world to ensure that the pump is commissioned correctly and is running as it should. As expected the system monitors the pumps vital components from the drive system, MPP, other subsystems and the operating components such as oil, filters and batteries. The amount of data read from the pumps is quite remarkable. The drive system alone monitors the motor windings for their temperature against the required hydraulic power of the pump, the bearing temperature against the running speed, pump differential pressure as well as ambient temperature and vibration data from the housing [2]. Similar readings are taken from the pump system as well as the subsystems.

A good practical example of how condition monitoring on these pumps can take effect was the detection of an increase in temperature in the pump casing to an unexpected and high level. The system has alarm settings and these had been exceeded causing the process to shut down several times. The recorded data was discussed with experts and the temperature design range was considered. In this case the alarm boundaries were raised and the process was able to continue unhindered. Downtime for this incident was three hours. Had condition monitoring not been in place with remote data streaming then engineers would have had to been dispatched to the field and in offshore operations this can take days due to flight availability and bed space, not to mention the associated costs of special helicopter flights.

It is clear from these examples that condition monitoring has vast benefits. If companies could overcome the perception that condition monitoring costs money and gives nothing in return they would realise that it actually, in most cases, could save vast amounts of money, time and increase production by large amounts [11]. Condition monitoring is intelligent maintenance and the choice not to use readily available sensors and techniques to monitor and diagnose faults within machinery in todays cut throat economic climate is potential business suicide. Data networks, computing power and code has improved leaps and bounds in the last decade to the point now, where examples shown in this section are easily achievable. Data can easily be streamed around the world, from the sea bed or just around the corner and we now have machines that can process this data real time and produce an output in a clear to read graphical format.

1.3.2 Examples of Condition Monitoring Techniques

The following section gives a brief overview of current condition monitoring techniques used to measure machine faults. Some of these techniques are used in industry to monitor machine health, some are more effective than others.

Oil Analysis

A technique already in widespread use within the large Diesel engine community. A sample of oil is usually taken from the sump, frequency is dependant on recommendations from specific engine manufacturers though it is likely to occur at the same time as an oil change. Oil analysis provides an idea of wear occurring within the moving parts via the type of debris contained within it. The test itself is cheap, ranging from £10-100. Various techniques may be used in the analysis of oil where a standard oil analysis will contain:

1. **Spectral Examination**. Determines the amount of wear metals, silicone, additives and coolant within the oil. It does this via a spectrometer machine which is highly accurate and provides the reading in parts per million (ppm). An example of the information gathered from this test could be the discovery of Chromium and Copper within the oil. Chromium would be associated with the piston rings, and would be caused by dirt coming through the air intake or broken rings. Copper is usually a sign of bearing and bushing wear, and will be elevated during the running in period when an engine is new. Thus, spectral analysis can very accurately indicate the metals or minerals contained within an oil. However, this will not give a 100% indication of where the issue lies only a good idea of where to look.

2. **Viscosity**. Determines the oil grade and whether its chemical structure has been altered in someway. This is usually measured in centistokes (cST) and is at a reference temperature of 40°C. The test is usually a measurement of how long it takes the oil to flow through a standard orifice. The viscosity test is not going to tell you exactly what is wrong with the engine, it will indicate to potential issues. For example, a decrease in viscosity would potentially

indicate ingress of fuel, refrigerant or solvents into the oil. An increase in viscosity would indicate water, soot or antifreeze ingress. Not particularly specific, but when used in conjunction with the other tests the bigger picture can be built up. [12]

3. **Insolubles**. Determines the amount of insoluble material present in the oil. The test consists of a centrifugal test where the oil is mixed with a heated agent and spun in a centrifuge. The insoluble materials gather at the bottom of the test tube and can then be identified and quantified. The test for insolubles is a good indication on how quickly the oil is oxidising, gathering contaminants and also how well the engines filtration system is working [13]. This test can provide some indications that something maybe wrong with the engine, but it can also indicate, simply that too long has been left between oil changes. A single bad test result is not a good indicator of an issue, several in a row would be a cause for concern.

4. **Flash Point**. Determines the lowest temperature at which the oil will flash, in other words produces enough vapour to ignite when exposed to a source of ignition. A change in the flash point compared to the fresh oil flash point shows the presence of contaminants. Flash point testing gives an indication as to whether there is any fuel or solvent ingress. Like the other tests this will not identify a root cause alone but when combined in a test series it will give a good idea of where the problem lies.

Whilst a useful technique, oil sampling is still a technique that should be used in conjunction with other more advanced techniques to build up the overall 'health' picture of an engine. The debris contained within oil samples typically only appear in sufficient concentration when the fault has already become significantly large compared to the same fault being detected via other methods.

Vibration Monitoring

Vibration monitoring is the most widely used condition monitoring technique, where the machines vibrations are analysed to determine incipient faults. It is popular, as almost every machine or process will produce some form of vibration. Difficulties do arise, however, at vibration measurement locations due to signal mixing caused by many vibration signals meeting at a single point as well as the presence of non-linear, non-stationary phenomenon which affect the signal transmission paths. Its use has been shown in section 1.3.1 demonstrating that it is being used today in industry quite successfully.

Vibration signals can be used to display frequency content as well as simple peak or root mean squared (RMS) values. Whilst overall vibration data is commonly taken to monitor for routine faults it is now clear that overall vibration monitoring does not hold a good level of condition monitoring data which it was once thought it did. Typically in industry the vibration sensor system picks up the total vibration level, amplifies it, time averages it and records it as a single value. These values are then trended over time to monitor the overall vibration from the monitored machinery. This overall vibration monitoring can be used to detect faults such as mechanical looseness, rotating or reciprocating imbalance, shaft misalignment, bearing damage, cavitation and electrical faults. Whilst overall vibration monitoring can detect these faults, it cannot distinguish between them because there is no frequency content in the data. Frequency content is required for fault diagnosis, this is where spectral vibration monitoring has the advantage in terms of diagnosis and how early it can detect a fault.

Spectral vibration monitoring allows the values of individual frequency peaks within a vibration frequency spectrum to be trended as individual parameters. This technique is now the basis of vibration condition monitoring. Rapid developments in signal processing methods and electronic hardware mean than this kind of functionality is available on portable handheld measurement devices. There are, however, issues associated with these units and this method of measurement. Most handheld units tend to take the overall vibration data then decide based upon the value recorded whether they should do a full spectral reading. They do this for several reasons, including trying to save storage space as the overall reading is a single value whereas the spectral value could be hundreds or thousands of values, thus another reason is to save time. However, as already noted, spectral analysis will detect faults long before the overall measurement and will also diagnose these faults. Unlike permanently mounted devices handheld devices are portable, which has distinct benefits, however, to be consistent, measurements must be taken in exactly the same location each time and proper contact must also be made with the surface of the machine as well.

Whilst an extremely popular technique for rotating machinery such as compressors, vibration monitoring on internal combustion engines or even large Diesel engines is strictly limited due to the complexity and highly transient nature of the vibration signals that could be recorded from the surface of the Diesel engine.

Instantaneous Angular Speed

Instantaneous Angular Speed (IAS), is a speed measurement of the engine crankshaft, the speed of which will vary as cylinders fire and subsequently compress. Using sensors such as a flywheel encoder the speed change is measured and is able to detect faults associated with the fuel injection and combustion systems. Some of the latest techniques [14] allow the fault to be located to a particular cylinder, however, all of the IAS techniques based on Diesel engines as yet allow the locating of faults but do not allow for the diagnosis of faults.

Cylinder Pressure Measurement

The in-cylinder pressure measurements in a Diesel engine include a lot of information on the condition of the engine and its combustion efficiency. This has its obvious drawbacks in that it requires obtrusive access to a cylinder head and whether the maintenance is carried out in house or by a maintenance company, equipment owners are never happy to have holes drilled in their cylinders. Studies [15] have shown that the use of an in-cylinder pressure transducer actually affects the cylinder pressure compared to a measurement taken unobtrusively and various studies [15, 16] have described how the air mixing varies throughout the cylinder during compression and combustion. Therefore taking the pressure at a single point does not provide an entirely accurate picture of the conditions throughout the entire cylinder. The conditions for the sensor are very extreme making a sensor life short, therefore increasing costs.

Despite its drawbacks, in-cylinder pressure measurements can be effective at assessing how well an engine is operating. It is suitable for detecting a range of faults from wear, sticking rings, damaged rings, incorrect injection timing, injector issues or valve problems. Not only can these issues be detected but they can usually be diagnosed with the collected data.

There are many techniques that have been developed in an attempt to obtain the cylinder pressure without having to measure it obtrusively. Johnsson [17] investigated the use of radial basis function with structure vibration and crankshaft speed fluctuation measurements as inputs into a network. His results were promising with his network being able to accurately reconstruct the pressure waveform despite a change in running conditions which it had not been taught. He also notes the issues associated with in-cylinder measurements as discussed above. El-Ghamry [18] utilised the acoustic emissions. He did this by using the acoustic emission to model and reconstruct the pressure waveform in the time domain. To do this the signal was split into two sections, compression and expansion. Two separate techniques where used on each section, polynomial fitting for the compression and regressive techniques during expansion. More relevant to this research, Miyamoto [19] utilised strain in the cylinder head bolts and carried this research out on a large marine Diesel engine and a small Diesel engine. This demonstrates the applicability of acoustic condition monitoring to large Diesel engines and the cross transfer from smaller to larger engines.

It is clear from the research carried out by El-Ghamry [18] and Gu [20,21] that a major advantage of acoustic measurements are their unobtrusive nature, something discussed further in Section 1.4.

Acoustic Condition Monitoring

Acoustic condition monitoring is mainly left to the research laboratory due to a strong perception that the acoustic monitoring of a Diesel engine may provide many complexities especially when the data is being taken in potentially noisy or less than idea conditions. Acoustic condition monitoring, however, does hold advantages over all other techniques presented within this section and is further discussed in Section 1.4. The background to acoustics and engine noise is also presented in Chapter 3.

Exhaust Monitoring

Exhaust monitoring has two main focuses, exhaust gas analysis and acoustic measuring in the exhaust stream. The content of exhaust gases provide information about the combustion quality, potential issues with the injectors and engine lubricants. Most exhaust analysis is carried out by passing the gas via a chemical analyser to register its component makeup.

In addition monitoring of the exhaust stream with acoustics can also give insight into valve and injector issues and other combustion affecting faults [22]. Jiang et al. utilised the popular ‘two microphone’ technique to analyse the standing wave within the exhaust pipe to detect valve and injector faults successfully. Whilst this technique has proven successful it is reliant on the obtrusive measurement of the exhaust gas flow which is not viable for industrial applications for the same reasons discussed in section 1.3.2. The question of how viable it is on large engine applications due to the high temperatures of the exhaust gases which are in the region of 500°C immediately upon exit is also present. Again providing potential high costs for sensors and their continual replacement.

1.4 Why Acoustic Measurements?

Within this chapter, vibration techniques have been discussed as the main form of condition monitoring since it was devised and first used in engine condition monitoring almost three decades ago. There has been a substantial amount of research carried out in the field of vibrations and in relation to vibrations from Diesel engines [23–26] for health monitoring purposes [27] .

There has been little research on the condition monitoring of Diesel engines and even less research on the acoustic condition monitoring of large Diesels. This is largely due to the perception that monitoring with acoustics would be incredibly complex if not impossible due to the normally noisy industrial environments. Despite its perceived difficulties, however, there are clear reasons why acoustic measurements could be a more attractive proposition than vibration measurements. The author, from his experience on industrial sites knows of no real world application of acoustic condition monitoring being used in a serious mission critical application.

Acoustic measurements have the advantage of being free standing, there is no need to connect, mount, drill the machine in any way shape or form making it a completely unobtrusive technique. This has the benefit of simplicity, highly moveable for use on different machines and is easy to move between sites and also benefits maintenance companies who's clients do not want their machines damaged or tampered with. There is also a clear advantage with the unobtrusive nature of this technique with respect to Diesel engine condition monitoring, high temperature resistant vibration monitoring equipment can be negated as there is no need to make contact with the engine. This serves to significantly reduce sensor and equipment costs.

There is also evidence to suggest that acoustic measurements can actually be more sensitive to certain events or processes compared to surface vibration monitoring. Chaudhri [28], who's research was based on reciprocating machinary, noted that a large change in fluid flow characteristics were highly noticeable in recorded acoustic data but not so noticable in the vibration data.

Within the last decade there has been a huge leap forward in acoustic sensor technology as well as in the computer systems and data acquisition systems that are used to sample and process the data. There has also been an increasing amount of research [29], which is discussed in chapter 3, on condition monitoring using acoustics, though there has been little work on Diesel engines, especially large Diesel engines.

Research utilising acoustics to monitor the condition of Diesel engines, not only small but large Diesel engines, is a new and unique avenue of research. It also has a significant benefit to the research sponsors who are looking for a non invasive monitoring technique.

1.5 Why Electrical Current Measurements?

The large driving factor behind a study into electrical current measurements is the clear issue of the greatest reason why black start Diesels will not start. There is an urgent need to investigate why these batteries test as healthy and in good condition yet the engine fails to start.

When an engine has a fault that may prevent it from starting, it could increase or decrease the amount of current needed to start the engine due to the transient friction of the engine subsystems, primarily the valve train and its associated components. This would make it harder for the engine to start. A suitable investigation would look at whether the current used by the engine at startup can reveal engine faults and produce a recognisable signal. Hence making this technique transferable to any engine with an electrical starting system. This technique would eliminate the need to run the engine for long durations and maybe avoid running it at all if information can be gained whilst the engine is cranking, thus, greatly reducing the cost and time involved in maintenance. Electrical current measurements are also non-intrusive, quick, simple and cheap to carry out.

The author knows of no other study into this area for the condition monitoring of a Diesel engine via its startup electrical system via his extensive research in the subject area as well as from his industrial experience. It is therefore a unique and new avenue of study.

1.6 Why Independent Component Analysis?

It is important to realise that processing of an acoustic signal is required to help produce meaningful outputs from the raw acoustic recordings. There is a wide array of signal processing techniques that have previously been investigated. Independent component analysis (ICA) has become increasingly popular over the years with major applications in medical research on brain activity, taking the output from an electroencephalogram (EEG), and applying ICA to it to find the underlying brain signals that have made up the EEG [30]. Chawala et al have carried out significant research [31] utilising ICA to remove noise and artifacts from electrocardiograms. The results produced electrocardiograms with a significantly lower signal to noise ratio (SNR), which has clear benefits.

It is therefore a natural progression that ICA would have an important place in image de-noising and particular work on removing reflections from images using ICA [32]. Yamazaki also demonstrated the ability to separate the reflections and the main image, demonstrating the ability of ICA as an image feature extraction technique. ICA has also been used to de-noise digital photographs of the noise that is produced by charge coupled device (CCD) sensors when operating in lower light conditions. As an imaging technique, ICA can also be used to analyse text documents [33]. The research by Ozawa et al clearly demonstrated that ICA was able to outperform the two methods that were currently in use for character recognition.

Of course, ICA is also able to separate audio that has become mixed, indeed ICA is able to separate most signals that have combined such as radio communications and seismic monitoring. The audio separation is of particular importance to this research. It is the the ability of the ICA to separate the recorded acoustic signal into the relevant sources that will allow engine event features to be located and identified from a sea of data which has already been demonstrated by Pontoppidan [34] where his research has shown that ICA has clear advantages over principle component analysis (PCA) with respect to fault detection [35]. The application of ICA in condition monitoring does not stop at acoustic measurements as He [36] et al showed, ICA was able to separate vibration signals to allow detection of gearbox faults. It is clear the applications of ICA are extensive.

1.7 Research Aims and Objectives

This research aims to provide an initial investigation into the condition monitoring and the output of the health status of Diesel engines using acoustic emissions. This will be achieved with acoustic data from varying engine conditions from healthy through a range of different faults which may be encountered by a service operator. This data will then be able to determine if there is a fault with the engine, the ultimate goal is to do so automatically without human intervention. Therefore, the objectives for this work will be to conduct experimental work on two different engine rigs, a small Ford 4-cylinder engine and a much larger Ruston 6-cylinder ship engine. The experimental work should be conducted fairly, accurately and ensure good data quality. Following data collection, the data will be processed. The data will be processed statistically at first to see if this will yield useful information without the need for complex computer intensive post processing. Following this, ICA will be implemented to see if this can provide any additional benefit. This process will occur with custom Matlab code that will be the basis of the future program that will allow for intervention less operation and thus automatic detection and output. The code will be robust and this will be initially verified by seeing how well it works across both different engines in two separate acoustic environments.

Based upon the conclusions from this work, further work will be specified.

1.8 Thesis Structure and Organisation

The thesis has been split into parts to highlight the experimental nature of this work. Within each part will be separate chapters relating to each part. The parts will be set out in the following way:

Motivation This will cover why this research is being conducted and what relevance it has in the real world.

Background This part will cover the background of the work being conducted and the relevance it has to this research.

Experimental Work This part will cover all the experimental work including information on the test rigs, all the instrumentation that was used and the faults that were seeded and how.

Results This part will present the results from the experimental data and is split into separate chapters to reflect the different processing techniques and the results encountered from each.

Conclusions The fifth and final part which is fairly self explanatory, it will provide the conclusions for the research and discusses ideas and concepts for future work.

Part II

Background

Chapter 2

Diesel Engines

2.1 Introduction

The Diesel engine, today, is one of the most widely used engines due to its efficiency and reliability. It has established itself well in many sectors such as in commercial vehicles, vans, trucks and plant machinary. It is also well established in industrial settings with many uses including backup power generation. Large Diesel engines are also used to power boats and container vessels both for propulsion and for electrical power.

Diesel engines are compression ignition engines as they do not require spark ignition like their petrol counterparts. Although on the 30th May 2006 this changed as MAN B&W released the first compression ignition petrol engine the 32/40PGI which operates using the Otto cycle [37]. Diesel engines work by controlling the air motion into and out of the engine and also by controlling the fuel injection. With these parameters working correctly, compression produces the ignition. Diesel engines are more efficient than petrol engines for three main reasons, they have higher compression ratios, during the initial compression period only air is present and the air and fuel mixture is always lean [38].

Diesel engines are very complex machines, with many systems and subsystems. There are many texts on Diesel engines, most of which are extremely large due to the complex nature of engines and the various techniques and technologies that have been used upon them throughout their history. Engine theory is based mainly upon idealised thermodynamic cycles, they were the basis for the design of the modern day engine. However, these cycles are indeed idealised and do not accurately represent the actual cycles that occur in the engine itself. To provide enough information on what is actually going on inside the engine during its operation we must look at the actual physical engine running cycle. To understand the health of an engine it is important to understand the physical cycles. This chapter provides the pertinent information on Diesel engine cycles and how they affect the running of the engine.

2.2 Basic Diesel Engine Cycles

At the core of every combustion engine there is a crankshaft. The crankshaft is the 'power output' component of the engine, used to drive whatever it is connected to. The crankshaft receives its energy input from the cylinder(s) connected to it. As the crankshaft revolves around 360° any components, such as the camshaft and gear train that are attached to it will move in relation to a 'crank angle'. As the cylinders are operating at certain crank angles, the systems that feed them with air and fuel will also need to operate at specific crank angles to allow for successful combustion. In essence, all engine operating events are related to the crank angle. This includes, inlet and exhaust valves opening and closing and fuel injectors injecting.

2.2.1 Two-Stroke Engines

Two-stroke engines are used in lower powered units such as chain saws and mopeds or in massive ship engines but rarely in medium sized units. The complete combustion procedure is completed once in every revolution of the crankshaft. Therefore, at every occurrence of top dead centre (TDC) combustion should occur. It could, therefore, be said that for the same given capacity, a two-stroke engine is more powerful than a four-stroke as it goes through two cycles for every one cycle of the four-stroke engine. As with everything, there are strengths and weaknesses. The weakness of the two-stroke is that it is not as efficient as the four-stroke. This reduction in efficiency lies with the exhaust and air induction process and thus poor scavenging. The four-stroke does not use scavenging due to its dedicated inlet and outlet strokes.

The two-stroke engine operates in the following sequence:

1. **Power Stroke**. At approximately 0°, top dead centre, combustion pressure acts on the cylinder head driving it downwards producing the engine power.

2. **Blowdown**. This the main part of the exhaustion process which tends to take place over 30° crank angle close to bottom dead centre (BDC at 180°). Due to the lack of piston stroke to aid exhaustion, two-stroke engines rely on the pressure differences between the combusted gases and the air on the other side of the exhaust valve to aid exhaustion.

3. **Scavenge**. This is the process where the remains of the exhaust gas are expelled as completely as possible given the cylinder design, port arrangements and other structural considerations. This process occurs before BDC and continues past BDC.

4. **Compression**. The cylinder drives upwards compressing the air for combustion.

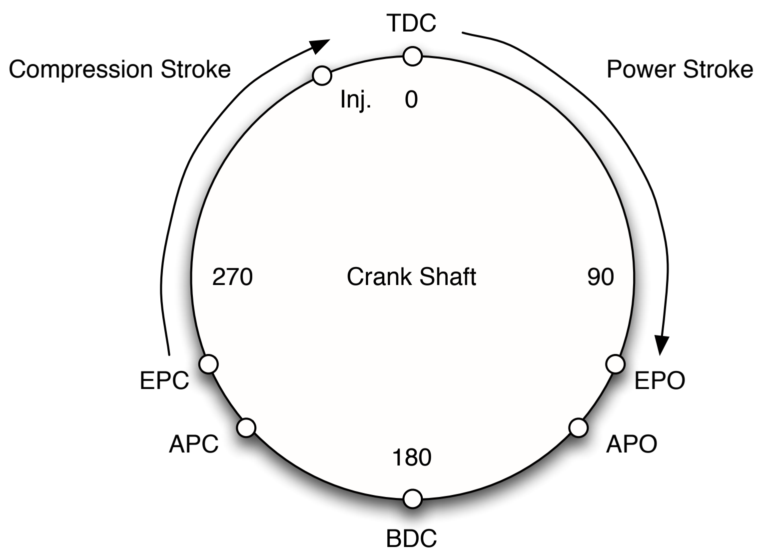

Figure 2.1: Simplified Two Stroke Cycle

Figure 2.1 shows the most basic cycle for a two stroke engine, a single cylinder. It can be seen that for a complete combustion cycle there will be one exhaust port opening event, one air port opening and one closing event per cycle. There will also be one injection event as the piston reaches TDC. If the engine had two cylinders then TDC for one cylinder would occur at BDC of the other to balance the engine out. The engine events would, therefore, associate with appropriate crank angles based on this. For example, based on a two cylinder engine:

Cylinder No.	TDC	EPO	APO	BDC	APC	EPC	Fuel Inj.
Cylinder 1	0°	120°	130°	180°	230°	240°	345°
Cylinder 2	180°	300°	310°	360°	50°	60°	165°

Table 2.1: Theoretical Example of a 2 Cylinder 2 Stroke Engine

Table 2.1 is completely theoretical and is not based on a real engine, it is merely to provide an example of how engine events will vary as more cylinders are added. This section has demonstrated that even in its simplest form, the Diesel engine has clear defined engine cycle events that occur at pre-determined and known crank angles.

2.2.2 Four-Stroke

Four-stroke Diesel engines are more common and have the widest variety of uses. Unlike the two-stroke cycle the four-stroke cycle has an extra stroke dedicated to the outlet of exhaust gases. It, therefore, takes two revolutions of the crankshaft to obtain a single successful combustion of a cylinder.

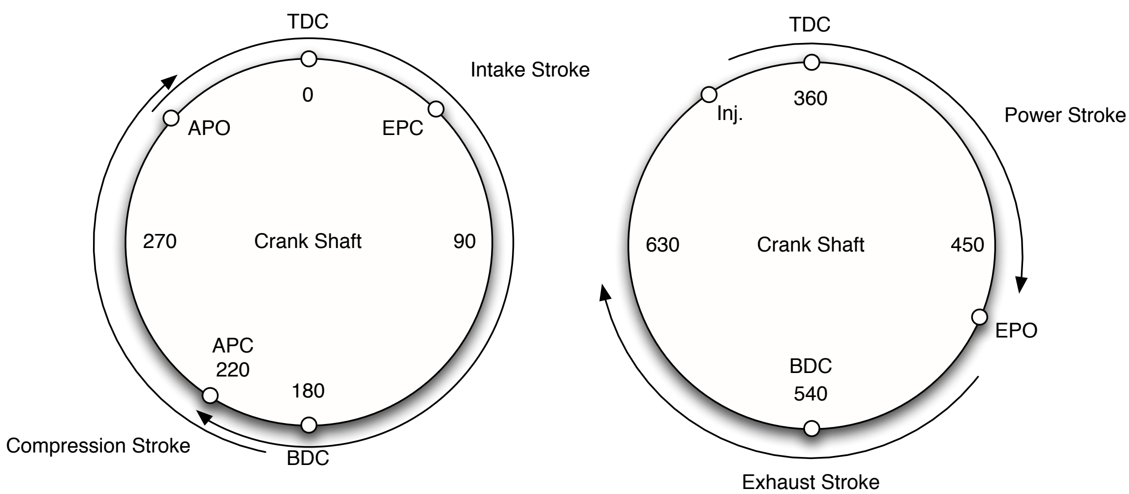

Figure 2.2: Simplified Four Stroke Cycle

The process of the four-stroke is outlined below:

1. **Air Intake Stroke**. Piston travels to BDC with the air inlet valve open. Clean fresh air is drawn in.

2. **Compression Stroke**. All valves are closed and piston travels from BDC to TDC compressing the air as it goes. Ignition occurs just before TDC (typically 15-20° though this varies between engines).

3. **Power Stroke**. Combustion forces the piston down to BDC, as it approaches BDC the exhaust valve opens.

4. **Exhaust stroke**. Piston travels to TDC with the exhaust valve open forcing the exhaust gas out of the cylinder.

Again, as cylinders are added the engine cycle events will offset in a 720° full cycle. For example an engine with 6 cylinders will have one cylinder firing every 120° over a full 720° four stroke cycle. Each of the valve and injection events for each subsequent cylinder in the firing sequence would, therefore, also be 120° offset from the previous one.

2.3 Research Engines

The previous sections gave an overview of how the basic Diesel engine cycles occur. Cycles vary from engine to engine and even two engines from the same manufacturer can have completely different cycles. This can be due to a range of reasons including, cylinder profile, valve profiles, type of injection system used and even whether the engine is turbo charged or not. It is, therefore, not appropriate to cover all these different variations that may affect Diesel engine cycles, instead, this section will cover the pertinent features of the engines used within this research and their expected cycles.

The two research engines both have very different engine cycles. This is not down to just their size but also due to different number of cylinders. The Ford engine is a four-cylinder engine, therefore, over a complete engine cycle of 720° there will be four combustion events. This will be one per cylinder, which will be 180° phased from each other. In comparison, the Ruston engine is a six-cylinder engine and will, therefore, have 6 combustions over a complete 720° engine cycle. The cylinders in this case will be 120° phase from each other. Tables 2.2 and 2.3 show the expected engine cycles for the two engines Under 'healthy' conditions there is a clear distinct

Cyl. No.	IPO	TDC1	EPC	IPC	BDC1	Fuel Inj.	TDC2	EPO	BDC2
Cyl. 1	707°	0°	13°	39°	180°	355°	360°	489°	540°
Cyl. 2	167°	180°	193°	219°	360°	535°	540°	669°	720°
Cyl. 4	347°	360°	373°	399°	540°	715°	720°	129°	180°
Cyl. 3	527°	540°	553°	579°	720°	175°	180°	309°	360°

Table 2.2: Ford FSD 425 Engine Cycle

Cyl. No.	IPO	TDC1	EPC	BDC1	IPC	Fuel Inj.	TDC2	EPO	BDC2
Cyl. 1	670°	0°	50°	180°	220°	701°	360°	490°	540°
Cyl. 5	70°	120°	170°	300°	340°	100°	480°	610°	660°
Cyl. 3	190°	240°	290°	420°	460°	220°	600°	10°	60°
Cyl. 6	310°	360°	410°	540°	580°	340°	720°	130°	180°
Cyl. 2	430°	480°	530°	660°	700°	460°	120°	250°	300°
Cyl. 4	550°	600°	650°	60°	100°	580°	240°	370°	420°

Table 2.3: Ruston 6RK215 Engine Cycle

cycle for each engine, where events occur at known crank angles. However, when one of these parameters changes the whole engine cycle process is differed in comparison to a 'healthy' cycle. For example, from table 2.2, if the inlet or exhaust port for cylinder one was to open later there would be a change from the designed parameters in the amount of air taken in for combustion as well as the engines ability to remove the exhaust gases quickly enough for smooth combustion to occur. Under these conditions there is a change to the designed cycle, thus, the engine has deteriorated from the known 'healthy' state. Similarly if the injectors are not opening at the correct pressures then they will inject at a different crank angle which will have a large effect on the designed combustion cycle.

2.4 Summary

This chapter has outlined the basics of the Diesel engine cycles, indeed it has only scratched the surface on some of the main sections of these very complex and advanced machines. The cycle diagrams that have been presented are based on a single cylinder. Typically a large Diesel engines have upwards of six cylinders with some having as many as twenty. It is clear that this will significantly increase the number of events occurring per crank angle. There are a lot of complex systems and events which contribute towards the combustion process, meaning there are many potential issues that can occur, to cover them all in this thesis would be impossible. For a more comprehensive overview of Diesel engines and their associated technology and cycles, Stone has an excellent supplementary text [38].

2.5 Conclusions

Diesel engines are systems that are based heavily on events occurring at known predetermined times. These times are related through crank angle, therefore, if a large enough sample size of data is taken from a running engine it could be expected that the data would repeat well for each cycle despite the highly transient nature of engines. With that in mind it would be expected that a change in the engine condition would vary particular events in relation to crank angle. For example, earlier or later injection will affect the pressure rise within the cylinder and the crank angle at which the combustion event will occur and even the intensity of the combustion. Poorly seated valves or a variation in the crank angle at which they open and close will also have an impact on the combustion and thus the angle at which it occurs. This is why so many researchers have concentrated on aligning data against the crank angle. However, without knowing the crank angle, the data should vary when compared to a healthy data set due to the effect upon the engine combustion which is the primary noise generation mechanism within an engine.

This leads to several conclusions. Mainly that a wide range of faults would affect the combustion within the engine. As combustion is the predominant acoustic source, they should be detectable acoustically due to the change in combustion that would occur. It also means that it will impact directly on the capability of a backup Diesel generator to take load successfully and to maintain itself in a generator set. Something that has been corroborated with the sponsoring company. In a wider context for Diesel engines in general, the effect on combustion no matter how small will have knock on effects on engine performance no matter what context it is used in. For example, less complete combustion within a car Diesel engine would produce excess emissions and potentially, depending on why it is occurring, sooting of the injectors further exacerbating the issue.

How well an acoustic condition monitoring technique will work without crank angle is not certain, all previous research aligns acoustic data to either the crank angle or to the in-cylinder pressure sensor from the first cylinder. The following chapter will discuss a range of research that has been conducted on Diesel engines and condition monitoring of Diesel engines. It aims to outline how Diesel engine research has progressed over the years and also looking at the main noise generation mechanisms and how they relate to this research.

Chapter 3

Engine Noise Studies

3.1 Introduction

The main aim of this research is to be able to detect a change in the engines condition via acoustic recordings. It is important, therefore, to understand the noise generating mechanisms within a Diesel engine to be able to understand how changes of certain engine systems may affect the acoustical output. With any machinery in operation, noise is produced. Whether they are jet, petrol or Diesel, engines all emit a high level of noise. The noise generation by combustion engines has become a major issue as the power, physical size and proliferation of combustion engines has increased. Today they are used in anything ranging from remote controlled cars to container vessels. There have been stringent enforcements on health and safety and emissions, including noise emissions. Despite the negative attributes of the noise produced by engines, it became rapidly apparent in the early half of the century that a change in engine noise was actually an indicator of the condition of the engine. Large audible changes such as this may have been possible a century ago, however, in todays modern engines faults are not easily discernible by ear. As discussed in chapter 1, condition monitoring is one such way in which health and safety of engines can be improved as well as maintaining the most economic and efficient operation in whatever role they fulfil.

Diesel engines, in particular are renowned for having higher noise levels than their petrol counterparts due to the higher compression ratio. It is this pressure ratio that makes them so attractive as this increases their efficiency and hence their proliferation. The higher compression ratio increases the forces on the piston at the point of ignition which not only causes larger vibrations within the engine body but also increases the forces exerted on the cylinder itself, which has a direct impact on the crank shaft. Overall this leads to an increase in engine noise emissions. However, due to combustion being such a fundamental part of Diesel engine noise generation, changes to any system contributing to combustion and engine running should have an effect on the acoustical output.

With the realisation in the early 1900's that noises produced by an engine can give an indication of how well it was running, it would appear that acoustic emissions may very well contain important information about the engines operation and its health. When looking at the possibility of developing an acoustic condition monitoring technique it is important to understand the sound generation mechanisms in a Diesel engine. The following chapter gives an overview of engine noise studies and a look at the most important work that has led to current research being carried out on engines and more specifically, Diesel engines.

It is important to understand the history of engines, both the early development of the petrol engine and the full development of the Diesel engine. Apart from the thermodynamic cycles, that were a crucial development in engine technology, there have been many pieces of research carried out to investigate what causes engine noise. Including how it affects the engine, how the noise can be reduced and how engine designs can be changed or improved to improve their running and their noise emissions. This chapter will show that much of the discoveries in the early 20th century hold true today and the advancements today are mainly in the areas of signal processing thanks to the rapid development of ever powerful computer systems and advancements in sensor technology.

Thorough understanding of noise emissions and noise generating mechanisms within Diesel engines is critical. How these noises vary in different conditions can aid the development of a monitoring system that can provide information in a useable format on how the engine is performing and how healthy it is, this is the basis of condition monitoring. This chapter will look at the noise generation systems and how they impact on the engine system. A range of work has been carried out on engine noise such as injector design, fuel injection, nozzle design, inlet air motion, cylinder design, fuel types, body design and vibration studies to name but a few. Knowledge of these studies will provide a foundation of the relevance of this work and how the variations within the engine may effect the acoustic emissions of the engine leading to the successful detection by acoustic sensors.

3.2 Noise Investigations

The occurrence of combustion within a Diesel engine exerts a force on the engine cylinder but does so for a very small duration, around 15° of crank angle [39]. This would, therefore, lead to the conclusion that engine vibration and hence engine noise emission is a transient vibration phenomenon [39] brought about by the large and very sharp impact on the cylinder walls. This phenomenon has given rise to various terms that today, are commonly used. They describe certain engine combustion or mechanical features such as“knock”, “piston slap” and “rumble”.

Only 16 years prior to the Diesel engine, Lord Rayleigh laid the foundations for vibration and sound studies with his original publication ‘The Theory of Sound’ in 1877 which was revised in 1945 [40, 41] and is still popular today. The most prominent parts of his work utilised in early engine studies were his research on sound caused by vibrations, vibrating systems, vibrating plates [40], secondary waves and his work on the vibration of solid bodies [41]. Rayleigh laid the foundations for the wave equation and the ground works for how vibration systems are described mathematically, his work is still used today to describe complex vibration systems. Little research followed, as noise and vibration at this point were not causing any detrimental effects to the operation of the latest machinery of the time. It was not until the early 1900’s when machinery was operating at higher speeds and for longer periods that issues arose.

Sir Harry Ricardo made significant advances in Diesel engine technology from the turn of the century. Whilst his advances were not made to directly reduce engine noise, they were to improve running and performance which in turn led to smoother running engines and thus reduced noise. Ricardo investigated the effects of fuel mixture strength on combustion on a two-stroke motorcycle engine that he designed, this would later go on to play a large part in his future research at the Department of Military Aeronautics. His major work here was to design a Diesel engine that gave all round performance similar to a petrol engine whilst being light weight, with major potential for use in aviation. The hope was that despite the high initial cost of the engine, this would be offset by the money saved in its operational lifetime due to its higher efficiency, reliability and reduced cost of maintenance.

Ricardo recognised that a rapid rise in pressure in the cylinder exerted a tremendous force on the cylinder walls [42]. Alongside this work Ricardo identified three stages to Diesel engine combustion [43]. The first was an initial delay period whilst the envelope of vapour is formed during which a substantial amount of fuel enters the cylinder with no real rise in pressure or temperature [43]. This is then followed by a rapid rise in pressure when the vapor becomes fully inflamed. The third stage consists of a less rapid and controllable rise when the temperature is so high that the droplets burn as soon as they entered the cylinder with hardly any delay [43]. Ricardo's estimations can be seen in figure 3.1 which he later verified as being correct via engine tests. Due to the large forces that combustion exerts on the cylinder walls it is the main contributor of engine noise emissions. How well combustion takes place is a major factor in how much force is exerted. For example, changing injection timing by a few degrees earlier or later would have a dramatic effect on the combustion process. Too early and liquid fuel will hit the cylinder walls and will instantly vaporise and cause knocking, injection occurring later would likely cause rough uneven and lower pressure combustion due to instant ignition. There is even a risk of sooting if the fuel is still injected after a critical point due to incomplete combustion. Both of these factors would have a significant impact on the combustion and vibrations within the engine and hence a change in the acoustic signal from a healthy condition should be detectable.

Ricardo's work would be the start of a plethora of work carried out worldwide

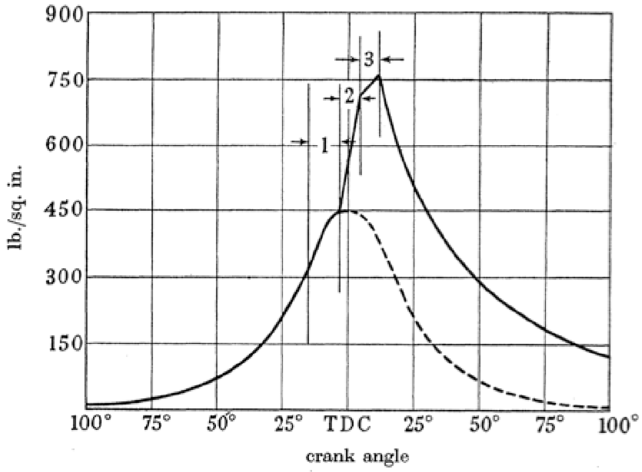

Figure 3.1: Ricardo's Proposed Three Phases of Combustion [43]

with much of the prominent work emanating from the United Kingdom, the United States of America and Germany. Like Ricardo's work [43], many researchers were investigating the way in which fuel was injected into the cylinder with variations in the injector nozzle type and even its position within the cylinder. Much of the research was based around the best way to combust the fuel to create a smoother running engine and thus reducing or even eliminating "knock".

One of the first major investigations, that occured alongside Ricardo's work, looked at combustion in Diesel engines and how the design of the injectors and the cylinders themselves directly affected the cylinder pressures and the structural impact on the engine. It was carried out by Fieldler [16, 44], who completed much experimental work, destroying many engines in the process. He fully recognised that engine combustion exerted huge forces on the engine structure. Through his research he determined that the way fuel was injected into the cylinder severely affected the combustion effectiveness as well as the pressures within, which if incorrect led to damage to the engine itself. He highlighted, like Ricardo, that the way in which the air enters the cylinder as well as the way the fuel is injected has a large impact on the engine combustion. Indeed, both Fieldler and Ricardo recognised that fuel should not touch the cylinder walls as this caused instant vaporisation of the fuel and thus engine knock.

Leading on from Fieldler, investigations into fuel quantities, quality [45] and their effects on combustion as well as the effects of nozzle types, air motion in the cylinder and the cylinder design itself [46] were carried out. This was due to the recognistion that detonation and shock forces were the main barrier in the advancement of increased compression ratios. These factors were directly affected by the cylinder head design, and whilst previous engine cylinder head designs and engineered fuels had kept the issue at bay, the increase in compression ratios introduced what Janeway described as "explosion roughness" which led him to compute a "roughness shock factor" which is the percentage increase in the restoring forces in the mechanical system over the applied forces. Taub [47] also described a "roughness factor" of R^2V, where R is the maximum rate of pressure rise during combustion compared to during compression. V is the percentage of the total pressure rise during combustion at the point where the maximum rate of pressure rise is achieved.

The existing designs according to Janeway, were designed on the basis that the shock of engine combustion was produced by the pressure rise when combustion occurred [46] and hence previous designs were produced to accommodate this pressure rise with respect to time. Janeway found empirically that, instead of giving nice smooth combustion, as would have been expected should the theory have been correct, it was actually quite rough. By theoretical analysis, Janeway determined that the acceleration rate of the pressure rise ($\ddot{\mathrm{p}}$) is the most predominate factor in affecting the forces exerted on the engine parts and the way in which they deflect as a result. The maximum deflection percentage increase was described as "the difference between the maximum restoring force and maximum pressure", he termed this the "Shock Factor". It is clear from Janeway's work that he held high regard for Ricardo, his work follows on closely from Ricardo's and as such it is no surprise that his opinions fit with those put forward by Ricardo and Boerlage and Broeze.

Many researchers did not entirely agree with Janeway, including, Le Mesurier and Stansfield [48, 49], Schweitzer [50], Rothrock [51], Hetzel [52], and Wilke [53] who all believed that the rate of pressure rise $\dot{\mathrm{p}}$ was a better criteria. Hetzel [52] and Rothrock [51] found an optimum correlation between the maximum rate of pressure rise and noise [39]. The author would tend to concur with the rate of pressure rise, if for no other reason than it has been extensively shown via experimentation [49, 51].

These experiments have shown that a more steady rise in the cylinder pressure provides a higher overall cylinder pressure for a more prolonged period compared to those with a shorter faster rise in pressure. These findings were linked directly to the crank angle at which injection occurred as well as engine temperature. The results from Rothrock's experiments showed that at an engine temperature of 185°F there was an increasing and more significant reduction in cylinder pressure with earlier injection. It was actually so severe, that it gave a reduction of almost 900lb per square inch. With an increase to 250°F there was still a small decrease with earlier injection but to a far less extent to where it was almost unoticable. Le Mesurier's experiments showed that as the injection point tends towards TDC and passes it the rate of pressure rise is greatly affected. There was also evidence from internal cylinder photography [51] which showed that later injection isolates the ignition to the ignition point in petrol engines and to the injection point in Diesel engines. However, one statement by Rothrock [51] that a 10° difference in injection caused little change in combustion shows how primitive the experimental equipment was when compared to today, as will be demonstrated later in this work.

Le Mesurier and Stansfield extensively studied the effects of different types of fuel on slow and high speed Diesel engines. They based their experimental work around Ricardo's theory that combustion in a Diesel engine can be split into three phases as shown in Figure 3.1. This allowed the comparison of the different fuels and how they affected combustion. It is from these combustion diagrams that they discovered that it was not solely the rate of pressure rise per degree of crank angle that determined the "shock" but also the duration of the highest rate of pressure was applied. Surprisingly, they discovered that speed reduction does little to slow the rate of pressure rise but it does increase the duration of pressure rise. Therefore, a slowing of the engine increases the likelihood of combustion shock. Through further experimentation they also discovered that the pressure within the cylinder at the time of fuel injection significantly slowed the fuel penetration causing an ignition delay and, therefore, fuels that naturally gave a longer delay could cause greater combustion shock than those that did not.

Le Mesurier and Stansfield continued their work [49] and showed that there are many parameters that affect the combustion process and that certain fuels are better under some conditions compared to others. They investigated different fuels, and their effect on delay and combustion shock, effect of the change in volatility, effect of fuel types on temperature, effect of drop size, effect of turbulence, effect of temperature on combustion and the effect of pressure. Similar conclusions, according to Le Mesurier, were obtained by Boerlage and Broeze [49] in 1931.

It must be remembered that the period in which this research was being carried was at the time when engine speeds and internal pressures were increasing. Little work had been carried out on different fuels, the last research was conducted to eliminate the issues of knock when engines made their first speed/pressure advancement. Through continual advancement there was a large amount of research carried out on fuel mixtures and combustion chamber design, these were relatively unchartered areas of research. It seems inconceivable today, to experience such running issues with an engine. Engines today, however, are computer controlled to vary many parameters depending on various conditions within the engine, essentially eliminating the issues Le Mesurier and Stansfield [49] and Boerlage and Broeze highlight in their papers. Add to this the advancements in chemistry and refining and the issues of 1931 are not substantial in todays modern engines.

Janeway [46] and Ricardo [42] had both attributed rough running to the torsional vibrations of the crankshaft. As well as torsional vibrations, bending vibrations and masses of the pistons and their connecting rods were also thought to contribute to the roughness. This theory would make sense, as all the fore mentioned items are connected together. Heldt [54] carried out some of the first research on the sound emissions from engines. Heldt's conclusions were that engine roughness consists of synchronous vibrations of the engine crankcase which occur due to combustion-pressure forces and the inertial forces of the reciprocating engine parts. He put forward a solution of stiffening the crankcase, both in horizontal and vertical planes. The stiffening increases the natural frequency of the crankcase so that only higher frequency harmonics can synchronise with it. Heldt's work demonstrated a realisation that engine parts and processes did in fact cause significant vibration and sound emissions, this would lead to numerous acoustic studies on engine structures and engine processes. Mount and Hope [55] concurred on Heldt's opinion stating that "rapid pressure fluctuations cause very high stresses in the surrounding metal parts". They believed that light unsupported metal structures such as the cover plates and cylinder cases were particularly noisy. Through much research [26,56–59] modern Diesel engines have been meticulously well designed to reduce noise transmission paths. Thus the frequency content of recorded engine noise is predominated by the combustion frequency characteristics, internal mechanical excitations such as crankshaft and body vibrations and the surrounding environment including the engines noise interaction with the environment [20]. A significant conclusion was made by Priede [60], when he compared the normalised cylinder pressure level and the peak gas pressure. These relate to combustion induced noise and mechanically induced noise respectively [60]. It showed that these two parameters are conflicting, smooth combustion is possible with higher peak pressures. Therefore, the reduction of noise in one area increases the noise in the other. Further research by Priede, Austen and Grover [61] concluded that the highest structural contribution to structural noise was from components such as the sump and the rocker covers. They estimated the reduction of these noise sources could lead to a 3.5dBa drop in emissions. Researchers should not, therefore, make the common assumption that engine noise is solely made up from combustion noise. As research by Priede and Grover [62] demonstrated, in the absence of combustion, the engine noise of its moving parts alone was 3-6dBa. Other sources also exist, such as bearing friction and fuel pump operation [57]. Ample demonstration that there are other factors involved.

The important points to take from this historical development of engine noise research is that change in noise is a good indicator of engine health. An increase or change in noise from a known healthy reference level has been shown to be a good indicator of a fault. The developments have shown just how many variables can go into changing the acoustic emissions of a Diesel engine. More importantly they have shown how issues such as fuel injection and air & fuel mixing can impact on the noise generation. Many of these early studies have investigated better ways to design engines for smoother more efficient running, the problems they investigate are very clearly applicable to condition monitoring. The previous paragraphs have really set the scene for engine research. As engine design has been ever advancing, noise generation mechanisms in engines have not changed since the research from the 60's and 70's. Whilst engine research has continued there has been a shift from heavy experimentation to mathematical modelling prior to experimentation, where the experimentation sets out to prove the model [63, 64]. This trend has increased as computer systems have increased in power. More recently the experimental side has crept back in to allow data collection from the engine followed by heavy post processing due to the rapid increase in computer power and far better and wider sensor technology. Indeed, there are now easy to use and lightweight commercial systems available for engine health monitoring [65] including Brüel & Kjaer Pulse Analyzer platform [66].

Manufacturers are now starting to build in monitoring systems in to their engines to monitor parameters such as cylinder pressures and injection rates. These systems are more for the efficient running of the engines to ensure that the combustion process is as optimal as possible and can be varied depending on the operating conditions of the engine to increase fuel efficiency and to reduce emissions. Some commercial systems aim to interpret this data for the use of condition monitoring, for example the cylinder pressure rise and fall. This can be used to determine combustion issues in particular cylinders. Temperatures could be used to do the same thing. Unfortunately, the pressure data must be aligned to crank angle and thus a shaft encoder is required [67, 68].

Whilst all these methods are valid they assume that there is potential to have access intrusively for in-cylinder measurements and the ability to mount and encoder and various other sensors and this is often not the case. There is, therefore, a large market that is not addressed by any current commercial system, though it would appear that none intrusive measurements are gaining interest [29, 69–74].

One way in which engine research has transformed with the push of post processing is a slew of work investigating how different faults and different engine conditions affect engine noise. As shown in section 3.2, engine noise studies have looked at a broad range of engine noise subjects. These include noise generation mechanisms, how noise and vibration is transmitted, how it is radiated, and how it can be reduced and controled. There have been many investigations based on a myriad of topics such as engine size, speed and load [75] at the most basic level. Advancing, types of fuel injection [57] and how fuel was injected was researched along with how camshaft and crankshaft [76, 77] interacted to provide engine noise. In these mechanically derived studies research has even gone as deep as to investigate the effect of different oil viscosities on engine noise emissions [49, 78] and how various systems interact together [79,80]. As Priede and Grover identified [62] this mechanical interaction does produce noise, but in the absence of combustion it is still a relatively small amount. Combustion studies [15, 81, 82] have been paramount and covering a wide array of topics. These have included the quality of the combustion process [67], pre-ignition [83–85], cylinder pressures [17, 27, 86–88] and abnormal pressure rise [15, 18], misfiring [89–91], injector timing faults [68, 92–95], valve issues [96] and inlet and exhaust noise [97, 98]. Encompassing both of these areas, engine vibration [26, 59, 99] has been a popular area of investigation including how these vibrations can be reduced [100]. A step forward from this, and really demonstrating how computational power has advanced, researchers are now looking at separating combustion and mechanical noise [101]. Quite what practical use this is, however, is not understood.

3.3 Summary

In summary, since the Diesel engine was invented there have been numerous noise studies to investigate noise generating mechanisms so that the engines could be made both quieter, more efficient and more stable. As the noise generation studies provided a better understanding of the mechanisms of noise generation within the engine and with increasing computer and sensor power condition monitoring studies have grown in popularity. The field has seen a lot of work in various monitoring techniques from oil samples to acoustic monitoring, the latter being less prolific. In the last five to ten years acoustic studies have gained in popularity though as quick as they have arrived they are rapidly being replaced by emissions studies. Research is driven by a number of factors, these include sensor and processing power and techniques but more importantly today, they are driven by money and business. Indeed, in the current economic climate with very high oil prices and increasing emissions regulations engine research is being driven by businesses and the need for more fuel economic and less polluting engines. Indeed Gu and Ball, who have led recent engine condition monitoring have now transitioned their research to emissions and biodiesel [102].

3.4 Conclusions

The author believes that condition monitoring is, and always will be a very important area for research. The changes in fuels, reductions in engine weights and other modifications to make them more efficient in the future will no doubt lead to new challenges in condition monitoring. The maintenance community will need to continue to evolve with these changes to ensure that engines remain reliable and safe.

There is a significant gap in research looking at techniques that work across multiple engines, small, large, low speed or high speed. Most research concentrates on a single engine, which whilst useful, does not show the applicability of the work in the widest possible context. This research sets out to bridge a part of that gap and goes to show the power of the technique discussed within this thesis compared to other research across multiple engines. It also looks at doing so without the need for the crank angle which has been the main basis of data processing to date. Previous researchers whether collecting vibration, pressure or acoustic data then align it to crank angle and from there produce an output based upon engine operating events. Again, this is reasonable, but not always possible to do. In addition to crank alignment, much of their data is heavily processed and distorted. This research sets out to address these concerns and see how data can be minimally processed and analysed without the knowledge of crank angle to advance the field of Diesel engine condition monitoring.

The following chapter will look at independent component analysis and provide a background into how it works and why it could be useful in the processing of acoustic data taken from a running engine.

Chapter 4

Independent Component Analysis

Acoustic measurements present some inherent issues when used to monitor machinery. First, there are many individual sources that make up the overall acoustic emissions of a operating piece of equipment. These range from operational components such as electric motors, gears or spinning shafts to more structure borne acoustic signals. Second, these structure borne acoustics are a result of the noise production of the operational components and this leads to transient vibrations which can interfere in the ability to detect the original sources clearly. As the machinery produces acoustic emissions they will interact with the surroundings in a prescribed way. The issue is that it is difficult to predict the environment acoustics as there will be reflections which are also detected whilst taking measurements. A major issue arises with the reflections as they interfere with the meaningful data, effectively causing unwanted noise in the recorded signals. This has led to skepticism that acoustic emissions can be used to detect machinery faults due to the complexity of the signals being recorded as well as the inherent issues with room acoustics.

When considering a raw acoustic recording, very little information can be gained directly from it. Data processing is used to extract the useful information from the raw signal. Techniques are readily available to transform the data into a more readable and interpretable state, such as transforming data in the time domain to the frequency domain. The particular processing technique used can be the difference between extracting a piece of useful information and not.

Indeed, for a Diesel engine in an industrial environment all of the above issues are present. The engine will have many acoustic sources when it is running. There will be sources associated with the combustion in each cylinder, sources for the cylinders moving within their liners, the crank shaft itself and all the transient surface vibration sources which will be combinations of all the other sources. There will also be sources that are unwanted, such as the reflection of acoustic emissions from walls and pipework of any industrial installation. The issue with Diesel engine noise is the amount of different sources it is made up from. To pick out pertinent features such as valves opening and closing or a combustion event there needs to be a way to separate the overall noise into the individual components it is made up from so they can be more easily identified. One such potential method for separating data is independent component analysis (ICA).

4.1 Why the FastICA Algorithm?

Signal processing techniques in the application of Diesel engine acoustic condition monitoring range from the very basic, such as those based upon statistical methods, through to advanced techniques such as blind source separation and neural networks. The more basic techniques include taking the moments of the data as demonstrated in chapter 6. The basic techniques have demonstrated little success in detecting the engine condition as demonstrated by the author [71] and his experimental cepstrum analysis of engine acoustic data.

It is common with engine acoustic monitoring to use more advanced processing techniques, and they have demonstrated good results [29, 103] in engine fault diagnosis. These techniques are based on methods applied in other avenues of research, namely speech [104], sound acoustics and image noise reduction [105] studies. Something these studies have in common, is the inherent problem they set out to solve. To observe a source signal or signals, mixed into an overall recorded signal. This is exactly what acoustic monitoring of an engine is trying to achieve, so that changes in the engines running condition can be identified in the overall recorded engine noise.

There are two main avenues that are typically investigated across the various other engine acoustic monitoring research. The first is applying event alignment to the acoustic data, this is done via a time stretch method to ensure that the data remains aligned despite changes in engine operation. Changes in engine operation, include changes in speed and load. Various takes on blind source separation are then applied, which aims to solve the overall problem of identifying the individual sources. A detailed explanation of blind source separation can be found in section 4.3. All other research currently published uses both of these methods to produce a physical output, upon which engine condition is quantified. This research aims to take the unique path of not requiring event alignment, in simple terms this means the data will not be aligned to crank angle. The benefit of not aligning the data means that the data obtained and processed in this thesis will be truly unobtrusive.

Blind source separation techniques have been around since the early 1980's and were based around solving biological problems. Independent component analysis, though not termed this at the time, is a major method of blind source separation. It was introduced by Hérault and Jutten [106], when they demonstrated experimentally that they were able to use their algorithm to converge to a linear approximation of the signal mixture. Various researchers contributed to blind source separation and chiefly ICA, a good overview was given by Jutten [107] in 2000. Despite the earlier approaches to separating blind signals, Chichocki and Unbehauen were the first to propose what is currently the most popular forms of ICA algorithms [108]. It became popular and widely adopted due to its robustness compared to other algorithms based on its concept of independence. Independent component analysis became well established and has been used in engine condition monitoring already [29, 103, 109] with success. The topic of ICA is expanded upon throughout this chapter with a good introduction in section 4.3. On the back of the current research at the time, Hyvärinen et al. proposed another form of blind source separation in the form of nonlinear principal component analysis (PCA) [110, 111].

Principal component analysis is a technique used in statistical analysis, feature extraction and data size reduction. It stemmed from the work of Pearson [112]. Given a set of multivariate data, it will find a smaller set of variables with less redundancy, that will provide as good a representation as possible. It has the same goal as ICA, but, PCA's redundancy is measured by correlations between data elements, while ICA works on the much more robust concept of independence. In ICA, there is also much less emphasis on the reduction of the number of variables given. Principle component analysis is, therefore, a good pre-processing technique in certain circumstances, something corroborated via experimental testing by Pontoppidan [113]. He demonstrated that ICA was capable of discriminating between two sources, whilst PCA was not. A requirement of PCA is that the estimated sources are orthogonal and this is why it failed to discriminate in this example. Conversely, ICA only requires the sources to be linearly independent and meant that it held a distinct advantage over the PCA. Further reading on PCA can be found in [114–117]

The non-linear PCA proposed by Hyvärinen et al. did not survive long given its shortcomings. In the mid 90's Bell and Sejnowski published their research on the Information maximisation ICA principal (INFOMAX) [118, 119]. However, INFOMAX had a shortfall in that it requires the mixing matrix to be square. This means that the number of sources must equal the number of observations. In the case of this research, that would mean having a microphone for each noise signal generated by the engine. This is not practical for engine acoustic monitoring, therefore, to use INFOMAX the dimensionality must be reduced using PCA so that the number of principal components is a lot smaller. A mathematical demonstration and experimental results of this can be found in the Ph.D thesis by Pontoppidan [29]. The INFOMAX principal was expanded on by Amari [120] using the natural gradient. This made a fundamental connection between Chichocki and Unbehauens algorithm and maximum likelihood estimation. In other words, it removed the limitation of requiring a square mixing matrix and, thus, PCA pre-processing to reduce the dimensions. A couple of years later Hyvärinen et al. presented the FastICA algorithm, which contributed to the application of ICA to large scale problems due to its computational efficiency [121, 122]. Its efficiency centres around the way the algorithm converges in a cubic fashion in comparison to other ICA algorithms which converge based on gradient descent methods, meaning a linear convergence [123]. A more recent author has also compared the performance of the INFOMAX and PCA algorithms compared to ICA and found that only ICA was able to provide the four components he was looking for [29]. This research was in relation to acoustic monitoring of large diesel engines and demonstrated that ICA was even able to separate the signatures that were independent of load from those that were dependent on load.

It is clear that ICA is a very powerful post-processing technique. It has been demonstrated by several authors to hold real experimental tangible benefits over other techniques such as INFOMAX and PCA. It has also demonstrated its applicability and usefulness in the field of acoustic condition monitoring of Diesel engines. When comparing ICA algorithms, the FastICA algorithm has shown to provide advantages over algorithms mainly on the basis of computational efficiency [121, 122]. This is an important criterion when comparing large datasets such as in this research. Additional advantages of the FastICA algorithm are the readily available Matlab software from the author of the algorithm, access to communicate with the author as well as a wealth of published papers, books and documentation on the algorithm and it is easy to use. All of which demonstrate a wide variety of uses and the widespread success in the application of signal separation across multiple disciplines.

4.2 Mathematical Foundations of ICA

This section will try and outline some of the mathematical concepts in a rudimentary manor so that any reader can understand it, but there are references to more advanced texts should they want to learn further. ICA uses the statistical properties of a signal to separate it into its component parts. At the very centre of statistics is the probability density function (PDF). The PDF is a function which describes how likely it is for a random variable to occur. Over its whole distribution the integral over its whole area is equal to one and all values are positive. For example, if we took a PDF of global mens heights and our PDF ranged from 0ft to 10ft then the PDF curve would likely peak around the 5ft or 6ft mark where statistically most males would fall and by the time the distribution reaches 10ft the integral of the distribution would be equal to 1 (No human has been more that 10ft tall).

Moments are also an important statistical concept. They represent the statistical parameters of a given function and can be applied to any function. Important parameters of a PDF can be found using moments, in fact moments can be used to rebuild a PDF. Taking a PDF, moments can be taken on the data to yield different information from the data. Moments based around the mean of the data, and not around 0, are known as the central moments and those around 0 are the raw moments. The general equation for the n^{th} raw moment of a continuous function can be described as:

$$\begin{aligned} \mu_n' &= \langle x^n \rangle \\ &= \int x^n f(x).dx. \end{aligned} \tag{4.1}$$

The moments are often taken about the mean (central moments). The central moments are denoted by μ_n and described as:

$$\begin{aligned} \mu_n &= \langle (x-\mu)^n) \rangle \\ &= \int (x-\mu)^n f(x).dx. \end{aligned} \tag{4.2}$$

Mean The mean is the sum of all the values in a distribution divided by the number of values. Based on the general equation and with $\mu_1 = 0$ it can be expressed in the following way:

$$f = \int_{-\infty}^{\infty} f(x).dx. \tag{4.3}$$

Variance Is the second central moment. It is the measurement of how far the data is spread out from each other, it allows the calculation of how far the data lies from the mean. Taking the square root of the variance, the standard deviation which is the second raw moment can be found. They are expressed as follows:

$$\begin{aligned} \mu_2 = & \quad \sigma^2 \\ f = & \int_{-\infty}^{\infty} x f(x).dx. \end{aligned} \tag{4.4}$$

Where $\sigma = \sqrt{\mu_2}$ is the standard deviation.

Skewness Is the third central moment. Is the measurement of how skewed the data is, taking the perfect PDF bell curve, it is the measurement of how much to the left or right this lies. Therefore, for a perfectly symmetrical bell shaped distribution the skewness would be equal to 0. Skewness can be descried in the following way:

$$f = \int_{-\infty}^{\infty} x^2 f(x).dx. \tag{4.5}$$

Kurtosis Is the fourth central moment. It measures how narrow and tall or broad and short the distribution is compared to the normal distribution of the same variance. In ICA, the fourth moment is used not the fourth central moment as it has some useful properties that the raw moment does not. The biggest benefit is that it can indicate the non-Gaussianity of a random variable. If the variable is of gaussian distribution then Kurtosis will equal zero where the fourth moment would not equal zero.

Gaussian and non-Gaussian are frequently used terms. A Gaussian distribution is also better known as a normal distribution. The normal distribution's associated PDF is a classical bell shape. It is one of few distributions whose cumulants beyond the first two moments are equal zero. Therefore, for statistical data which may have significant independence, the normal distribution is not robust enough to deal with 'outliners', which are data that falls far from the mean. A typical example if a non-gaussian distribution would be white noise, which is a random signal with a consistent power spectral density. As it has equal power at any frequency, this would be represented as a flat line if plotted.

The important point to realise about PDFs and moments is that if all the relevant moments are known then the distribution can be rebuilt. For example, a Gaussian distributions moments from the third moment onwards are zero. Therefore, if the mean and variance are known then the distribution can be recreated. ICA is somewhat similar, it is heavily reliant on the higher order moments to distinguish the non-Gaussianity, but if these moments are known then the distribution can be recreated.

There are other techniques that manipulate the data to a more usable format in addition to the moments. Fourier transformation is one such technique that decomposes a signal into its constituent frequencies. For a recording from a Diesel engine this would allow the event frequencies to be picked out, an example of which can be seen in figure 1.4, chapter 1. The Fourier Transform can be expressed as shown in equation 4.6.

$$F(f) = \int_{-\infty}^{\infty} f(t)e^{-ift}dt \tag{4.6}$$

This form, in terms of frequency is much more useful than that of time as so much of the generation and the response is dependent on the frequency of the wave. However, 4.6 is an ideal function that has its limitations in real life applications. For example, when sound is recorded it will not have a continuous function or a full history from $-\infty$ to ∞. Therefore, two issues exist, the need to sample over a finite period of time and data sampling. The Fourier Transform is rewritten into a discrete version to take into account the finite time period. Now that there is only a finite period for the signal the frequency is now a discrete function instead of a continuous one. Therefore, the angular frequency becomes:

$$\omega \rightarrow k\omega_0 \tag{4.7}$$

Where k is an integer and ω_0 is the fundamental angular frequency, $2pi/NT_s$. The time is also discrete and, thus, becomes:

$$t \rightarrow nT_s \tag{4.8}$$

The integral is now a sum, so the discrete Fourier Transform is defined as:

$$DFT(k) = \sum_{0}^{N} f_n e^{-ik\omega_0 nT} \tag{4.9}$$

The Matlab code used within this research returns the discrete Fourier transform (DFT) for the data that is input which is discussed further in section 6.1.1.

Something these processing techniques have in common is that they all transform the data into a more relevant view for the work at hand. ICA, is different to this in so much that it is not transforming the data but analysing it and based upon this analysis it separates the data into what it considers to be the independent components that have combined together to produce the data set recorded.

4.3 Introduction to ICA

ICA is a method used to identify statistically independent and non-gaussian components that make up multidimensional statistical data such as acoustical recordings. The following section will set out to introduce the concept of ICA and how it can be applied and some of the issues involved.

In a simple demonstration, a scenario is presented which consists of three signals emitted by objects or people such as radio waves, mobile phone radiation, brain signals or speech. There are three observation points all at separate independent locations. The observation points record the sum of the signals in the space as time signals which are typically labelled $x_1(t)$, $x_2(t)$ ... $x_n(t)$. Each of the recorded signals will be a weighted sum of the signals which are labelled $s_1(t)$, $s_2(t)$ ... $s_n(t)$. Figure 4.1 shows three independent sources, their signal emissions and then being

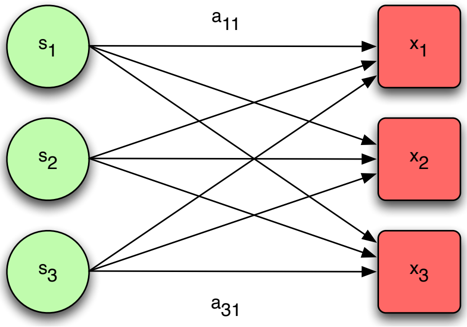

Figure 4.1: BSS Problem with Three Sources

received at the three observation points. It is, therefore, easy to see that the mixture of the three signals at each of the three observation points will be different. In a physical context the sources $(s_i j)$ could each be a human being talking. The observation points $(x_i j)$ could be recording microphones. In this example microphone x_1 will have a heavier weighting to source s_1 which is closer to it than source s_3. The reverse could be said of microphone x_3, this shows how each microphone would record the three sources in a different way. The problem then exists on how the original signals can be separated into their original form. In terms of the physical example, the recording would sound like three people speaking at the same time and it would be very hard to distinguish what any one person was saying. If the sources could be separated, then three individual speeches would be left over clearly identifiable and a replica of the original. This is the basis of the popular 'cocktail party' problem.

Figure 4.1 can be explained with a simple set of equations (Equation 4.10) which show the sum of the mixed signals for each of the observation points.

$$\begin{aligned} x_1(t) &= a_{11}s_1 + a_{12}s_2 + a_{13}s_3 \\ x_2(t) &= a_{21}s_1 + a_{22}s_2 + a_{23}s_3 \\ x_3(t) &= a_{31}s_1 + a_{32}s_2 + a_{33}s_3 \end{aligned} \tag{4.10}$$

Where a_{ij} are the component distances of the microphones from the sources.

The problem, therefore, requires the estimation of s_1, s_2 and s_3 using only the recorded signals from the observation points x_1, x_2 and x_3. Time delays or other factors such as reverberation are neglected. If the mixing parameters, a_{ij}, were known then the problem could be solved via traditional methods, however, a_{ij} is not known which makes the problem more difficult. Jutten and Herault's [124] solution was to assume statistical independence of the original signals, therefore, independent component analysis makes the assumption that the mixing parameters, a_{ij}, are sufficiently different enough to make the matrix that they form invertible [121]. There is, therefore, a matrix W with coefficients w_{ij} [125], equation 4.10 can, therefore, be rewritten as:

$$\begin{aligned} s_1(t) &= w_{11}x_1(t) + w_{12}x_2(t) + w_{13}x_3(t) \\ s_2(t) &= w_{21}x_1(t) + w_{22}x_2(t) + w_{23}x_3(t) \\ s_3(t) &= w_{31}x_1(t) + w_{32}x_2(t) + w_{33}x_3(t) \end{aligned} \tag{4.11}$$

Hyvärinen et al [121] used very general statistical properties to estimate matrix W so that the sources could be estimated by their FastICA algorithm program. The algorithm program was freely available on their research website when this thesis was published in 2011 [126]. Their solution was to compare the statistical independence of the signals. They found that non-gaussianity in itself proved enough to determine the w_{ij} coefficients, therefore, rewriting equation 4.11:

$$\begin{aligned} y_1(t) &= w_{11}x_1 + w_{12}x_2 + w_{13}x_3 \\ y_2(t) &= w_{21}x_1 + w_{22}x_2 + w_{23}x_3 \\ y_3(t) &= w_{31}x_1 + w_{32}x_2 + w_{33}x_3 \end{aligned} \tag{4.12}$$

The original sources, $s_1 - s_3$ are found if $y_1 - y_3$ in equation 4.12 are independent. Figure 4.2 provides a flow diagram that shows the entire process from source signals to the mixing and returning back to the separated signals.

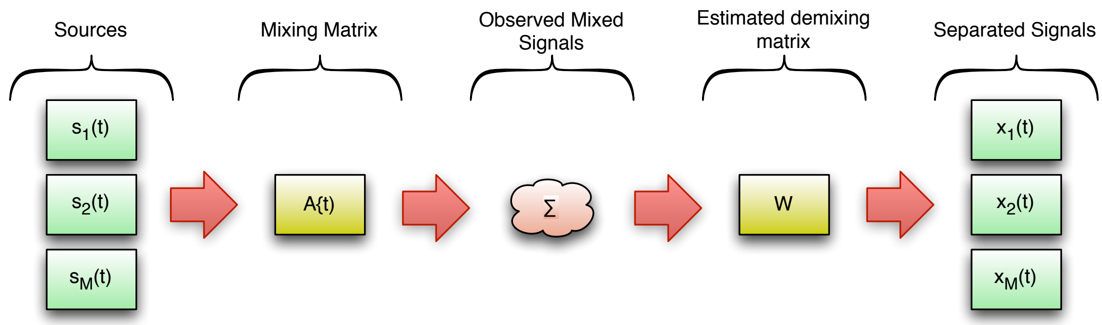

Figure 4.2: BSS Flow Diagram

4.4 How the FastICA Program Works

Figure 4.2 has given a simplistic overview of what occurs from start to finish in a problem utilising ICA. Section 4.3 has already described the first half of the process flow in figure 4.2. It has shown how it relates both mathematically and physically. However, it did not explain what happens between the observed mixed signals and the separated signals. When the observed mixed signals are presented to the FastICA program, it checks to ensure the data is mixed and that it has more than two dimensions. The program will then put a message that it has removed the mean, in fact the data has been centred which sets the mean to zero. The mean is effectively removed from the post processing process as it does not contribute to the overall processing, in fact it is a hinderance as it is typically several magnitudes larger than the fluctuations and will consume a lot of storage during processing. Therefore, the mean is removed prior to processing and added back after. The program then checks against a list of settings which can be modified. The settings allow for a few variations in how the algorithm runs. The data within this thesis was processed using the default settings which has been validated in other research successfully [127]. This research compared ICA, in particular FastICA's performance in extracting a component of auditory events and was found to produce results with lower signal to noise ration than difference wave and optimal digital filtering. The standard settings can be seen in 4.1. Other examples of ICA's success can be seen in section 1.6.

The settings were varied with the simulated data shown within this chapter and it was found that it did not change the outputs from the program in anyway. The various parameters are discussed in more detail in the program authors book [121]. Following the settings the program then proceeds in one of two ways. If whiten-

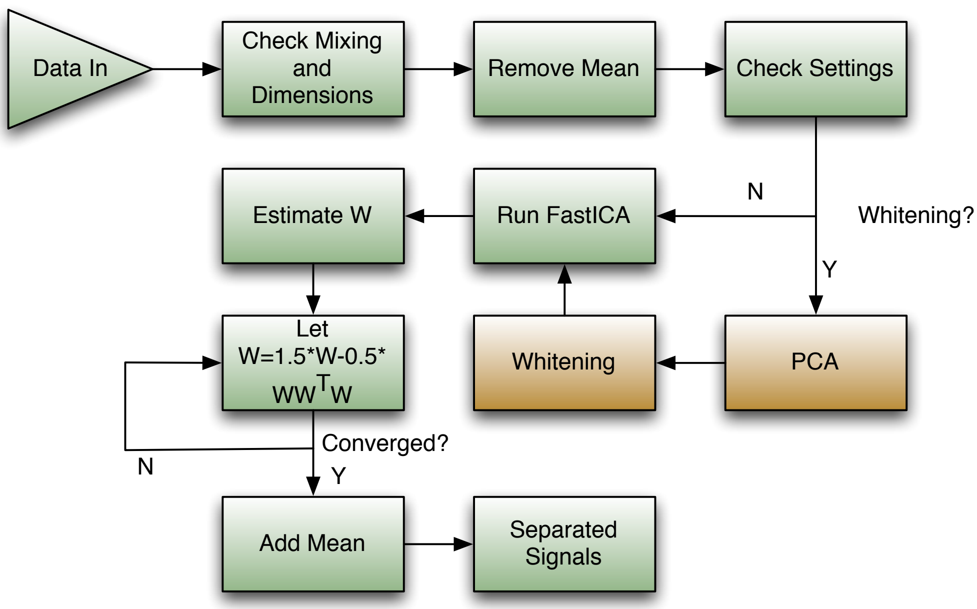

Figure 4.3: FastICA Program Flow

Option	Standard Setting
Approach	Deflation
Nonlinearity(g)	Pow3
Stabilisation	Off
Initial State	Random
Display Mode	Signals

Table 4.1: Standard Settings for the FastICA Algorithm

ing has been requested, principle component analysis (PCA) is run on the data to convert a set of data that maybe correlated and makes it into uncorrelated variables known as principle components. Prior to PCA the data needs to be whitened. Whitening is a transformation that aids de-correlation by converting the covariance matrix which essentially creates a new matrix with random variables with the same variance as the original variables. Following on from whitening, the Fixed-point algorithm is run (If no whitening is requested then this would have run at the point of PCA). The algorithm runs and carries out iterations until it converges to a point where the coefficients of the transfer matrix is within 10^{-6} of the previous coefficient. This is the point at which the transfer matrix is as least random as possible. Hyvärinen [121] has shown that the FastICA algorithm converges much faster than other algorithms as it does so in a cubic fashion, not linearly. This conclusion was also realised by Giannakopoulos, who found it to be 10-100 times faster [122] than other algorithms. He showed that it typically converges after 5-20 iterations. However, the program has a maximum default of 1000 iterations beyond which it makes more sense in terms of time to simply restart the process. When the data has converged, the mean is added back to the data and the output independent sources are presented. The whole process has been simplified in figure 4.3

4.5 Numerical Example of ICA

Using the FastICA program that has been outlined above, six signals were generated to provide an example of the inputs and outputs to the program. The signals generated were created in Matlab and, therefore, are not subject to time delays, reverberation or noise. The signals can be seen in figure 4.4, these are the source signals. For the purpose of this example these are six sources that have been emitted at six various locations in space. The signals are then observed at six points where they have mixed with each other in transit to the observation point as demonstrated in equation 4.10. Each signal will be a weighted sum of the source signals dependent on their mixing matrix $A(t)$, which in this case was a randomly generated $6x6$ matrix. The mixed observed signals can be seen in figure 4.5 This is where the purpose of

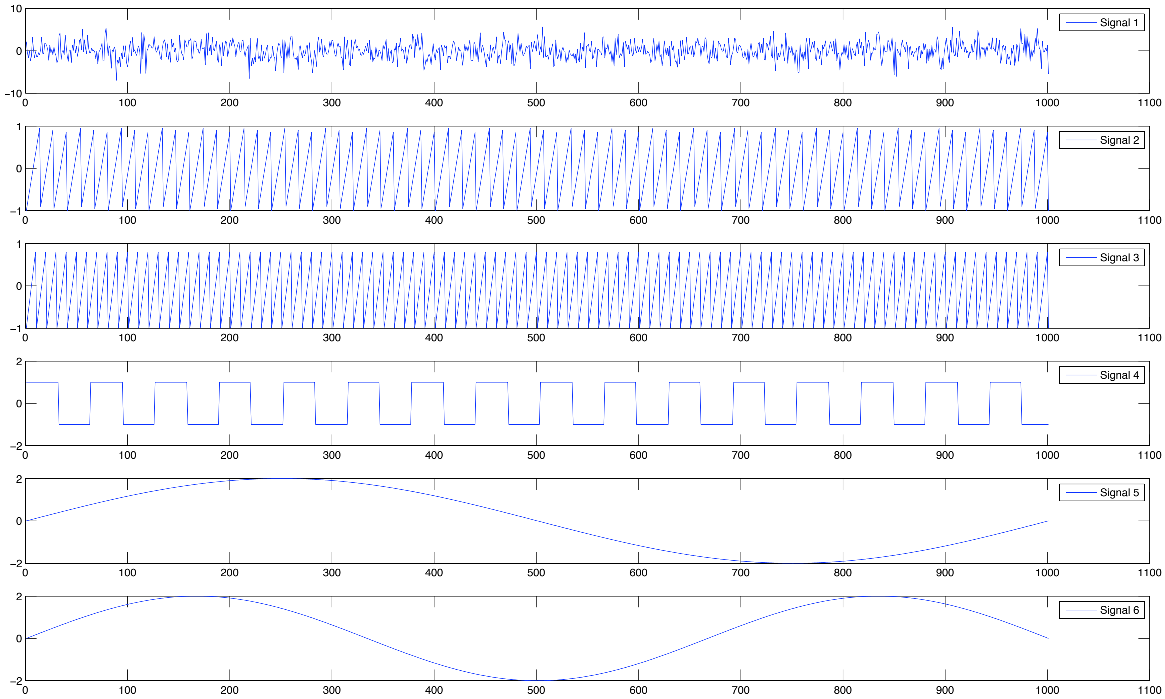

Figure 4.4: Source Signals

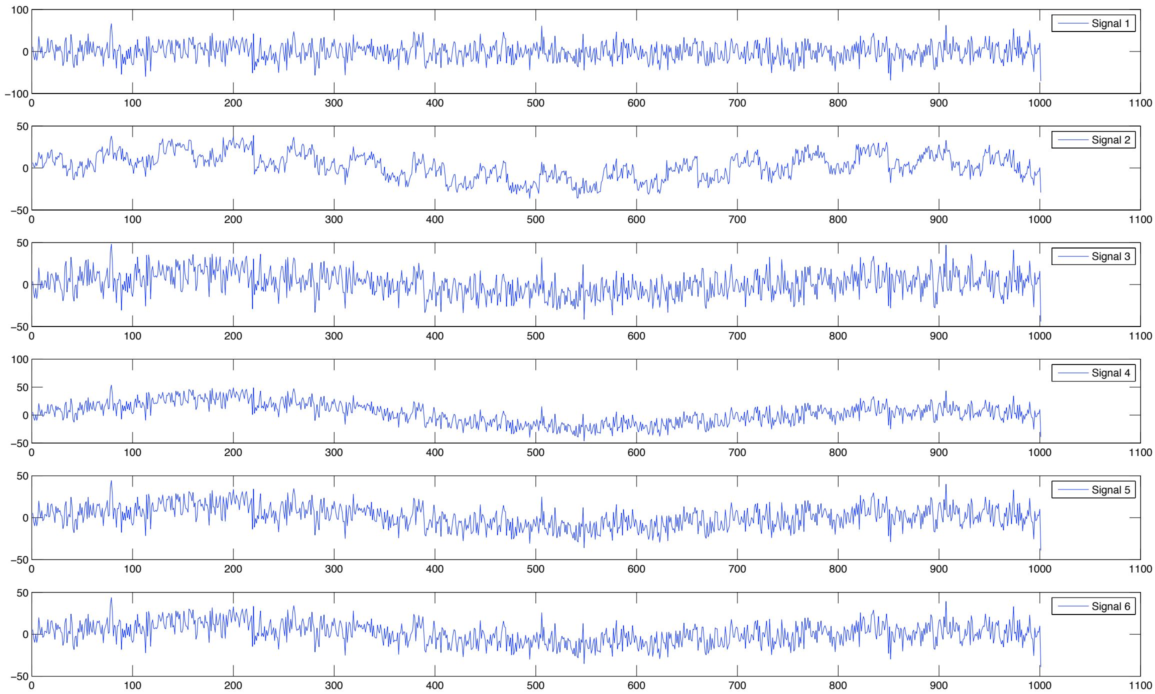

Figure 4.5: Observed Mixed Signals

ICA comes in, these signals are the observed signals, and the source signals are required for a particular purpose. There is no information within the mixed signal to explain how they were mixed and, therefore, there appears to be no easy way to return to the source signals. With the assumption that they are all independent from one another the FastICA algorithm [121] estimates the mixing matrix to maximise

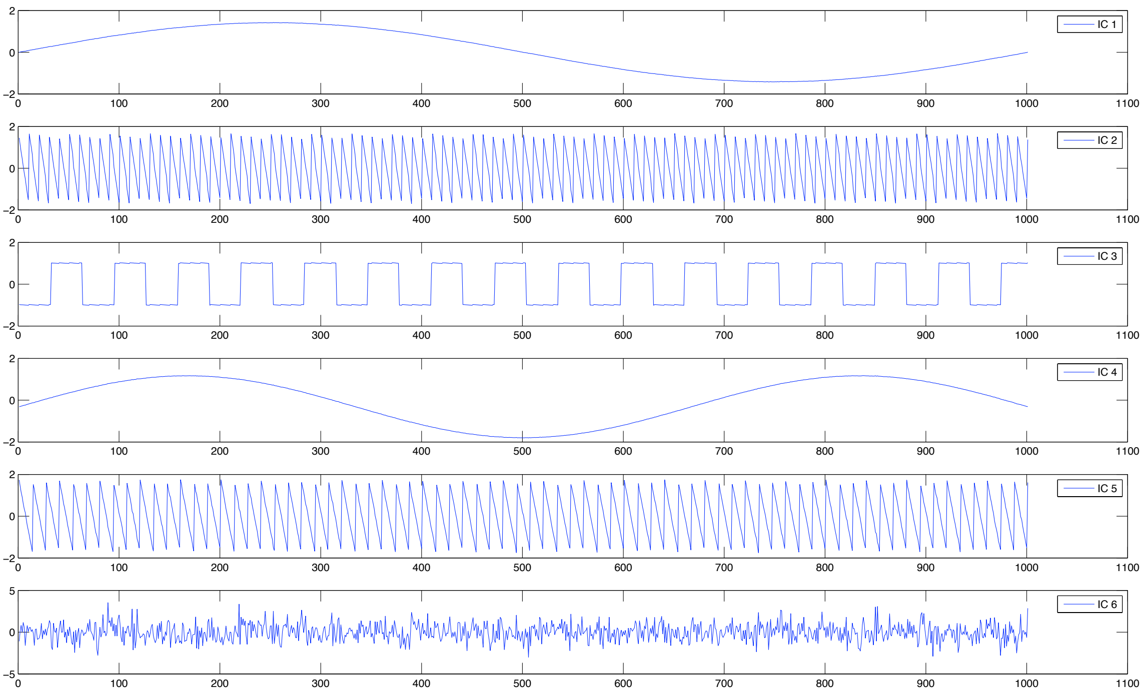

Figure 4.6: ICA Output

the non-gaussianity and then proceeds to run on the data until the data converges to a determined level of non-gaussianity. The output can be seen in figure 4.6. The output is clearly made up of the original source signals, though there are a few differences between the original sources and the processed independent components. First, the amplitude has been normalised, secondly some of the signals have reversed direction. This demonstrates some of the restrictions in ICA which will be further discussed in section 4.6.1, despite these restrictions this practical example shows that ICA is indeed able to separate signals that have been mixed via a random mixing matrix.

This section has presented an example of independent component analysis in the simplest terms. Clearly, in real world situations there will be noise which adds extra complexity to the ICA model. Although there are ICA methods proposed by Hyvärinen in his research [121] it is not recommended that this method is used, instead the signals should have the noise reduced or removed prior to being passed through the ICA algorithm. There are other issues associated with independent component analysis that must be considered when applying the technique to machinery condition monitoring, again these will be discussed in section 4.6.

4.6 ICA Issues

Independent component analysis faces a few issues in that several assumptions have been made in the model, these include, assumption of statistical independence, requirement for non-gaussian distributions and assumption that the mixing matrix is square. These restrictions and indeed the ambiguities involved with ICA are discussed in the following sections

4.6.1 ICA Restrictions

As mentioned above, there are certain assumptions that must be made for the ICA model to work:

1. **The independent components are assumed statistically independent.** The assumption of independence is the main crux of ICA, it is really the only thing that is needed for ICA to be able to estimate the mixing matrix and thus work correctly, which is why ICA is applicable to so many different areas. Statistical independence can be defined simply by two events A and B (probability densities) that are independent if and only if:

$$P(A \cap B) = P(A)P(B) \tag{4.13}$$

Therefore, in terms of the ICA problem, where independent signals would be seen as two separate independent events such as equation 4.13, y_i is, therefore, independent if and only if the following is true:

$$P(y_1, y_2, ..., y_n) = P(y_1)P(y_2)...P_n(y_n) \tag{4.14}$$

2. **The independent components must have *nongaussian* distributions.** ICA is not possible with gaussian distributions as the higher order cumulants are equal to zero, this higher order information is required for the ICA model to

be successful. Whitening is the best example of why this is the case. As described previously whitening is the transformation of the observed vector into a new vector whose components are uncorrelated and have variances equal unity [128]. When the assumption is made that the joint distribution of two independent components, s_1 and s_2, is gaussian, the joint PDF can be described as:

$$P(s_1, s_2) = \frac{1}{2\pi} exp(-\frac{{s_1}^2 + {s_2}^2}{2}) = \frac{1}{2\pi} exp(-\frac{||s||^2}{2}) \tag{4.15}$$

Assuming the data is whitened and thus has an orthogonal mixing matrix **A**. The PDF can be transformed using:

$$p_z(z) = \frac{p_x(f^{-1}(z))}{|f'(f^{-1}(z))|} \tag{4.16}$$

Where $A^{-1} = A^T$ holds true for an orthogonal matrix, the joint density of the mixed signals x_1 and x_2 is:

$$P(x_1, x_2) = \frac{1}{2\pi} exp(-\frac{||A^T x||^2}{2})|detA^T| \tag{4.17}$$

Now $||A^T x||^2 = ||x||^2$ and $|detA| = 1$ because of the orthogonality of **A**, and if **A** is orthogonal, as well as A^T. Therefore:

$$P(x_1, x_2) = \frac{1}{2\pi} exp(-\frac{||x||^2}{2}) \tag{4.18}$$

Equation 4.18 shows that the orthogonal mixing matrix does not change the PDF. The original (equation 4.16) and mixed distributions (equation 4.18) are exactly the same and hence there is no way that the mixing matrix could be estimated from the mixtures. Hence, if the distributions are gaussian then there is now way of estimating the mixing matrix to return to the original source signals.

3. **Assume that the unknown mixing matrix is square.** The assumption is made that the number of observed signals is the same as the number of IC's. This assumption makes the estimation process much simpler. Therefore, once the matrix **A** has been estimated it can be inverted (as discussed in section 4.3) to **B** and the IC's can be given by:

$$s = Bx \tag{4.19}$$

There is also an additional assumption that the mixing matrix is invertible, if it is not then there would be redundant mixtures and, therefore, some will be left out as the number of mixtures would not equal the number of independent components.

4.6.2 Ambiguities of ICA

It is important to realise that the ICA model has some ambiguities:

1. **The variance of the independent components is lost.** The mixing model can be expressed in the following ways:

$$x = As \tag{4.20}$$

The original source signal **s** and the mixing matrix **A** are unknown. Therefore, if there was a scalar multiplier in one of the sources s_i then this could be cancelled by dividing the corresponding column a_i of **A** by the same scalar.

$$x = \sum_{i=1}^{n} a_i s_i \tag{4.21}$$

$$x = \Sigma(\frac{1}{\alpha_i}a_i)(s_i\alpha_i) \tag{4.22}$$

The ICA model fixes the magnitudes of the independent components. It does this by assuming that each has unit variance: $E\{s_i^2\} = 1$. By fixing the magnitude the amplitudes of the resultant output signals are lost, this can be seen in figure 4.6 where the amplitudes have been fixed in comparison to the input signals in figure 4.4.

2. **Order of IC's cannot be determined.** As **s** and **A** are not known the order of the terms in equation 4.21 can be changed thus meaning any of the IC's could be identified as the primary one. Due to the permutations that are potentially possible, a permutation model is substituted into equation 4.20 giving $x = AP^{-1}Ps$. Ps is the original source signals in different orders and AP^{-1} is a new unknown mixing matrix that will be solved by the ICA. Practical examples of this issue have been presented in figures 4.4 and 4.6.

3. **Varying Numbers of Sources & Microphones.** It has already been demonstrated that the ICA works well when the number of sources and the number of independent components is the same. There are two other possible situations, however, that is more sources than microphones and more microphones than sources. When there are more microphones, the model will believe there are more mixed signal inputs than there are actual independent components. This presents some serious issues when the algorithm is run as the matrix dimensions will not be the same. The program uses PCA to reduce the matrix size until it matches the number of independent components, making the matrix square once again. The PCA does present the risk of loosing independent components in the process. This should not impact any research due to there always being numerous sources from what is being measured as well as from the surroundings. Therefore, this research will not suffer this issue, indeed, it will suffer the opposite. That is where there are far more independent components than there are microphones. This will have an effect on the ICA output,

it is not as catastrophic as having more mixed signals than independent components though. A simple example was created and run through the FastICA program and is discussed below. Figure 4.7 shows four source signals that

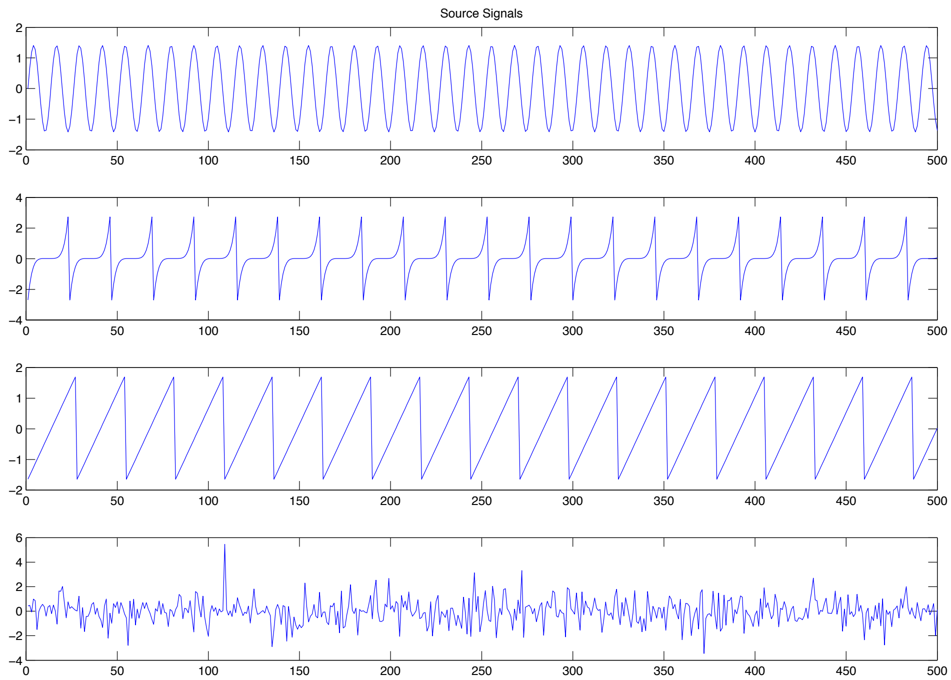

Figure 4.7: Source Signals

were created in Matlab were processed through the ICA algorithm. These specific signals have been chosen for specific reasons. The first signal, the sinusoidal wave is continual, the values are smooth and consistent throughout the waveform. The second and third waveforms are discontinuous in that they contain rapid and sudden changes in values and the fourth is completely random. The reason why these waveforms were chosen will become clear when they are separated.

The signals were mixed using a generic and random mixing matrix which does not represent any physical sources or dimensions. The signals were mixed so that the simulation equated to the system having three microphones observing the space for signals. This means there are three mixed signals which are shown in figure 4.8. These signals demonstrate how the microphones would perceive the signals. There is little resemblance to the source signals in the

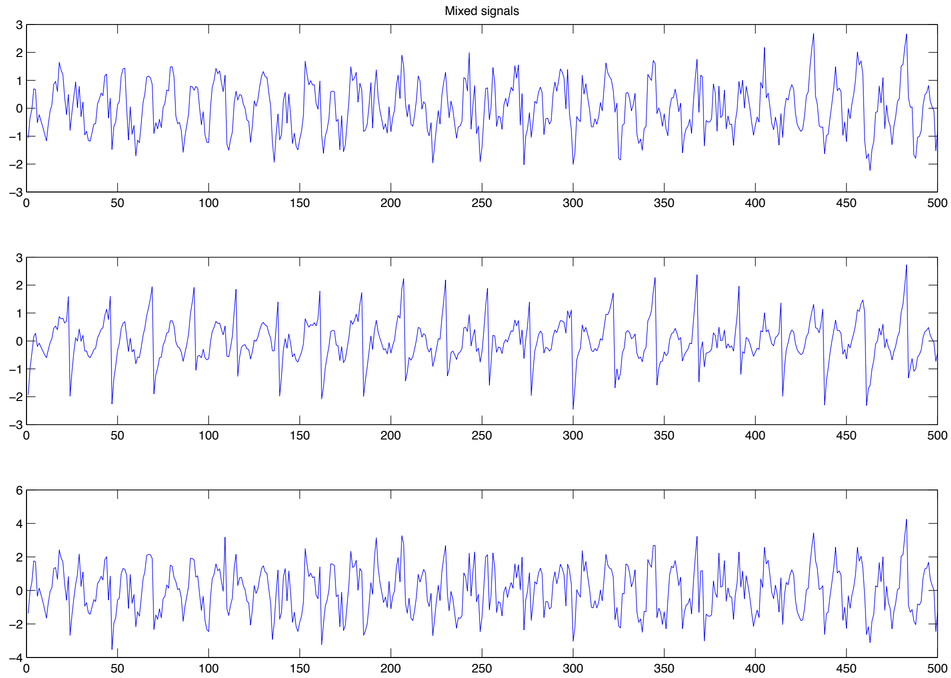

Figure 4.8: Mixed Signals

mixed signals. Separating the signals through the FastICA algorithm separates the signals into figure 4.9. The separated signals provide some interesting conclusions on how the program handles more sources than microphones.

In figure 4.9, the top signal clearly represents the second signal from the original sources, the second signal the third from the sources and third and final signal appears to represent the sinusoidal wave from the original sources. The fourth and final signal from the sources, the random signal has not been presented. However, the random signal is the most gaussian and therefore it is the signal that the algorithm gets furthest from predicting. As a result of this, the fourth most gaussian signal is mixed in with each of the three output signals. This is further corroborated when the effects of the random signal are observed on the three outputs. The discontinuous signals have had less of an impact from the random signal than the sinusoidal wave. This is because the discontinuous signals are really independent and, therefore, do not get as distorted with the random signal as the sinusoidal waveform. A final observation, it is demonstrated again that the inputs and output order from the algorithm are different which was highlighted in 4.6.2 item two.

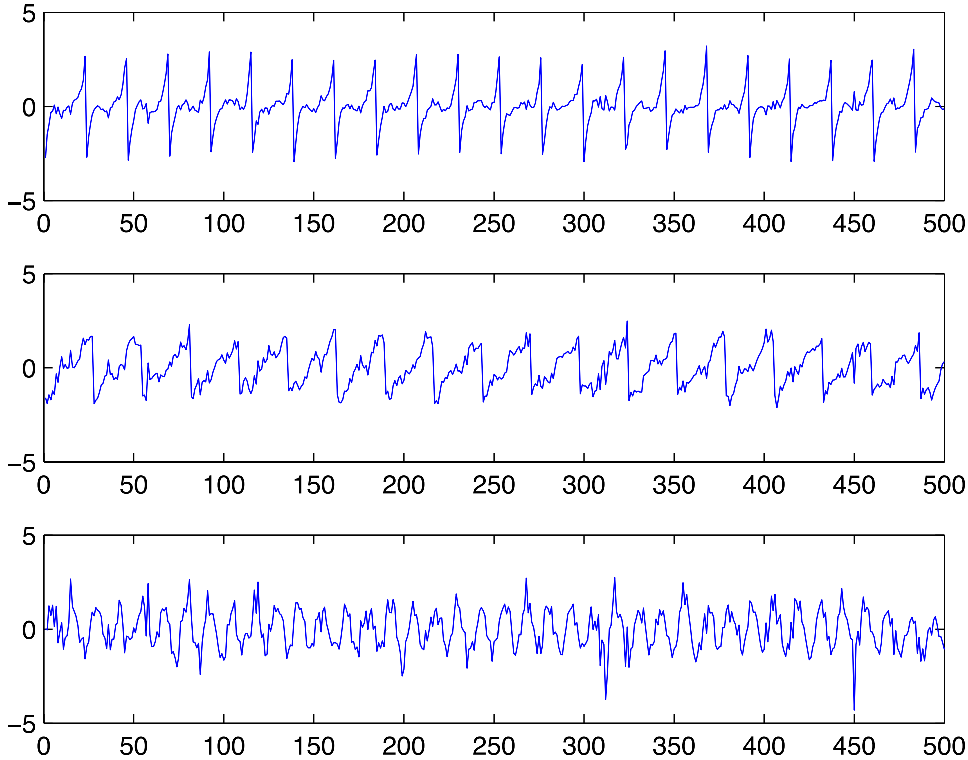

Figure 4.9: Seperated Signals

4.7 Summary

This chapter has shown the application of ICA and how it relates physically as well as mathematically to help the reader gain an overview of the principles of ICA. Whilst providing the background information on the principles of ICA and indeed the FastICA algorithm, the most important parts of this chapter have been the practical examples using the FastICA algorithm. Independent component analysis and the FastICA algorithm have demonstrated the ability within this chapter to separate mixed signals into their original components. This has a huge potential in engine acoustic monitoring where the observed signals are a combination of many source signals. One of the biggest concerns about using the algorithm was how it would handle more sources than mixed observed signals. This chapter has demonstrated a simulated trial of this situation and the results are encouraging. It should not be forgotten that the examples presented here are very simple simulations, the recorded data from a running engine will be much more complex.

4.8 Conclusions

There are range of important conclusions that can be drawn from this chapter. Some issues have been presented such as the loss of variance and the output order of the independent components. These are more caveats than anything else. For example, the loss of variance is not an issue as it is all relative between the datasets. Trials were run to see how this changed on the same data run through the FastICA program many times. The variance was the same each time. The variation again is not an issue, it really only provides issues when coding the detection program. The code will need to be more intelligent to detect matching components instead of simply reading the output data matrix the same as the input. Indeed, the single biggest issue raised is the question of how the FastICA program will cope when there are varying numbers of sources in comparison to microphones.

If there are more microphones than sources then the matrix will become singular and the FastICA algorithm will struggle to work. It will utilise PCA to balance the matrix but this carries the risk of loosing independent components. However, this will not occur in practice due to interactions of the acoustic signals with the environment and how these reflect and reverberate back to the microphones. The opposite issue is the most likely outcome, where there are more sources than microphones. This has been investigated and the results show that the output signals are affected particularly by gaussian (random) signals. It was also discovered that the more singular (independent) the signal is, the more likely the ICA is to separate the signal and it to be least affected by gaussian signals. On this basis, it would be expected that with ICA processing the separation of events between individual cylinders should be possible. To what extent the ICA will benefit the detection of engine faults is unknown and is the main question that will be answered in later chapters.

The following chapter will present the experimental work that was carried out throughout this research. It will show the vast amounts of work that went into preparing the test facilities and how they were setup. It will also show how the various faults were seeded. This chapter will lay the main foundations for the data collection to allow accurate post processing.

Part III

Experimental Work

Chapter 5

Experimental Test Rigs

5.1 Introduction

The main practical focus of the research is accurate data collection followed by post processing the data with ICA, as presented in chapters 1 and 4. The post processing will look at how it can be used to better aid detection and diagnosis of faults on Diesel engines especially large engines. A major part of this research work was, therefore, experimental and this chapter outlines the steps taken to ensure fair, accurate and appropriate experimentation was carried out to aid data collection for the ICA post processing.

5.2 Test Rig Objectives

Experimental facilities for condition monitoring are an important way in which to seed faults in machinery of known and quantifiable seriousness. It also allows for the investigation and measurement of these faults in a safe and instrumented environment. The nature of this research required that there be two test rig facilities, a small and a large Diesel engine. The small rig allowed the author to run test simulations with known fault conditions before moving to a large Diesel engine that requires a large amount of fuel and man power to run.

Both of the experimental rigs were situated to allow easy access to areas that could be modified to induce a common fault or faults that maybe found in a Diesel engine in an industrial environment. These experimental rigs will allow the faults to be seeded and appropriate measurements to be taken to allow use of the described post processing techniques to evaluate their applicability to condition monitoring.

There are a number of objectives that needed to be fulfilled by the experimental rig facilities:

- **First objective**, the rig needs to be applicable to the sponsoring company. In this case a large Diesel engine is applicable.
- **Second objective**, the rigs must be able to seed injection and valves issues.
- **Third objective**, to allow acoustical data to be recorded as well as other experimental data that shows system behaviour as a result of system change.
- **Fourth objective**, to provide sufficient experimental data both baseline and with faults seeded to allow sufficient testing of the post processing techniques.

The research consisted of many engine rigs across the sponsoring companies client sites but with two main experimental rigs being used at the University of Manchester. The following sections detail the specifications of the experimental rigs and the instrumentation used on both.

5.3 Instrumentation

The major advantage of experimental work carried out within a laboratory is that the engine test rigs can be fully instrumented. This not only allows measurement of the outputs the researcher is interested in but he or she can also measure the effects seeded faults have upon the engine operating conditions.

Factors such as temperature and humidity are not factors which affect the ICA processing as the original source and its propagation process are not known. The ICA is not affected by how the waveform has propagated, and as discussed in section 4.6.2, one of the ambiguities of the ICA is that the variance of the independent components is lost. An arbitrary scalar multiplier is applied which means it does not matter how the waveform has propagated. The experiments for both engines were carried out in an environment with consistent conditions such as the dimensions of room closed lab doors, no additional physical equipment within the room and consistent microphone positioning. As certain environmental conditions such as room temperature, humidity and air pressure do not affect the data quality, they were not recorded. The data presented in this work is from data with like for like conditions. However, data was also collected when there were small variations in some of the physical conditions within the room. This includes open lab doors and additional equipment added to the room. When comparing this data to the data from the controlled environment the data was unaffected, showing the robustness of this technique.

This section covers the instrumentation used on the test engines giving both a brief overview of the technology and justifying why the sensors have been used on the test engines.

5.3.1 Microphones

This research is ultimately about the acoustic condition monitoring of Diesel engines, therefore, microphones are the fundamental sensor required for this research. Microphones have been around for decades, they are acoustic transducers that sense the changing pressure waves in the air and convert this to a changing electrical signal. This signal can then be amplified and played back through speakers for the likes of music concerts or the signal can be collected and analysed possibly revealing the subtle onset of a machine fault.

Brüel & Kjaer (B&K) are a well known microphone manufacturer that provides superb quality microphones for the academic and industrial community. The tests were completed using the B&K 4135 externally polarised free-field condenser microphones for accurate acoustic measurement. It is an excellent choice of microphone for this application as it has a high resistance to humidity and a wide range of temperatures.

The 4135's have an upper frequency limit of 100kHz which is well above the level that would need to be detected (5-10kHz), where they are consistently sensitive between 10Hz and 5kHz. Below 10Hz and greater than 5kHz the sensitivity is not as consistent [129] though above 5kHz the reduced sensitivity is far less than that of below 10Hz and is still suitable for testing up to 100kHz. This particular microphone also has a maximum operating noise level of over 170dB which again, far exceeds the noise they will be subjected to.

5.3.2 Microphone Preamplifiers

The microphones were used in conjunction with quarter-inch field effect transistor preamplifiers. Microphone preamplifiers are used to amplify the voltage produced in a microphone to a more usable level. This is required as the microphones have a very small capacitance as do even very short cables. Therefore, without amplification the signal would be severely affected at the data recorder end. This is especially important in this case as the capacitive load issue is worse with very small condenser microphones than it is with larger ones and can cause potential issues with the collected data such as lower dynamic range and higher distortion. There is even the risk of damaging the microphone due to capacitance discharge which can cause the diaphragm to rupture [130].

2618 Preamplifier

The type 2618 preamplifier unit was used in conjunction with each of the 4135 microphones. Each was powered by a B&K 2807 power supply unit. The specifications of the 2618 can be seen in table 5.2.

The low input capacitance and its high input resistance give the 2618 a very

Frequency Response Characteristic	Free-Field and Random
Open Circuit Frequency Response (±2dB)	4Hz to 100kHz
Open Circuit Sensitivity mV/Pa	4
Lower Limiting Frequency, -3dB	0.3-3Hz
Resonance Frequency	100kHz
Polarised Cartridge Capacitance at 250°Hz	6.4pF
Influence of Static Pressure at 250Hz (dB/mbar)	-0.0007
Influence of 1m/s^2 Axial Vibration (dB re.20μPa)	59

Table 5.1: Brüel & Kjaer Type 4135 1/4" Microphone Specifications

Gain	-20dB, 0, +20dB±0.2dB
Input Resistance	Approx. 100GΩ at 20°C > 500MΩ at 100°C
Input Capacitance	< 0.4pF
Frequency Range	2Hz-200kHz
Output Voltage and Current	Max. 3V RMS (sin) 15mA peak
Output Impedance	< 50Ω
Noise (0dB gain)	(20Hz-200kHz), after 3 to 4 minutes <70μV with 6pF across input and <120μV with 3pF across input
Supply Voltages	120V, 12.6V
Temperature Range	-20°C to +100°C

Table 5.2: Brüel & Kjaer Type 2618 Preamplifier Specifications

small loss of voltage, some 0.6dB when used with the 4135 microphones.

The 2618 has a very low output impedance which allows the use of longer cables which has obvious benefits during testing. They also have adjustable gain which allows the signal to be conditioned for use over the longer cables [130]. The 4135 microphones screw directly into the preamplifiers field effect transistor input housing as shown in figure 5.1. At the opposite end of the cable from the microphone connection is the booster amplifier which is used for driving long cables [130]. It has a selectable Gain of +20, 0 and -20dB.

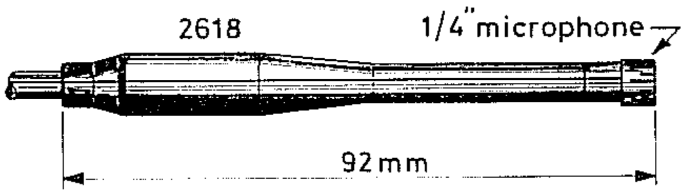

Figure 5.1: Preamplifier with a 4135 Microphone [130]

5.3.3 Dynamic Pressure Sensor

On both test engines cylinder one head unit has been modified to contain a Kistler pressure sensor, model number 6125A which meets all the necessary criterion for the conditions it will be subjected too. The sponsoring company will not have the ability to use such a sensor in the field as it is intrusive. It is purely for experimental work as it allows the effects of valve and injector issues to be identified in terms of combustion parameters as well as ensuring that the IAS data being collected is accurately aligned with TDC. This data will be used by another researcher who was carrying out a separate investigation. The sensor will also allow the operator to operate the engine safely when faults have been introduced to the cylinder.

The sensor works when pressure acts on its surface which is a diaphragm, pressure acting on it causes it to deflect and a voltage is induced. This voltage can then be equated to a pressure value. Table 5.3 summarises the specification of this sensor.

Parameter	**Value**
Pressure Range	0-25MPa
Sensitivity	-15.8 pC
Linear error	±0.2 FSO
Temperature Range	-50° up to + 350°

Table 5.3: Specifications for Kistler 6125A pressure sensor

5.3.4 Temperature Measurement

Both experimental engines are equipped with temperature measuring equipment. These readings, like the pressure readings are of little importance for the acoustic research, but are necessary for the safe operation and validation of setting changes in the engine. A thermocouple is a sensor made up of two or more junctions between dissimilar metals. Due to the contact potential between them, a change in temperature will affect this potential, this can be read and calibrated to represent a temperature to the operator. There are many types of thermocouple, each has slightly different properties and hence different voltage outputs for various temperatures.

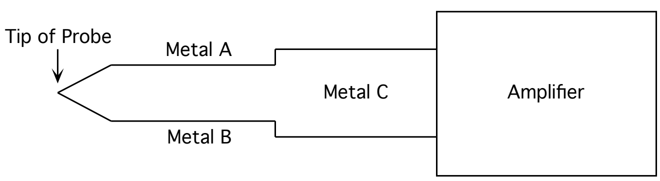

Figure 5.2: Thermocouple With Cold Junction Compensation

Both engine rigs utilise K-type thermocouples. The K-type thermocouple gives a more than adequate temperature range for use anywhere on the rig, including for measurement of exhaust gases, where only the R and S type would compare. The major deciding factor when choosing the K-type thermocouple is the performance to cost trade off.

Type	**Conductor**	**Accuracy**	**Output (mV)**	**Range °C**
K	Nickel: Chromium/Nickel Aluminium(Chromel/alumel)	0-400±3°C 400-1100±1%	4.1 @ 100°C	-200-1100

Table 5.4: K Type Thermocouple Properties

5.4 Data Acquisition System & Software

Sinocera YE6231B The Sinocera data acquisition system (DAQ) system connects directly to a PC system via firewire (IEEE 1394) and interacts with the software discussed below. It allows for up to 8 channels to be measured simultaneously at a maximum sampling rate of 100kHz per channel. The device available has 6 available channels as two of the channels are allocated to strain gauge measurement boards. The unit also has built in pre-amplification allowing the user to increase the gain by 10 and 100 times, which is equivalent to 20dB and 40dB respectively. It also has a built in signal to noise indicator so the user can identify when the system is setup optimally.

Microlink 751 The Microlink 751 is a USB portable environmental monitoring box that measures temperature, strain, pressure, pH, voltage and current through 16 differential analogue channels. It has up to 32 digital inputs and outputs with an integrated analogue-to-digital converter that reduces electrical noise. It comes with its own software called Windmill which allows real time data collection. The 751 unit is being used to take all the temperature readings from both engines and will displays them in real time allowing the monitoring of engine temperatures to allow safe operation.

Windows XP Not used for the data acquisition but the operating system (OS) the data collection machine is running.

Sinocera YE7600 Software YE7600 is Sinocera's general purpose software which supports all DAQ systems from the company. It is the interface used to interact with the Sinocera unit, allowing the user to change the sampling rate, sampling time, data format, signal sources and also allows the user to condition the signals.

Labwindows/CVI Version 5.5 A National instruments programme which is a programme that allows the user to create electronic instrumentation for the engine rig written in C programming language. Labwindows/CVI is a type of what you see is what you get (WYSIWYG) control panel editor which allows the instrumentation panel to be created using existing libraries and code generation making the creation of C code much easier. The created control panel can be used to monitor temperature, vibrations, IAS and loads via the PowerDAQ board.

Windmill Is the software for the Microlink 751 that collects data from up to thirty two thermocouples and converts the voltage output from these into readable temperatures which can then be exported into Labwindows/CVI for display. Dynamic Data Exchange (DDE) has been used to allow the two programs to communicate and for Labwindows/CVI to read the live temperature data for display in the electronic control panel.

Matlab A standalone program used to analyse the collected data. Matlab is a numerical computing environment and programming language. It allows for the complex calculation of functions and algorithms and will be used for the post processing of collected data. It is also the software platform that the ICA algorithm used in this work was written for. This is discussed further in chapter 4.

5.5 Fault Simulation and Seeding

This section provides an overview of the faults that will be seeded on the engines and the subsequent sections relating to each engine will provide more details on how the faults were seeded. The faults were introduced into cylinder one on both engines (cylinder four for electrical current work) with varying severity and measurements were taken so that the data can be analysed with methods discussed in chapters 6 and 7, to test their applicability to Diesel engine condition monitoring. Battery, valve and injector issues were identified as areas to concentrate on for several reasons. These were highlighted in chapter 1 section 1.2.3. Backup generators need to be able to start and take load, therefore, systems associated with startup are critical. As a result a current measurement technique was investigated and this investigation can be seen in appendix E. After the engine has started, taking load is the next critical phase. For the engine to take load and not be dropped by the generator control systems, the combustion process and the associated systems must be functioning correctly and be stable. Diesel engines critically rely on the correct fuel to air mixture and compression ratios, therefore, issues such as injector opening pressures, timing and valve settings will be seeded. These avenues of investigation have also been corroborated with the sponsoring company, PS^2, whose main issues are start-up and putting the engine on load, therefore, these particular faults should provide relevant data for processing.

There will be three main areas investigated on the test engines, electrical current, valves and injectors, these will then be split into several faults:

1. **Electrical Current Draw Under Different Faults**

    - **Miss-Fire.** This fault will effectively give no combustion into cylinder four. The effect will be a four cylinder engine running with only three combusting cylinders which will have to work much harder to maintain certain speeds. **(Ford)** Available in appendix E.
    - **Leakage** This will cause the compression pressure within the cylinder to be significantly reduced, thus, having an effect on the combustion in this

cylinder. It will again lead to the other cylinders having to work harder to maintain constant speed. **(Ford)** Available in appendix E.

2. **Valve Issues**

   - **Vary the inlet valve clearance.** This will provide to little or too much fresh air into the first cylinder. The effect will be better or worse combustion and hence higher or lower temperatures due to the increased force of combustion or, the reverse, the decreased force of combustion. **(Ford & Ruston)**
   - **Vary the exhaust valve clearance.** Depending on whether the clearance is increased or decreased there will either be full exhaustion, more so than normal, or the potential for combusted material to remain in the cylinder due to incomplete exhaustion affecting the combustion within the cylinder. **(Ford, only early opening on the Ruston)**

3. **Injector Issues**

   - **Vary the injector opening pressure**. The Ford injectors are easy to disassemble and modify so that their opening pressure can be varied. The opening pressure affects when the fuel is injected into the cylinder head and how much is injected. **(Ford)**
   - **Vary the fuel rail rod clearance**. The fuel rail rod controls how much fuel goes to each injector. Increasing or decreasing its length varies how much fuel is delivered to the particular injector. **(Ruston)**
   - **Vary the injector rocker clearance**. The rockers actuate the valves and the injector at set crank angles dependent on their settings. Changing the clearance of the rocker on the injector changes the point at which fuel is injected into the cylinder relative to TDC. **(Ruston)**

The acoustic work is the main research focus within this thesis and the electrical current work was an initial investigation that was carried out in the run up to gaining access to the large diesel engine test rig and is, therefore, presented in appendix E.

5.6 Ford FSD 425

The Ford FSD 425 is a 3.2 litre four-cylinder four-stroke direct injection Diesel engine details of which can be seen in table 5.5. This engine is mainly used in marine and transportation roles including Fords famous transit van. This engine is fully instrumented to measure not only the basic operating conditions including speed, load and temperatures but also many interim parameters including engine cylinder pressure, instantaneous angular speed and injection pressure.

Type	Diesel, 4-Cylinder, High Speed, Direct Injection
Bore	93.67 mm
Stroke	90.54 mm
Cubic Capacity	2496 mm^3
Power Output	52 kW at 4000 rpm
Torque	146 Nm at 2500 rpm
Injection Sequence	1-2-4-3
Compression Ratio	19:1
Compression Pressure	3.38 MPa (at starter motorspeed)

Table 5.5: FSD 425 Specifications

The FSD engine had a series of maintenance procedures carried out on it prior to the testing. All parameters including valve clearance, injector opening pressures, dynomometer calibration and oil levels were checked and corrected if necessary. The oil was drained and replaced with new oil and the oil and fuel filters were changed after standing dormant since 2003.

The Ford engine is located in an engine cell occupied by itself and another engine. The room is approximately 5.7x5.7x4m with minimal pipe work above the engines. The rig setup can be seen in figure 5.3. The main vertical pipe is the air inlet to the engine manifold and this is directly behind the cylinders. The blue and green metallic pipes and the tank towards the front of the engine is for the water cooling system. The exhaust actually exits the engine below it and proceeds under the floor towards the main exhaust extraction system.

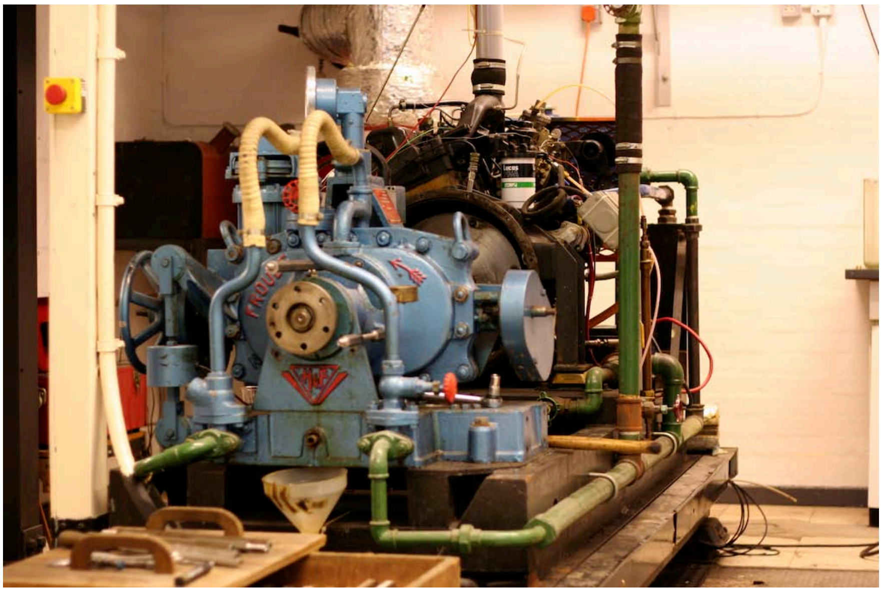

Figure 5.3: Engine Rig Setup

5.6.1 Ford FSD 425 Engine Monitoring Setup

As well as the actual data collection equipment and its setup, there was a host of sensors such as thermocouples, pressure sensor and torque sensor that were used to allow the safe operation and monitoring of the engine throughout testing, all of which can be seen in figure **??**. None of the data collected regarding temperature or pressure is used directly within the research though it does provide a live feedback of the effects of seeded faults upon the engine. All temperatures were passed back to the Microlink unit discussed in section 5.4, then fed to the PC for live monitoring of the measured temperatures. The torque applied by the dynamometer was sent directly to the engine control panel in the engine control room. This simply provides a digital value read out of the current setting.

The figure shows the following:

1.	Air intake temperature	7.	Cylinder 2 exhaust temperature
2.	Water in temperature	8.	Cylinder 3 exhaust temperature
3.	Water out temperature	9.	Cylinder 4 exhaust temperature
4.	Total exhaust temperature	10.	Torque sensor
5.	Oil sump temperature	11.	Magnetic pickup and TDC optical sensor
6.	Cylinder 1 exhaust temperature	12.	Cylinder 1 in cylinder pressure sensor

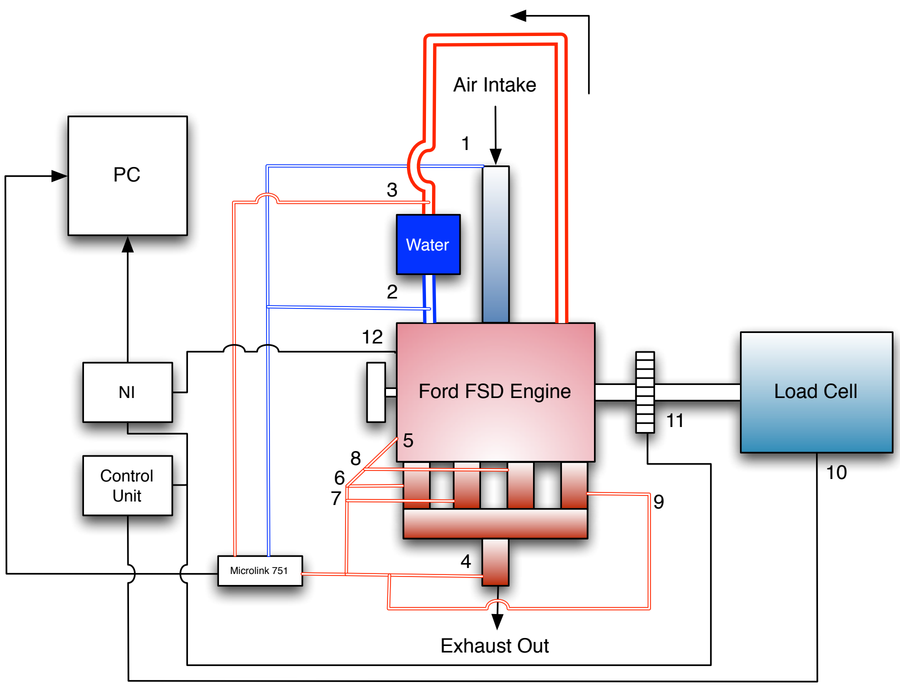

Figure 5.4: Schematic diagram of the Ford FSD monitoring system

5.6.2 Ford FSD 425 Experiments

The following section will look at the experiments that were carried out upon the Ford engine, and how the faults were seeded. Various faults were seeded and the engine was run through various conditions. As detailed in section 5.3, every practicable step was taken to ensure that these processes were repeatable and conducted accurately.

The engine was run through various operating conditions, varying speeds and loads. These various conditions can be seen in table 5.6. For every run the engine was brought up to running temperature prior to data collection.

Speed (RPM)	Loads %
900	0
1000	0,20,40,60,80
1500	0,20,40,60,80,100,120
2000	0,20,40,60,80,100
2500	0
3000	0
Maximum Load is 146 Nm	

Table 5.6: Operating Conditions (Basline) for the Ford FSD 425

Figure 5.5 shows a schematic of the test setup. The Sinocera unit has six useful channels, five were used for acoustics and one for the tooth count signal, which was recorded for another researcher. All channels were set to sample at 100kHz. The four microphones closest to the engine were mounted 10cm from the individual heads vertically above them on a rigid metal bar which was physically isolated from the engine. This was as close as was practicable without physical interference with the engine but allowed for reasonable audio separation between cylinders, by being close to the cylinder to maximise the separation of the acoustic signals between the cylinders. Once the initial measurement of 10cm was made, this distance was maintained throughout to ensure fairness and reproducibility of data across all the tests. There was a fifth microphone, on a microphone stand, 60cm back from the engine block to give an overall sample of the acoustics during running.

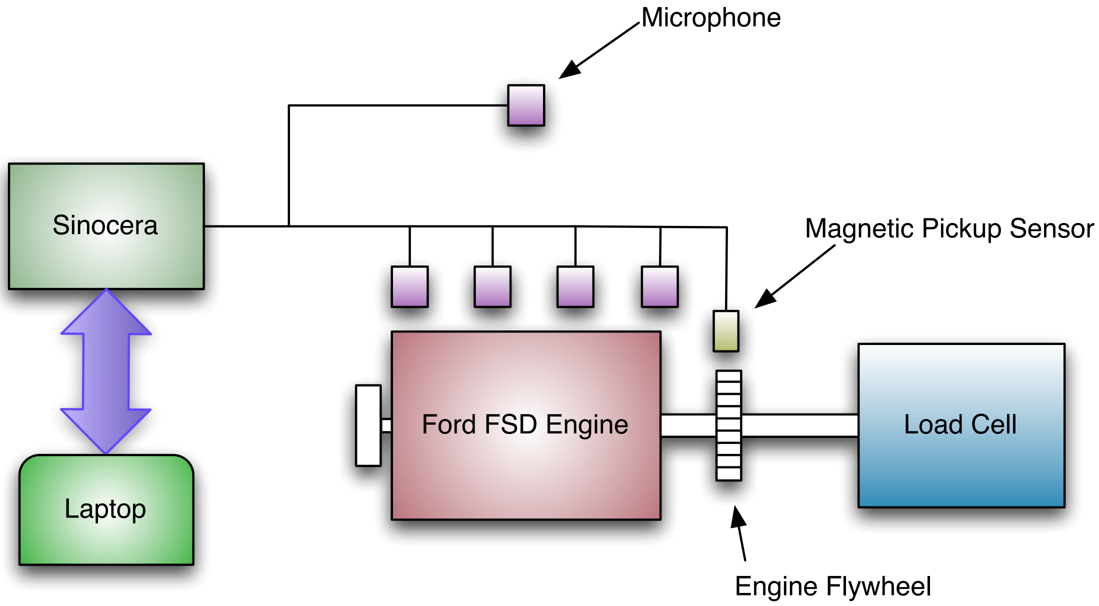

Figure 5.5: Schematic diagram of the Ford FSD test system

Seeded Faults

Varying the Valve Settings on the Ford FSD 425 Varying the valve settings on the Ford engine is relatively simple. The valves are actuated via a camshaft which acts upon a rod that moves the rocker head. This then acts on the valve spring which actuates the valve unit. Varying the clearance between the rod and the rocker unit that it impacts on will vary the opening time of the valve and in the extreme case affects how much the valve opens. Figure 5.6 shows the components that make up the main sections of the combustion system. Where the arrow labelling the 'inlet valve' meets the rocker arm shows where the clearance between it and the spring below are changed using a feeler blade and a ring spanner.

Table 5.7 shows the adjustments that were made to the Ford engine to simulate valve issues.

Valve	**Orig. Setting**	**Adj. Setting**	**Effect**
Inlet	0.20 mm	0.70 mm	Opening Late
Exhaust	0.38 mm	0.76 mm	Opening Late

Table 5.7: Valve Faults Simulated on the Ford FSD 425

Figure 5.6: Components Operating the Valves

Varying the Injector Opening Pressure on the Ford FSD 425 Adjustment of the injector first requires its removal. This is achieved by uncoupling the fuel pipe from the injector, removing the fuel leak pipe by undoing the banjo bolt and releasing the clamp which holds the injector down into the engine with force. All of these components can be seen in figure 5.7. Once removed the injector must be disassembled and the spring that controls the needle within the injector must be adjusted. The injector must then be tested and reinstalled correctly with a fresh washer as the high temperature and the force exerted on the washer due to the injector clamp mean it is not reusable.

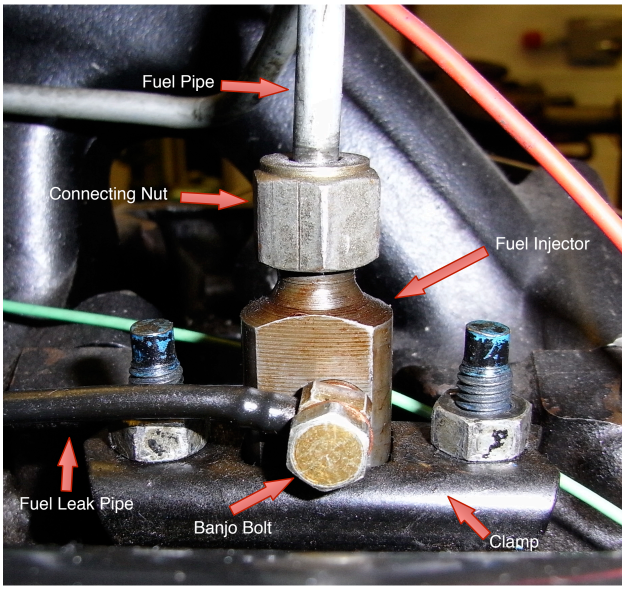

Figure 5.7: Components of the Fuel Injector System

It should be noted that anyone who undertakes such work must be extremely careful to never expose any part of their body to the spray as the high pressure can cause the fuel to penetrate the skin and can cause death. It is advised that anyone carrying out such work should take the injectors to a dealer or fuel injection specialist.

The following adjustments were made to the Bosch injectors to affect their opening pressure on the Ford FSD engine.

Orig. Setting	**Fault 1**	**Fault 2**
260 bar	220 bar	170 bar

Table 5.8: Injector Faults Simulated on the Ford FSD 425

5.7 Ruston 6RK215

The second experimental test rig facility was the 6RK215 Ruston Diesel engine. This engine is a six cylinder direct injection medium speed Diesel engine with a power output in the region of 1MW compared to the Ford's 52kW. The full engine specifications can be found in table 5.9. The engine is located in its own bay with the approximate dimensions 15x15x15m, there is little pipe work above the engine unlike the Ford, however, there are other items in the room such as the main exhaust pipe, control room, compressed air tank, fuel tank and a crane system overhead. Whilst these items may have a small impact on the room acoustics they have the advantage that they provide a realistic simulation environment similar to a clients site.

Type	Diesel, 6-Cylinder, Medium Speed, Direct Injection
Bore	215 mm
Stroke	275 mm
Cubic Capacity	2496 mm^3
Power Output	1080 kW at 1000 rpm
Torque	10310 Nm at 1000 rpm
Injection Sequence	1-5-3-6-2-4
Compression Ratio	13.4:1

Table 5.9: Ruston RK215 Specifications

This particular engine is widely used in marine applications from powering small craft to power generation on large vessels. The engine is now part of the MAN B&W engine line up since Ruston was bought by MAN and all spare parts required to refurb this engine have been purchased from MAN PrimeServ[1] based in Stockport.

Several major pieces of maintenance had to be carried out on this engine before it could be used, this included removal of the old sensors from previous research. New sensors were then added to the engine as required for the specific research, including a new DAQ system. The engine also had a maintenance overhaul where there was a complete oil change and sump clean including changing all of the filters. New anti freeze and cooling water solution was added due to the years of stagnation of the engine. Several exhaust seals and rocker cover bolts were replaced as necessary.

[1]More information on MAN Diesel PrimeServ can be viewed at `http://www.manbw.com/primeserv`

During the experiments there were a number of issues that arose and maintenance had to be carried out around these events. These included the removal of cylinder one head as there was a fault detected with a push rod. All other cylinders were inspected for the same fault. The high pressure fuel line also had to be replaced due to rupture as well as the fuel rail blocks being secured as they were found to be causing issues with the amount of fuel being injected into the cylinders. Their incorrect operation was leaving some cylinders with too little fuel and others with too much fuel being injected. It should be noted that this was a very small issue, with little effect on the engine.

5.7.1 Ruston Cylinder One Maintenance and Repair

The initial requirement to remove cylinder head one was to gain access to an internal pressure sensor that needed to be identified. The result of this work was that the sensor could not be identified as it had been fitted to an internal housing and was, therefore, impossible to remove without causing damage to the sensor or the housing. The sensor was eventually removed with its housing so that a new identifiable one could be fitted.

To reach the sensor the whole cylinder head had to removed from the engine body. This process was started with the removal of the rocker cover. This is shown in figure 5.8, the connecting rods, rockers and the top of the injector can be seen clearly.

The rocker assembly was removed so that access could be gained to the nuts that hold the cylinder head to the main body of the engine to allow for removal of the push rods. It must be noted that all valve clearances are lost and will need to be reset when the unit is re-assembled.

Figure 5.9 shows the head after the rocker unit was removed. The tops of the injector unit and valves can now be seen to the rear of the head. The cable for the in-cylinder pressure sensor can be seen just behind the back left valve head in figure 5.9. This sensor is located in a drilled tube around 25cm long all the way through the cylinder head at an angle.

Figure 5.8: 6RK215 Cylinder One With Rocker Cover Removed

Figure 5.9: 6RK215 Cylinder One With Rocker Unit Removed

The push rods were removed and the left hand push rod oil feed hole was found to be blocked and had wear on the top surface as well as wear on the rocker ball joint where lubrication had not been taking place due to the blockage. The wear can just be seen in 5.9 by the rusty discolouration compared to the other push rod ends. Although this is not why the initial removal work was carried out, it was an important discovery and a worthwhile piece of work. Had this remained undiscovered the surfaces would have continued to wear due to the complete lack of oil flow. Abnormal signals would have been produced which could have hampered the authors work and also the valves controlled by this rod and rocker could have been affected.

Due to this discovery every cylinder was stripped and all push rods were inspected, no further issues were found. Upon refitting the rocker units all the valve and injector clearances were inspected to ensure they were set correctly and equally. As a further precaution in light of the rod blockage the sump was inspected for debris, several large pieces of debris were detected and the oil was subsequently drained, the sump cleaned and fresh oil put back into the engine. The fuel and oil filters were also replaced as part of this work.

This maintenance work has ensured the safe operation of this engine, and the accurate recording of data for the tests that were carried out upon it.

5.7.2 Ruston 6RK215 Engine Monitoring System

Figure 5.10 shows the monitoring system used on the Ruston engine, as can be seen it is very extensive. Not only are these sensors important for the safe operation of the enigne during testing they also provide information instantly about the engine setup. Due to the large amount of maintenance that was carried out on this engine prior to the experimentation it was critical to have the information these sensors provided to ensure the engine was operating normally and that combustion was equal amongst all six cylinders. Indeed, several issues were discovered, including the incorrect fuel injection rod settings. Thanks to these sensors, the issues were quickly corrected and the experimentation could take place.

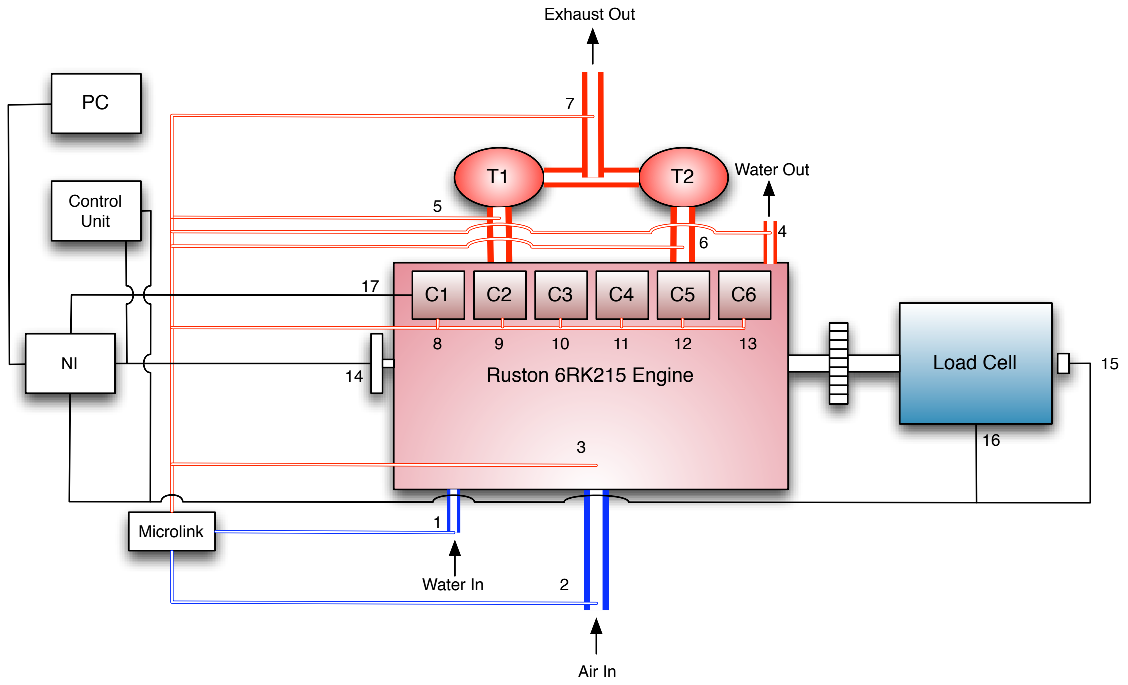

Figure 5.10: Schematic diagram of the Ruston monitoring system

The rig utilises the following sensors:

1.	Water in temperature	10.	Cylinder 3 exhaust temperature
2.	Air in temperature	11.	Cylinder 4 exhaust temperature
3.	Oil Sump Temperature	12.	Cylinder 5 exhaust temperature
4.	Water out temperature	13.	Cylinder 6 exhaust temperature
5.	Air temperature into turbo 1	14.	Shaft encoder
6.	Air temperature into turbo 2	15.	Shaft speed
7.	Exhaust out temperature	16.	Tourque meter
8.	Cylinder 1 exhaust temperature	17.	In-cylinder pressure sensor
9.	Cylinder 2 exhaust temperature	18.	Oil pump temperature

5.7.3 Ruston 6RK215 Experiments

The following operating conditions were used when testing the Ruston engine. This engine operates over a different speed range compared to the Ford.

Figure 5.11 gives an overview of the sensor setup for data collection. All six channels were used this time for acoustics, giving one microphone per cylinder and all at 100kHz sampling rate. The microphones were mounted upon a gantry which

Speed (RPM)	**Loads %**
600	0,10,25
750	10,20,25,50,75,100
900	25,50,75,100
1000	25,50,75
Maximum Load is 10310 Nm	

Table 5.10: Operating Conditions (Basline) for the Ruston 6RK215

was isolated from the engine vibrations on microphone stands. This means there was no physical connection between the engine and the microphones. They were positioned with the same considerations as the Ford microphones but further back as the engine is much larger. The microphones were measured accurately to be 39 cm from the cylinder rocker cover and all measured to ensure that each microphone was pointing towards the centre of its respective cover. This can be seen more clearly in figure 5.12. This distance was arrived at purely as it was the closest the equipment could get before parts of the stands would contact the engine body.

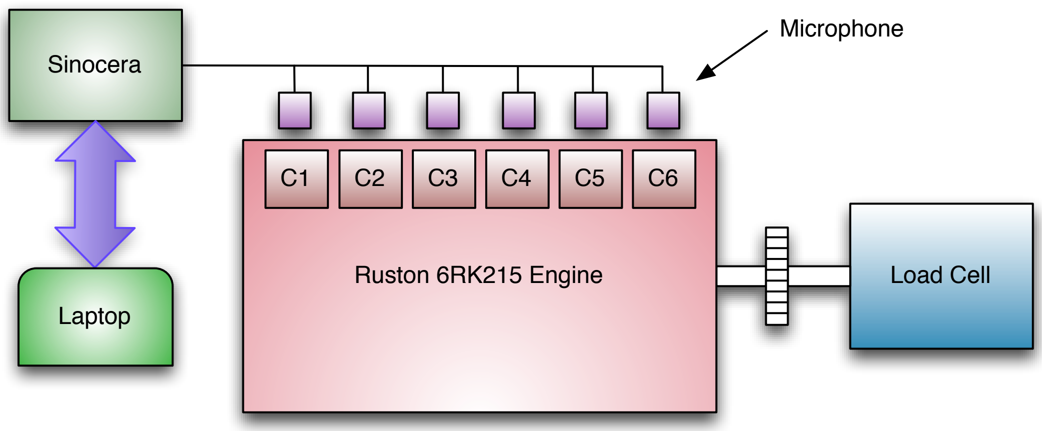

Figure 5.11: Schematic diagram of the Ruston test system

Seeded Faults

Varying the Valve Settings on the Ruston 6RK215 Like the Ford, the valve settings are changed in much the same way on the Ruston. It was only possible to gain one fault setting however as it is incredibly difficult to make small incremental changes in the clearance, therefore, the maximum clearance that was deemed safe was used. The adjustments made to the Ruston 6RK215 to simulate valve issues

Figure 5.12: Microphones Installed on the Ruston 6RK215

can be seen in table 5.11.

Valve	Orig. Setting	Adj. Setting	Effect
Inlet	0.38 mm	0.2 mm	Opening Early
Exhaust	0.63 mm	0.35 mm	Opening Early

Table 5.11: Valve Faults Simulated on the Ruston 6RK215

Only early opening was simulated as later opening was deemed not safe on an engine of this magnitude given how hard it was to make small changes to the clearance.

Varying the Injector Settings on the Ruston 6RK215 Two different injector faults were seeded, both injector timing and fuel injection amount. To seed the injection timing fault the adjusting nut on the injector rocker arm was adjusted by a set amount, each adjustment had a corresponding crank angle reference. According to the manufacturers manual, a 60° adjustment of the nut gave a 1° advancement (or decrease) of crank angle for when the fuel is injected. The manual also stipulates that it is not recommended to adjust more than 240° or 4° of crank angle. The adjustments made to simulate this fault can be seen in table 5.12.

Fault	**Setting 1**	**Setting 2**	**Setting 3**	**Setting 4**
Earlier Injection	+60° (1°)	+120° (2°)	+260° (4°)	+290° (5°)
Later Injection	-60° (1°)	-120° (2°)	-180° (3°)	+260° (4°)

Table 5.12: Injector Timing Faults Simulated on the Ruston 6RK215

In addition to the injector timing faults, the fuel amount was varied. Although the fuel amount is not quantifiable the adjustments made to the fuel rod are. The rod controls how much fuel is fed to the injector and its length was adjusted to either inject more fuel or to inject less. The adjustments are shown in table 5.13.

Fault	**Setting 1**	**Setting 2**	**Setting 3**
Too Little Fuel	-0.6mm	-1.2mm	-1.8mm
Too Much Fuel	+0.6mm	+1.2mm	Not Viable

Table 5.13: Injector Fuel Amount Faults Simulated on the Ruston 6RK215

Setting three for ‘too much’ fuel was not viable due to the cylinder temperatures that were reached on this setting. It was deemed unsafe to proceed.

5.8 Summary

The experimental work is the most critical part of this research. It provides the data for which all the results and conclusions for this work will be based. One of the main points of the data collection is to collect a good set of baseline data of the engine in a healthy state. This then allows for the comparison between the baseline data and the simulated faults that have been presented within this chapter. Therefore, without the restoration and maintenance work covered in this chapter the data integrity could not be guaranteed. Indeed, issues were raised with the engine, such as the blocked push rod and these were corrected prior to data collection. The work also consisted of the necessary groundwork to test and reinstall all of the sensors correctly and ensure they were functioning properly. These sensors allow for the safe and reliable operation of the engine. Indeed, where certain fault settings have not been utilised it is because data from sensors whilst running the engine under that condition presented safety concerns.

Crucially this work provided much necessary learning for the author and improved his learning with good hands on experience which has led to a greater appreciation of the processes within the engine.

5.9 Conclusions

The experimental work has formed a very large part of this research work. It has provided useful context for how this technique could be applied outside of a laboratory environment and the issues that this may pose. The main issue is how the initial baseline data would be collected. It is critical to ensure the engine is completely healthy, however, within a lab temperature and pressure can be monitored to ensure the system as a whole is running correctly. If the system is installed on a brand new rig which has undergone manufacturer testing this maybe not a concern, however, existing rigs may not be as easy. Baseline data that maybe even slightly affected by a small very undetectable issue could cause follow on issues with fault detection.

Another issue that is apparent from the experimental work is that in a real world application there would need to be an effective way in which to install the microphones. If the system were to be used by a service company, then there would need to be a way to ensure that at every visit the microphones were in the same position as before. For a permanent installation the same issue exists for when they microphones need to be move for maintenance. Later chapters will conclude how the microphone positioning affects the data.

Another consideration that was raised from this work is whether significant maintenance work on the engine would require a new baseline set of data. In theory replacing a major component on the engine and returning the engine to a healthy state should not effect the baseline data taken from the engine. When comparing the post repaired engine to the original healthy data the engine should be classed as healthy. However, in practice this is not so easy. Even a small change in machining tolerance or a nut not tourqued as much as one just removed would change the vibration transmissions and therefore effect the acoustic emissions. Taking a new baseline data set after major maintenance would potentially devalue the system as the system will be degraded naturally through wear by this point and taking a new set of baseline data is effectively setting this wear back to zero.

The experimental work carried out within this research, apart from being crucial, has provided a lot of experience and knowledge to the author and has presented many topics for consideration and further work. The following chapters will present the results of the experimental work and draw conclusions on how applicable acoustic measurements are for engine fault monitoring.

Part IV

Results

Chapter 6

Statistical Processing Results

This chapter investigates the initial findings of the measured data, both in its raw state and after some simple statistical processing. It is advantageous if firm conclusions can be made about the health of an engine from the time signal or from some very simple statistical processing.

This method was investigated as it would provide potential advantages such as rapid lightweight processing that would be very easy to conduct on the fly in the field. It starts by looking at the raw time data and what advantage or disadvantages this may hold. The time domain is then converted to the frequency domain and various conclusions are made on the output from the fast Fourier transform (FFT). The output of the FFT is then processed using basic statistical methods to see if these can improve the results to make the detection of a fault easy and clear.

In this chapter, results from the data are presented and conclusions are drawn on the potential of the statistical techniques for condition monitoring. All results unless stated otherwise are from microphone one (channel 1) which was the microphone located closest to cylinder 1. This is the cylinder in which the faults were seeded. Any other microphones are numerically linked to the cylinder numbers, for example, microphone two (channel 2) is located next to cylinder 2, microphone three (channel 3) is located next to cylinder 3 and so on. The frequency is always displayed in Hertz.

6.1 Ruston 6RK215

Data from the Ruston was investigated first as the acoustic data should be easier to process from a larger engine due to the spacing of the cylinders. This will provide less mixing of the acoustical signals before reaching the microphones. The Ruston also runs significantly slower than the Ford engine which may make statistical post processing easier as there will be more data points per cycle for a particular sampling frequency. The acoustical environment and the engine itself have been discussed previously in chapter 5 along with the faults that were seeded on the engine.

6.1.1 Large Diesel Engine Airborne Acoustic Waveforms

There are several important factors to remember when looking at the sound field surrounding an engine. First, the sound field varies with direction. The noise from cylinder combustions will for example, be louder to the front of the Ruston engine, than to the rear. This is because the cylinders are mainly shielded by the turbo chargers and the exhaust system. The time, which effectively equates to distance, is also a variable in the sound field. Physically, the running and mounting conditions will also have a significant impact upon the emitted sound field. This research looks at detecting a change in the running of the engine from the sound field to determine if the engine has a fault or not. All of these factors are affected by the acoustical environment which causes reflections and reverberations within the sound field.

With these considerations, figure 6.1 shows the raw time domain signal recorded from one of the microphones in the test setup. When sampled at a sample rate of 100kHz for 1s. It shows the time steps on the x axis in terms of data points which gives a resolution of 1Hz and a maximum measured frequency of 50kHz, well above the audible range. At these frequencies, anti-aliasing is naturally applied by the characteristics of the microphones. On the y axis is the arbitrary amplitude value that is recorded by the Sinocera unit, it does not relate to volts or mV but is consistent throughout all the recorded data. Clearly little, if any information can be taken about the engine condition from this signal in the current form.

It is possible to convert the data from the time domain to the frequency domain,

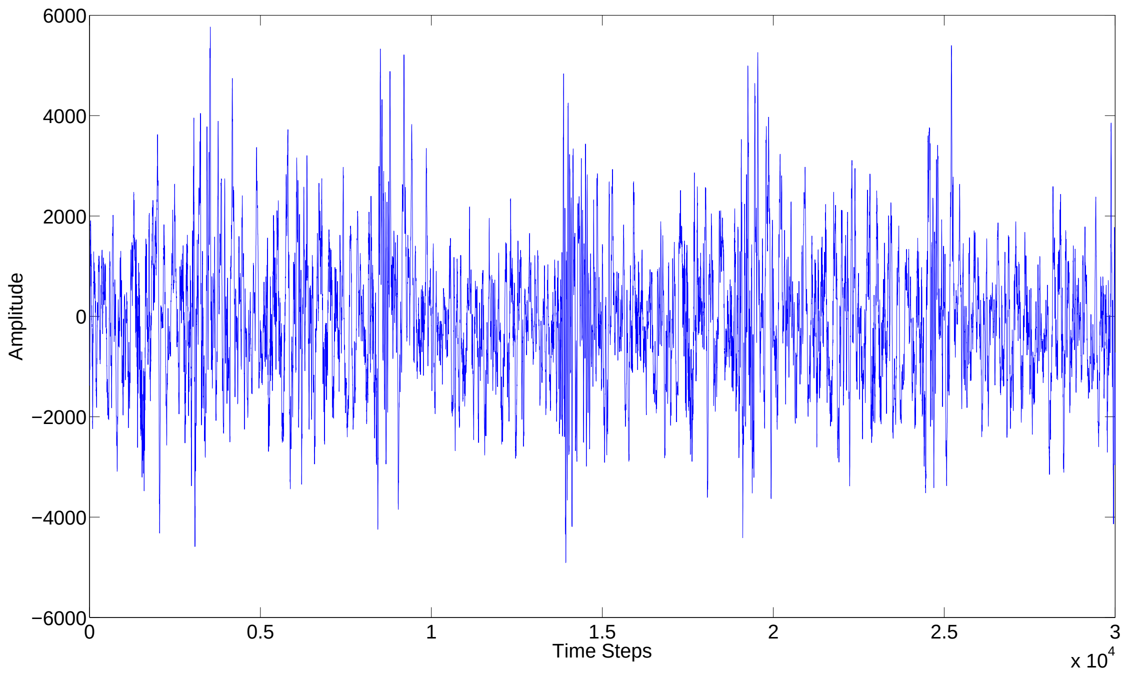

Figure 6.1: Raw Healthy Data at 750RPM and 25% Load

the most common domain used in acoustic data processing. It provides two main advantages. First, it easily represents the signal in terms of how much of the data makes up a particular frequency . Second, these frequencies allow for important machinery characteristics to be identified. It provides the amplitude for the frequencies as well as giving an idea of their distortion it is, therefore, less susceptible to small variations in the engine operating conditions such as a small speed fluctuation. Such a fluctuation would affect the time domain data.

To convert the data to the frequency domain, the Fourier transform is used. A Fast Fourier Transform (FFT) or several FFT's are used to calculate the discrete Fourier transform (DFT) and the inverse of the DFT. It is the DFT itself that converts time domain data into the frequency domain. In this research two algorithms were used to convert the date, Rader's algorithm [131] [132] and Cooley-Tukey algorithm [131] [133]. These two algorithms were used as they compliment each other well, the Cooley-Tukey algorithm breaks DFT's into even smaller DFT's. This allows Rader's algorithm to compute the DFT, decomposing large prime factors, something the Cooley-Tukey cannot. Using dedicated algorithms for each part not only provides better results but improves computational performance and the combination of these two algorithms are also built into Matlab, which simplifies the program code used within this research. There are a large other number of algorithms available, but the algorithms used in this research suffice and spending a large proportion of time looking at all the other various algorithms detracts from the main part of the research.

The output of this Matlab FFT can be seen in figure 6.2. The data output is between 0Hz-100kHz, however, there will be harmonics of the main frequencies at the higher frequencies. These, however, contain far less energy than the harmonics at the lower frequencies. As a result, the plot was limited to the first 200Hz, to show the main frequency peaks more clearly. It shows, that the data has a low signal to noise ratio of approximately 10dB, which is important for accurate post processing.

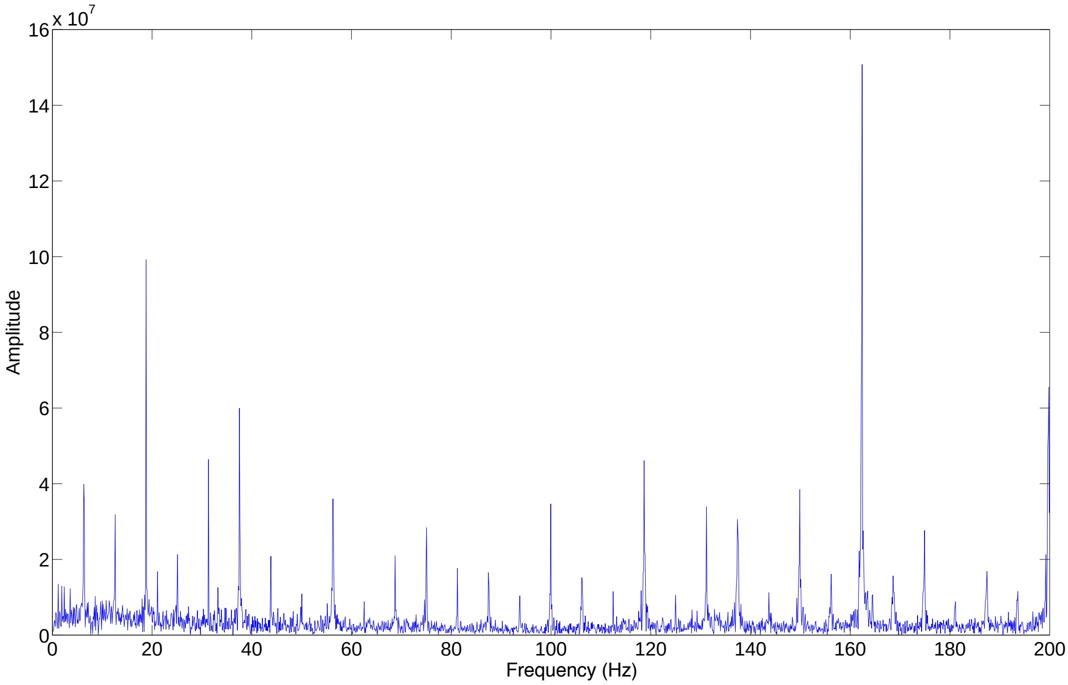

Figure 6.2: FFT of Healthy Data at 750RPM and 25% Load

The FFT plot (Figure 6.2) shows some distinct events at frequencies which correlate to the running engine. The engine revolution frequency is 12.5Hz and all of its corresponding harmonics, 25Hz, 37.5Hz, 50Hz and so on, can clearly be identified. As a four stroke engine, the Ruston will provide each cylinder with a fuel injection and a combustion event for every 720° of crank angle. Therefore, for every 360°, three of the cylinders will fire creating a frequency peak at three times the fundamental frequency of 12.5Hz i.e. 37.5Hz. The peak at 75Hz would most likely be the closing of the inlet and exhaust valves, something that would occur twice per crank revolution of every other revolution per cylinder. The large dominating peak located at 162.5Hz, is the thirteenth harmonic of the firing frequency. It will be shown later in this chapter that this peak represents an event that relates to thirteen engine orders which is approximately 4.3 cylinder orders. The location of this peak at a none whole cylinder order, implies that whatever is causing this peak is related to the cycle itself not directly to the cylinder. For example, this could relate to a sticking piston which is causing vibrations on the cylinder liner due to poor lubrication. However, this is only one possible explanation and there is no conclusive evidence to identify what this peak is.

As well as the engine order at 12.5Hz, there is also a peak at 6.25Hz which corresponds to half an engine order. This is associated with a complete cycle not just a single revolution. The harmonics of the half order correspond to the harmonics of the engine order but also as harmonics at other half orders such as 18.75Hz, 31.25Hz, 43.75Hz and so on.

6.1.2 Healthy Data at Different Speeds

Chapter 5 discussed the re-conditioning process that was carried out and the processes in which each cylinder was adjusted so that they were all working as consistently and as equally as possible. To begin with, healthy data sets were collected which would act as baseline data. This will act as a reference for all other data. In industrial settings, data will often be collected and compared to data taken when the machine was new. This allows the operator to compare the two sets of data and to pick out any changes which may relate to a fault. There are two operating parameters that will change the recorded data from a Diesel engine and should be investigated. The two parameters are speed and load.

A good demonstration of how the FFT signal changes with engine conditions is shown in figure 6.3. This figure shows two healthy data sets, one at 750RPM and the other at 900RPM, both at the same load. The differences are clear, the data is qualitatively the same but peaks appear in different locations to represent the higher revolution speeds of the engine, as well as an increase in amplitude on most peaks demonstrating the increased energy in the data due to a faster harder running of the engine.

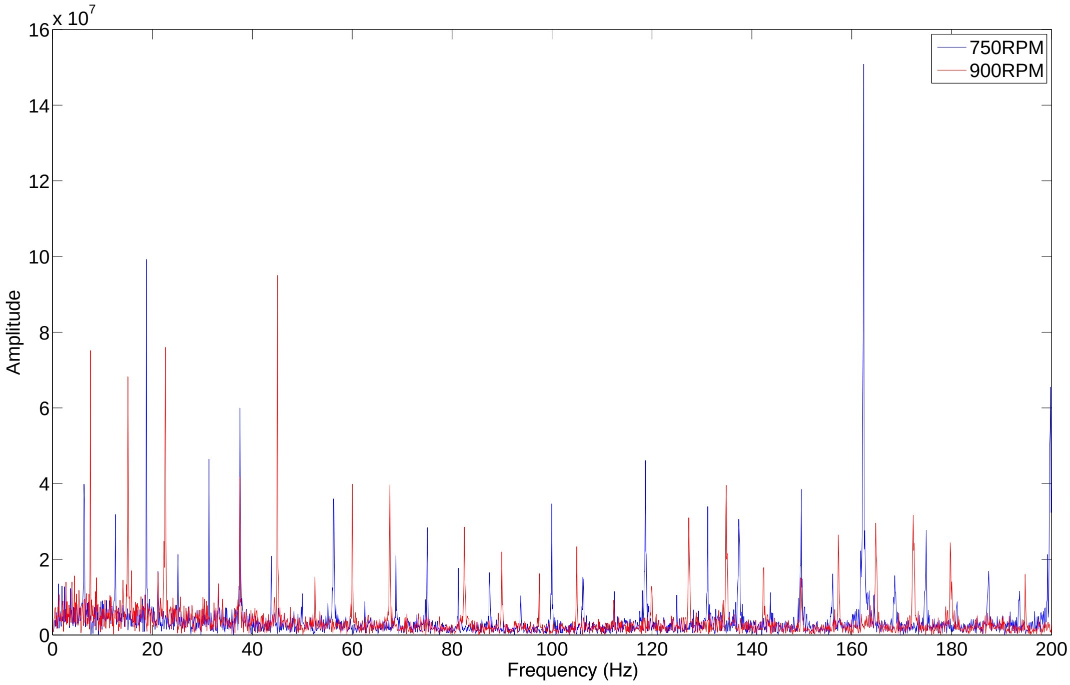

Figure 6.3: FFT of Healthy Data at 750RPM and 900RPM and 25% Load

Engine events, such as valves opening, valves closing, injection and combustion events relate directly to a particular crank angle and are often described in terms of the angle. For example, for every one crank revolution of the Ruston engine three cylinders will fire. When plotting the FFT of the two different speeds against engine order all the events that refer to cyclic events, i.e the ones whose period is related to the engine cycle, will appear at specific engine orders.

Taking the same data from figure 6.3, both sets of data were plotted against engine order, this is shown in figure 6.4. Noticeably, both sets of data now collapse on top of each other, demonstrating the relationship of both sets of data to cyclic events in the engine and showing that despite the rotational frequency difference they correlate to the same events. Whilst not dominating, there are peaks at engine orders of 3, 6, 9, 12, which is expected for a six cylinder engine with three cylinders firing, six closing events of valves and twelve complete cylinder strokes per crank revolution.

The same data can also be viewed in cylinder order (Figure 6.5), which is fundamental to the engine order. Three engine orders relates to a single cylinder order, six

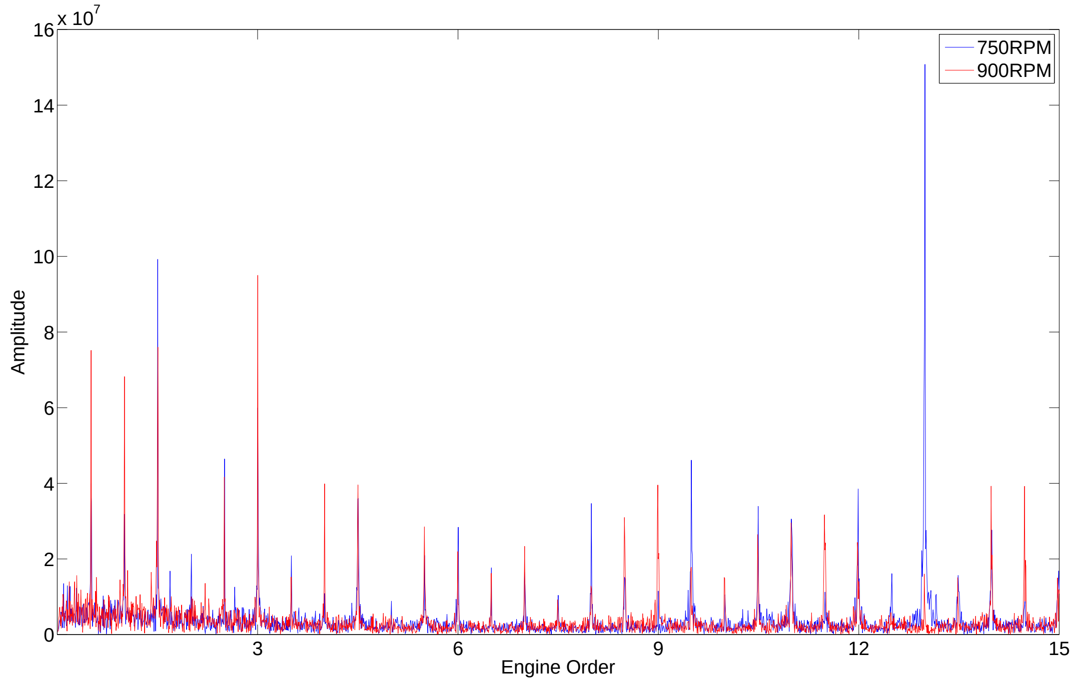

Figure 6.4: FFT of Healthy Data at 750RPM and 900RPM and 25% Load in Relation to the Engine Order

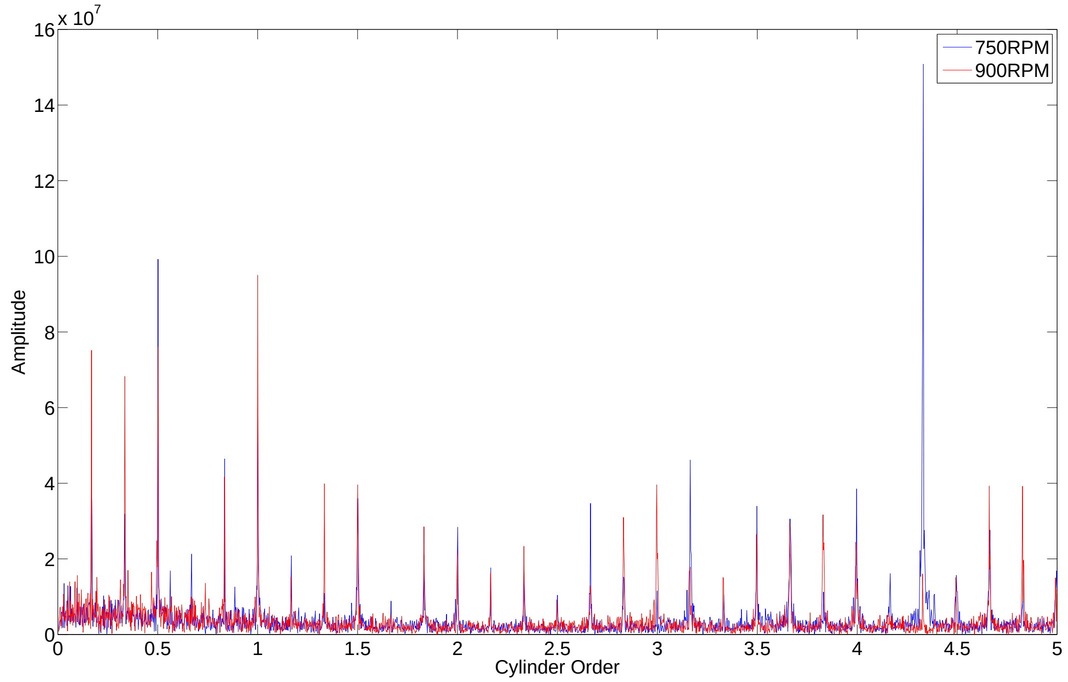

Figure 6.5: FFT of Healthy Data at 750RPM and 900RPM and 25% Load in Relation to the Cylinder Order

engine orders to two cylinder orders and so on. The important thing to understand is that noise events are associated with one of three types of source event on the engine. Some are associated with the cylinders directly, these include; valve opening events, injection and firing of an individual cylinder. Others are associated with the engine, such as the firing of a set of cylinders for a whole crank cycle. The third are miscellaneous events including reverberations and external noises.

The two main variables in a running engine are its speed and load. Therefore, the next logical step is to investigate how varying the load will affect the data.

6.1.3 Healthy Data at Different Loads

As well as operating at different speeds, engines operate at different loads. With varying speeds, a healthy engine exhibited a shifted FFT output. When considering the same speed and different engine loads this is not the case. Figure 6.6 shows the only effect that a change in loads has is on the amplitude of the peaks at the main frequencies. Indeed, it was noted by Priede [57] that the effect of engine load on engine noise was "very slight".

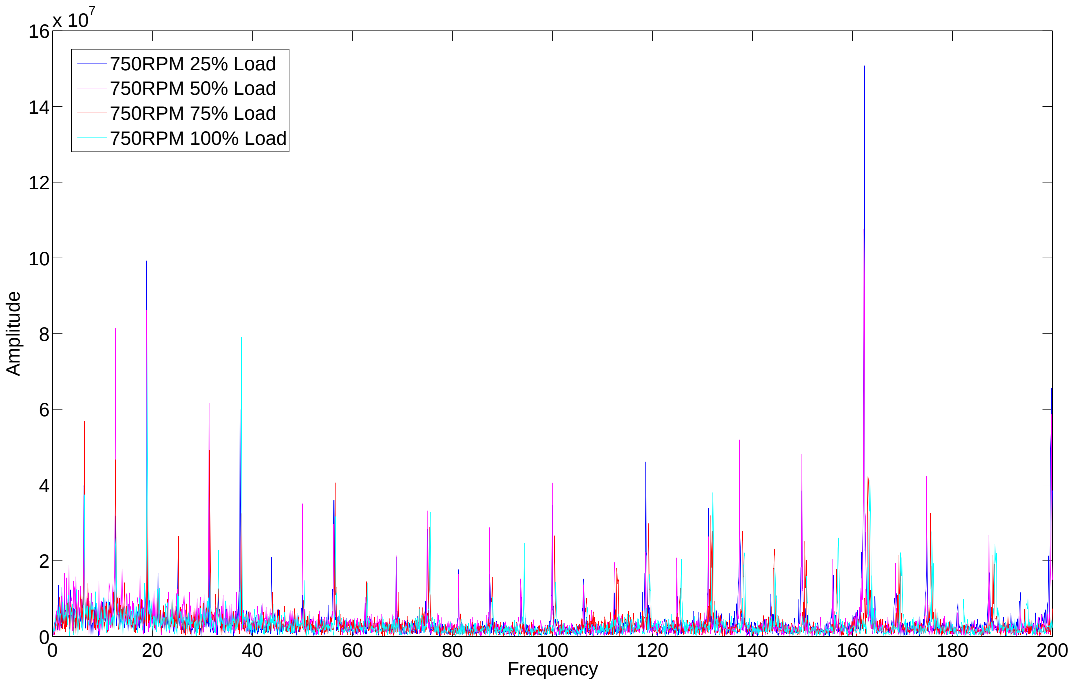

Figure 6.6: FFT of Healthy Data From Microphone 1 at 750RPM and 25%, 50%, 75% and 100% Load

From figure 6.6 it appears that the events occur at the same frequency with varying amplitudes depending on the load. There is no correlation between the amplitude of the signal and the load except at 81.25Hz (6.5 engine orders, 2.16 cylinder orders),106Hz (9 engine orders, 3 cylinder orders) and 162.5Hz (13 engine orders, 4.33 cylinder orders). Two of the peaks are directly related to each other, 162.5Hz is a harmonic of the peak at 81.25Hz. The ninth engine order relates directly to the cylinder orders. The thirteenth order as previously discussed may very well relate to a sticking cylinder. It occurs at an order that represents a whole cycle event and one that appears to decrease with load. This represents the cycle becoming smoother over the full period compared to lower loads where it is rougher and thus more noisy. For varying loads, this could be due to the increased amount of fuel the solenoids will distribute to the cylinders with an increase in load. This will allow for the smoother movement of a potentially poorly lubricated cylinder.

Indeed, through various results (Appendix A), even on different channels and for various conditions it is clear that the thirteenth order does not exist at such magnitudes on channels four to six as it does on channels one to three. As this order only appears on channels one to three, with it occasionally showing on channel four, it may be localised to a single cylinder or to the first three cylinders. The first three cylinders share the same inlet and exhaust routes as well as the same turbocharger. The test engine has been used for numerous years for various research, including changes in the cylinder one head itself and modifications to the injector unit and turbocharger for that cylinder. It is possible that despite the good running of the engine there is an event at thirteen engine orders that has been created due to increased wear or modification to the first cylinder or a system that serves the first three cylinders. There is no way of confirming what is causing this event and another Ruston 6RK215 engine would be required to see if it was specific to this engine or is specific to the engine model in general.

It is also apparent that load has a small impact on the signal to noise ratio (SNR), comparing figure 6.2 to 6.6 alone shows how the low level peaks around 1×10^7 have become more masked with the increase of load.

The FFT plot whilst useful, is not easy to view especially with multiple sets of data overlapped on top of each other. The FFT contains well defined peaks and it would not be unreasonable to assume that anything not displayed as a clear distinct peak is in fact noise. With that assumption, Matlab code was written to locate all the peak points from the FFT data and then Matlab was used to plot these peak plots.

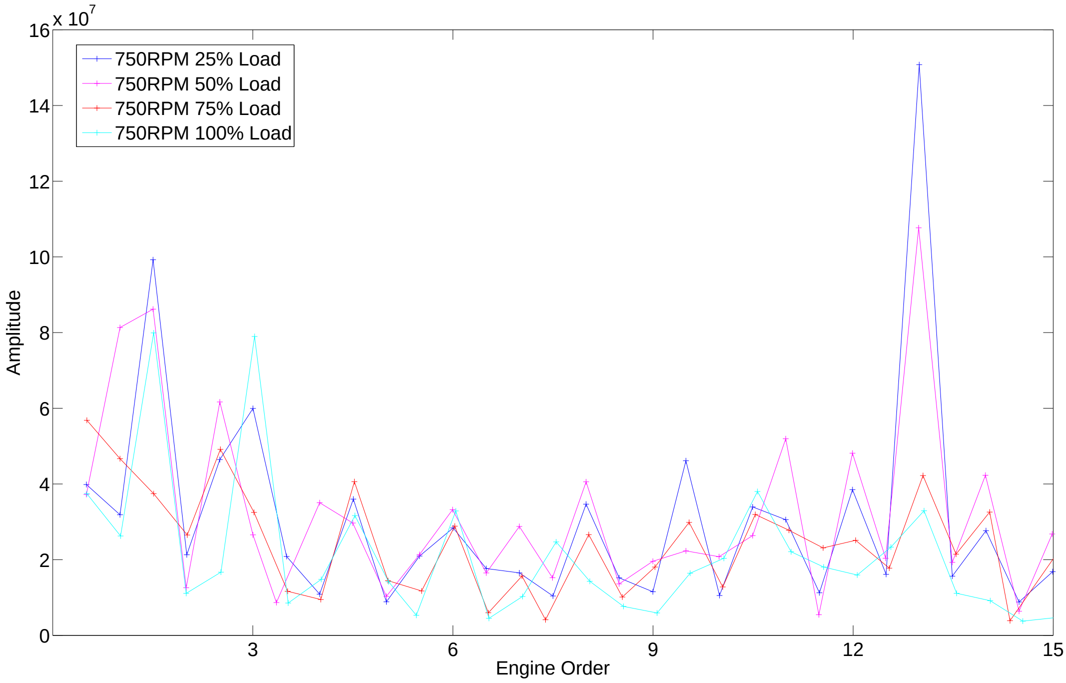

Figure 6.7: Peak Plots of Healthy Data From Microphone 1 at 750RPM, 25%, 50%, 75% and 100% Load in Relation to the Engine Order

The peak plot from the FFT in figure 6.6 is displayed in figure 6.7, where the relationship of the data both in the lower and higher engine orders can now be seen more easily. Despite the increase in clarity from the plot there is very little in the way of a pattern to distinguish low loads from higher ones. It should be noted that at the third engine order the highest load dominates, though there is no clear pattern for the other orders at this point. Indeed the only peak that gives a clear picture of the varying loads is the peak at thirteen engine orders. The increase in amplitude at the third order is expected as each cylinder will be working and driving the cylinder harder as the load increases to maintain a stable engine RPM. The decrease at thirteen orders is also expected as the higher orders tend to relate to the overall cycle, therefore, as the engine starts to work harder the noise is more cylinder isolated meaning these orders decrease with load.

6.1.4 Too Little Fuel Fault

The fault seeding for too little fuel is discussed in section 5.7.3. The fault was seeded in three different severities, fault one, the spill port was opened by an extra 0.6mm, fault two, by 1.2mm and fault three by 1.8mm. These faults were not quantified but the fault was capped at 1.8mm as the other five cylinders were running very hot at this setting. This is to be expected, injecting a lesser amount of fuel into a cylinder will lower the combustion pressure and reduce power transfer from the combustion process to the crankshaft. This power reduction, as well as the weight and friction of the faulty cylinder system means the remaining cylinders need to work harder to maintain stable power output and to carry the faulty cylinder.

Ultimately, a reduction in fuel injection will affect the ratio of fuel to air. This will affect how well the combustion process is carried out. Typically, for the more serious fault in this series, it would not be unrealistic to expect that the flame may extinguish during combustion due to the decreased ratio. It might be thought that this would reduce the overall engine noise, on the contrary, this would significantly increase the engine noise due to rough combustion.

In real world situations this fault will likely develop through wear at the spill port. It could also be easily induced by accident if a service engineer was working on the cylinder rocker system or the head itself and failed to reset the clearance correctly.

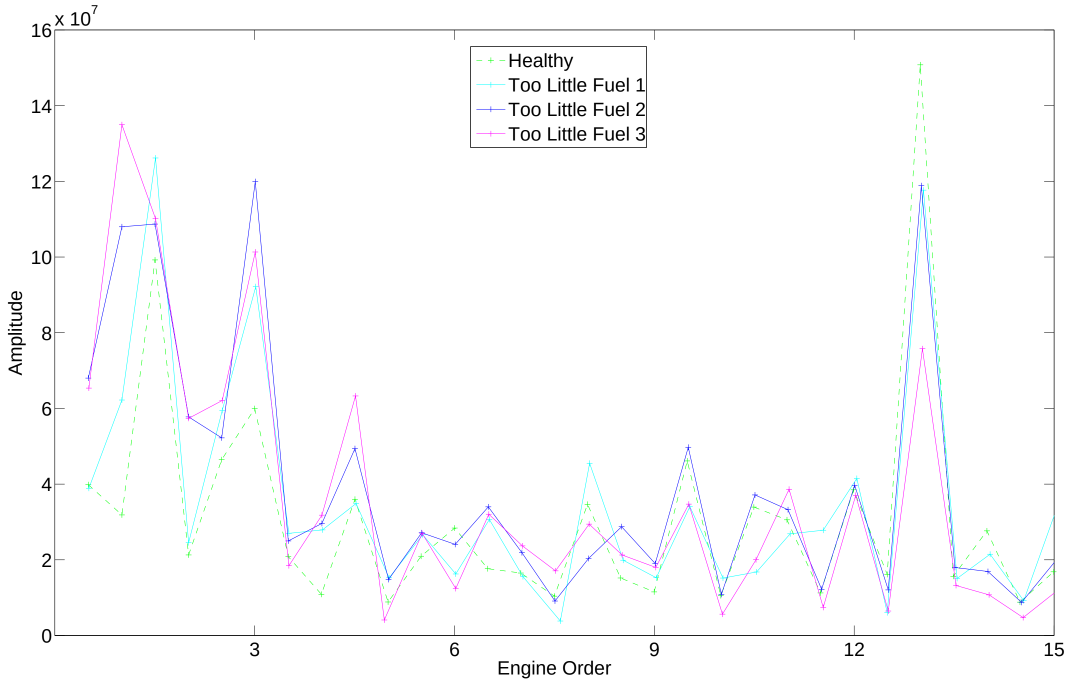

Figure 6.8: Peak Plot of Healthy vs Too Little Fuel Fault at 750RPM and 25% Load

At the same speed and load the fault for both severities provides little evidence in the FFT as to the presence of the fault. The only difference in comparison to the healthy FFT data are changes to the amplitude of the peaks. This is not a conclusive parameter to clearly identify a fault though is a weak indicator. Like before, figure 6.8 shows at the thirteenth engine order a reduction in amplitude as the severity of the fault increases. However, as previously stated this order is suspected of relating to an event or process that would not be present in a completely healthy Ruston engine. Whatever this issue is, it did not affect the even temperatures amongst the cylinders nor did it appear to affect the smooth running of the engine.

Importantly from figure 6.8 it can be shown that although not in order, the lower orders increase in amplitude with the severity of fault seeded. As this measurement is from the microphone nearest the cylinder with the seeded fault it would not be surprising that the amplitude increases as the amount of fuel being injected decreases. This maybe due to uneven or incomplete combustion due to the reduced fuel, indeed, if the flame goes out this would increase combustion unevenness and further increase the amplitude.

Cylinder one will not be combusting as hard, or at least, not as evenly. The reduced work by this cylinder will be picked up by the cylinders which follow on from it. Indeed figure 6.9 shows the same data from channel five, which is located at cylinder five. From table 5.9, cylinder five is the next firing cylinder after cylinder one. There is still a strong shift to the lower engine orders (even when negating the thirteenth order) with clearer sharper peaks at one, two and three engine orders for the two most severe faults. This not only reinforces the measurement from microphone one, but would indicate that the shift to lower orders is a direct indication on the more rough running of the engine due to the fault at cylinder one and its affects on the cylinders that follow on closely from it. The difference in amplitude scale can be negated as the microphones were not calibrated relative to each other for this work meaning these scales cannot be compared fairly.

Unlike channel one in figure 6.8, which shows a more consistent spread across the engine orders, there is a distinct lack of higher orders in figure 6.9. This demonstrates the increased work carried out by cylinder five in the absence of full combustion from

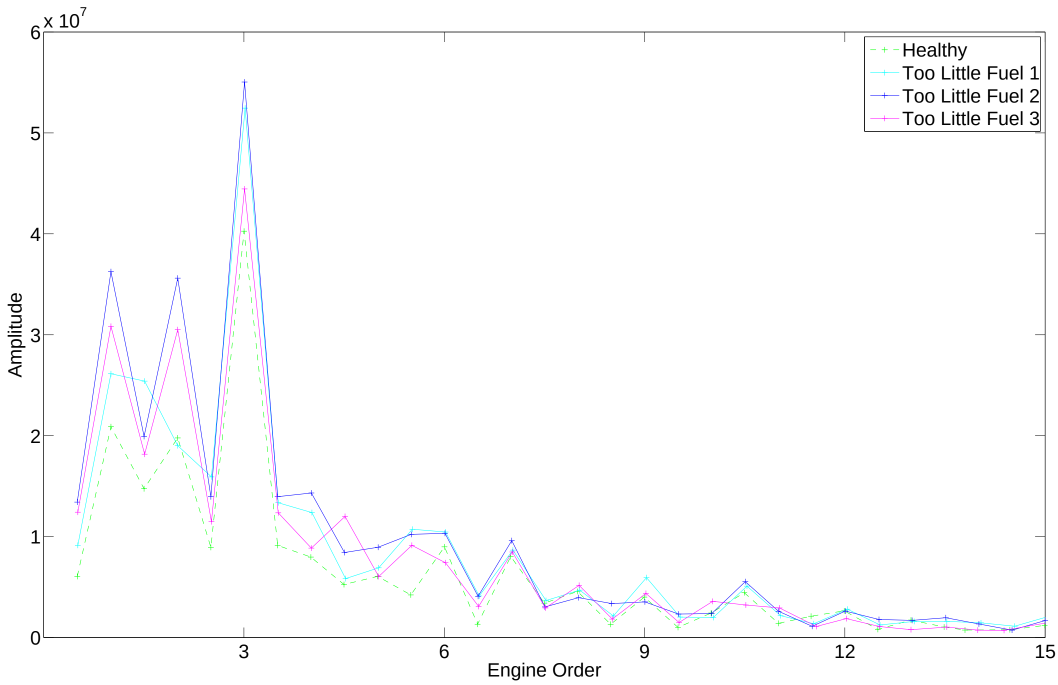

Figure 6.9: Peak Points of Healthy vs Too Little Fuel Fault at 750RPM, 25% Load - Channel 5

cylinder one. Looking at channel three, which is located closest to cylinder three (Figure 6.10), it can be seen that there is restoration in the later engine orders and the thirteenth order which may be due to the proximity of this sensor to cylinder one.

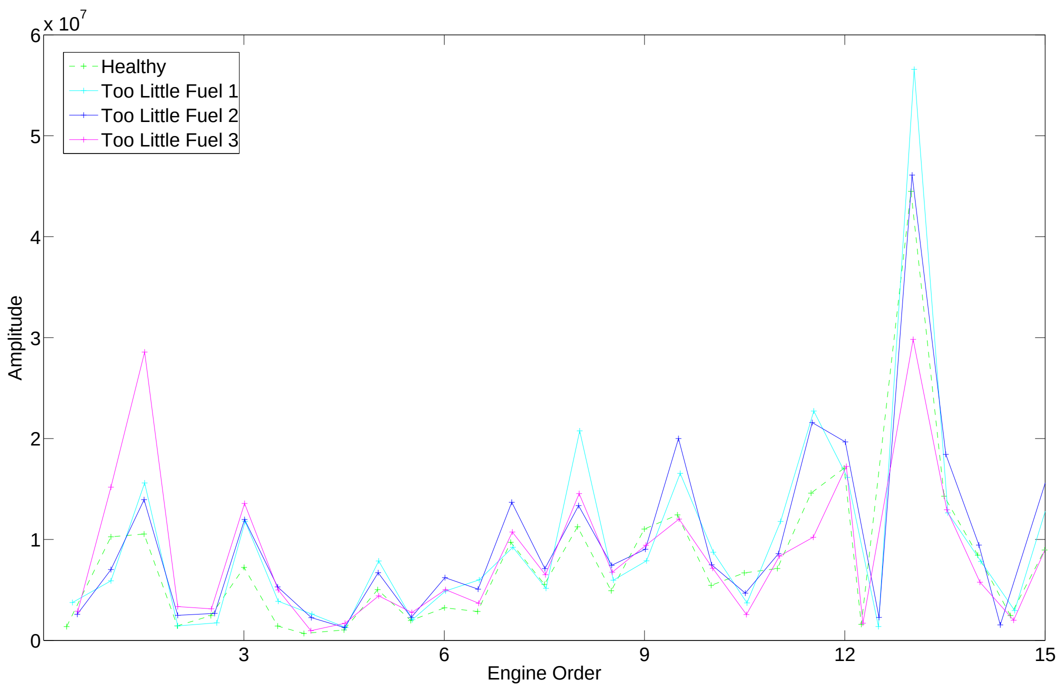

Figure 6.10: Peak Points of Healthy vs Too Little Fuel Fault at 750RPM, 25% Load - Channel 3

The return to a more even spread signifies that this cylinder is doing more work than if the engine were healthy but not picking up the extra load that cylinder five is, due to the fault. There is still a distinct dominance by the faults at engine orders one and three which would indicate that under these faults the cylinder is working harder than when the engine is healthy. Figure A.6 further corroborates this theory. It shows the channel closest to cylinder six, which fires after cylinder three, which is shown in figure 6.10. It can clearly be seen that again there is an increase in the higher orders as the later cylinders suffer less from this issue, however, under faulty conditions there is still a dominance at the first engine order by the faulty conditions.

Typically researchers look into the RMS and the kurtosis values of the data to establish the variations in the data with the premise that an engine running less smoothly due to increased load or because it has a fault will have more variations in the measured data. These parameters have previously been investigated in a paper by Moore [71] using the kurtosis function of Matlab which normalises the function with respect to the standard deviation of the distribution. The outcome of this work was that the RMS and kurtosis values did give some indication of a fault but that it was not very reliable. Indeed when the kurtosis was carried out on the raw time signal it was very erratic. Instead of using the raw time data the kurtosis of the peak point data was used to calculate the kurtosis of the data in this research and this showed far more promise than when used on the raw data of the results from the published paper. However, it was still not consistent enough and, therefore, the central moments of the peak point data were taken instead.

Figure 6.11 shows the values of the various normalised moments of the data sets and also the mean of the healthy data sets for a particular speed and load. One standard deviation either side of the mean was also plotted. Therefore, any data falling outside of these thresholds can be seen to be significantly different from the healthy data, and as such, most likely faulty. It is clear from this figure that the two faulty cases are within the bounds of the healthy data, except at the second moment where the two more serious faults are detectable and the least serious is detectable but is very close to the boundary of the healthy data.

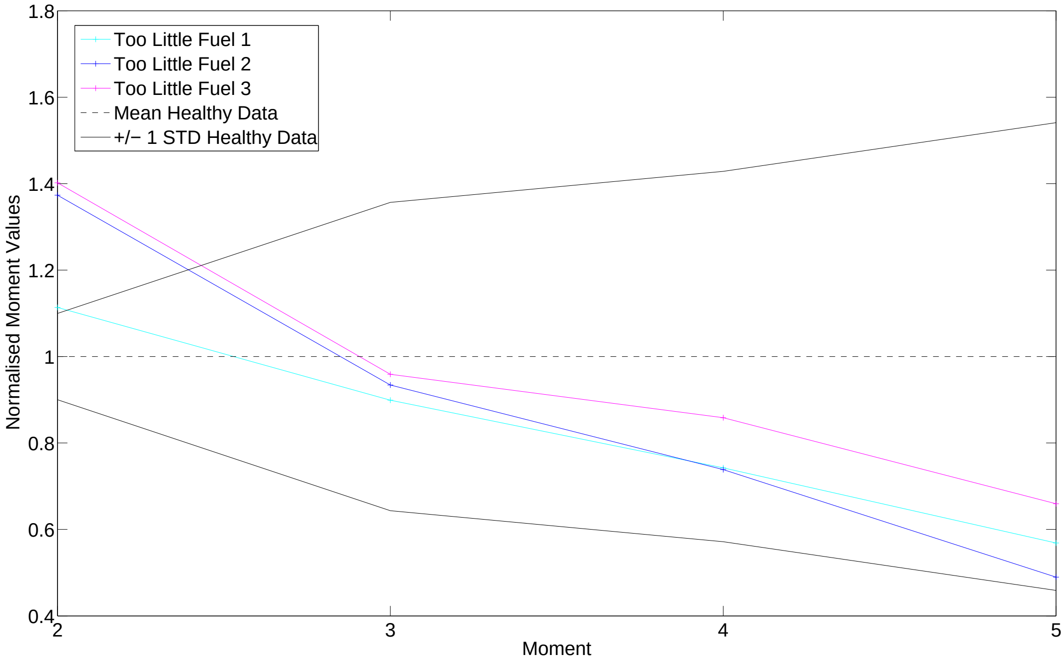

Figure 6.11: Moments of Healthy vs Too Little Fuel Fault at 750RPM and 25% Load

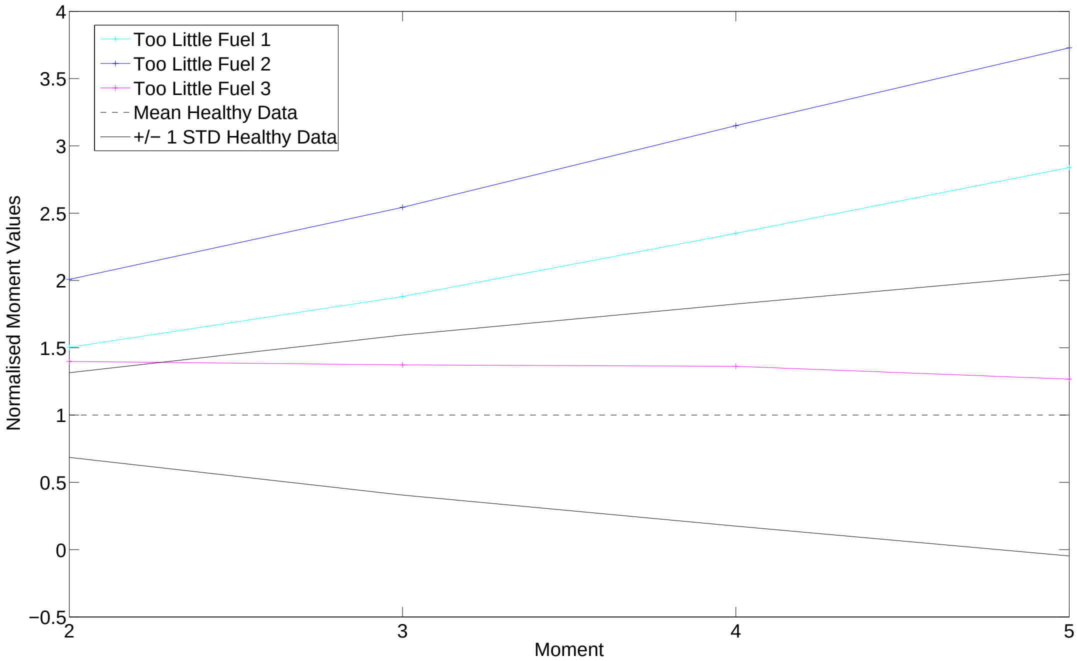

Figure 6.12: Moments of Healthy vs Too Little Fuel Fault at 750RPM, 25% Load - Channel 5

From this figure it is not easy to distinguish between the faulty and healthy data. Figure 6.12 shows that it is not an isolated result, even a microphone situated a long way from that of figure 6.11 allows for the detection of only two of the faulty cases, except at the second moment where all are detectable. This figure has also demonstrated the unreliability of this technique for distinguishing the fault severity as it is unable to detect the most serious fault at the third, fourth and fifth moments. However, looking at a number of plots together makes it more reliable, though the operator must know what they are looking for.

The results so far have looked at data for 750RPM and 25% load and channel one. Different channels have also been investigated to see how they relate to the results from channel one. Again, varying speeds and loads need to be considered especially when there is a seeded fault.

6.1.5 Too Little Fuel - Varying Speeds and Loads

The relationship of how healthy data is affected by speed and load changes, as well as how a fault of too little fuel being injected at the same RPM across the various channels has been investigated. The general conclusion is that the results have small identifiable relationships to reflect what is going on, but it is very unclear. An increase in load causes a reduction in the higher order moments, mainly in those that are representative of incomplete cylinder moments as they relate to the whole cycle. The increase in load increases the amplitudes in the lower orders indicating an increase in the work done by individual cylinders as a reaction to the increased load. The relationship between the various channels has shown a consistent trend that explains how the engine is reacting to the seeded fault, however, these channels lead to various conclusions about whether the engine is healthy or faulty. Given the identified effect of these parameters on engine output, the most appropriate way of investigating the effect of varying speed and loads on the engine with the fault seeded is to collate all the data. This includes the channel outputs for all speeds, loads and for all three faults. The collated data can then be analysed to see how successful the method is at detecting the faults.

The percentage of results that gave at least one successful identification of a fault existing was 88%. However, the percentage of results that gave a successful identification of all the faults, was 38%. From all the results, including those that didn't successfully detect a fault, only 14% of them were able to correctly identify the severity of the faults. Figures 6.11, 6.12 as well as A.1 - A.6 are a good example not only of the variability of the detection rate but also of the lack of ability of this method to detect the severity of the faults.

It could be expected that a technique may not identify the least serious faults but it would be expected to detect more serious faults consistently. The results show 63% detection rate of the least serious fault, 38% for the second most serious and 50% for the most serious fault at all moments. These results demonstrate that it would be incredibly hard to reliably use the statistical outputs to diagnose a lack of fuel injection on a Diesel engine. This could potentially be improved by taking the average of a larger set of healthy data which should 'tighten' the standard deviation boundaries. This would then increase the chance that data that falls within the healthy bounds currently, may be outside the new healthy bounds after they have been 'tightened'.

When looking at the same data, but this time with a change in criteria for a successful detection, the outcome was improved when only one moment is used as a success. The detection of at least one of the three faults was now increased to 100%. However, the percentage of the data that detected all of the faults was lower at 75%. The moment that was most common for fault detection within that 75% was the second moment. The percentage of results that were successfully able to order the faults by their severity was just 25% again reinforcing the lack of ability for the moments to identify fault severity. It should also be noted that out of the 75% of results that detected a fault, some were very close to one standard deviation from the mean of the healthy data. A good example of this is figure 6.11 and it would be debatable, whether these results when plotted with a mean and standard deviation of far more healthy data sets (tighter bounds) could actually fall within the healthy bounds, conversely they could be even more clearly defined as faulty. Again, this might be improved if more healthy data sets were available as it may produce a tighter band. This could then be compared against a faulty condition, averaged over a number of separate runs. Indeed the experiment would have been repeated to produce this data had the engine not been removed. As a result this will have to remain future work.

Despite the apparently high detection rate when using only one moment, it is questionable that this actually means the technique is reliable. For data to be detectable at the second order and then to become undetectable at the third, fourth and fifth moments would tend to say that even at the second moment the data is not distinctly different to the healthy data. Figure 6.11 as well as figure A.9 and A.11 are good examples of this. Indeed figure A.9 shows that even the second most serious fault is included in the data despite the fact it is in and out of the healthy bounds.

The detection rate for the particular moments is an important point to consider. The second moment gave a fault detection rate of 83%, the third 63%, fourth 58% and the fifth 63% for all of the fault severities across all of the data.

On the whole, the results demonstrate that there is no consistent results and that sometimes the moments will be greater than the mean and sometimes they will be lower for the same fault (Figure A.8). The method is, therefore, not very robust. It is not good at detecting all the faults for all moments and even when it does, it would not give an operator an accurate picture to the severity of the fault. There is also the issue that these tests contain six channels of acoustical data. Different channels give different interpretations as seen in figures 6.11 and 6.12. Therefore, if this technique were to be used, it should be carried out on a single microphone at an optimal location, as multiple microphones could provide the operator with mixed results.

Also, when considering figures A.1 - A.6 it can be seen that the thirteenth order only appears to exist at 750RPM. It would now appear it is limited to the first three channels and to a particular speed. This adds further weight to the suggestion that the thirteenth engine order tone is somehow related to a sticking valve or another issue.

6.1.6 Too Much Fuel

The fault was seeded in two different severities, fault one, the spill port was closed by an extra 0.6mm and fault two, by 1.2mm. These faults were not quantified but the fault was capped at 1.2mm as the first cylinder was running very hot at this setting. This is to be expected, injecting a greater amount of fuel into a cylinder will produce a more ferocious combustion, however, this is only true up until a point. Having too much fuel during injection will severely change the fuel to air ratio and will most likely lead to unburned fuel and sooty deposits within the cylinder. This will affect how well the combustion process is carried out. Typically, for the more serious fault in this series, it would not be unrealistic to expect that there will be a significant increase in incomplete combustion with a rise in sooty deposits and smoke in the exhaust. This would significantly increase the engine noise due to rough combustion.

Figure 6.13 reinforces the previous conclusions. It shows the dominance at lower orders for faulty conditions and also a slight reduction in the thirteenth order. The dominance at the lower orders is not in order of severity, the least severe is most dominant and the most severe between the healthy set and the least severe set. This plot doesn't show what would be expected, an increase in the dominance with the increase in fault severity.

However, it does show an increase in amplitude when there is a fault. This is either because more fuel is causing a more fierce combustion or it will increase combustion roughness. It does this by providing to much fuel so that it cannot all be burnt, producing combustion by-products and thus making the combustion process less efficient and increasing the overall noise. At the thirteenth order this will probably only cause a smaller drop in amplitude compared to load or too little fuel. This is because the uneven combustion from too much fuel will not contribute as much to the reduction in cycle roughness as too little fuel would.

Increasing the speed whilst maintaining the same load (figure 6.14), changes the lower order results as well as dramatically losing the large peak at the thirteenth order. Increasing the load further for the same RPM produces figure 6.15. These two figures combined with the figures in appendix A.2 are an ample demonstration of just how little of a trend there is in this data. Regardless of the speed or load they show just how hard it is to get a clear picture from the FFT as to what

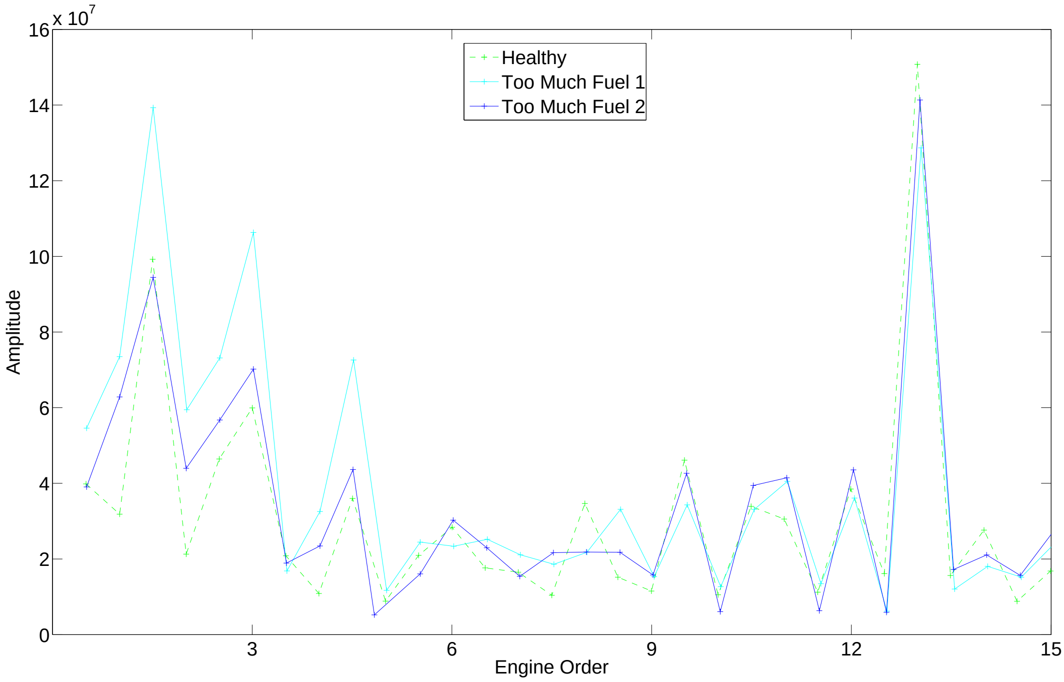

Figure 6.13: Peak Plot of Healthy vs Too Much Fuel Fault at 750RPM and 25% Load

is happening within the engine. They also demonstrate the complexities involved in using such a technique in an uncontrolled acoustic environment. Indeed, the acoustic environment was not investigated and this investigation is looking at the applicability of this technique with no knowledge of the surrounding environment.

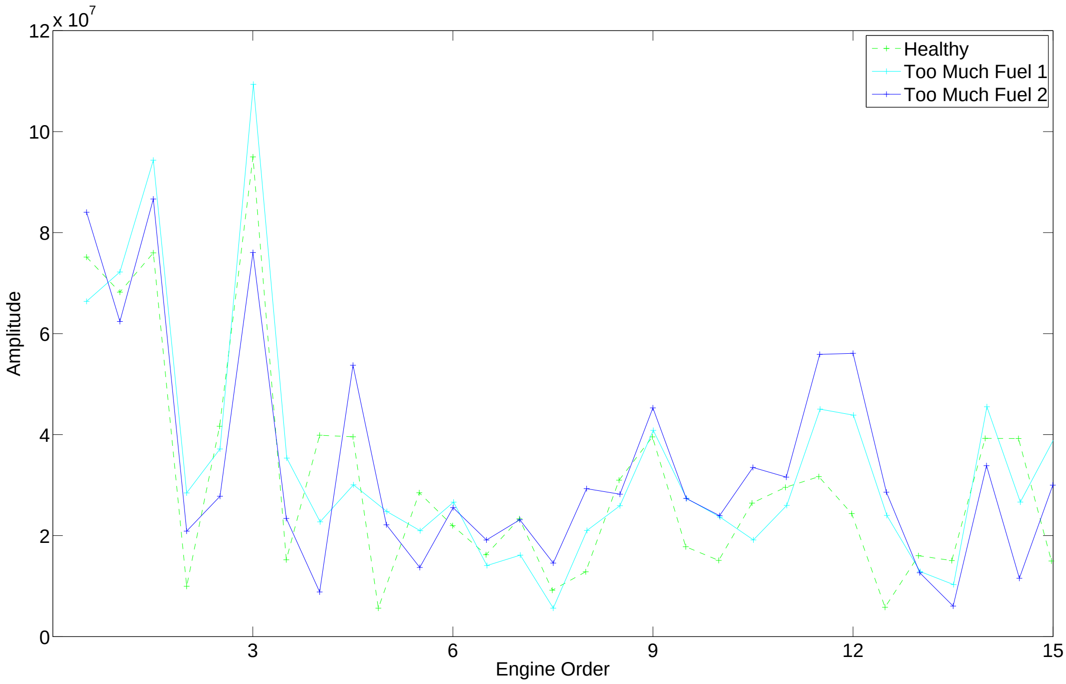

Figure 6.14: Peak Plot of Healthy vs Too Much Fuel Fault at 900RPM and 25% Load

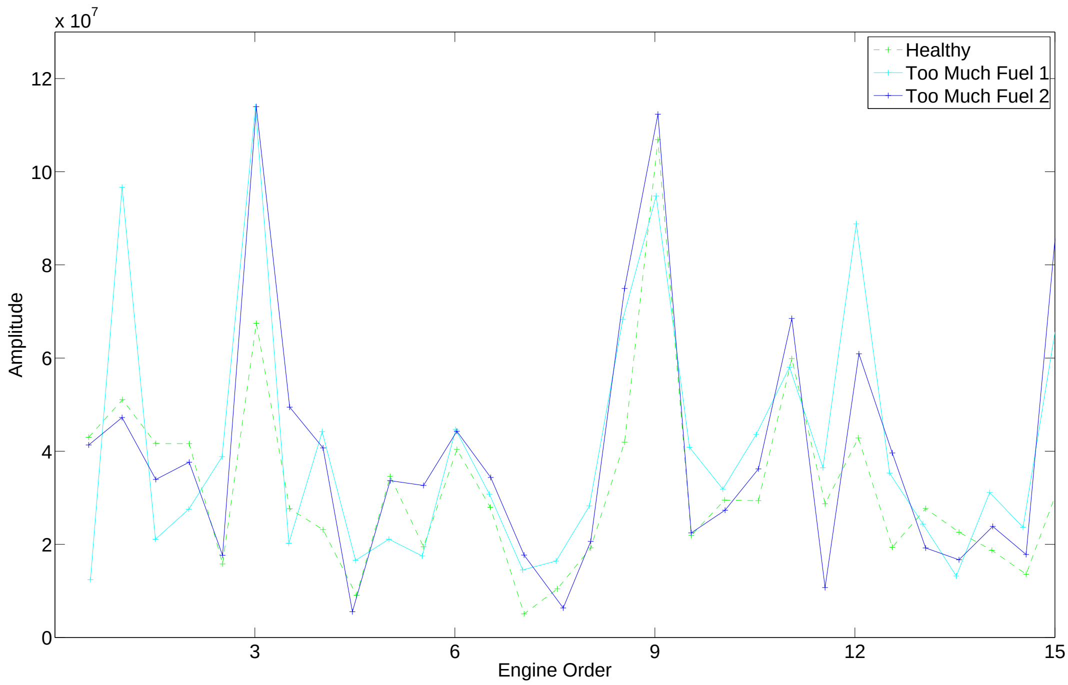

Figure 6.15: Peak Plot of Healthy vs Too Much Fuel Fault at 900RPM and 75% Load

Figure 6.15 goes on to reiterate the previous plots and demonstrates that even the increase in load from figure 6.14 would leave an operator bewildered.

The moments for the data in figures 6.14 and 6.15 were calculated and plotted in figures 6.16 and 6.17 respectively. These plots confirm the idea taken from the peak plot graphs, that there was little relationship between the data at 25% load compared to that at 75%. They show a dramatic difference in the results they provide and whilst on the whole they detect both faults it is concerning just how different each output is and how this may affect an operator when interpreting these plots.

Figures A.13 - A.15 are included to show that this unpredictability continues across the whole speed and load spectrum.

Just as data was collated for too little fuel, it was also collated from various speeds and loads for various channels of data to give the overall picture of just how effective the statistical data is for detecting this particular fault. To start, a successful detection is when it is clear at all moments. The percentage of results that gave successful detection of at least one fault was 33% compared to too little fuel which was 88%. The percentage of results that successfully detected all of

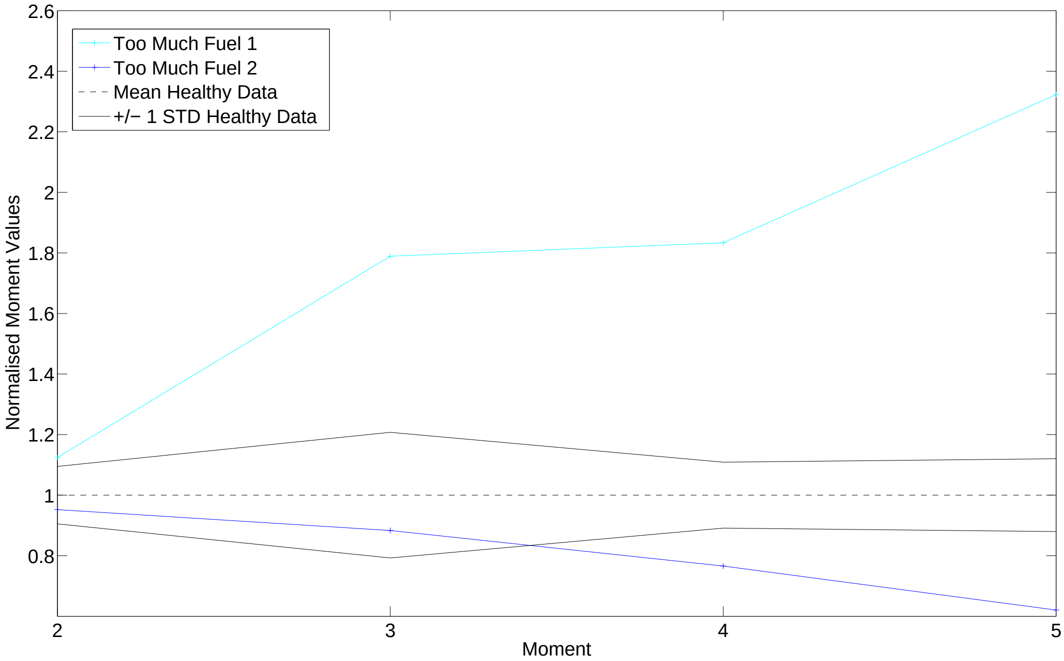

Figure 6.16: Moments of Healthy vs Too Much Fuel Fault at 900RPM and 25% Load

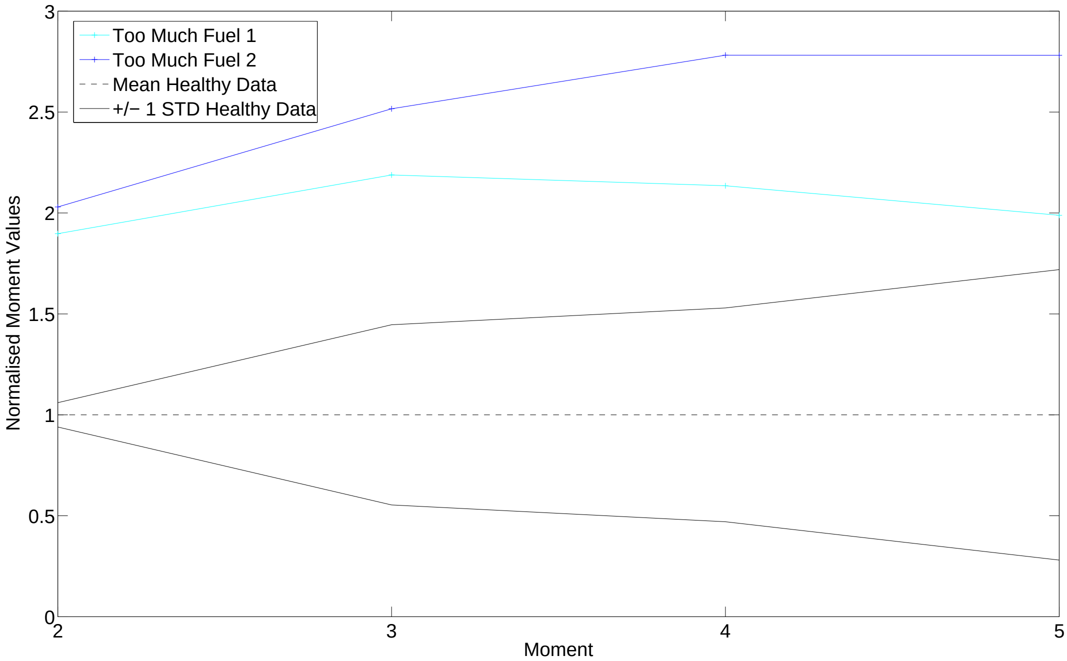

Figure 6.17: Moments of Healthy vs Too Much Fuel Fault at 900RPM and 75% Load

the faults was 17% a reduction of 21% from too little fuel. Figures 6.16 and 6.17 show how there is no consistency to the output, showing that the severity cannot be determined. The least serious fault is detectable 50% of the time and the most serious 33% of the time which would concur with the results of too little fuel. The expectation that the most serious fault would be more detectable that the lesser faults is again not correct. There is likely a good explanation as to why too much fuel is less detectable than too little fuel which has been touched on previously. It would make sense that when too little fuel is injected there is a large scale event of the flame extinguishing which would cause a large increase in engine noise. This would not be expected with too much fuel.

Changing the detection standard so that a successful detection level is lowered to at least one moment the chance of detecting at least one fault is 67% compared to 100% from the previous fault. This falls further to 50% for the detection of all the faults down 25% from the too little fuel fault.

The results for this fault agree and have similar conclusions to the fault of too little fuel. There are few consistencies within the results and the detection rate is significantly lowered for this fault. Even when allowing a successful detection to occur at a single moment the detection rate is too low. It is clear that the injection of too much fuel into the cylinder adversely affects the combustion parameters but it would appear not as much as when there is too little fuel, at least when analysing the results statistically. The increased detection of the least serious fault compared to that of a more serious one reinforces previous comments that the method is not robust or reliable enough.

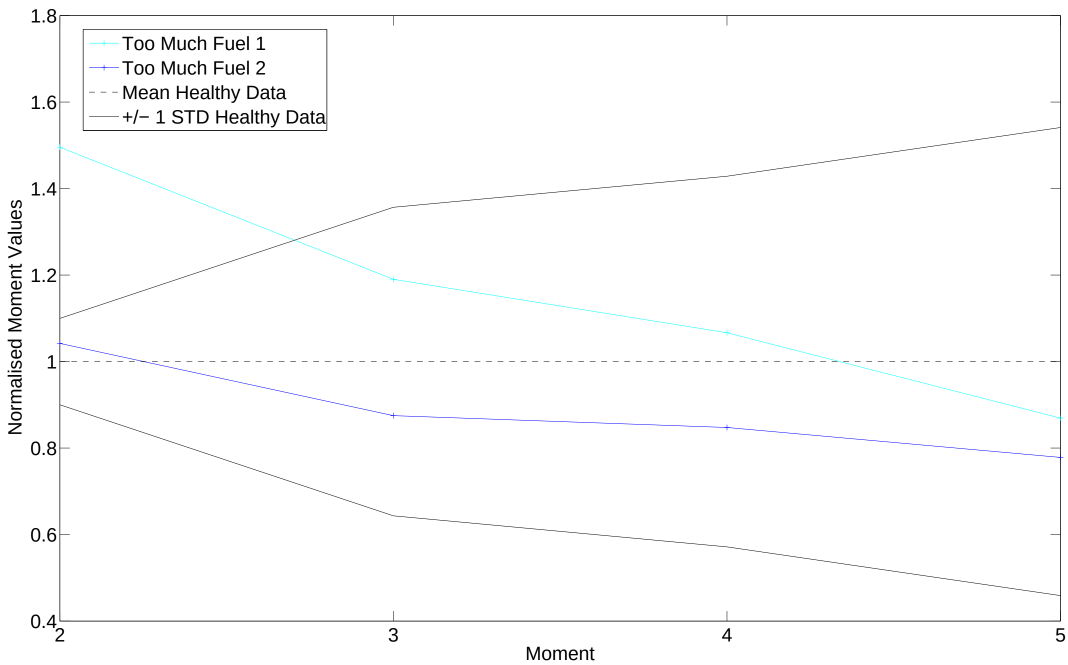

Figure 6.18: Moments of Healthy vs Too Much Fuel Fault at 750RPM and 25% Load

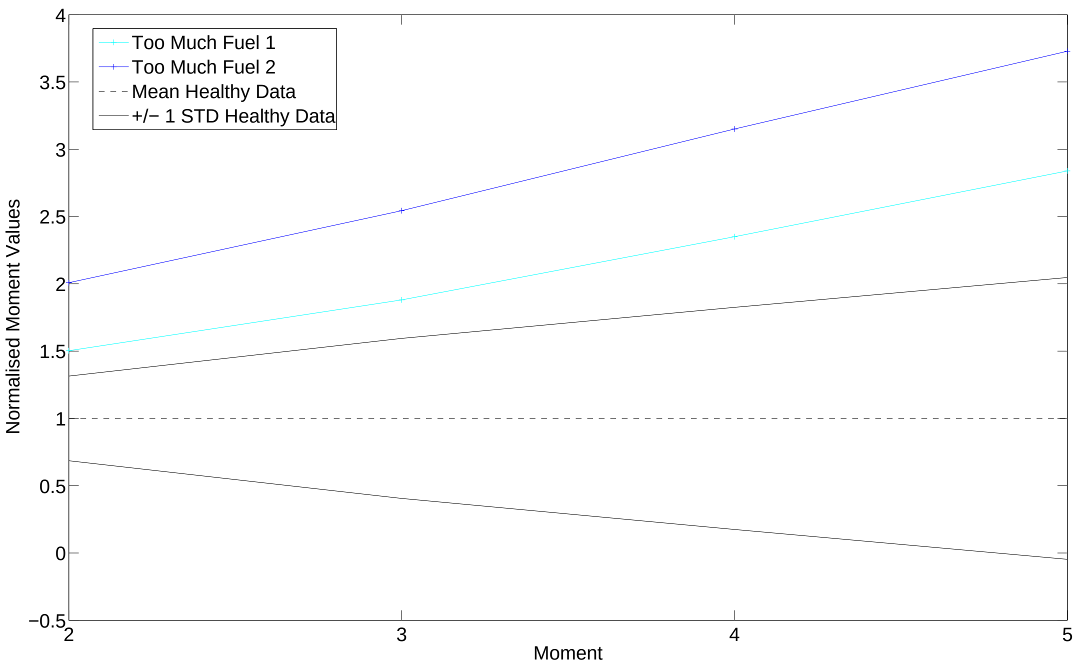

Figure 6.19: Moments of Healthy vs Too Much Fuel Fault at 750RPM and 25% Load - Channel 5

Figure 6.19 when compared to 6.18 which is the same data set, but different channels again displays the issue with this technique when used with multiple microphones. It can also be seen from the figures within this chapter that the thirteenth order is again not visible at 900RPM (Also visible in figures A.13 - A.15). Again every aspect of the results displayed here confirm the discussion from the previous fault. Whilst it is possible to detect a fault using this method it is not reliable.

6.1.7 Early Injection

Early injection is simulated by adjusting the injector clearance via the injector adjuster. A 65° turn of the adjuster equates to a 1° advance or retraction depending which way the adjuster is turned. There were four tests carried out, 1°, 2°, 4° and 5°. The 3° setting was left out when the initial tests were done due to time constraints on the test day. The intention was to return to complete these tests again, however, test facilities were not available. However, 4° and 5° have been recorded to compensate.

As Rothrock stated [51], a small change in the injector timing will have only a small impact on the engine running. However, it will have a more detrimental effect on the engine structure itself which should be detectable. A small change, of 1°, represents only 0.28% of the crank revolution. As the fault increases in seriousness, fuel will be injected at a lower cylinder pressure which means it may not burn as rapidly, running the risk of sticking to the sides of the cylinder and leaving remnants behind. The faults seeded in these tests may not be serious enough for this to occur, they should however, cause a premature combustion and greater more prolonged force on the cylinder head which has a direct impact on the crankshaft. An engine running even with the most minor infliction of this fault is operating outside of the designed combustion cycle. Excess stress will be placed on the engine components, as well as increasing noise, it will also cause premature wear.

Figure 6.20 reflects the same characteristics as previous results. There is an increase (in general) in the lower orders, especially the third order, with severity of faults seeded. Conversely the thirteenth order again decreases with fault severity, though not quite in fault severity order.

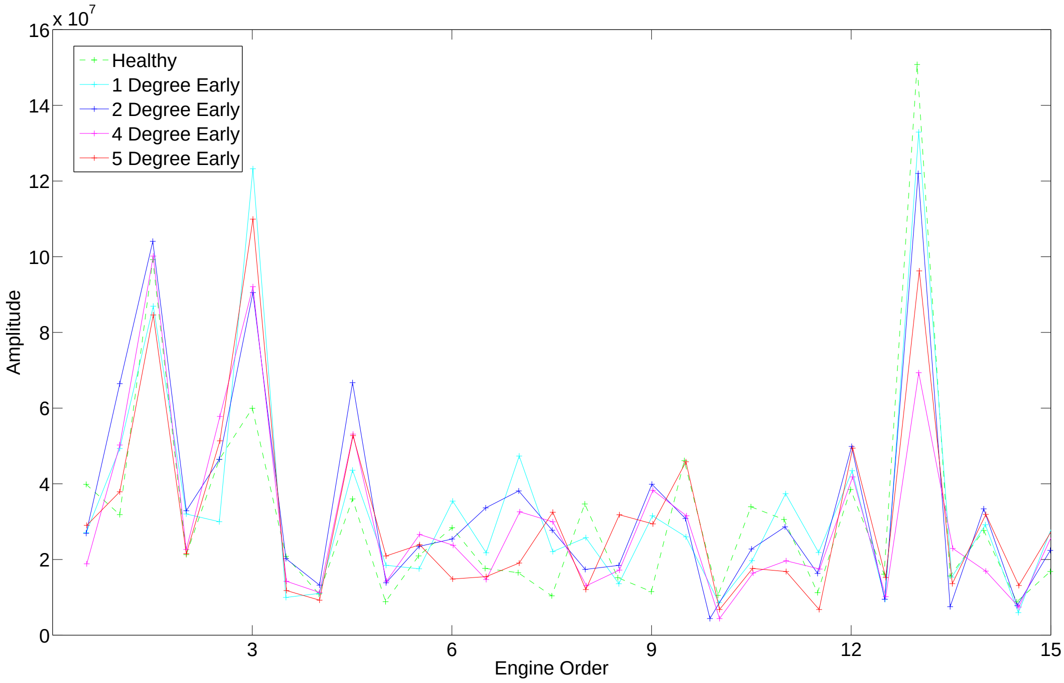

Figure 6.20: Peak Points of Healthy vs Early Injection at 750RPM and 25% Load

The same trends across the various channels occur, the shift from a fairly balanced distribution to little or no high order components with a rebalance to all orders as successive cylinders after the faulty cylinder fire. Figures 6.20 and 6.21 show the start of that trend which has been seen previously. Again the thirteenth

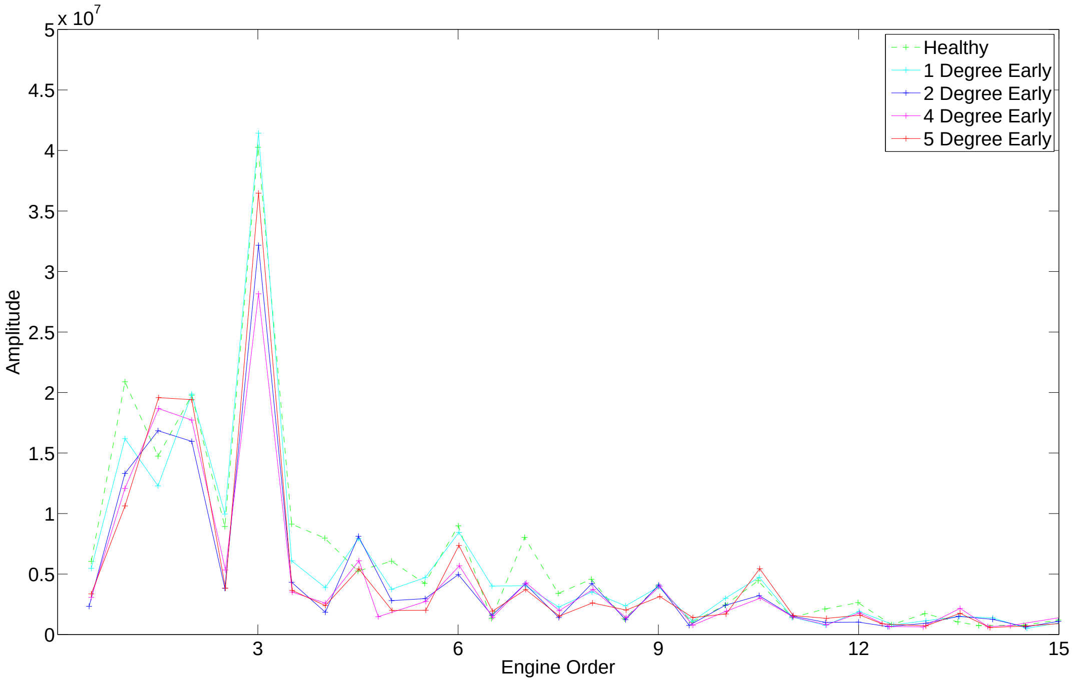

Figure 6.21: Peak Points of Healthy vs Early Injection at 750RPM and 25% Load - Channel 5

order does not appear on the any results above 750RPM, all the existing trends can been seen in results for this fault in Appendix A.3.

The moment plots for the above peak plots are shown in figures 6.22 and 6.23. They confirm that there is a strong variation between the channels which will provide successful results for one channel but not for another. Indeed they also show how varied the order is in the detection of faults, for instance, in figure 6.22 the worst case fault is located just above the second worst case. In figure 6.23 this has changed so that it is above the second and third worst cases and just below the least severe.

When the detection criteria is set so that a successful detection is one where the fault shows at all moments, the results are not encouraging. The chance of detecting at least one of the faults was 57% and all faults just 14%. In terms of order of severity, it was found that 4° and 5° earlier settings are usually confused in the output order and this contributed to 0% of the results being able to detect the fault severity regardless if they were able to detect a fault or not.

Relaxing the detection criteria to a single moment allowing a positive detection, the rate of detection for at least one fault rose to 94% and the rate for detecting all faults raised by 69% to 83%.

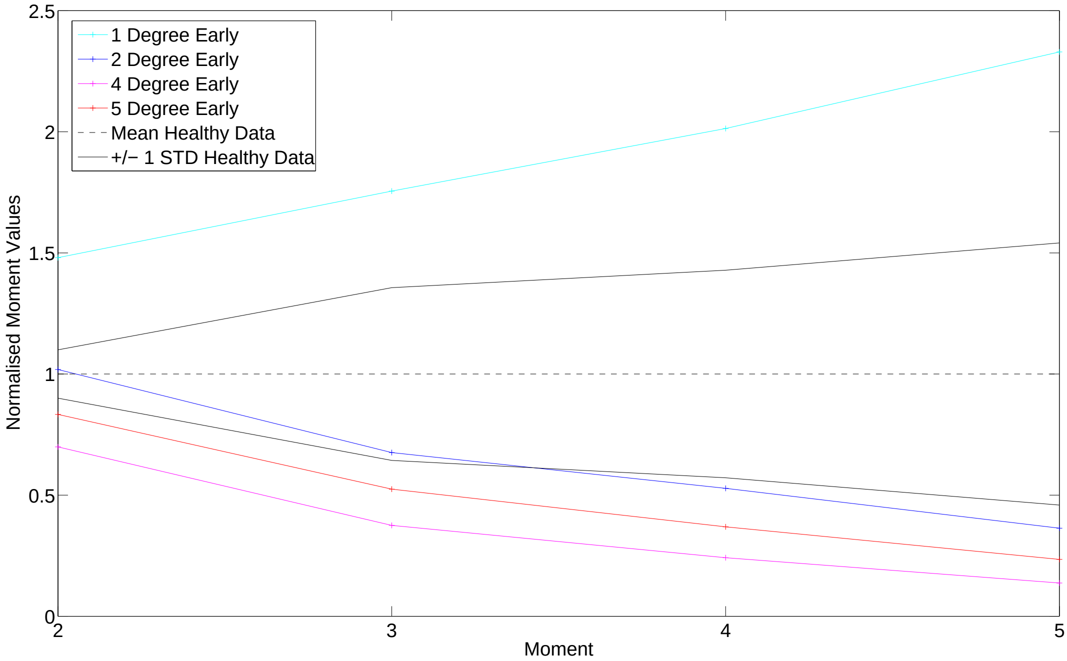

Figure 6.22: Moments of Healthy vs Early Injection at 750RPM and 25% Load

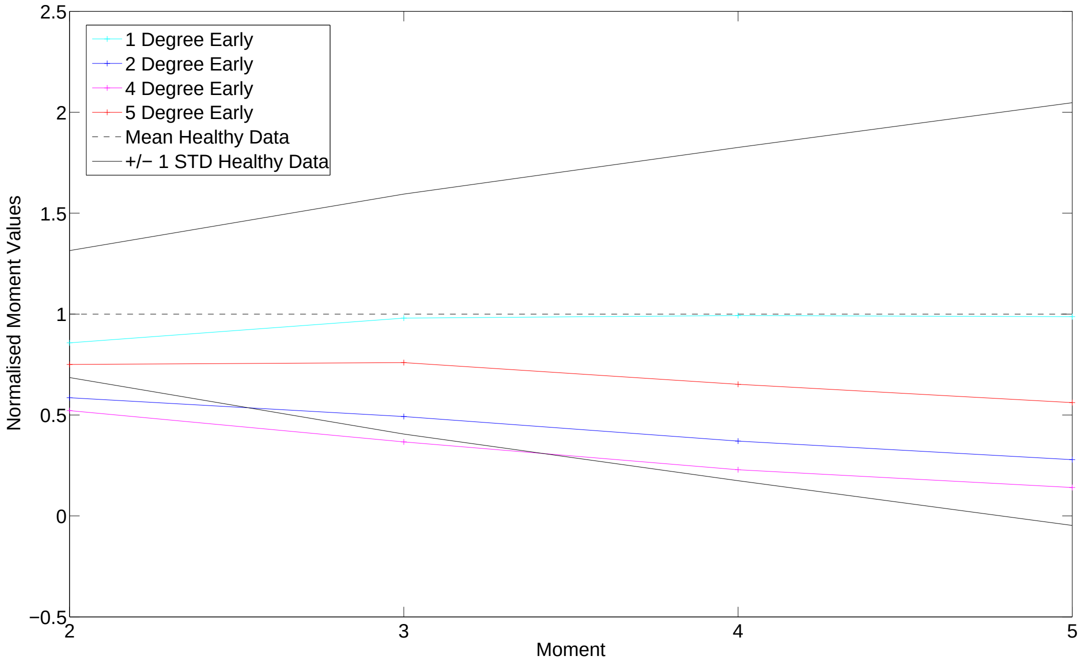

Figure 6.23: Peak Points of Healthy vs Early Injection at 750RPM and 25% Load

6.1.8 Late Injection

Late injection is seeded in the opposite way to early injection. Despite the difference in injection timing the results, again, follow similar trends to all the other results within this chapter. Again, there are higher amplitudes in general at the third order and the lower orders in general, with a reduction at the higher orders. There is also the same distribution between the channels relating to the response of the cylinders that follow on from a faulty cylinder in the firing sequence. The results can be seen in appendix A.5, they show that little information can be gleamed from the peak plots and again, across channels there is no real correlation (Figures A.49 and figure A.50).

The detection rate for this fault is slightly better than early injection. When the detection criteria is such that a fault shows at all moments the detection rate is 57% for the data to detect at least one fault and 14% of the results detecting all of them. These are the same as the previous fault, however, the ability for all the results to identify the correct order for the fault severity increased to 14%. When the criteria was increased so only a single moment is required the detection rate increases to 100% but only 29% of the results could detect all the faults at a single moment. This last result was significantly lower than the previous fault. The large variation in the ability to detect the fault only serves to reinforce that using statistical methods is a weak indicator of a fault existing.

6.1.9 Valve Faults

Valve faults were seeded by varying the clearances, only one setting was investigated due to time constraints before the facilities were removed. The most serious case, deemed safe to seed, was induced first in the inlet valve and then in the exhaust valve after the inlet had been reset.

There are no new points of interest from this data. The various channels still give conflicting results and the same trends and changes in the orders occur. The results can be viewed in appendix A.5. The results show that there is a good chance of detecting a valve issue, a 71% chance of detecting at least one fault which is detectable at all moments and 43% chance of detecting all faults at all moments. The results for a single moment are even better, with 100% for both at least one fault as well as all faults. From the data it was found that 93% of the results showed a detection at the second moment, 93% at the third moment, 79% at the fourth moment and 71% at the fifth.

6.1.10 Summary

The results from the Ruston engine have demonstrated the basic ability of the statistical processing of the acoustical data in detecting faults with the engine. They do well in showing the changes in the engine and how these change when there is a fault. This was expected due to the large spacing between the engine cylinders which allowed for less mixing of the acoustical signals before reaching the microphone as well as reducing the cross noise from other cylinders further down the engine. However, they often provide a very confusing picture when viewed across different speeds and loads. So much so that visually, the FFT and the peak point plots are of little use for fault diagnosis. There would be no way of concluding that a fault exists from the plots, though an indication could be given.

Looking at the moments gave a much clearer picture of the relationships between the data, both the different faults and also how different it is from the healthy data. It also showed how variable the data is in terms of fault diagnosis from channel to channel and how unreliable they are at showing the fault severity. Whilst these plots are an excellent way of giving a definite yes or no as to whether there is a fault present, there was far to much inconsistency across the five moments to be able to rely on this method. Indeed, looking at the detection rate of the results that were detectable, at all of themoments compared to the typical 95%+ when using only one moment, it is clear that the data is very close to and indeed encroaches within healthy bounds. The author would not classify these 100% success rates as a success at all due to the high level of data that was only detectable at a single moment or two moments from four. As such the results for those faults that are visible at all moments is the most reliable data and most reliable indication of a fault, these ranged from 33% - 88% with the average being 59%.

Clearly, with such wide variation between not only channels of data for the same speed and load but also between data from different speeds and loads this method cannot be trusted in live industrial scenarios to reliable detect these faults within a Diesel engine. Whilst a result of 88% or even the average of 59% for faults showing at all moments may seem like an acceptable detection rate, this was for a single set of data taken on a single day. Whilst the author would like to repeat all of these tests to see how these figures change this is not possible. Regardless of whether this could be repeated again or not, six tests per fault with six channels (more than 180 sets), consistently showed the complete lack of the ability to detect fault severity with some results showing the most serious fault well within the healthy bounds. There is no discernible way of identifying what the fault is, the results from the valve faults provide a prime example. Figures A.1 and A.19 show no discernible distinction between the faults and there is no way of knowing what the fault is unless you know that the data entered into the code is faulty in the first place.

In short, the statistical methods are a fairly weak indicator that a fault exists. Despite the increased spacing between the cylinders there is still evidence of blending of the signals from each cylinder as well as reflections from the room and additional noise. As a result any effects that may exist are diluted by changes in these other parameters making it extremely difficult to use this method as a fault detection system. It would, therefore, be expected that these results would be even worse on the Ford FSD engine due to the small spacing between the cylinders. The following sections will go on to present the results from the Ford engine.

6.2 Ford FSD425

The Ford FSD engine as well as being much smaller than the Ruston engine is also much faster. The size differences make acoustical signal collection from the Ford inherently more difficult. The size means the cylinders are located very close to each other, this will increase signal blending between cylinders something that was less of an issue on the Ruston.

6.2.1 Small Diesel Engine Airborne Acoustic Waveforms

The time domain signal for this engine looks the same as the one presented in figure 6.1 for the Ruston. Again the FFT of the data was taken, producing the expected results similar to the Ruston engine.

Figure 6.24 shows the FFT of one of the sets of Ford data up to 300Hz, again

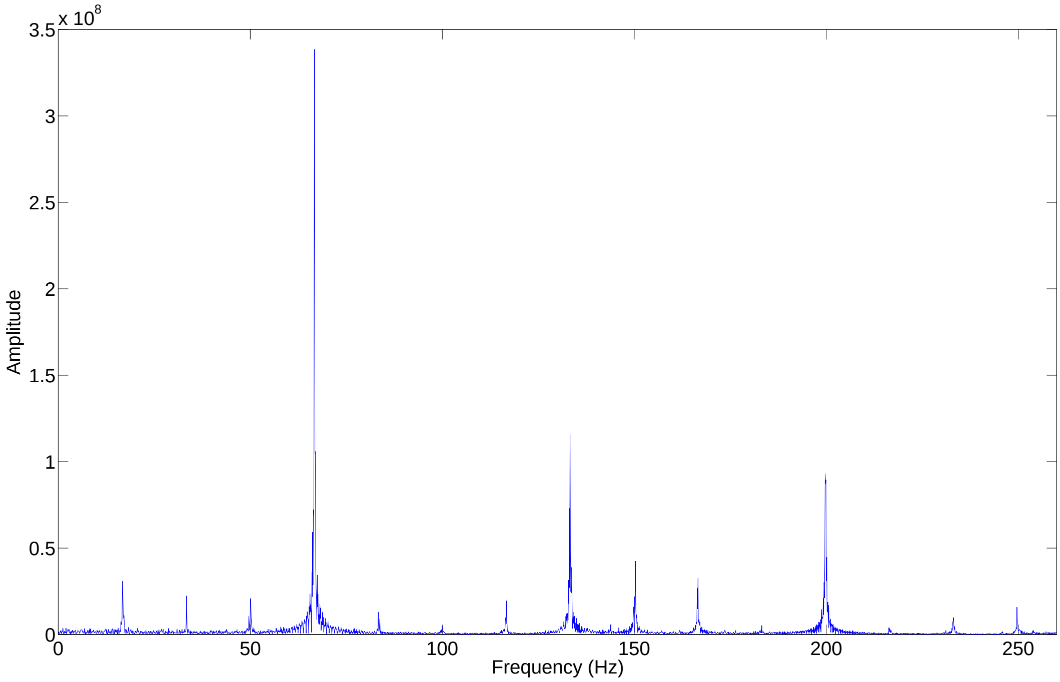

Figure 6.24: FFT of Healthy Data at 2000RPM and 0% Load

with a very low SNR, even lower than that of the Ruston. The Ford FFT data is not as sharp or exact on the relevant frequencies for this particular speed and load. Indeed for the revolution frequency in some of the data there is an error of less than 1Hz which naturally increases in margin with the progression to higher frequencies. This is not unexpected, it is caused by a small percentage error in the engine control system. For example, if the engine control system for figure 6.24 said the engine was at 2000RPM the plot should reflect a peak at 33.33Hz which it does, however a peak at 34Hz would equate to 2040RPM, a 2% error. With potential marginal errors in the microphones and preamplifiers as well as the engine control system, 2% is an acceptable level of error. Examples of the slight margin of error will follow shortly in figure 6.25.

In figure 6.24 the frequencies are correct and can be seen that the engine revolution speed of 33.33Hz and the corresponding harmonics such as 66.66Hz (large dominating peak) and 99.99Hz (Incredibly small) can all be identified from the plot. The half engine order of 16.6Hz is also present along with the harmonics of the half order.

6.2.2 Healthy Data at Different Speeds

Figure 6.25 shows that the speed change is again reflected in the FFT. The data at 1500RPM has shifted to frequencies that represent the change in the revolution speed, there is also significant broadening of the peaks. The peak 150Hz with the 1500RPM data is actually spread over 3Hz with multiple peaks within that space. All of the peaks for this data set are broader and have multiple peaks. The figure also highlights the issue described previously, where data is not located exactly at the expected frequencies. The data for 2000RPM is accurate whereas the data for 1500RPM is out slightly. For example, the rotational frequency should be located at 25Hz but the data shows it as 25.71Hz. This equates to an error of 2.84% or a representation of 1542.6RPM. The error continues, naturally, through the harmonics of the data. Instead of a peak at 50Hz it is seen at 52.23Hz, a peak that should be at 100Hz is at 103.6Hz and so on. The error is an inaccuracy in the speed reporting, as changing the value for the sampling time aligns all of the data correctly so that it appears at the correct frequencies. When changing the sampling time to align this data, it will make the data at 2000RPM have a constant drift from where it should be. Whilst it is possible to plot both of these set's of data to allow for experimental error, as it is confirmed that this is why the peaks are not aligned, it is not necessary.

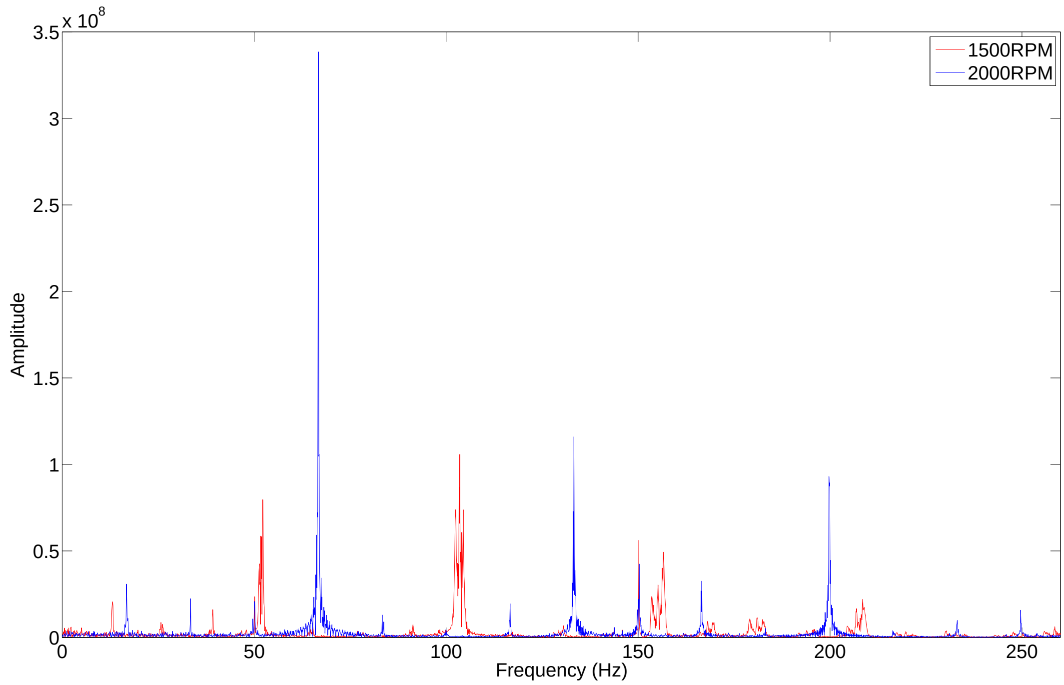

Figure 6.25: FFT of Healthy Data at 1500RPM and 2000RPM at 0% Load

Despite the variation in frequencies due to the difference in speeds and the broadening of the peaks the data, like the Ruston data, it will correspond to engine orders. Figure 6.26 shows both sets of data with respect to engine order.

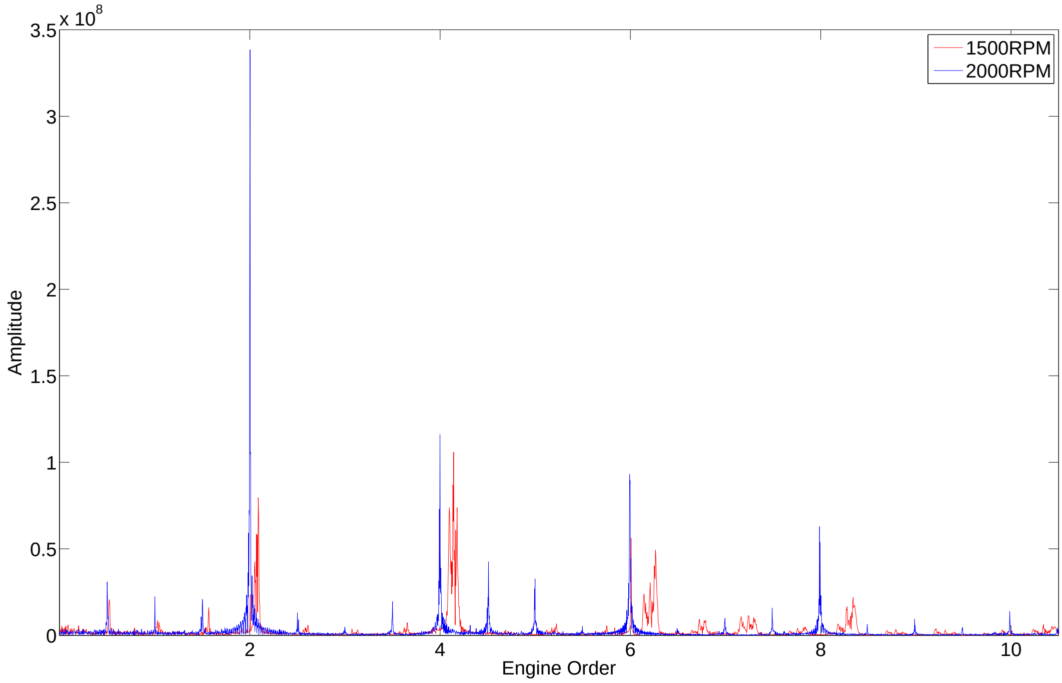

Figure 6.26: Engine Orders of Healthy Data at 1500RPM and 2000RPM at 0% Load

The slight error and the increase in the error with higher frequencies is evident for the data at 1500RPM. However, both plots collapse down together with these peaks representing events at specific orders. Similarly, both sets of data also equate to cylinder order as shown in figure 6.27.

For every revolution of the Ford crankshaft, two cylinders will fire. This is reflected in the engine order plot at two engine orders, or two events happening per revolution. This then reflects as one cylinder order to reflect that combustion is occurring, a single large event per cylinder cycle. There are also fewer and certainly smaller peaks at the half cylinder orders and the none half or whole cylinder orders representing a smoother overall cycle within the engine in comparison to the Ruston. This is likely to be due to the significantly smaller cylinder size.

6.2.3 Healthy Data at Different Loads

Figure 6.28 shows the same speed at various loads. Similar to the Ruston it can be seen that the frequency basically remains the same, whilst the amplitude varies.

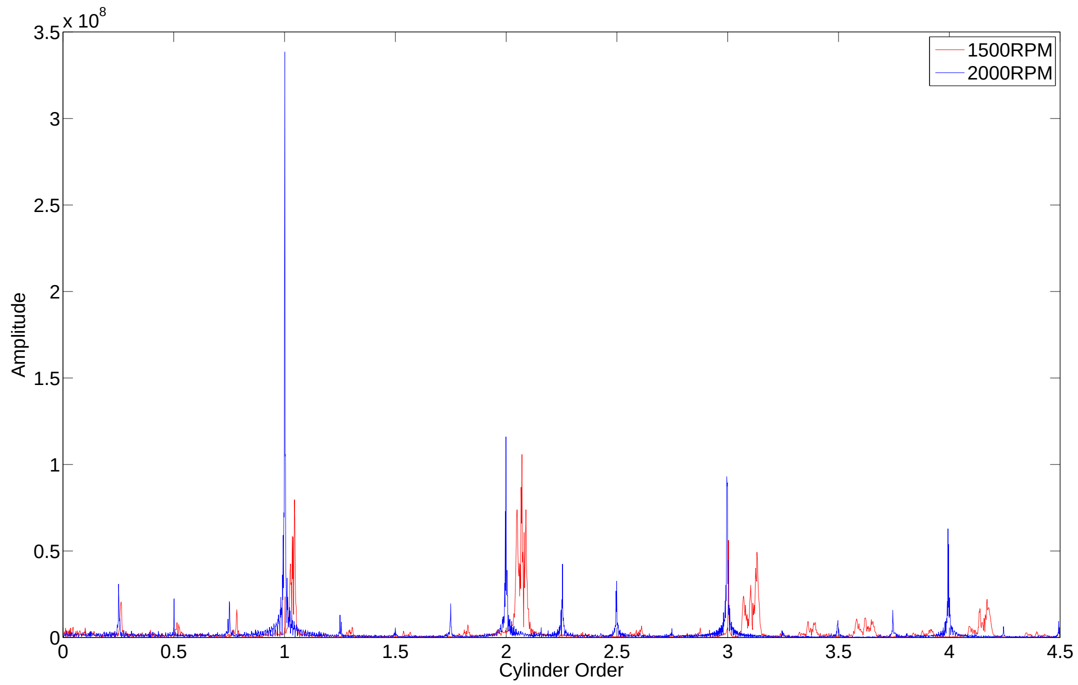

Figure 6.27: Cylinder Orders of Healthy Data at 1500RPM and 2000RPM at 0% Load

There is no correlation between the amplitude and the load except in the region of 133Hz which corresponds to two cylinder orders. Unlike the Ruston, however, the addition in these plots of broadening peaks with increased load (and different speeds). These broadened peaks also contain multiple smaller peaks before and after the main one. There were a number of guards and panels on the engine which were installed to meet health and safety guidelines. It is possible that these extra panels and guards are excited at particular speeds and loads and are made to resonate at particular frequencies. Whilst not ideal, the panels could not be removed and they do not affect the results adversely, they only make it harder to process.

As before, the FFT plot is very crowded and it is best to view only the peaks. Plotting these peaks against engine order figure 6.29 was produced.

Figure 6.29 shows the similarity in the data in terms of peaks occurring at the same engine orders and also shows that for different loads the amplitude is affected, though this varies in whether it is increased or decreased at the different orders. Indeed, this plot confirms that there is no correlation between loads and amplitude.

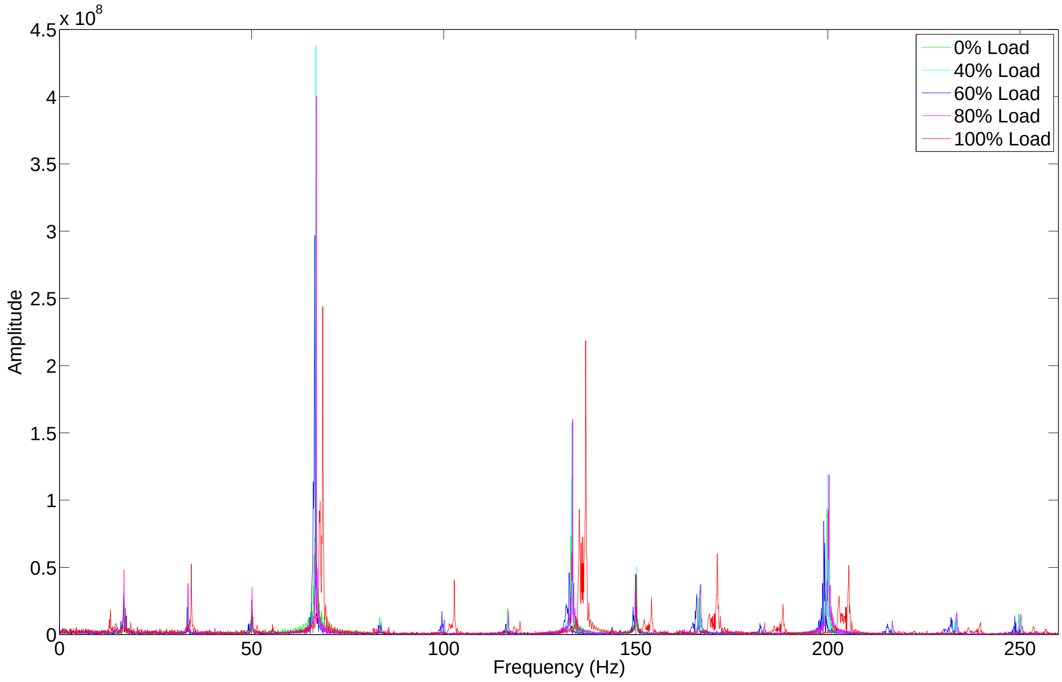

Figure 6.28: FFT of Healthy Data at 2000RPM and 0%, 40%, 60%, 80% and 100% Loads

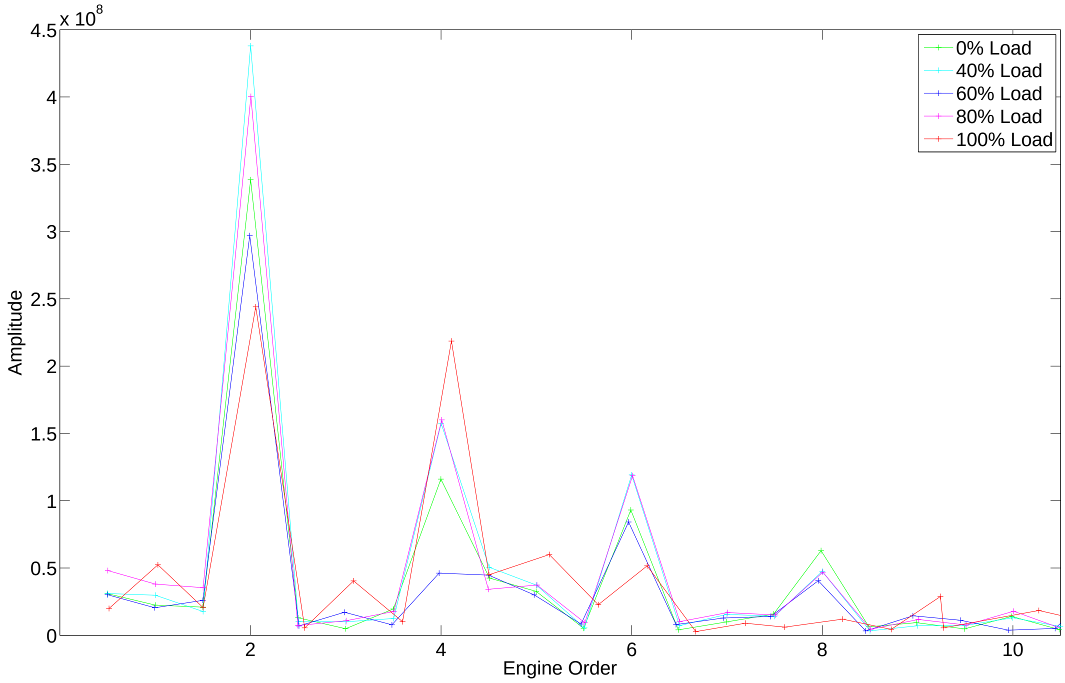

Figure 6.29: FFT of Healthy Data at 2000RPM and 0%, 40%, 60%, 80% and 100% Loads

6.2.4 Injector Opening Pressure Fault

The Ford FSD425 is a direct injection engine and the injectors on this engine are actuated by fuel pressure which causes the needle to lift from the seat when it is high enough to allow the injection. When the pressure falls again, the needle returns to the seat and injection is stopped. If this opening pressure is changed both the opening and closing pressure will be affected as well as the time at which injection takes place as each injector has a separate line from the pump. It will also affect how well the fuel atomises as it is the force at which fuel passes through the nozzle holes which cause it to atomise fully. Improper atomisation could lead to incomplete mixing of the fuel to air mixture as well as increasing combustion roughness due to uneven atomisation in the cylinder volume. Rougher combustion would increase overall engine noise which should be detectable acoustically. The fault was seeded in accordance with chapter 5.6.2 using two severities from the normal healthy opening pressure condition of 260 bar. Both 170 bar and 220 bar were simulated and tests run over various speeds and loads like all the tests prior.

Similar to the Ruston results, the engine orders which relate directly to the cylinder orders show a change between the healthy and faulty conditions. Also similar to the Ruston is the lack of fault severity ordering. Figure B.22 shows that at two and four engine orders, which relate to one and two cylinder orders, the more serious fault decreases the amplitude of the peak.

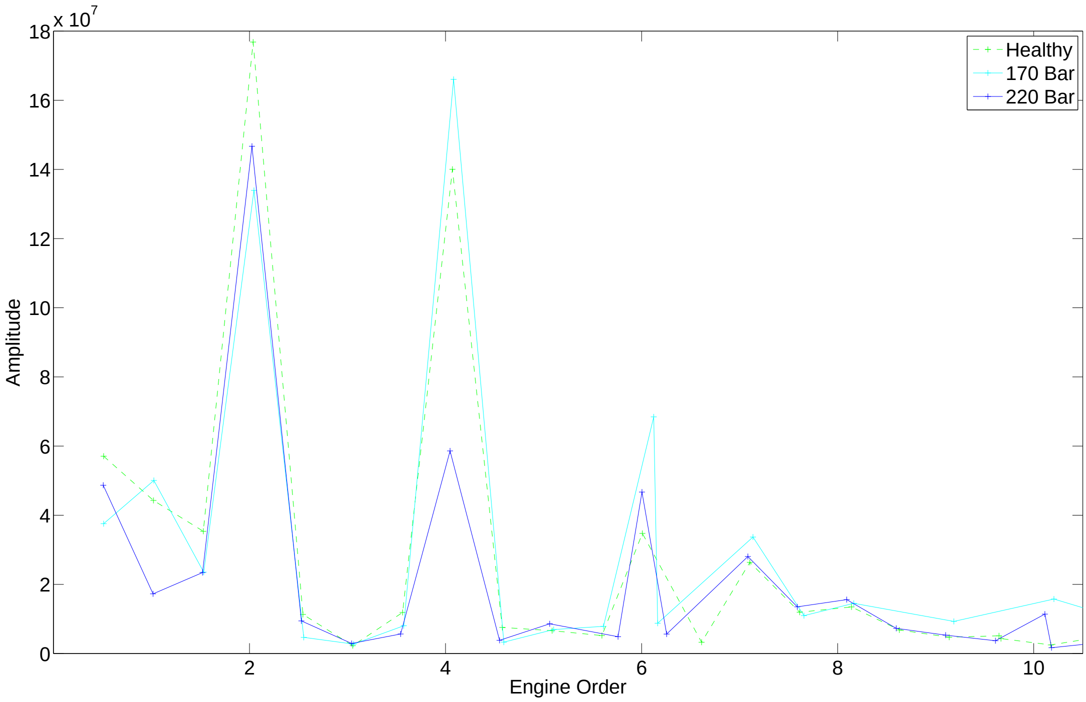

Figure 6.30: Peak Points of Healthy vs Varying Injection Pressure at 1500RPM and 40% Load

Apart from at the second, fourth and sixth engine orders the data sets compare closely to each other. It would, therefore, appear that there is a variation in the cyclic events but not in the cycle to cycle variations. This does not mean the variations do not exist, it is probable that the variations are not as detectable due to the rapid blending of the sources. The microphones were located very close to the head of the injectors which may be why the cyclic events, particularly for an injector fault are clearly visible.

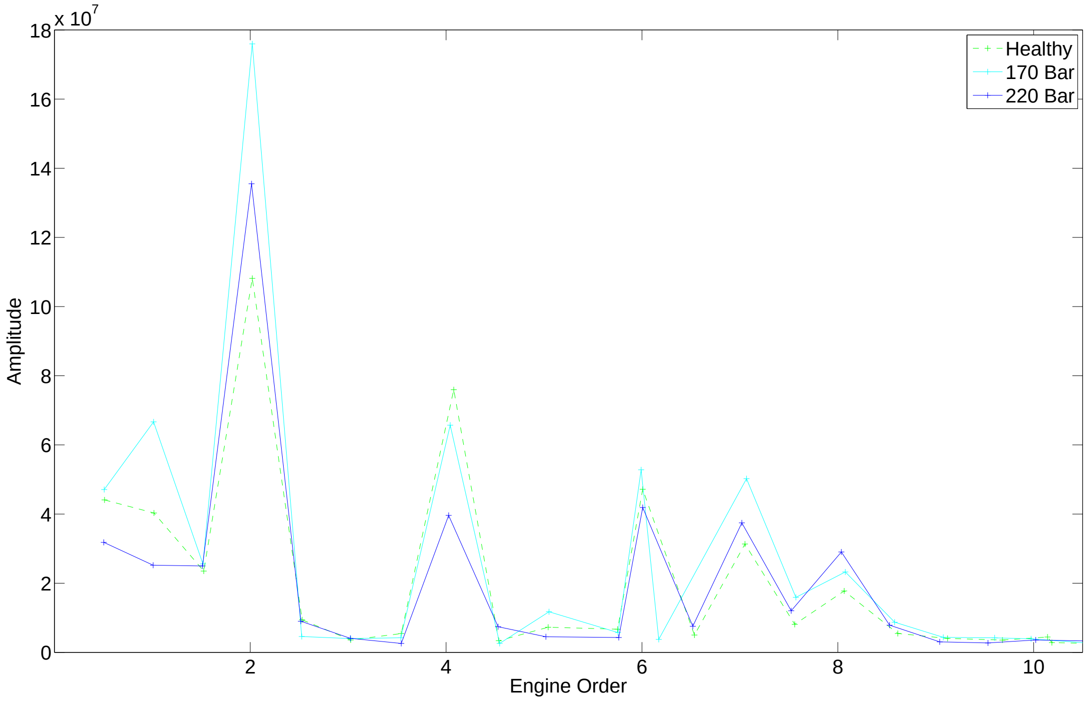

Figure 6.31: Peak Points of Healthy vs Varying Injection Pressure at 1500RPM and 80% Load

Figure B.23 shows just how little a change in load affects the output. Doubling the engine load has had minimal effect on the plot except at the second and fourth engine orders, where the amplitude has been significantly reduced on the fourth engine order. The second order increases with load which is most likely due to flame extinguishment because of incomplete atomisation. This is something that would be more seriously affected at higher loads as the engine is trying to combust harder to maintain a steady speed at the heavy load. These plots as well as the plots in appendix B.1 show that the speed and load has little effect on the plots and they appear to be more consistent throughout than the Ruston data plots. As well as speed and load having little effect on the plots, the data from different channels reflect little difference also. This is due to the rapid blending and can be seen in figures 6.32 and B.25 when compared to figure B.23.

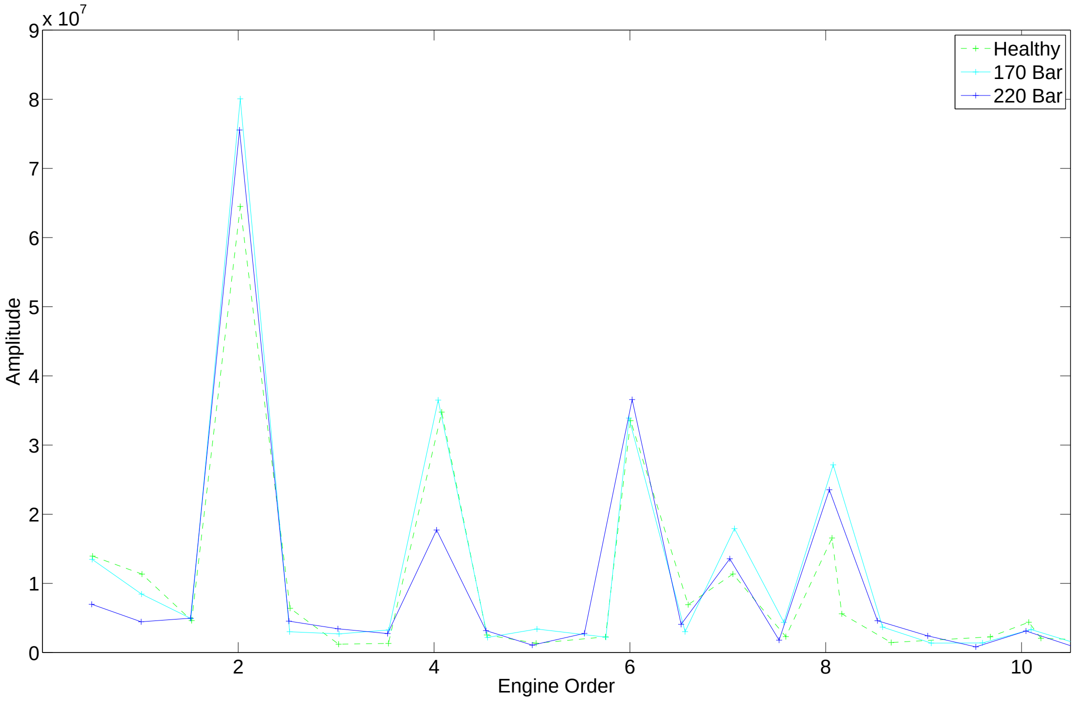

Figure 6.32: Peak Points of Healthy vs Varying Injection Pressure at 1500RPM and 80% Load - Channel 4

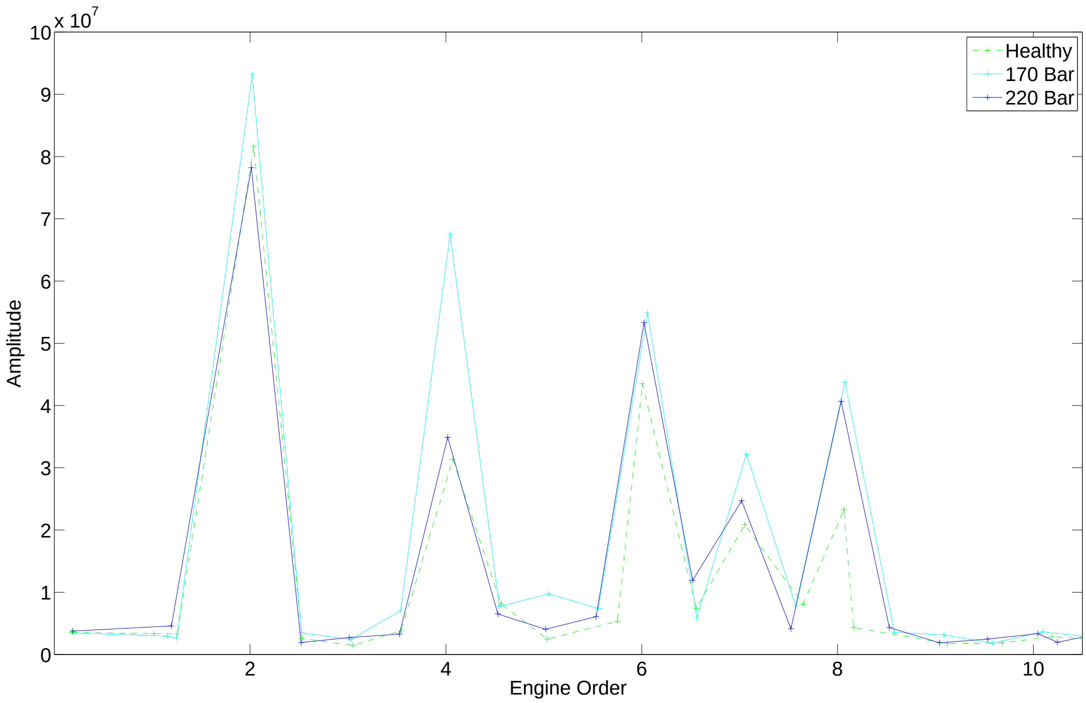

Figure 6.33: Peak Points of Healthy vs Varying Injection Pressure at 1500RPM and 80% Load - Channel 5

There is little variation between the microphones which were located next to the engine (Figures B.23 and 6.32). There was however, an increase in the higher engine orders when compared to the microphone that was situated a metre back from the engine, figure B.25. The similarity between the two datasets next to the engine was expected, due to rapid blending. The difference between those and the channel located away from the engine was also expected as it is likely to be affected differently by the room acoustics. especially the reflections and reverberations. These same differences, though not vast can been seen again in figure B.6 and B.30 .

Despite the more consistent outputs from the Ford data, the plots once again reflect the issues found with the Ruston data when being used for fault diagnosis. There is no way of interpreting the plots to give a clear indication as to whether there is a fault or not. In some instances the healthy and worst case fault are very similar. This can be seen in the fourth engine order in figure 6.32. This issue also means that a severity indication cannot be gained from these plots. Once again the moments were plotted and compared for the results and they can be seen in appendix B.1. These particular results indicate that independent of speed, the higher load data can on the whole distinguish between a faulty and healthy engine with an 80% success rate.

6.2.5 Valve Faults

The valve fault was simulated as it was on the Ruston engine. The most serious setting, deemed safe, was used. Clearance was changed on the inlet valve from 0.2mm to 0.7mm and the exhaust from 0.38mm to 0.76mm. Both of these faults are discussed in chapter 5.6.2. The results are again consistent with the injector faults. The engine orders are again showing a change between healthy and faulty conditions, unlike the other results there are no multiple severities in this data, just healthy and faulty. Figure B.19, shows that at the second engine order the peaks are of higher amplitudes when there are valve faults present when compared to the healthy data. This is not consistent throughout and it would appear that an increase in engine load reverses this pattern as demonstrated in figure B.22. It would appear that this trend is isolated to a load of 40% as at 80% the trends seems to reverse. Something that is consistent across the results, however, its the shift to higher orders with an increase in the engine load, though this is again more prominent in the data taken from channel 5.

The fairly random nature of this data again shows that this method of processing the data is not reliable. An engine at 1500RPM with no load produces results that would allow for easy fault detection, as soon as load is added, these results become meaningless. It is not even simple enough to say that these measurements should be carried out at no load as figure B.26 shows that a simple change in engine RPM now renders that theory incorrect.

The shift to higher orders with increasing load is clearer in the moment plots B.31 through to B.42 show. These plots demonstrate that the faulty data falls outside the healthy bounds at the higher loads. Looking at the results presented, 33% of the plots identify both faults at all moments, 42% detectable on one of the moments and 58% would detect at least one of the faults on one of the moments. These are not encouraging results.

6.3 Summary

The Ford results are, on the whole, a good reiteration of the Ruston results. However, the results did highlight some important considerations to take forward into the ICA processing. The data has highlighted potential for discrepancies between the recorded speeds and the actual speeds reflected within the data. This is most likely due to a small percentage error within the engine control unit. Looking at the data it would appear that this would equate to no more than 2%. It was also evident that the frequency peaks broaden as load is increased, as they broaden they gain multiple peaks which could present issues in future signal analysis.

The data agrees with the Ruston data in that there is no distinguishable patterns within the data that aid in fault detection. The healthy and the worst case faulty conditions compare well in some instances showing that like the Ruston engine, data it is not suitable for fault detection. In contrast to the Ruston data though, there is a smaller impact of speeds and loads on the data and it appears more consistent outside of the main engine orders. Due to this increased consistency, the valve faults show more clearly that as the engine load increases with these faults there is a shift in the data to higher engine orders. This is also most prominent on the microphone that was located 1m back from the engine. Comparing data from the microphones closer to the engine to the microphone stood back, there is a difference within the data. This highlights the importance of microphone positioning and ensuring consistency in their location.

In all the Ford data has confirmed that across two different engines analysing the data in this way is not a viable or effective way of detecting faults. There is no consistency or viable way to process the data to produce a reliable output that could be used by an operator to detect and diagnose faults.

6.4 Conclusions

The results clearly demonstrate that it is not viable to base conclusions on engine health from the outputs of this processing. Within this chapter the data has been interpreted by hand, however, even with an automatic system this would probably yield no better results. For a technique to be viable it must produce clear outputs for the operator that will remove the need for heavy interpretation and thus higher levels of knowledge. If at all possible the system should allow for automatic detection and warning. The data having been processed as shown within this chapter does not allow for any of this functionality. Even interpreting each result individually is impossible, or guess work at best.

The data shows that there is clearly changes at whole engine orders when the engine state is varied. However, events at none engine orders appear random at best. The none full engine orders are at a much lower amplitude, so there is potential to set a threshold on the data to only focus on the main engine orders which seem to be more greatly impacted upon when there is a change. As the main engine orders are related to cyclic events i.e the ones whose period is related to the engine cycle they should contain a lot of important information about the engines status. Focusing upon these parts of the data should yield useable and more simplistic data sets for comparison.

The varying of the speed has little impact on the data when comparing various speeds together, however, it can introduce new frequency peaks as shown in figure 6.4. As can be seen around thirteen engine orders, a large peak has appeared as well as one just after nine engine orders, though this is much less significant. There is no way to determine what is causing these peaks though one issue could be a change in vibrations throughout the engine when the speed is changed which is increasing these none cyclic frequencies. At whole engine orders the speed has much less effect than when the engine load is varied.

Looking at the moments of the data does little to improve fault detection and therefore it can be concluded that this is not a viable solution to proceed with. In theory data that is significantly different from the reference set should lie outside one standard deviation from the mean of the healthy data. In practice this does not appear to be the case. The results from these outputs was subject to interpretation and depending on how a successful detection was classified varied the results wildly.

Despite the fact that the health condition cannot be determined from these results, there are some useful conclusions that can be drawn to aid fault detection code moving forward. Any code that is written for fault detection needs to be able to cope with a discrepancy within the control system as well as potential double peaks within a main frequency peak. It would also be beneficial to set a threshold on the data to remove the lower level frequencies, simplifying the data and concentrating on the main engine orders. The following chapter will present the results of the ICA processing as well as presenting the program code that has been created for data comparison and fault detection.

Chapter 7

Independent Component Analysis Results

Independent component analysis should hold several advantages over the statistical processing. First, ICA looks for independent components (IC's) in the signals from multiple microphones by looking for the signals which are as independent as possible. It does this by looking at the non-gaussianity within the signal whereas the statistical processing actually looks at the data as a whole from each individual microphone. Another advantage of ICA over statistical processing is coping with the variations between microphones. This will affect the output and the relevance of the data in comparison to each other and there will also be effects of noise from other cylinders and other engine events which are of no relevance to the ICA algorithm.

There are, however, some issues that have previously been identified in chapter 4. The FastICA algorithm output is variable, from the same set of data IC one on a re-run of the code may no longer be located in slot one of the plot and could be in any of the five other locations. If it is a particularly weak IC, it may not even appear again. Using the same data sets that were used in the statistical processing, the FastICA algorithm was applied to see if there were benefits to using ICA for fault detection.

7.1 Processing Code

As shown in the previous chapter, the data can in some instances provide an idea of whether there is a fault on the engine, but it was neither reliable or conclusive. The severity of the fault could also not be identified. Whilst this is of some use, the application for which this research is based requires a definitive answer as to whether a fault exists, and ideally how severe the fault is. The statistical work has shown the detection of the least serious fault and not the most serious or vice versa and this is not a viable working solution.

As before, the processing code was initially investigated on the Ruston engine. It was believed this would provide larger and much more clear mixing matrix for the ICA maximising the likelihood of producing clear positive results. As was identified in chapter 4 each time the ICA is run on the same data the independent components will tend to be made up of similar components which will vary output location as well as be made up of varying smaller components.

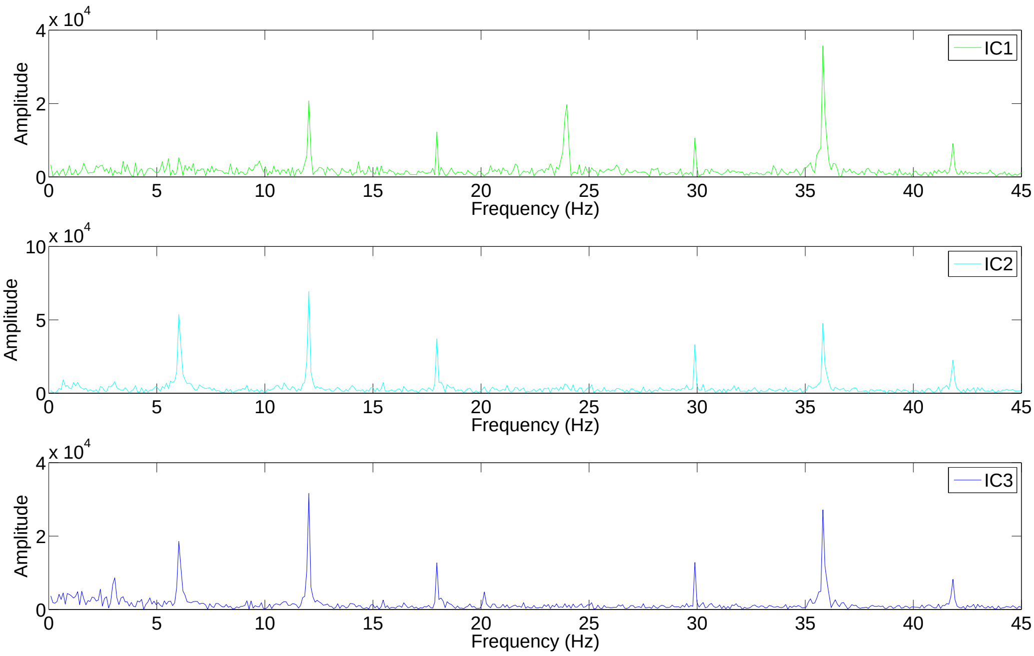

Figure 7.1: FFT of ICA Output, First Run, IC's 1-3 at 750RPM and 25% Load

Figure 7.1 and 7.2 show the first run through the ICA of healthy data at 750RPM and 25% load. Figures 7.3 and 7.4 show the same data but from a second run through the ICA to demonstrate how the IC outputs vary for each run. For example, IC one from figure 7.1 is IC two on figure 7.3. The initial issue with the ICA processing

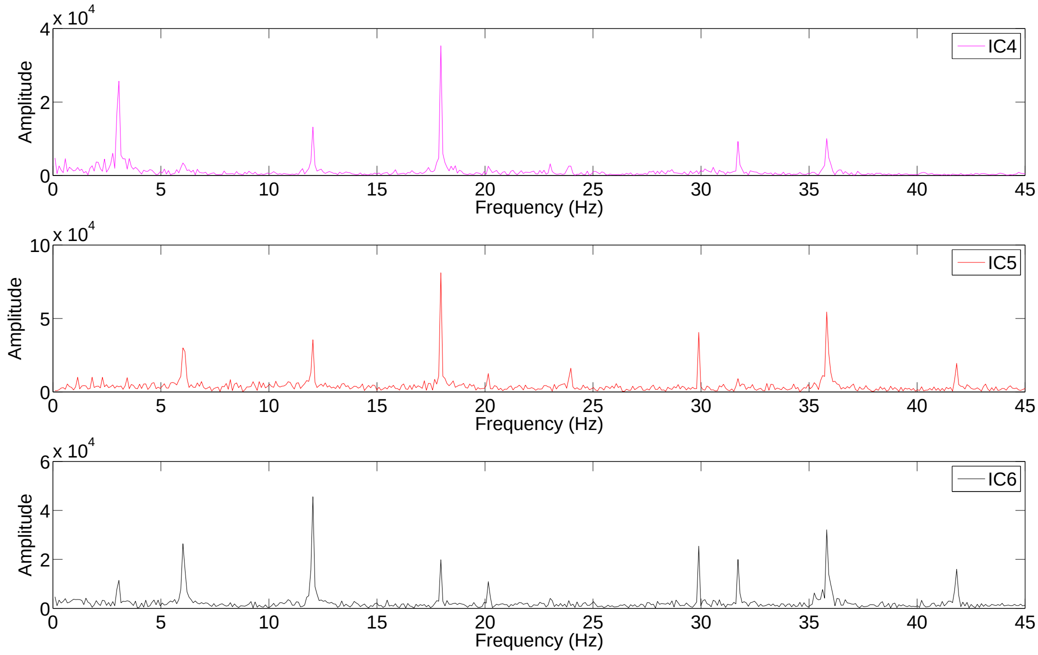

Figure 7.2: FFT of ICA Output, First Run, IC's 4-6 at 750RPM and 25% Load

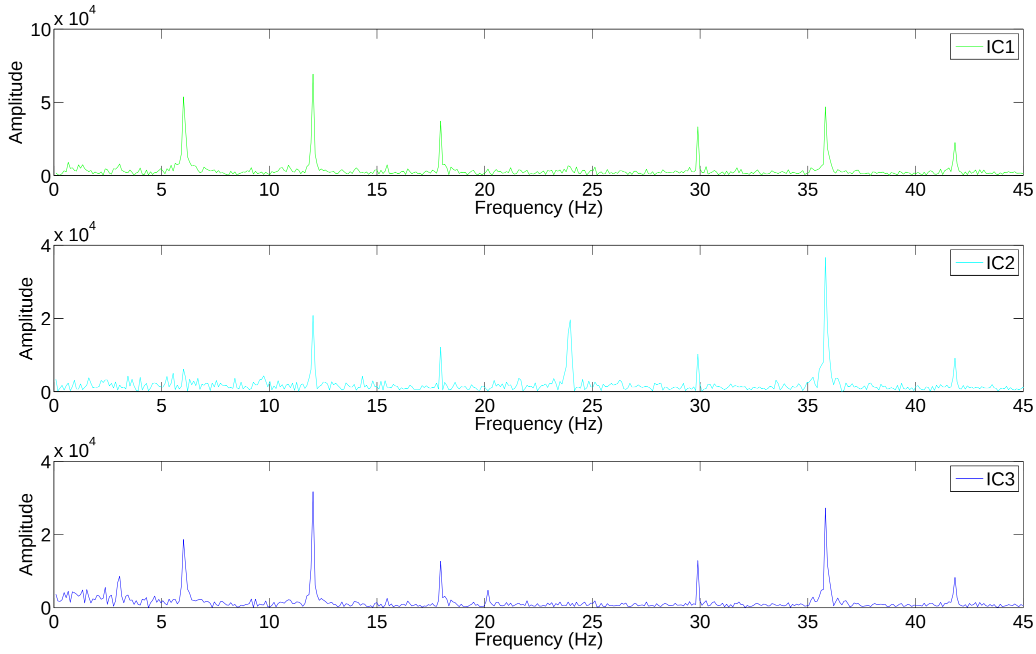

Figure 7.3: FFT of ICA Output, Second Run, IC's 1-3 at 750RPM and 25% Load

was how to compare like for like outputs from various data sets given the variation in the output.

The process flow for the program can be seen in appendix D.1 and will be discussed throughout this chapter. The processing code commences by loading in the relevant data sets and removing any channels of data from the data set which are not required. For the Ruston data this was not required, however, for the Ford

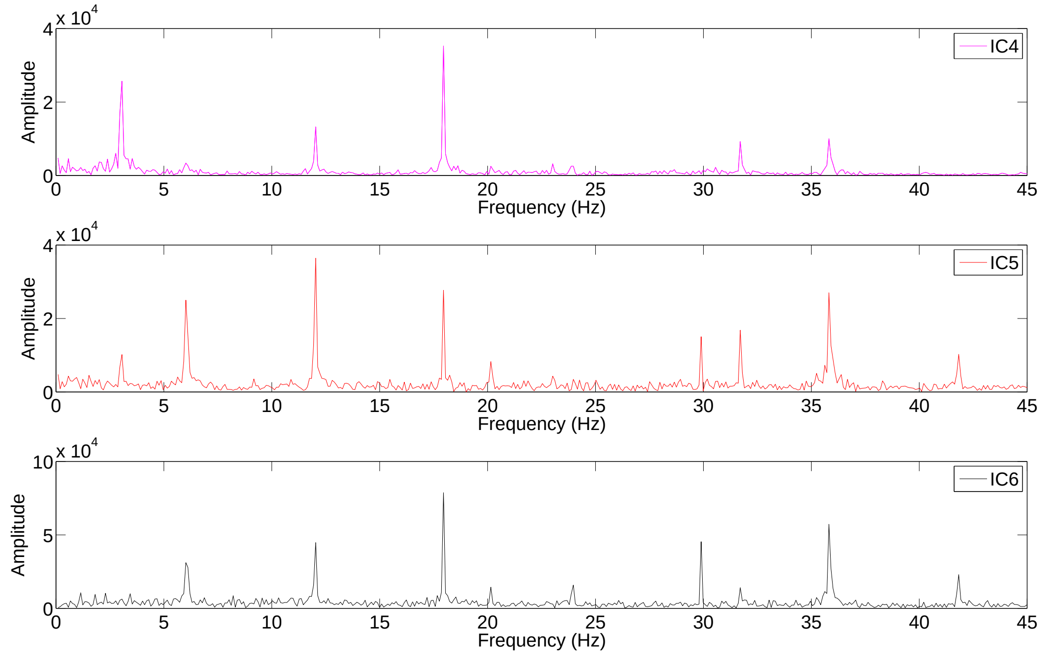

Figure 7.4: FFT of ICA Output, Second Run, IC's 4-6 at 750RPM and 25% Load

channels five and six were removed. Channel six was TDC data taken by another researcher and channel five for the microphone stood back from the engine, the reason for it being removed is discussed later. At this point the data is passed through the FastICA algorithm and the iterations are run on the data until it converges. This output is then processed using the Matlab built in FFT algorithms discussed in chapter 5. The process then proceeds to analyse the datasets to identify if they match.

7.1.1 Detecting the Peak Points

Figure D.2 expands on figure D.1 and shows how the code interacts to detect the peak points. The following section will describe this process. Following processing through the ICA algorithm the code proceeds to look for key features within the data. The signal threshold was set so that the code could search above this point and discard anything below. This meant the program code did not have to search all of the data which is time consuming and processor intensive as it would include all the small noise peaks which are not major features. This is where this research differs from others which work in reverse, filtering out the larger more dominant data and then filtering through the lower level data to detect very small changes.

Instead this research recognises that the change in the dominant data peaks is an inherent indication to the change of the operating mode of the engine. To filter out the lower level data the mean of the data was used as the threshold, multiplied by an integer that was set depending on the signal to noise ratio and the broadness of the main peaks in the data.

The code then analyses all the data points of the remaining data above the threshold. When it reaches a datapoint value greater than zero it assumes this to be a new peak, it compares the latest detected value to the previous stored value. For example the first point it comes to, that is a none zero value, has a value of one. When looking at the previously stored value it will be zero. The code, therefore, sets the new peak value of one in its memory and stores the corresponding frequency at this point. The code then moves on to the next point and this for example could be two, this is more than the previously stored value of one so the value of one is discarded and two is stored as the new peak with its corresponding frequency value. This continues, until this upward trend changes and there is a decrease in value. For example a stored peak is at a value of five and the next value the code reads is four. The code recognises that five is greater than four and knows that the data has peaked out at five at the corresponding frequency. It processes through the whole data set like this recoding the peak points and their frequency and amplitude values. There is a built in peak error check, where the code checks whether a previous peak point has been set within 20Hz of the current peak point to ensure that if more than one peak has occurred in a main frequency peak that the largest peak value is maintained and the others are discarded. This value was chosen as it allows a sufficient range for even the broadest of frequency peaks that might contain several peak points.

The code then compares the peak point values from all data being processed to the reference data set. The process flow for this can be seen in figure D.3. This was coded to allow for the slight differences in locating peaks which was seen in the Ford data, again due to minor speed discrepancies and control system error. It was also found that even in the Ruston data there were slight discrepancies between data sets and without this comparison it would not be possible to match the independent components (six per data set). To combat this, the code takes the peak point value from data set one and then looks ±4Hz and if the value in the other data set is within this threshold the peak point is then set to the value from data set one. For example if the program is running three sets of data and a peak point in data set one is located at 25Hz, 27Hz in data set two and 20Hz in data set three the output at this point in the program will become 25Hz, 25Hz and 20Hz respectively. The code at this point also 'best fits' the data to allow for IC's being output in a different order each time. The code essentially looks at the peak point results and matches a best fit solution to ensure that the data is always matched to the maximum possible.

Following the frequency checks the code then goes on to compare the amplitudes of these peaks to ensure they are within a certain threshold. The threshold was determined through trial and error. The values were determined by processing the healthy data sets for both engines through the code for both ICA and FFT processing. The values were chosen based on those which provided the maximum amount of outputs when comparing like healthy data sets. This is a viable method as it is providing the maximum output from the healthy data comparison whilst keeping the values for the threshold as low as possible thus maximising the potential to detect faulty data. All the data is compared to this threshold and when a data set is compared to the healthy reference set and it is within this threshold then it is classed as healthy. Anything falling outside of this boundary is said to be significantly different and thus potentially faulty. Based upon this process and assuming there is 100% accuracy it would be expected that comparing two healthy datasets at the same speed and load would yield a full six outputs in the case of the Ruston and five for the Ford. This is one output per measured channel and thus per IC. For a suspected faulty dataset versus a healthy reference set it would be expected that there would be no outputs, representing a significant difference in the data.

Based upon the expectations for the outputs of the data, the data taken from both engines was run through the FastICA Algorithm as well as being compared

Healthy		170 Bar		220 Bar		0.7mm Inlet		0.76mm Exhaust	
ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT
80	80	85	54	77	69	67	58	75	50

Table 7.1: ICA vs. FFT Percentage Success Using Pass or Fail Criteria

using only the standard FFT output. The results were tabulated and are presented in the next sections. The outputs of the program code depend on how the results are classified. Throughout the processing there were three possibilities. The first, and most simple method was to have a pass or fail criteria based upon the threshold. Therefore, when comparing two healthy datasets, if there was even one output then this was classed as a pass. When comparing a faulty set and the healthy reference set for a pass there had to be no outputs. If there was even one, then this was classed as a fail. An example of the output success from this method can be seen in table 7.1. This was determined to be not as informative as actually using the number of outputs as an indication as to the degree of matching. Therefore, the second possibility is to use the total number of outputs as the criteria, also based around the threshold. This is the main technique that was used and is discussed and results presented further in this chapter. The third and currently experimental possibility is to forget the threshold and to actually analyse the data to calculate the actual numerical difference in the data. For example, a perfect match would provide an output of one, data that is 20% different would have a value of 1.2 and so on. The initial investigations into this method seemed to work well on the Ford data. Certainly the healthy data was providing the expected results and similarly the faulty data when compared to this healthy data also provided good results. The Ruston engine, however, did not provide as clear cut results. The difference between healthy and faulty could be distinguished, but, the values for healthy versus healthy was not as expected. This process is something that would need to be expanded upon by future researchers.

7.2 Ford FSD425 Results

The Ford engine had a much smaller cylinder spacing than the Ruston. As a result, one would expect the faults to be more difficult to detect. This, of course, means that any advantages from using a particular processing technique are likely to be more significant. The data was processed by looking at the five channels, one per cylinder. The fifth channel was a channel that was stood back from the engine around 1 metre. This channel could be removed from the overall processing as it is 1m back from the cylinders. Therefore, it was a measurement of the resultant sound emitted from the whole engine block. Comparing this data to that of a microphone only a few centimetres from a cylinder will not provide as close a match as comparing the cylinder recordings, however, since all data sets contain all five channels this will not affect the results. For these results the channel has been left in. The comparisons were, therefore, made based on five channels.

Data was compared via the processing code such that healthy data would first be compared against healthy data and then versus each of the faulty sets and the output could then be tabulated. Results were calculated against the expected output of the program should things work to 100% of how it is theoretically expected to perform. This means for healthy versus healthy sets of data at the same speeds and loads it would be expected that the program matches all five channels of data and thus outputs five plots showing the matching channels. When making the same comparison with a healthy and a faulty set there would be no output expected as the data is expected to be significantly different enough to not match.

		Healthy		170 Bar	
Speed	Load	ICA	FFT	ICA	FFT
1500	20	3	3	1	0
1500	40	3	4	0	1
1500	60	4	4	0	0
1500	80	5	4	1	3
% Success		75	75	90	80

Table 7.2: ICA vs. FFT Results Example For Ford FSD425 Engine

An example of the collated data for some speeds and loads for both healthy and a faulty condition are shown in table 7.2, this table shows how the data is collated. The number of outputs from the program code is recorded for each speed and load and for both the ICA and the FFT processing. For healthy sets the percentage of success is calculated as shown in equation 7.1 and the faulty sets via equation 7.2.

$$\% \text{ Success Healthy} = \frac{\text{Number of Results Output}}{\text{Number of Tests x Potential Outputs}} \text{x } 100 \tag{7.1}$$

$$\% \text{ Success Fault} = 100 - \left(\frac{\text{Number of Results Output}}{\text{Number of Tests } \times \text{ Potential Outputs}} \right) \times 100 \tag{7.2}$$

Running all of the data gathered for the Ford data through this processing program the results shown in table 7.3 were collated.

Healthy		170 Bar		220 Bar		0.7mm Inlet		0.76mm Exhaust	
ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT
67.5	62.5	92	85	94	88	93	85	83	77

Table 7.3: ICA vs. FFT Percentage Success for Each Set of Data

The percentage success for the results in table 7.3 cover all loads at 1000, 1500 and 2000RPM. However, two sets of collated data were removed from processing as they did not yield any results when the healthy datasets were compared. The speeds and loads for these sets were 1500RPM at 0% load and 2000RPM at 60% load. There is potential that these results were affected by the engine guards which may be vibrating badly at these specific settings and affecting the data. This shows that the healthy data should be verified via the program at the time of data collection to ensure a good match. Suggestions for how the program may handle this in the future are discussed in chapter 8.

The results for the healthy data may not appear as good as the data for a faulty set versus a healthy reference set. However, given the highly transient nature of the signals measured from a running Diesel engine, to have a full five outputs would be exceptional. Table 7.2 shows that the number of outputs for the healthy data range from three to five, for other speeds one and two outputs have been recorded, though this is not common. If the final results were based on the requirement for three outputs instead of the full five to classify as healthy then the results would be increased to around 95% success. This would still provide a valid comparison, as the results for the faulty data versus the healthy data is based on there being no outputs at all. As the data in table 7.2 shows, very few results across all the speeds and loads for the faulty data ever produced an output, this trend continued across the rest of the data. Therefore, based on a more relaxed detection criterias for the healthy data the results would increase as shown in appendix table C.1.

Table 7.3 also demonstrates that across all of the data that the ICA has indeed provided an improvement to the data for detection. This is not unexpected as the Ford cylinders are located close together and the data will suffer from acoustic blending. Therefore, the FFT data will suffer from this issue as it is run through the program code to compare each of the channels. This will lead to a hinderance when trying to match the data between sets and channels. Whereas the ICA data will contain the most independent signals found in the data after it has been processed and should match better between datasets and channels.

7.3 Ruston 6RK215 Results

The Ruston data was processed in exactly the same way as the Ford, except the results were based upon six channels due to he increased number of cylinders. The same criteria was used to calculate the percentage success of the data, the results of which can be seen in appendix tables C.2, C.3, C.4, C.5 which were taken at a range of loads over 750 and 900 RPM.

As before, the results for the ICA versus the FFT for the healthy data appear to be significantly lower than the faulty results. This is due to the result criteria and how a successful detection is calculated. Reducing the number of required outputs for successful healthy detection to a lower number improves the detection rate. This can be seen in appendix table C.6. Whilst evaluating all of the faulty data against healthy data the maximum number of outputs ever seen was two.

This was also rare with the majority of results producing no outputs. It would, therefore, not be unrealistic to drop the matching criteria for comparing healthy data to three or even four output matches. Even with the criteria change, the FFT data still outperforms the ICA which is not the case for the Ford engine. There is no real explanation for this. The ICA data, whilst not providing a vast improvement does improve every other result over the FFT. This is likely a result of the cylinder spacing. The Ruston cylinders are well spaced and so the signals are already relatively independent. Therefore, the ICA has a reduced impact on this data compared to the Ford. The results are consistent for each fault, there is no fault that is not as easily detectable as the rest which is a good result and also shows the sensitivity of the technique to even subtle changes in the engine operating conditions.

7.4 Summary

This chapter has presented the program development that was built upon learnings taken from chapter 6 so that robust code could be written to automatically process engine data. The code allows for faster processing and removes the need for each set to be evaluated by eye. Instead the program shows the user the matching data, which provides a direct indication on how well the data matches and thus how similar it is. As a direct consequence of this the program can detect a fault. In short, if the data is very well matched then the data sets are the same whether it is a healthy reference set or a set of a known fault. If the data is not well matched then the sets being compared are significantly different. Indeed, whilst processing the results it was found that the program can distinguish between fault severities, healthy and faulty data and different faults. However, whilst useful and very powerful it does require a reference data set which for a fault comparison would assume that faulty data already exists.

The results tables show for both engines that both methods are able to distinguish between a healthy dataset and a faulty dataset. This is a vast improvement on the data processing in chapter 6 where there was no reasonable way to distinguish whether there was a fault or not. There are, however, some observations from the results. The healthy versus healthy data results in a poor comparison, though this is not due to an issue with the data but how the detection criteria are set. Reducing the number of outputs required for a successful detection improves these results whilst not reducing the integrity of the system. It is clear when comparing the data from both engines that the ICA has improved the results for both engines apart from on the healthy versus healthy comparison on the Ruston. The Ruston data has also improved to a lesser degree with the ICA processing. As previously discussed this is most likely due to the increased separation in the cylinders and thus a relatively independent set of data when compared to the rapidly blended data from the Ford engine due to cylinder closeness.

7.5 Conclusions

The processing technique demonstrated within this chapter could be used to reliably detect a fault on the Ford or Ruston Diesel engine in its current form if they were real world working engines. It would be able to detect and diagnose the faults covered within this thesis as the data for various conditions exists. In all, the post processing has shown the ability to produce reliable results without the need for extensive data processing, distortion and this lightweight method has been improved upon with the addition of a fast processing algorithm. The algorithm has had good success in various fields including engine health monitoring [29]. The algorithm has demonstrated the ability to improve the results from a standard FFT analysis and in practice the data does not take much longer to process with the algorithm.

An initial investigation at removing the threshold process for determining the level of matching in the data was also carried out. Whilst the program is successful here, it could yield issues on other engines or in different acoustic environments. It was, therefore, concluded that instead of having a threshold cut off point, producing a single numerical value representing the 'degree of match' of the data would be a better process. This would provide a better overall picture of the matching of the data rather than the program comparing each of the frequency peaks and a preset threshold. Initial results from this process have been encouraging on the Ford but less so on the Ruston. This subject is covered further in chapter 8.

The technique has also proven to be robust on both a small and large engine. Something not seen from other research. In addition to this it also demonstrates the ability for condition monitoring of Diesel engines in absence of any form of crank angle indicator, again something not seen in any other research or industrial systems. However, there are some issues involved with how well this technique will work practically. In the real world it would be unlikely that an operator would have a full set of faulty data covering every potential fault so that data collected could be compared to this. This is one reason why other researchers have stuck rigidly to aligning data to crank angle. There are a number of potential solutions to this issue and these will be discussed in chapter 8.

In all the current program developed within this research has demonstrated the effective ability to detect changes in the engine health status of both a small and a large Diesel engine. With known recorded faulty data it is able to compare this to healthy data and determine that there is a fault. Comparing this faulty dataset to other faulty sets of different faults and different severities the program will match the fault to the exact same fault and severity. It is able to achieve this in the absence of any other data, therefore, it does not require cylinder synchronisation. The following chapter will conclude this research and will aim to set out future work based upon the issues and challenges faced from the work presented within this thesis.

Part V

Conclusions

Chapter 8

Conclusions & Future Work

Maintenance has evolved over the last century. Moving from schedule based to predictive and condition based monitoring. There was an early correlation with noise emissions from machinery and its 'health'. With Diesel engines specifically, this did not have an impact until the middle of the century when engine speeds and pressures were ever increasing with advancing technology. Other disciplines lead the way with the field of vibrations, reciprocating machinery forming a strong and early basis for condition monitoring. Much vibration work was carried out on Diesel engines but an engine is not cyclic or as steady as a piece of reciprocating or rotating machinery. It is a highly transient system and, therefore, vibration monitoring going back thirty or more years ago did not yield very good results. As technology has progressed, namely sensors, computer systems and software techniques, vibration monitoring have been utilised for engine monitoring where previously the signal could not be manipulated sufficiently.

Across the board condition monitoring has become more prevalent over the last few decades due to the increasing demand for businesses to become more profitable and lean. It has also increased in popularity for health and safety reasons, as legislation has become increasingly stringent in the workplace as well as more stringent environmental regulations. Indeed in some industries condition based monitoring is a full discipline. Condition monitoring has manifested itself in many applications from aircraft to paper mills and has changed the concept of maintenance from schedule based to intelligence based. Condition monitoring has proven successful in many industry sectors as first discussed in chapter 1. Indeed, the research community is also reporting successes with fault detection of machinery including Diesel engines. From the examples discussed in chapter 3, it would appear that there are two main advancing areas for condition monitoring, vibration and acoustics. Vibration is mainstream for rotating machinery including pumps, compressors and fan blades. It has also been used in Diesel engine monitoring with much more limited success due to the highly transient nature of the system, signals are often highly contaminated with noise. Investigations into acoustic measurements in Diesel engine monitoring have begun, due to the rapid attenuation of the signal between the engine surface and the microphone which is showing to provide better results than vibration data by lowering the noise level and thus providing a better signal to noise ratio.

Little work has been carried out on Diesel engines specifically in the field of condition monitoring. Engine manufacturers of large Diesel engines have really only started to incorporate monitoring systems to their engines over the last few years, a far cry from car manufacturers. These systems, however, are not full blown condition monitoring systems. For example, the engine on a BMW 5 series when it is running low on fuel can detect the lean mixture entering banks one and two and report this via the computer system to the dash for driver alert. The system even knows to shut down the injector coils to prevent damage further down the system. Whilst, in essence, this could be seen as a condition monitoring system, the system output provides the user or maintenance individual with an idea of what the sensors are reading but does not offer a specific fault output.

Indeed, the work in this field is all very similar. It is typical that the researcher picks a fault, simulates it and records the data. They then proceed to use post processing techniques to visualise the fault. This is great, but it has no concept in the real world. Acoustic environments change, they are not ideal, the engine is tampered with, the sensors are not precision placed and the operator is not a thirty year veteran. Under these conditions how well does current research fair? Probably not very well.

This thesis, has covered an initial investigation into the condition monitoring of Diesel engines using acoustic monitoring. The research has focused on the real world, having a robust system that is actually useable, both to an operator and in an operating environment. The work has shown that there is good potential in the data to be able to detect a change in engine status from the healthy condition. The work has taken a different tact to existing research that concentrates on complex signal processing, filtering and ideal experimental setups. Instead of filtering the data to find the actual small features within a signal that are causing the issue, which relies on knowing the crank angle, this research looks at the bigger picture. It does not require crank angle or any other known signal to be able to align data. Going back to basics it was determined that the overall recorded signal changed enough between the healthy and faulty states to be able to determine a difference in the engine health.

Out of the two measurements covered in this thesis acoustic measurements have the widest scope. Existing research has shown that acoustic measurements are sensitive enough to even detect the tappet clicks of the injectors and valves, something the initial investigation into electrical measurements practically rules out. Despite this the electrical measurements hold promise as it is cheap, non-intrusive and can be carried out without starting the engine. The acoustic measurements offer advantages over vibration measurements not only in clarity of data but reduced sensor requirements. For vibration measurements it is common place to use two sensors, one in line with piston travel the other perpendicular to the cylinder to detect vibrations in both planes. If all cylinders are to be monitored this would be 12 senors on the Ruston engine, this would have required a larger and more expensive data acquisition unit. Acoustic sensors also do not interfere with the engine in anyway, vibration sensors must be mounted on the engine which requires stripping of engine paint and likely a permanent base mount glued to the structure. This is both costly, impractical and not viable in all circumstances.

This chapter brings the work into context by drawing overall conclusions from the different strands of research as well as looking at areas that could be investigated moving forward in the future.

8.1 Conclusions

This work has successfully shown that acoustic signals can be used to detect and monitor conditions and to detect faults when they occur. Through comparison of data with a reference data set, the health of the engine can be determined to the extent that if the reference set is a known fault this will compare favourably with another dataset with the same fault. Therefore, the current work is a full detection and diagnosis package in its early stages. It has also demonstrated that this is a practical solution that would work in a real world situation. It has shown promise on two different class of engines in two acoustic environments and has shown to be robust. The robustness has been demonstrated in the microphone placement. Although every care was taken to place the microphones exactly as they were before they were moved for certain measurement procedures it would be impossible to replace them exactly, despite this the technique has still worked well. The laboratory rooms also resembled engine rooms at some of the industrial sites the author has worked on with over head pipes and other noise generating systems within them. This provides a realistic test environment for the program. The data has also shown good success across the full range of speeds and loads which will allow the flexible use of this technique in the field both with and without load bank testing. The initial tests without load banking should provide reliable results to give a service company the confidence to request load bank testing by their client. This is a major step forward for Diesel generator maintenance companies.

Despite all the positives some issues did arise during this work. One such issue was the unexpected lower success rate for a healthy data detection compared to the fault detections. This appeared across both engines and how this data is ultimately interpreted is down to how the data is classified. When the criteria is based upon requiring a full set of outputs compared to a reduced number of two or three it greatly impacts on the perceived success of detection. Looking at the data across both engines as a whole, two to three outputs would be a suitable criteria set for matching of healthy data. This increases the success to the eighty and ninety percent range. Another factor which may be affecting this rate is the threshold. An initial investigation has also been started at removing the threshold classification system and replacing it with a percentage matching system. In theory, two identical sets in this system would produce an output of one to represent a perfect match. This value would increase as the data becomes increasingly different. The initial results from this brief study look promising on the Ford engine, however, not so promising on the Ruston engine.

The results have also shown that ICA has indeed provided a benefit over the FFT results for both engines. It appears to provide a more reliable indicator for fault detection, however, by how much depends on the class of engine. This is evident in the Ruston engine where the acoustic emissions are already relatively independent due to greater cylinder spacing. For smaller engines; those with small cylinder spacing, the ICA has increased successful detection to a greater degree than on the Ruston. Questions were raised about how well the ICA will perform depending on the number of sources and number of microphones. It is clear that in this instance the issue will be many more sources than microphones. The effect of this will be that each output will be a combination of several sources, therefore, there is scope for future work looking at how this can be improved or indeed can the number of microphones be reduced for a more practical industrial system whilst maintaining good detection [103]. The acoustic monitoring has proven to be sensitive for a range of faults and fault severities. Indeed, Rothrock's statement in the 1930's [51] that a 10° difference in fuel injection timing makes no noticeable difference, is now incorrect in 2011. This is thanks to the massive advancements in computer and sensor technologies within the last few decades.

The small study on start up current fault detection in appendix E was also successful. It has amply demonstrated that there is a potential to detect faults by monitoring the current whilst the engine cranks or starts. Clearly there is a measurable increase in system friction when a fault is present which causes the starter motor to be engaged for longer. One area that was not addressed fully is just how low the severity of the fault can be for this technique to still detect it. If it were to only be applicable to some of the faults measured in this work then the method is not a viable solution for real world monitoring.

A personal learning to take forward is that there should have been a better file naming system and better file storage. There should also have been extra information such as lab temperature, exhaust temperatures and various other engine outputs that whilst not used in this research should have ideally been recorded for prosperity. Better file naming and filing conventions would have severely reduced the time taken when processing the data. Moving forward it would be beneficial to look at a database system for storing and recording data so it can easily be called upon, and also reducing data size as each Matlab file for a ten second recording was 50mb.

8.2 Future Work

One of the biggest issues presented in the research was the lower success rate for the healthy data comparison. A solution for this issue it to adjust the success criteria, however, in the long term a more robust solution is required. An initial investigation into a new way of classifying the data has already been made by removing the thresholds and was briefly discussed in section 8.1. If a numerical value can be calculated on the difference in datasets then a 'traffic light' system could be setup to provide a classification of their health status. The initial results appear to work well on the Ford data but not so well on the Ruston. The healthy data on the Ruston is providing the biggest issue. Ironically, it is most likely the acoustic mixing due to the close proximity of the cylinders which has improved the outcome of this process for the Ford data as the similarity between data sets will be increased. The Ruston data suffered due to one or two frequency peaks out of six or seven per data set that were significantly different and thus significantly increasing the value output. Whilst this increase in output is still far smaller than the faulty data it somewhat thwarts the automatic classification of data based upon its output value. The code could be improved to compensate for this, allowing the code to be selective in which peaks should be genuinely considered and which should be ignored. The degree of matching between two healthy sets and between a healthy and faulty set should be analysed and based upon this a solution on how the program could selectively drop certain peaks could be ascertained. This is, therefore, an important piece of future research.

Another way in which the Ruston healthy data could be improved upon would be to take a larger baseline set and to take the median value from these sets. If one hundred sets were taken and a medium data set taken then thresholds could be set 'tighter' to the median which would aid in improving the healthy versus healthy comparisons. It is entirely probable that with only three sets sampled in this work that either end of the spectrum has be collected. Therefore, it would be beneficial to program in a data comparison module to the program code that would allow the comparison of the data, binning bad data automatically and also collating and storing relevant peak points and the median values of the amplitudes across all data. Indeed, the program could be set to collect data and the operator could walk away whilst the system goes about collecting tens, if not hundreds of sets and then at the end it would analyse all the data together removing bad data and recollecting until a base set exits.

Once these two issues are investigated rigorous testing is required, several problems are present. Currently the technique has been trialed on two different class of engine. It has not been tried on the same engine model in different environments. There are a number of issues to be investigated. For example, how well would this technique work if the data sets from this Ruston 6RK215 were taken and compared to a Ruston 6RK215 in a ship hull half way around the world. The variables would be a different acoustic environment and a variation in the engine due to wear and different replacement parts (some newer than others). That is one avenue of investigation. Another would be to take an engine in one environment, measure it and then transplant it to a new location and measure it again and then compare the data. This would give a reflection on how much the acoustic environment would affect the data.

Commercially another issue arises. In its current format the only reason a fault can be detected is because that fault has been seeded and recorded on the engine already. Taking a new engine, how would a fault be diagnosed. Currently a baseline dataset could be taken when the engine is installed and from there it will detect a change in the engine health, however it will not allow for diagnosis as this faulty data would not exist for comparison. Existing research and commercial products use crank angle to be able to diagnose faults. However, as an unobtrusive technique there is no mechanical crank angle data available. Looking at the original raw acoustic recording there appears to be enough information contained within the signal to allow for cylinder alignment from this data. There is an obvious potential issue with this which does not exist with taking this data from the flywheel. The flywheel is accurate as the measurement is taken from a single rotating face and this face cannot vary, providing a signal clearly every 360°. Trying to achieve this via acoustics is inherently more difficult. Currently, the healthy time domain data shows that the data can be aligned to show the cylinder firing every 0.013 seconds. If there were a fault upon that cylinder this could adjust the crank angle at which this event occurs and this has a knock on effect for the rest of the data for subsequent cylinders. There would need to be strict tolerance control on any code written to achieve this goal. Since all data would be subsequently aligned to a particular channel which has been aligned to a theoretical crank angle, the first data set must be accurate. Assuming the first set is aligned successfully there maybe issues with subsequent data if it contains a fault that changes the crank angle at which combustion is occurring. This would allow the program to be able to detect a fault using the data comparison then use more advanced processing to diagnose the fault with the data versus theoretical crank angle. There are certainly other ways to potentially overcome this issue. The engine manufacturer could run the engine in an anechoic chamber and record the data, including faulty data, then this data could be played back in the engine room when the engine is installed to 'condition the system'. This would negate the need for crank angle and allow for automatic detection. This is certainly an interesting problem and a significant piece of follow up research.

To overcome the data storage issues the code could work from a database of data, since low level data is not required the data storage requirements are small.

The operator could input a speed and load and this would automatically call the data from the database. This would also allow for the easy comparison of input data against faulty datasets from the database, as well as improving speed especially if the ICA processing could be stored in the database. The program could be used to compare, first, against healthy baseline data. If a match occurred the process would halt there. If there was no match the program could follow through checking the recorded data against other known faulty sets in the database. These could be recorded by the manufacturer or stored throughout the life of the engine as and when faults are discovered and rectified.

In terms of the FastICA algorithm, more investigation could be carried out into the various more complex settings that this algorithm contains. An investigation could be based upon the data collected in this work but varying the ICA settings. There is also potential to experiment physically with the number of microphones. This research covered the issues with simulations, however, further research could incorporate engine tests varying the number of microphones to see if they number can be reduced or indeed if more microphones increases accuracy. This work could incorporate data from this research by simply excluding channels to see how the results vary, however, the author would suggest that repeating the experiments and replacing the lower or higher number of microphones in more appropriate locations, to take account for the change in number would be more effective.

There are some additional considerations that should be investigated as engine technology is advancing. The experimental engines and all of the engines currently installed in the many locations the author has visiting as part of this research have all contained engines which are not computer controlled or run on any cycle variation technology. However, as engines become larger and aim to be more fuel efficient and less polluting, manufacturers are turning to technology. Computer controlled engines are one such variant where various parameters such as injection timing and fuel quantities can be varied on the fly to best meet certain criteria. Variable valve timing is another technology which varies the valve timing to again best meet certain engine performance criteria. These systems do not just provide questions and challenges for this research but also for the rest of the condition monitoring community who base their results heavily off crank angle. Future work could look at how these parameters affect fault detection but also how repeatable baseline data is after the engine has been adjusted and reset.

8.3 In Summary

The research presented within this thesis, and the resultant code in its current form is already a very useful tool. With more work this could be extended to produce an incredibly powerful condition monitoring tool. Indeed, there are no tools on the market at the time of writing that can detect engine faults without additional engine information such as the crank angle. If the crank angle can be obtained acoustically then this will aid in the addition of the many plethoras of existing research into one powerful package. It would allow the existing program to do a quick analysis of the data. If a difference is detected it could use the acoustic crank angle data, a more detailed analysis could be performed by a more qualified operator who could produce a fault diagnosis. This would provide a complete detection and diagnosis system.

Appendices

Appendix A

Ruston Non ICA Results

The following appendix provides a sample of some of the data that has been collated and processed without ICA processing for the Ruston engine which is discussed in chapter 6. The Ford data can be found further on in appendix B.

A.1 Too Little Fuel

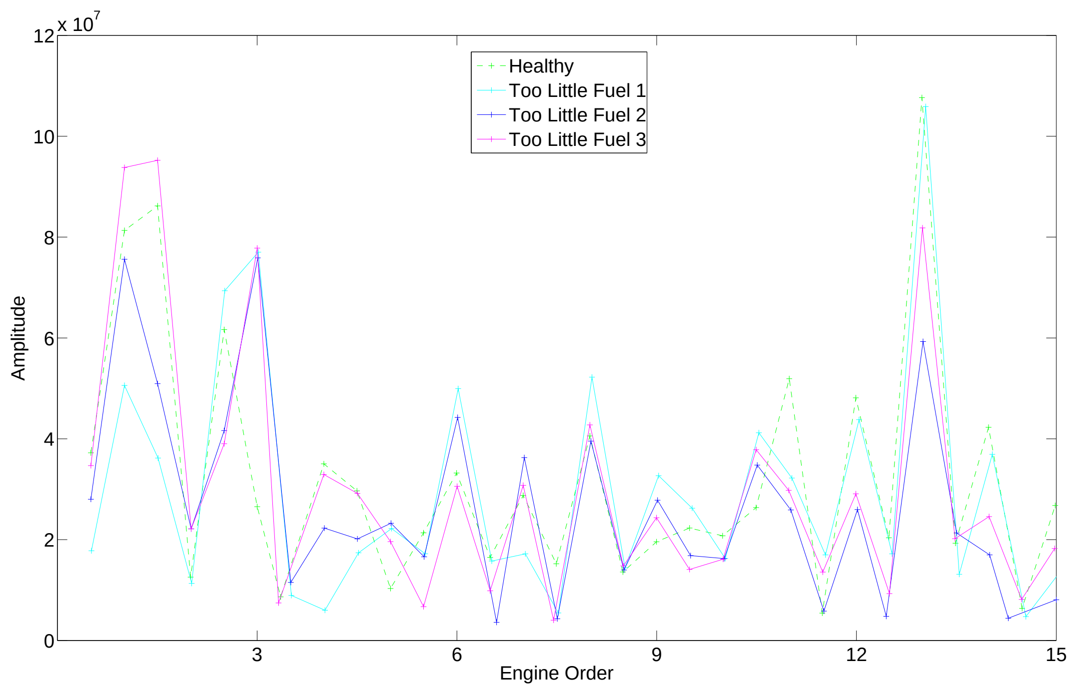

Figure A.1: Peak Points of Healthy vs Too Little Fuel Fault at 750RPM and 50% Load - Channel 1

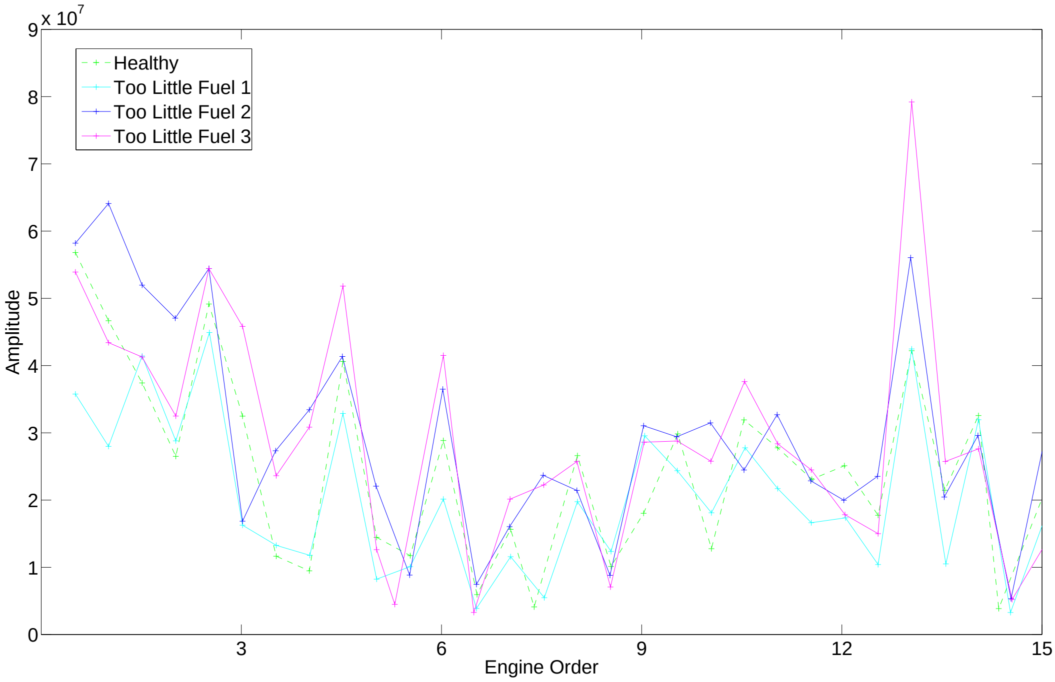

Figure A.2: Peak Points of Healthy vs Too Little Fuel Fault at 750RPM and 75% Load - Channel 1

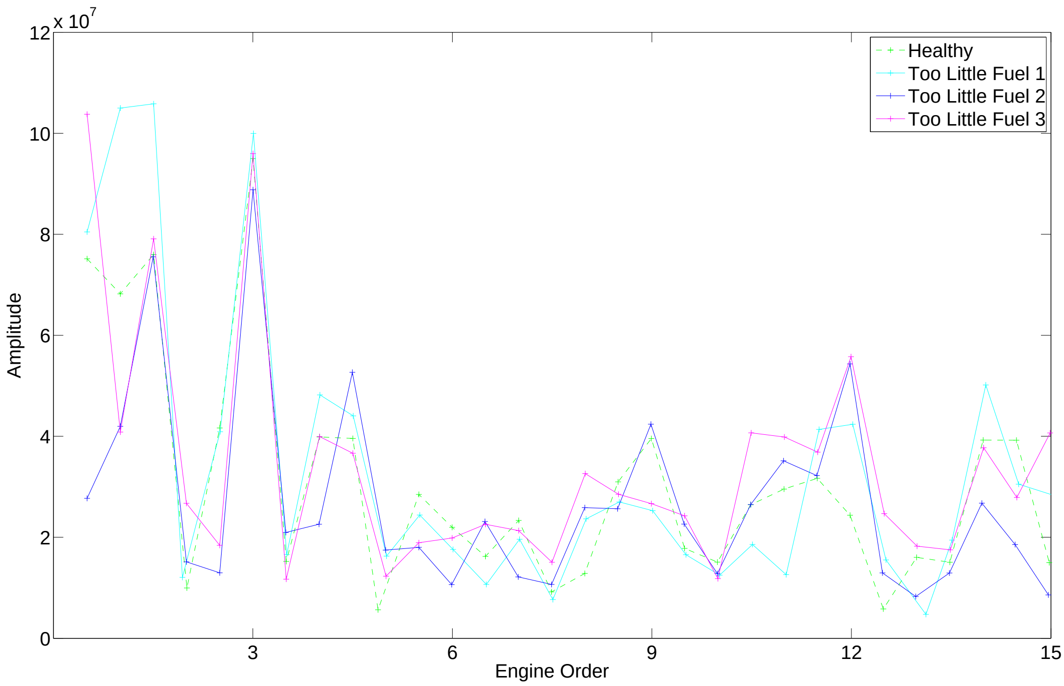

Figure A.3: Peak Points of Healthy vs Too Little Fuel Fault at 900RPM and 25% Load - Channel 1

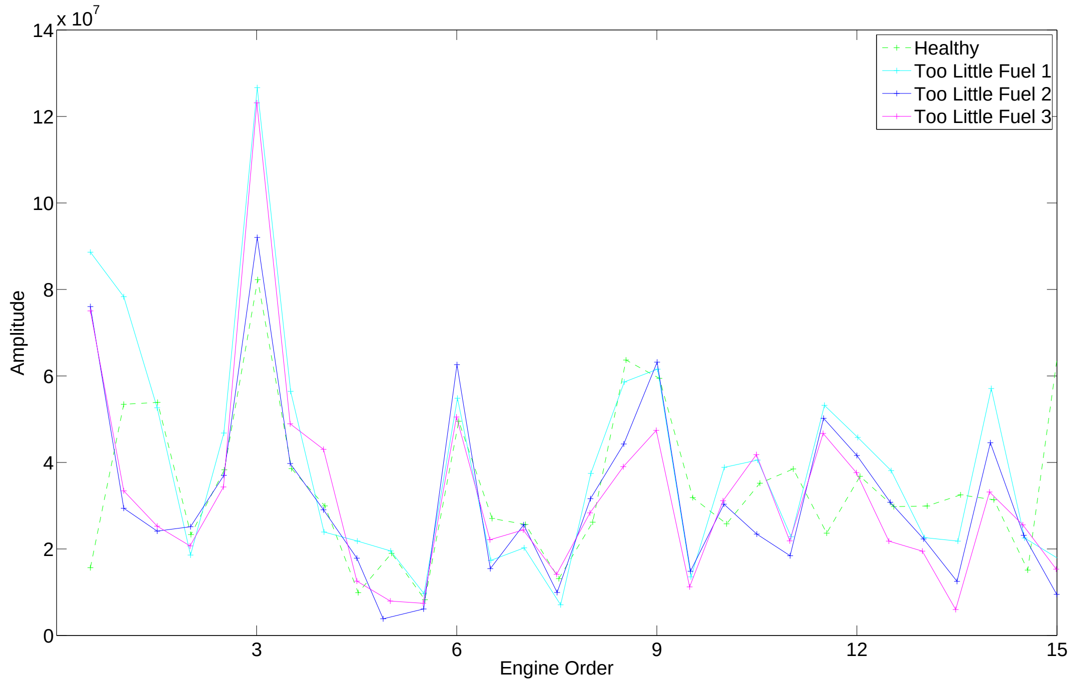

Figure A.4: Peak Points of Healthy vs Too Little Fuel Fault at 900RPM and 50% Load - Channel 1

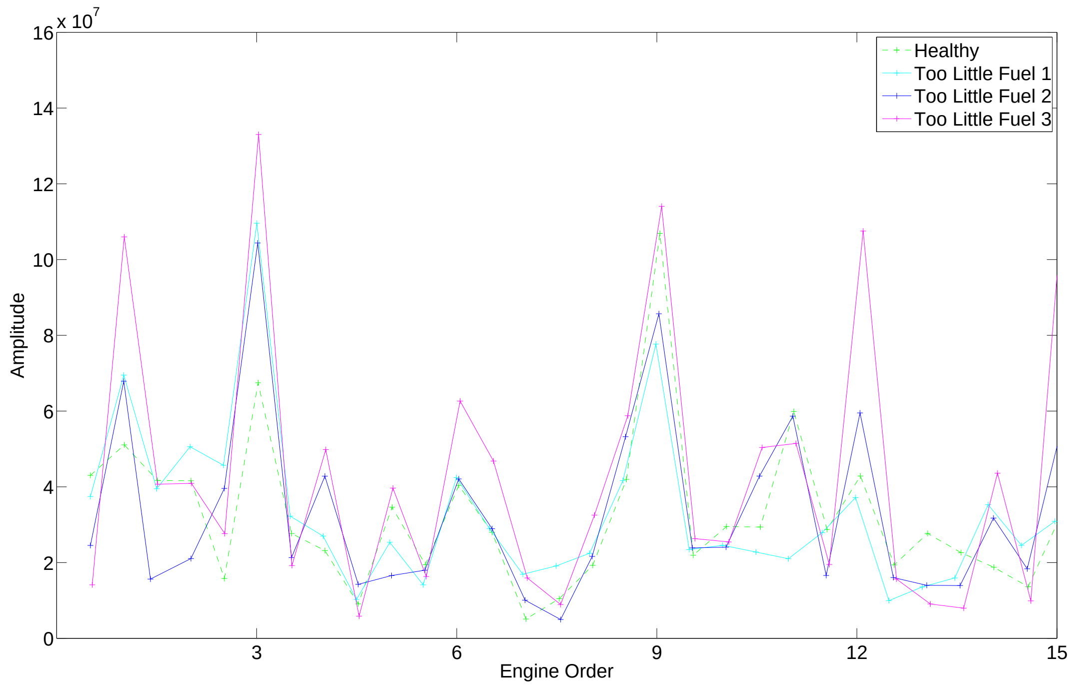

Figure A.5: Peak Points of Healthy vs Too Little Fuel Fault at 900RPM and 75% Load - Channel 1

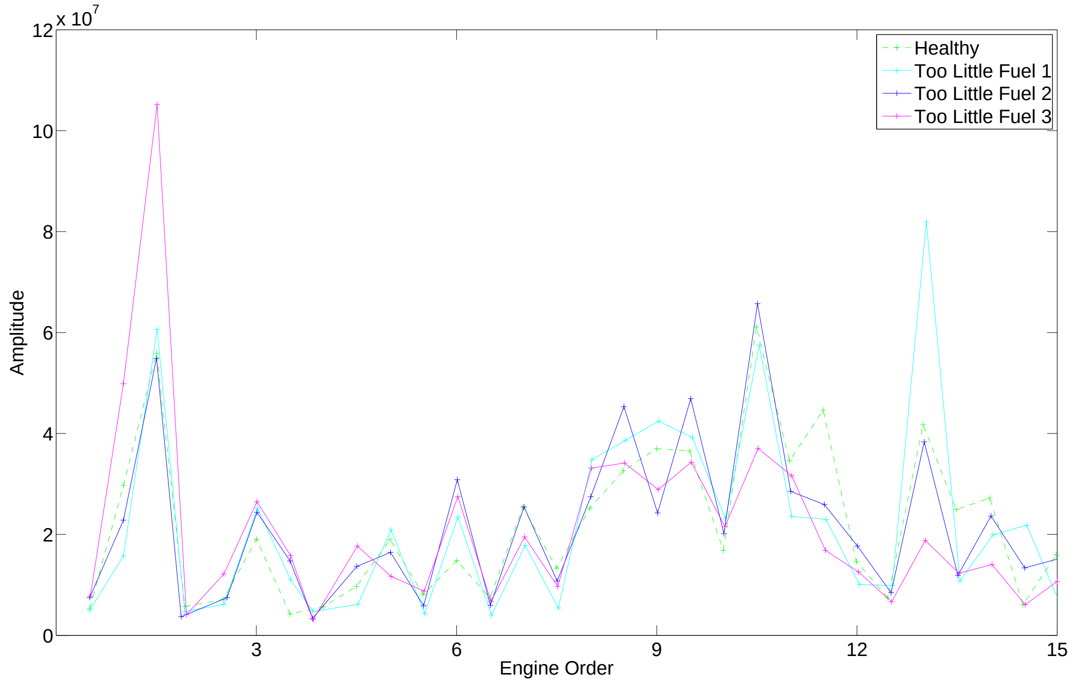

Figure A.6: Peak Points of Healthy vs Too Little Fuel Fault at 750RPM, 25% Load - Channel 6

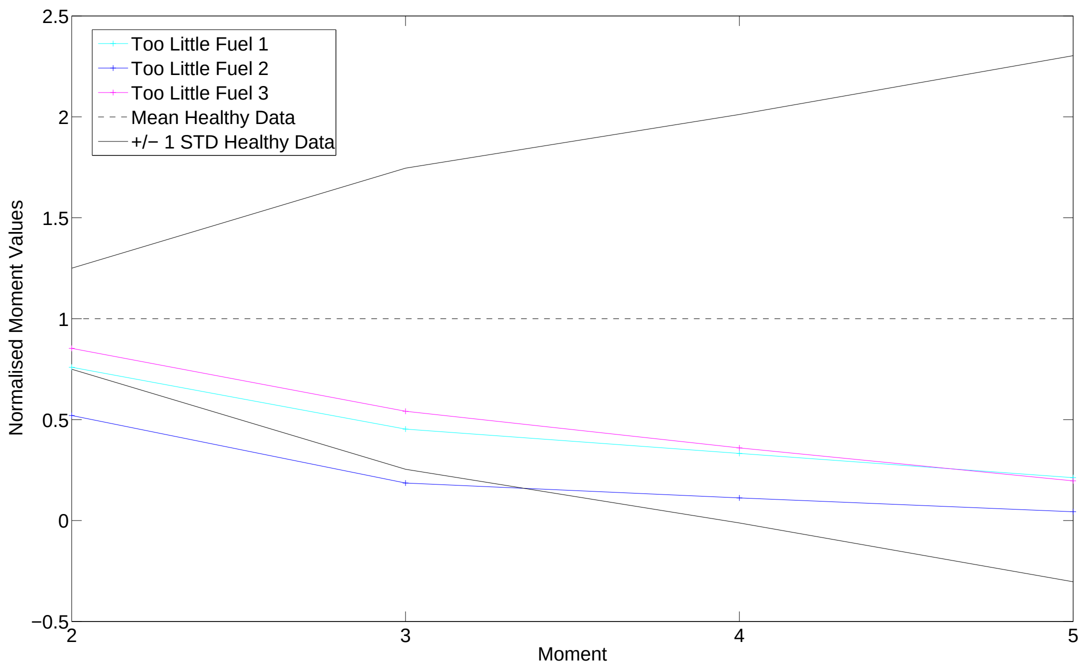

Figure A.7: Moments of Healthy vs Too Little Fuel Fault at 750RPM and 50% Load - Channel 1

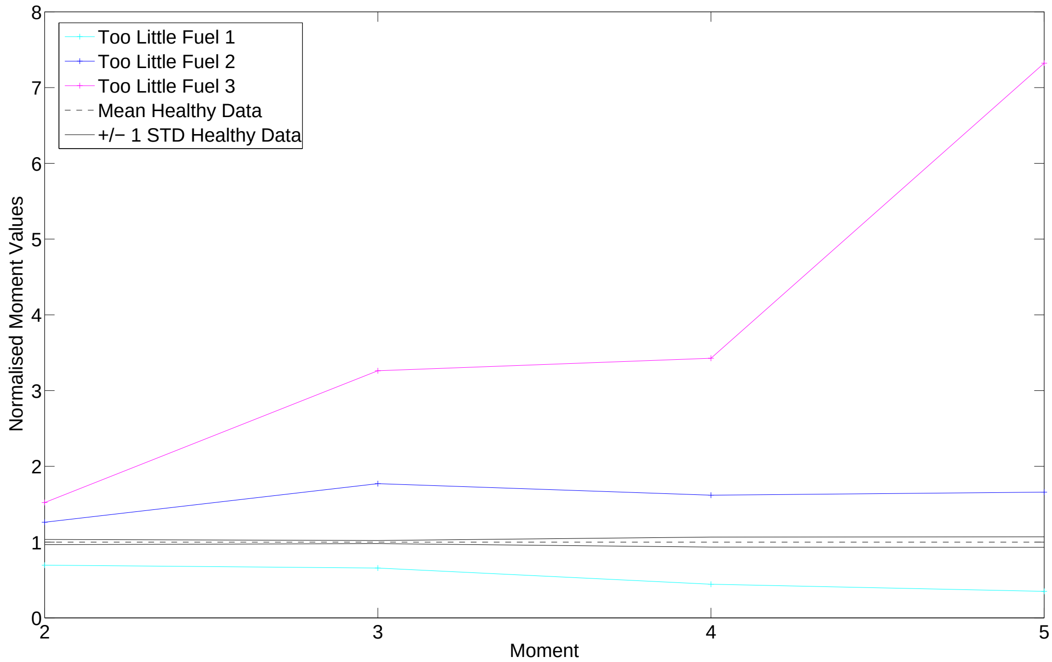

Figure A.8: Moments of Healthy vs Too Little Fuel Fault at 750RPM and 75% Load - Channel 1

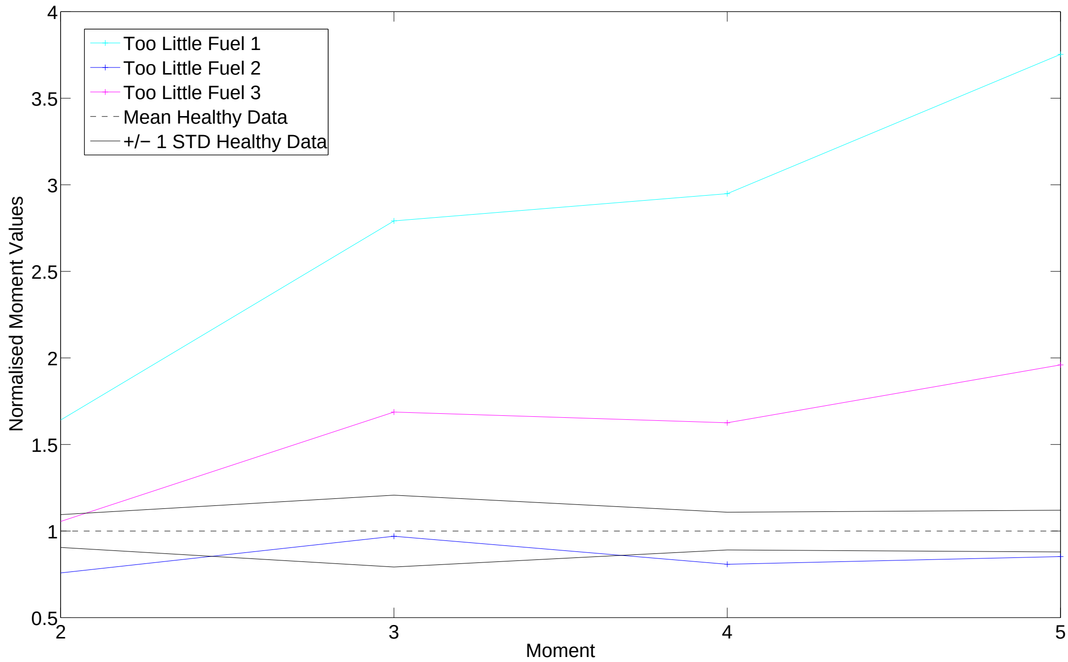

Figure A.9: Moments of Healthy vs Too Little Fuel Fault at 900RPM and 25% Load - Channel 1

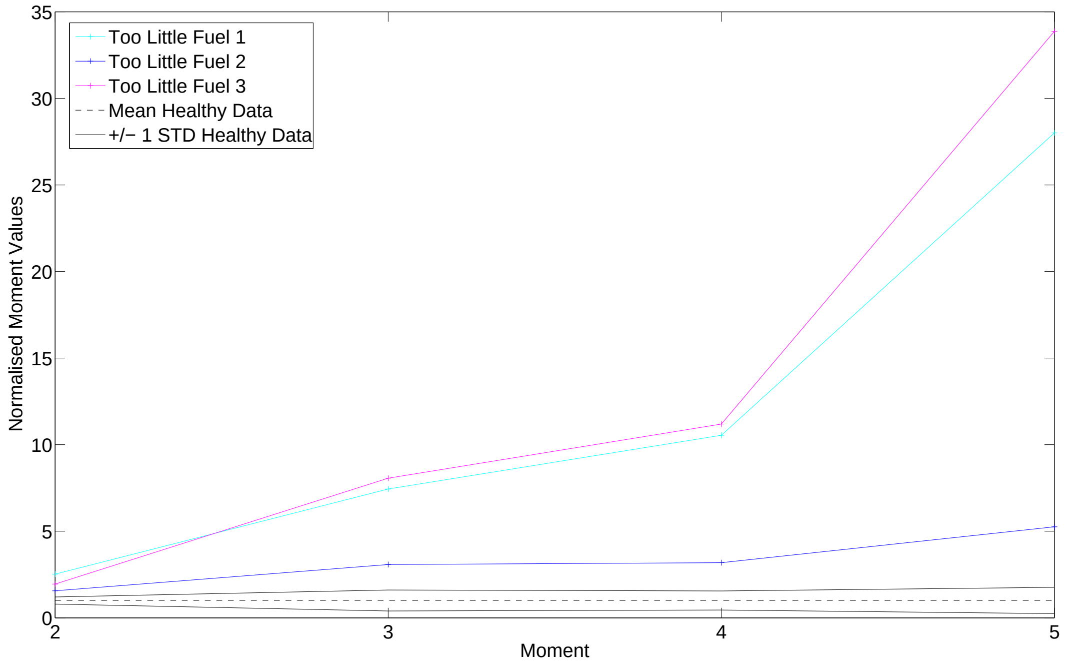

Figure A.10: Moments of Healthy vs Too Little Fuel Fault at 900RPM and 50% Load - Channel 1

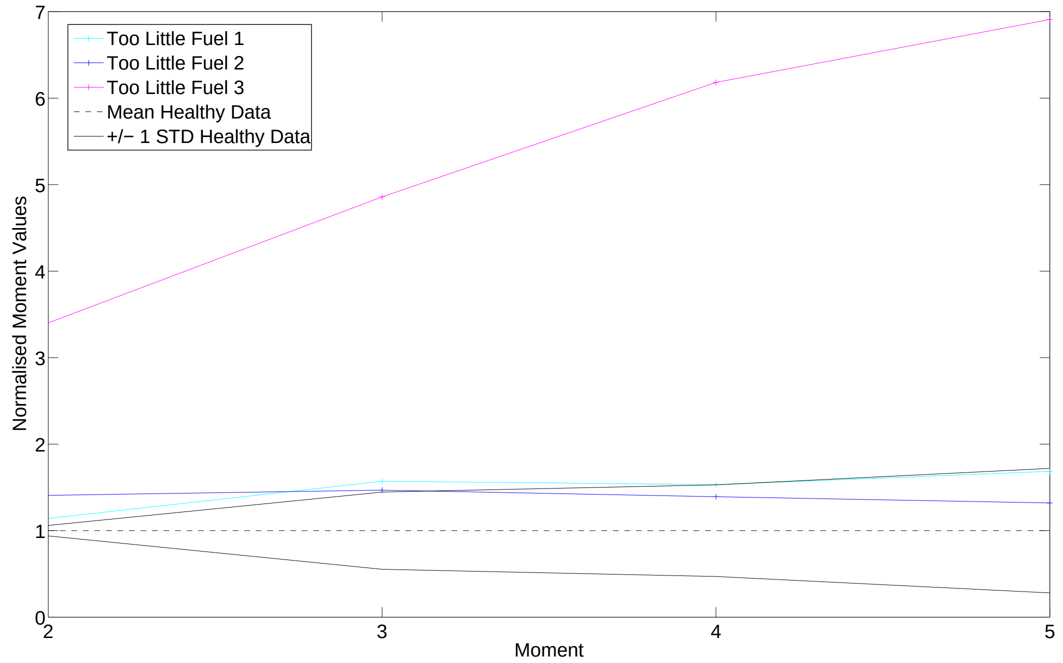

Figure A.11: Moments of Healthy vs Too Little Fuel Fault at 900RPM and 75% Load - Channel 1

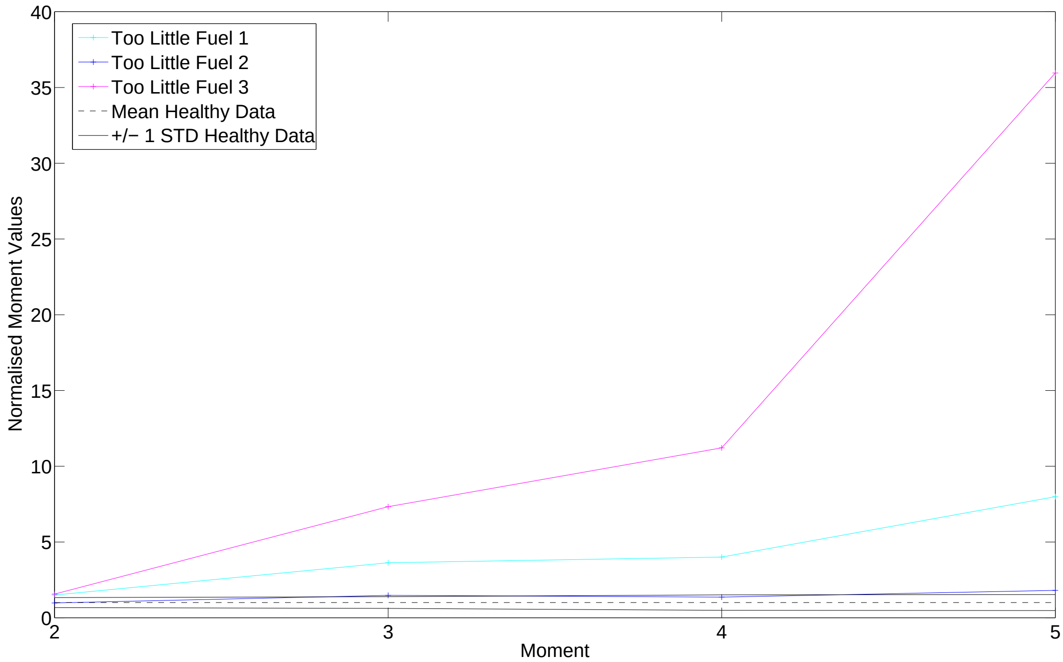

Figure A.12: Moments of Healthy vs Too Little Fuel Fault at 750RPM, 25% Load - Channel 6

A.2 Too Much Fuel

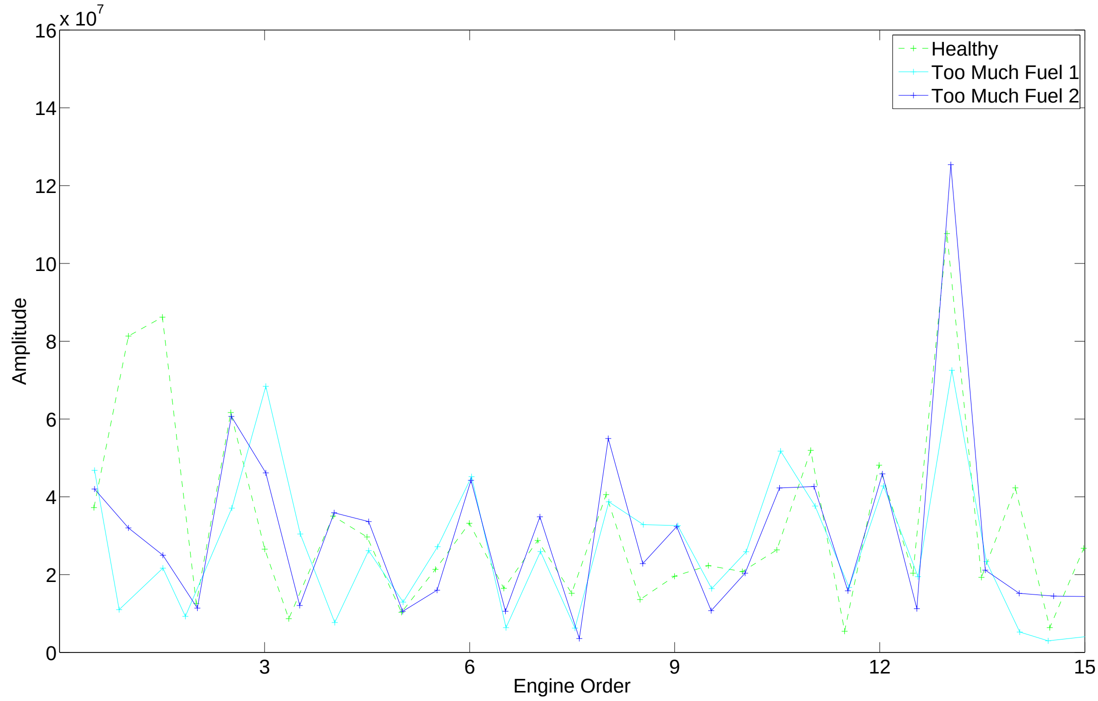

Figure A.13: Peak Plot of Healthy vs Too Much Fuel Fault at 750RPM and 50% Load - Channel 1

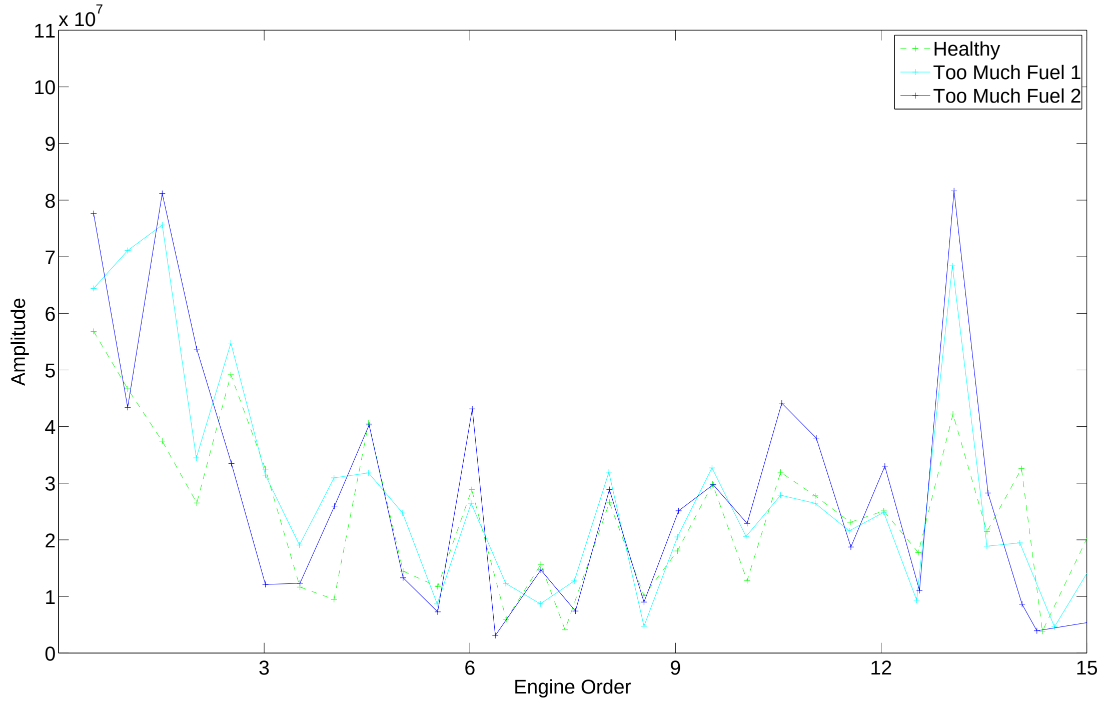

Figure A.14: Peak Plot of Healthy vs Too Much Fuel Fault at 750RPM and 75% Load - Channel 1

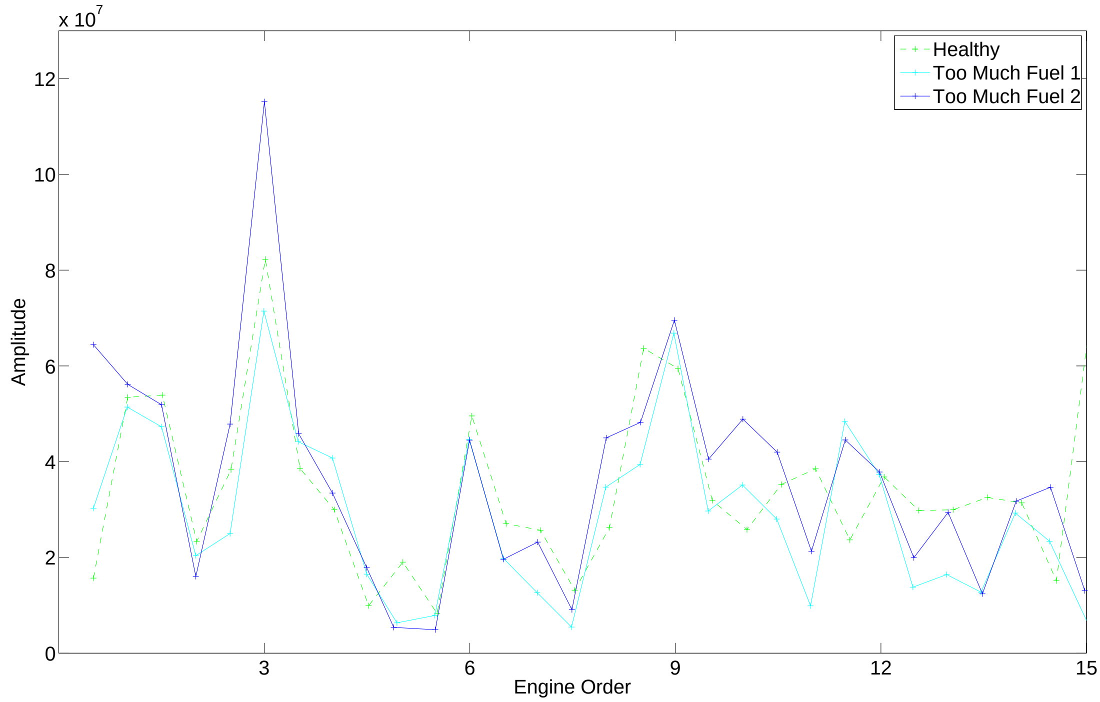

Figure A.15: Peak Plot of Healthy vs Too Much Fuel Fault at 900RPM and 50% Load - Channel 1

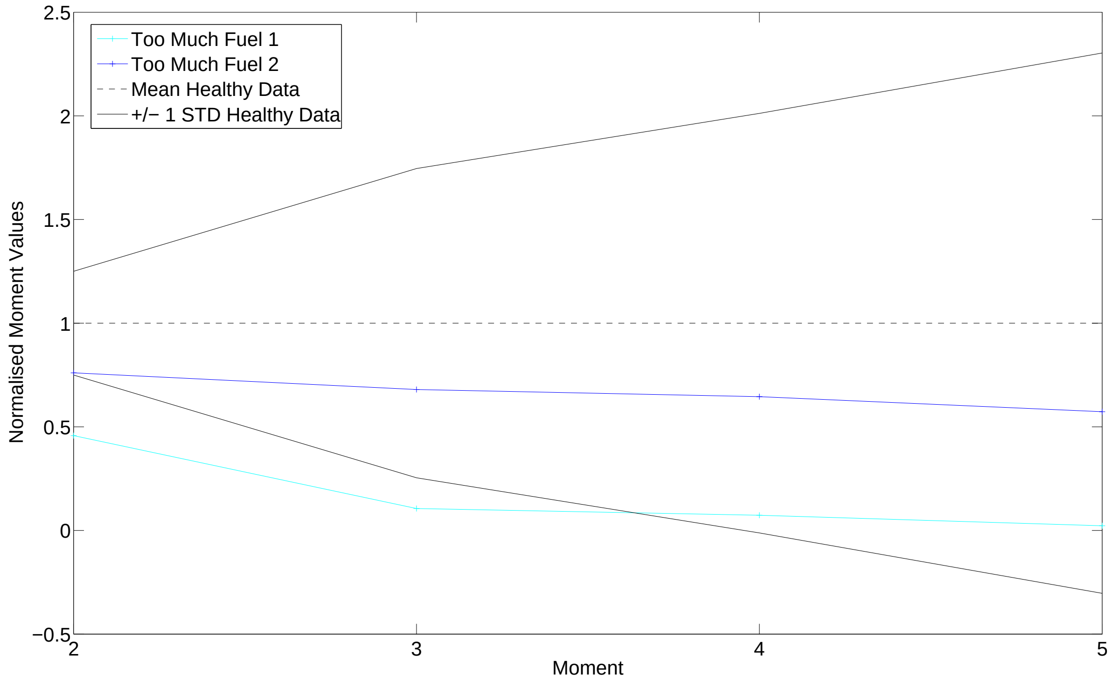

Figure A.16: Moments of Healthy vs Too Much Fuel Fault at 750RPM and 50% Load - Channel 1

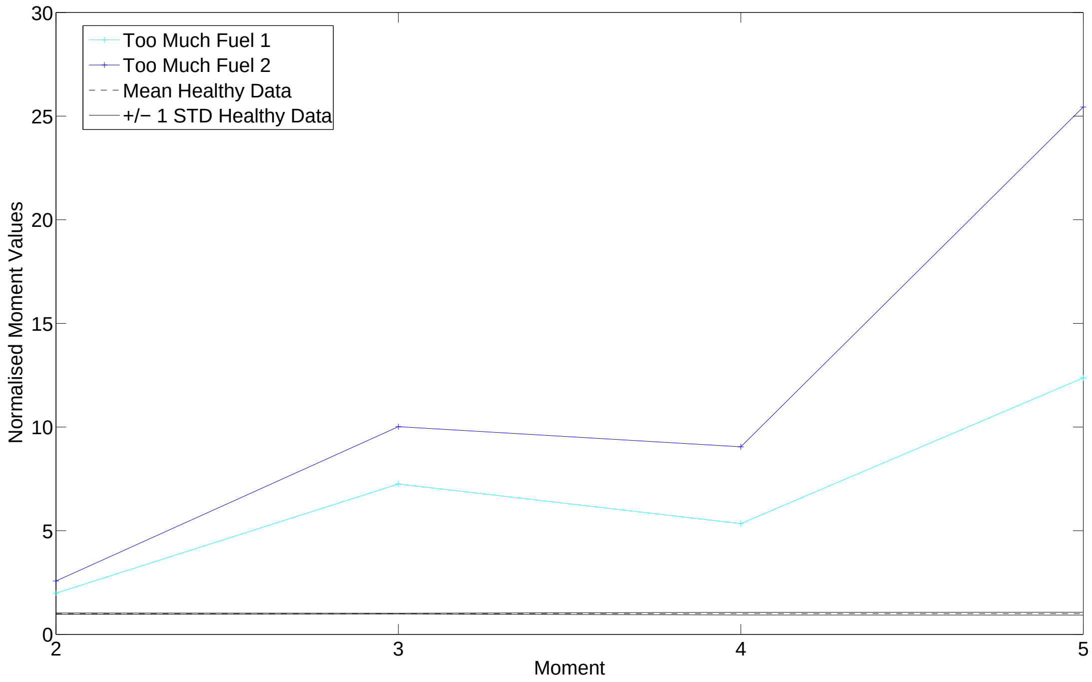

Figure A.17: Moments of Healthy vs Too Much Fuel Fault at 750RPM and 75% Load - Channel 1

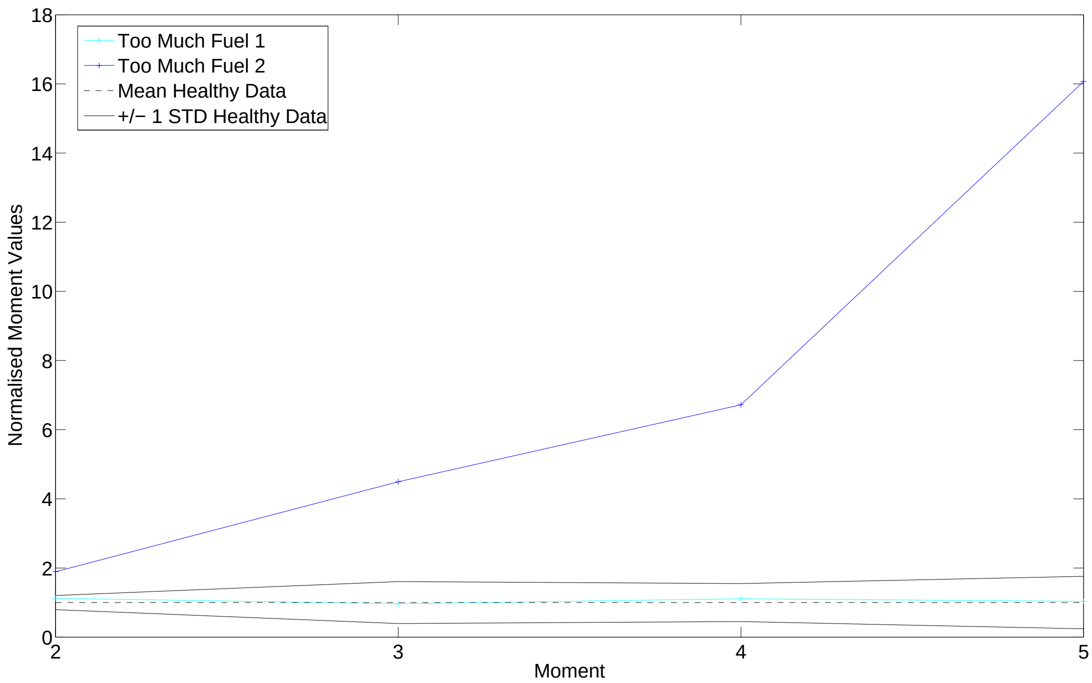

Figure A.18: Moments of Healthy vs Too Much Fuel Fault at 900RPM and 50% Load - Channel 1

A.3 Early Injection

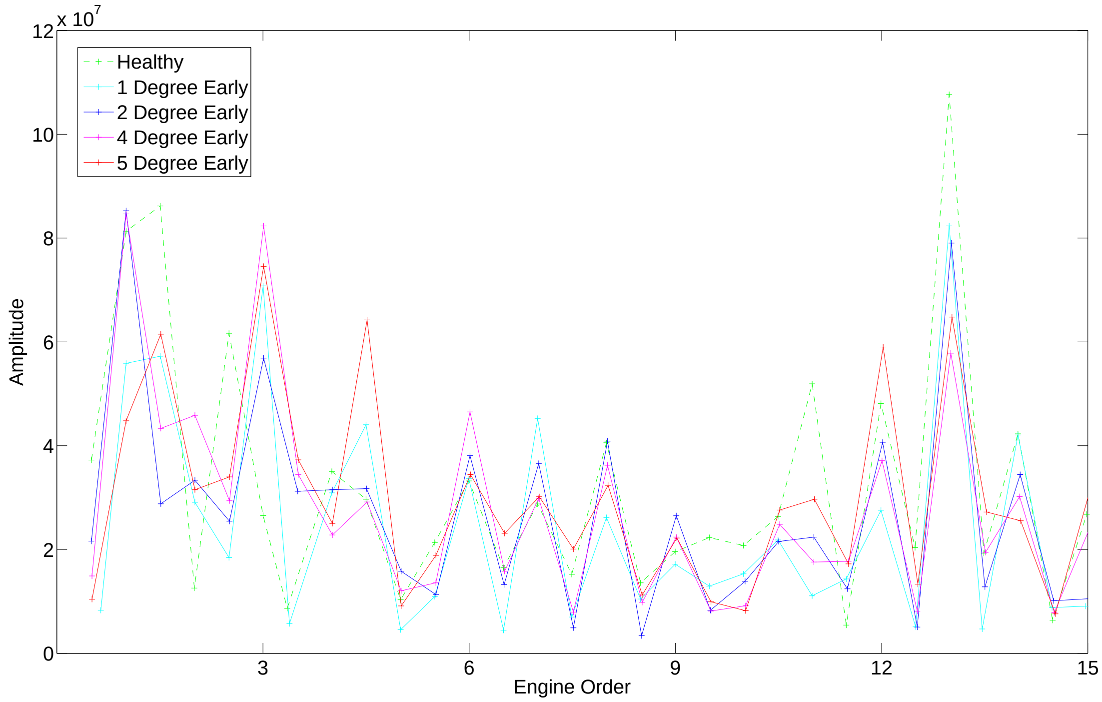

Figure A.19: Peak Points of Healthy vs Early Injection Fault at 750RPM and 50% Load - Channel 1

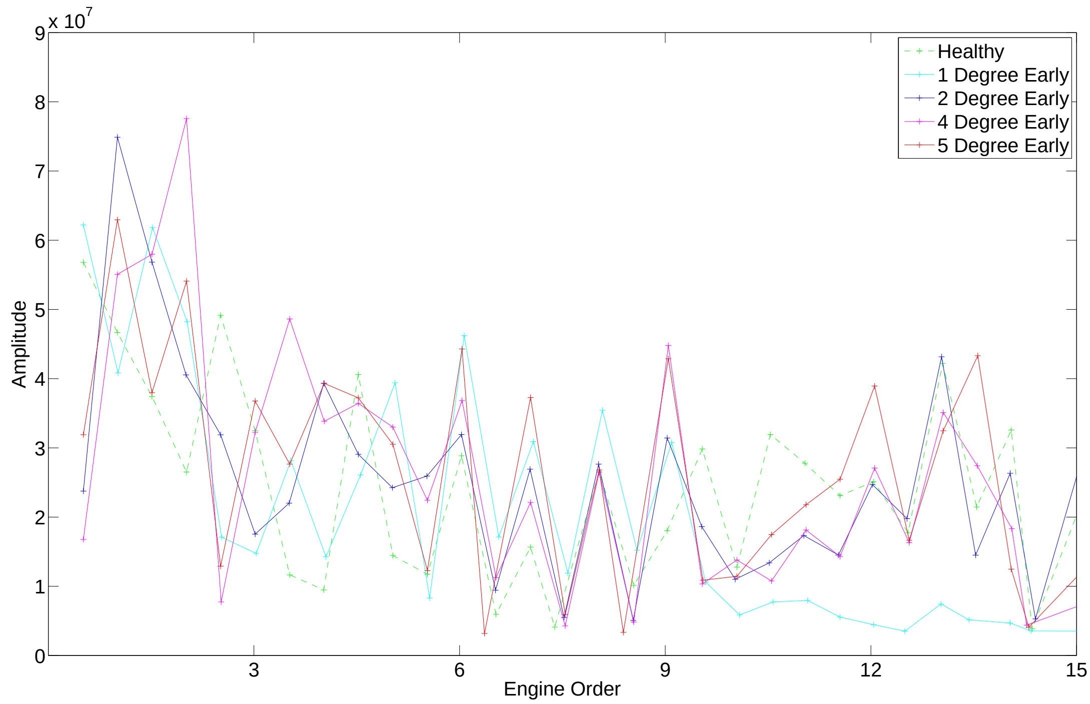

Figure A.20: Peak Points of Healthy vs Early Injection Fault at 750RPM and 75% Load - Channel 1

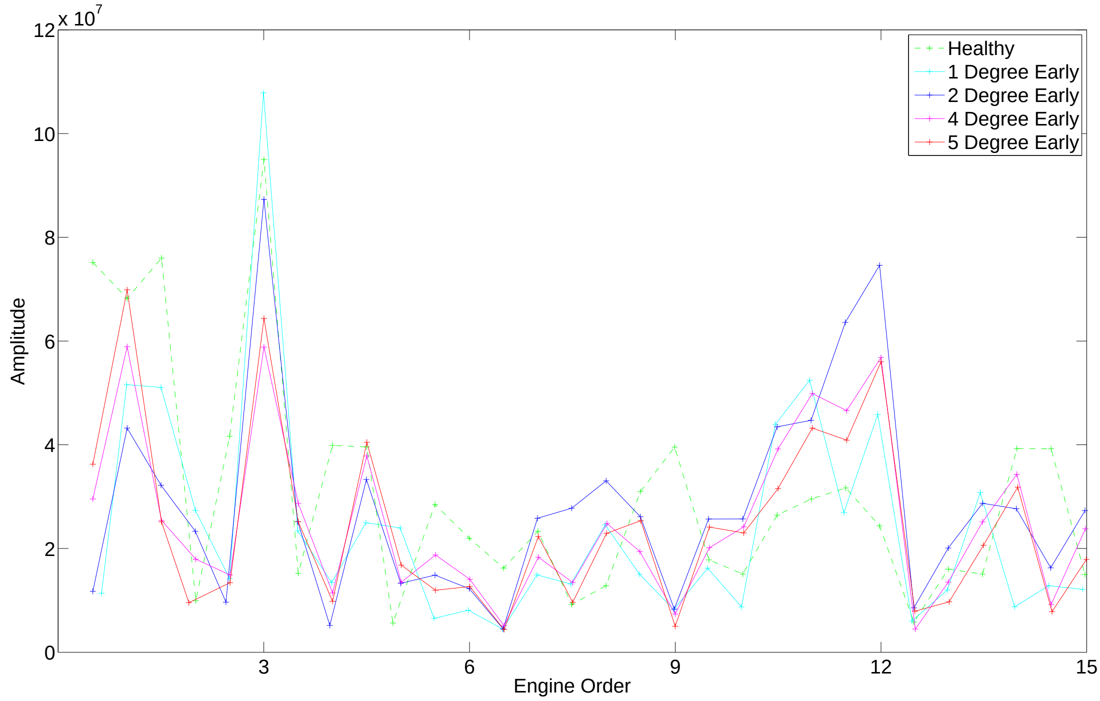

Figure A.21: Peak Points of Healthy vs Early Injection Fault at 900RPM and 25% Load - Channel 1

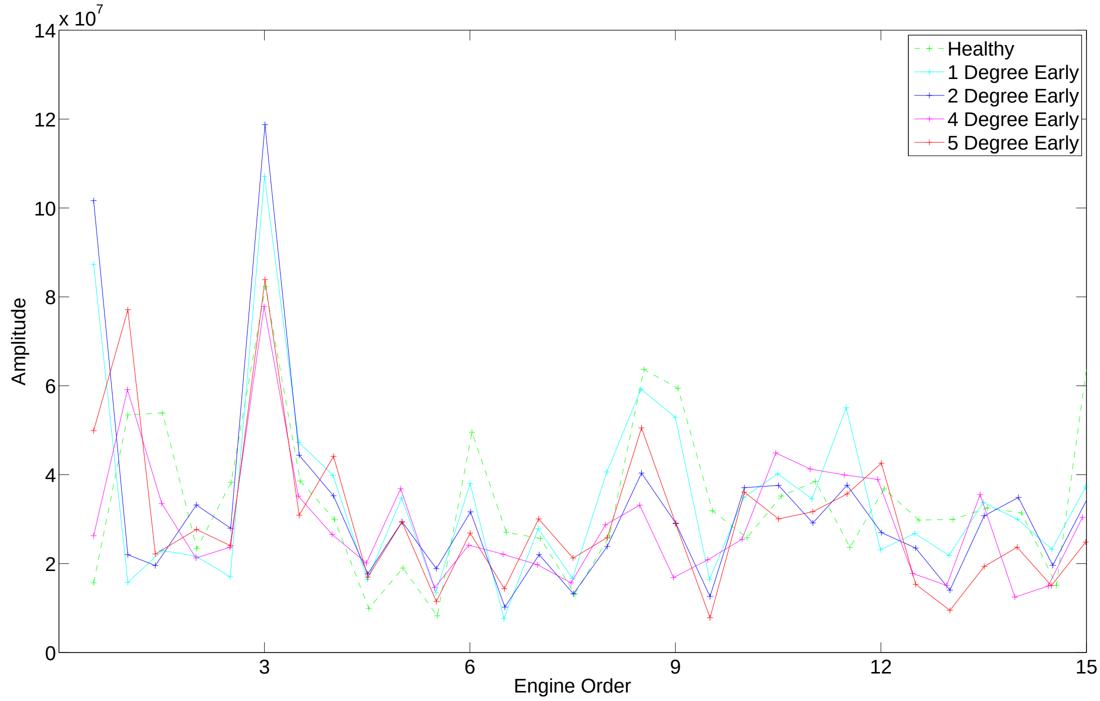

Figure A.22: Peak Points of Healthy vs Early Injection Fault at 900RPM and 50% Load - Channel 1

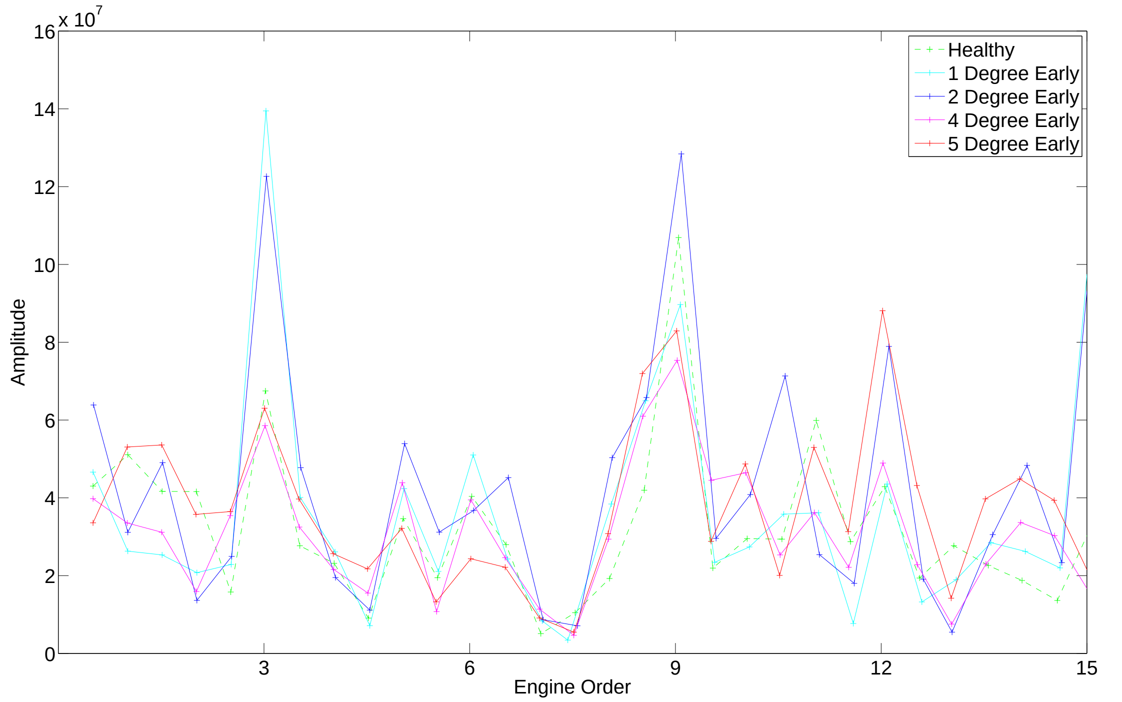

Figure A.23: Peak Points of Healthy vs Early Injection Fault at 900RPM and 75% Load - Channel 1

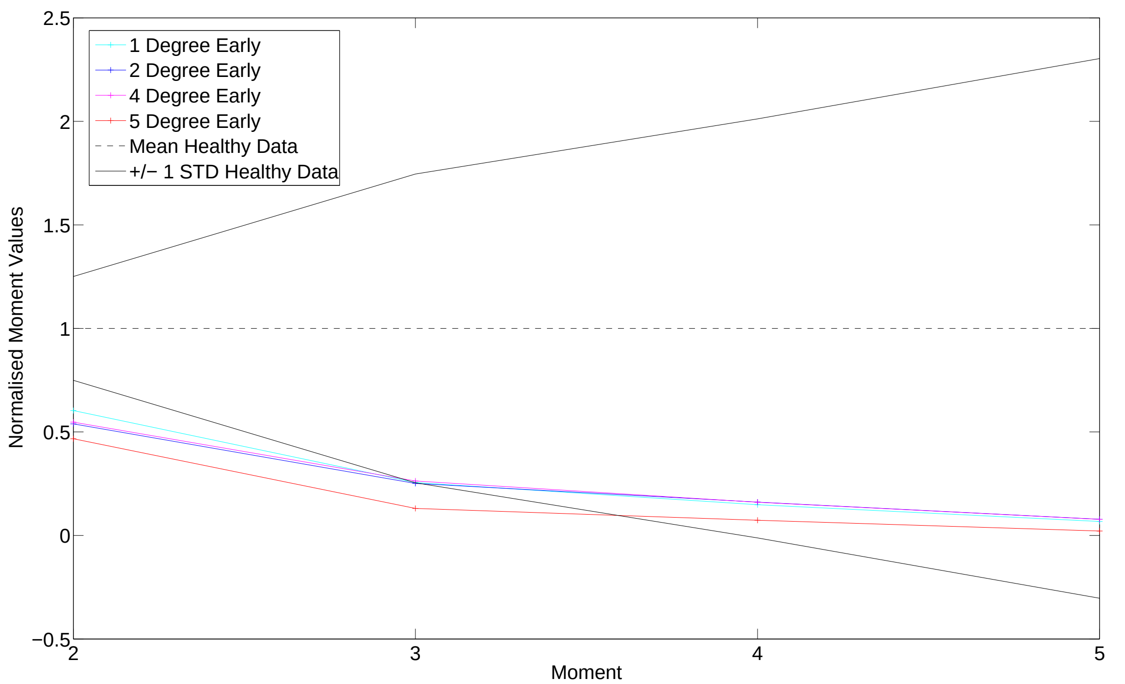

Figure A.24: Moments of Healthy vs Early Injection Fault at 750RPM and 50% Load - Channel 1

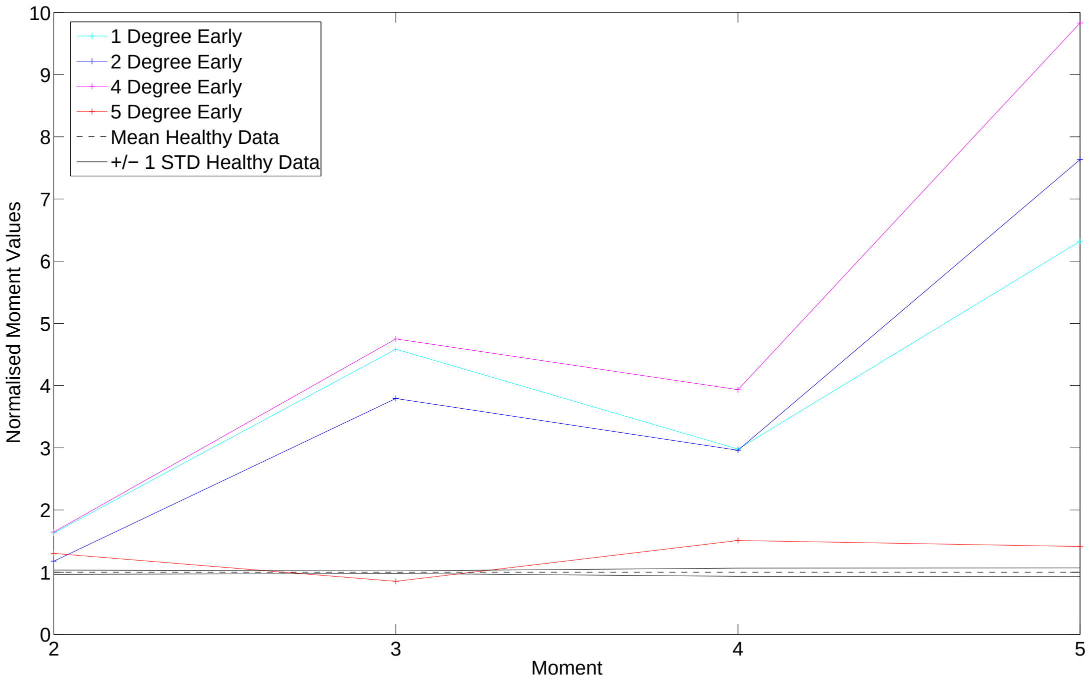

Figure A.25: Moments of Healthy vs Early Injection Fault at 750RPM and 75% Load - Channel 1

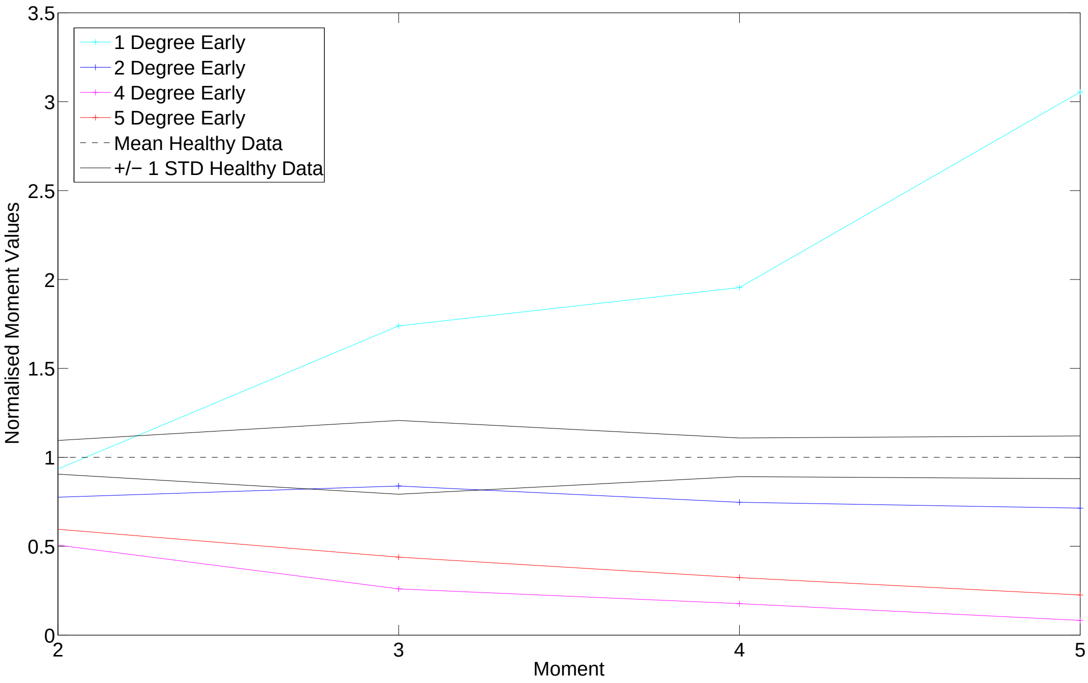

Figure A.26: Moments of Healthy vs Early Injection Fault at 900RPM and 25% Load - Channel 1

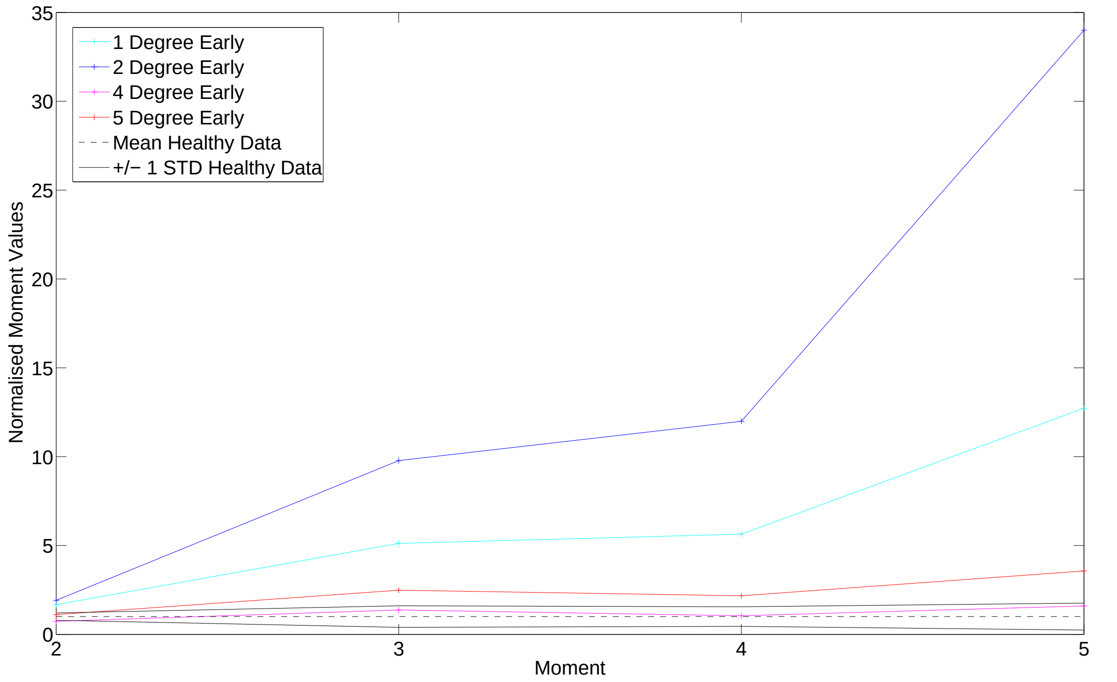

Figure A.27: Moments of Healthy vs Early Injection Fault at 900RPM and 50% Load - Channel 1

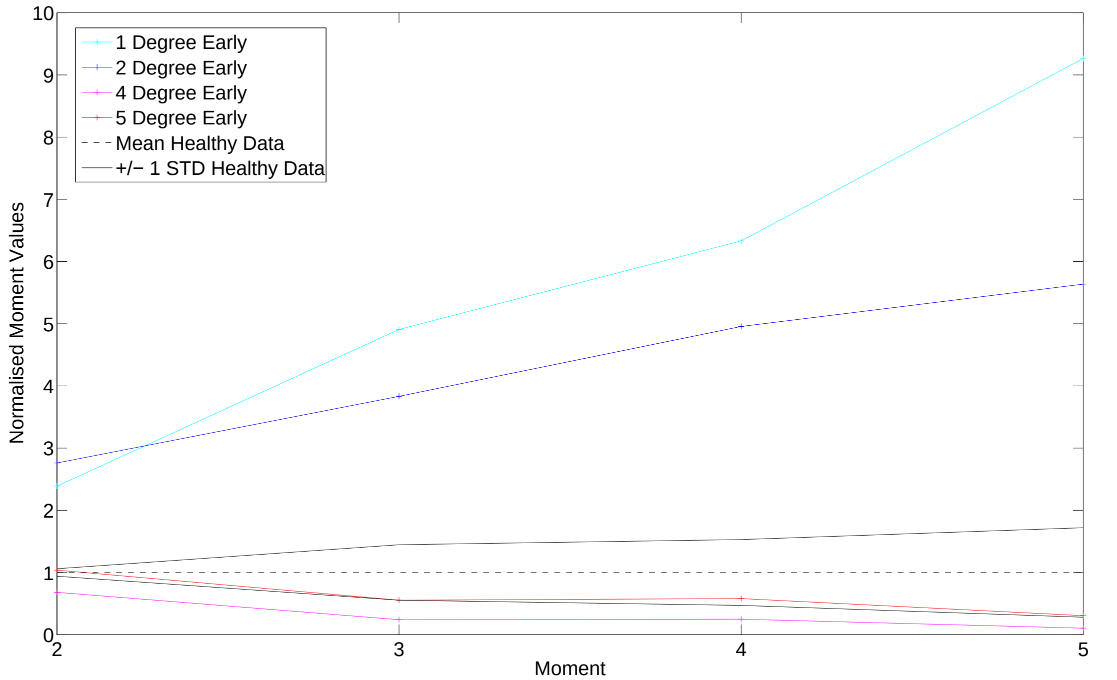

Figure A.28: Moments of Healthy vs Early Injection Fault at 900RPM and 75% Load - Channel 1

A.4 Late Injection

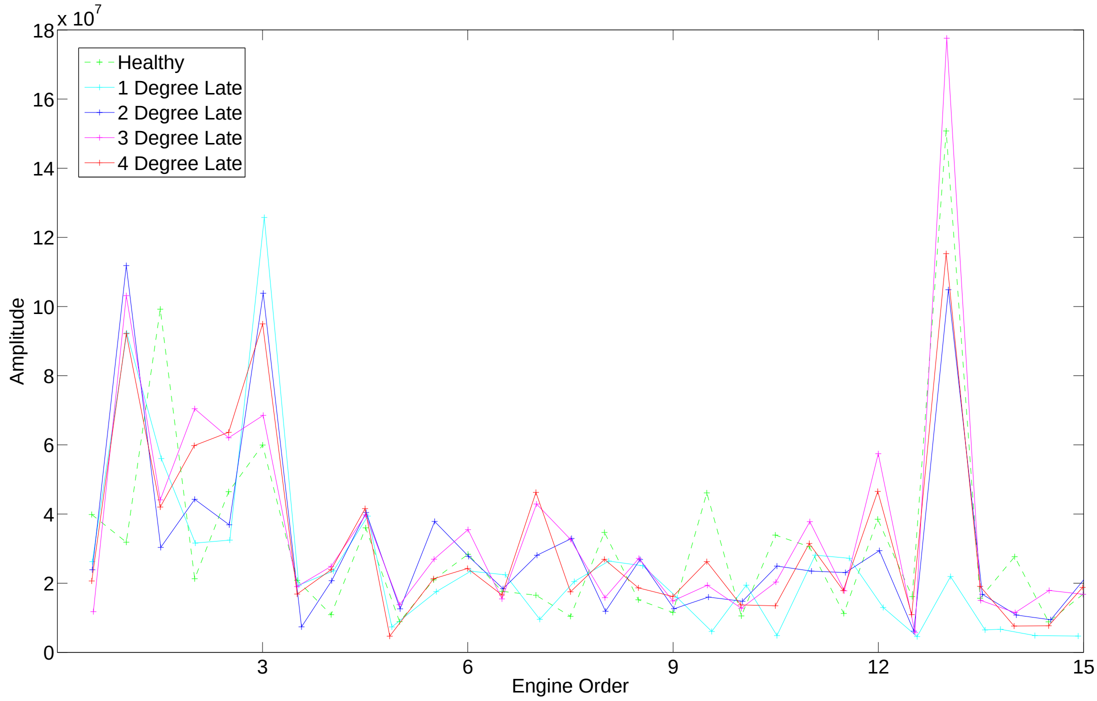

Figure A.29: Peak Points of Healthy vs Early Injection Fault at 750RPM and 25% Load - Channel 1

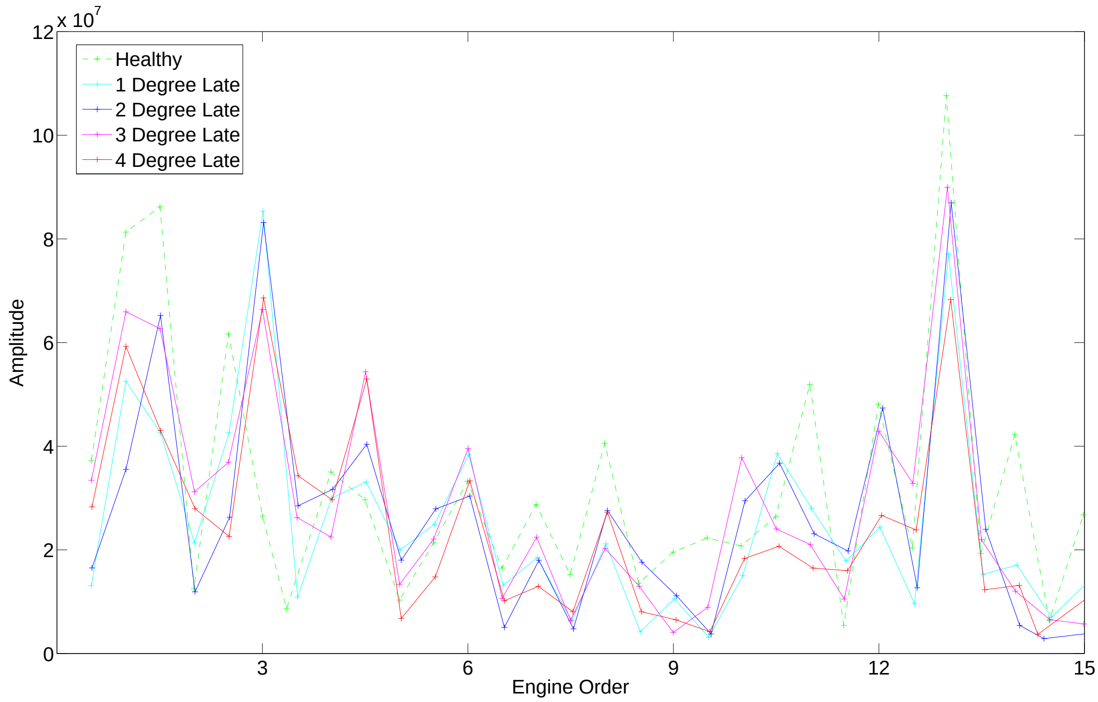

Figure A.30: Peak Points of Healthy vs Early Injection Fault at 750RPM and 50% Load - Channel 1

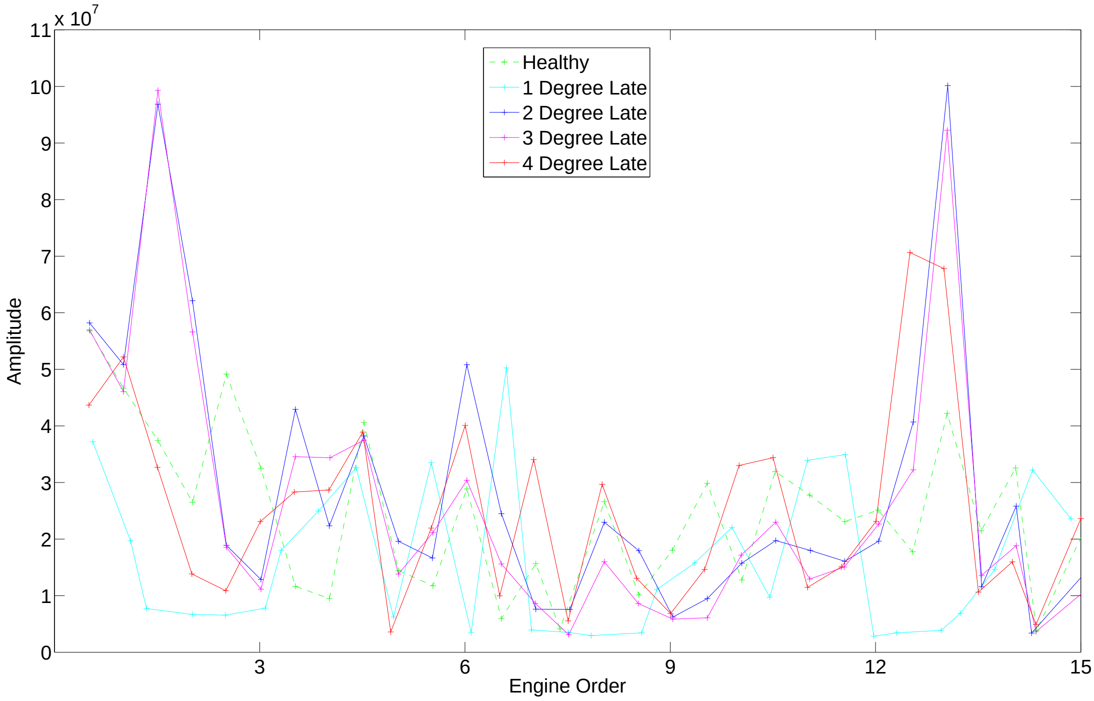

Figure A.31: Peak Points of Healthy vs Early Injection Fault at 750RPM and 75% Load - Channel 1

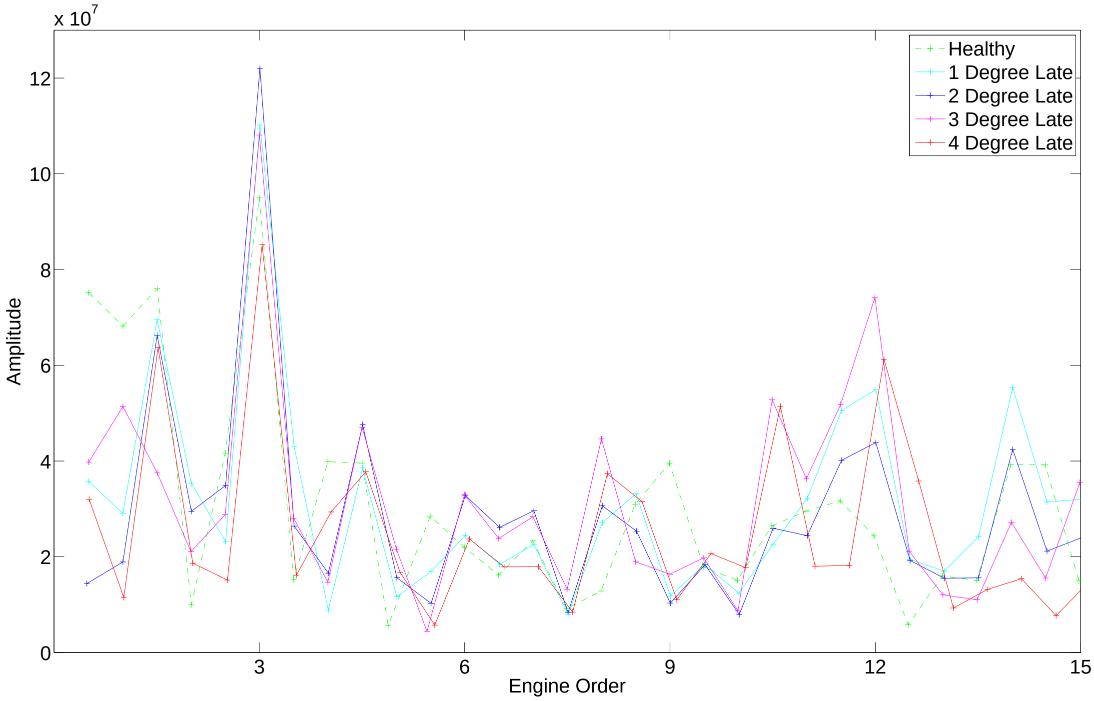

Figure A.32: Peak Points of Healthy vs Early Injection Fault at 900RPM and 25% Load - Channel 1

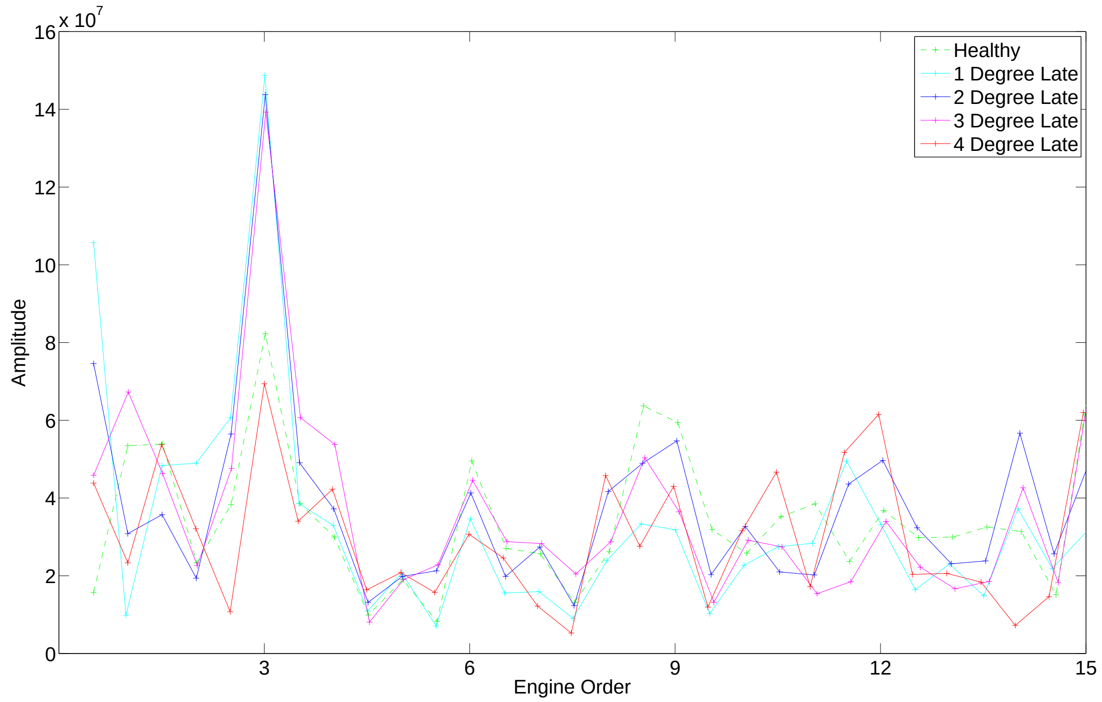

Figure A.33: Peak Points of Healthy vs Early Injection Fault at 900RPM and 50% Load - Channel 1

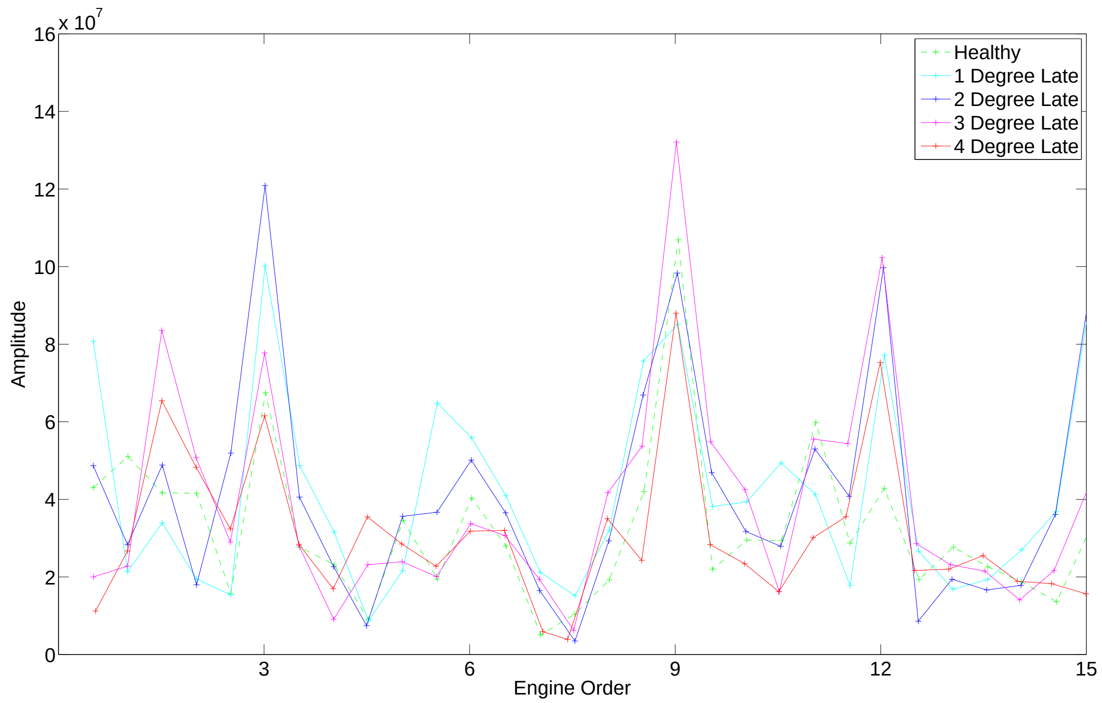

Figure A.34: Peak Points of Healthy vs Early Injection Fault at 900RPM and 75% Load - Channel 1

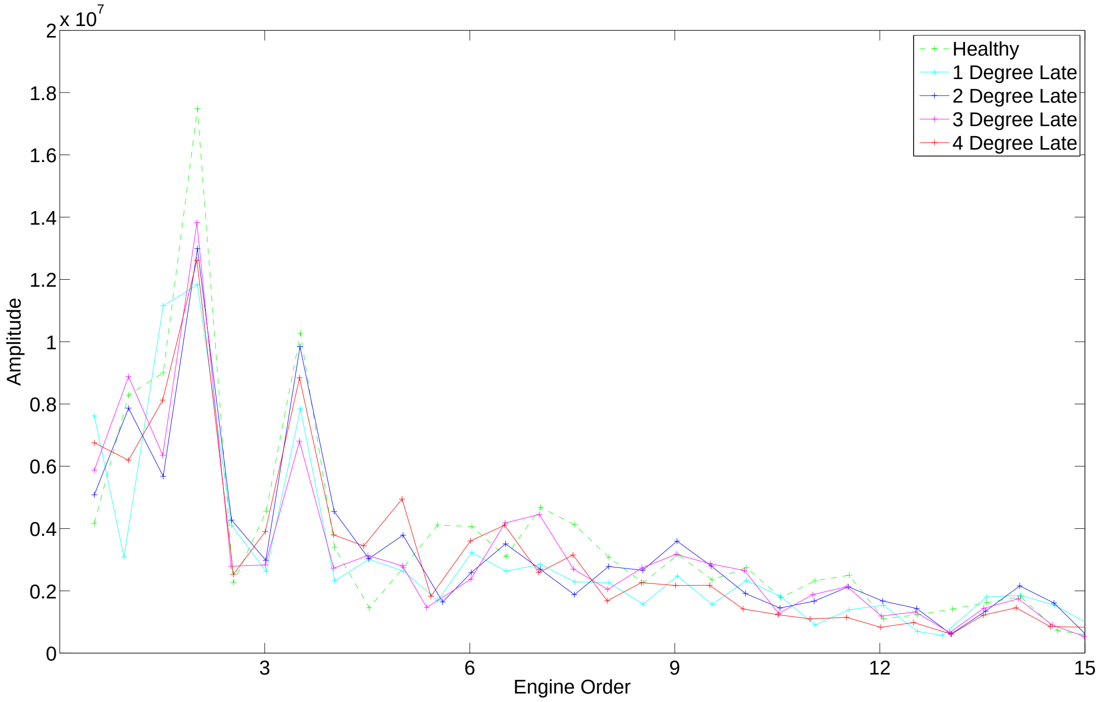

Figure A.35: Peak Points of Healthy vs Early Injection Fault at 750RPM and 25% Load - Channel 5

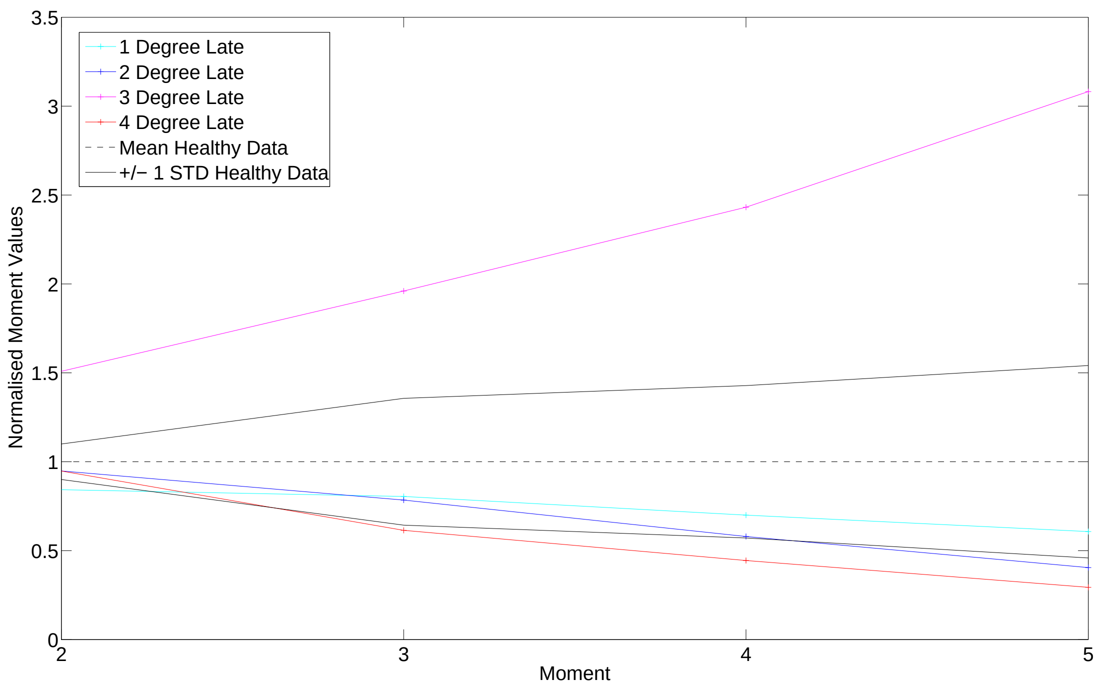

Figure A.36: Moments of Healthy vs Early Injection Fault at 750RPM and 25% Load - Channel 1

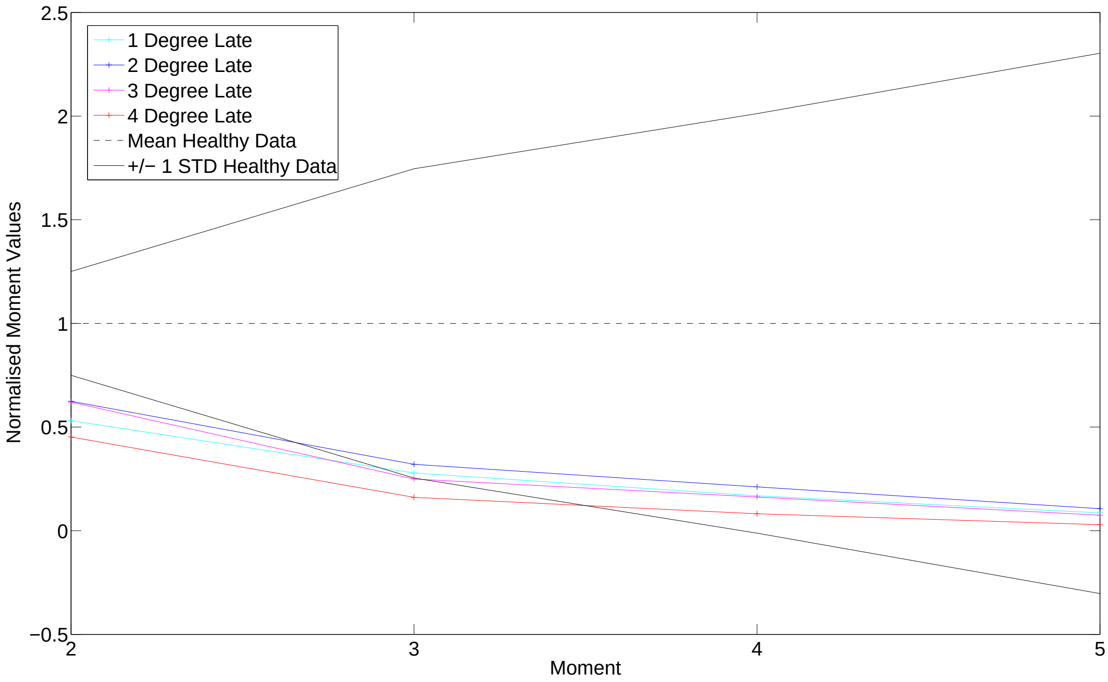

Figure A.37: Moments of Healthy vs Early Injection Fault at 750RPM and 50% Load - Channel 1

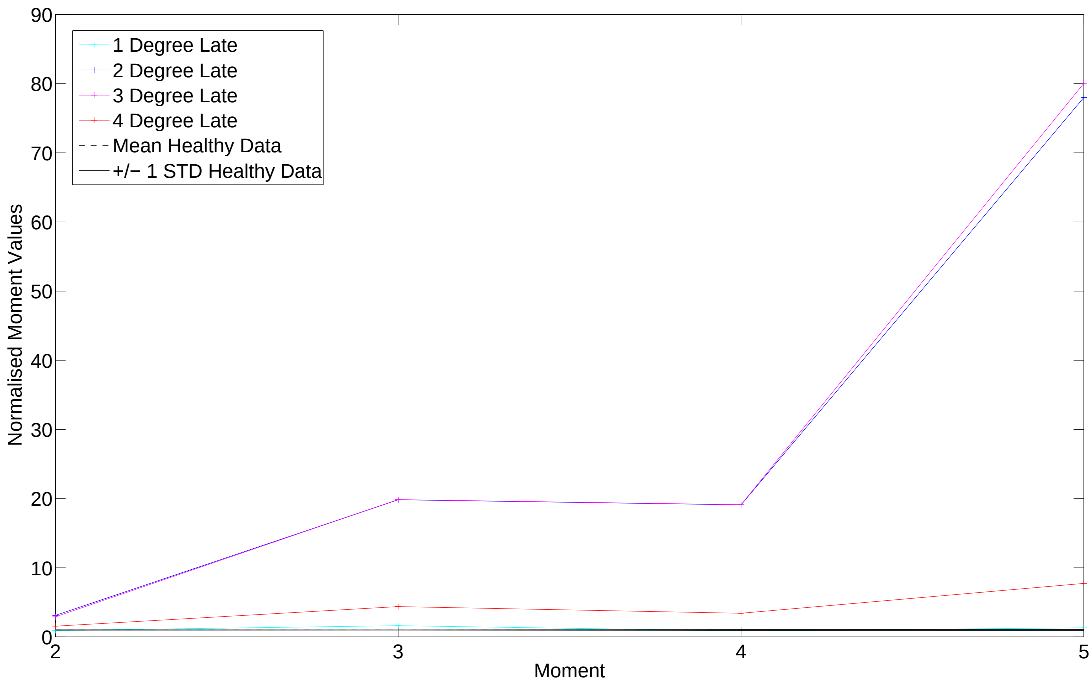

Figure A.38: Moments of Healthy vs Early Injection Fault at 750RPM and 75% Load - Channel 1

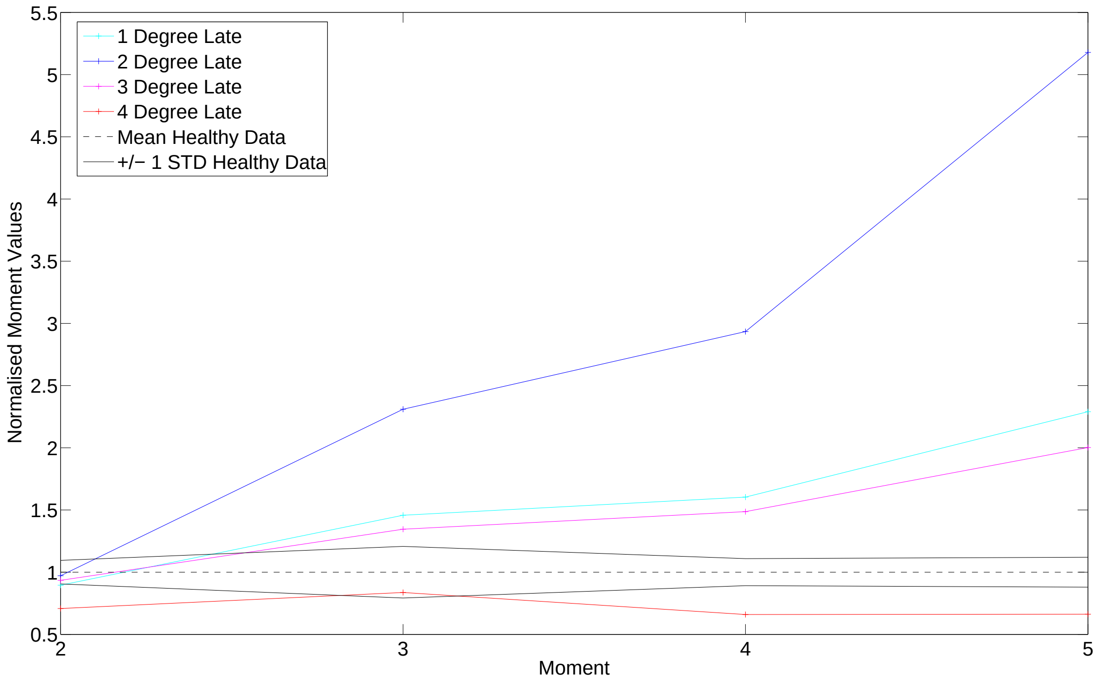

Figure A.39: Moments of Healthy vs Early Injection Fault at 900RPM and 25% Load - Channel 1

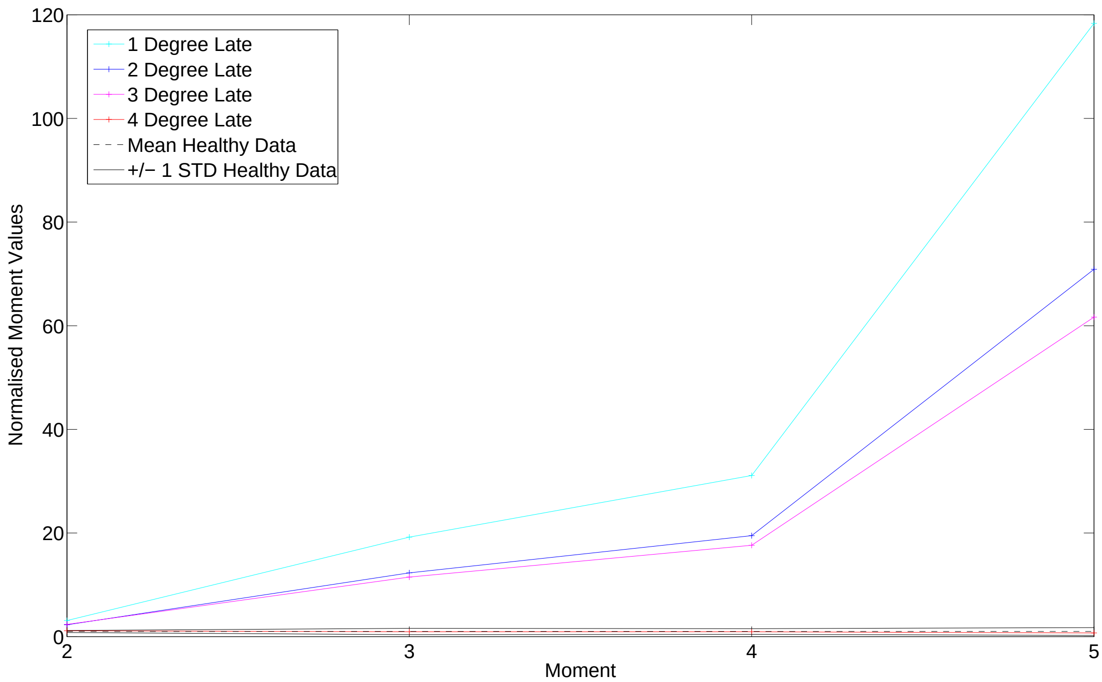

Figure A.40: Moments of Healthy vs Early Injection Fault at 900RPM and 50% Load - Channel 1

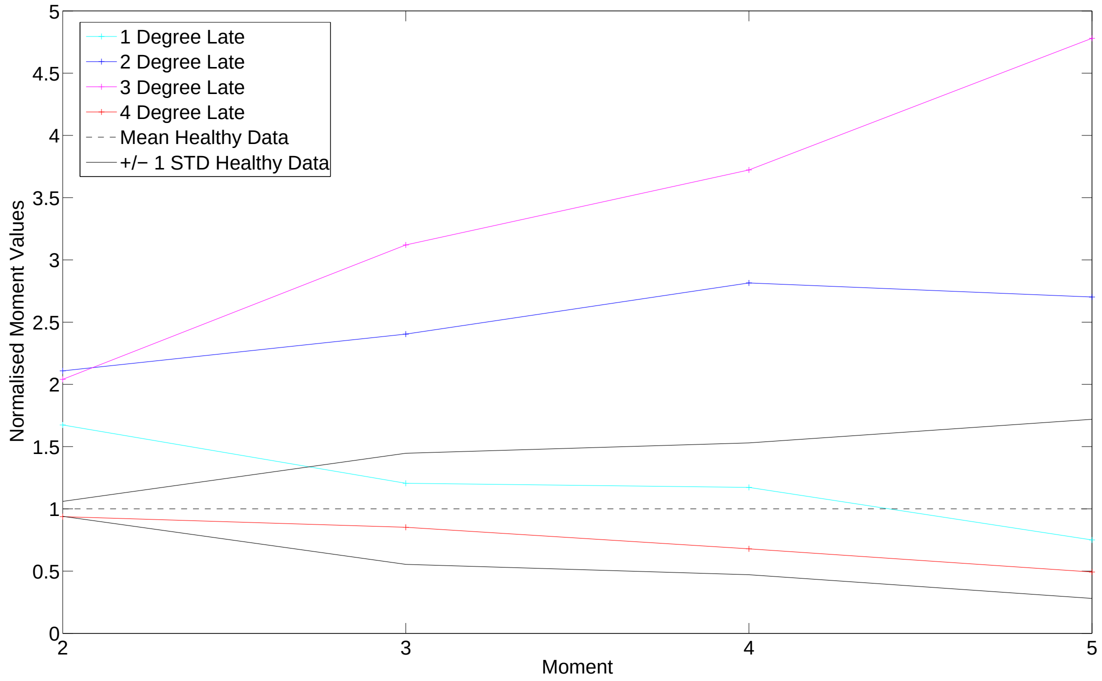

Figure A.41: Moments of Healthy vs Early Injection Fault at 900RPM and 75% Load - Channel 1

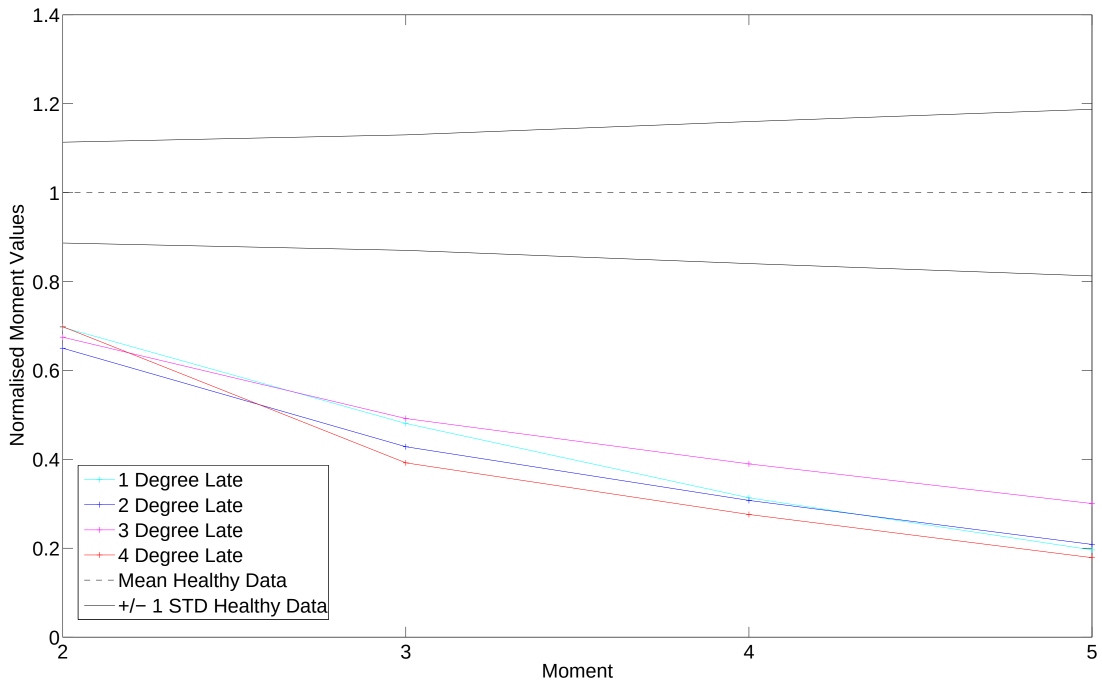

Figure A.42: Moments of Healthy vs Early Injection Fault at 750RPM and 25% Load - Channel 5

A.5 Inlet and Exhaust Valves

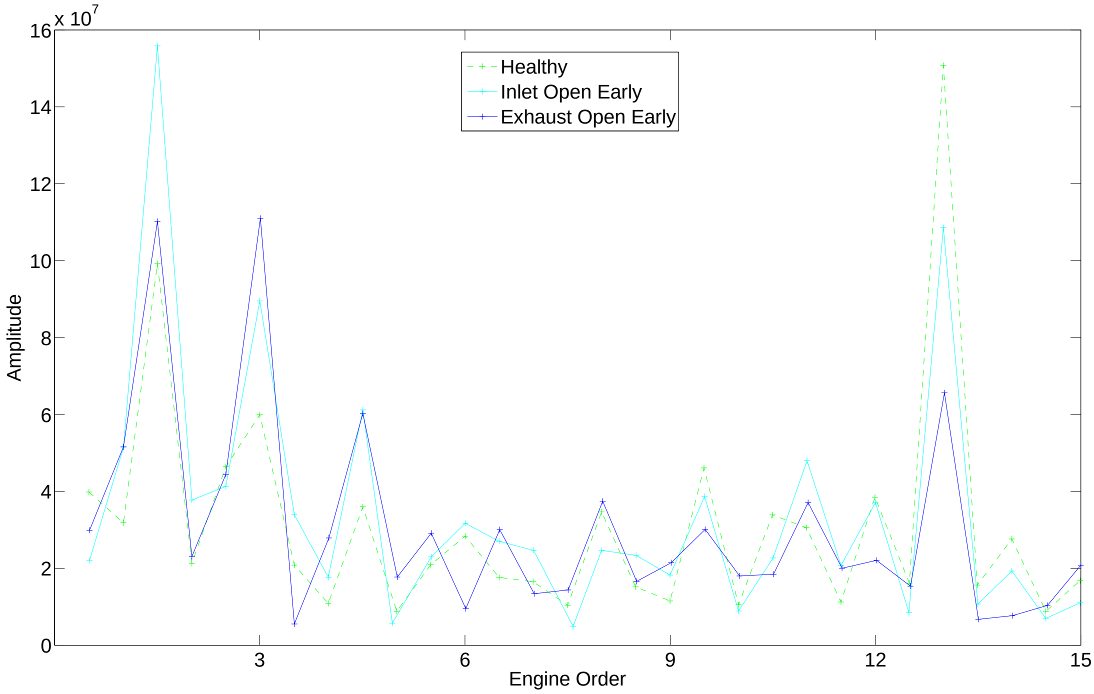

Figure A.43: Peak Points of Healthy vs Valve Faults at 750RPM and 25% Load - Channel 1

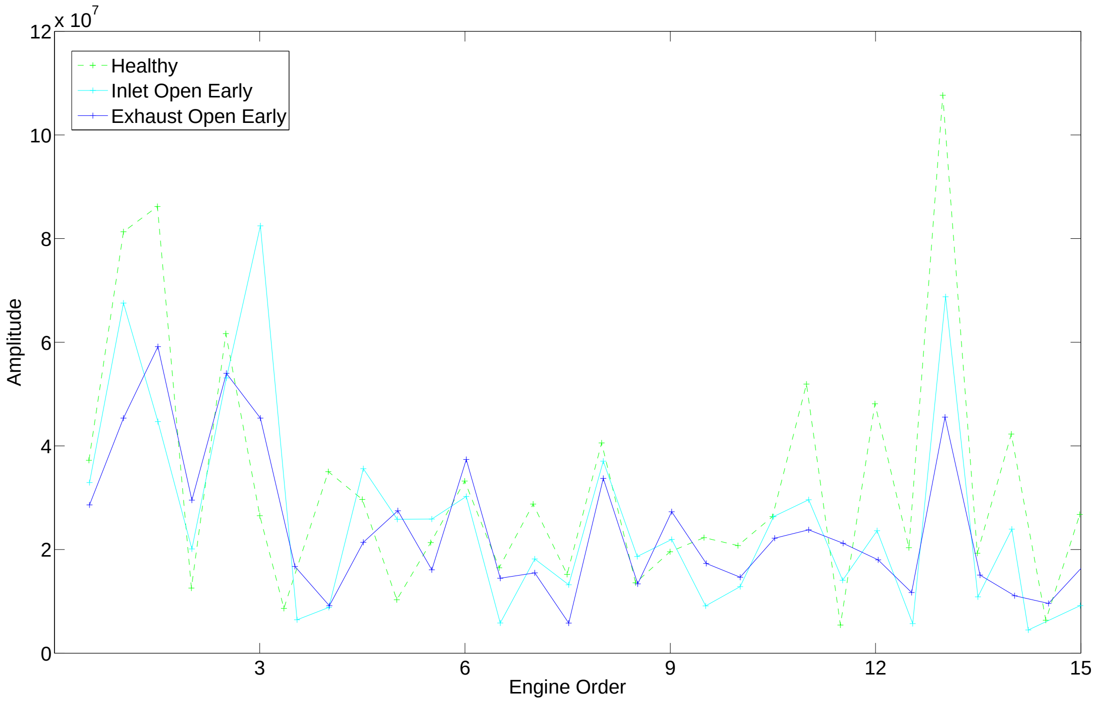

Figure A.44: Peak Points of Healthy vs Valve Faults at 750RPM and 50% Load - Channel 1

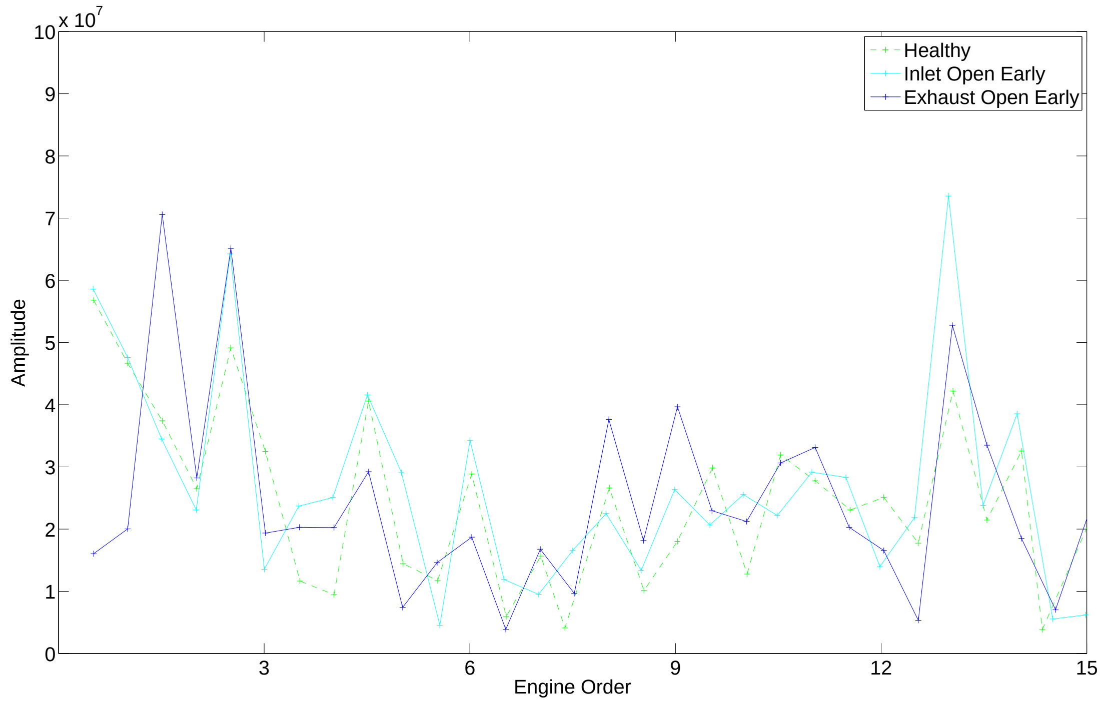

Figure A.45: Peak Points of Healthy vs Valve Faults at 750RPM and 75% Load - Channel 1

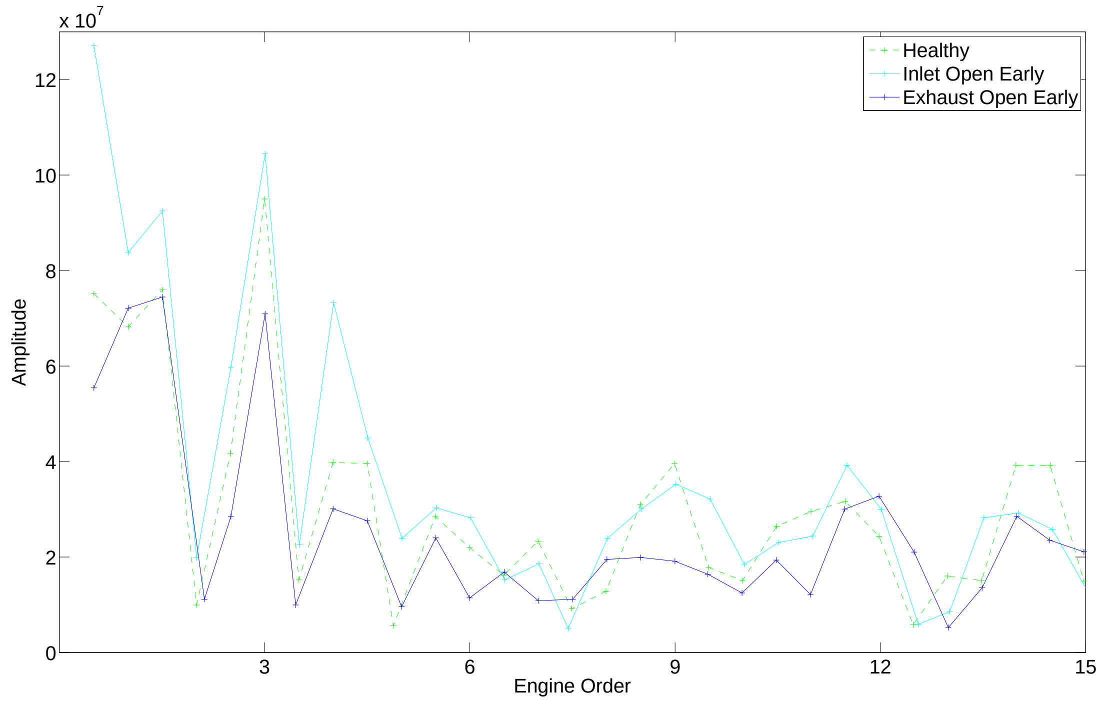

Figure A.46: Peak Points of Healthy vs Valve Faults at 900RPM and 25% Load - Channel 1

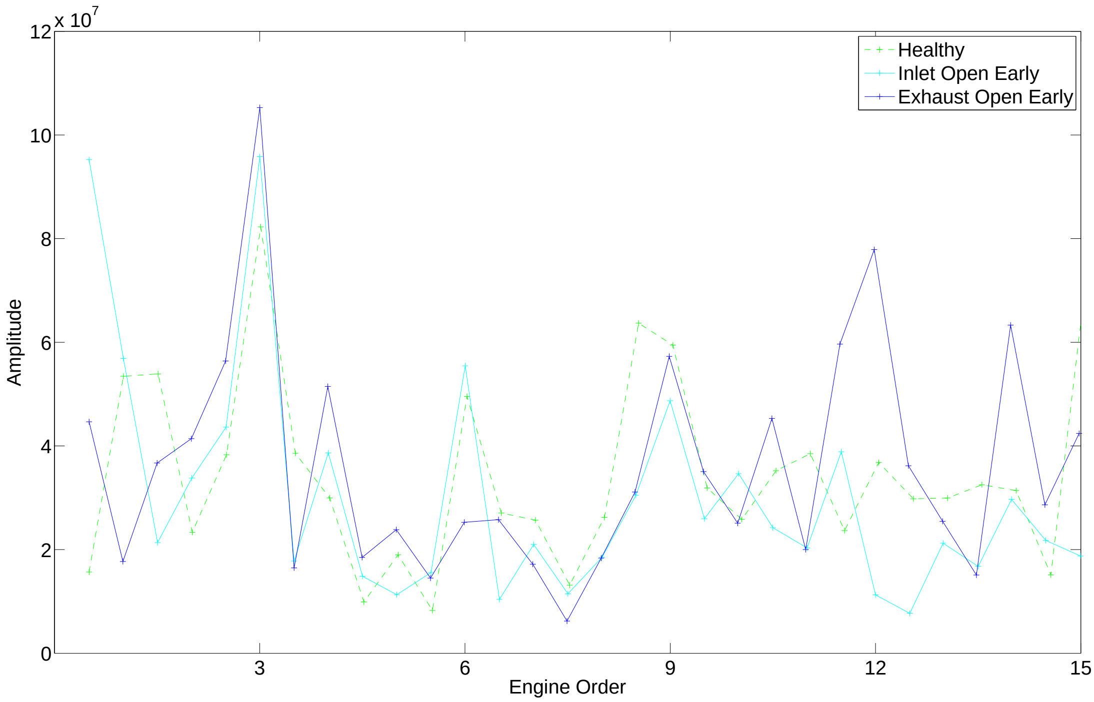

Figure A.47: Peak Points of Healthy vs Valve Faults at 900RPM and 50% Load - Channel 1

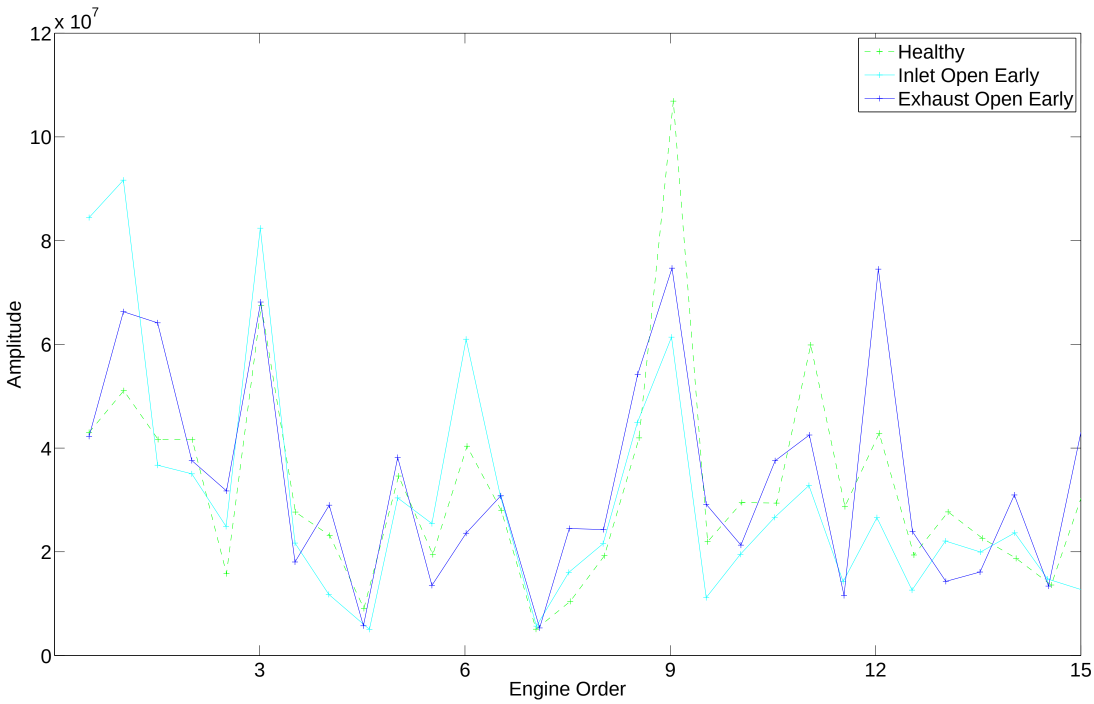

Figure A.48: Peak Points of Healthy vs Valve Faults at 900RPM and 75% Load - Channel 1

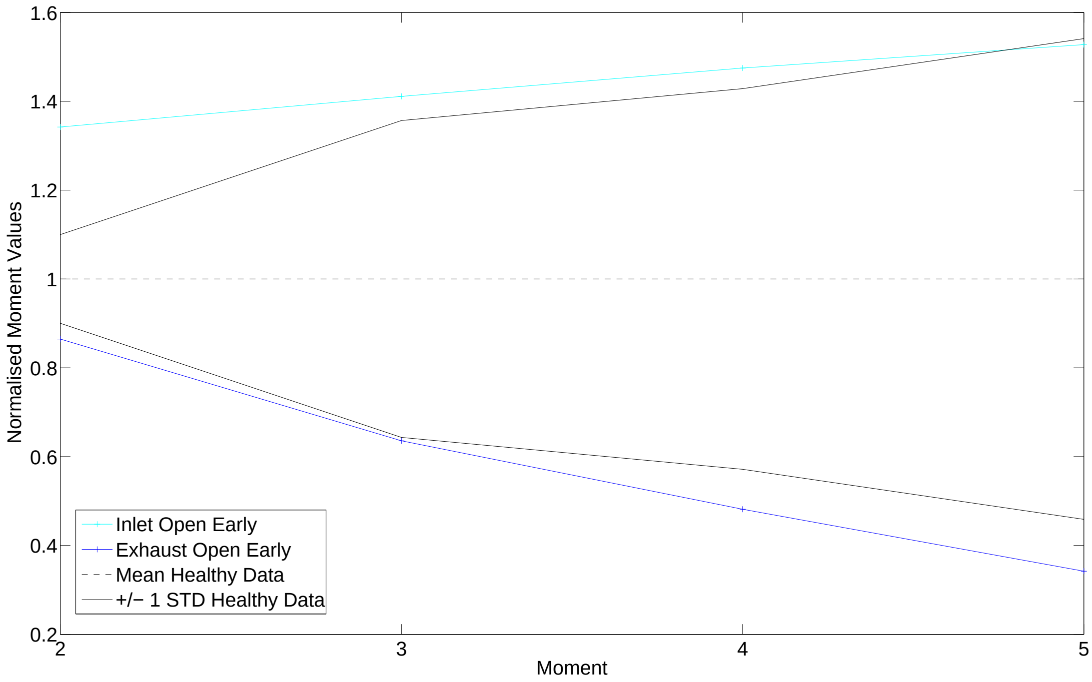

Figure A.49: Moments of Healthy vs Valve Faults at 750RPM and 25% Load - Channel 1

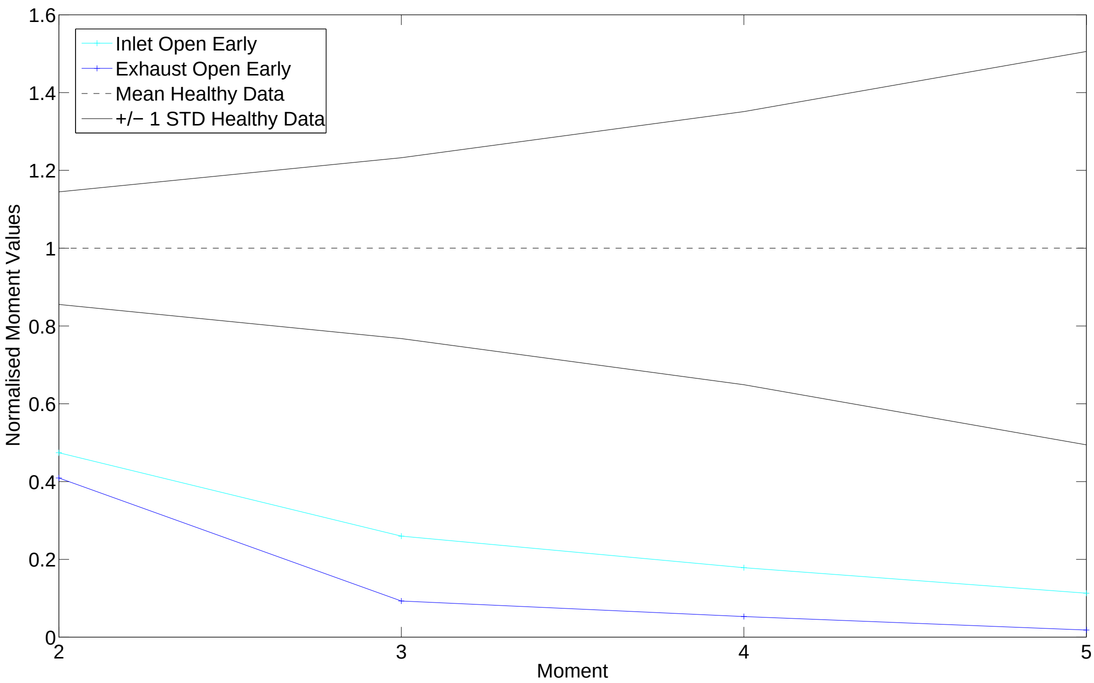

Figure A.50: Moments of Healthy vs Valve Faults at 750RPM and 25% Load - Channel 3

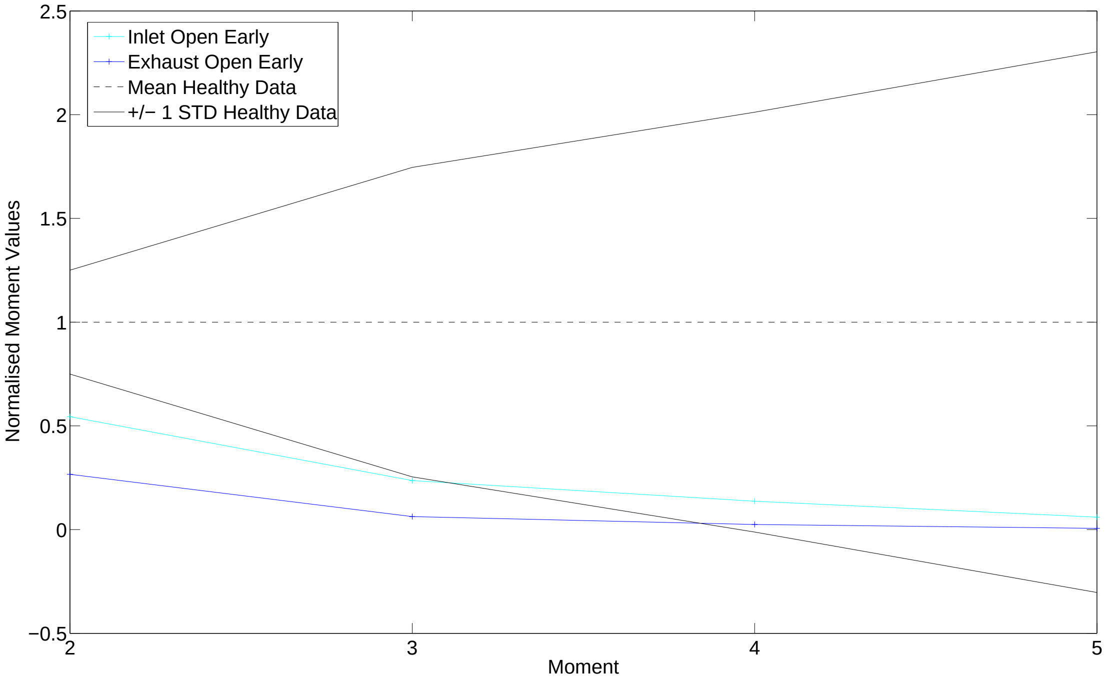

Figure A.51: Moments of Healthy vs Valve Faults at 750RPM and 50% Load - Channel 1

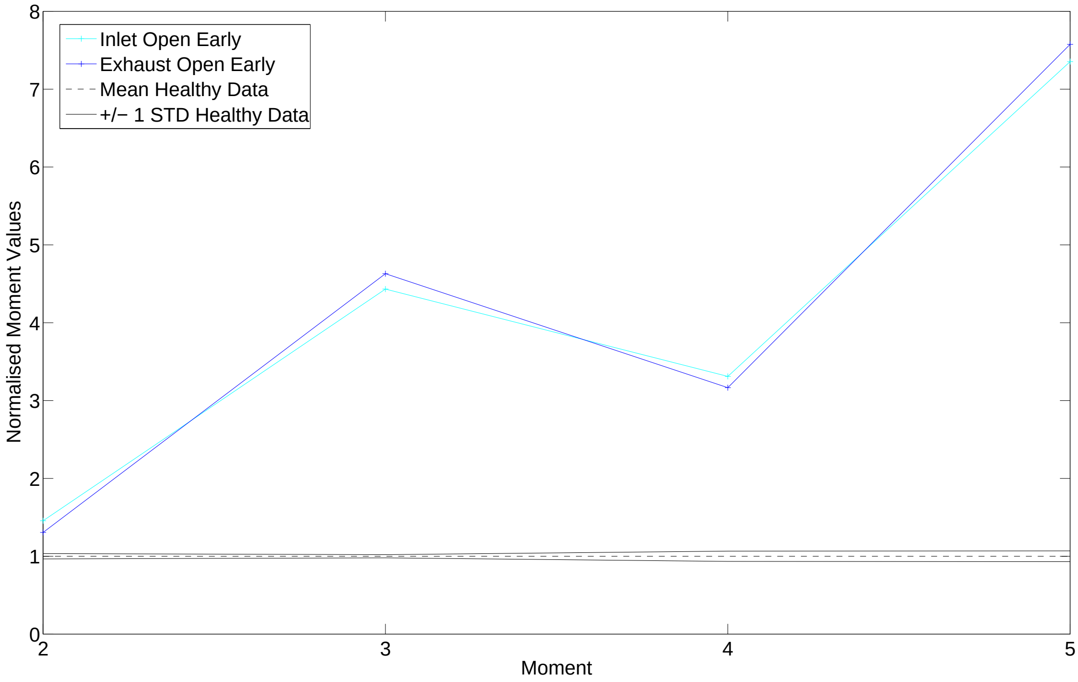

Figure A.52: Moments of Healthy vs Valve Faults at 750RPM and 75% Load - Channel 1

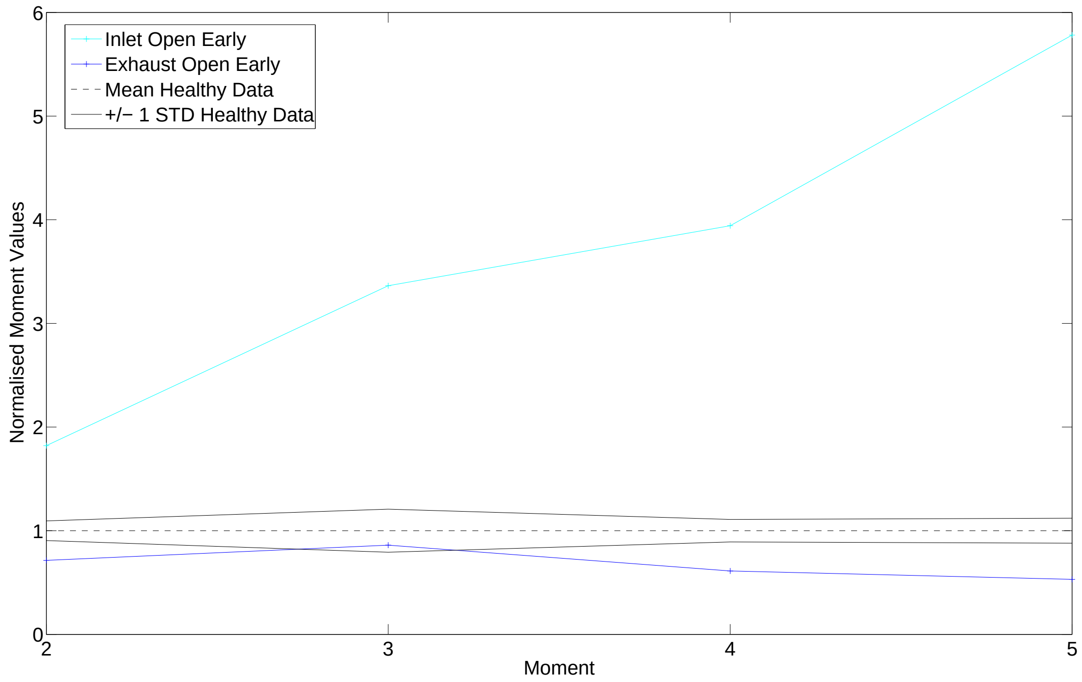

Figure A.53: Moments of Healthy vs Valve Faults at 900RPM and 25% Load - Channel 1

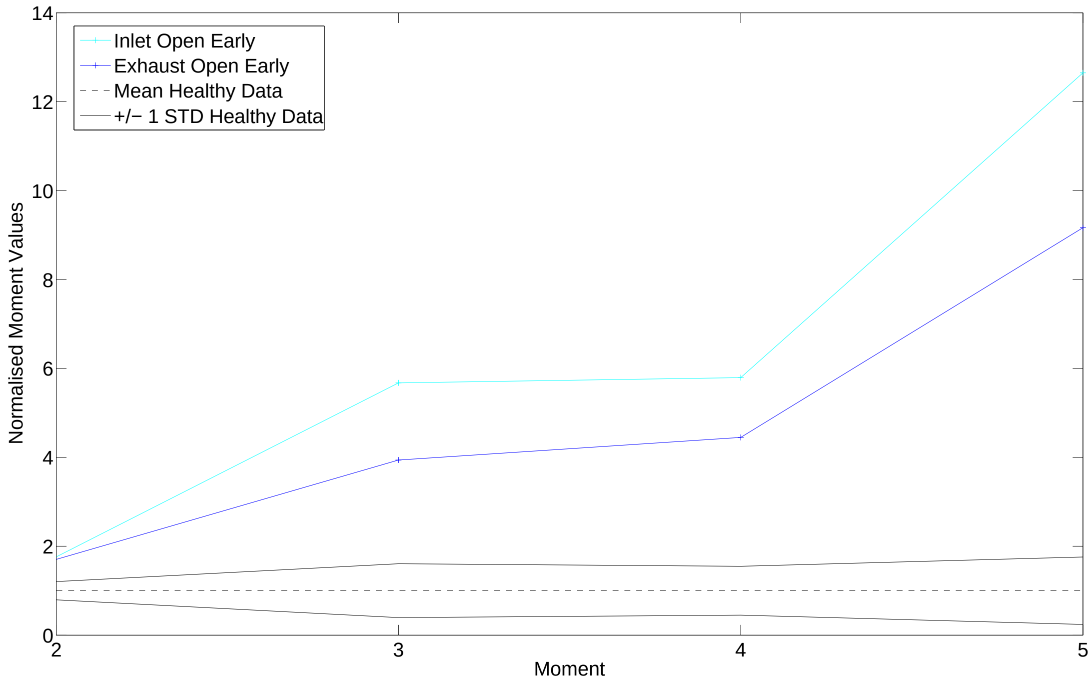

Figure A.54: Moments of Healthy vs Valve Faults at 900RPM and 50% Load - Channel 1

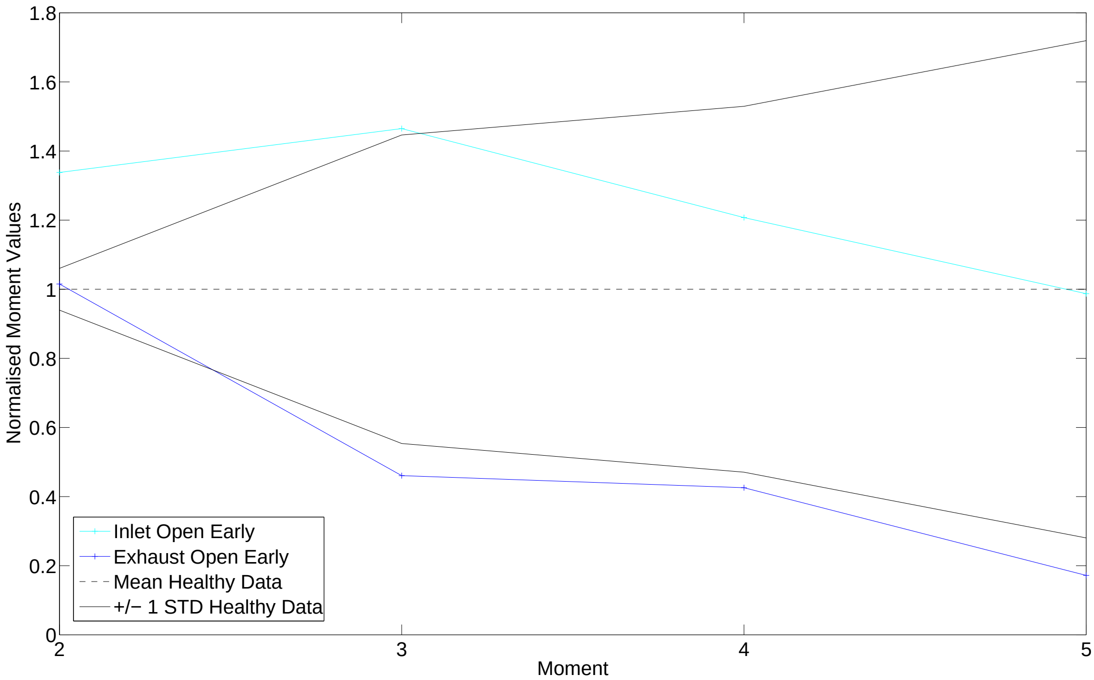

Figure A.55: Moments of Healthy vs Valve Faults at 900RPM and 75% Load - Channel 1

Appendix B

Ford Non ICA Results

The following appendix provides a sample of some of the data that has been collated and processed without ICA processing for the Ford engine and is discussed in chapter 6.

B.1 Varying Injector Opening Pressures

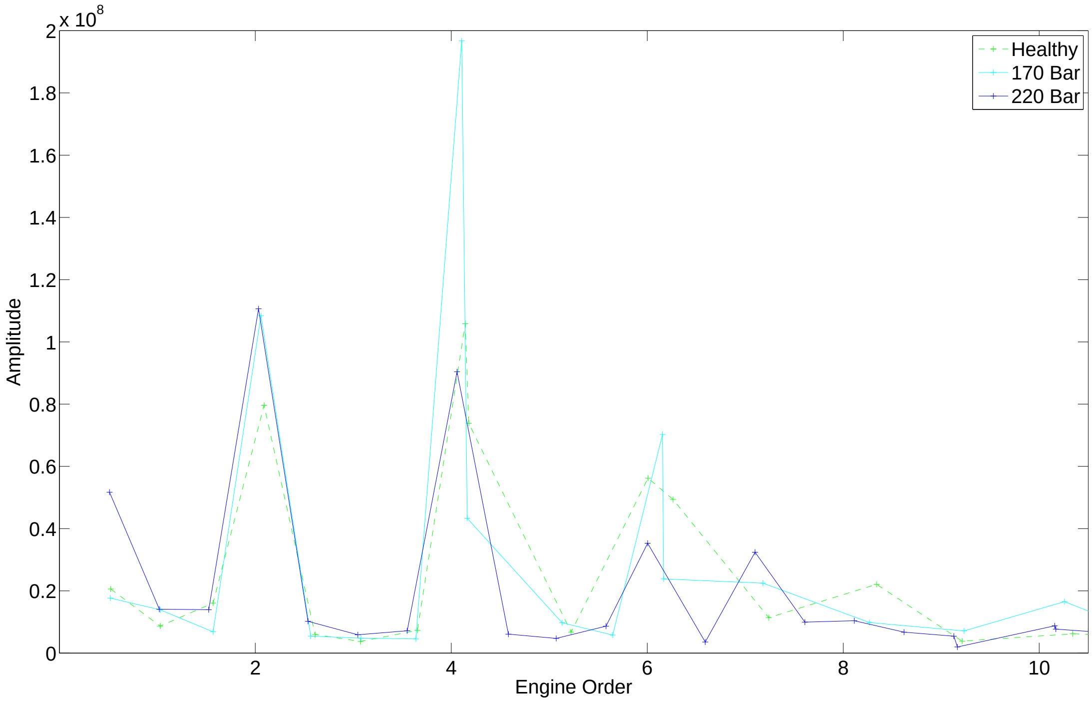

Figure B.1: Peak Points of Healthy vs Varying Injection Pressure at 1500RPM and 0% Load - Channel 1

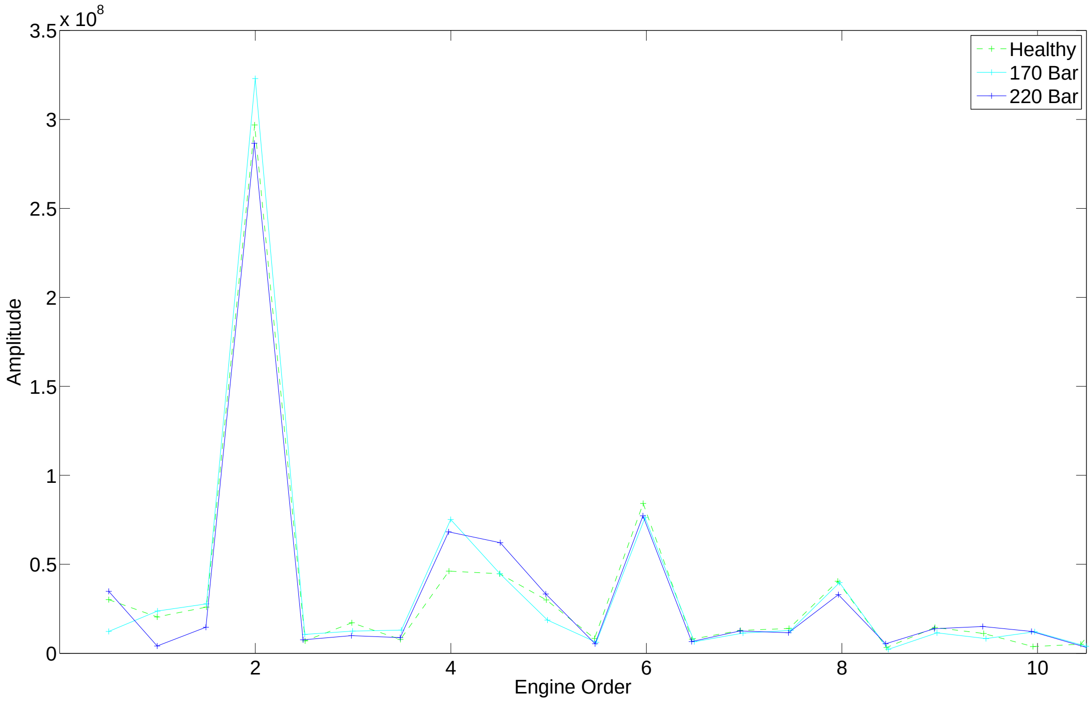

Figure B.2: Peak Points of Healthy vs Varying Injection Pressure at 2000RPM and 40% Load - Channel 1

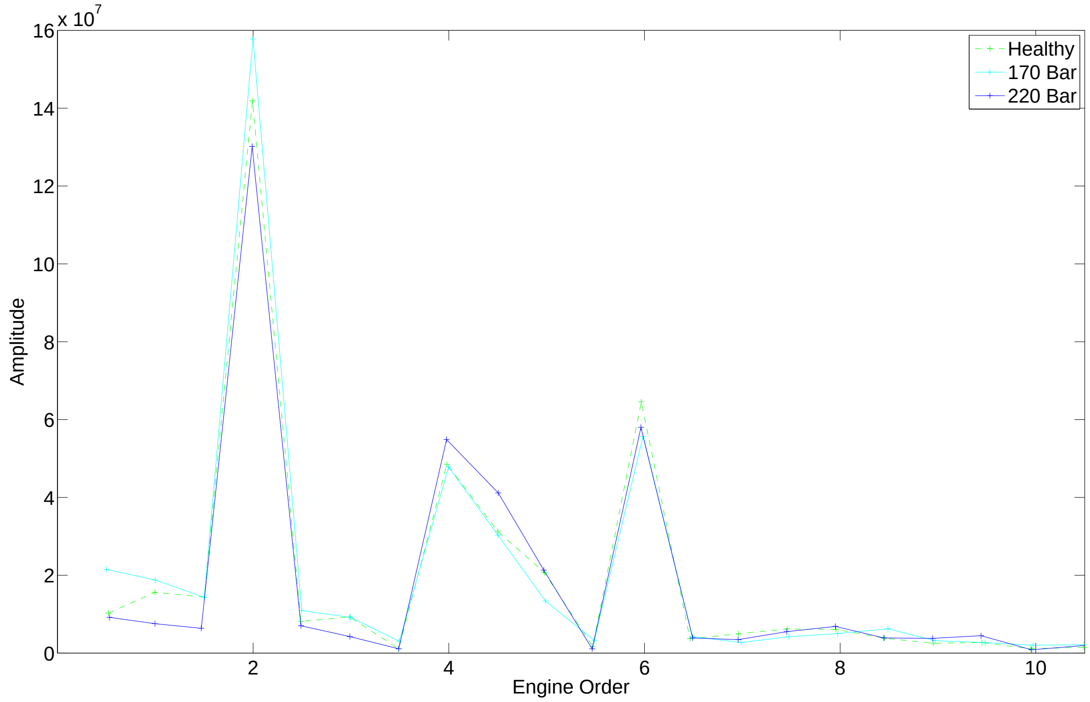

Figure B.3: Peak Points of Healthy vs Varying Injection Pressure at 2000RPM and 40% Load - Channel 4

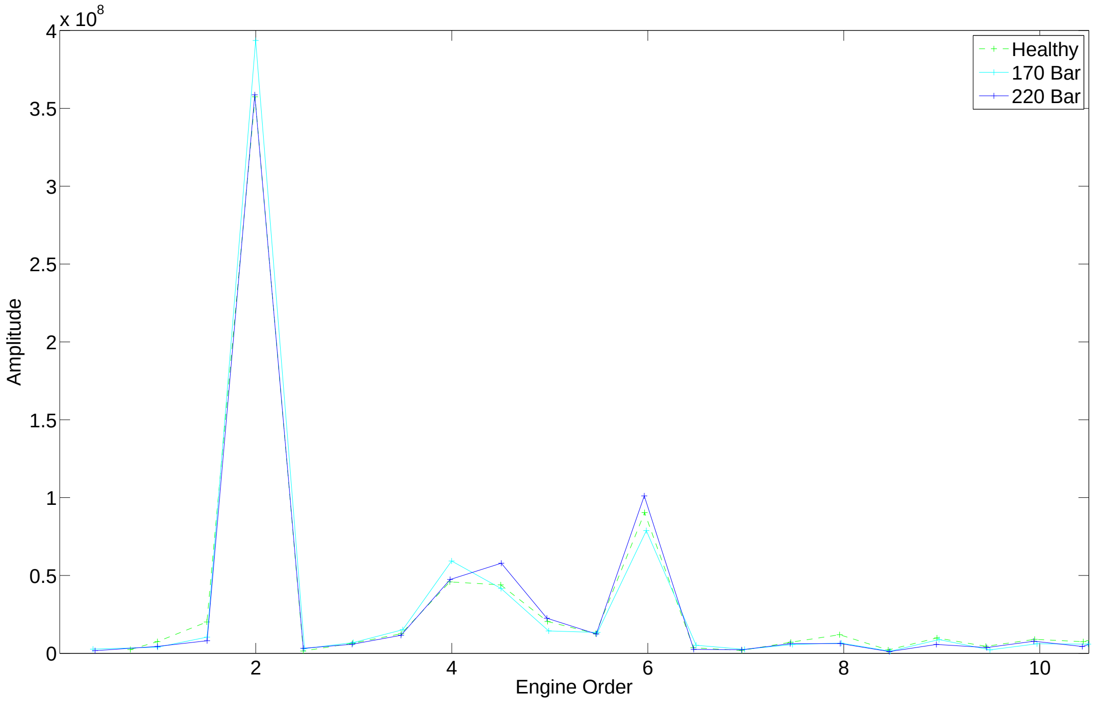

Figure B.4: Peak Points of Healthy vs Varying Injection Pressure at 2000RPM and 40% Load - Channel 5

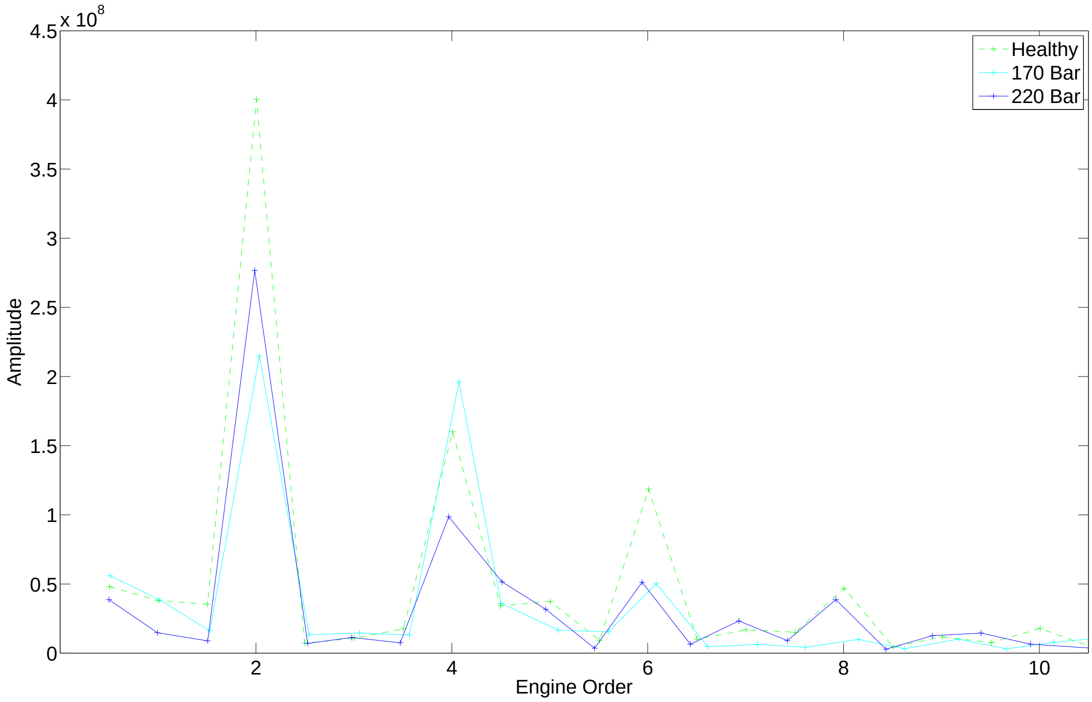

Figure B.5: Peak Points of Healthy vs Varying Injection Pressure at 2000RPM and 80% Load - Channel 1

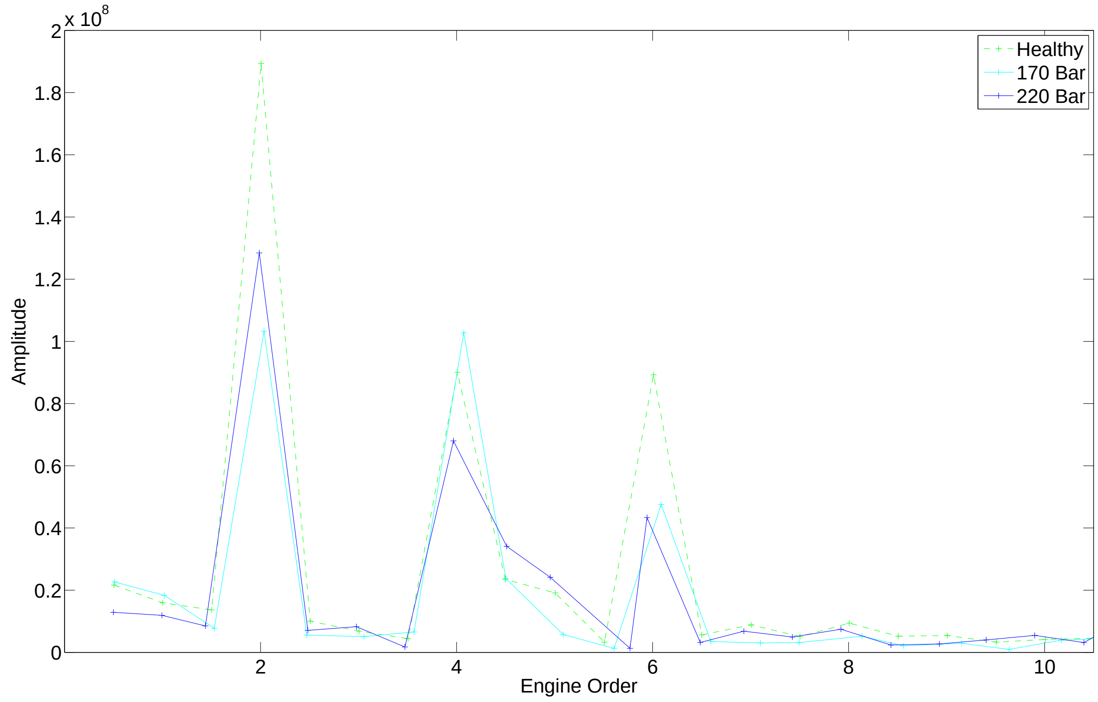

Figure B.6: Peak Points of Healthy vs Varying Injection Pressure at 2000RPM and 80% Load - Channel 4

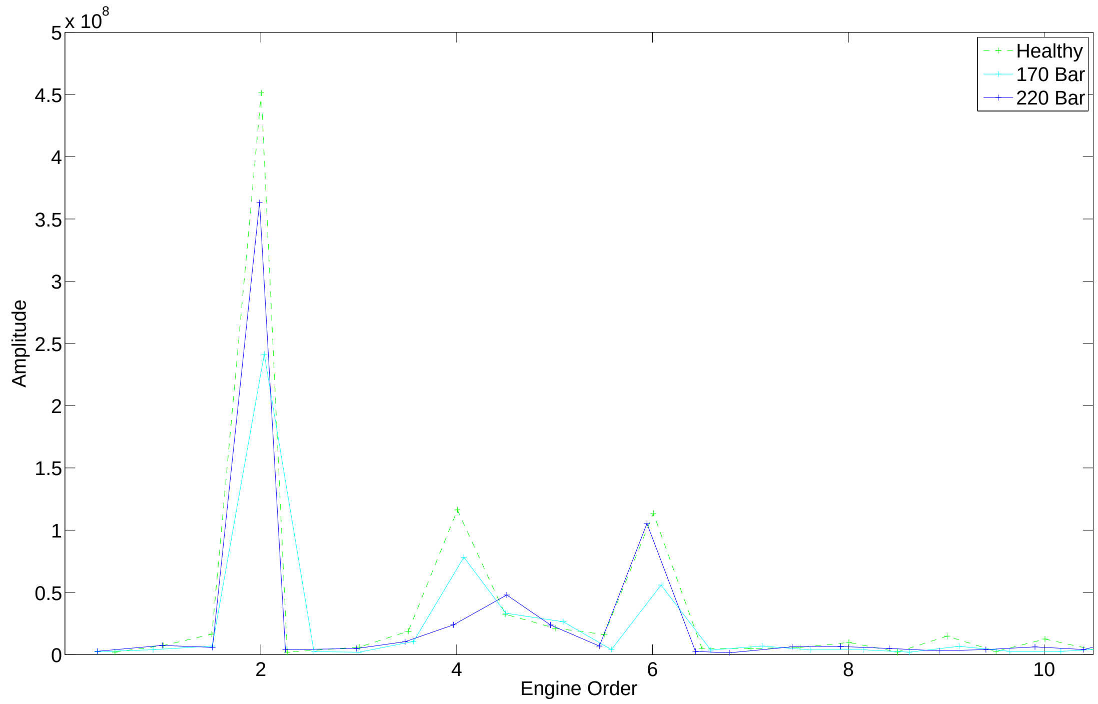

Figure B.7: Peak Points of Healthy vs Varying Injection Pressure at 2000RPM and 80% Load - Channel 5

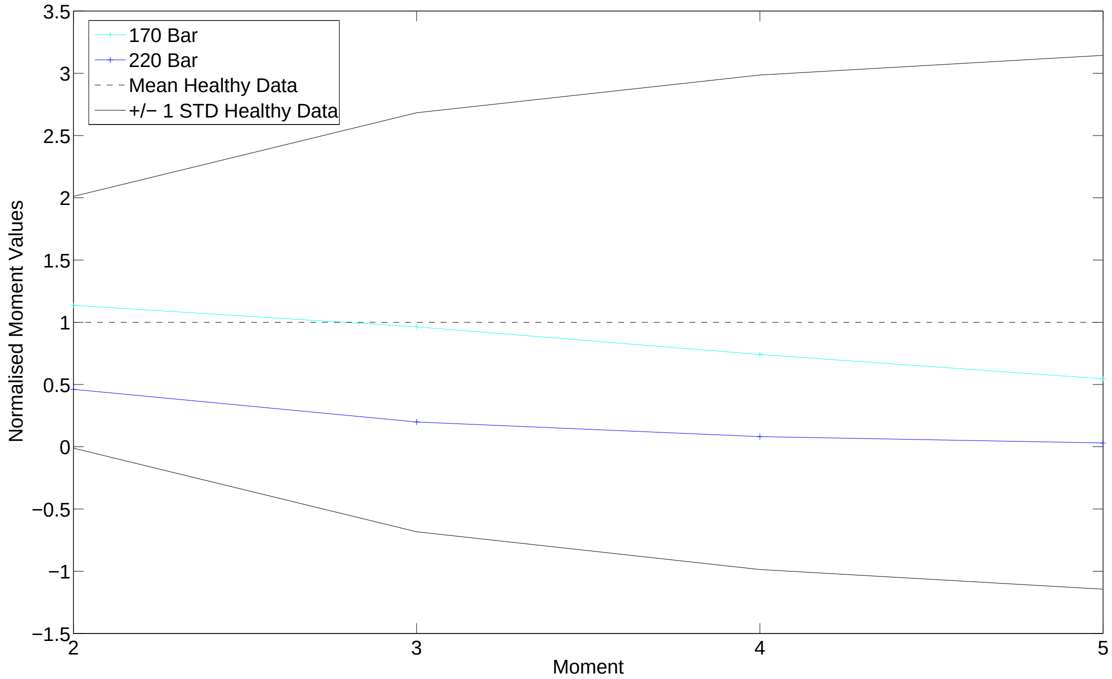

Figure B.8: Moments of Healthy vs Varying Injection Pressure at 1500RPM and 0% Load - Channel 1

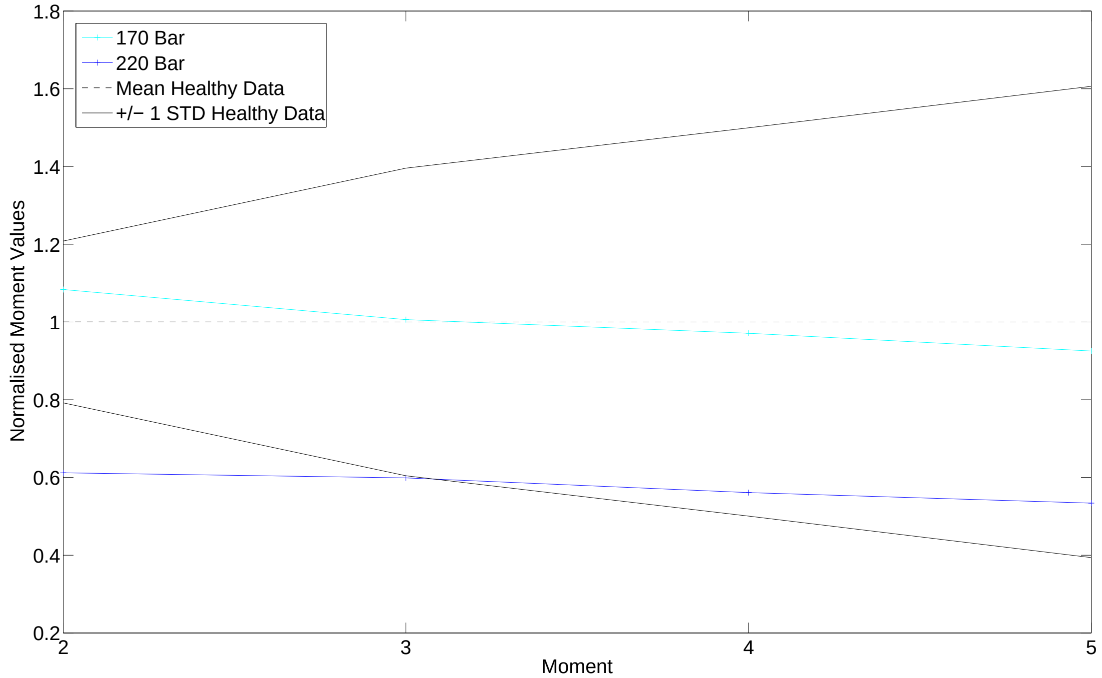

Figure B.9: Moments of Healthy vs Varying Injection Pressure at 1500RPM and 40% Load - Channel 1

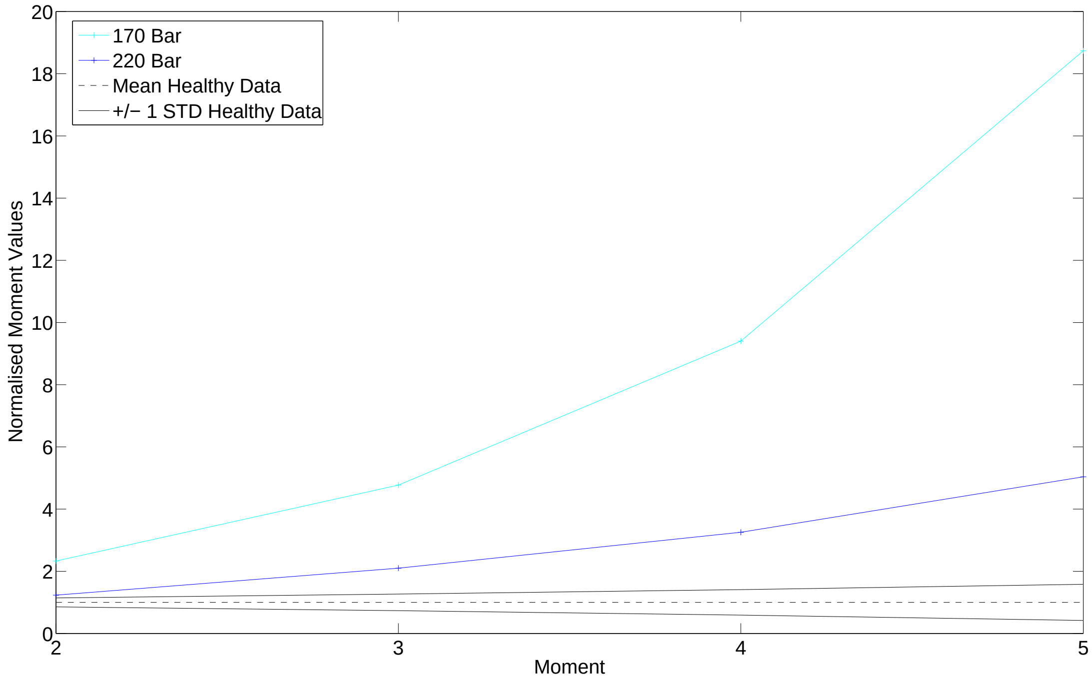

Figure B.10: Moments of Healthy vs Varying Injection Pressure at 1500RPM and 80% Load - Channel 1

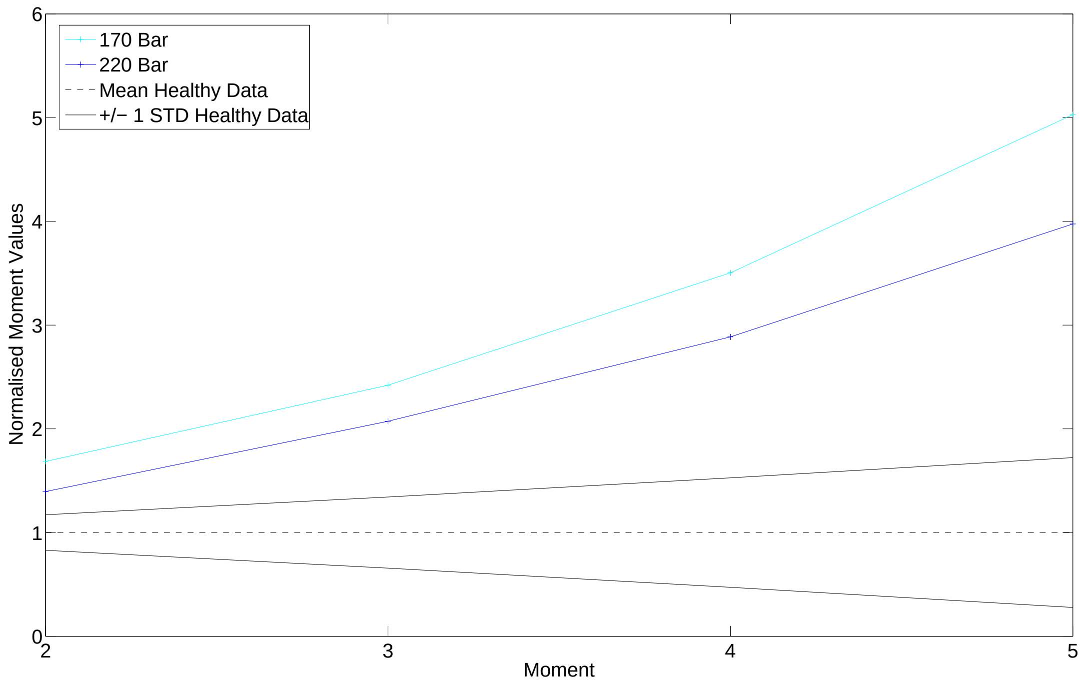

Figure B.11: Moments of Healthy vs Varying Injection Pressure at 1500RPM and 80% Load - Channel 4

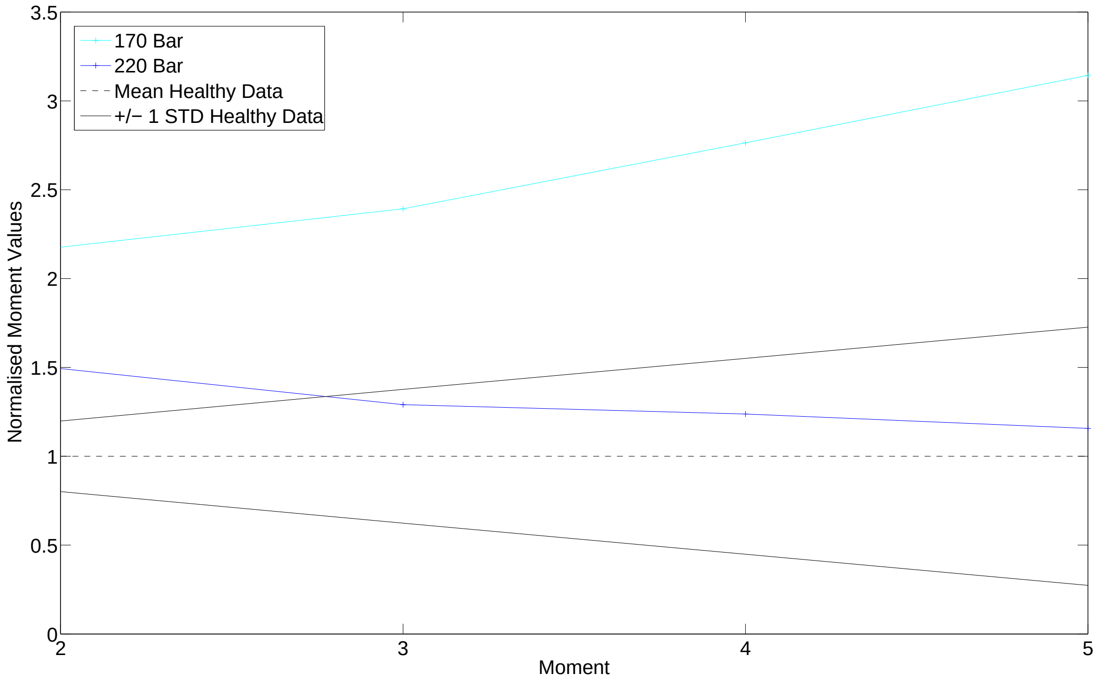

Figure B.12: Moments of Healthy vs Varying Injection Pressure at 1500RPM and 80% Load - Channel 5

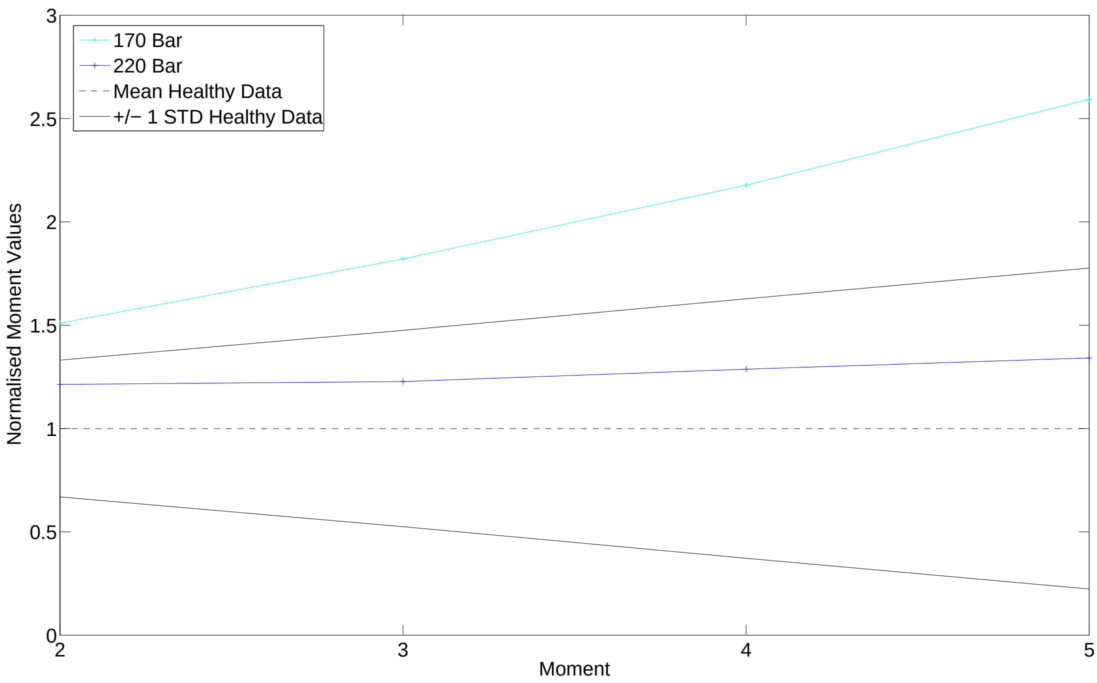

Figure B.13: Moments of Healthy vs Varying Injection Pressure at 2000RPM and 40% Load - Channel 1

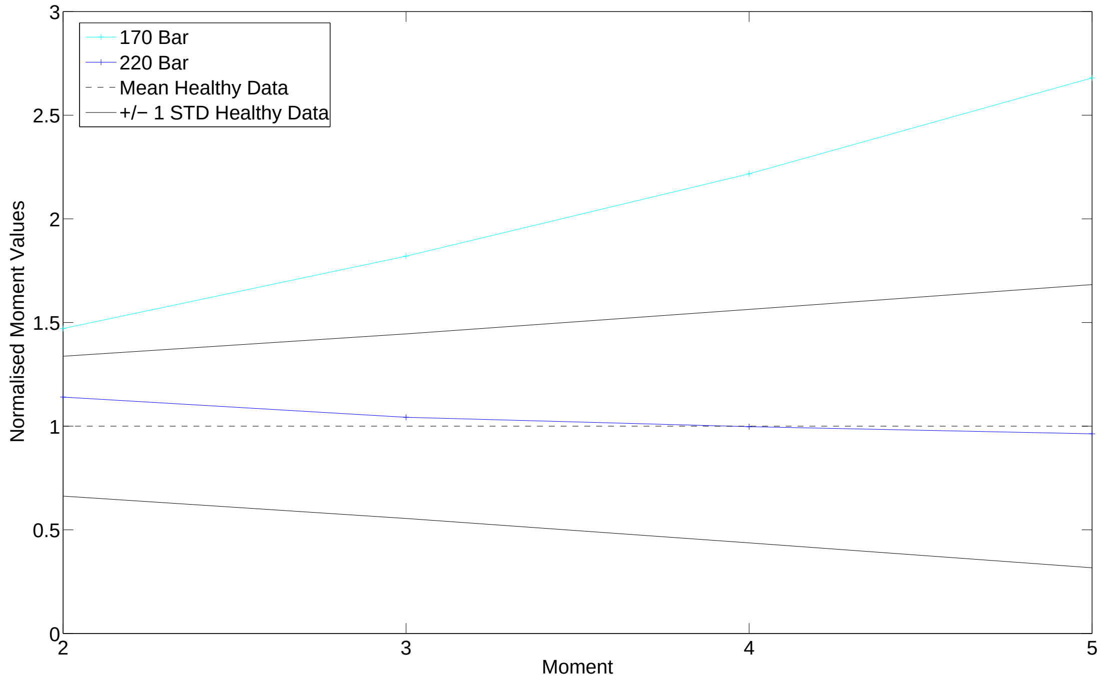

Figure B.14: Moments of Healthy vs Varying Injection Pressure at 2000RPM and 40% Load - Channel 4

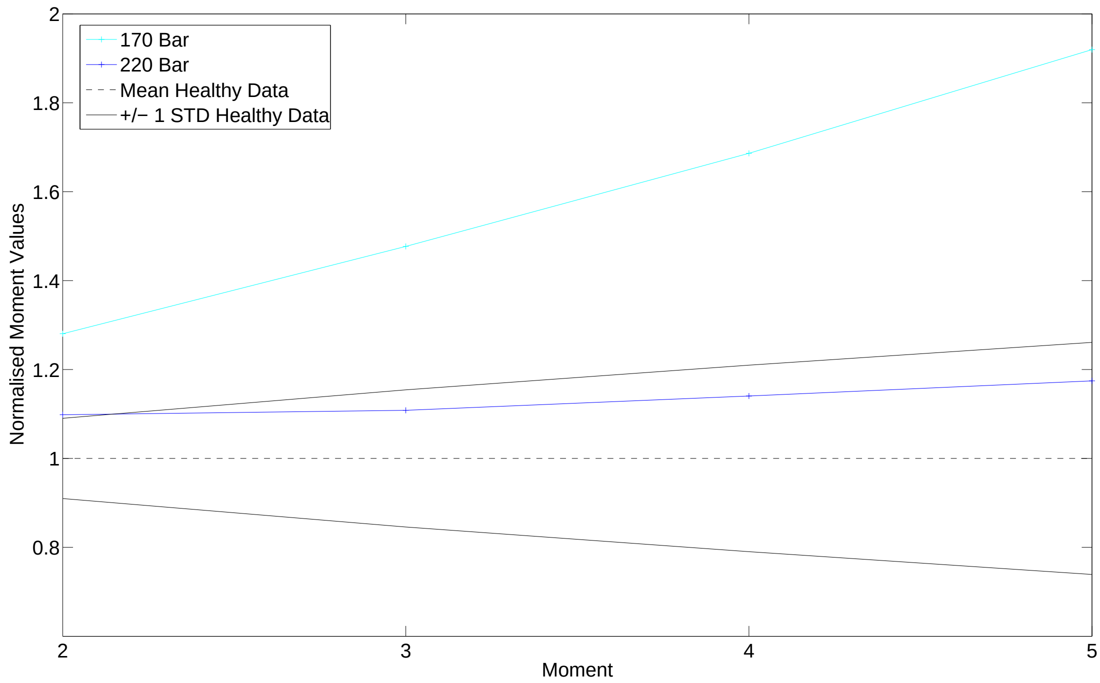

Figure B.15: Moments of Healthy vs Varying Injection Pressure at 2000RPM and 40% Load - Channel 5

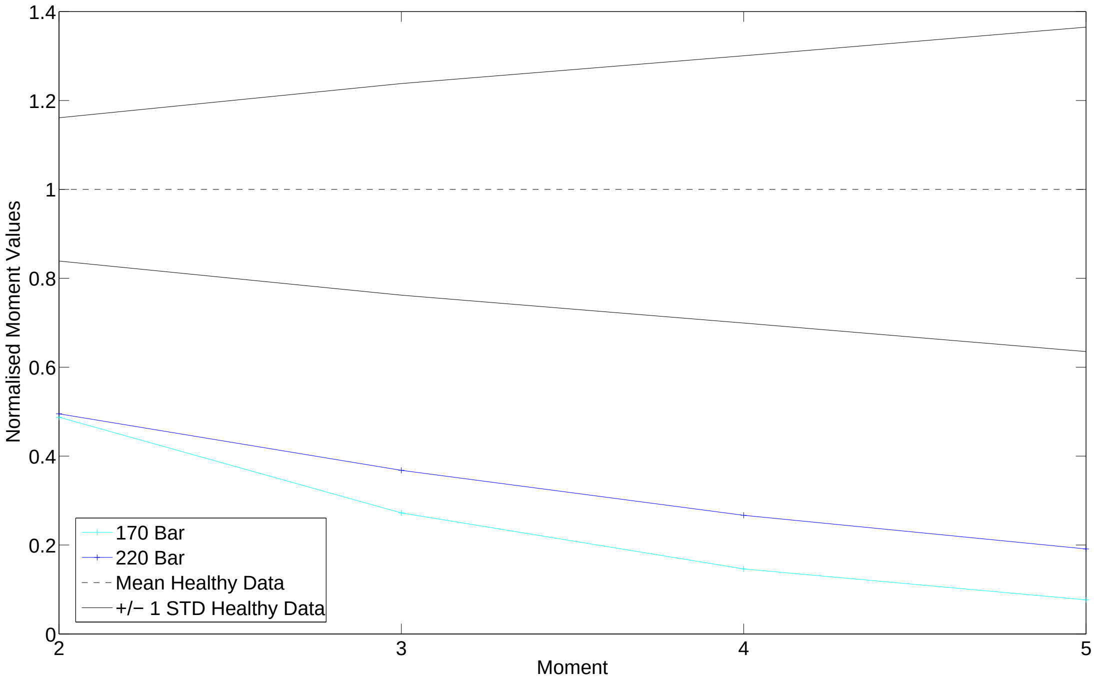

Figure B.16: Moments of Healthy vs Varying Injection Pressure at 2000RPM and 80% Load - Channel 1

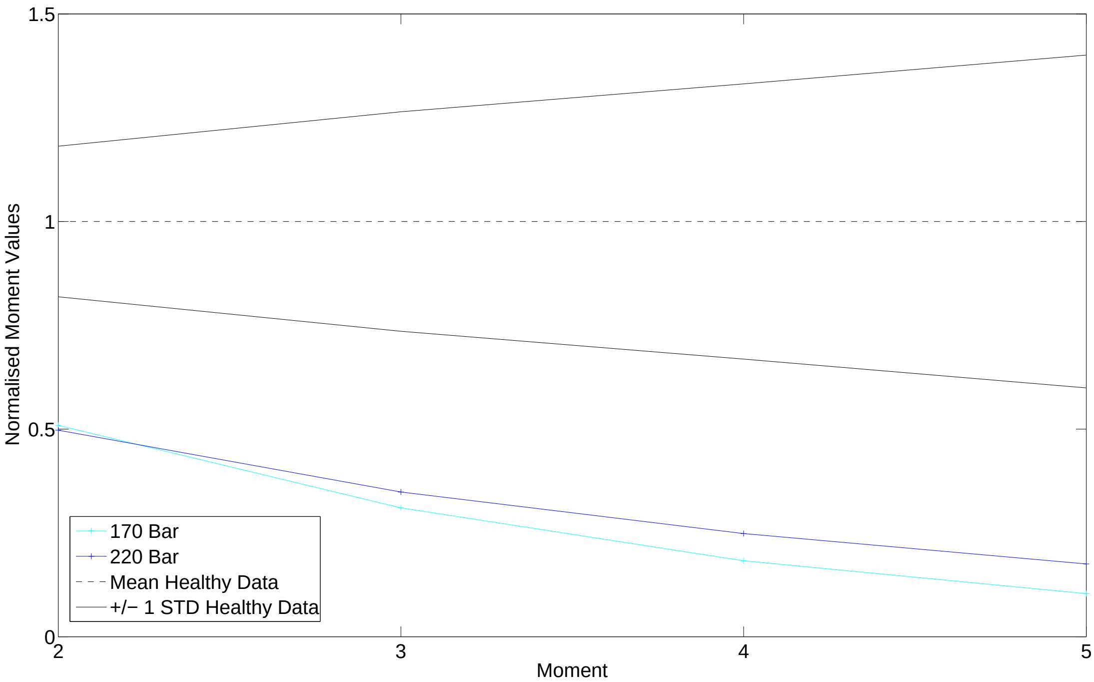

Figure B.17: Moments of Healthy vs Varying Injection Pressure at 2000RPM and 80% Load - Channel 4

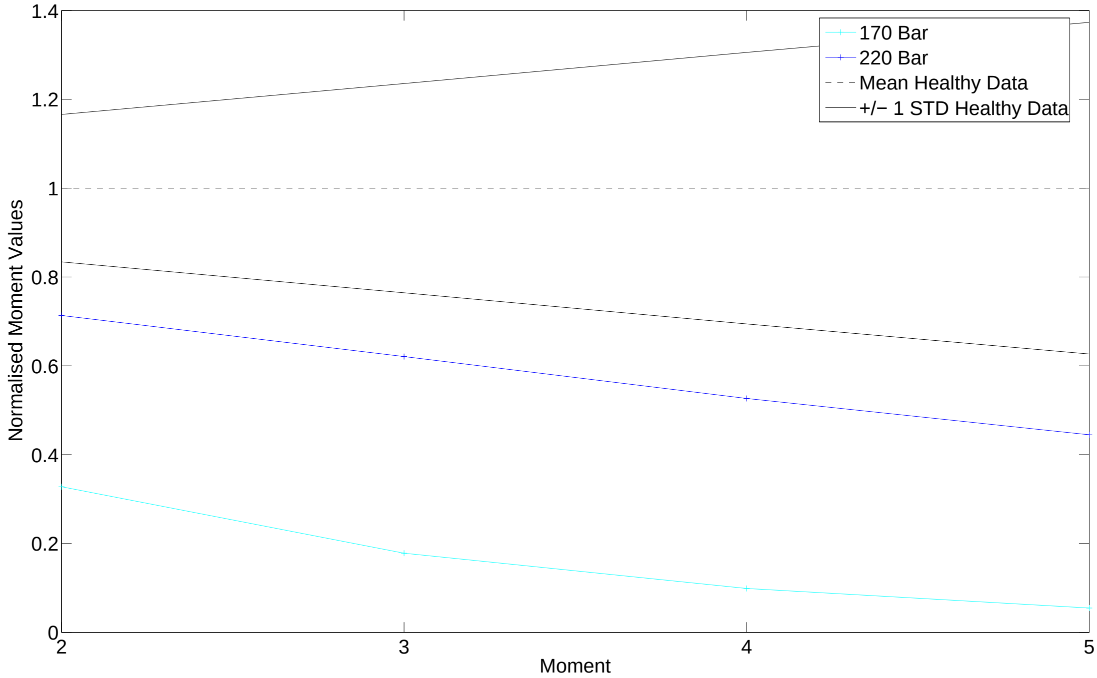

Figure B.18: Moments of Healthy vs Varying Injection Pressure at 2000RPM and 80% Load - Channel 5

B.2 Varying Inlet and Exhaust Valve Opening Time

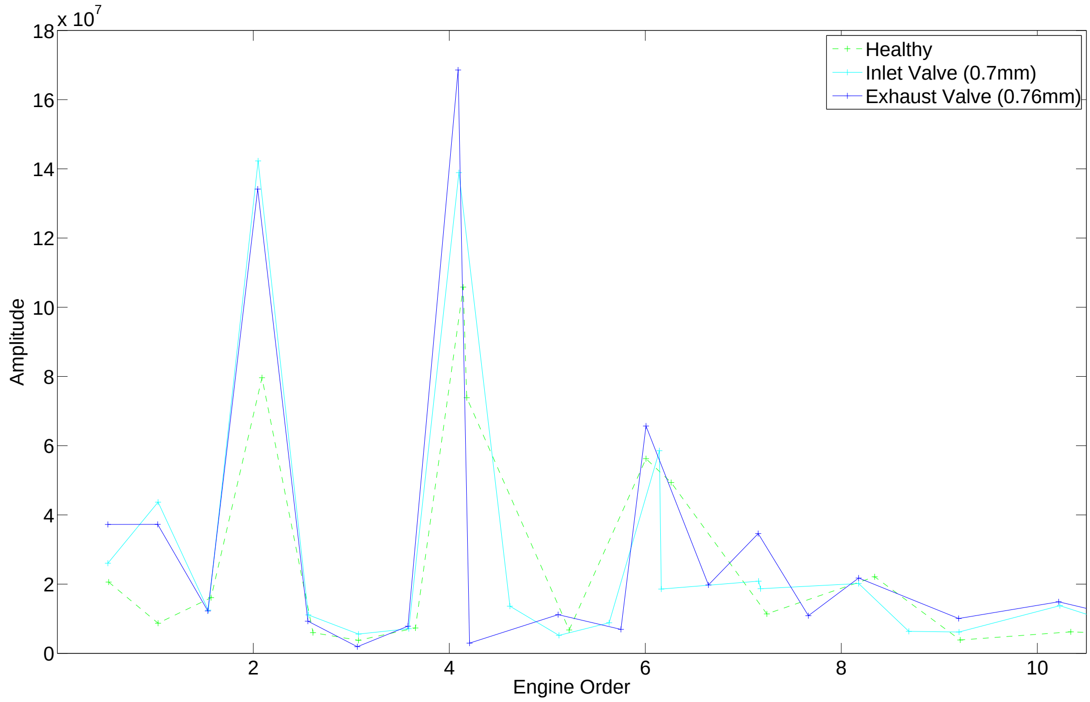

Figure B.19: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 0% Load - Channel 1

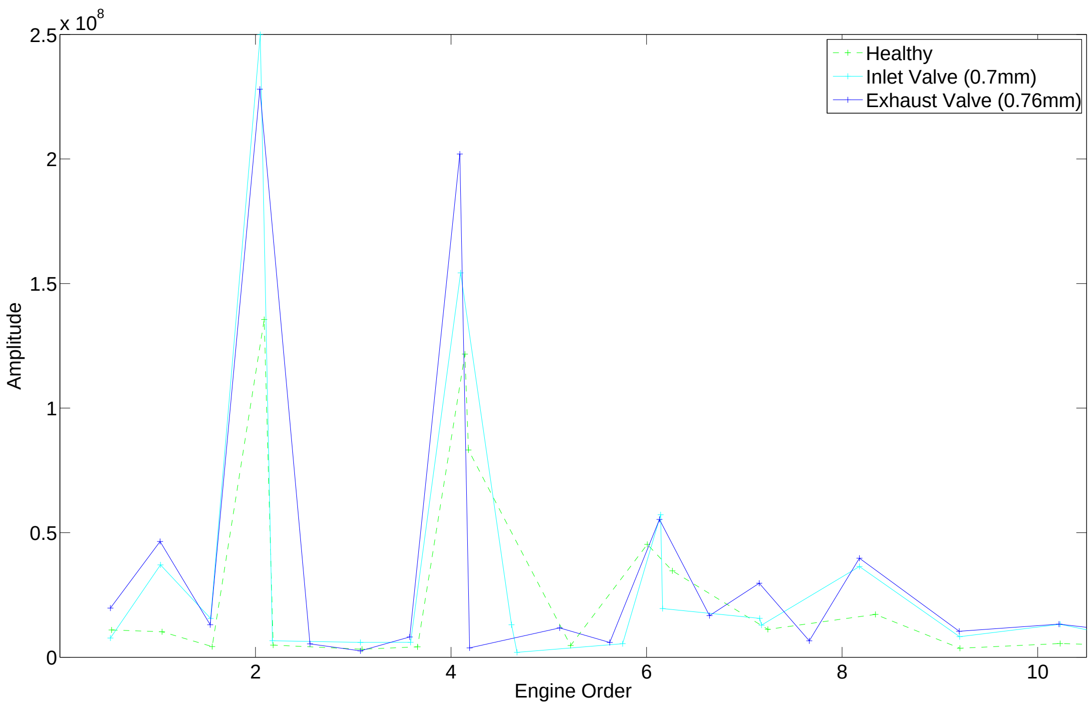

Figure B.20: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 0% Load - Channel 3

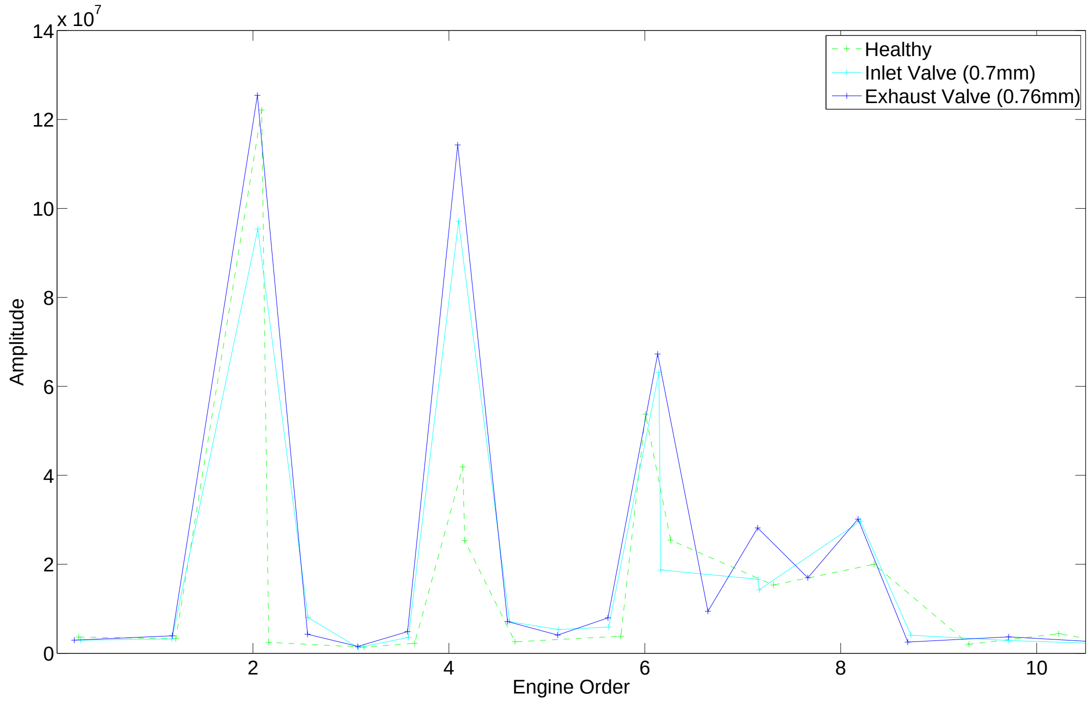

Figure B.21: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 0% Load - Channel 5

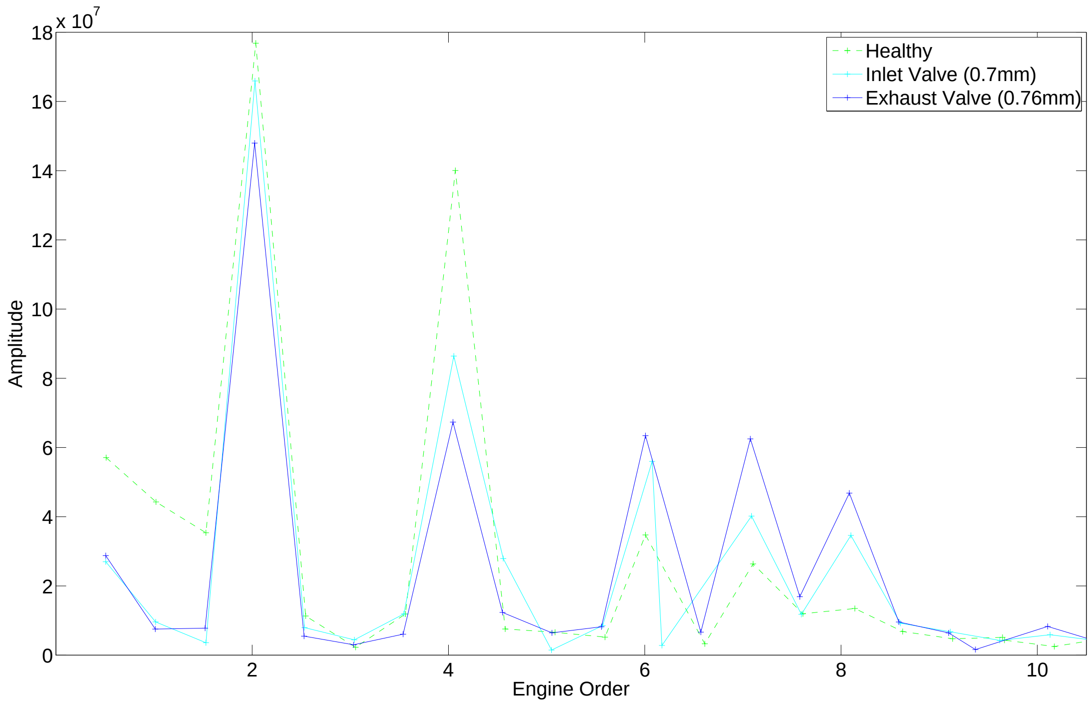

Figure B.22: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 40% Load - Channel 1

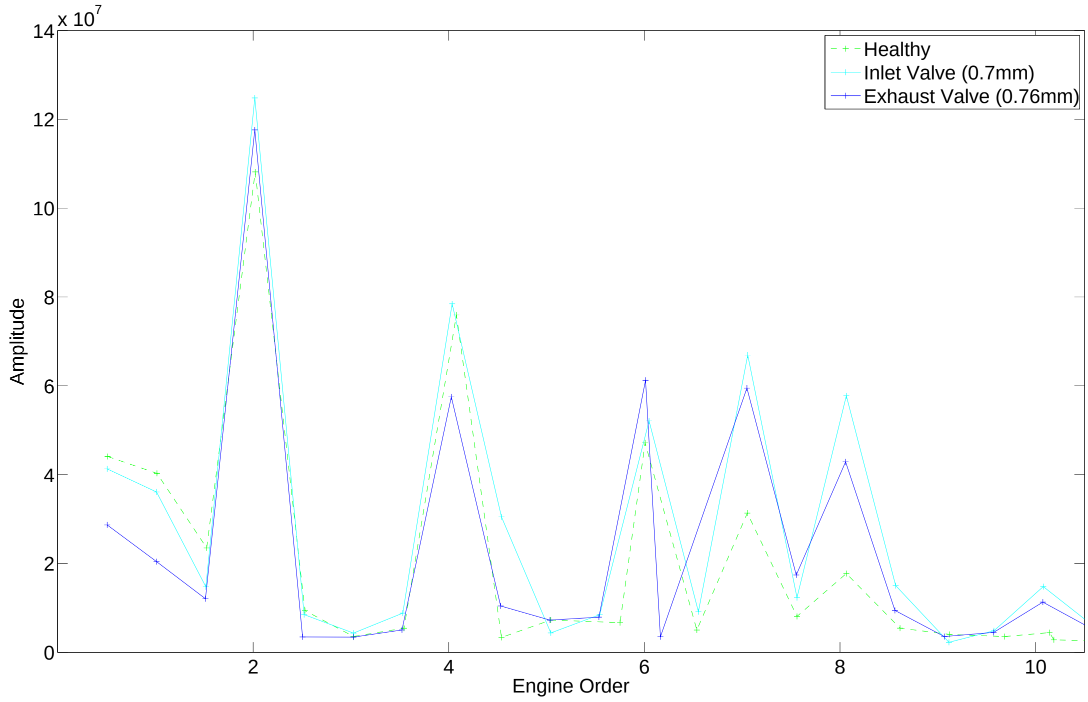

Figure B.23: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 80% Load - Channel 1

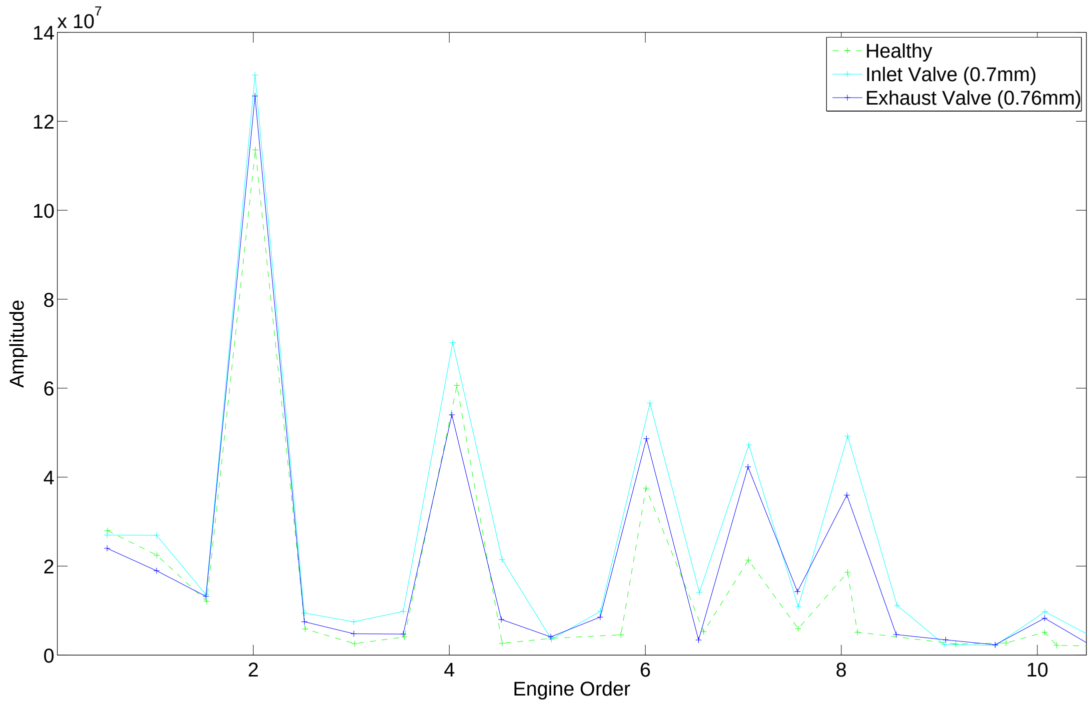

Figure B.24: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 80% Load - Channel 2

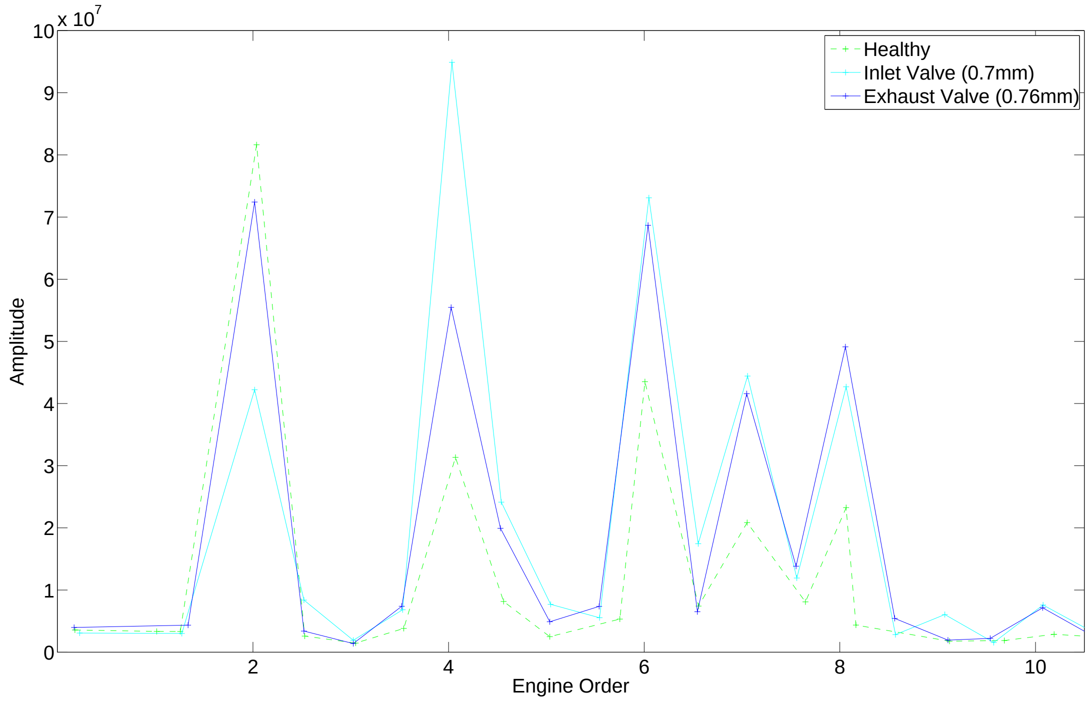

Figure B.25: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 80% Load - Channel 5

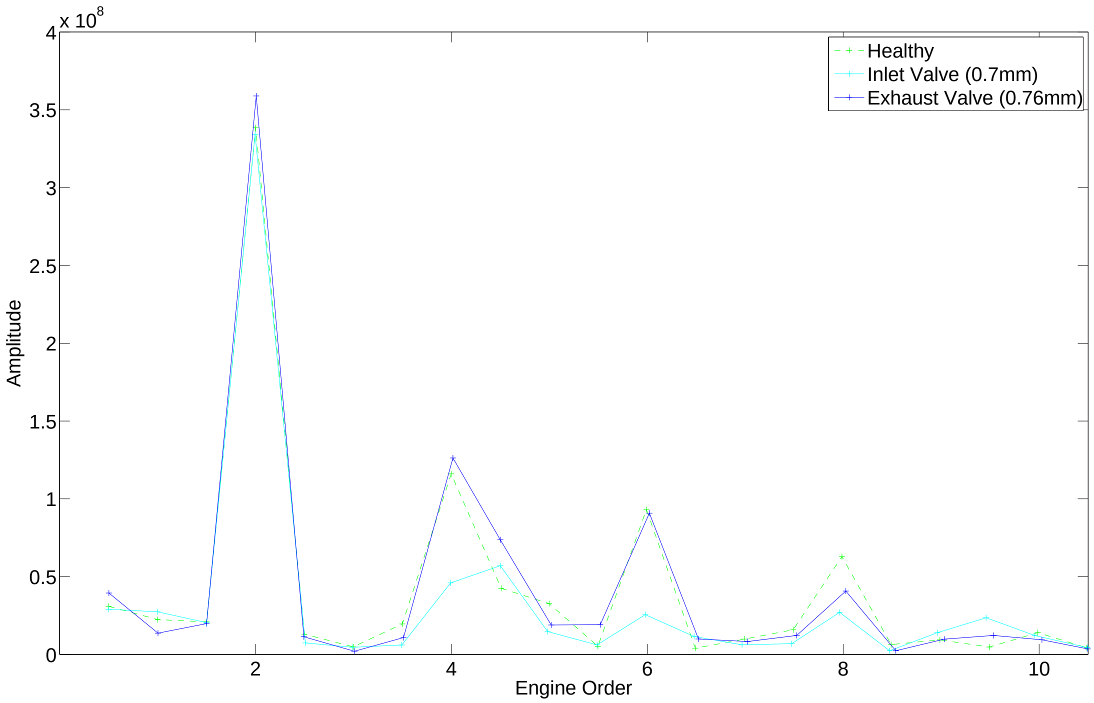

Figure B.26: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 0% Load - Channel 1

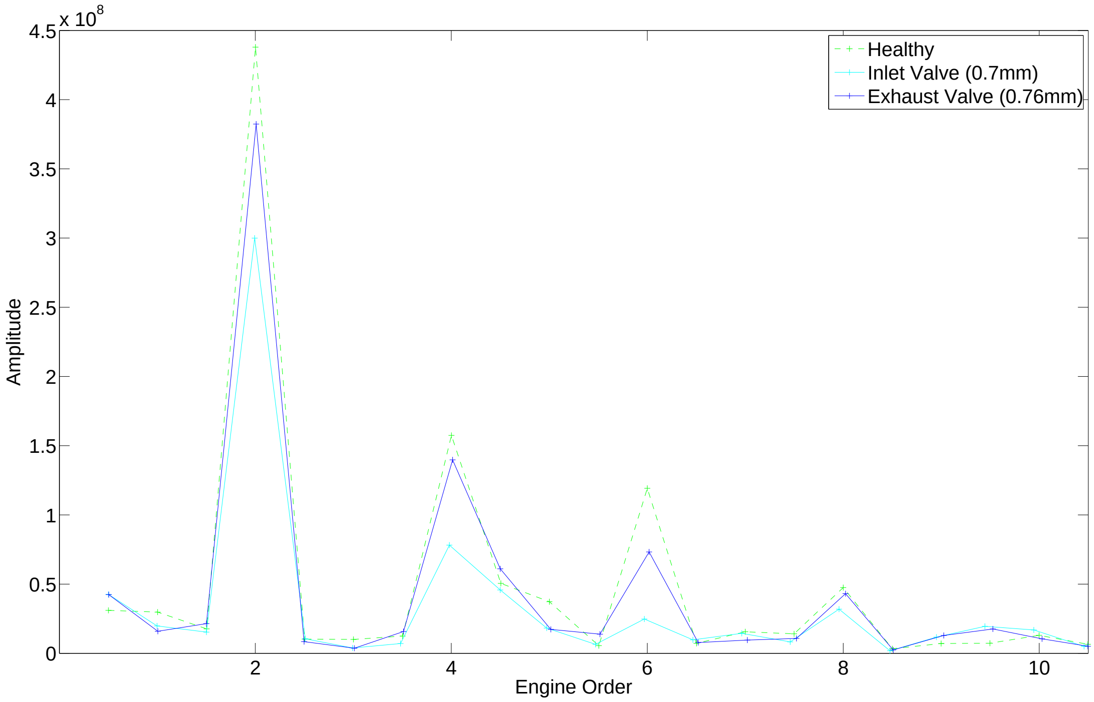

Figure B.27: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 40% Load - Channel 1

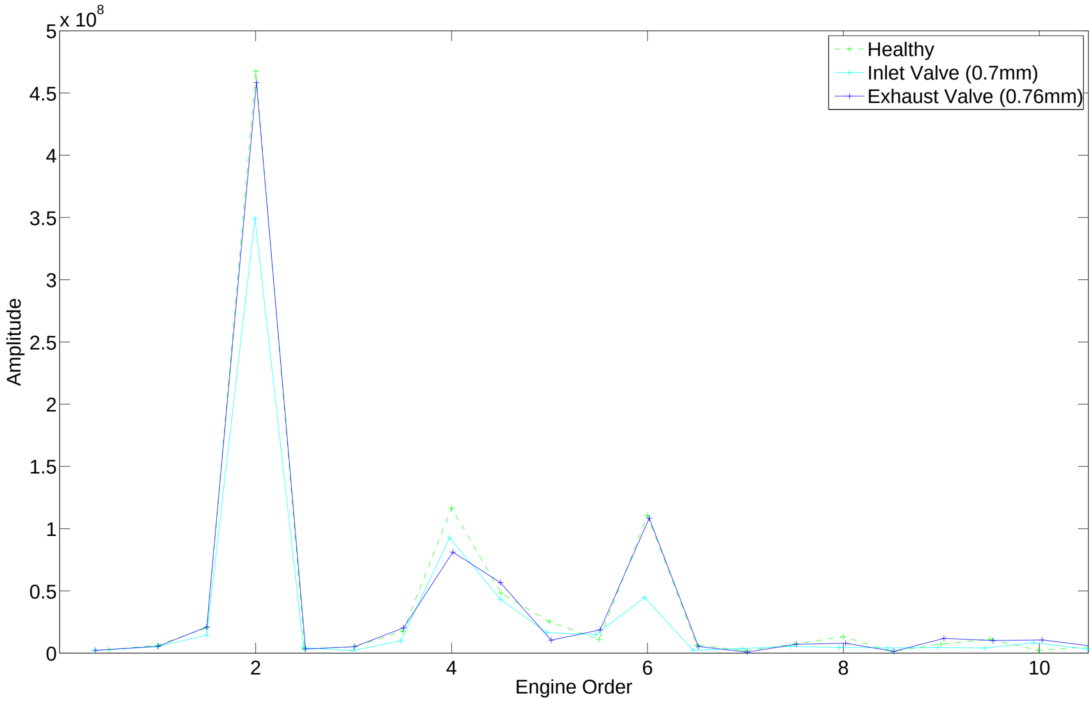

Figure B.28: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 40% Load - Channel 5

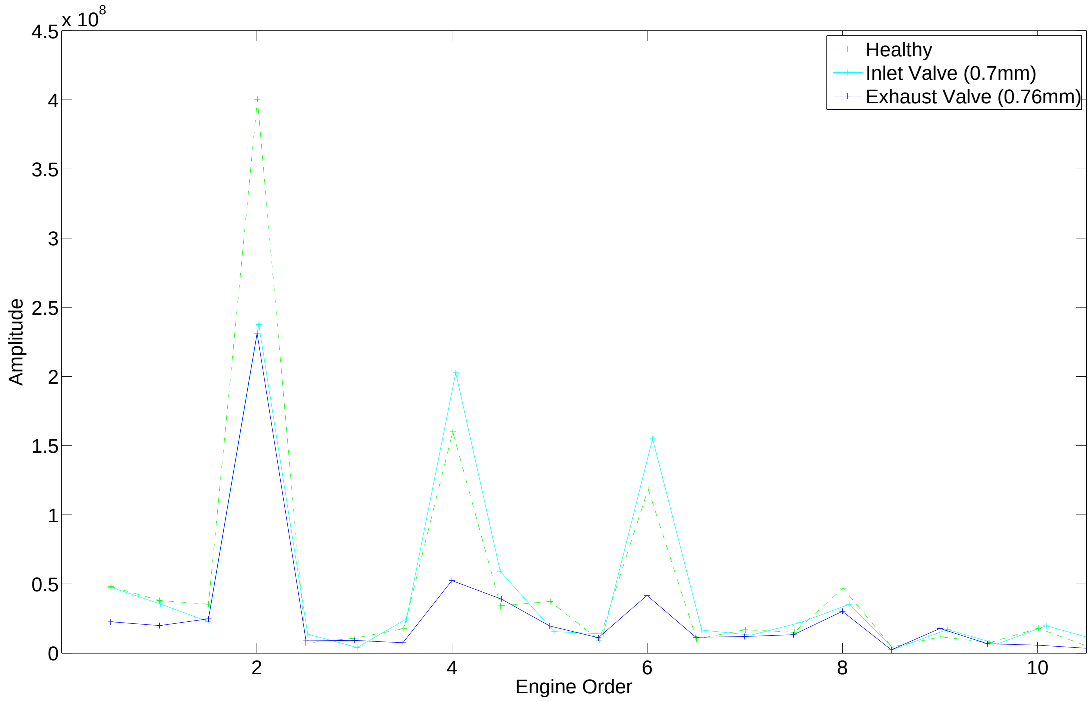

Figure B.29: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 80% Load - Channel 1

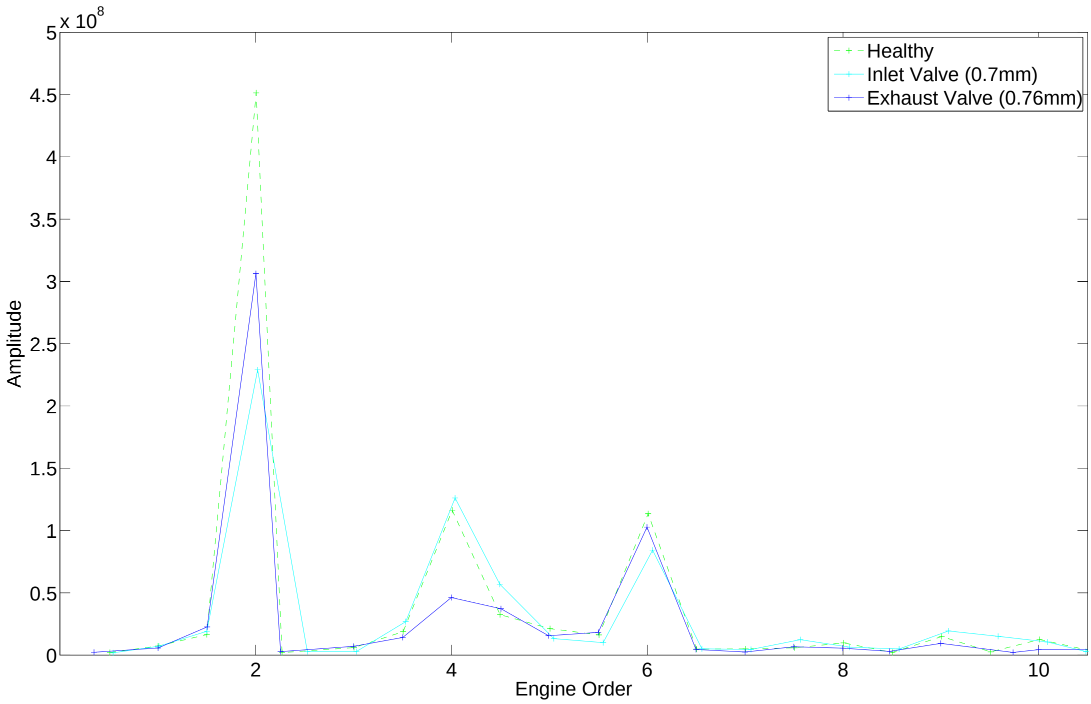

Figure B.30: Peak Points of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 80% Load - Channel 5

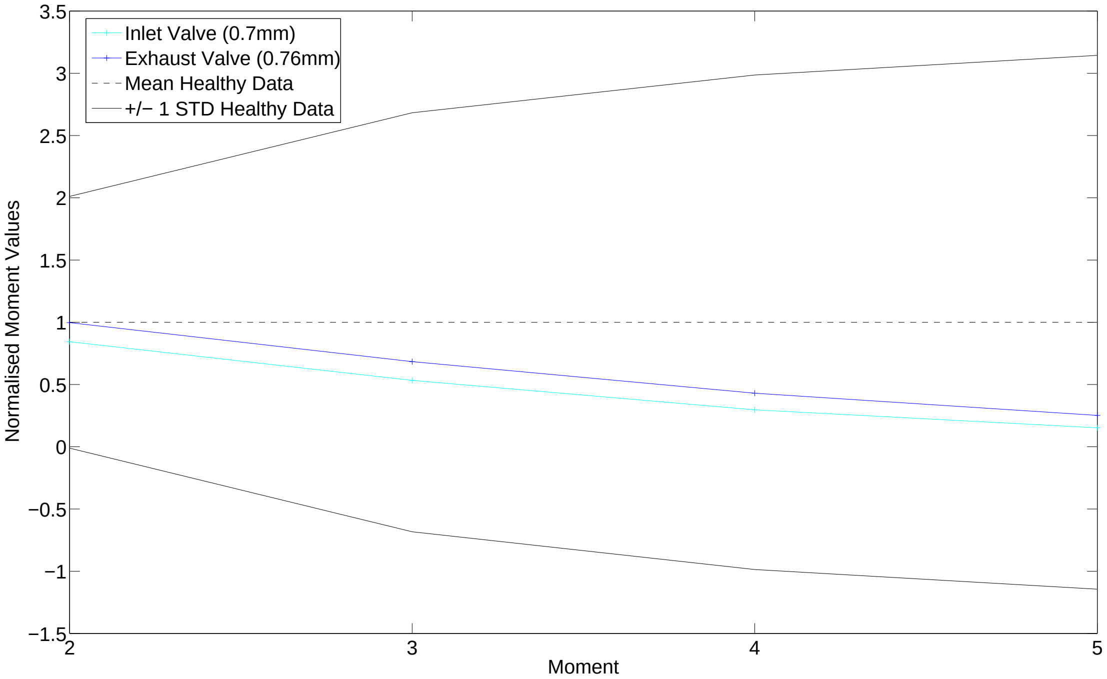

Figure B.31: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 0% Load - Channel 1

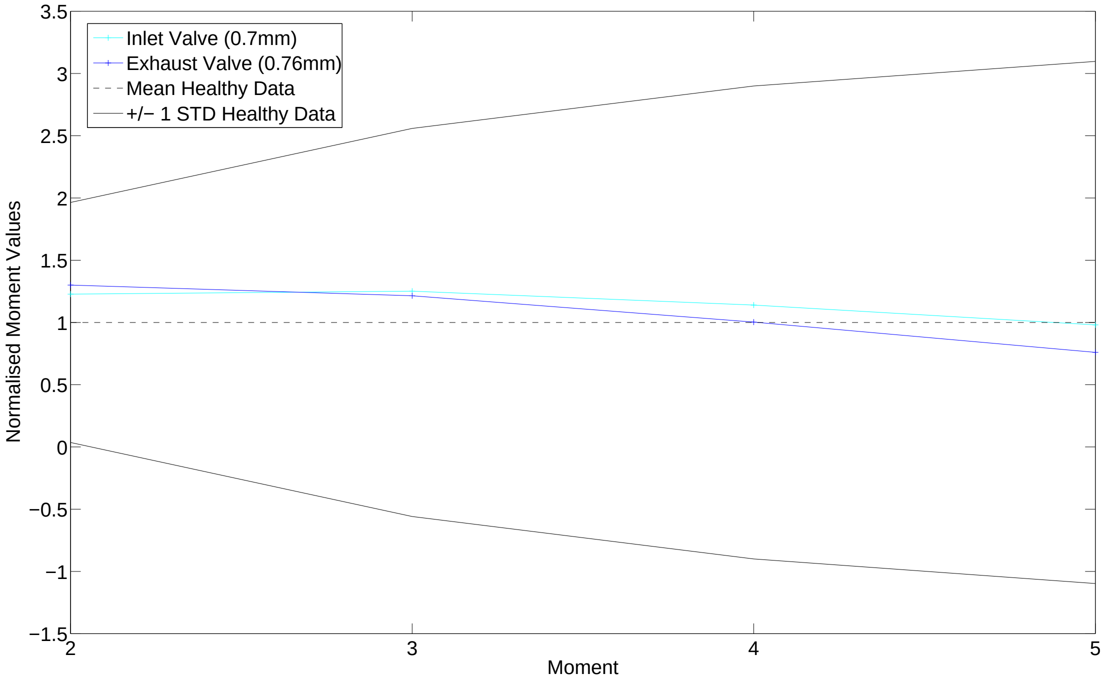

Figure B.32: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 0% Load - Channel 3

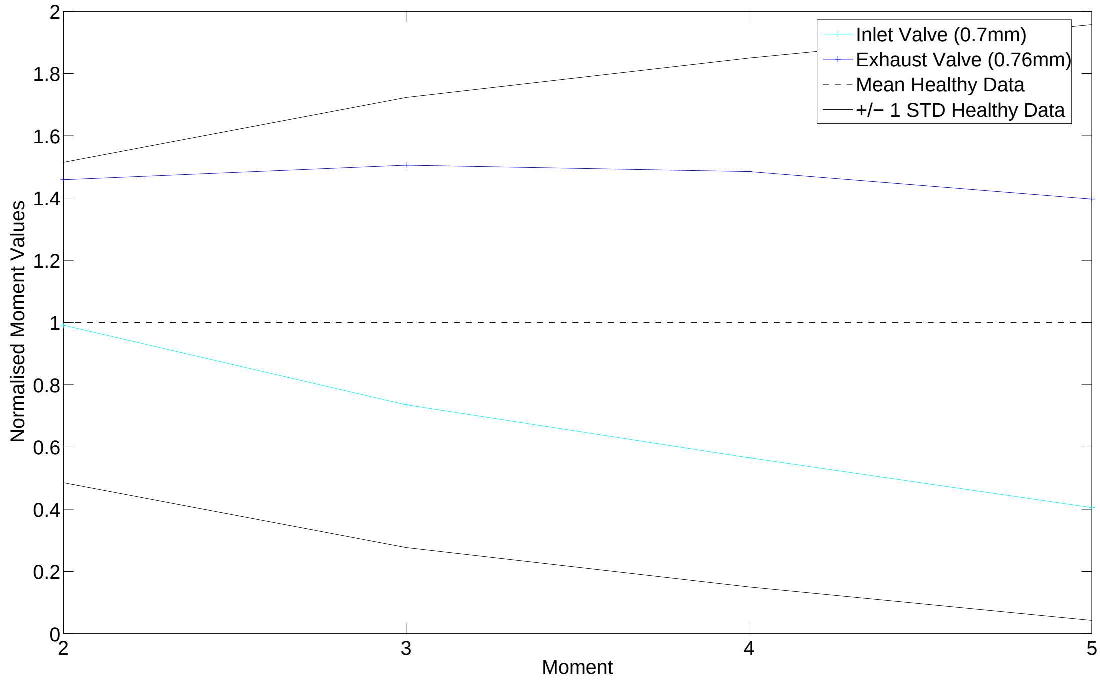

Figure B.33: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 0% Load - Channel 5

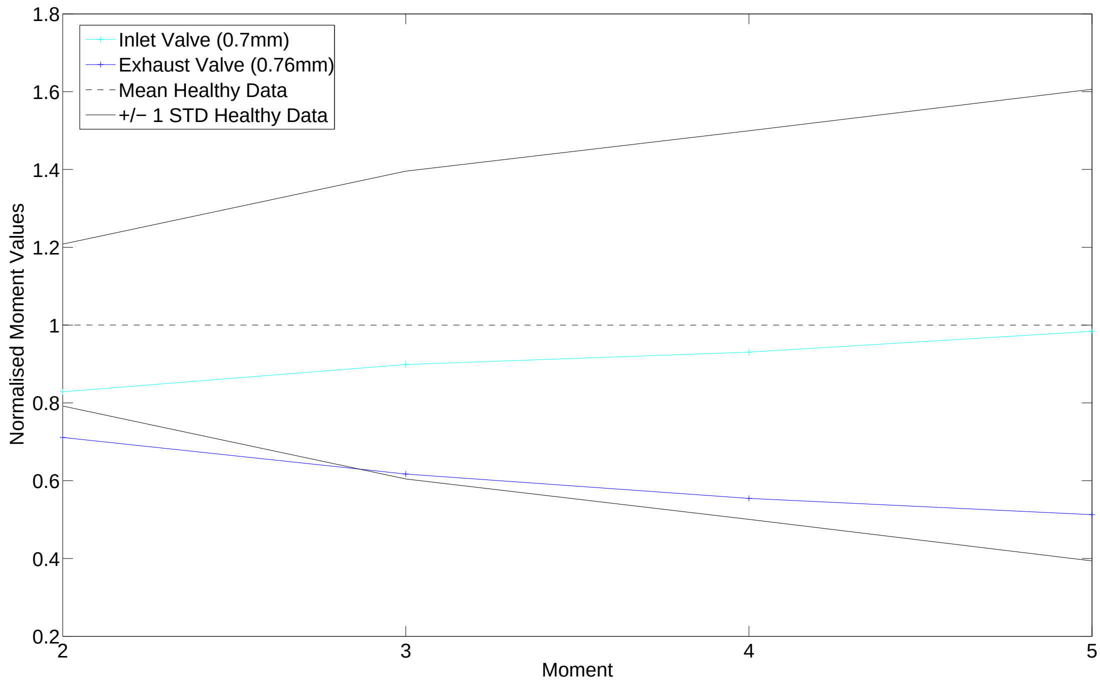

Figure B.34: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 40% Load - Channel 1

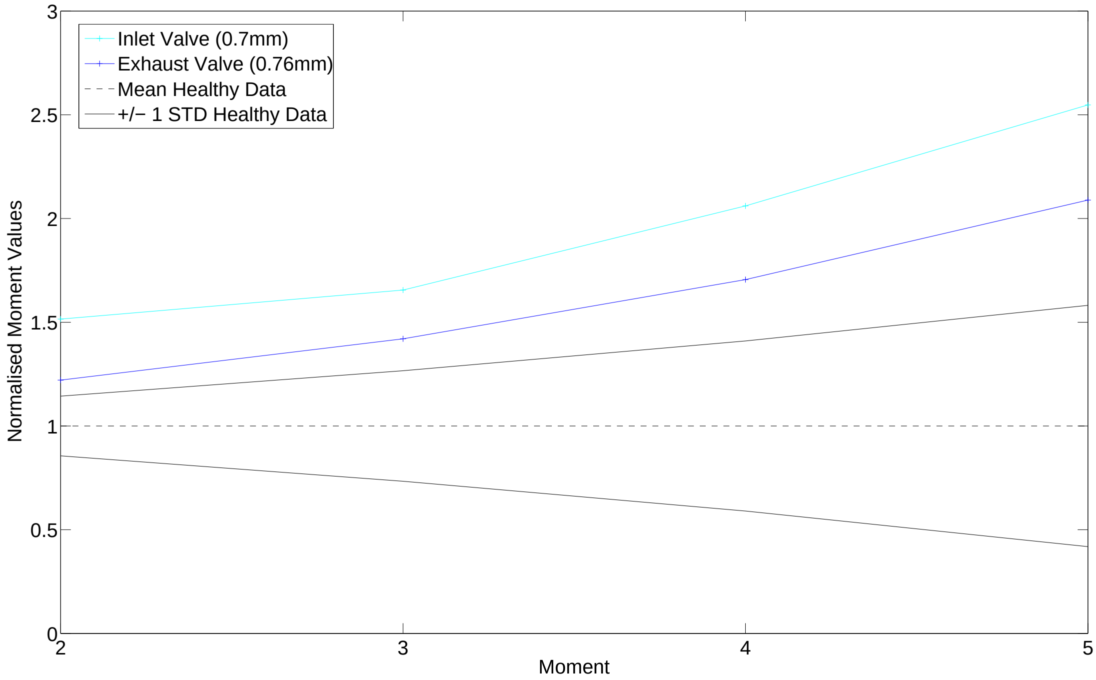

Figure B.35: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 80% Load - Channel 1

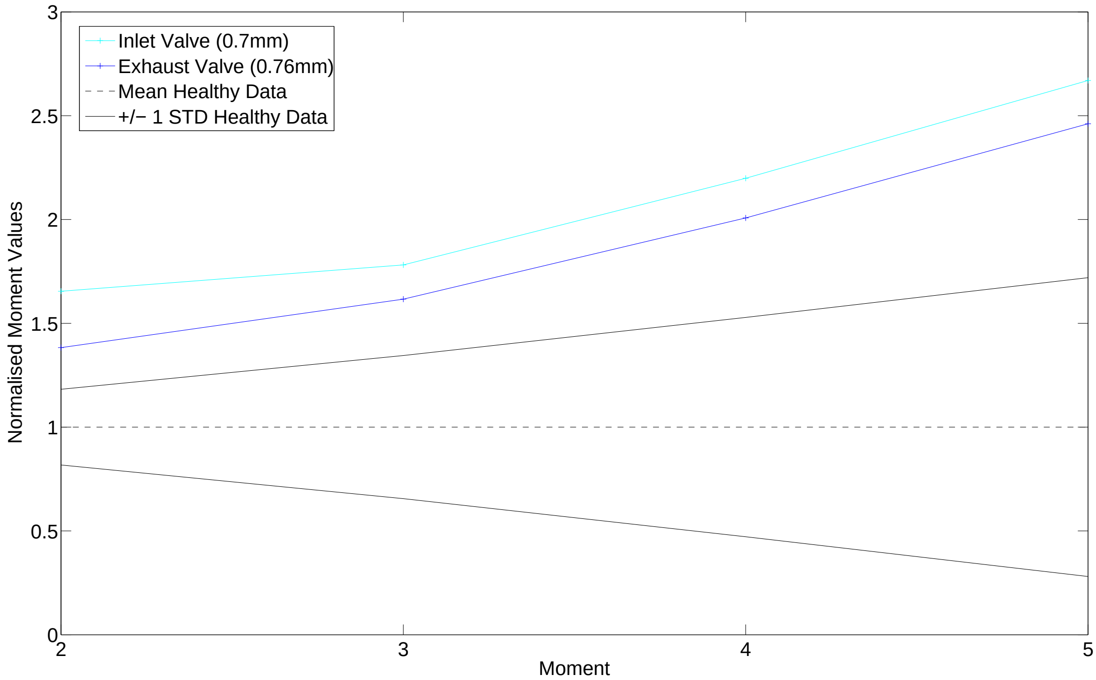

Figure B.36: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 80% Load - Channel 2

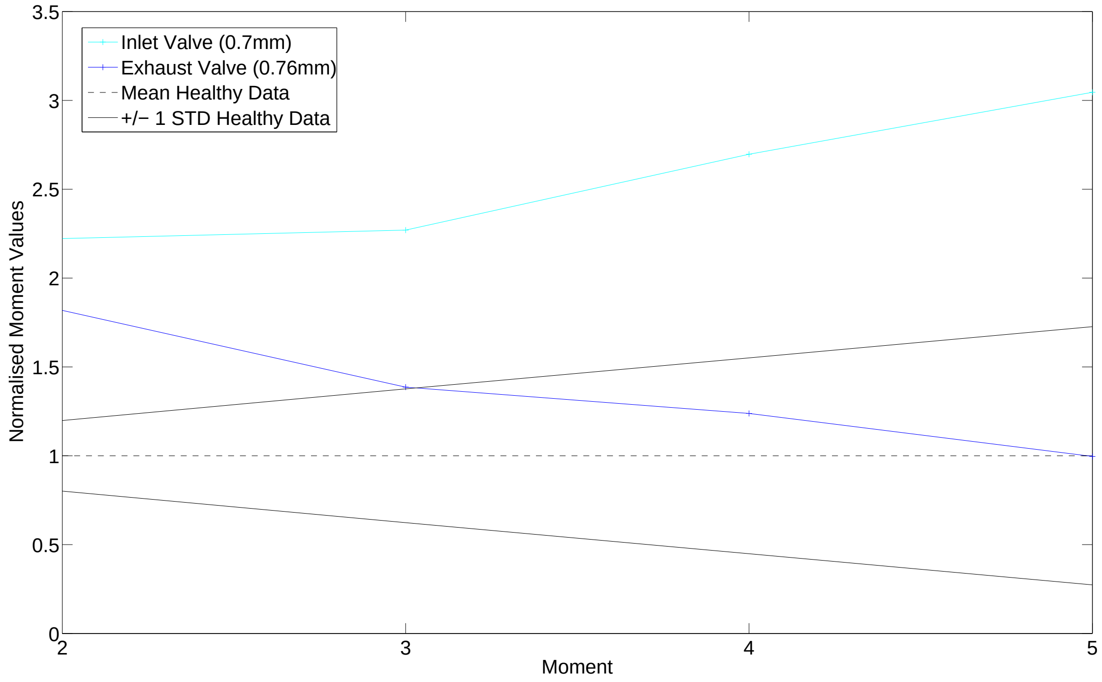

Figure B.37: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 1500RPM and 80% Load - Channel 5

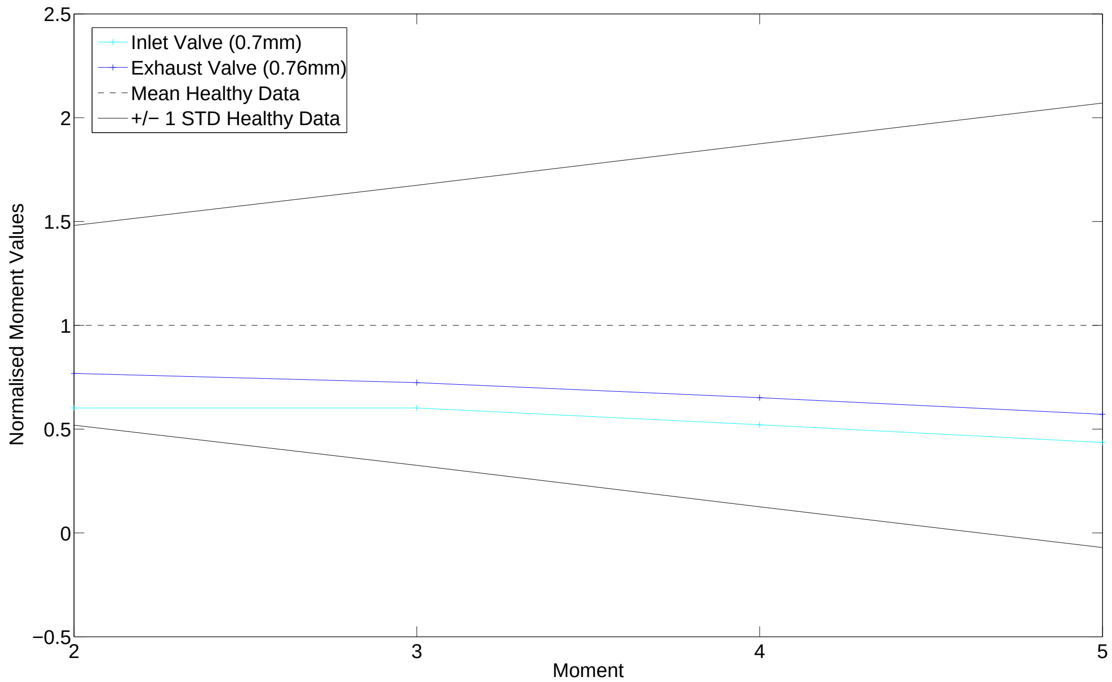

Figure B.38: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 0% Load - Channel 1

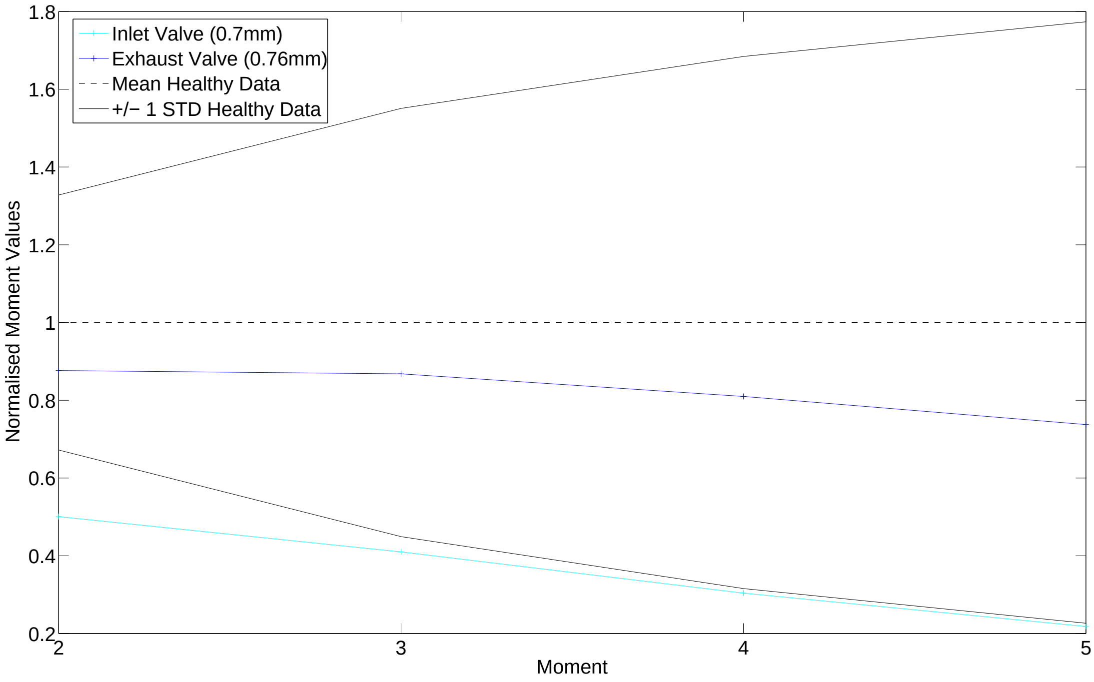

Figure B.39: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 40% Load - Channel 1

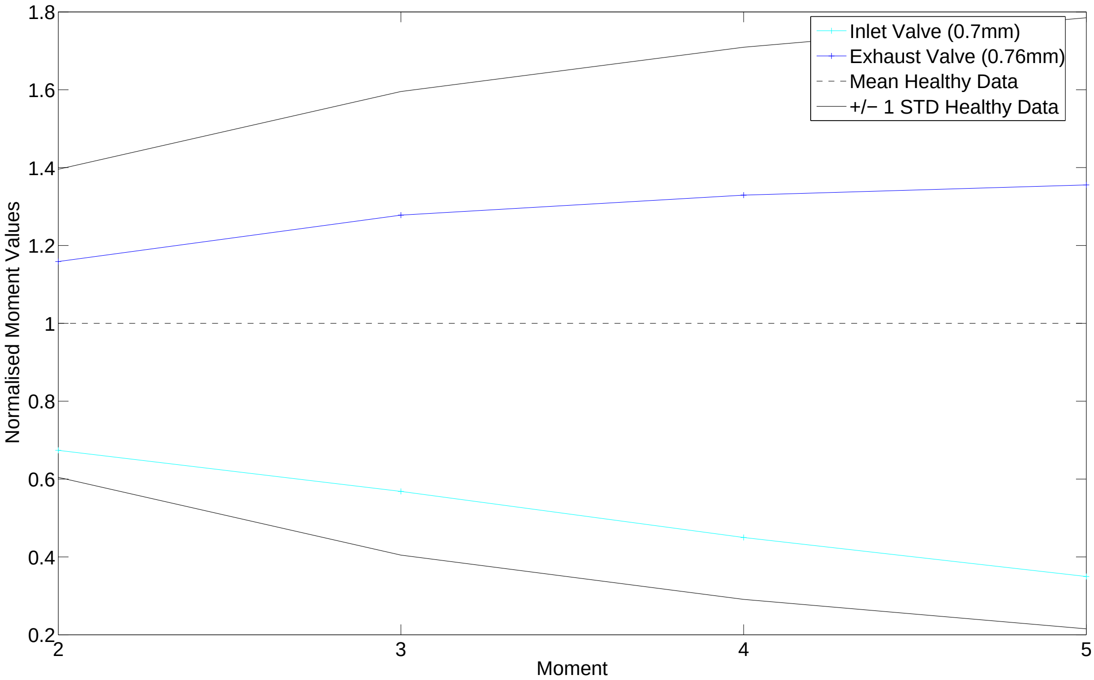

Figure B.40: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 40% Load - Channel 5

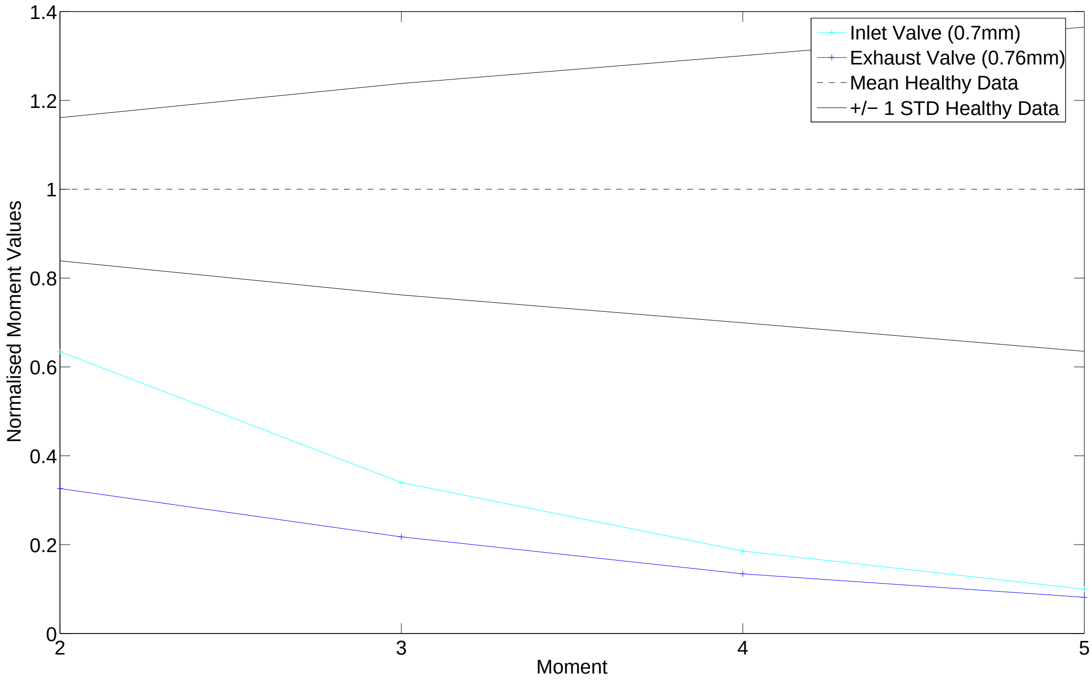

Figure B.41: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 80% Load - Channel 1

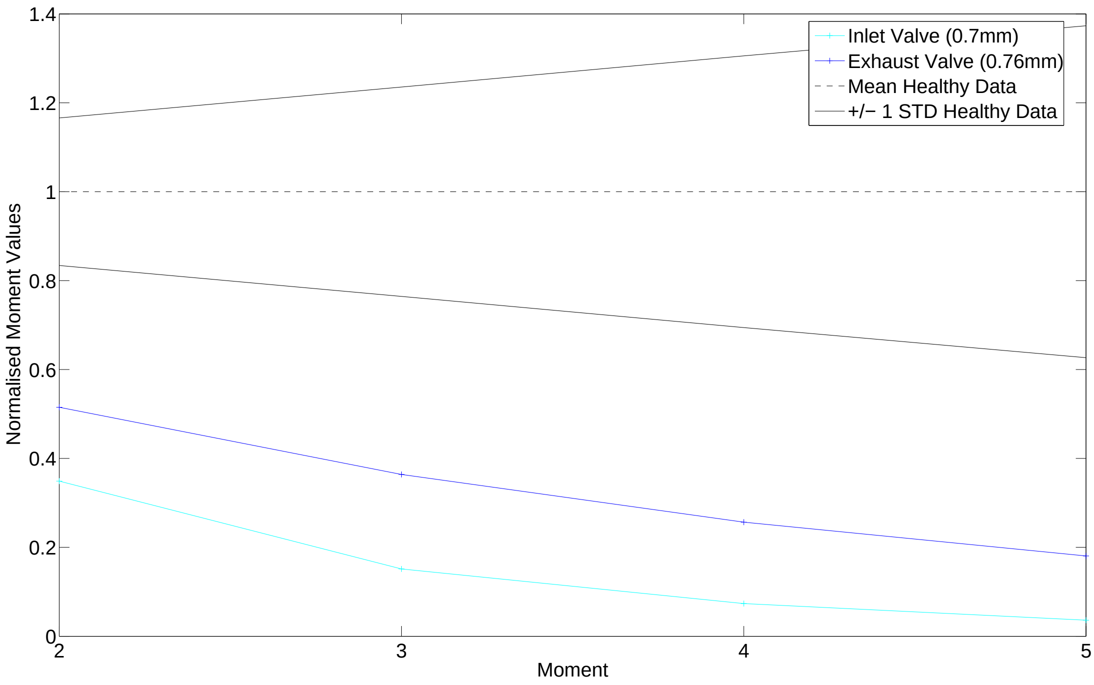

Figure B.42: Moments of Healthy vs Later Inlet or Exhaust Valve Opening at 2000RPM and 80% Load - Channel 5

Appendix C

ICA Results Tables

The following appendix presents the results tables for the ICA processing, the discussion of which can be found in chapter 7.

	Healthy	
Num. IC's	ICA	FFT
5	67.5%	62.5%
4	81%	78%
3	95.8%	87.5%

Table C.1: Healthy Data Detection: Reduced Output Requirement Criteria

Healthy		TLF 0.6mm		TLF 1.2mm		TLF 1.8mm		TMF 0.6mm		TMF 1.2mm	
ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT
54	65	95	88	100	100	98	93	100	93	100	98

Table C.2: ICA vs. FFT Percentage Success for Healthy & Too Little & Too Much Fuel Fault

1 Deg Early		2 Deg Early		4 Deg Early		5 Deg Early	
ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT
100	98	100	98	100	100	100	98

Table C.3: ICA vs. FFT Percentage Success for Earlier Injection

1 Deg Late		2 Deg Late		3 Deg Late		4 Deg Late	
ICA	FFT	ICA	FFT	ICA	FFT	ICA	FFT
100	90	100	98	100	93	100	98

Table C.4: ICA vs. FFT Percentage Success for Later Injection

Inlet Open Early		Exhaust Open Early	
ICA	FFT	ICA	FFT
100	90	100	98

Table C.5: ICA vs. FFT Percentage Success for Earlier Inlet & Exhaust Opening

	Healthy	
Num. IC's	ICA	FFT
6	54%	65%
5	65%	78%
4	72%	91%
3	79%	96%

Table C.6: Healthy Detection With Reduced Output Requirement Criteria

Appendix D

Program Process Flows

The following appendix presents the process flow diagrams for the ICA processing program that was written in this research. The discussion on these flow diagrams can be found in chapter 7.

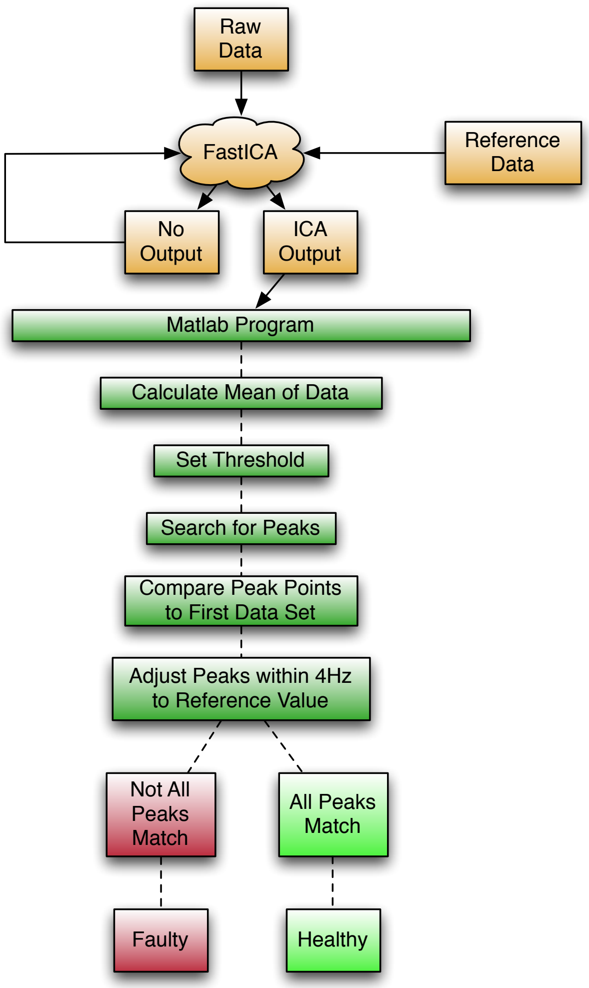

Figure D.1: Flow Diagram of ICA Processing Process

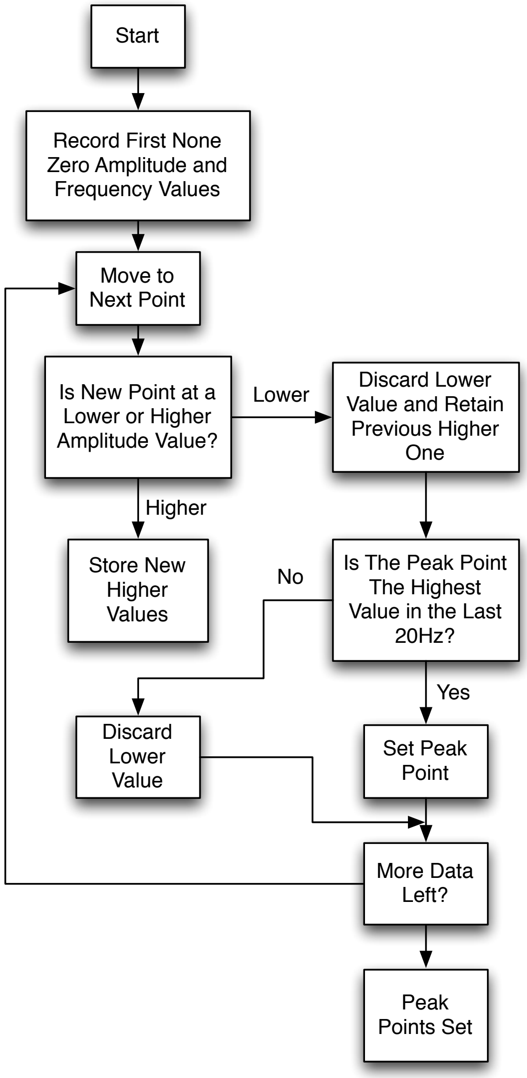

Figure D.2: Process Flow For Detecting Peak Points

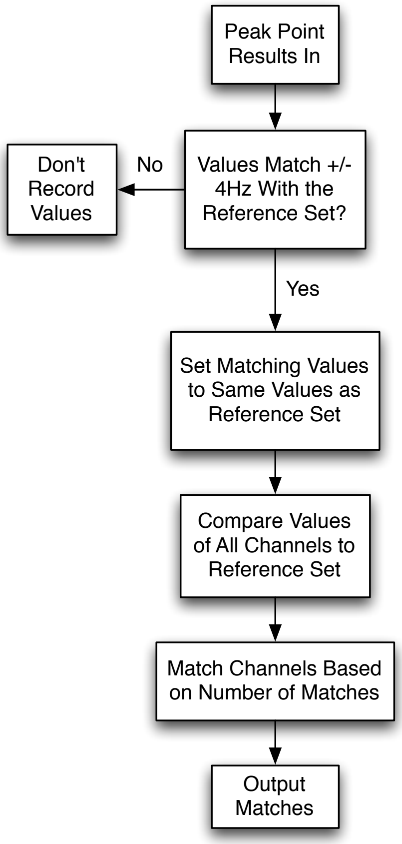

Figure D.3: Process Flow For Comparing Peak Points

Appendix E

Electrical Current Monitoring

E.1 Introduction

This chapter provides and brief introduction to the background theory of research conducted in collaboration with Peter Charles [134], a researcher in the same interest group. The work investigated the influence of engine faults on the engine starter motor current and whether the start-up or cranking phase of the engine could be used to detect faults.

The basis for this research is that when an engine has a fault it could be expected to increase or decrease the amount of current needed to start the engine due to the transient friction of the engine subsystems, primarily the valve train and its associated components. This would make it harder or even easier for the engine to start. This work is an investigation into whether the current used by the engine at startup can reveal engine faults by producing a recognisable signal. Hence, making this technique transferable to any engine with an electrical starting system. This technique would eliminate the need to run the engine for long durations and maybe avoid running it at all, thus greatly reducing the cost and time involved in maintenance.

E.2 Background

E.2.1 Starter Motor

As discussed in chapter 2, there are four sections to a Diesel engine combustion cycle, intake, compression, combustion and exhaust. To start these cycles however, a great deal of force is required to move the pistons and the flywheel through the cycle, this is carried out by the starter motor [134].

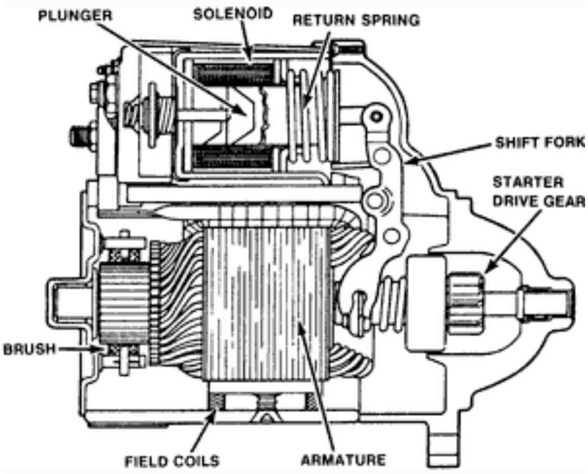

Figure E.1: Typical Starter Motor [135]

Figure E.1 shows a typical electrical starter motor. It is an electric motor which works by passing current through a coiled wire to create a magnetic field. It is the main component involved in starting the engine. The initial phase of engine startup is started by the electric current being passed from the battery to the starter motor by the second terminal of the solenoid. The current passes through the field coil and the carbon brushes. Within the solenoid the contacts are met due to the passing current and the lever moves forward, moving the pinion gear towards the flywheel ring. The flywheel starts rotating and so the crank and pistons also move. The starter motor has to be able to turn the flywheel and its attachments which include the pistons, connecting rods and any friction associated with this motion. There is, therefore, a large current draw from the battery upon startup and this is the current that may hold information on engine health.

The flywheel inertia is maintained due to the flywheel's mass and it continues to rotate faster. When it is at the required speed the pinion drive de-clutches from the flywheel. When the switch is released the magnetic field collapses and the starter motor ceases to function. This whole process from current draw to pinion de-clutching will happen in seconds.

If the current could be measured between the battery and the engine, there could be information on how well the process of starting the engine is going. Knowing how well it performs would be directly influenced by how easy or hard the starter motor is finding it to start the engine. This would therefore provide a good indication to engine health. The following sections will look at current measurements.

E.2.2 Current Measuring Device

There are three main technologies that can be used to measure current, sense resistors, Hall Effect sensors and current transformers. The choice of which technology to use depends mainly on two variables, cost and performance.

Sense resistors consist of a resistor placed in series with a load. They work in principle with ohms law whereby the voltage drop across the device is proportional to the current [136]. Sense resistors are advantageous when small currents are to be measured, whilst there are special sense resistors for higher currents they suffer badly with insertion loss and lack of isolation from transient voltage potentials [136]. They also require extra instrumentation and amplifiers to extract the signal from them. The fact these sensors are limited to small currents automatically excludes them as a feasible method for this research as the current draw from the battery is expected to be up to 1000A.

Current transformers work on the basic principles of transformers where an alternating current in the first coil creates a magnetic field and induces a changing voltage in the second coil, better known as Faraday's Law of Induction. Current transformers do not suffer insertion loss like the sense resistors and do not require an external power source. The only limitation, is that they can only be used with AC current.

Hall effect sensors come in two varieties, open and closed loop. This research was conducted using a hall effect sensor as it was readily available, within specification and could be easily integrated into the experimental setup unobtrusively. The following section will look at the two types of sensor as well as how the current measurements are obtained.

Principles

A magnetic field is produced when an electric charge exerts a force on other moving charges. The current can be measured directly by using a galvanometer but this method involves breaking the circuit, thus is intrusive. For condition monitoring this would prove to be a drawback and a method that allows the measurement to be taken unobtrusively is preferred. In this research a current clamp was used which operates on the principal of the Hall Effect.

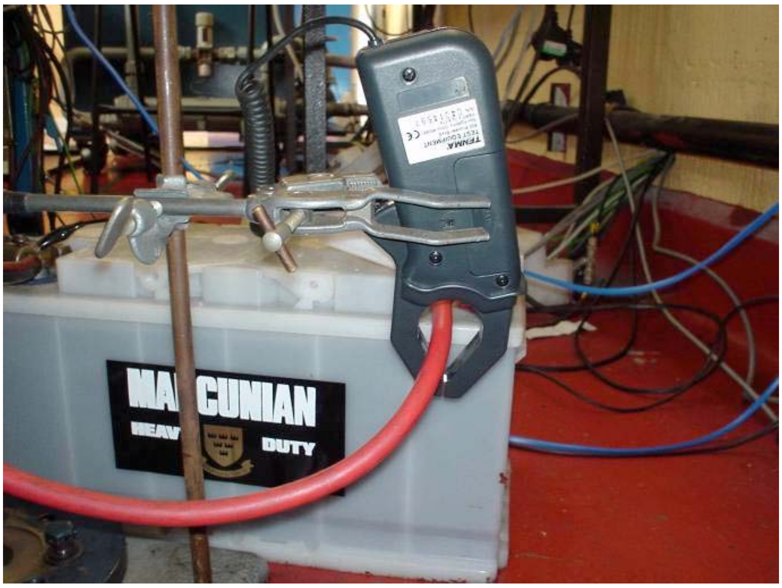

Figure E.2: Tenma 600A Current Clamp

Figure E.3 shows the principles of the Hall Effect. The current flowing through a cable will create a magnetic field perpendicular to it, B, and this will vary with the level of the current. The charges are affected by this magnetic field and this will cause charge accumulation

As the electric charge is creating a magnetic field, which will vary over time, the current measuring clamp can be used to detect changes in this magnetic field because as it passes through a semiconductor resistor it will generate a differential voltage which is proportional to the field. This can be seen in figure E.3.

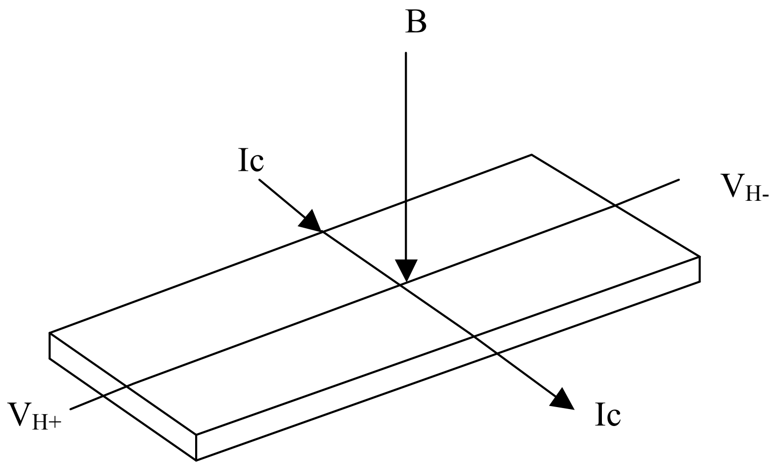

Figure E.3: Simple Pictorial Representation of the Hall Effect [136]

When a conductor has a current flowing through it, concentric magnetic field lines will be created. If this current conductor is presumed to be infinitely long then the magnetic field strength can be defined as:

$$B = \mu_0 I/2pr \tag{E.1}$$

Where u_0 is the permeability of free space, I is the current and r is the distance from the centre of the current conductor. To increase the signal out of a Hall effect element the number of turns on a slotted ferrous toroid can be increased N times so that [136].

$$B = \mu_0 NI/2pr \tag{E.2}$$

In an open loop sensor the output is simply amplified and read as a voltage, in the closed loop system it is not as simple. It has a number of coils around the clamp that themselves generate a magnetic field that cancels out the primary magnetic field from the conductor.

The advantage of closed loop sensors is that they are very accurate. They have linearity better than 0.1%. They also have a feedback system which allows them to respond rapidly, typically less that one micro second [136]. Another advantage is that it uses the cancellation of the magnetic field, therefore, cancelling many inaccuracies such as offset drift. All of these advantages far exceed what is possible with open loop sensors. It also has its limits in that it requires the sensing unit to be powered via mains (Not always possible on site) and it can require a significant amount of power [136]. This can make the units large and impractical for portable measuring. The size of the current that can be measured by a closed loop unit is also significantly reduced by the extra power requirement and because it is limited to the size of the secondary coil as to how large a field it can cancel.

The Tenma clamp used in this research is a open loop Hall Effect sensor. It is portable, easy to setup, fairly cheap and its specifications allow it to take measurements for the engine used in these tests.

E.3 Experimental Work

The tests covered a number of parameters such as clamp placement, position of cable within the clamp, different faults and faults whilst both cranking and starting fully.

Figure E.4 shows a pictorial view of the experimental setup and shows the different positions the current clamp was placed along the battery cable. This is to investigate how the position of the current clamp relative to the battery wire and relative to the engine may affect the readings. Data was taken close to the engine (E), equal distance between engine and battery (M) and close to the battery (B). The cable position within the clamp was also varied with 5 different locations being measured (0,1,2,3,4). This is represented in figure E.4. These positions were compared to a base line data set taken at position 'M' and with the cable at position '0' which can be seen in figure E.5 . This was to investigate if varying position or cable location affects the readings of the clamp, thus determining how careful an on-site engineer would have to be in setup should this technique be applied industrially. The current clamp is a unit that fits around the cable between the battery and the engine and works by detecting the change in the magnetic field in the cable and outputting a small voltage to represent this change. The unit used in this research was

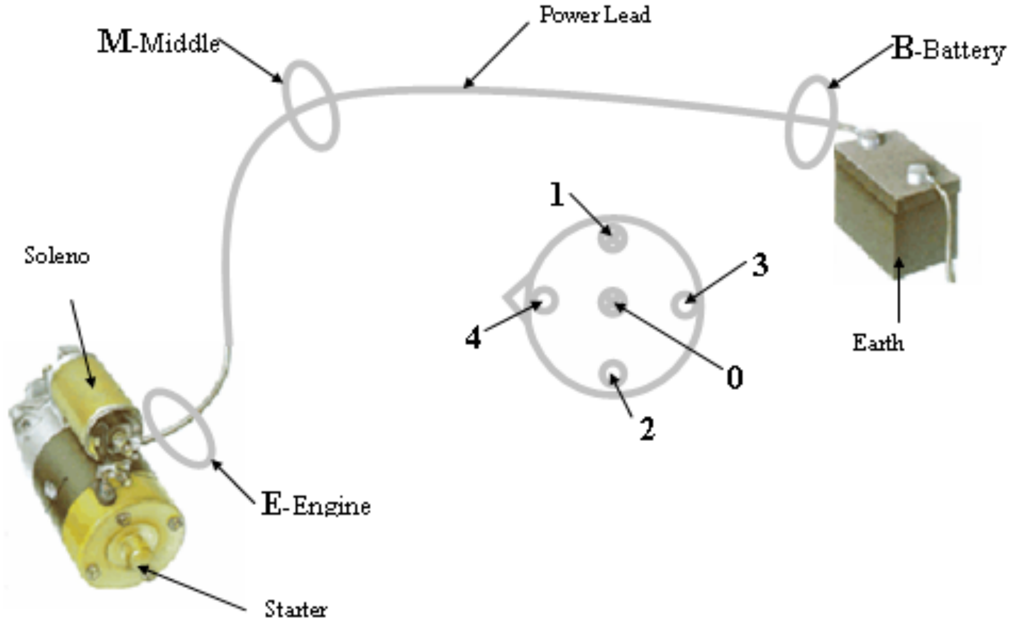

Figure E.4: Current Clamp Test Setup

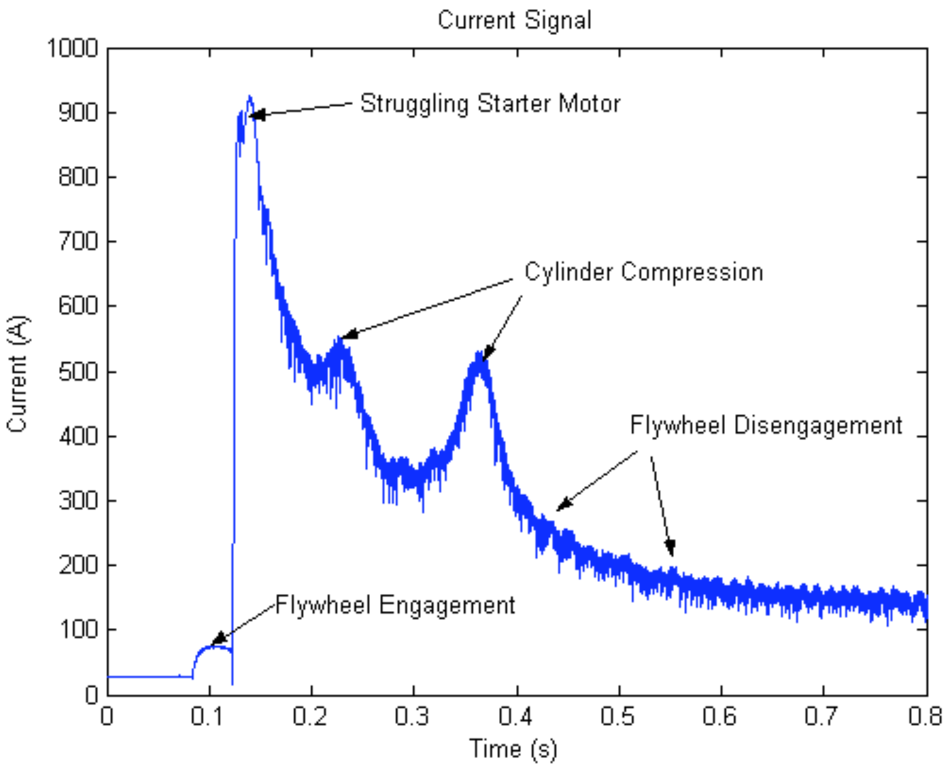

Figure E.5: Engine Current Signal

a Tenma 600A AC/DC Current Clamp, part number 72-6174 as seen in figure E.2. Its operating temperature range is 0 °C-50 °C and at standard room temperature of 23 °C it has the following accuracy:

- DC Current: 0-600A = +/-(2% reading +2A)
- AC Current: 50Hz-400Hz
  - 0-300A= +/-(2% reading +2A)
  - 300A-500A = +/-(3% reading +2A)
  - 500A-600A = +/-(6% reading +2A)

This unit was chosen as it was readily available and it produces an acceptably small amount of error up to 600A. Although the unit is only specified up to 600A, contact with the manufacturer identified that the clamp would still measure above this limit for a brief time but potentially with more error. Given that the time in which the clamp would be measuring above 600A, approximately 0.05 of a second, it was deemed suitable for this application.

Seeded Faults

There were two main faults seeded on the engine for the current testing, leakage in the cylinder head and misfire. The leakage in the cylinder head was simulated by creating a hole in cylinder four by removing a screw. The removal of the screw gives a significant reduction in compression in cylinder four, certainly not a subtle fault. To simulate the misfire the fuel pipe of cylinder four was disconnected, giving a none firing cylinder.

E.4 Results

Utilising the vast array of sensors that were installed on the experimental rig various data signals were collected far beyond a simple current measurement which has allowed a more in depth look at how various engine parameters are affected alongside the current reading when there is a fault with the engine.

One of the additional signals that was measured was cylinder pressure. It was measured both in healthy and faulty conditions. The seeded faults discussed in chapter 5 will affect the cylinder pressure, these experiments show how this affects the engine startup. Figure E.6 shows the pressure signal of cylinder one. It presents a healthy engine pressure signal and the two faulty conditions overlaid to show how the cylinder pressure is affected by the faulty conditions. The faulty conditions delay the pressure peak in respect to time, showing that with a fault it takes the engine longer to achieve a successful start. There is no reduction in pressure, in fact pressure is slightly increased as the three healthy cylinders work harder to compensate for cylinder four, which contains the seeded fault.

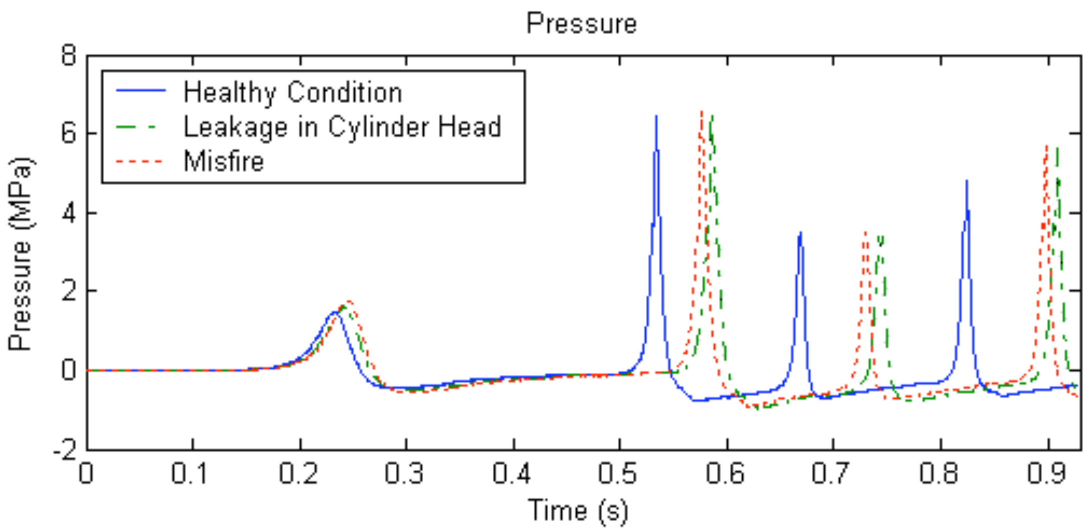

Figure E.6: Engine Pressure Signal

Instantaneous angular speed (IAS) data was then utilised to investigate how the engine speed would vary between healthy and faulty conditions. IAS is a measurement of the flywheel speed. This speed would be investigated for both engine cranking and for full engine starts. Briefly looking at figures E.7 and E.8 there are clear differences between the healthy and the faulty conditions though more noticeably so in full engine starts (figure E.7). In figure E.7 there is a good initial correlation between healthy and leakage IAS traces, however, misfire shows a rapid loss of speed at the combustion point of cylinder four. Thereafter, the leakage condition follows suit as the engine speed picks up the leakage is having a more profound effect on the following cylinders. After 0.4 seconds the correlation is lost and the healthy

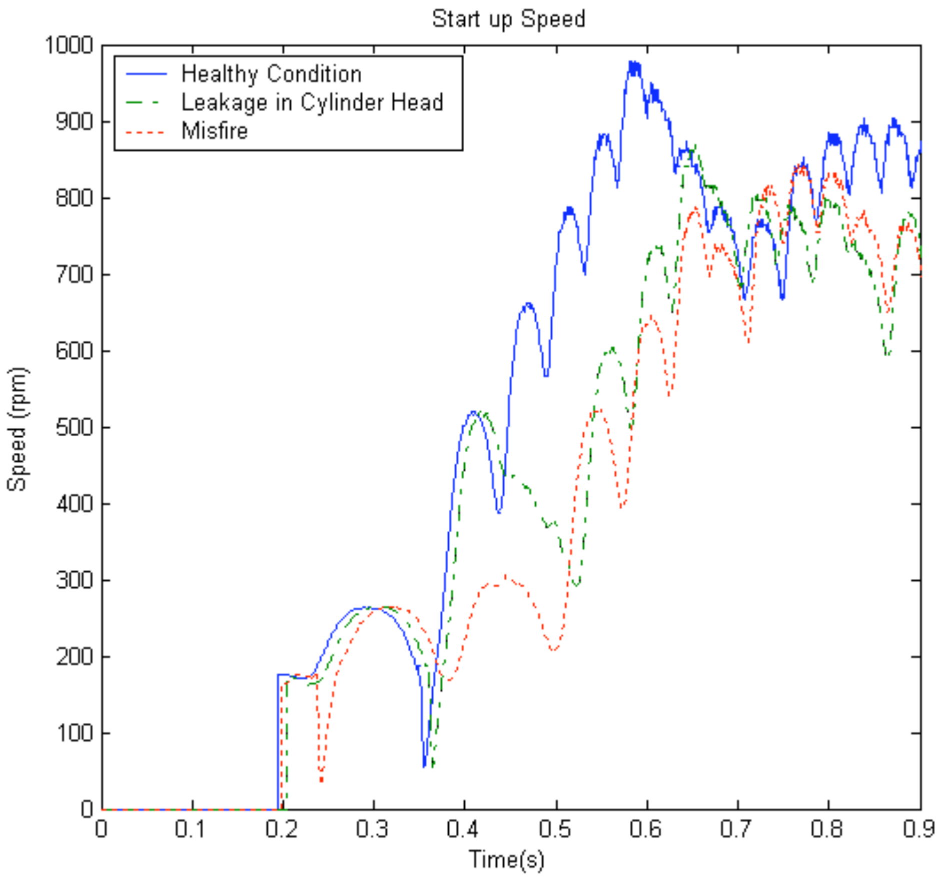

Figure E.7: Startup Speed Signal

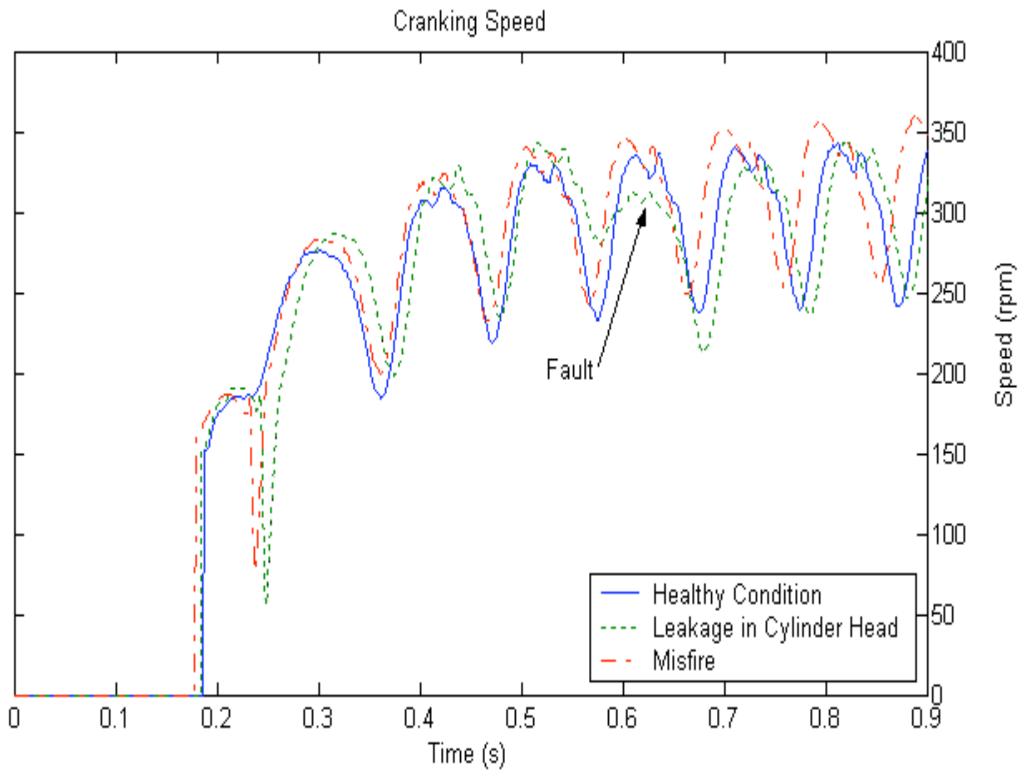

Figure E.8: Cranking Speed Signal

signal demonstrates that a healthy engine increases its speed more rapidly and also stabilises at a higher idle speed more rapidly. These faulty conditions are at the more severe level than it would be ideal to detect, however, figure E.7 demonstrates that the faults could potentially be less severe whilst still being detectable.

Figure E.8 shows that the biggest indicator of a fault is upon the first compression of cylinder four, where there is a noticeable difference between healthy and faulty conditions. However, after the first compression it becomes less distinguishable on the second compression of cylinder four at around 0.66 seconds. There is still enough of a speed drop and time delay in the signal to signify leakage and, therefore, a less severe form of leakage could be applied and still be detectable. Misfire is less detectable whilst cranking. This is because there is no pressure loss (besides the difference of the lack of combustion) and there is still compression of the air in the cylinder.

This data is an 'ideal' set of data as it is synchronised so that cylinder four is always firing first, in real world applications this is not the case. It is, therefore, highly likely that the signal seen around 0.66 seconds in figure E.8 is as severe as an on site engineer would see it, if he or she was to record and view these signals. This needs to be considered when considering this techniques applicability in the field.

After this initial investigation, the current signal that was recorded can now be overlaid with the IAS and pressure signals to build up a bigger picture. Figure E.9 presents three plots, healthy, leakage and misfire as the engine cranks. The healthy plot shows good clear pressure peaks as cylinder one compresses and a nice consistent pattern in the IAS data, increase in speed as a cylinder fires and a drop off as the next one compresses. The current data on top also shows how, as each cylinder compresses more current is drawn from the battery as the starter motor works harder to compress the cylinder. The leakage plot clearly shows the leakage in cylinder four. This is represented with little decrease in the speed due to the massive decrease in resistance on the cylinder due to the loss of compression as well as less current draw as less power is required to move the cylinder. Misfire appears to not be as easy to identify, in fact there is no clear indication of a fault despite how severe the fault

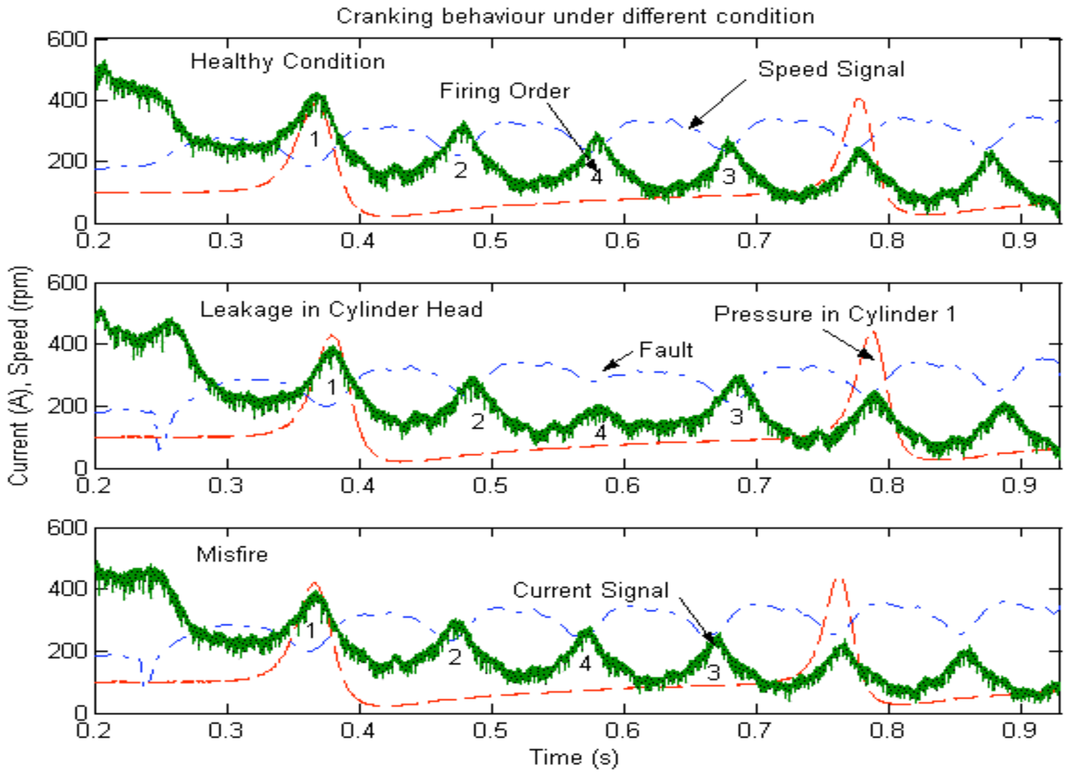

Figure E.9: Cranking Behaviour Under Different Fault Conditions

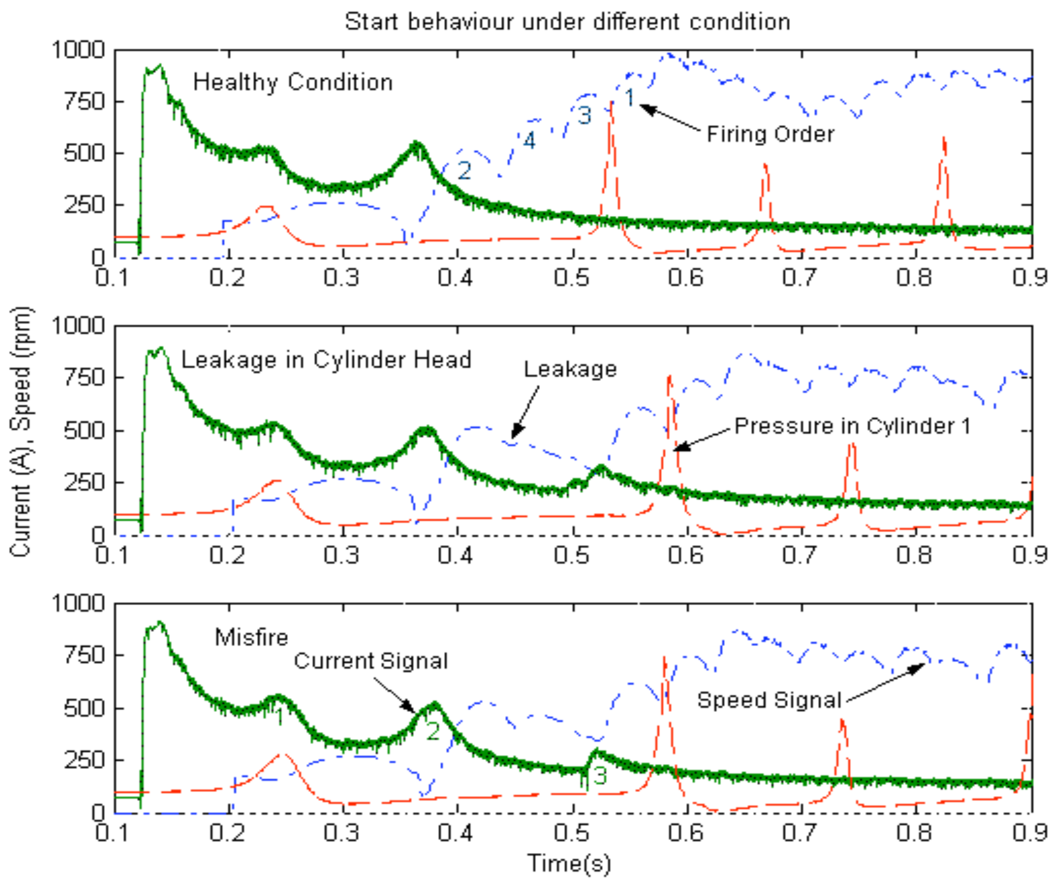

Figure E.10: Starting Behaviour Under Different Fault Conditions is. This doesn't rule out the current measurement technique for fault detection, but it does mean that it would appear that misfires cannot easily be detected in the cranking phase of the engine.

Figure E.10 contains the same three plots, but for a full engine start. The healthy engine plot shows the rapid increase in engine speed followed by a stable speed output. The current signal also drops off nice and consistently once the engine and the starter motor disengages. The leakage plot shows a different story. Compared to the healthy plot, the speed signal can clearly be seen to deteriorate as cylinder four is to compress and fire, cylinder three is also severely affected as it works after to carry cylinder four. The current signal shows that there is an extra draw of current as cylinder three compresses, showing that it takes one more cylinder cycle to start the engine with a severe leakage fault compared to no faults. The same is replicated for the misfire fault. This time the misfire fault is detectable, unlike the cranking phase. Both of the faulty plots also show that the average engine RPM after start compared to the healthy engine is lower. This may go on to stabilise with time.

E.5 Conclusions

The presented results have demonstrated that monitoring the engine current draw whilst cranking the engine and starting it fully has the potential to show faults on the engine. The data was taken in ideal conditions, with extra sensors that help to provide a lot of good additional information that can be overlaid with the current measurements. This extra data allowed for data synchronisation to compare between data sets, something that would not be possible in the field. The laboratory conditions also allowed for the data to be started in the same crankshaft position, though this is not totally out of the question on an industrial site. The data presented here has shown that this technique has potential despite these practical drawbacks.

Several potential data quality influencing factors were investigated, including variation of clamp position along the cable, cable position within the clamp. It was conclusive that the clamp or cable positioning had very little impact on the results obtained from the clamp.

Despite the severity of these faults, figure E.6 showed that there was only a small impact on the time in which the engine took to start and also a small increase in cylinder pressures to compensate for the faulty cylinder. This shows that, to a maintenance engineer on site, there may not be much physical evidence of a fault developing. However, with this technique cranking can be used as a rapid compression test that will not require a full engine start. Cranking demonstrated some fault determining ability both in figures E.8 and E.9. However, when only the current signal is considered, as it would be in the field, cranking has issues identifying the misfire condition.

When progressing to full startup conditions (figure E.10), both faults were clearly detectable with the current signal. The way this was identified was due to the extra current draw for another crank revolution for the cylinder following the faulty one. This is due to the increased work required to overcome the pressure/power reduction due to the fault. After the engine gets to a certain speed the other three healthy cylinders are able to support the faulty one. This leads to a reduction in the speed of the whole engine causing it to remain below normal operating performance. This technique could be used to detect less severe faults as the extra current spike with a severe fault is relatively large

In conclusion, the current measurement of a starting engine both in the cranking and full start up states is able to reveal faulty conditions within the engine. It has the potential to not only detect a fault but be able to tell if it is leakage or misfire as misfire cannot be seen whilst cranking but it can when the engine is under full start. There is clearly merit in this work and further work and research into this area should yield a lot of information for engine condition monitoring.

E.5.1 Further Work

There are many ways in which this work can be expanded. It was conducted as a brief investigation into whether it was even possible to utilise the current during startup. This work has shown that this technique is applicable but there are several areas that need to be investigated.

Fault Severity

The work discussed in this chapter was carried out with a fairly serious seeded fault. The leakage could be heard with the human ear and misfire was seeded as a whole cylinder not firing. Further work should be carried out to find out how severe a fault needs to be before it can be detected. Clearly if a fault can be heard with the human ear it is already at a too serious of a point to be able to carry out scheduled maintenance and there may already be secondary damage occurring elsewhere as a result of the first severe fault.

Without Engine Synchronisation

At the moment the engine starting position is being synchronised. There is also a pressure sensor in cylinder one that is used to synchronise the signals and to make them easier to read. Neither of these methods is an option in an operational engine. This research, therefore, needs to be repeated with a none position synchronised engine and with varying fault severity to find out if the fault can be detected and located.

IAS vs Current Measurement

It was shown in figure E.7 and E.10 that IAS gave clearer and more visible indications of the seeded faults. A comparison of the two techniques would be appropriate as both have their advantages and disadvantages in terms of on site measurement and cost of monitoring equipment.

Battery Condition

If the current measuring technique is to be used commercially on a range of engines it is important to investigate the effect of battery condition upon the output signals and whether these hinder the ability to detect the fault.

Generic Engine

There is no evidence at the current time that this technique would work on every type of electric start engine in regards to variables such as engine size, injection systems, piston types or cylinder arrangement. A study should be carried out on a range of engines, with some small and large faults if possible.

Closed Loop System

It is clear from section E.2.2 that there are in theory many advantages for the quality of the results with using a closed loop sensor. An investigation into just how much better the results are, or worse, compared to the open loop system would be a viable piece of research. If there is a significant improvement, and if it increases the detection capability of this method then a higher cost and less portability can be justified for industrial use.

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