2008

Variability analysis of engine idle vibration

Carol Lynn Deck
University of Windsor

VARIABILITY ANALYSIS OF ENGINE IDLE VIBRATION

by

Carol Lynn Deck

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive and Materials Engineering
in Partial Fulfillment of the Requirements for
the degree of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada
2008

Your file Votre référence
ISBN: 978-0-494-42258-8
Our file Notre référence
ISBN: 978-0-494-42258-8

ABSTRACT

Vibration in motor vehicles is largely influenced by the engine and thus has become the focus of much automotive testing. Engine idle vibration is focused on since deviations in the vibration signature are prevalent at this operating condition.

The objective of this thesis was to derive a best-practice method for the analysis of engine idle vibration. Variability of the engine vibration signatures was calculated through the implementation of multiple analysis techniques. These methods included: angle domain analysis, the fast Fourier transform, the discrete cosine transform, the moving average model, and the auto-regressive moving average model. Also included in the investigation were examinations of data normalization, detrending, and filtration. The results of the analyses were then evaluated with reference to the correlation between similar engines and the identification of outliers.

It was found that the fast Fourier transform analysis technique provided the best overall results. The moving average model and the auto-regressive moving average models were also identified as methods that have great potential in vibration analysis but are limited by their computational intensity.

DEDICATION

To my family and friends for their continuous support, understanding, patience and encouragement.

ACKNOWLEDGEMENTS

The author would like express thanks to the team members at Ford Motor Company's Powertrain Research and Development Centre at the Essex Engine plant for providing the results of their testing for analysis in this work. A special thanks goes out to the graduate students and the dynamometer technicians for their aid in conducting the experiments from which the results of this research are based.

Many thanks are given to my advisors Dr. Ahmadi and Dr. Gaspar for their continuous support and direction. Special recognition is also given to Dr. Lalman, Dr. Rankin, and Dr. Zamani for their role as committee members.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

2V	2-valve
3V	3-valve
a	acceleration
a_i	ith coefficient value
ADC	Analog-to-Digital Converter
ADACS	Automated Data Acquisition and Control System
AR	Auto-Regressive
ARMA	Auto-Regressive Moving Average
β	best-fit coefficient
b_i	ith coefficient value
BDC	Bottom-Dead-Centre
c	damping coefficient
c_i	ith average coefficient value
c_v	coefficient of variation
CAN	Controller Area Network
CI	Compression Ignition
CID	Cylinder or Cam Indicator Signal
DC	Direct Current
DCT	Discrete Cosine Transform
DFT	Discrete Fourier Transform
δ_{st}	static deflection
ε_i	residual error
E	number of engines
ECU	Electronic Control Unit
f	analog frequency
F	objective function or digital frequency
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
F_o	Magnitude of force
f_m	maximum sampling frequency
f_s	sampling frequency
F(t)	continuous time force function
i	data index
ICP	Integrated Circuit Piezoelectric
IIR	Infinite Impulse Response
ISO	International Organization for Standardization
k	spring stiffness or multiplying factor
LF	Left Front
LR	Left Rear
m	mass
M	ratio of dynamic to static motion
MA	Moving Average

n	total number of samples, cycles, or poles
N	number of analysis points
NVH	Noise, Vibration & Harshness
PERDC	Powertrain Engineering Research & Development Centre
QOS	Quality of Service
r	Frequency ratio or Euclidean distance
RF	Right Front
rpm	Revolutions Per Minute
RR	Right Rear
σ	standard deviation
S	samples per cycle
SAE	Society of Automotive Engineers
SI	Spark Ignition
t	time in seconds
T_s	sampling interval
TDC	Top-Dead-Centre
x(t)	continuous time displacement
x[n]	discrete time displacement
$x_p(t)$	periodic time signal
X	amplitude of displacement
X(f)	continuous frequency
X[k]	sampled frequency
x	linear displacement with respect to time
$\dot{x}$	linear velocity with respect to time
$\ddot{x}$	linear acceleration with respect to time
$\bar{x}$	arithmetic mean
VXI	VME eXtensions for Instrumentation
ω	radian frequency
ω_c	cut-off frequency
ω_n	undamped natural frequency
$\hat{Y}$	predicted value of variable
Y	measured value of variable
ζ	damping ratio
θ	phase angle
ϕ	phase angle

CHAPTER 1 – INTRODUCTION

The engine is the heart of any vehicle and is the source that converts the fuel to power; this also means that it is a main source of noise and vibration. Noise, vibration and harshness (NVH) influences the perception of quality to the customer; for some the sound and feel drive a sale, while on the other end of the spectrum noise and vibration issues are often the origins of customer complaints.

While noise and vibration are separate concerns of the consumer they are often tied quite closely together. Vibration is often the source of most noise and if vibration is focused upon a twofold reduction in NVH concerns can be attained. In the course of the combustion process the engine creates vibration through combustion forces and mechanical motion. This vibration is spread throughout the vehicle due to resonance, production of further mechanical motion, and the resulting movement of the vehicle.

Part of a customer's expectation of manufactured goods is mass production repeatability. With engines this means that the presumption is that they will sound, feel and react in the same manner. NVH is a key fact in the assessment of the calibre of a product. Slight defects and deviations from the norm can contribute significantly to a vehicle's interior noise and vibration. To insure the standardization of the product a quality of service (QOS) test is often performed.

1.1 Background

In this study vibration data from tests performed at the Ford Powertrain Engineering Research and Development Centre (PERDC) at the Essex Engine plant is analyzed. Outlines of their testing and analysis processes are described below.

1.1.1 Testing

Ford Motor Company is constantly testing its product for quality and repeatability. At the PERDC in the Essex Engine plant noise and vibration quality tests are performed on a regular basis as part of the QOS evaluations. The results from this testing are used for target setting, verification, benchmarking, and databasing [1].

Data from a large sample of engines is gathered in the initial QOS test performed on each engine model. A succession of engines is collected as they come off the production line and are set aside for analysis. The original dataset consists of at least thirty engines as established by the Ford corporate standard; this amount is considered the minimum sample size to represent a normally distributed population. Results of this preliminary investigation are known as the baseline and are the benchmark for subsequent tests. Following the baseline evaluation, QOS tests are performed quarterly or semi-annually on samples of six engines. These engines are collected and tested in the same process as that of baseline.

In addition to the standard noise and vibration test each engine in the QOS check at the Essex Engine plant also undergoes a second test known as the 'Prosig Test'. This investigation examines vibration and sometimes noise at steady states and is named for the data acquisition system used. The standard test collects vibration data from eight locations on the engine; the setup and data collection methods are described in detail in Chapter 4. Additional transducers are often added to the setup to allow for further investigation of different aspects of the engine. Three different operating conditions are part of the standard test; idle, partial-load, and wide-open throttle. These specific speeds and loads are part of a typical testing procedure and are quite prevalent in normal driving activity.

The centre also evaluates and troubleshoots engines that are considered faulted. These engines are obtained from Ford engine manufacturing plants, final vehicle assembly plants, and from dealerships. An initial idle 'Prosig Test' is performed on each engine and a root cause analysis investigation is initiated. At this point repairs may be performed on the engine and another test run. This cycle is repeated until the source of the problem is determined.

1.1.2 Analysis

Quality of service testing is part of the ISO (International Organization for Standardization) quality management system utilized by Ford, Chrysler and General Motors. This standard is in place to help ensure the consistency of the end products and to aid in the continual improvement process; in other words the objective of this tool is to put forth the best product every time. All of this is in place not only as a best business practice but for the benefit of the consumer.

Data acquired from the QOS evaluation compares the tested engines to their sample group and to the baseline; subsequently the results are analyzed for improvements or deterioration. Ideally over time the product should have lower variability and less noise and vibration; this is due to continual development of the engine model. In reality, while slight improvements are expected deterioration can occur when slight changes in the product are imposed. These changes can include wear and tear on a mould, change of part suppliers, and alterations in manufacturing material.

Results from the QOS runs of the 'Prosig Test' are analyzed for variance over the engine cycle. In the calculation of the variance the data is first resampled into the angle domain with reference to the crankshaft and is then broken down into thirty engine cycles. The variance is then calculated for each crankshaft angle. Analysis of the variance includes total average variance, maximum variance comparison, and overlaid engine variance plots. Faulted engines are analyzed through a visual inspection of the variance of each accelerometer. Significant amplitude variance spikes are focused on and faults are surmised from the angle of the crankshaft and the accelerometer location.

1.2 Purpose

Results of the 'Prosig Test' are not part of the official QOS investigation and hence most of the data has been filed away for future analysis. The purpose of this research is to propose an alternate method of analysis for the 'Prosig Test' data. In conclusion this method could be used to create a formal quality testing and analysis procedure to aid in the compliance of the ISO standard of quality.

1.3 Objectives

The focus of this thesis is to analyze the engine vibration data using multiple techniques and to conclude which is the best practice method. To fulfill the purpose of this study the following research objectives must be carried out:

1.) Evaluate engine idle vibration using various analysis techniques

2.) Access the feasibility and functionality of the different methods

3.) Present recommendations for future vibration analysis research and alternative analysis techniques

The following chapters delve into the research and background of the testing and analysis techniques of the study at hand and are concluded by the results and recommendations.

CHAPTER 2 – LITERATURE REVIEW

This chapter is a review of the literature pertinent to this study. Included in this section is a discussion about engine noise and vibration, also reviewed is information pertaining to vibration testing and various data analysis techniques. Many aspects of this thesis have been investigated and assessed by the scientific and engineering community and are presented here to build a foundation for the work presented in the following chapters.

2.1 Noise, Vibration and Harshness in Internal Combustion Engines

A vital tool in the evaluation of internal combustion engines is the analysis of noise, vibration, and harshness. From these observations assessments of combustion and mechanical workings can be made. All in all NVH is tied in tightly to the overall subjective view of the operation of an engine.

Noise and vibration often go hand in hand. In many cases vibration is the root cause of noise and noise is frequently the only notable symptom of abnormalities. While vibration is part of the rotating machinery's operation in practice it is minimized to lessen its infringement on the system.

In essence each engine model should have the same noise and vibration signature. Deviations from this signature depending on severity denote variation due to manufacturing processes, abnormalities of parts, and even so far as a foredoomed catastrophic failure.

2.1.1 Vibration

Vibration in internal combustion engines is due to mechanical motion, combustion forces, and structural resonances. Most vibration reflects poorly on an engine since it alludes to energy loss, possible defects and often brings with it undesirable noise [2]. While a minimal amount of vibration is acceptable, an increased amount can lead to mechanical failure and or unsatisfactory perception by the consumer.

Engine vibration can be broken down into deterministic and stochastic components. The characteristic vibration signature is defined by the deterministic portion of the signal which is easily masked due to random noise. To be able to separate the two components the vibration signal must be captured over multiple cycles. A steady-state signal is best used in this type of interpretation.

The combustion force causes vibration by creating mechanical motion and through the variation of in-cylinder pressure. During the firing phase of the cycle the vibration in the engine block is often at its peak amplitude. According to Chandroth et al. [3] cylinder pressure fluctuations cause the engine structure to vibrate and are the source of most engine vibration. Inconsistency in combustion cycles can also lead to large cycle-to-cycle variations whose discrepancies can lead to unwanted vibration.

2.2 Acquisition of Vibration Data

In order to obtain the desired vibration data from an engine consideration must be given to the design of the experiment. The conditions under which the data is collected along with the acquisition equipment and setup of the experiment need to be determined.

2.2.1 Operating Conditions

Operating conditions play a large role in the vibration of the engine. The engine speed, load, oil and coolant temperature, and the environment in which it is run are all contributing factors. Engine speed can bring out different resonant frequencies. Furthermore load imparts additional stress on the system, which can change the motion of mechanical components. Vibration may occur only during a certain temperature range; this can often be attributed to the expansion and contraction of the engine's internal workings. The environment also plays a role with the temperature and pressure effecting the gases and fluids used in the system. Operating conditions should be controlled to limit variability and to allow for closer examination of distinct states.

2.2.1.1 Idle

In vibration analysis the idle operating condition is often focused on because noise and vibration are more noticeable and prevalent in this state. At increased speeds the distinct vibration and noise issues can be masked due to the many internal processes. Machinery is also less prone to erratic movement at higher speeds because the mechanical motion becomes streamlined with less irregular movements to cause abnormal vibration and noise.

At idle the rate of speed is close to the lowest that an engine can operate at; if the speed is dropped the rotational force due to combustion may not be strong enough to turn the crankshaft and the engine will stall. This makes it very susceptible to variability and the engine must overcompensate for slight irregularities. At low engine speeds the combustion is most prone to abnormalities due to the fact that the air density and fuel mass fed into the system are at their lowest levels. The mixture in the cylinder is hence prone to uneven distribution which causes variability in the combustion process [4]. Deviations in combustion can lead to an oscillation in engine speed which may result in a firing frequency that excites resonant vibrations of the engine structure. This variation was part of the focus of an investigation on engine idle vibration preformed at the University of Sheffield [5].

The opinion of the driver is also of key concern because the cycle-to-cycle variation is more perceptible at this speed. A rough or unsteady idle leaves a poor impression of the vehicle and a slight knocking sound from an engine can be grating to the individuals in the automobile. Vibration is also transmitted from the engine to the vehicle frame and thus further affecting the occupants [6]. The expectation of the customer is that at idle the automobile should have little to no detectable vibration and noise.

Engine idle vibration has very deterministic characteristics intermixed with random non-stationary events [5]. This means that an idling engine will have a distinct vibration signature. The variation between the signatures of various engines and engine families is the focus of this investigation.

2.2.2 Transducers

Measurement of engine vibration can paint a picture of the mechanical operations within the engine. Accelerometers are the most common type of transducer used in the analysis of vibration response of rotating machinery [7]. In measuring acceleration this sensor is best suited because it directly measures the desired quantity and has a large bandwidth. The vibration signature is also easily acquired by mounting accelerometers on the engine. This transducer has usage restrictions because its internal workings limit the environmental conditions and vibration amplitude it can be exposed to.

Another type of vibration measurement tool is the laser vibrometer. This instrument measures the velocity of the surface vibration using the principle of the Doppler effect. Unlike the accelerometer, vibration information is gathered with no physical contact and the operation is not limited by temperature and vibration amplitude. Also, with the aid of software the laser vibrometer can measure a single point or scan a predefined surface. In a study of automotive NVH Beidl et al. [8] used the laser vibrometer to view the surface vibration distribution of an engine. This type of analysis can be used for finding sources of vibration and also in the investigation of radiant noise.

2.2.3 Cylinder Indicator

A cylinder or cam position indicator (CID) sensor gives information to synchronize the vibration signal to the engine's events. The output of the signal can also be used as a tachometer whereby the speed of the system is calculated from the reciprocal of time between the pulses. Precision in the conversion of the time signal to the angle domain is related to the number of pulses per cycle. With a greater amount of pulses there is less smearing of data since this will better represent the actual speed of the engine by accounting for more of the inter-cyclical speed changes [9].

2.2.4 Measurement Location

Measurement location is a key detail in the collection of useful and effective vibration data. The position selected will receive information from many different internal sources because of the propagation of vibration through the structure. In selecting a position it is essential to choose a point where the desired observed signal is most prominent and the vibration due to other components is minimized.

A vibration signal acquired from the cylinder head of an engine gives a strong correlation to the cylinder pressures and the motion of the piston [3]. Measurements taken at the top of cylinder head also include vibration from the valvetrain. From the analysis of the data derived from the block lug locations information about the main bearings, pins, connecting rods and other components can be obtained.

2.3 Data Analysis Techniques

The main objective of this research was to examine engine idle vibration variability using multiple analysis techniques. Many numerical methods were investigated and are discussed below and in the following chapters.

2.3.1 Time Domain Analysis

Raw time data is not often used in the analysis of engine vibration. Identifying characteristics are difficult to extract from time data and the signal in most cases is post-processed to obtain the desired information. Therefore examples of raw time data analysis of engine vibration are few and far between.

One form of time domain analysis is the root mean square which gives a statistical measure of the magnitude of the signal [2]. This simple method can be used as a preliminary indication of variability. Another type of time domain investigation is the implementation of modeling techniques such as a trend prediction tool. Sinha [10] uses samples of time data in his modeling techniques to monitor vibration.

2.3.2 Angle Domain Analysis

An internal combustion engine is a rotating machine that operates within a defined cycle; hence the time data can be synchronized to the angle of rotation. The angle of the crankshaft is often the position reference of the system, with the initial point being the top-dead centre of the combustion stroke of cylinder one. Fluctuations in speed due to the angular velocity of the crankshaft vary from cycle-to-cycle and also within the cycle. To be able to align the vibration signatures of an engine to its cycle a transformation to the angle domain is necessary. This allows for comparison of events and their timing within the cycle. Angle domain analysis is quite useful in distinguishing faults in an engine since the position in the cycle can often attribute the cause to active processes. The results of this technique can also transform a non-stationary vibration signal into a stationary one.

With the aid of a reference such as the CID signal the data series is correlated to the engine cycle. Tjong [11] employed a technique whereby a wheel with 360 teeth was attached to the crankshaft. An encoder monitored the passage of the teeth and was used to trigger data sampling. This process is known as synchronous sampling. Similar testing applications were discussed by Gade et al. [9] with vibration data collected along side an angle reference source and the data consequently being post-processed into the angle domain.

2.3.3 Frequency Domain Analysis

Analysis of a vibration signal in the frequency domain is an effective method for gathering characteristics of an engine. The transformation of a time signal into the frequency domain produces a signal that includes the range of frequencies contained in the time signal along with the quantity at each given frequency. Frequency content of an engine can offer much information on its operation because defects are often characterized by a distinct frequency range. Workings of individual rotating components of an engine can also be identified from the frequency spectrum [12].

2.3.3.1 Fast Fourier Transform

The fast Fourier transform (FFT) is the most common method used to transform time data to the frequency domain. It is a computationally efficient variation of the discrete Fourier transform (DFT) which converts a signal into the frequency domain by breaking the time signal into a summation of sinusoids and cosines.

Analysis of engine vibration using the FFT should be limited to constant speeds. Variation in speed can lead to shifting characteristics since the frequency content of a signal is tightly intertwined with the rotational speed [3, 5]. The FFT is not effective in the analysis of vibration that is intermittent and transient because of its non-stationary nature.

An FFT can be used on both time and angle domain signals as discussed by Blough and Gwaltney [13]. The analysis of engine vibration data with speed variation is possible if the data is first resampled into the angle domain. As a result the aspect of the rotational speed is removed and an FFT can then be performed with the data being transformed into the order domain [8, 14]. This method was not utilized in this study because the variation of speed is limited because the engines idled at a relatively constant speed. Also the frequency content due to the idle speed is an identifying attribute of an engine since each model has a distinct idle speed.

2.3.3.2 Discrete Cosine Transform

The discrete cosine transform (DCT) is different from the discrete Fourier transform because it is a real transform and utilizes only a summation of cosines; this also implies that it has lower computational complexity. Calculation of this method is performed by a variation of the FFT [2, 15] which again reduces the amount of computations required. Applications of the DCT are numerous with the most common being data compression. Makoto and his associates [16] utilized the DCT to compress large amounts of vibration data where the original signal was reconstructed with minimal loss.

Energy in the DCT is predominantly concentrated at low frequencies. With image and audio compression the original data mostly contains low-frequency features hence the higher frequencies of the DCT can be discarded without significant loss. Consequently the original object is represented by a smaller amount of coefficients in the frequency range and can be reconstructed almost perfectly rendered. This is only part of the compression process and is outside of the scope of this thesis and will not be given further consideration.

Widespread deployment of this technique has been attained with it being utilized in standard audio, image and video processing methods. Some notable applications of the DCT and its variants are common digital file formats such as; JPEG, MPEG-2, MPEG-4, MP3 and WMA.

2.3.4 Predictive Models

A predictive model is a mathematical representation or a process that can forecast future behaviour. This type of model is often employed in economics and weather to report future expectations. The modelling process utilizes a mathematical formula whereby the coefficients can be used to compare datasets.

2.3.4.1 Moving Average Model

A moving average (MA) model creates a representation of the observed data by a weighted summation of its current and past input values. Implementations of this technique are commonly used for smoothing of data and for forecasting results.

This model is characterized by a finite length impulse response sequence [17]. It offers stability with a simple implementation; its downfall is that it requires more coefficients to represent the data than other similar methods. The model is only based on a limited amount of past values so transient errors or random noise do not effect the whole data series. A limited memory is an attribute that needs to be taken into account. Other techniques in contrast to the MA model consider all past values and an isolated random event is never forgotten.

2.3.4.2 Autoregressive Model

An autoregressive (AR) model is another linear prediction formula which creates an estimation of a data series through a summation of the current value and past values of the output of the model. This type of model is also known as a maximum entropy or all poles model. In many cases it is used as a smoothing function. This modeling technique has a wide variety of applications ranging from astronomy to urban planning.

2.3.4.3 Autoregressive Moving Average Model

The autoregressive moving average (ARMA) model combines the MA and AR models. Analysis of vibration data using an ARMA model was implemented by Sinha [10]. This model is useful not only in identifying characteristics through the coefficients but can also be used in trend prediction. Implementation of the ARMA model can be completed in both the time and frequency domain. The time domain method is more tedious since the stability of the model is difficult to achieve. A unique method for deriving the coefficients in the time-domain was implemented by Box and Jenkins [2]. It is a tool that is widely used in the field of econometrics. When implementing the ARMA model in the frequency domain the phase of the system is lost and hence the time signal cannot to be accurately rebuilt. In many cases this is not of concern since the correlation of the parameters is the focus of the study and vibration data is often only analyzed in the frequency domain.

Coefficients of the AR portion of the ARMA model can lead to instability and difficulty in achieving parameter values that reproduce the original data. This problem was discussed in an SAE paper written by Ippili and his associates [18]. In this thesis research stability was also an issue and was resolved by analyzing the data in the frequency domain and controlling the AR parameters.

The ARMA model is a general model for a linear system as discussed by Nishizawa et al. [19] and Nise [20]. An approximate model can be realized even if the system is slightly non-linear by increasing the order. Selection of the order of the model is discussed by Nishizawa et al. [19] and Leser et al. [21]. The order of a system should increase with the number of samples but this also leads to greater computational time. In this research the order of the model selected took into account the calculation time, the correlation of the coefficients between engines, and the representation of the study's data.

2.3.5 Regression Analysis

In dealing with multiple variables it is often found that the change of one of these terms is associated with a variation in other variables. In many cases a mathematical relationship can be determined that relates these changes. Regression analysis is a statistical technique used to determine the best mathematical expression that quantifies the relationship between variables.

Data from the series is fed into the mathematical equation with the output being very close to original input. The difference or error is known as the residual and the goal of regression is for it to be minimized. This derived relationship is often used in future prediction where the mathematical model is based on past input values.

There are two main types of regression analysis; linear and non-linear. A linear regression is characterized by coefficients of regression that are multipliers of the terms of the mathematical expression. In non-linear regression the coefficients are included in a function of the equation; for example the coefficient could be part of an exponential term. Non-linear regression is also used when a best fit of the linear regression is not possible. Additionally this process is used when the data of the system is multidimensional; where multiple inputs combine to form a distinct output.

Many different methods can be used in regression analysis such as; least squares, maximum likelihood, robust and Bayesian methods [2]. In this study the linear least-squares analysis method is used.

2.3.5.1 Least Squares Regression

The least squares regression method approximates an over-determined system of equations. Coefficients of the mathematical equation are determined by minimizing the difference between the actual data and the output of the model. This difference or error term is called the residual. As a result of multiple iterations the sum of residuals is minimized and hence the model will approximate the system of equations.

In the calculation of the coefficients of the MA and ARMA models the least-squares regression is most commonly used [10, 18, 22, 23]. These models utilize the least squares method to fit a curve to the data. As discussed by Moler [24] the curve fitting problem is one that is most often solved by this regression method.

CHAPTER 3 – THEORY

The theoretical aspects related to engine vibration testing and the analysis of the resulting data are described in this section. Topics covered in this chapter include important aspects of: digital signal processing in connection with the acquisition of analog data, properties of accelerometers, introductory internal engine combustion theory, fundamentals of vibration, and basics of electronic filters.

3.1 Digital Signal Processing

In order to store an analog signal on a computer the signal must be transformed into a digital signal. This process is called analog-to-digital conversion and is performed by devices called analog-to-digital converters (ADC). The electronic device digitizes an input analog voltage or current signal; a summary of the inner-workings of the ADC can be seen in below in Figure 3.1.

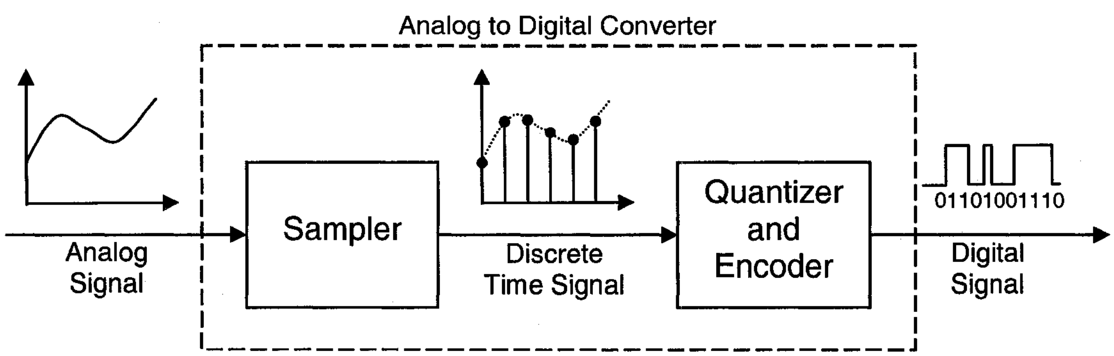


Figure 3.1: Block Diagram of an Analog-to-Digital Converter (ADC)

Sampling takes a continuous signal and captures the analog data at regular intervals. A series of discrete values which represent the range of the input signal is then compared against each sample. In a process called quantization, the separate samples are converted into numbers by selecting the closest value from the discrete series. The result of this conversion process is a digital representation of the analog signal.

3.1.1 Sampling

An analog signal is continuous in time and must be converted to a constant flow of digital values. This translation into discrete-time is achieved by taking samples of the input signal at isolated instants. Sampling can be regarded as the product of the analog signal and a unity amplitude impulse train. The time interval between samples can be uniform or variable and is dependant on the sampling technique used.

A uniform or periodic sampling is achieved by taking samples at equal time intervals of length T_S. The time interval between samples is known as the sampling period or sampling interval and the inverse is called the sampling rate or frequency.

$$f_s = \frac{1}{T_s} \qquad (3.1)$$

Variable or synchronous sampling has many different implementations, which include removing superfluous data and event analysis. In this discussion variable sampling is taken at constant intervals with reference to the angle of the crankshaft.

Both techniques have their pros and cons. Uniform sampling establishes a relationship between time variables of continuous-time and discrete-time signals. It also gives a more accurate representation of the vibration signal. The variable sampling method is often superior if the event is proportional to the rotational speed. This can ease the analysis of events in comparison to each other and help identify where in the cycle the event is occurring.

3.1.2 Sampling Rate

There are two main types of sampling; uniform and variable. With uniform sampling the rate is measured in samples per second, often expressed as Hertz or bytes per sec. In this study the variable sampling rate is tracked according to the revolution of the cam with reference to the position of the crankshaft; the measurement unit is expressed as samples per degree.

The sampling process can lead to the potential loss of information; with a shorter sampling interval, there is a reduction in the amount of information loss. Ultimately in sampling there will always be some loss in information no matter how short the interval used. It is important to consider the frequency content of the incoming signal in selecting a sampling rate.

Using the Nyquist-Sharron sampling theorem, the appropriate sampling rate can be selected from the maximum frequency of interest, f_m [2]. The theorem states that a measurement signal can be sampled without loss of frequency information or aliasing if the sampling rate is more than double the highest frequency of interest.

$$f_s > 2f_m \tag{3.2}$$

Where: f_m = the maximum frequency of interest

$\frac{f_s}{2}$ = the Nyquist frequency or critical frequency

In practical application frequencies close to the Nyquist frequency may still be distorted in the sampling and reconstruction process, therefore the bandwidth should be kept below the Nyquist frequency by some margin. The loss in information from undersampling or sampling close to the Nyquist frequency is caused by spectral overlap and aliasing.

3.1.3 Resolution and Gain

Resolution in digital to analog conversion denotes the number of discrete values that can be produced over the dynamic range of the analog input. The resolution is expressed in bits and thus the number of discrete values is most often a power of two. In this study the resolution of the data acquisition system was 16 bit; this means that the analog data can be converted to one of 65536 or 2^{16} different levels. More discrete values or levels and a greater sampling rate will result in a finer resolution and an increased accuracy of the reproduction.

The dynamic range is the span between the maximum and minimum amount of input that an acquisition device can measure. A gain factor is a magnification of data within this range. Amplification of the resolution is achieved from an increase in the gain factor. By focusing on a smaller range a more detailed representation of the data is obtained. The highest gain factor which encompasses the input signal's range without clipping (occurs when the analog signal amplitude exceeds the range that can be recognized by the ADC converter) should be selected. This narrowed range will ensure that the data is acquired at its maximum resolution.

3.1.4 Quantization and Encoding

The process of approximating a continuous signal using a finite number of amplitude levels is known as quantization. In this procedure the analog input signal is quantized by rounding each sample to the nearest quantization level. Each quantized sample is represented by series of zeros and ones (bits) with the series length being in this case being 16 bits.

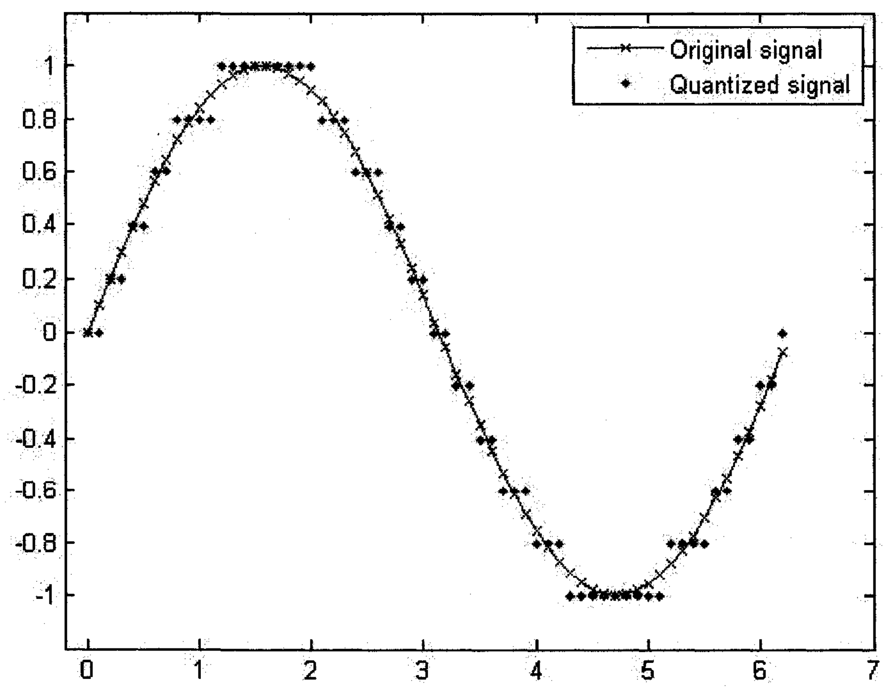


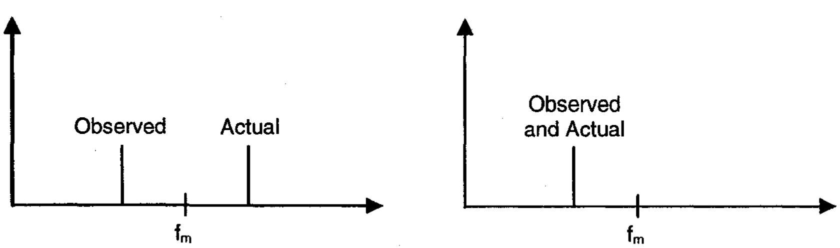
Figure 3.2: Comparison between a Continuous Signal and a Quantized Signal

Quantization error or quantization noise is known as the difference between the original sample amplitude and the quantized level. The magnitude of the instantaneous error from the truncation can vary from zero to half of the difference between levels. As can be seen in the Figure 3.2, the maximum quantization error is 0.1.

The quantization of analog signals will always lead to some loss of information no matter how fine the quantization levels. Oversampling can be used to offset this loss in accuracy by distributing the quantization noise over a larger number of samples.

3.1.5 Aliasing

Aliasing refers to the effect that causes different continuous signals to become indistinguishable from each other when reconstructed. This happens when frequencies greater than the f_m fold back over the maximum frequency. Thus, frequencies greater than f_m appear as lower frequencies as can be observed in Figure 3.3.



(a) Frequency Folding (Aliasing) (b) No Aliasing

Figure 3.3: Difference between Proper and Improper Sampling

Depicted in Figure 3.4 is an example of the aliasing phenomenon. In the figure the black circles denote the sample rate of the analog signal. The red curve is the actual analog signal and the blue curve represents the reconstructed curve from the sampled data. It can be seen that this higher frequency data because of the sampling rate appears to be at a lower frequency. Thus the unique identification from reconstruction becomes impossible because the legitimate and aliased components are indistinguishable.

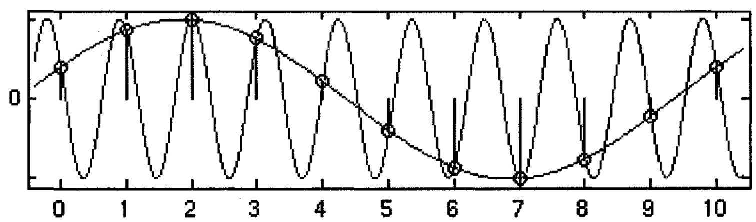


Figure 3.4: Two Different Sinusoids that Fit the Same Sample Data [2]

To alleviate this problem an anti-aliasing filter is employed in the ADC system. Most anti-aliasing filters are low-pass filters that attenuate frequencies above the Nyquist frequency of the sampling rate. The anti-aliasing filter will in practical application remove most aliasing but because the filter is not ideal some roll-off will occur. Oversampling at a rate greater than 2.56 times the maximum frequency of interest ($2.56f_m$) will also help minimize the remaining effects.

3.1.6 Oversampling

Sampling data at a rate greater than the twice the maximum frequency is a practice known as oversampling. This will give a better representation of the input signal because of the larger amount of samples. While this procedure can reduce errors it also can impose an added computation burden.

Oversampling can eliminate aliasing in the frequency range of interest by increasing the bandwidth of the acquired signal. In post-processing the extra frequency range can be filtered out along with left over remnants of aliasing from the roll-off of the anti-alias filter. Also the oversampling process can reduce noise from the input signal and that caused by quantization. This is done though averaging and distribution of the noise power over a larger frequency range.

3.2 Accelerometers

An accelerometer is an electromechanical device used to measure acceleration. Depending on the transducer it can measure static acceleration such as gravity or more commonly the dynamic acceleration caused by vibration or motion. There are a wide range of applications for these devices from measuring vibration in cars and buildings to monitoring seismic activity. Many electronic devices incorporate accelerometers, some examples include; changing the display orientation on an interface screen on a hand held device and measuring speed and distance in a portable fitness monitor.

3.2.1 Piezoelectricity

Piezoelectricity is a property of materials which become polarized in response to mechanical stress [25]. When the material is strained by an applied force it produces opposing surface charges and hence generates a voltage difference between the surfaces. The piezoelectric effect is also reversible whereby the material will exhibit stress or strain when in an electric field.

A unique attribute of piezoelectricity occurs in crystals that have a unit cell which is noncentrosymmetric; this means that the structure of the crystal has no centre of symmetry. The structure when unstressed has a central point of mass shared by both the positive and negative charges. This crystalline structure is altered when stressed and the central point of mass becomes different for the positive and negative charges causing polarization.

Materials that exhibit the piezoelectric effect include quartz crystals and ceramics. Many of these materials occur naturally but man-made variations are often utilized. A wide range of applications employ piezoelectric materials, these include; accelerometers, microphones, speakers, filters, spark generators, and clocks.

3.2.1.1 Piezoelectric Accelerometer

In an accelerometer the piezoelectric material measures the applied acceleration. Inside the accelerometer the piezoelectric material is attached on one side to a rigid base, while the other is fastened to a seismic mass as can be seen in Figure 3.5. Force from the mass acts directly upon the piezoelectric material when the transducer is subjected to acceleration. This force in accordance with Newton's second law of motion is equal to the product of the acceleration and the mass.

$$F = ma \tag{3.3}$$

The piezoelectric material reacts to this applied force by generating a proportional voltage difference between its surfaces. Electrodes connected to either side of the piezoelectric material transmit the signal out of the accelerometer.

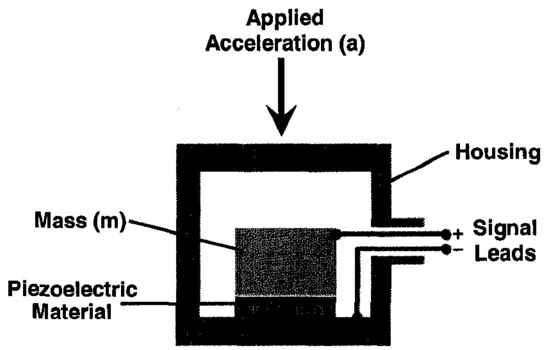


Fig 3.5: Principle of a Piezoelectric Accelerometer

Most accelerometers used in vibration measurements are piezoelectric. These sensors have many beneficial characteristics such as; a wide frequency and dynamic range, and are quite robust and have high stability. Additionally, the units are generally very compact and low in weight. Furthermore, this transducer has no moving parts to wear out and is self generating; therefore it does not require external power to operate.

3.2.2 Compression and Shear Type Accelerometers

Accelerometer designs include a multitude of mechanical configurations and measurements types. Historically most accelerometers were compression type with its simple construction. The mass exerts a compressive force on the piezoelectric material in this formation much like that seen in Figure 3.5. These transducers are very stable with high rigidity but are sensitive to environmental influences such as base strain and temperature fluctuations. In addition this type of accelerometer is often the largest and heaviest of its family since it requires a greater mass due to its sensitivity-to-mass ratio.

Shear mode accelerometer designs have the piezoelectric elements arranged between a central post and a seismic mass. A compression ring encompasses the assembly and applies a slight force to ensure rigidity. When accelerated, a mass wields a shear stress on the piezoelectric elements and a proportional charge is hence produced. This type of transducer has a very high sensitivity-to-mass ratio and is less susceptible to environmental influences. The unit can be quite compact which minimizes its overall mass. In testing sensor mass is very important since extra mass can affect the structure through additional loading.

3.2.3 Charge Mode and Internally Amplified Accelerometers

The output signal from the piezoelectric accelerometer requires some conditioning before it can be read by analysis and acquisition equipment. Charge mode accelerometers contain only the sensing element with no extra electronics in their housing. Output from this transducer is a high impedance electrical charge. The electrical signal travels through a cable to a charge amplifier which converts the charge input and outputs a proportional low impedance voltage. This type of accelerometer can withstand greater environmental changes as well as high temperatures and amplitudes. The downfall is the sensitivity of the sensor's output signal to corruption; to mitigate this issue low noise cabling should always be utilized.

Internally amplified accelerometers contain built-in signal conditioning microelectronics. The output signal of the sensor is a low impedance voltage which is less sensitive to signal degradation. However, due to the internal circuitry the accelerometer is limited to the temperature range capability of the built-in electronics. This transducer also has high amplitude limitations since a large acceleration could create an electronic charge that is large enough to overload the internal circuitry. Additionally these accelerometers require a constant voltage to operate.

3.3 Internal Combustion Engines

In studying engine vibration signatures it is essential to have a basic understanding of the workings of internal combustion engines. These engines derive power from the expansion produced by the combustion of fuel and an oxidizer within the engine. The work is done when the expanding hot gases move parts such as pistons and rotors in a transformation of thermal energy into mechanical energy.

Internal combustion engines are generally used for propulsion but can also be used in mechanical drive applications such as pumps and compressors. Engine types include reciprocating and rotary engines and turbines along with a variety of combustion strategies and cycles with applications ranging from airplanes down to lawn-mowers. The focus of this discussion will be on the reciprocating four-stroke engine cycle used to power automobiles.

3.3.1 Four-Stroke Engine Cycle

The majority of motor vehicles today have engines which operate on a four-stroke cycle. These four strokes are known as intake, compression, expansion, and exhaust and occur over two rotations of the crankshaft. Both spark ignition and compression ignition engines employ this cycle. A simple depiction of the four-stroke cycle can be seen below and a brief description of its operation follows; this is referenced from Heywood [26] and other sources [2, 27].

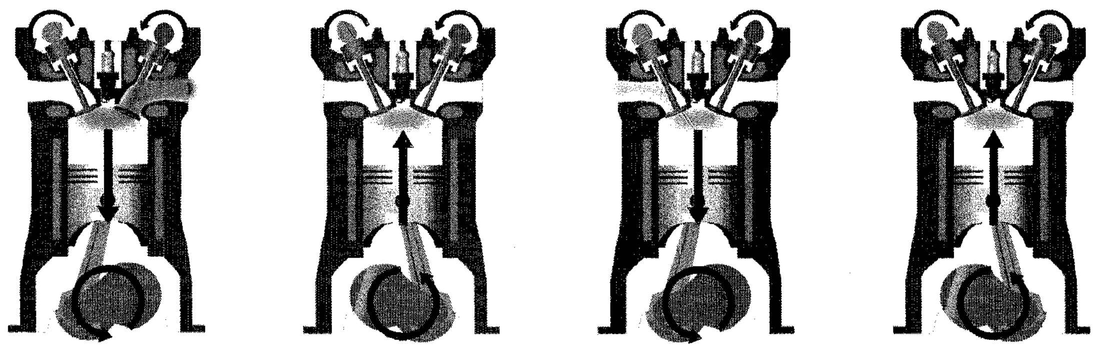


Figure 3.6: The Four-Stroke Operating Cycle [2]

The intake or induction stroke starts with the piston at top dead centre (TDC) when the cylinder volume is at its minimum. At this point in the cycle the piston starts its descent with the intake valve open and the exhaust valve closed. As the volume of the cylinder increases it creates a vacuum and draws in air. Fuel also enters the cylinder at this time either through direct injection or from the intake as an air-fuel mixture. As the piston falls the air and fuel continue to mix. The stroke ends with the piston at bottom dead centre (BDC) and the intake valve closing.

In this cycle the second stroke is known as the compression stroke. It begins with the piston ascending and thus compressing the air-fuel mixture to a fraction of its original volume. Shortly before the piston reaches TDC combustion is initiated. The ignition is either instigated by a spark plug firing in spark ignition (SI) engines or from autoignition where the fuel spontaneously ignites due to compression in Diesel cycle or compression ignition (CI) engines.

Next the expansion or power stroke occurs following combustion with the piston at TDC. The heat and pressure increase due to combustion results in the expansion of gases in the cylinder. This pushes the piston to descend as the volume of the cylinder is forced to increase. As the piston reaches BDC it is filled with the end products of combustion; at this time the exhaust valve opens.

Finally the four-stroke cycle is concluded with the exhaust stroke. At this stage the intake valve remains closed and the exhaust valve is open. The piston ascends purging the cylinder of the spent combustion gases through the exhaust valve. As the piston reaches TDC the intake valve opens, the exhaust valve closes, and the cycle is complete.

3.3.2 Spark Ignition Engine

Spark ignition engine refers to an internal combustion engine whose ignition is prompted by a spark. The four-stroke spark ignition cycle is often referred to as the Otto cycle after its inventor Niklaus Otto [28]. Another identifying attribute is the location of the air and fuel mixing; in SI engines typically the air and fuel are combined in a chamber before they are drawn into the cylinder. Gasoline is the fuel generally used by this type of engine.

3.4 Vibration

Oscillation of a body about a reference position or state of equilibrium is known as vibration. The number of waves of this oscillation over a period of one second is defined as the frequency and the maximum displacement is called the amplitude of the vibration. Vibration of a system is said to be forced if it is caused by some mechanical excitation. In the case of engine vibration the source is from both the internal combustion and the mechanical motion. The frequency content of the vibration is directly related to the mechanical workings and the rotational speed and loading of the engine.

Analytical analysis of the vibration response of an engine is quite complicated and can be theoretically realized by computer modeling software. The complex system can be broken down into a sum of spring-mass-damper models. Consequently the fundamentals of vibration can be understood through a study of the simple spring-mass-damper model.

The vibration system entails the transfer back and forth of potential energy to kinetic energy and visa versa. Potential energy is represented by the spring; a device which stores mechanical energy. Next the kinetic energy is encompassed by the mass which gains or loses energy in relation to its change in velocity. The final piece is the damper which dissipates the energy of the system [29].

In this brief overview some of the fundamentals of vibration will be described along with the basics of a single-degree of freedom system with damped forced vibration.

3.4.2 Classification of Vibration

Vibration can be classified in many different ways. In this section the cause and limiting factor of vibration will be explained.

3.4.2.1 Free and Forced Vibration

Free vibration refers to the resulting vibration from an initial event. The motion of the system after the initialization incident is maintained only by the internal transfer of forces within the system. Alternatively forced vibration occurs when an external force is applied to the system. Often this exciting force is periodic in nature and the resulting vibration of the system is equivalent to the forcing frequency.

3.4.2.2 Undamped and Damped Vibration

A system where the resultant energy from the initial conditions is conserved is known as undamped vibration. The energy of the system is continuously exchanged between potential and kinetic energy and the vibration will continue indefinitely. This is an idealized case because almost all systems are actually damped to some degree.

When a vibration system loses energy due to friction or some other type of resistance it is described as damped. The amount of damping is relative to the time it takes for the motion to stop or the energy of the system to be dissipated. A system's damping may be large enough to prevent the initial vibration from occurring or it may be small and oscillation of the system will continue for a period of time.

The amount of damping is described by the damping ratio (ζ). In a spring-mass-damper system it is characterized by

$$\zeta = \frac{c}{2m\omega_n} \tag{3.4}$$

Where: c = damping coefficient
m = mass
ω_n = undamped natural frequency

This ratio defines the type of system damping; if it is greater than one it is over-damped, equal to 1 it is critically damped, and less than one it is under-damped. In an over-damped system there is no oscillation of the system and it has a slow aperiodic decay as it returns to the equilibrium point but an under-damped system has oscillations that diminish over time. The critically-damped system is the borderline point between these two cases.

Damping can be caused by different types of friction such as: dry friction, fluid friction, and internal friction. A special case of fluid friction where the frictional force is directly proportional to the speed of the moving body is called viscous damping [30]. This type is the most commonly used damping mechanism and will be used in the spring-mass-damper system described in the following section.

3.4.3 Forced Vibration System

The vibrations that arise from an internal combustion engine are classified as forced vibration. Combustion in the engine and the ensuing mechanical impacts are the excitation force of the vibration. Depicted in Figure 3.7 is a basic spring-mass-damper model with a single degree of freedom. An overview of the governing equations will be presented.

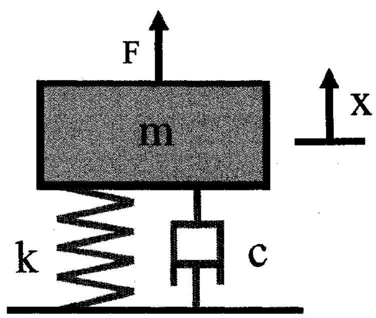


Figure 3.7: Spring-Mass-Damper System [2]

A system with a mass of weight *m*, a damping coefficient *c*, and a stiffness of *k* is subjected to a periodic force *F(t)* with magnitude F_o and its governing equation of motion is

$$m\ddot{x} + c\dot{x} + kx = F_O \cos(\omega t) = F(t) \tag{3.5}$$

Where: x = linear displacement with respect to time
$\dot{x}$ = linear velocity with respect to time
$\ddot{x}$ = linear acceleration with respect to time
ω = radian frequency

The motion of the mass like the forcing function is also harmonic and is described as

$$x(t) = X\cos(\omega t - \phi) \tag{3.6}$$

Where X is the amplitude and ϕ represents the phase angle of the vibration response. Substituting Eq. (3.6) into Eq. (3.5) we arrive at

$$-Xm\cos(\omega t - \phi) - c\sin(\omega t - \phi) + k\cos(\omega t - \phi) = F_O\cos(\omega t) \tag{3.7}$$

Using trigonometric relations and manipulating the above equation the solution gives

$$X = \frac{F_O}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}} \tag{3.8}$$

and

$$\phi = \tan^{-1}\left(\frac{c\omega}{k - m\omega^2}\right) \tag{3.9}$$

This provides the amplitude and phase shift of the resulting vibration. Next dividing both the numerator and denominator of Eq. (3.8) by k and substituting Eq. (3.8) and Eq. (3.9) with the following

$$\omega_n = \sqrt{\frac{k}{m}}, \zeta = \frac{c}{2m\omega_n}, \delta_{st} = \frac{F_O}{k}, r = \frac{\omega}{\omega_n} \tag{3.10}$$

Where: δ_{st} = static deflection
r = frequency ratio

the subsequent equations are obtained

$$M = \frac{X}{\delta_{st}} = \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} \tag{3.11}$$

and

$$\phi = \tan^{-1}\left(\frac{2\zeta r}{1-r^2}\right) \tag{3.12}$$

Where *M* is the magnification factor, which is the ratio of the dynamic to the static motion.

Expressed in Eq. (3.9) is the phase difference between the forcing function and the steady-state response of the system. The frequency response of this system with different frequency ratios can be found in Figure 3.8. From this plot it can be noted that greater damping is required near the resonant frequency. In most systems the resonant frequency is avoided by keeping the natural frequency and the forcing frequency far apart.

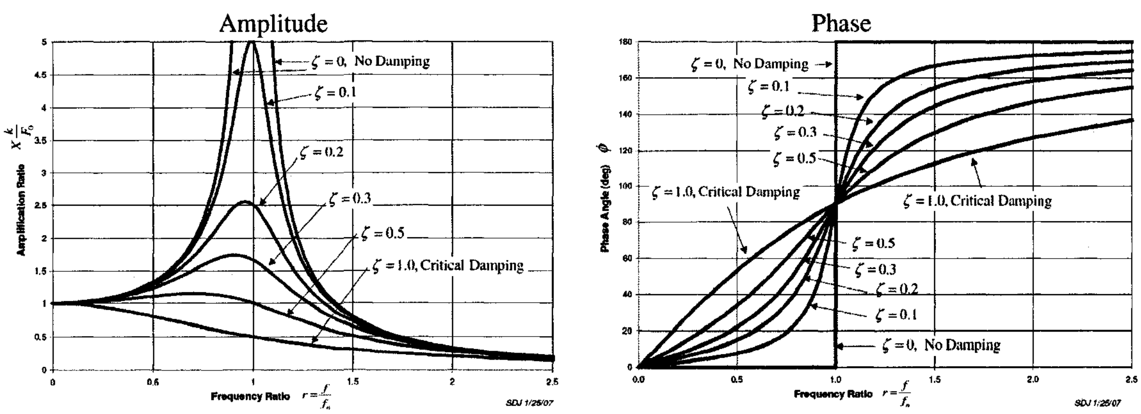


Figure 3.8: Frequency response [2]

3.5 Filters

A filter is a device which obstructs the passage of something, while allowing other portions to penetrate through. In this study it is an electronic circuit or its digital realization that remove undesired frequency components from an input signal [31].

Filters can be classified by family and passband. The family outlines the design criteria, while the passband denotes the transmitted frequencies. There are four fundamental passbands; lowpass, highpass, bandpass and bandstop. These filters are depicted in Figure 3.9. Another passband is the allpass filter which permits all frequencies to pass but modifies the phase of the output. Some common filter families are Butterworth, Chebyshev, Elliptic and Bessel. Each possesses distinct specifications in the definition of their transfer function (filtered output versus original input).

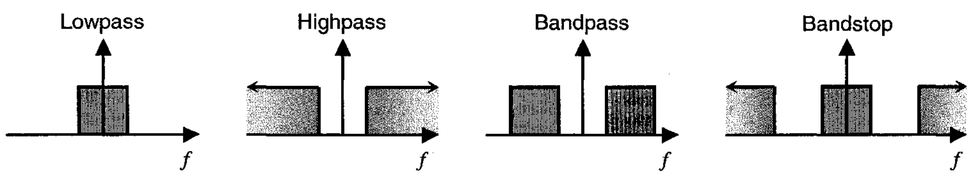


Figure 3.9: Ideal Filters

3.5.1 Lowpass and Bandpass Filters

Two filter types used in this research are lowpass and bandpass filters. A lowpass filter attenuates high frequencies, while allowing lower frequencies to pass through. Utilization of lowpass filters can be found in such applications as subwoofers which project low frequency sounds. They are also implemented in radio transmitters where harmonics are removed from the outgoing signal. A lowpass filter is called an anti-aliasing filter when it is used to remove high frequencies to prevent noise and distortion in a digital signal.

The bandpass filter only retains frequencies within a certain range; filtering out higher and lower frequencies. This filter can also be realized by combining a lowpass with a highpass filter. These filters are often used in wireless transmitters and receivers because of their limited bandwidth.

3.5.2 Ideal and Real Filters

Filters depicted in Figure 3.9 are ideal; this means that the filter has a constant gain with full transmission in the passband, complete attenuation in the stopband, and no transition band. Ultimately it is impossible to build an ideal filter but by creating a high order filter it is possible to approach the desired result. The fallout from this is that as the order rises the filter becomes more expensive and time delays can be introduced. In the digital realization the downfall is that it requires more computational time and can lead to issues such as instability.

Illustrated in Figure 3.10 is a real lowpass filter. In the design of a filter there are different types of criteria to consider; this includes the ripple in the pass and stopbands and the slope of the transition band.

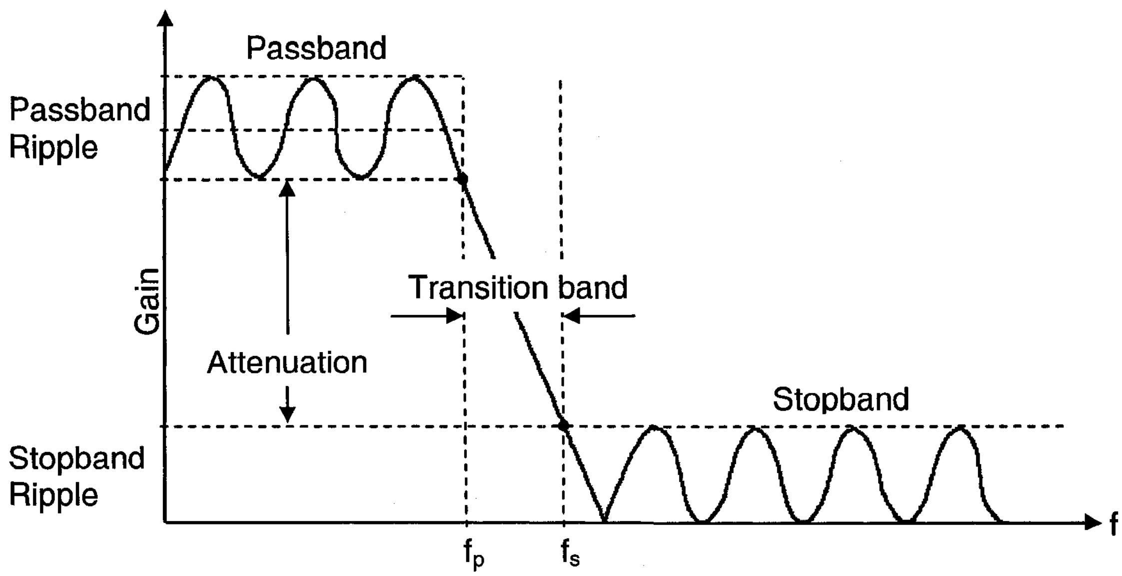


Figure 3.10: Non Ideal Lowpass Filter Characteristics

3.5.3 Butterworth Filter

A Butterworth filter also known as a maximally flat filter is one of the basic electronic filters [32, 33]. The passband of this filter has a mostly flat response with no ripples and a minimal deviation from unit gain. This filter's downfall is the slow roll-off to the stopband. The steepness of the decline to the stopband can be increased by a higher order implementation but this quickly complicates the circuit. To analyze the filter the Laplace transform is used; this tool transforms the time data into complex angular frequency data in the s-domain. Poles of the filter in the s-domain are equally spaced in the negative half plane. They are located π/n radians apart on a half circle of radius ω_c; where n is the number of poles and ω_c is the cut-off frequency of the filter. The Butterworth filter is used in this study as an anti-aliasing filter in the data acquisition system and is digitally realized in the processing of time data.

CHAPTER 4 – EXPERIMENTAL DETAILS

This chapter delineates the experimental setup, test procedures and equipment used for the acquisition of data in this research study. Data was acquired as part of ongoing testing at the Ford PERDC in the Essex Engine plant.

4.1 Test Engines

The engines surveyed in this investigation consisted of a baseline of 30 engines and 3 comparison sets of 6 engines. The baseline engines are 5.4L 3-valve Triton engines; these are production engines used in QOS studies. This engine model has been in production for over five years with more than 2.5 million engines built. Due to the scale of production a large amount of data was available for this research.

Two of the comparison groups, the 4.6L 2-valve and the 6.8L 3-valve Triton are also from QOS production engine studies. The final comparison set consists of faulted 5.4L 3-valve Triton engines. These engines were either returned from dealerships or from the assembly plant. The severity of the faults varies from severe to mild.

4.2 Test Conditions

Engines were warmed up to normal in-vehicle operating conditions and were idled in neutral; a no load condition. This idle speed was generally 600 rpm but varied between engine families with speeds up to 700 rpm. The engine oil temperature was controlled by the cooling water to approximately 180 °C and the test cell temperature was also regulated to 20 °C. Data from the constant-rpm idle conditions was collected in three measurement runs on each engine.

4.3 Dynamometer and Test Cell

The engines were setup on a dynamometer test stand using the same transmission and mounting brackets that are used in the vehicle. This setup allowed for a close representation of the function of the engine without requiring the whole vehicle to be tested. Reproduction of in-vehicle conditions and repeatability between tests was further aided by the controlled environment of the test cell.

An alternating current dynamometer was used to provide speed and load on the engine. In this test the dynamometer was not engaged in the neutral idle condition hence other than its relation to the controls of the cell its effect was negligible.

4.3.1 Test Chamber

Experiments were performed in a semi-anechoic chamber. This type of environment allowed for a reduction of noise and vibration from external sources and minimization of reverberation. A T-slotted bed plate was used to securely mount the engine test stand. The bed plate was attached and levelled to a foundation isolated from the rest of the building structure. This provided rigidity and minimized the infiltration of external vibration to the test setup.

4.3.2 Dynamometer, Test Cell and Engine Controls

The dynamometer was linked to a controls desk where a Hewlett Packard UNIX work station was running Automated Data Acquisition and Control System (ADACS) software. This computer system was also connected to the engine via a VXI chassis. Together the arrangement controlled and monitored the test cell equipment and enabled automated and manual testing for powertrain development and examination. A second system running ATI Vision controled the powertrain calibration and modified variables of the ECU (electronic control unit). This communication utilized a CAN network to interface with the ECU.

4.4 Sensors

In this experiment only two types of sensors were used in the acquisition of the engine data. A collection of eight accelerometers were installed at various locations about the engine for vibration measurement. Also the built in CID sensor from the engine was utilized to synchronize the vibration data to the engine cycle.

4.4.1 Accelerometer Locations

Accelerometer locations were selected to give the best overall view of the vibration signature of the engine. Consideration was given to the transmission path of vibration from the valvetrain assembly, piston assembly, and cylinder head and bore along with the ease of setup. The positions selected are as follows: front and rear cylinder head tabs and block lugs on both left and right sides of the engines. In the figure below the transducer locations can be seen.

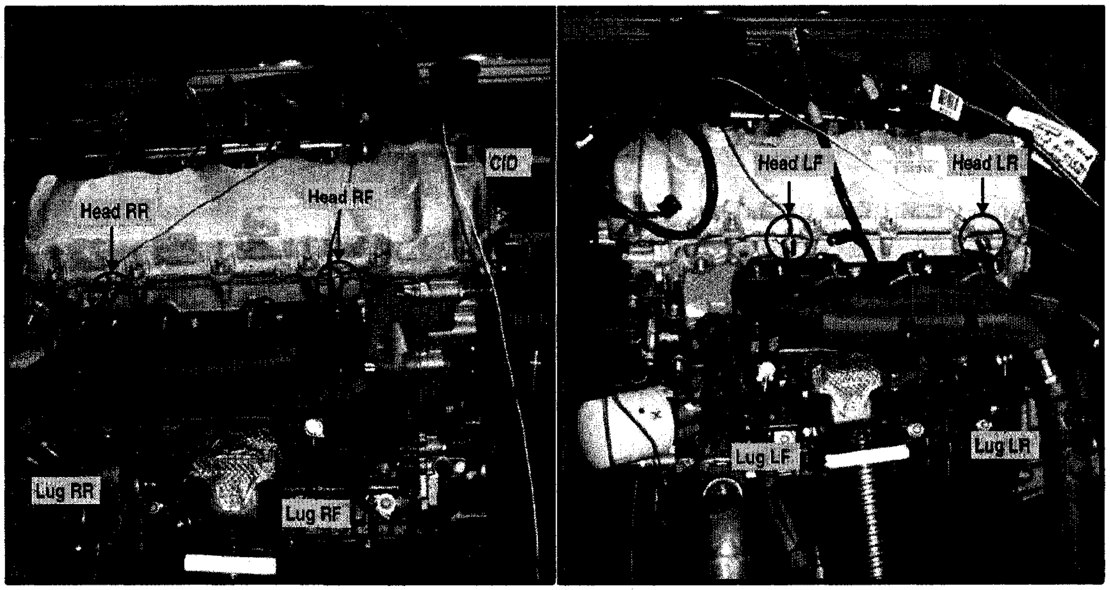


Figure 4.1: Accelerometer Mounting Locations

The mounting surfaces on the engine were smoothed where necessary using fine grit sand paper and were cleaned with LPS Electric Contact Cleaner before being instrumented. This was done to ensure the uni-directionality and repeatability of measurements.

Two different mounting methods were used on the accelerometers; adhesive and magnetic. These methods were chosen to balance ease of installation and removal, damage to the engine, and loss of frequency range.

Transducers were affixed to the engine using the adhesive method on all of the head tabs and non-ferrous block lugs. A cylindrical brass base (9mm in diameter and 5 mm thick) fitted with a set screw was adhered to the engine lugs using Loctite 404 Quick Set Instant Adhesive. Finally, the accelerometers were threaded onto the bases and hand tightened.

The magnetic mounting method was used only on the blocks that were fabricated of cast iron. This is a fast and easy method of mounting but also slightly diminishes the dynamic range of the accelerometer due to the force of the magnet.

Surfaces of the installation sites were flat and smooth so as to not affect the frequency response. In both mounting methods the bases of the sensors have such a nominal mass in comparison to the overall engine that the loss in frequency range is considered to be negligible. Also, the rate of acceleration in this type of testing is low; with high rates of acceleration these mounting methods would suffer from a diminished frequency range.

4.4.2 Cylinder Indicator

The output signal of the CID sensor was obtained to allow for subsequent angle domain analysis. Connected to the camshaft this sensor was used to identify when cylinder one was approaching top dead centre (TDC) of the power stroke. Acquisition of this signal was also useful in the monitoring of engine speed. The output of this signal was either a sinusoidal type wave or a square wave dependant on the engine family being tested.

In most engines the CID sensor is located on the front of the cylinder head as can be seen in Figure 4.1. The 3-valve engines contain two CID sensors; in this experiment the signal was collected only from the sensor on the odd/right bank of the engine. The other engines in this study have only a single sensor. Output from the CID was acquired by splitting the signal between the engine wiring harness and the data acquisition system.

4.5 Data Acquisition System

Analog signals originating from the accelerometers on the engine and the CID sensor were converted to a digital signal by the Prosig 5600 data acquisition unit. The digital output of the system was connected to a laptop where the incoming data was monitored and stored upon acquisition.

This data acquisition unit features 16 input channels with the ability to expand to 64 channels. It has an input range of ±10V, a sampling rate of up to 100 kHz per channel, and 16-bit ADC resolution. A Windows based laptop computer was used for controlling the setup and acquisition of the data and communicated with the acquisition unit through the parallel port connection. Further specifications of this system can be found in Appendix A. This system was chosen for its portability, ease of setup, minimal processing time and other previously discussed system attributes. A complete test setup including the acquisition system can be seen in Figure 4.2.

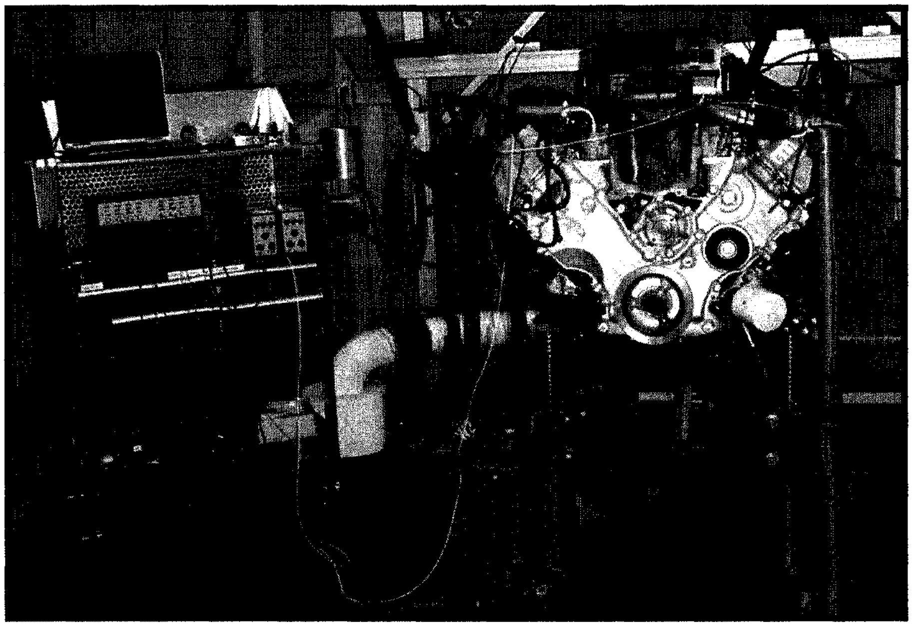


Figure 4.2: Engine Test Setup

4.6 Instrumentation

The engine vibration data for this study was collected using accelerometers and their accessories. In the following section an overview of each component will be discussed. Specifications for this equipment can be found in Appendix A.

4.6.1 Brüel & Kjær Type 4366 Charge Accelerometer

This is a piezoelectric, charge mode, DeltaShear accelerometer. A charge amplifier is required to extract the output signal from the transducer. It is relatively insensitive to temperature, highly receptive, and very durable. Due to a high impedance output it requires the use of low noise cables. The DeltaShear is comprised of three piezoelectric elements in the formation of a triangle which are surrounded by three masses. This arrangement is held together by a clamping ring. The masses convey the incoming vibration from the base through to the piezoelectric elements outputting a high impedance electric charge proportional to the input force. This type of accelerometer was used because of its ability to withstand the high temperatures near the exhaust manifold.

4.6.2 Brüel & Kjær Type 5974 8-Channel Charge Amplifier

The piezoelectric charge mode accelerometers feed their signal into the charge amplifier. Subsequently the charge amplifier converts the charge from the transducer to an output voltage. The system works as an inverting amplifier with the use of a high gain operational amplifier. This low noise amplifier has individual settings for transducer sensitivity and has a wide frequency range. In this study the low-pass filter was turned off, the high-pass filter set to 0.3, and the input sensitivity adjusted to10 $pC/m/s^2$.

4.6.3 Brüel & Kjær Type 2635 Charge Amplifier

This charge amplifier was used in the same manner as the type 5974. It is intended for use in vibration measurement with piezoelectric accelerometers. As an extra system it was only used if additional input channels were required and it also served as a backup when channels failed on the type 5974 charge amplifier.

4.6.4 Brüel & Kjær Type 4294 Calibration Exciter

In the verification of accelerometers this instrument provided a reference vibration level. A controlled oscillation of 159.15 Hz at 10 m/s^2 was supplied by this compact battery operated vibration source. Each accelerometer was threaded onto the calibrator with a 10-32 UNF stud and a quick check of the output function in comparison to the calibration was performed.

4.6.5 Cable Assemblies

The cables used with the accelerometers were low-noise 10-32 coaxial cables. Standard BNC cables were used to connect the charge amplifier and the CID to the data acquisition system. Cable lengths were minimized with the accelerometer and CID cables being 10 ft in length and the remaining BNC cables having a length of 3 ft. This minimization was employed to diminish and when possible eliminate effects on the frequency response and the introduction of noise and distortion into the signal.

CHAPTER 5 – DATA ANALYSIS METHODS

After the engine vibration data is collected it must subsequently be analyzed. In this study the focus is on the variability between engines. A multitude of techniques are available to aid in the investigation of variability. The domain of the analysis and the mode of transformation between domains is another factor for consideration. With engine vibration data it is quite common to transform the acquired time domain data into the angle or frequency domain. This chapter describes the mathematical computation methods used in this research.

5.1 Descriptive Statistics

Descriptive statistics refers to the basic statistical procedures used to summarize and simplify data [2]. In general, these measures are used in the presentation of data through graphs, figures and tables. Mathematical implementations of these methods are included as part of the calculation of other measurement techniques.

5.1.1 Mean

The arithmetic mean or standard average is a common statistical analysis tool which is used through out this study. A mathematical average of a set of data is known as the mean. It is found by summing all the numbers in a set and dividing by the size of the array (*n*).

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{n}(x_i + \cdots + x_n) \qquad (5.1)$$

In the indication of central tendency this is the most common method used. This approach is not to be used if the data has skewed or uneven distribution or if it contains outliers; since these can lead to false interpretation of results.

5.1.2 Standard Deviation

A statistical measure of dispersion or variation of a data set from its mean is measured by the standard deviation. It is derived by taking the square root of the variance; where the variance measures the average squared difference between the mean and the data point. The calculation of standard deviation (σ) is as follows

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5.2}$$

The standard deviation is a measure of the scatter of values in a data set and its units are the same as the mean and that of the data set. A large value indicates that data points are fairly removed from the mean whereas a small standard deviation denotes that the data points are clustered together. In this study the standard deviation was used to measure the variation of the modeling results.

5.1.3 Coefficient of Variation

From the coefficient of variation a measure of repeatability of a sample can be attained. This measure of dispersion is the ratio of the standard deviation to mean of the sample set.

$$c_v = \frac{\sigma}{\bar{x}} \tag{5.3}$$

In this study it was used to measure the degree of variation between processing methods.

5.2 Least Squares

The least squares method is a mathematical optimization technique used to obtain the best estimates of unknown coefficients. Through the minimization of the sum of the square residuals this linear regression procedure determines the estimated value of the coefficients. The calculated residual or error ε_i is the difference between the observed value and the value predicted by the model.

$$\varepsilon_i = \hat{Y}_i - Y_i \tag{5.4}$$

Minimization of the sum of the squared deviations between the data and the model estimates is found through the evaluation of the following equation.

$$F = \min \sum_{i=1}^{n} (\hat{Y}_i - Y_i)^2 \tag{5.5}$$

Regression of the system is used to evaluate the relationship between multiple variables to produce a single equation. The least-squared analysis is considered to be a linear regression method because it is a linear function of its parameters. A linear model is defined by a series of equations which are simultaneously solved to estimate the best fitted coefficients as in the following matrix equation.

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} 1 & x_{21} & x_{31} & \cdots & x_{p1} \\ 1 & x_{22} & x_{32} & \cdots & x_{p2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{2n} & x_{3n} & \cdots & x_{pn} \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \tag{5.6}$$

One of the most commonly used regression methods for solving overdetermined equations is the least squares method. The results of this method are considered to be a maximum-likelihood estimate of the coefficients. It is often used in curve fitting for interpolation, extrapolation, and smoothing of data.

5.3 Detrend

The dc-offset of the system is the offset of the signal from zero and is generally undesirable. To reduce a steady-state time series to a zero-mean the series average is subtracted from each sample. In other words the constant offset or linear trend is removed, which results in a time-series centered about zero. The formal equation for this detrending technique is

$$y_{\text{det}}[n] = y[n] - \bar{y} \tag{5.7}$$

This technique also removes discrepancies in the frequency domain, most prominently the asymmetry at 0 Hz.

5.4 Variability Analysis

Variability analysis is a tool used to measure statistical dispersion or correlation. In this study it was used to find how similar the vibration signature was from engine to engine. The analysis of variability in this study began with finding the average value for each coefficient or analysis point. This is done as follows

$$c_0 = \frac{1}{E}\sum_{q=1}^{E} a_0^q \tag{5.8}$$

With E being the number of engines utilized in the study. Summing the analysis points from each set of engine data and dividing by the number of engines determines the average value c_0. The number of coefficients is dependant on the method being utilized with some methods comparing each data point, while others simply compare calculated coefficients. A matrix multiplication is used as a straightforward method to find the average values as in the following equation.

$$\begin{bmatrix} a_0^1 & a_0^2 & \cdots & a_0^E \\ a_1^1 & a_1^2 & \cdots & a_1^E \\ \vdots & \vdots & \vdots & \vdots \\ a_N^1 & a_N^2 & \cdots & a_N^E \end{bmatrix} \begin{bmatrix} \frac{1}{E} \\ \frac{1}{E} \\ \vdots \\ \frac{1}{E} \end{bmatrix} = \begin{bmatrix} c_0 & c_1 & \cdots & c_N \end{bmatrix} \tag{5.9}$$

The difference between the average value and the analysis point is the subsequent area of scrutiny. A radius or Euclidean distance is calculated for each as

$$r^1 = \sqrt{(\mathrm{a}_0^1 - c_0)^2 + (\mathrm{a}_1^1 - c_1)^2 + \cdots + (\mathrm{a}_\mathrm{N}^1 - c_N)^2} \tag{5.10}$$

This radius gives the shortest distance in Euclidean space, $\Re^n$ with the dimension of the space defined by the number of analysis points, *N*.

The above calculations are only good for a single accelerometer. If the entire range of 8 accelerometers is to be analyzed each of the corresponding coefficients must be grouped together.

$$\begin{bmatrix} a_{0,1}^1 & a_{0,1}^2 & \cdots & a_{0,1}^E \\ a_{1,1}^1 & a_{1,1}^2 & \cdots & a_{1,1}^E \\ \vdots & \vdots & \vdots & \vdots \\ a_{N,8}^1 & a_{N,8}^2 & \cdots & a_{N,8}^E \end{bmatrix} \begin{bmatrix} \frac{1}{E} \\ \frac{1}{E} \\ \vdots \\ \frac{1}{E} \end{bmatrix} = \begin{bmatrix} c_{0,1} & c_{1,1} & \cdots & c_{N,8} \end{bmatrix} \tag{5.11}$$

Next the radius is calculated for each:

$$r^1 = \sqrt{(\mathrm{a}_{0,1}^1 - c_{0,1})^2 + (\mathrm{a}_{1,1}^1 - c_{1,1})^2 + \cdots + (\mathrm{a}_{\mathrm{N},8}^1 - c_{N,8})^2} \tag{5.12}$$

The determined radii of each engine results in a real number; the larger the number the further the data is from the mean, while a lower number denotes greater similarity to the average.

5.5 Angle Domain

This analysis method involves transforming a time domain series into the angle domain. In this study this was easily done because the measurement was collected from a rotating machine; an SI engine. An example of the time domain vibration signal and its transform into the angle domain can be seen in Figures 5.1 and 5.2.

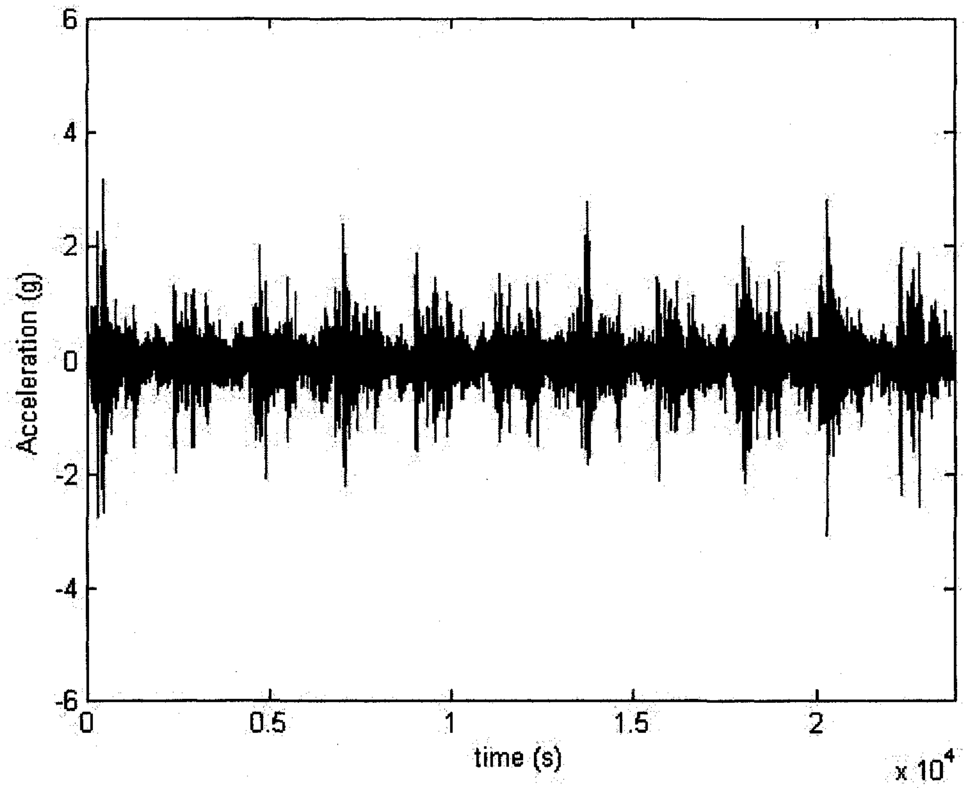


Figure 5.1: Raw Time Domain Vibration Signal

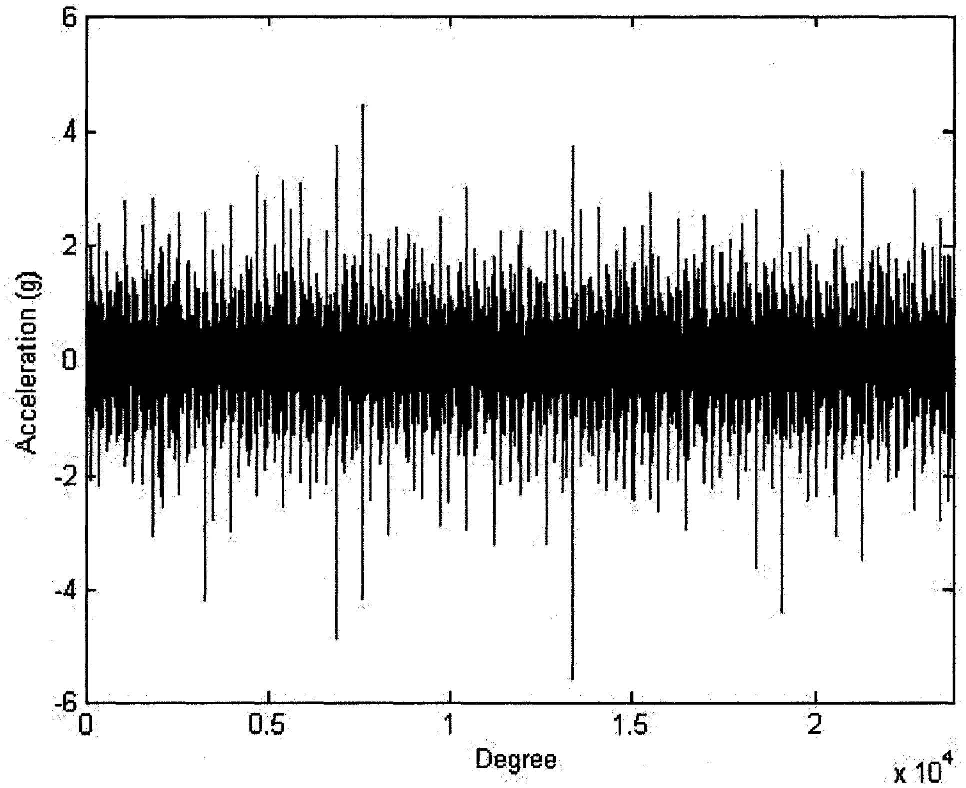


Figure 5.2: Transformed Angle Domain Vibration Signal

The vibration signal is directly related to the engine parts and hence if the speed of the engine varies the vibration signal will also vary correspondingly. At idle the engine may seem to be at a constant speed but slight variations in speed are a frequent occurrence. By tracking the CID signal the angle of the crankshaft can be discerned. Combining this information with the time data series the information is resampled into the angle domain.

5.5.1 Angle Domain Average

Finding the angle domain average or cycle average is accomplished through the determination of the mean of respective points from each cycle. Angle domain data is separated into cycles and each corresponding term is averaged. This results in a single cycle which is a general representation of the overall data series.

$$\bar{x}_p = \frac{1}{N}\sum_{k=1}^{N} x_{kp}, p = 1,2,3,\ldots S \tag{5.13}$$

Where p = Sample Index
K = Cycle Index
S = Samples per Cycle
N = Number of cycles
$\bar{x}_p$ = p_{th} average value.

An example of the angle domain average can be seen below; this single cycle series is calculated from the same data used in Figures 5.1 and 5.2.

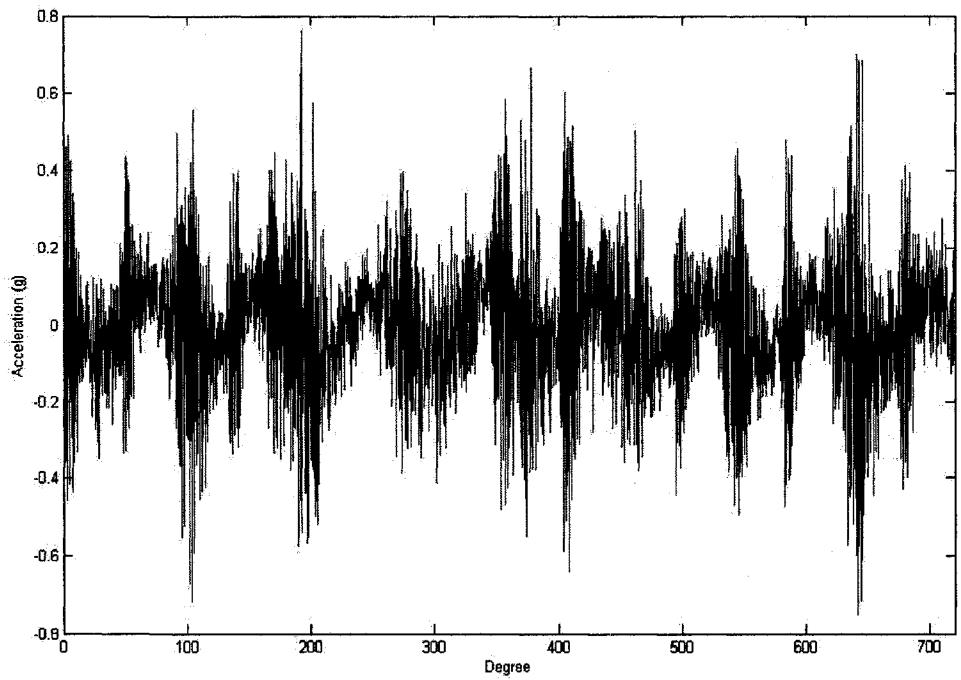


Figure 5.3: Single Cycle Angle Domain Average Vibration Signal

This method of analysis is an effective way of monitoring cyclical or periodic events. Furthermore a transient or random event and noise are generally eliminated due to the averaging over the cycles. In this study 30 cycles are averaged to produce the single cycle angle domain average vibration signal.

5.6 Frequency Domain Analysis

Time domain data can only give a limited view of vibration. The frequency domain provides a description of periodicity and frequency content of the time domain signal. Many methods are best suited to analysis in the frequency domain and the frequency characteristics key to vibration analysis can only be found in this realm. The methods used in this research's time to frequency domain transformations and the analysis techniques utilizing the frequency data are discussed in this section.

5.6.1 Fourier Analysis

Frequency domain analysis is based on Fourier methods and tools. Fourier analysis is based on the concept that every signal can be decomposed into a sum of sinusoids. This tool is widely used and its applications range throughout the scientific community. In vibration monitoring and diagnosis of rotating machinery it is an invaluable tool. An expected frequency content and amplitude of an engine can be found with deviations denoting a possible problem in the engine. Fourier analysis is used in the majority of the analysis techniques used in this study.

5.6.1.1 Fourier Series

The Fourier series is used to decompose a periodic signal into its periodic components. It is a linear combination of harmonics of the fundamental frequency f_o of the periodic signal $x_p(t)$ and its multiples kf_o. The coefficients of this series are the least squares fit to original signal. There are three key forms of the Fourier series: trigonometric, polar, and exponential.

The trigonometric form of the Fourier series is the sum of the sines and cosines at multiples of the fundamental frequency with the dc offset represented by a_o.

$$x_p(t) = a_o + \sum_{k=1}^{\infty} a_k \cos(2\pi k f_o t) + b_k \sin(2\pi k f_o t) \tag{5.14}$$

In the polar form of the series the trigonometric series combines coefficients into magnitude and phase.

$$c_k \angle \theta_k = a_k - jb_k \tag{5.15}$$

$$x_p(t) = c_o + \sum_{k=1}^{\infty} c_k \cos(2\pi k f_o t + \theta_k) \tag{5.16}$$

From this evaluation form it is apparent that the periodic signal is made up of multiple sinusoidal components each with their own amplitude, phase difference, and frequency.

Using complex conjugates of the sine and cosine pairs the exponential form of the Fourier series is found.

$$X[k] = |c_k| e^{j\theta_k} \tag{5.17}$$

$$X[-k] = |c_k| e^{-j\theta_k} \tag{5.18}$$

$$x_p(t) = \sum_{k=-\infty}^{\infty} X[k] e^{j2\pi k f_o t} \tag{5.19}$$

Fourier series coefficients can be established over a single period since each period is identical. A frequency spectrum or amplitude spectrum of *X[k]* is a series of discrete values at harmonics of the fundamental frequency. The exponential Fourier series coefficients *X[k]* are related to the periodic signal by the following expression

$$X[k] = \frac{1}{T} \int_{-T/2}^{T/2} x_p(t) e^{-j2\pi k f_o t} dt \tag{5.20}$$

These three equivalent forms of the Fourier series only describe completely periodic signals. However, the Fourier series is the building block in the relationship between the periodic and aperiodic signals.

5.6.1.2 Fourier Transform

The Fourier transform is a mathematical formula that provides a frequency domain description of a continuous time domain signal. A frequency domain transform depicts both the frequency amplitude and the phase of the time signal.

In the representation of a periodic signal evaluation limits are generally one period in length. To encompass aperiodic signals the length of the period is infinitely increased. By increasing the period the harmonic spacing approaches zero and the frequency spectrum becomes continuous. The Fourier transform is as follows

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \tag{5.21}$$

Where the inverse Fourier transform is

$$x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi ft} df \tag{5.22}$$

This transform pair describes the relationship between the frequency domain and time domain representation of any continuous-time signal.

5.6.1.3 Fourier Transform of Discrete-Time Signals

A discrete time signal arises from the sampling of a continuous signal. The sampled or discrete signal, while still related to its parent signal becomes an ordered sequence of quantities equally spaced in frequency. When transformed into the frequency domain the sampled signal becomes continuous and periodic. The transform pair of the discrete-time signal is given by

$$X_p(F) = \sum_{n=-\infty}^{\infty} x[n] e^{-2\pi nF} \tag{5.23}$$

and

$$x[n] = \int_{-1/2}^{1/2} X_p(F) e^{j2\pi nF} dF \tag{5.24}$$

A relationship between periodicity in one domain and sampling in the other is held by the Fourier series and the discrete Fourier transform. This implies that if a signal is discrete and periodic in one domain than it should also be discrete and periodic in the other domain [32].

The transformation in this case of Fourier analysis requires an infinite number of iterations to synthesize a signal if it is aperiodic. Since computers can only process information that is discrete and finite computation of this algorithm in digital signal processing is impossible.

5.6.1.4 Discrete Fourier Transform

The data in this study was of finite duration. Another kind of Fourier analysis is required to analyze this type of data which is called the discrete Fourier transform. An input signal and the resulting transform are sampled in both the time and frequency domain with an N point time domain signal transforming into an N point frequency domain signal. The DFT and its inverse are written as

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-\frac{j2\pi nk}{N}}, k = 0,1,2,...,N-1 \tag{5.25}$$

and

$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} X[k] e^{-\frac{j2\pi nk}{N}}, n = 0,1,2,...,N-1 \tag{5.26}$$

Results of the DFT give a set of N equations for each data sample or N^2 arithmetical operations. Where data has both periodic and aperiodic parts the number of samples required to encapsulate the significant values demands a prolonged duration of the captured signal. The number of samples is therefore quite substantial and the calculation of the transformation computationally intensive. For this reason algorithms have been formulated to reduce the number of multiplications.

5.6.1.5 Fast Fourier Transform

Computationally efficient algorithms to obtain the DFT are known as the fast Fourier transform. These methods use far less calculations thus reducing the computation time. The algorithm reduces the DFT into many smaller-sized DFTs. There are two types of methods: decimation in time and decimation in frequency.

The FFT was discovered more than a century ago but for practical purposes was never used. With the dawning of the age of the computer the tool required to realize the algorithm arrived. Today the FFT is one of the most common algorithms used in digital signal processing and can reduce more than a hundredfold the computation time of the DFT.

An example of the reduction of computation can be seen in the total number of multiplications: the DFT requires N^2 and the FFT entails only $0.5N\log_2 N$. From this it can be seen that with a short duration of samples the computational difference is minimal but as the number increases the FFT becomes computationally superior.

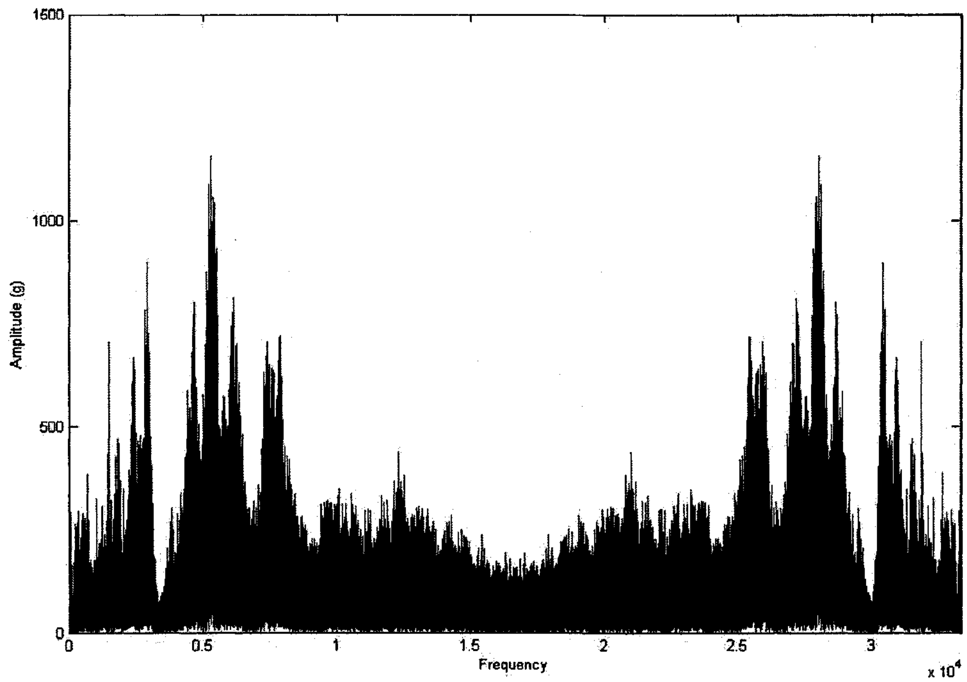


Figure 5.4: FFT of a Vibration Signal

5.6.2 Discrete Cosine Transform

The discrete cosine transform is similar to the discrete Fourier transform but uses only real numbers. A Fourier transform uses a summation of sine and cosine waves to represent a signal whereas the discrete cosine transform only uses cosine waves. The DCT transforms a finite sequence by creating a periodic and symmetric sequence from which the original data can easily be recovered.

There are multiple ways to do this hence there are multiple variations of the discrete cosine transform. Different methods of calculating the DCT are defined by the symmetry about its endpoints and half sample points. The version known as DCT-II (or just DCT) is the most common and is the one used in this study. Outlined in Eq. (5.27) is the calculation for the transform of the DCT.

$$X_{DCT-II}[k] = \sum_{n=1}^{N-1} x[n] \cos\left(\frac{\pi k}{N}\left(n+\frac{1}{2}\right)\right), k = 0,\ldots,N-1 \tag{5.27}$$

It has even symmetry about the half sample points and at k=0 and is odd when k=N-1. The resulting transform is a real and even sequence with only half the terms of its DFT counterpart. Another difference from the DFT is that the DCT's power is concentrated in its lower frequencies.

The inverse DCT is

$$x[n] = \frac{1}{N}\sum_{k=0}^{N-1} \beta[k] X_{DCT-II}[k] \cos\left(\frac{\pi k}{N}\left(n+\frac{1}{2}\right)\right), n = 0,\ldots,N-1 \tag{5.28}$$

$$\beta[k] = \begin{cases} \frac{1}{2}, & k = 0 \\ 1, & k = 1,\ldots,N-1 \end{cases} \tag{5.29}$$

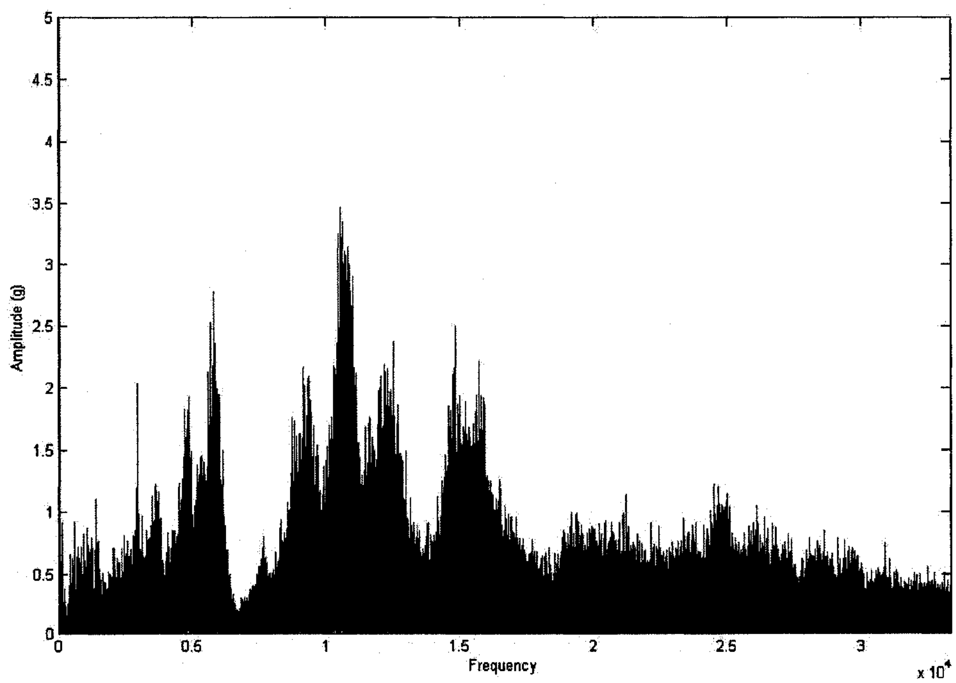


Figure 5.5: DCT of a Vibration Signal

5.6.3 Normalization

The purpose of normalization is to create a non-dimensional ratio. This allows for easy comparison of data sets by removing variability and hence allowing the characteristics of the system to be compared. The normalization of data in this study is calculated by

$$y_{norm}[n] = \frac{x[n]}{x_{\max}} \qquad (5.30)$$

In the frequency domain the normalization should be implemented because the FFT is dependant upon not only the input amplitude but also the length of the series. It was not necessary in this research to use normalization since the data sets under study were of equal length and sampling frequency.

5.6.4 Moving Average Model

A MA model is a feedforward or non-recursive model. To calculate the output of the system a weighted sum of the current and past input values is utilized. A discrete time representation of a moving average is

$$y[n] = \sum_{k=0}^{N} a_k x[n-k] \qquad (5.31)$$

The name of the model is derived from its defining equation; the output of the model is directly related to the weighted sum or moving average of the input terms. Coefficients of the MA are a_k and the order or length of the system is given by N. Model order indicates the number of concurrent input terms that are incorporated in the system.

To build the model a z-transform is implemented. The resulting transfer function of the moving average is

$$H(z) = \sum_{k=0}^{N} a_k z^{-k} = a_0 + a_1 z^{-1} + a_2 z^{-2} + \ldots + a_N z^{-N} \tag{5.32}$$

A block diagram of this system is illustrated below.

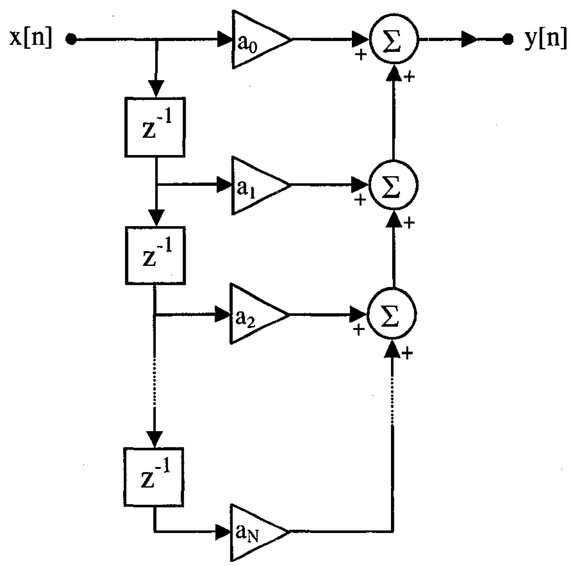


Figure 5.6: Block Diagram of the Moving Average Model

This model is quite stable because the poles are all located at the origin. Further to this the model contains only zeros and is hence defined as a finite impulse response (FIR). This means an impulse inputted into the system will result in a response of finite duration. In other words the output of the system is dependant only on the current input and a limited number of the preceding input samples.

To compare the data to the proposed model we must use a Fourier representation of the transfer function. The discrete time Fourier transform can be found by evaluating z on the unit circle.

$$z = e^{j\omega} \tag{5.33}$$

From the substitution of Eq. (5.33) into Eq. (5.32) the following transfer function is obtained

$$H(e^{j\omega}) = \sum_{k=0}^{N} a_k e^{-j\omega kT} = a_0 + a_1 e^{-j\omega T} + a_2 e^{-j\omega 2T} + \ldots + a_N e^{-j\omega NT} \tag{5.34}$$

Up to this point the MA model has been depicted as ideal, where the output of the system is accurately represented by the moving average coefficients. In this study the coefficients are optimized to produce an output that is as close as possible to the input sequence. The error or difference between the input and output is minimized through the use of the least-squares regression of the MA coefficients.

5.6.5 Autoregressive Model

An autoregressive model is a type of feedback or recursive filter which is used as a linear prediction formula. The system has a memory of its past output values along with the present value of the input. This model depicts a time series as a linear function of its past values.

$$y[n] = x[n] + \sum_{p=1}^{M} b_p y[n-p] \tag{5.35}$$

Coefficients of autoregression are b_p and the order or length of the system is denoted by *M*. The order of the model denotes how many lagged past values are included in the model. An estimation of the current term is formulated from a weighted sum of previous terms; these weights are the coefficients of the model.

To realize the model a z-transform is utilized. The resulting transfer function is:

$$H(z)=\sum_{p=0}^{M}\frac{1}{b_p z^{-p}}=\frac{1}{b_0+b_1 z^{-1}+b_2 z^{-2}+\ldots+b_M z^{-M}} \tag{5.36}$$

Where b_0=1.

The block diagram of this system is illustrated below.

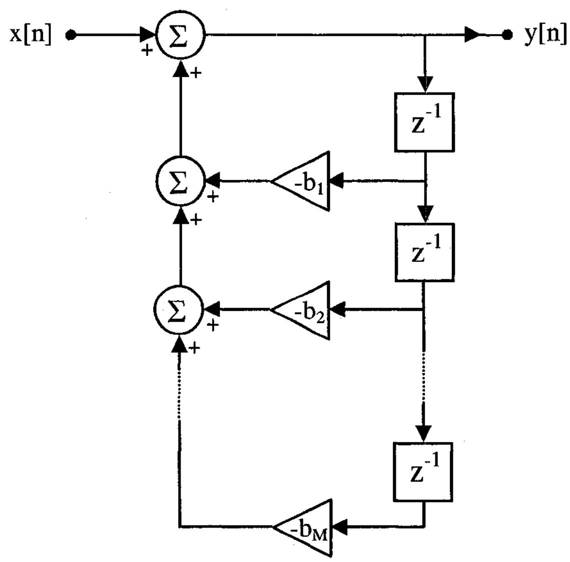


Figure 5.7: Block Diagram of the Autoregressive Model

This model has only poles and no zeros, which makes it a type of infinite impulse response filter (IIR). As a result if the incoming data consists of a single impulse the response will carry forward for an infinite duration. This portends that every sample of input data will affect all the proceeding output samples.

For analysis purposes the z-transform of the sequence is converted to the Fourier transform as follows

$$H(e^{j\omega}) = \sum_{p=0}^{M} \frac{1}{b_p e^{-j\omega pT}} = \frac{1}{b_0 + b_1 e^{-j\omega T} + b_2 e^{-j\omega 2T} + \ldots + b_M e^{-j\omega MT}} \qquad (5.37)$$

To ensure stability of the system the poles of the model are limited to the real half of the unit circle.

The equations above portray the AR Model in an idealized situation where the input is perfectly denoted by the autoregressive coefficients. These equations in most cases include an error or residual term. In finding the optimized coefficients of the model this residual term is minimized. To estimate the coefficients in this research the least-squares regression was implemented.

5.6.6 Autoregressive Moving Average Model

The autoregressive moving average (ARMA) model combines both the AR and MA models. This system amalgamates the weighted sum of the past and present input values and its own past output values to formulate the current output of the model. The time domain difference equation of the ARMA model is described by:

$$y[n] = -b_1 y[n-1] - \cdots - b_M y[n-M] + a_0 x[n] + a_1 x[n-1] + \cdots + a_N x[n-N] \qquad (5.38)$$

or

$$\sum_{p=0}^{M} b_p y[n-p] = \sum_{k=0}^{N} a_k x[n-k] \qquad (5.39)$$

Where the order of the AR part is *M* with coefficients b_p and the order of the MA part is *N* with coefficients a_k.

Again the model is transformed into the z-domain which generates the subsequent transfer function

$$H(z) = \frac{\sum_{k=0}^{N} a_k z^{-k}}{\sum_{p=0}^{M} b_p z^{-p}} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + ... + a_N z^{-N}}{b_0 + b_1 z^{-1} + b_2 z^{-2} + ... + b_M z^{-M}} \qquad (5.40)$$

The corresponding block diagram of the system is depicted in the following figure.

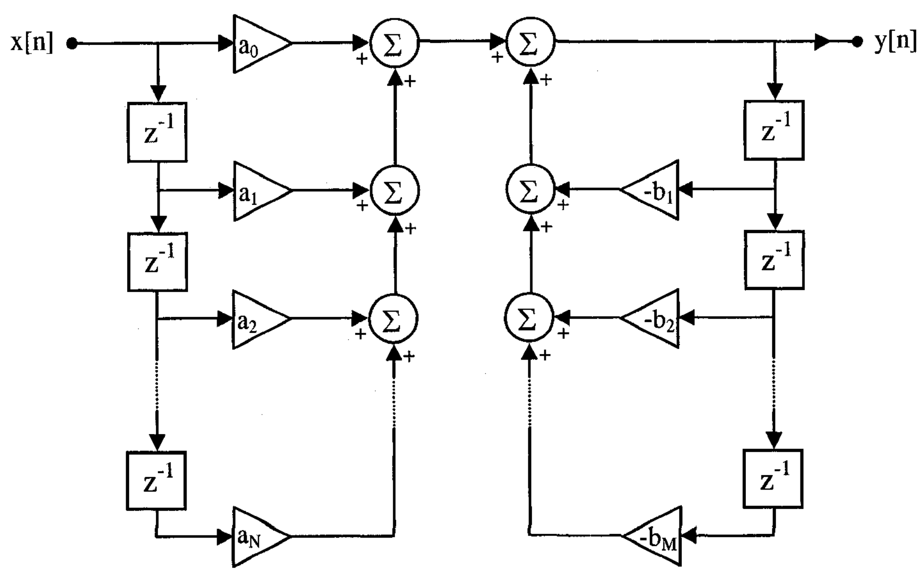


Figure 5.8: Block Diagram of an Autoregressive Moving Average Model

This model contains both recursive and non-recursive parts and is considered to be an IIR filter. There are both poles and zeros included in the system hence lagging terms from both the input data and the output data are integrated because of the amalgamation of the AR and MA models.

The Fourier transform representation of z-domain equation is required for computation of the parameters and is defined as:

$$H(e^{j\omega}) = \frac{\sum_{k=0}^{N} a_k e^{-j\omega kT}}{\sum_{p=0}^{M} b_p e^{-j\omega pT}} = \frac{a_0 + a_1 e^{-j\omega T} + a_2 e^{-j\omega 2T} + \ldots + a_N e^{-j\omega NT}}{b_0 + b_1 e^{-j\omega T} + b_2 e^{-j\omega 2T} + \ldots + b_M e^{-j\omega MT}} \qquad (5.41)$$

This model exhibits a greater versatility than both the AR and MA models alone. It requires the least number of coefficients and hence less computation and time. The same rules apply to ensure stability of the system where the poles of the model are limited to the real half of the unit circle as in the AR model. To find a best fit of the coefficients to the model the least-squares regression is again used to minimize the error term.

CHAPTER 6 – RESULTS AND DISCUSSION

Results of the data analysis are presented and discussed in this chapter. Eleven separate methods were used in the investigation of raw and filtered data. The groups of engines examined were the 30 baseline QOS 5.4L 3V engines and the three comparison groups: faulted 5.4L 3V, QOS 4.6L 2V and QOS 6.8L 3V engines. Variability in the four groups was studied along with the correlations between the comparison groups and the baseline. The findings presented in this section are only a selected portion gathered from this experiment. A complete set of results can be found in the appendices along with graphs depicting each analysis method.

6.1 Raw Data

The original data was used as part of the analysis process. Like the current Ford post-processing procedure the results of the experiment were not filtered. This meant that the data could include aliasing and vital information may perhaps be lost as was discussed in Chapter 3. Another issue was that the measurement transducer's amplitude response frequency limitations were well below that of the sampling rate. All of this considered the losses were judged to be a null point since each test was prone to the same issues.

6.2 Filter Data

The analysis methods were also carried out using filtered data from the original series. This filtration process provided results which included only the 3 to 6000 Hz range. A description of the grounds behind the selection of the range of interest can be found in Appendix G.

Two different techniques were employed in the filtering of the data. In the frequency domain analysis an elimination process was utilized whereby all but the frequency range of interest was discarded. A significantly smaller data series than the original was created from the data; these results provided a reasonable rate of compression for ease of storage. The second method of filtration was applied in the angle domain analysis methods. In the Ford Processing and Resampling Utility a built-in 6^{th} order Butterworth filter rendered the filtered data results.

6.3 Angle Domain

Transforming the time domain data into the angle domain provided a method whereby the data could be synchronized to the cycle of the engine. This approach also supplied a means of identifying outliers. In Figure 6.1 the comparison of the baseline average to a faulted engine is depicted. This visually displays how the deviations from the norm can be identified.

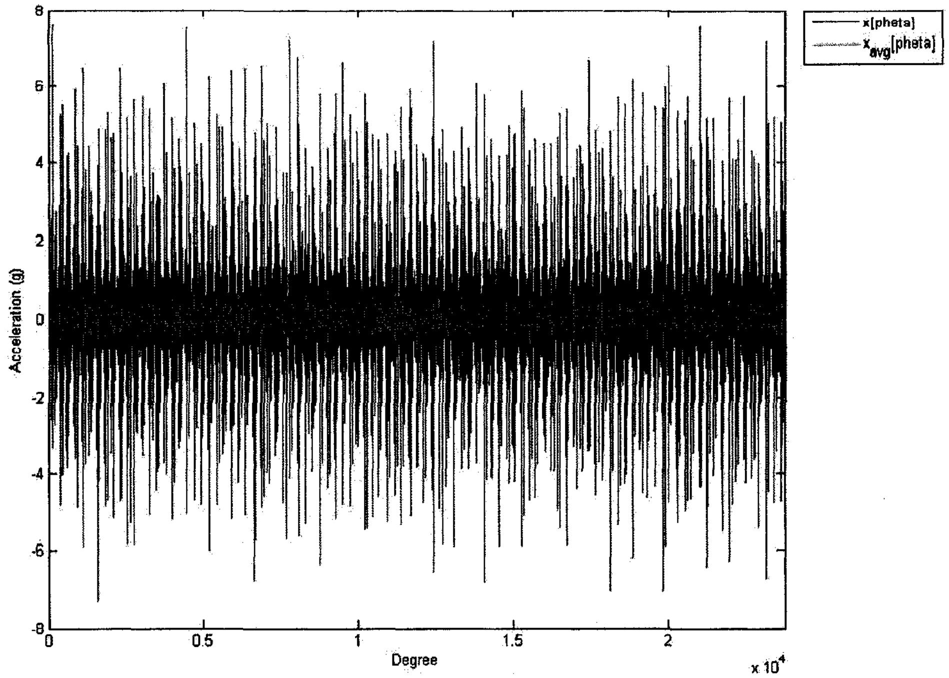


Figure 6.1: Angle Domain - Comparison of a Faulted 5.4L 3V Engine to the Baseline Average

From the computation a slight reduction in data was obtained but the decrease was considered too minimal to be useful. On the whole this method was an effective tool in the vibration analysis process but other techniques in this study provided superior results.

6.4 Cycle Average

The cycle average was used in the current 'Prosig Test' analysis procedure. Results of the cycle average provided a significant reduction in the size of the data, in most cases the data experienced at least a thirty-to-one compression ratio. Since this is an averaging process transient problems are often minimized and not apparent in the end results. A study of the variance in this case would be a viable alternative. The cycle average process was able to identify major defects but without filtering was prone to slight irregularities.

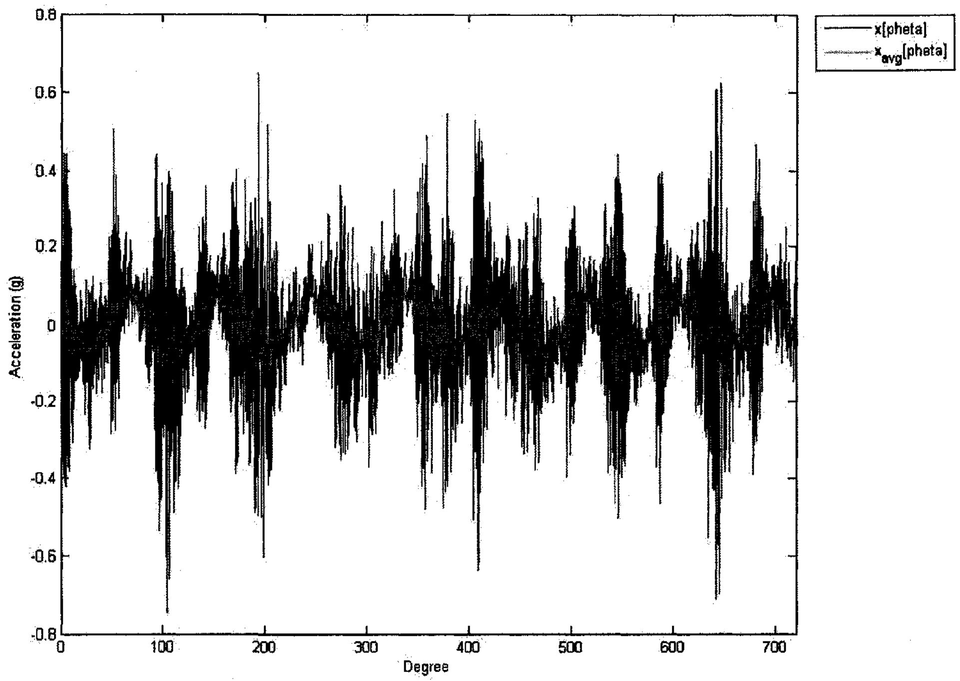


Figure 6.2: Filtered Angle Domain Cycle Average - Comparison of a Faulted 5.4L 3V Engine to the Baseline Average

From this analysis a significant reduction in data was obtained; the data was stored in this form to alleviate the extra calculation due to the time to angle domain conversion and the averaging process. The current Ford analysis process utilizes the cycle average data and the computation time from the raw data is significant enough to necessitate the extra storage of data. Overall this method was improved by the filtering process.

6.5 Fast Fourier Transform

A glimpse of the frequency content of the vibration signature was provided by the fast Fourier transform. In this study the best overall results were obtained from this technique. The trend of the frequency signature of the baseline engines was captured by way of this analysis process. From Figure 6.3 it is quite evident that the baseline average is a good representation of the frequency content of the 5.4L 3V engine. A notable deviation from this average will cause faulted or outlying engines to easily standout. The filtered version of this method does not present these qualities and can only recognize major outliers.

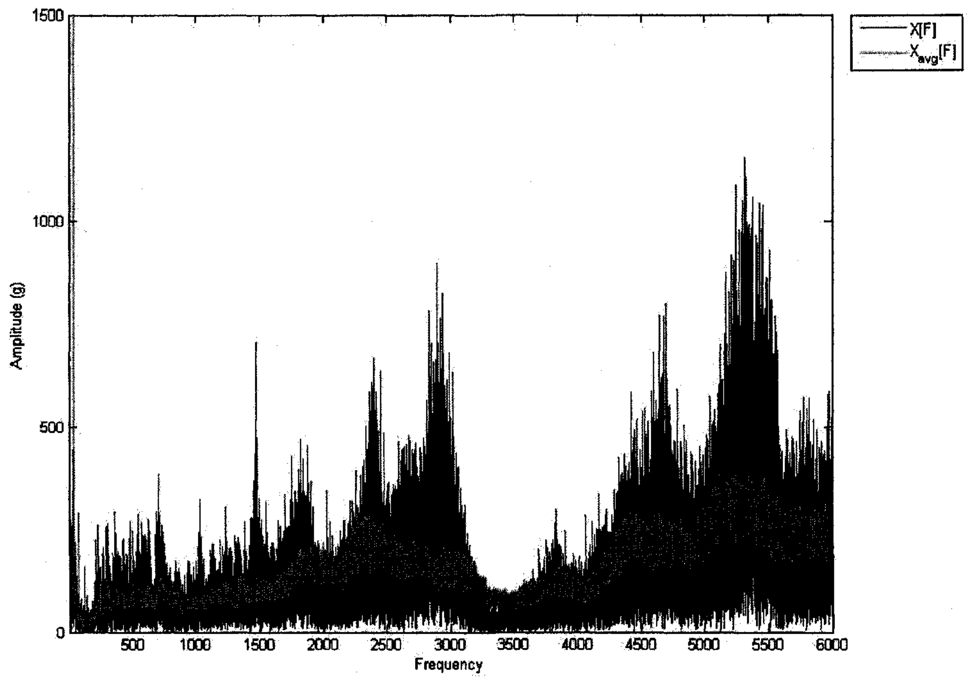


Figure 6.3: Filtered FFT - Comparison of a 5.4L 3V Engine to the Baseline Average

6.6 Discrete Cosine Transform

Findings derived from the discrete cosine transform were similar to that of the FFT. These methods are closely related hence parallel results were expected. In this study the analysis technique was only second to the FFT by a small margin. An example of the DCT of a series and its comparison to the baseline average is found in Figure 6.4.

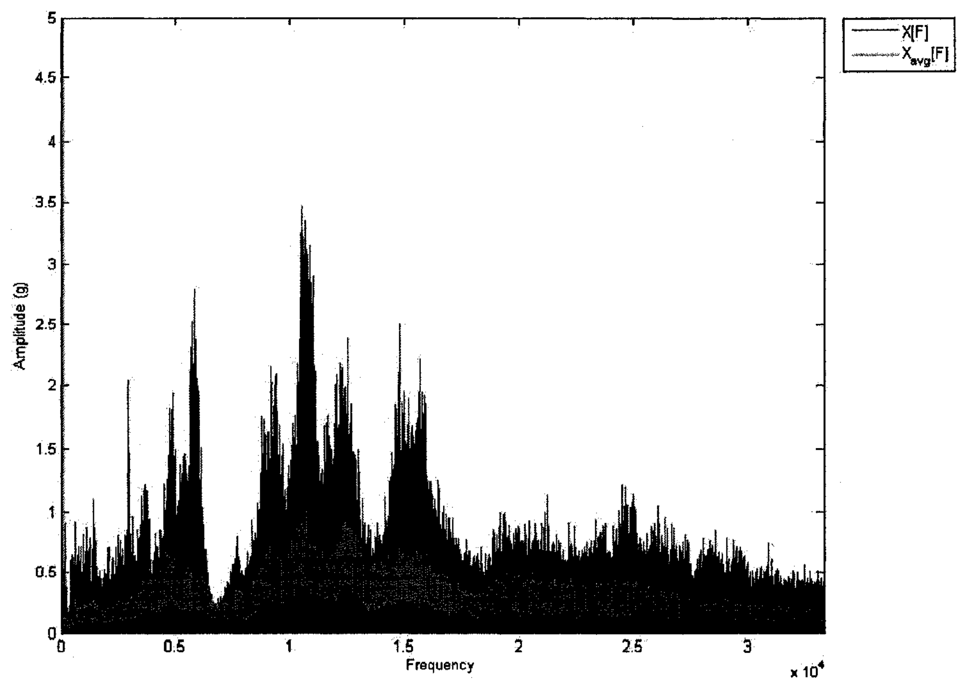


Figure 6.4: DCT - Comparison of a 5.4L 3V Engine to the Baseline Average

Drawbacks of the DCT implementation were the same as the FFT when the 3 to 6000 Hz filter is implemented. Due to the nature of the DCT the majority of the energy is concentrated at the lower frequencies. Filtering of the data using a wider filtered range could provide enhanced results.

6.7 Moving Average

The moving average model presented some of the best results for variability analysis and fault detection. This method compressed the data into 20 coefficients that represented the whole frequency signature. An example of the results can be found in Figure 6.5. The FFT of the vibration signature is overlaid with Y[F] which is the modeled output of the FFT, this is compared with $Y_{avg}[F]$ of the baseline average model. A basic outline of the FFT is depicted by the model with surprising accuracy. As the number of coefficients rises the precision of the replication will be intensified.

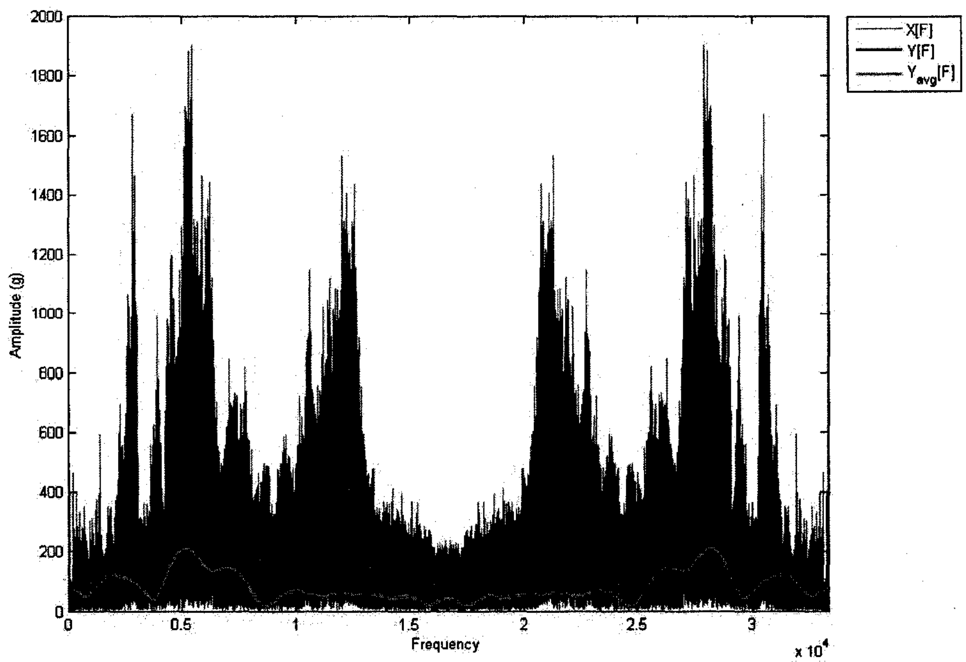


Figure 6.5: MA - Comparison of a Faulted 5.4L 3V Engine to the Baseline Average

This analysis method does not provide as accurate results as the FFT but this could be improved with a greater amount of coefficients. The downfall of this tool is the computation time involved. In comparison to the other techniques the predictive models duration of analysis was more than a hundredfold times that of the others evaluated in this study. The simple calculation of the 20 coefficients for the baseline engine took days in contrast to the minutes the other techniques required. Further details on the duration of computation time in comparison to the results can be found in Appendix F.

6.8 Autoregressive Moving Average

Results similar to that of the moving average were achieved by the auto-regressive moving average. This method was limited in accuracy due to the fact that only 10 coefficients were used; 5 from both the MA and AR portions. The deficiency was apparent when the data was plotted as seen in Figure 6.6. Here the model output Y[F] is close to the outline of the FFT but the baseline average Y_{avg}[F] does not provide any useful data other than to depict the locations of the expected peak amplitudes. The computation time of this method was also similar to that of the MA with the analysis taking place over many days.

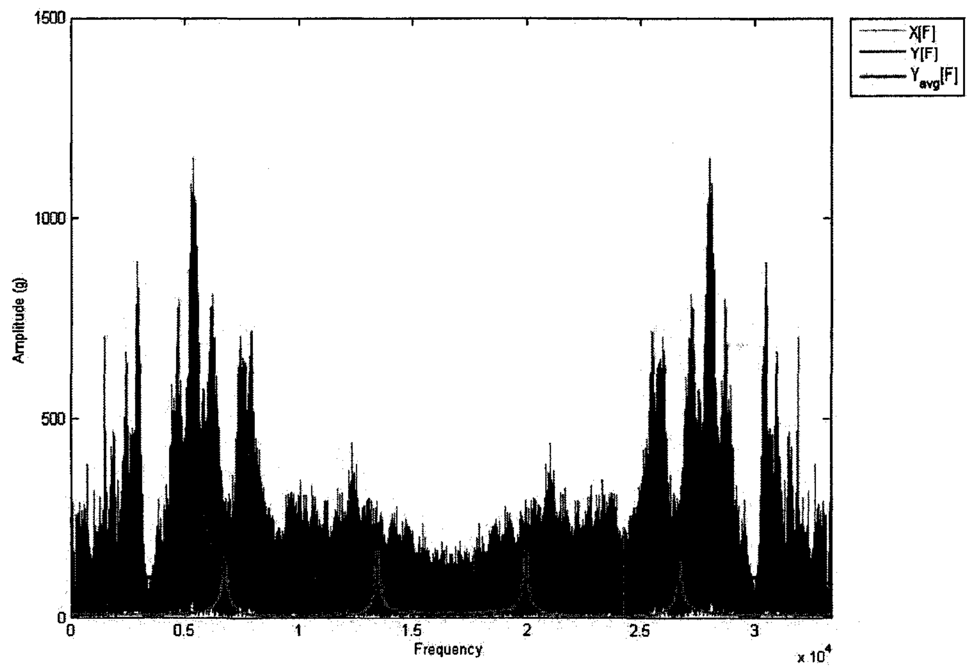


Figure 6.6: ARMA - Comparison of a 5.4L 3V Engine to the Baseline Average

6.9 Detrend

In the detrending process the dc offset was removed. The outcome of this process provided slightly improved results in the angle domain analysis of the original data although no change was found when it was used with the filtered results. In this study the data had a limited amount of dc offset but in practice it is not an uncommon occurrence. The offset can be caused by grounding problems or noise due to the equipment. At times these issues cannot be avoided and with the current Ford procedure this data cannot be used and is often discarded. By removing the dc-offset of all data more accurate results can be found with less data discarded.

6.10 Frequency Domain Normalization

The normalization procedure implemented in this project did not provide an accurate non-dimensional comparison ratio. Many of the scrutinized data series had extremely high amplitudes in the low frequency range. An example of two similar data series which contained isolated peak amplitudes that were significantly different can be seen in Figure 6.7 and 6.8. In this case the result of normalization does not provide viable comparison data. The filtered data supplied a more consistent normalization ratio but was often still determined by the lower frequency spikes. To provide a more suitable comparison of the data a different normalization method should be used.

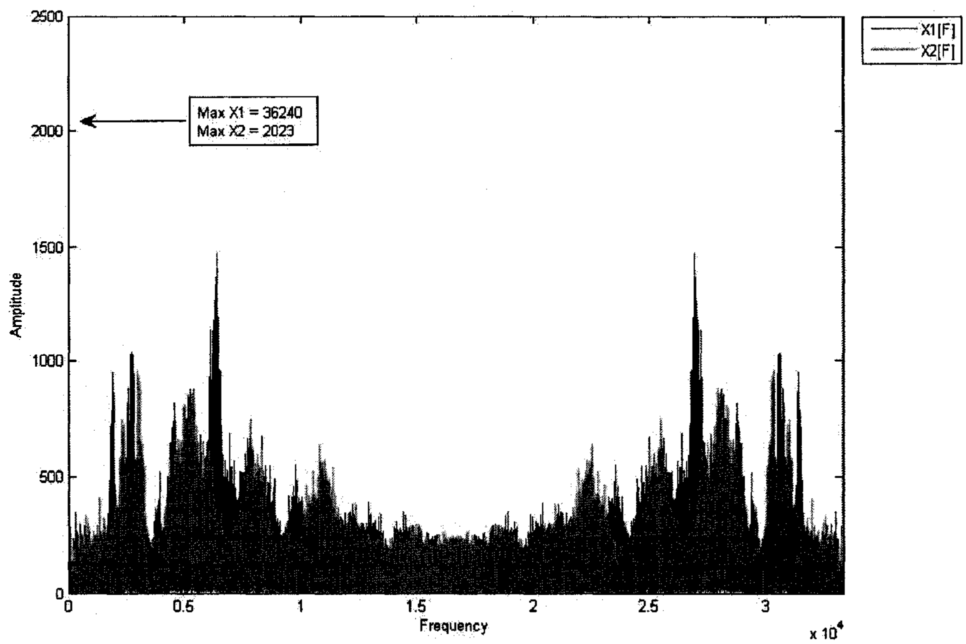


Figure 6.7: Two Similar Frequency Series with Significantly Different Maximum Amplitudes

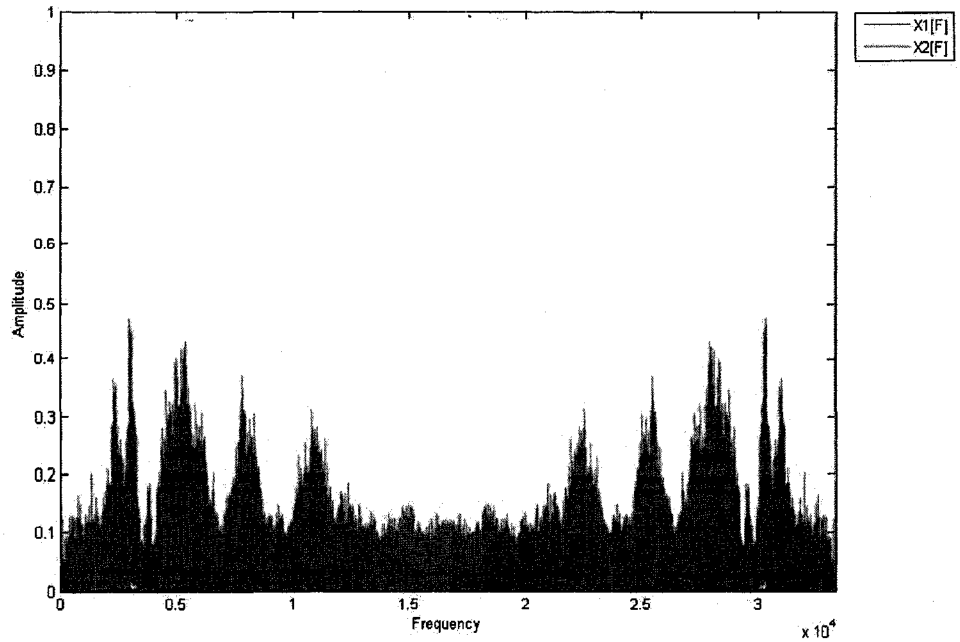


Figure 6.8: Normalization of Two Similar Frequency Series with Significantly Different Maximum Amplitudes

When looking at the maximum amplitude in the 2 to 15 kHz range it was found that even when comparing an average engine to that of the worst faulted engine the maximum amplitudes were only two-fold apart. This detail leads to a question of the necessity of normalization of this type of data.

CHAPTER 7 – CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached on the basis of the analyses performed on this study's engine idle vibration data.

1. The FFT analysis technique provided the best overall results in the analysis of variability between engines and identification of outliers. It had a coefficient of variance of 0.1 and was able to distinguish major and minor deviations from the baseline.
2. On the whole the DCT and the angle domain analysis offered adequate results in the study of variation and recognition of faults.
3. The MA and ARMA models gave an excellent representation of the data with a limited number of coefficients. This technique however was computationally too intense to provide a beneficial solution.
4. In the angle domain improved results can be obtained by detrending the data to remove the dc-offset. This process removes noise from the system and provides a more accurate representation of the vibration signature.
5. The normalization process in this study gave erratic results. Due to the similarity of frequency amplitudes this extra step was deemed unnecessary.

The following recommendations are provided for the Ford PERDC team and those wishing to further investigate the analysis techniques examined in this thesis.

1. Expanding on the Ford's current investigation process using the cycle variance with the processes used in this study could provide a viable QOS procedure.
2. Including microphones as part of the testing procedure will present a better overview since the vibration sensors are limited to their mounted locations. The microphones would supply a comparison of the audible deviations which are of vital importance.
3. Additional accelerometers on the main bearings and on each side of the cylinder head would improve analysis of the engine's internal workings.
4. Further research should be done on the MA and ARMA models. These methods have the potential to provide extremely compressed data that accurately represents the vibration signature.

REFERENCES

1. Ford Motor Company. *Powerplant Mount Vibration Test Procedure.* Corporate Engineering Test Procedure 03.00-L-451.
2. Wikipedia Contributors (2007) Wikipedia, The Free Encyclopaedia [online] Wikimedia Foundation. http://en.wikipedia.org [2007, September 17]
3. Chandroth, G., A. Sharkey, and N. Sharkey (1999) *Cylinder Pressures and Vibration in Internal Combustion Engine Condition Monitoring.* Proceedings of Comadem 1999. Sunderland, UK.
4. Gani, E. and C. Manzie (2004) *Intelligent Computing Methods for Indicated Torque Reconstruction.* Proceedings of Intelligent Sensors, Sensor Networks and Information Processing Conference, (pp. 259-264). Melbourne, Australia: Australian Research Council, Canberra, Australia.
5. Ajovalasit, M. and J. Giacomin (2003) *Analysis of Vibrations in Diesel Engine Idle Vibration.* Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineers, Volume 217, (pp 921-933). Institution of Mechanical Engineers, Westminster, London.
6. Alashe, W. and J. Bedi (1994) *Engine Idle Quality Improvement using a Fuzzy Logic Controller.* Proceedings of the 37th Midwest Symposium on Circuits and Systems. Volume 2, (pp 1511 – 1514). Institute of Electrical and Electronics Engineers, New York, New York.
7. Norton, R., R. Stene, J. Westbrook, and D. Eovaldi (1998) *Analyzing Vibrations in an IC Engine Valve Train.* SAE Paper 980570.
8. Beidl, C., A. Rust, and M. Rasser (1999) *Key Steps and Methods in the Design and Development of Low Noise Engines.* SAE Paper 1999-01-1745.
9. Gade, S., H. Herlufsen, H. Konstantin-Hansen, and N. Wismer(1995) *Order Tracking Analysis.* Denmark: Brüel & Kjær A/S.
10. Sinha, B. (2002) *Trend Prediction from Steam Turbine Responses of Vibration and Eccentricity.* Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Volume 216, (pp 97-104). Institution of Mechanical Engineers, Westminster, London.
11. Tjong, J. (1992) *Engine Dynamic Signal Monitoring and Diagnostics.* Doctorate Dissertation, University of Windsor, Windsor, Ontario.
12. Brüel & Kjær (1998) *Vibration Measurement and Analysis – Lecture Notes.* Brüel & Kjær Sound and Vibration Measurement A/S.
13. Blough, J. and G. Gwaltney (1999) *Summary and Characteristics of Rotating Machinery Digital Signal Processing Methods.* SAE Paper 1999-01-2818.
14. Idehara, S., U. Miranda, A. Mesquita, and M. Dias (2003) *Instantaneous Rotational Speed Identification Using The Directional Wigner Distribution and its Application to Order Analysis.* SAE Paper 2003-01-3732.
15. Khayam, S. (2003) *The Discrete Cosine Transform* (DCT): Theory and Application. East Lansing, Michigan: Michigan State University.

16. Tanaka, M., M. Sakawa, K. Kato, and M. Abe (1998) *Application of Wavelet Transforms to Compression of Mechanical Vibration Data.* Electronics and Communications in Japan – Part III Fundamental Electronic Science. Vol. 81, Issue 10 (pp. 16-25) Scripta Technica.
17. Mignolet, M. (1987) *ARMA Simulation of Multivariate and Multidimensional Random Processes.* Doctorate Dissertation, Rice University, Houston, Texas.
18. Ippili, R., P. Davies, and A. Bajaj (2003) *System Identification of Quasi-static Foam Behaviour and its Application in H-Point Prediction.* SAE Paper 2003-01-2207.
19. Nishizawa, S., M. Ikeda, H. Enomoto, N. Sato, J. Oyama, and T. Hamano (2001) *NC Control Point Estimator for Shape-Controlled Coil Spring.* SAE Paper 2001-01-0495.
20. Nise, N. (1995) *Control Systems Engineering* (4th Ed.). California: Addison-Wesley Publishing Company
21. Leser, C., L. Juneja, S. Thangjitham, and N. Dowling (1998) *On Mult-axial Random Fatigue Load Modeling.* SAE Paper 980696.
22. Valdero, E. (2002) *Linear Least Squares Estimation of the First Order Moving Average Parameter.* Barcelona, Spain: University of Barcelona.
23. Fox, John (2002) *An R and S-PLUS Companion to Applied Regression.* California: Sage Publications.
24. Moler, C. (2005) *Numerical Computing with MATLAB.* Philadelphia, Society for Industrial and Applied Mathematics.
25. Kasap, S.O. (1997) *Principles of Electrical Engineering Materials and Devices.* Massachusetts: McGraw Hill Companies, Inc.
26. Heywood, J.B. (1988) *Internal Combustion Engine Fundamentals.* New York: McGraw-Hill, Inc.
27. Çengel, Y.A. and M.A. Boles (1998) *Thermodynamics: An Engineering Approach.* New York: WCB/McGraw-Hill.
28. Borman, G. L. and K. W. Ragland (1998) *Combustion Engineering.* New York: WCB/McGraw-Hill.
29. Rao, S.S. (1995) *Mechanical Vibrations* (3rd Edition). Massachusetts: Addison-Wesley Publishing Company, Inc.
30. Johnston, E. and F. Beer (1990) *Vector Mechanics for Engineers – Dynamics* (2nd S.I. Metric Edition). Singapore: McGraw-Hill Book Co.
31. Roden, M.S. (1996) *Analog and Digital Communication Systems* (4th Ed.). New Jersey: Prentice Hall Inc.
32. Ambardar, A. (1999) *Analog and Digital Signal Processing* (2nd Ed.). California: Brooks/Cole Publishing Company.
33. Proakis, J.G. and D.G. Manolakis (1988) *Introduction to Digital Signal Processing.* New York: Macmillan Publishing Company.
34. Brüel & Kjær (1998) *Vibration Transducers and Signal Conditioning – Lecture Notes.* Brüel & Kjær Sound and Vibration Measurement A/S.

BIBLIOGRAPHY

1. Daws, M.C. (2002) *Assessment of the Impact of Camshaft Machining Inputs on Valve Train Sound Quality Using Vibration Analysis.* Master's Thesis, University of Windsor, Windsor, Ontario.
2. Glover, I.A. and P.M. Grant (2000) *Digital Communications.* London, England: Prentice-Hall Europe.
3. Kojovic, N (2005) *Vehicle Interior Sound and Vibration Numerical Estimation Method Based on Engine Radiated Sound and Mount Vibration.* Master's Thesis, University of Windsor, Windsor, Ontario.
4. Leitzinger, E.R. (2002) *Development of In-Process Engine Defect Detection Methods using NVH Indicators.* Master's Thesis, University of Windsor, Windsor, Ontario.
5. Oppenheim, A. V. (1999) *Discrete-Time Signal Processing* (2^{nd} Ed.). New Jersey: Prentice-Hall, Inc.
6. PCB Piezotronics Vibration Division (2003) *Product Catalog: Sensors For Acceleration, Shock, Vibration, and Acoustic Measurements*. New York: PCB Group, Inc.
7. Rowe, A. (1999) *Engine Defect Source Identification by Enhanced Signature Analysis*. Master's Thesis, University of Windsor, Windsor, Ontario.
8. Sauvé, K. (2005) *Reducing Valvetrain NVH Through the Experimentation of Vibration Dynamics in a Camshaft Phaser System.* Master's Thesis, University of Windsor, Windsor, Ontario.
9. Strang, G. (1999) *The Discrete Cosine Transform. SIAM Review*, Volume 41, No 1, (pp 135-147). Society for Industrial and Applied Mathematics, Philadelphia, Pennsylvania.

APPENDICES

A. EQUIPMENT SPECIFICATIONS

Table A.1: Specifications for the Prosig Data Acquisition System Model P5600

Prosig Model P5600		
Specifications	**Unit**	**Value**
Analog Inputs	Channels	8
Sampling Rate	kHz per Channel	Up to 100
Internal Storage Capacity	Samples per Channel	10^6
Resolution	bit	16
Overall Accuracy (at gain < 1000)		± 10%
Sensitivity (gain = 1)	μV	± 300
Sensitivity (gain = 1000)	μV	± 0.3
Input Voltage Range	V	± 10 to ± 0.00125
Input Impedance	MΩ	10
Communications		High Speed Serial
Signal Inputs		Direct Voltage and ICP
Gain		1 to 8000
Anti-Alias Filter (Butterworth low pass)	dB/octave	48
ADC	bit per Channel	16
Excitation Voltage	Vdc	Up to 10
Excitation Amperage	mA	30
ICP (4mA)	Vdc	24
Operating Temperature	°C	0 to + 40
Humidity	RH	80%
Weight	kg	3
Control (from PC)		Mouse and Keyboard

Table A.2: Specifications for the Brüel & Kjær Type 4366 Charge Accelerometer

Brüel & Kjær Type 4366 Charge Accelerometer		
Specifications	**Unit**	**Value**
Charge Sensitivity	pC/ms^{-2}	5 ± 2%
	pC/g	50 ± 2%
Voltage Sensitivity	mV/ms^{-2}	4 ± 2%
	mV/g	40 ± 2%
Mounted Resonance	kHz	16
Frequency Range – 10%	Hz	0.1-8000
Capacitance	pF	1100
Max. Transverse Sensitivity	%	<2%
Piezoelectric Material		PZ23
Construction		Delta Shear
Temperature Transient Sensitivity	$ms^{-2}/°$	0.02
Magnetic Sensitivity (50Hz to 0.03T)	ms^{-2}/tesla	1
Acoustic Sensitivity (154 dB SPL)	ms^{-2}	0.001
Minimum Leakage Resistance at 20°C	GΩ	20
Ambient Temperature Range	°C	-74 to 250
Maximum Operational Shock (Peak)	km/s^2	± 20
Maximum Continuous Sinusoidal Acceleration	kms^{-2}	20
Maximum Acceleration with Mounting Magnet	kms^{-2}	50
Weight	G	28
Case Material		Stainless

Table A.3: Specifications for the Brüel & Kjær Type 5974 8-Channel Charge Amplifier

Brüel & Kjær Type 5974 8-Channel Charge Amplifier		
Specifications	**Unit**	**Value**
Charge Input		TNC
Maximum Input	V RMS	7
Input Type		Grounded or Floating
CMRR	dB	>40
Input Sensitivity (± 0.2 dB)	pC/ ms^{-2} (30 dB gain)	0.316
	pC/ ms^{-2} (20 dB gain)	1.00
	pC/ ms^{-2} (10 dB gain)	3.16
	pC/ ms^{-2} (0 dB gain)	10.00
High-pass Filters (-1 dB)	Hz	0.3, 1, 3, or 10
Low-pass Filters (-1 dB)	kHz	1, 5, 10, or off (40)
Integrator Gain – Velocity for 0 dB	Hz	16
Integrator Gain – Displacement for 0 dB	Hz	4
Integrator Lower Limiting Frequency	Hz	1
Fixed Out Calibration	mV/ ms^{-2}	10
Output Impedance	Ω	50
Output Impedance with semi-floating output	Ω	100
Maximum Output Level	V RMS	7
Overload Level	V peak	10.5
Channel Separation at 10 kHz	dB	>80
Output Noise (0.3 Hz to 22 kHz)	μV (0 dB gain)	<10
	μV (+10 dB gain)	<30
	μV (+20 dB gain)	<60
	μV (+30 dB gain)	<170
Operating Temperature Range	°C	0 to 50
Signal Output		BNC

Table A.4 Specifications for the Brüel & Kjær Type 2635 Charge Amplifier

Brüel & Kjær **Type 2635 Charge Amplifier**		
Specifications	**Unit**	**Value**
Charge Input		TNC
Maximum Input	pC	10^5
Sensitivity Conditioning	pC/ms^{-2}	0.1 to 10.99
Amplifier Sensitivity	mV/pC	0.1 to 10000
Acceleration	mV/ ms^{-2}	0.1 to 1000
Velocity	V/ ms^{-1}	0.01 to 100
Displacement	mV/mm	0.1 to 10000
Signal Output		BNC
Maximum Output Voltage	V	8
Maximum Output Current	mA	8
Output Impedance	Ω	<1
DC Offset	mV	<±50
Frequency Range Acceleration	Hz	0.2 or 2 to 10^5
Frequency Range Velocity	Hz	1 or 10 to 10000
Frequency Range Displacement	Hz	1 or 10 to 1000
Low-Pass Filter – Switchable	kHz	0.1, 1, 3, 10, 30, and >100
Inherent Noise	pC	$5x10^{-3}$
Rise Time	V/µs	2.5
Operating Temperature Range	°C	-10 to 55

Table A.5 Specifications for the Brüel & Kjær Type 4294 Calibration Exciter

Brüel & Kjær **Type 4294 Calibration Exciter**		
Specifications	**Unit**	**Value**
Frequency	Hz	159.15 ± 0.02%
	$rads^{-1}$	1000
Acceleration (± 3%)	ms^{-2} (RMS)	10
Velocity (± 3%)	mms^{-1} (RMS)	10
Displacement (± 3%)	µm (RMS)	10
Transverse Amplitude	% of amplitude	5
Maximum Mounting Torque for Accelerometer	Nm	0.5
Signal Duration	sec	100
Maximum Load	grams	70
Mounting Thread		10-32 UNF
Temperature Range (± 3%)	°C	10 to 40
Temperature Range (± 5%)	°C	-10 to +55
Power Source (battery)	V	9
Weight	Grams	500

B. SINGLE ACCELEROMETER GRAPHS

The plots in this appendix are examples of the implementation of different analysis methods on a single accelerometer. Results are overlaid with the average baseline data from the same accelerometer location. The single accelerometer data was gathered from Engine 19 of the baseline and is compared with the baseline data that was summarized from the thirty QOS 5.4L 3V engines. Data was acquired from the right front cylinder head (Head RF) position.

In the plots of the modeled data the FFT was first plotted and was then overlaid by both the model output of the single accelerometer and the baseline average model.

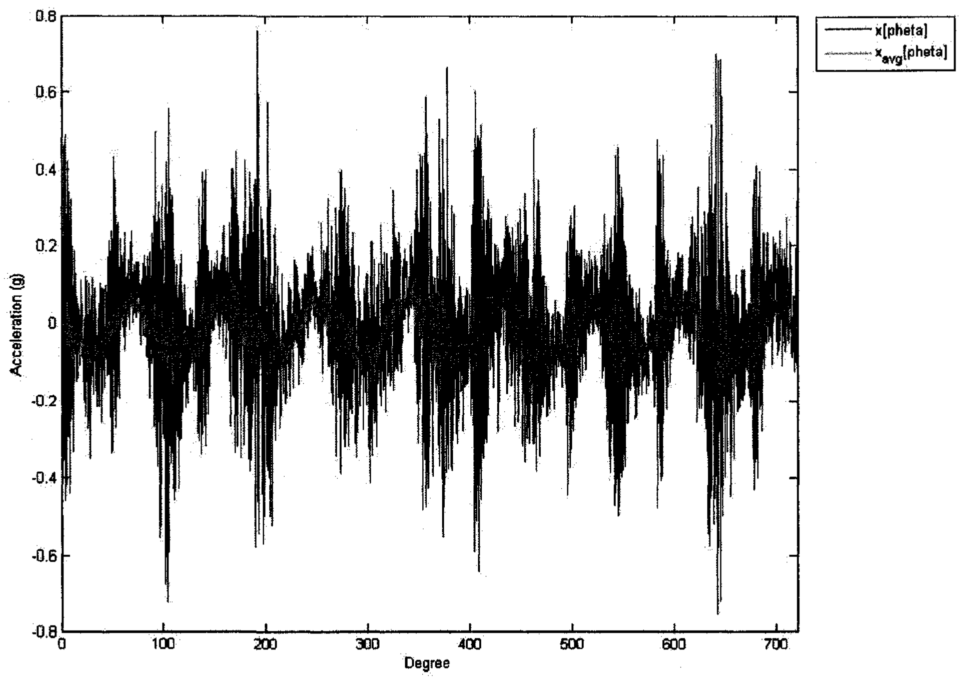


Figure B.1: Angle Domain Cycle Average - Comparison of a 5.4L 3V Engine to the Baseline Average

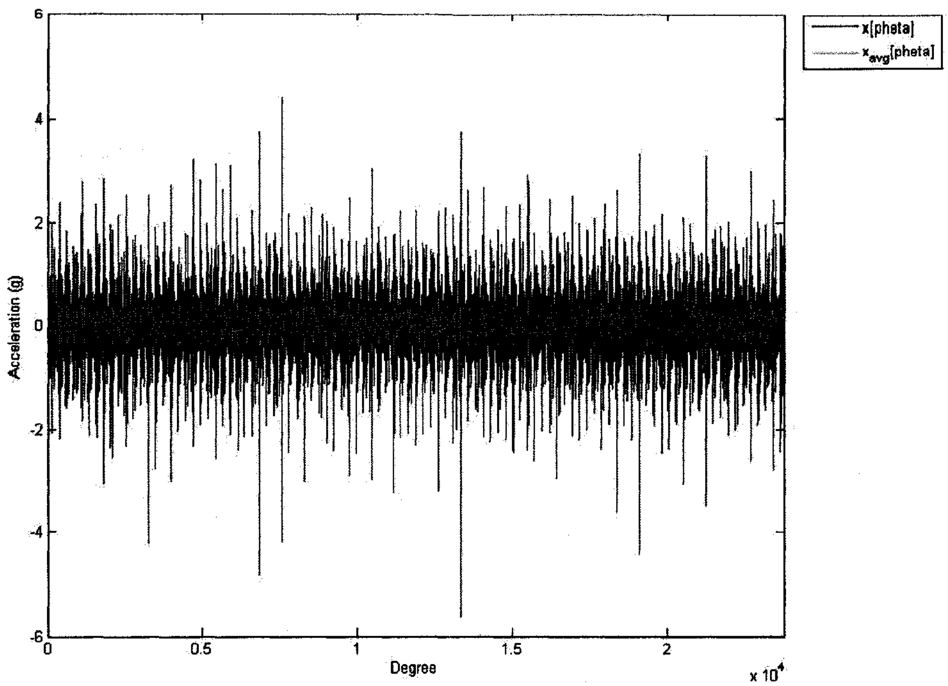


Figure B.2: Angle Domain - Comparison of a 5.4L 3V Engine to the Baseline Average

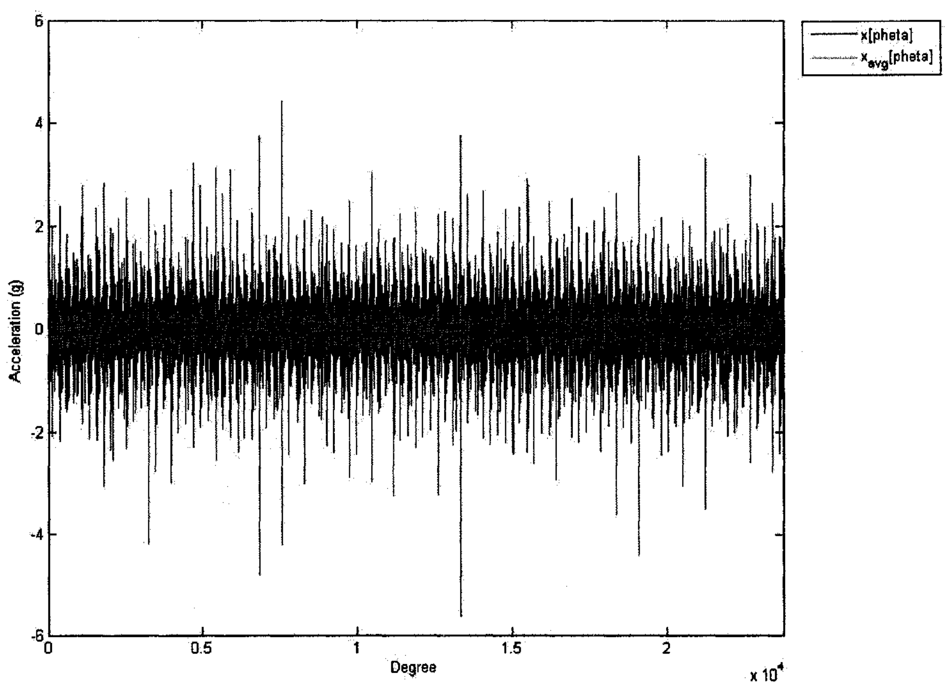


Figure B.3: Detrended Angle Domain - Comparison of a 5.4L 3V Engine to the Baseline Average

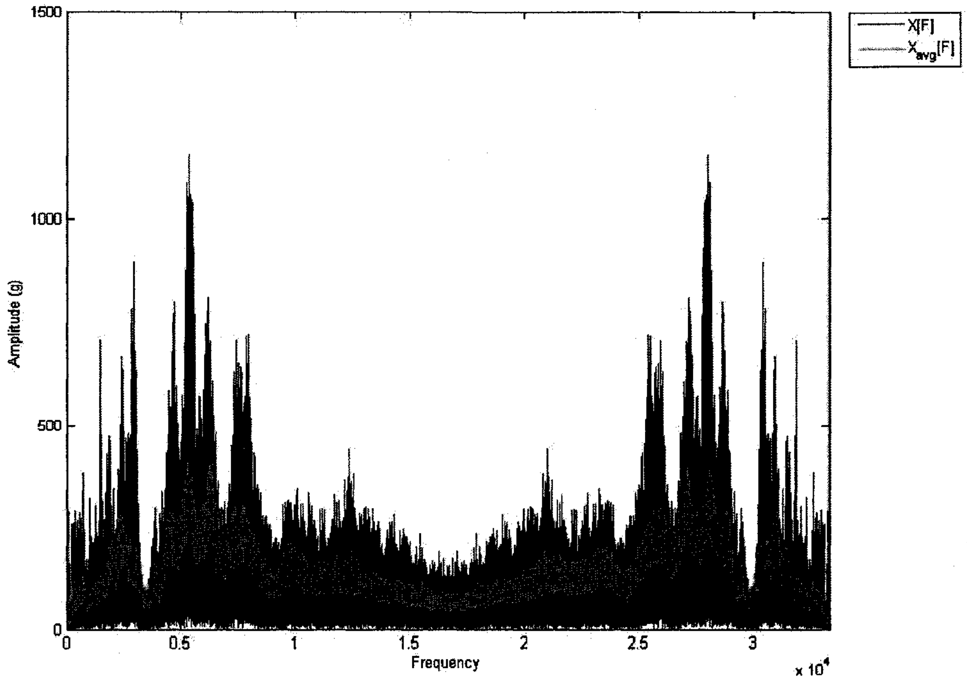


Figure B.4: FFT - Comparison of a 5.4L 3V Engine to the Baseline Average

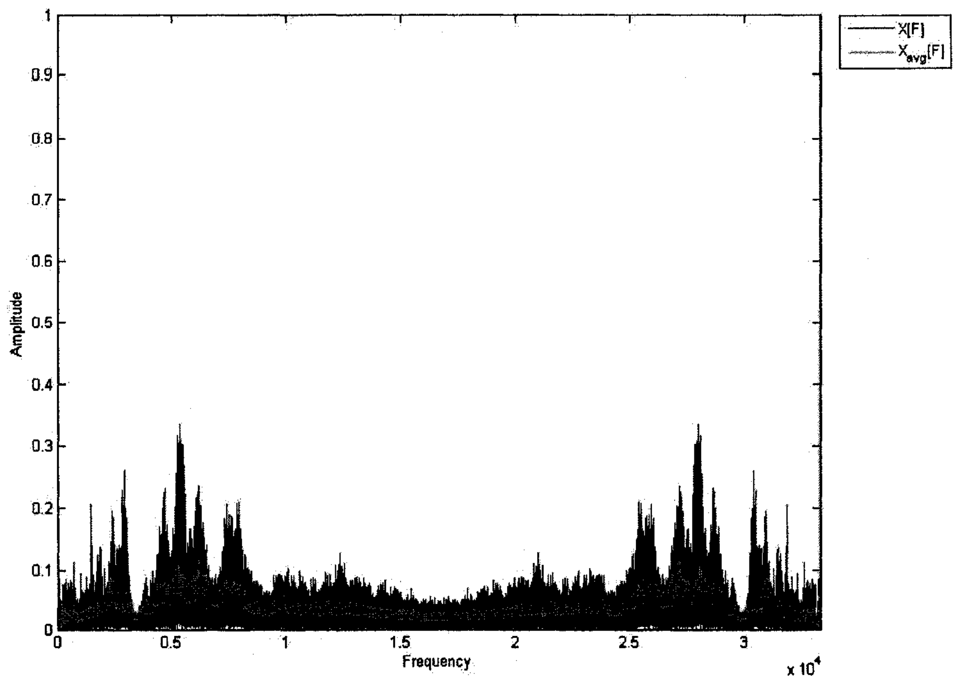


Figure B.5: Normalized FFT - Comparison of a 5.4L 3V Engine to the Baseline Average

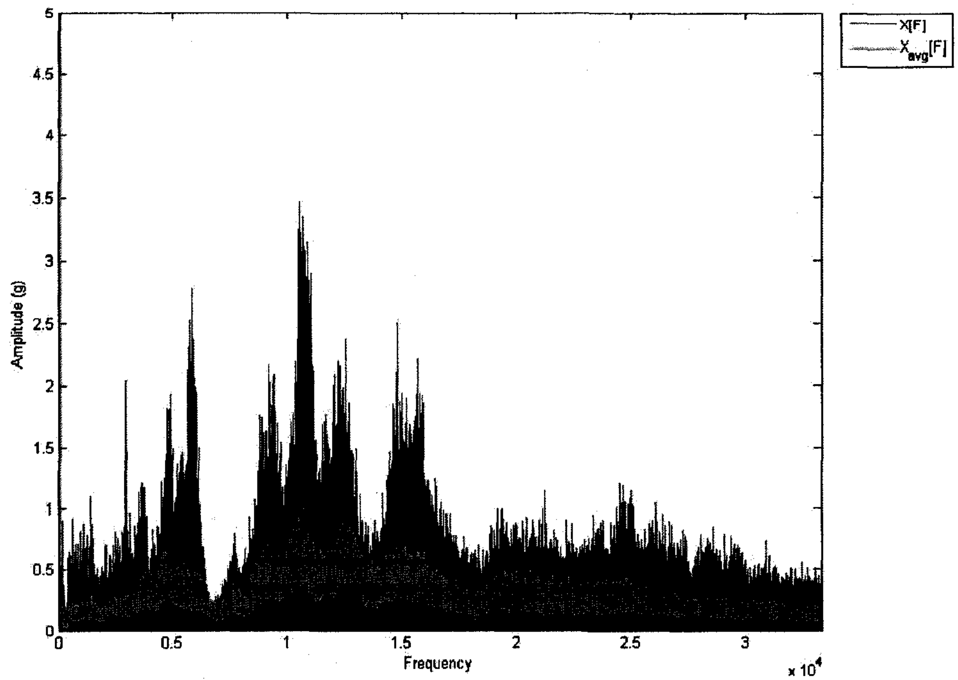


Figure B.6: DCT - Comparison of a 5.4L 3V Engine to the Baseline Average

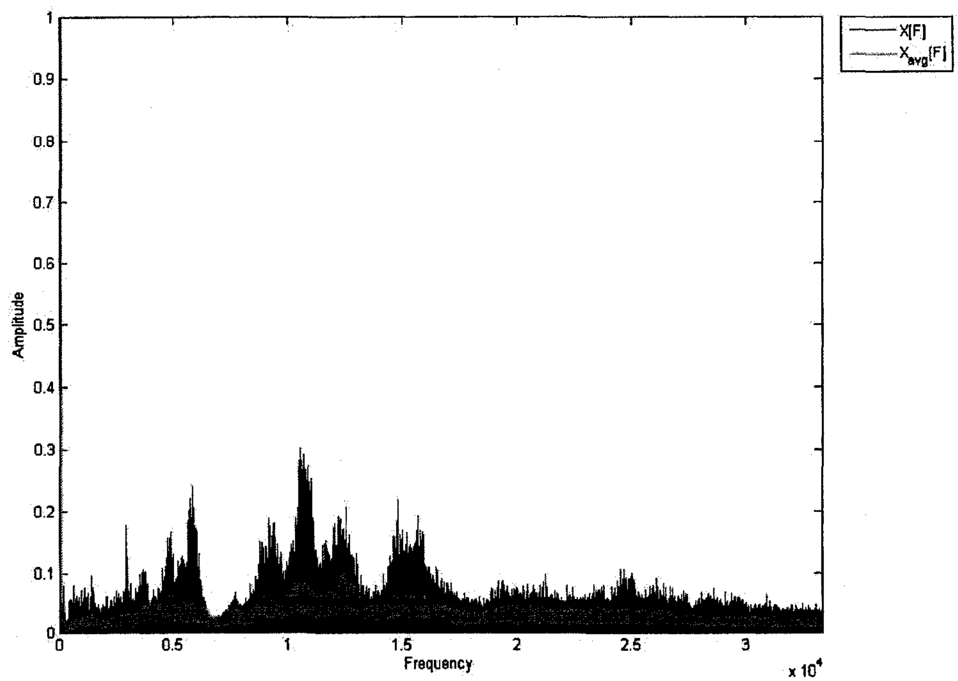


Figure B.7: Normalized DCT - Comparison of a 5.4L 3V Engine to the Baseline Average

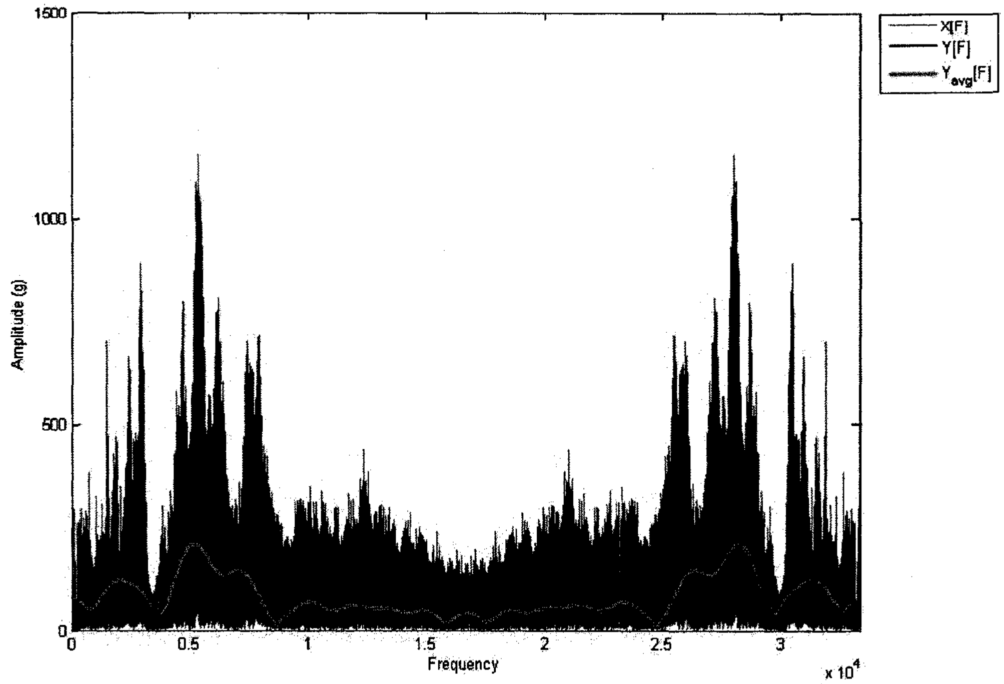


Figure B.8: MA - Comparison of a 5.4L 3V Engine to the Baseline Average

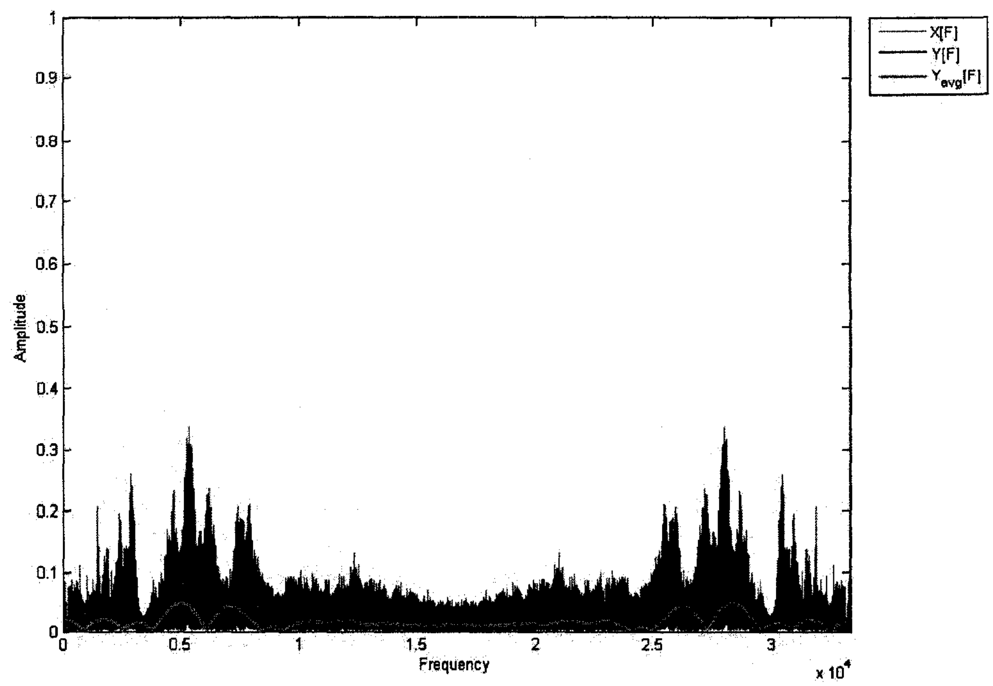


Figure B.9: Normalized MA - Comparison of a 5.4L 3V Engine to the Baseline Average

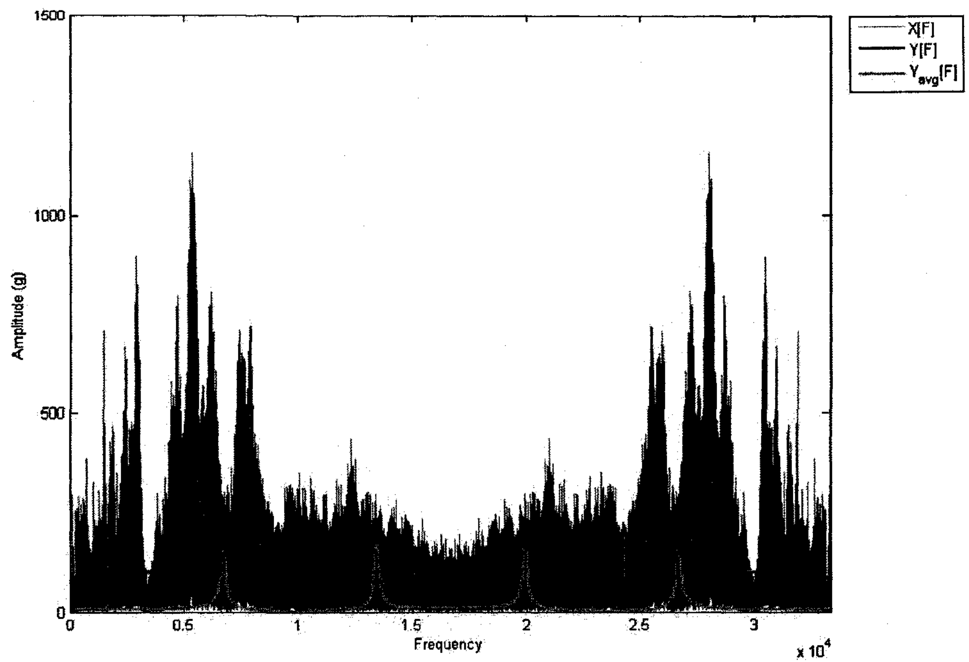


Figure B.10: ARMA - Comparison of a 5.4L 3V Engine to the Baseline Average

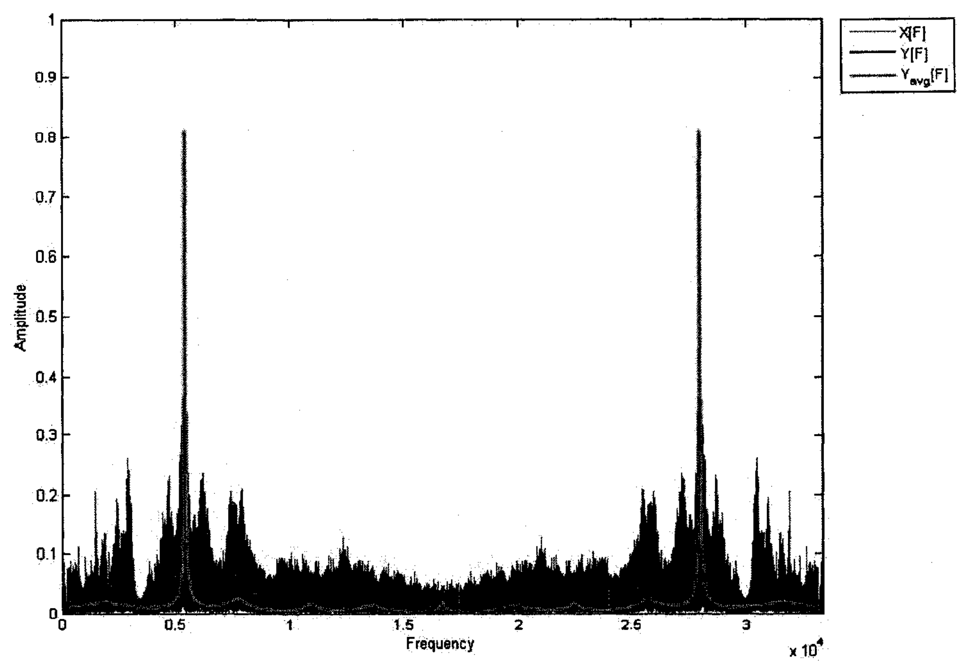


Figure B.11: Normalized ARMA - Comparison of a 5.4L 3V Engine to the Baseline Average

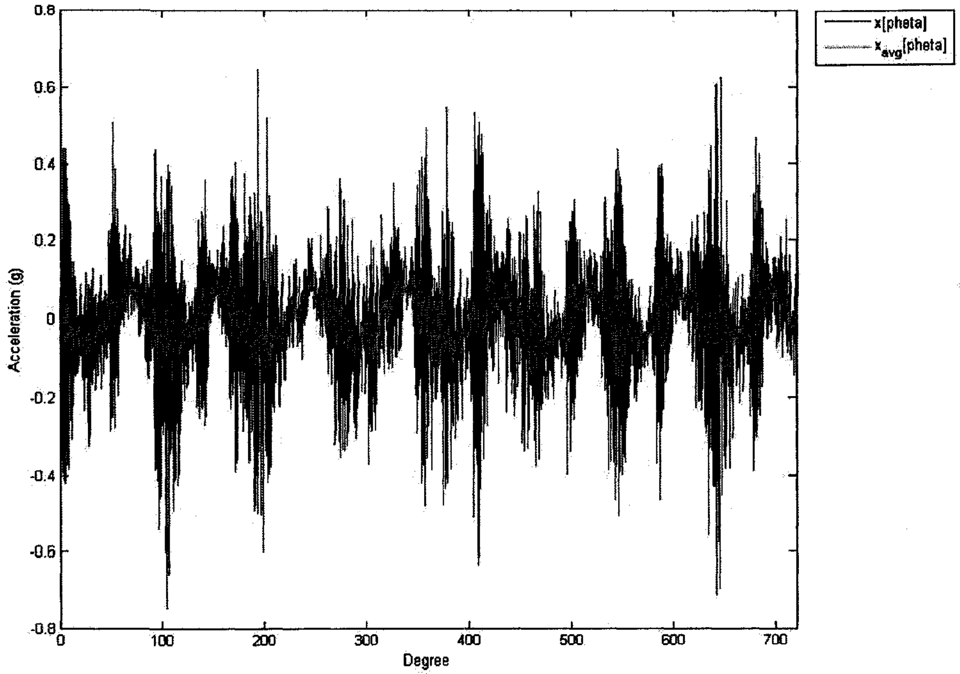


Figure B.12: Filtered Angle Domain Cycle Average - Comparison of a 5.4L 3V Engine to the Baseline Average

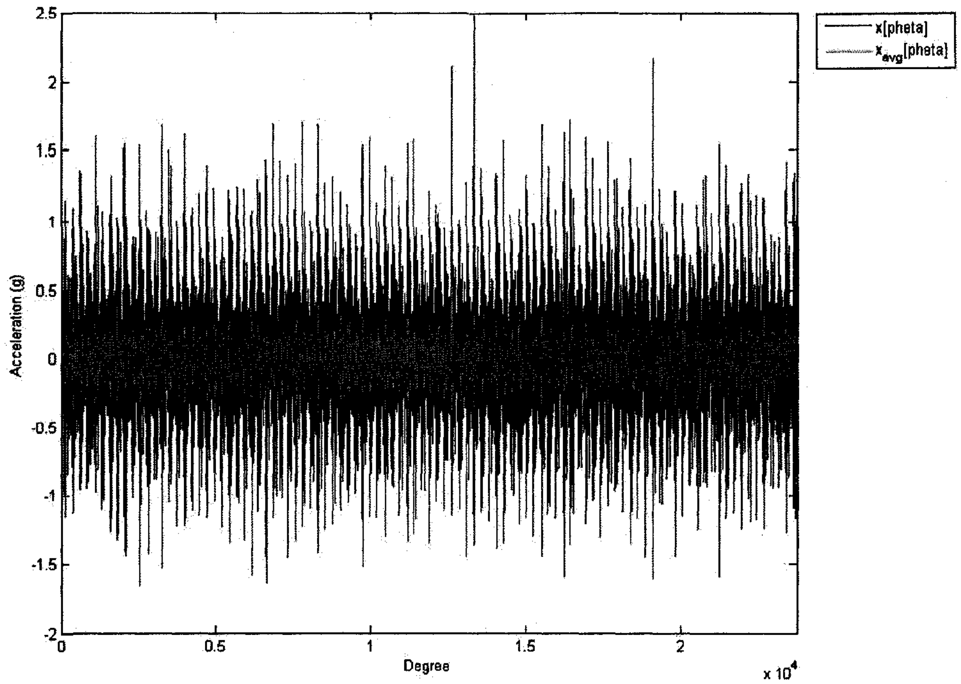


Figure B.13: Filtered Angle Domain - Comparison of a 5.4L 3V Engine to the Baseline Average

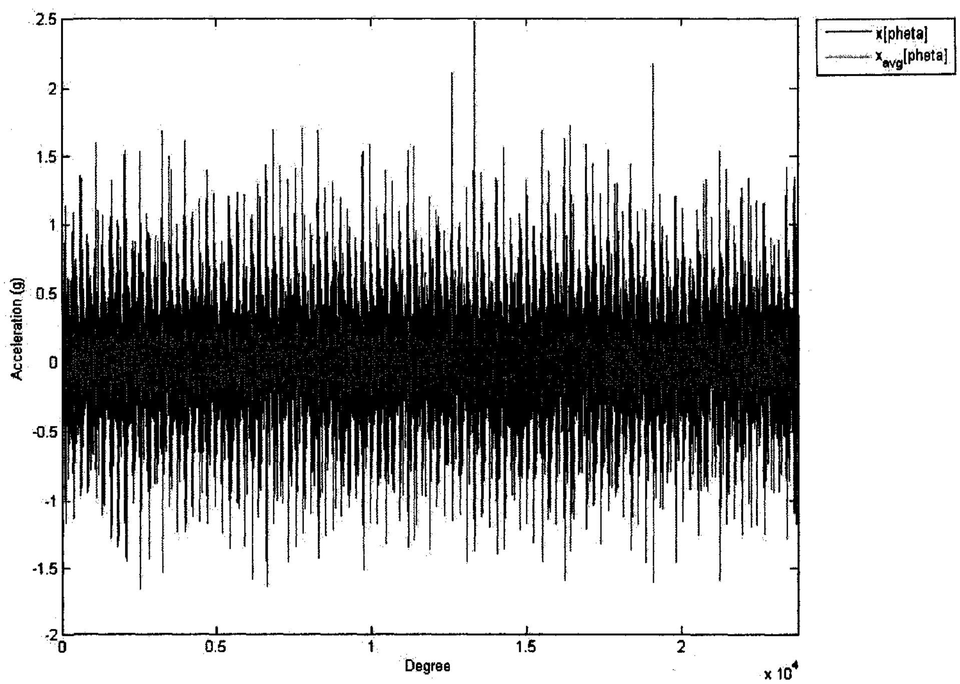


Figure B.14: Filtered Detrended Angle Domain - Comparison of a 5.4L 3V Engine to the Baseline Average

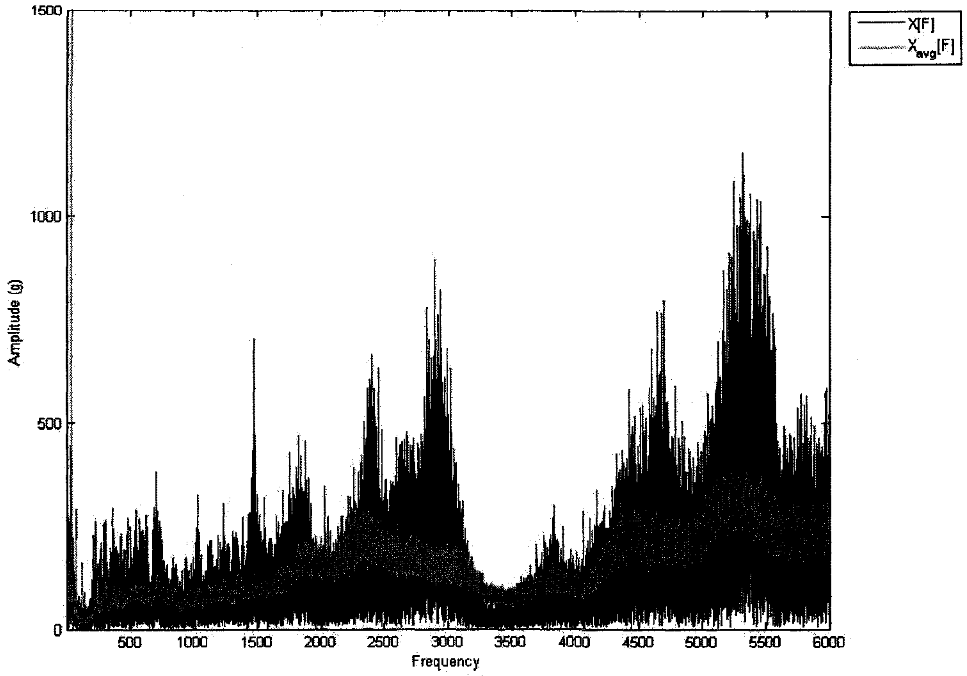


Figure B.15: Filtered FFT - Comparison of a 5.4L 3V Engine to the Baseline Average

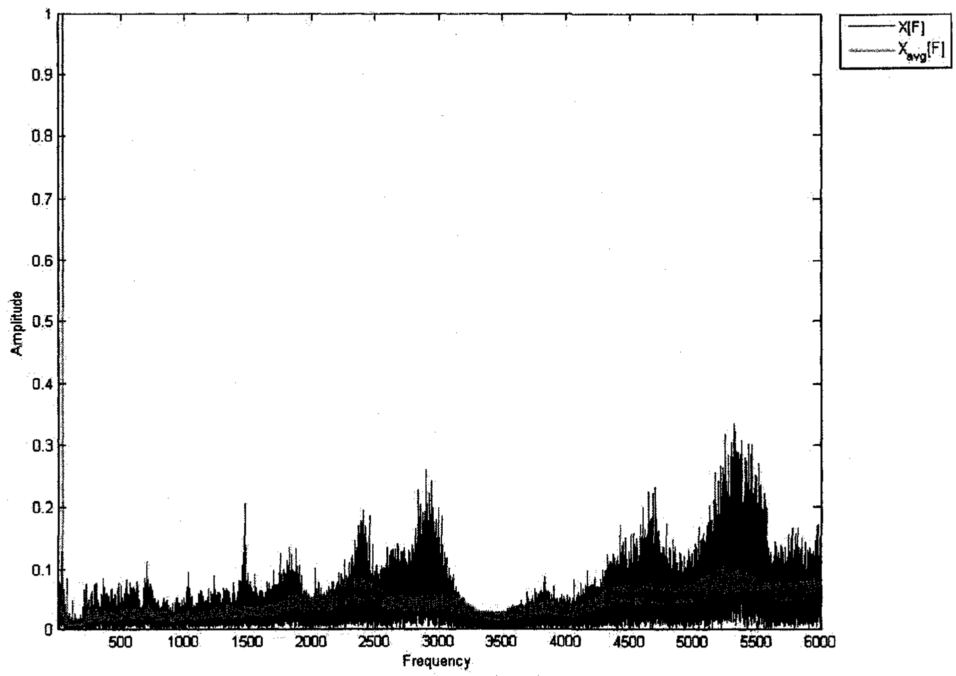


Figure B.16: Filtered Normalized FFT - Comparison of a 5.4L 3V Engine to the Baseline Average

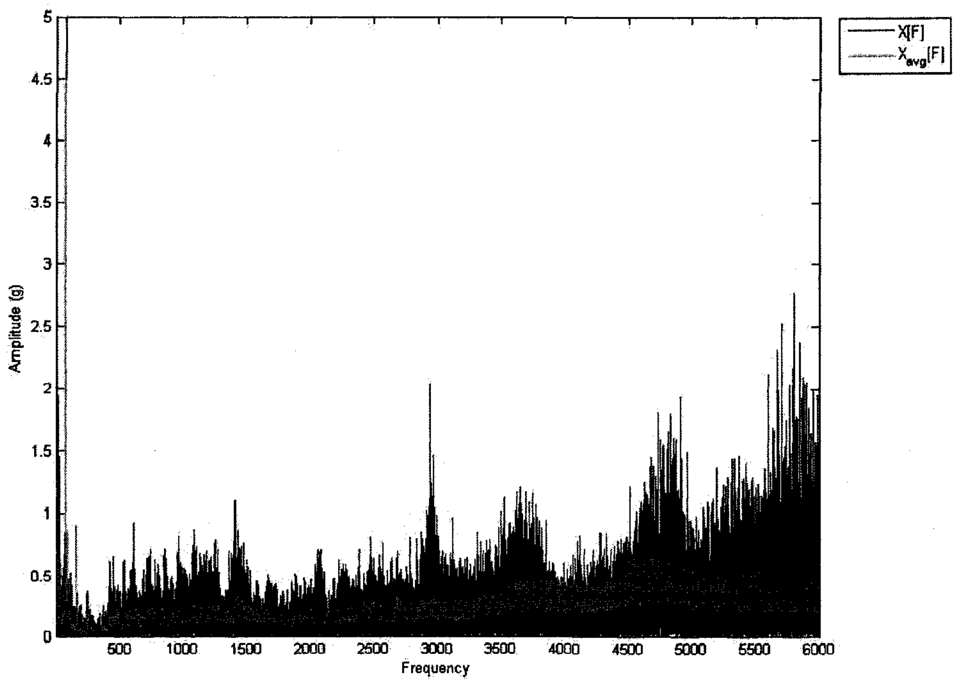


Figure B.17: Filtered DCT - Comparison of a 5.4L 3V Engine to the Baseline Average

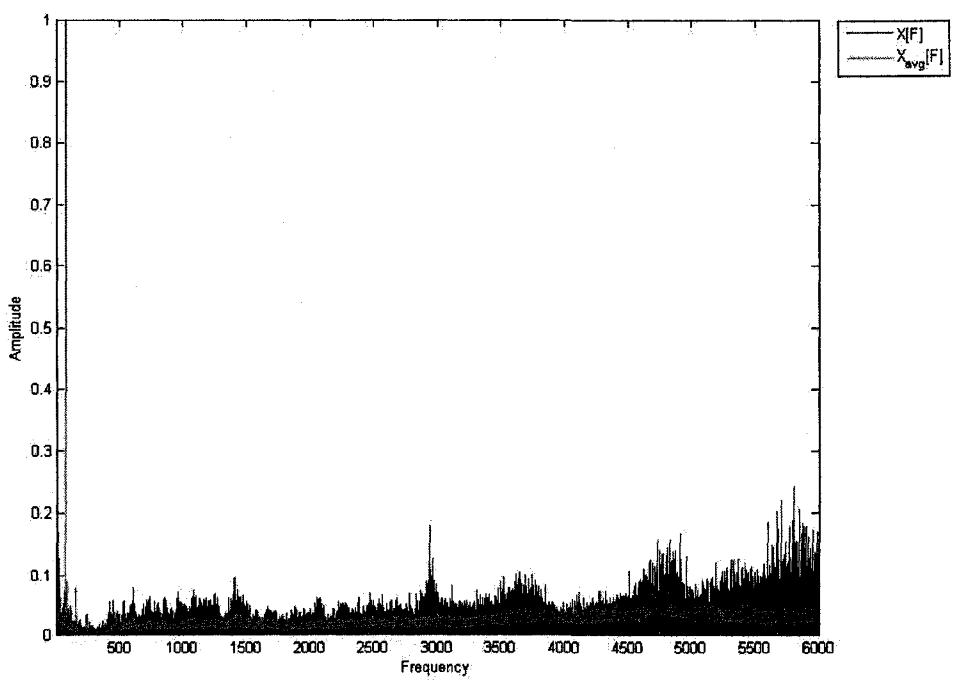


Figure B.18: Filtered Normalized DCT - Comparison of a 5.4L 3V Engine to the Baseline Average

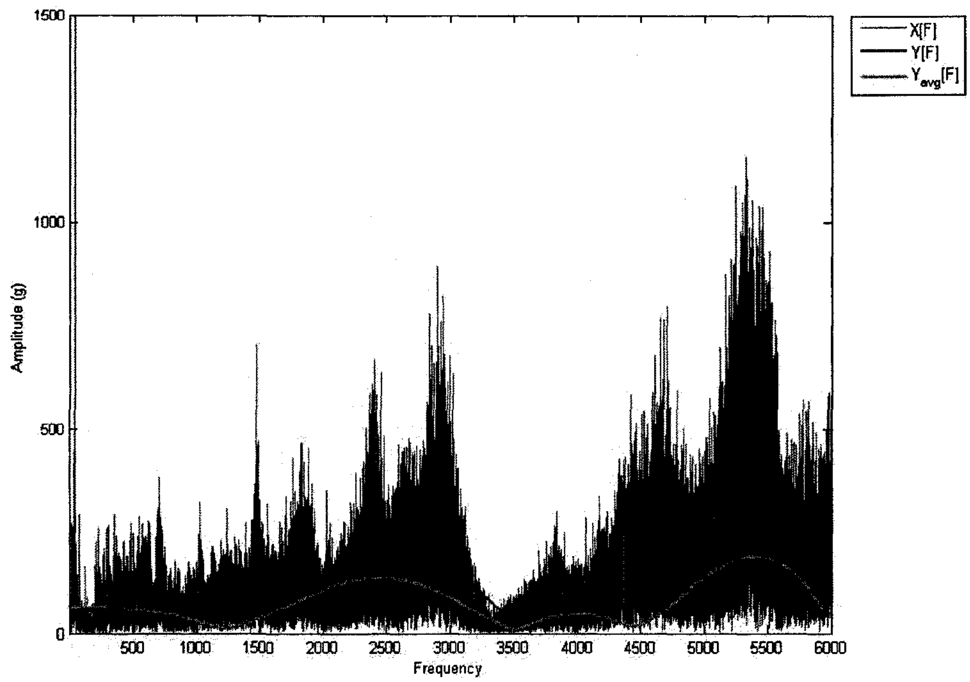


Figure B.19: Filtered MA - Comparison of a 5.4L 3V Engine to the Baseline Average

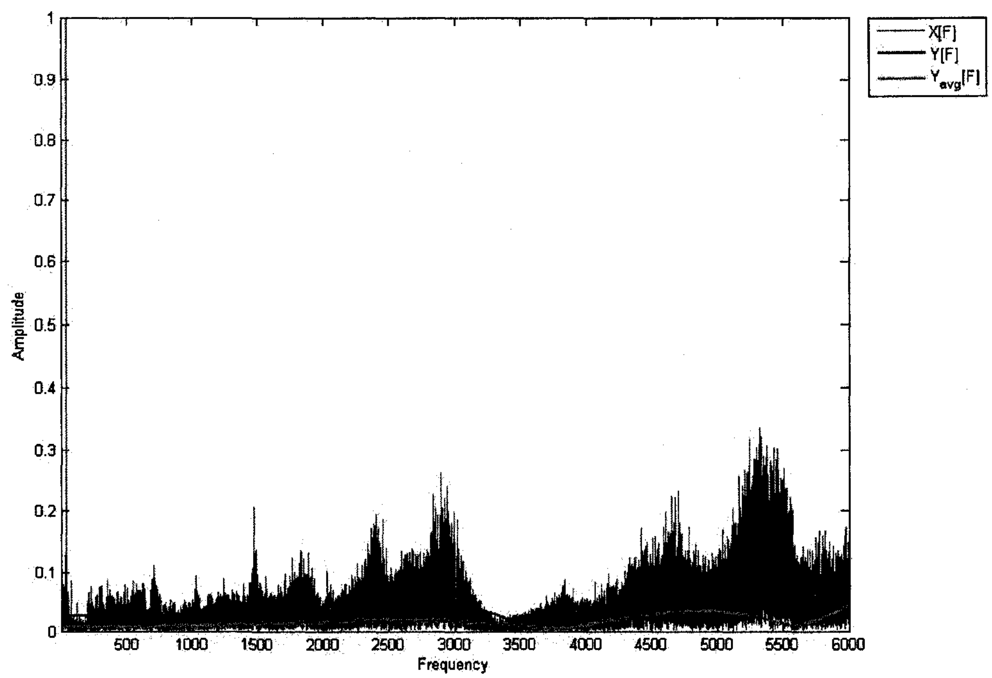


Figure B.20: Filtered Normalized MA - Comparison of a 5.4L 3V Engine to the Baseline Average

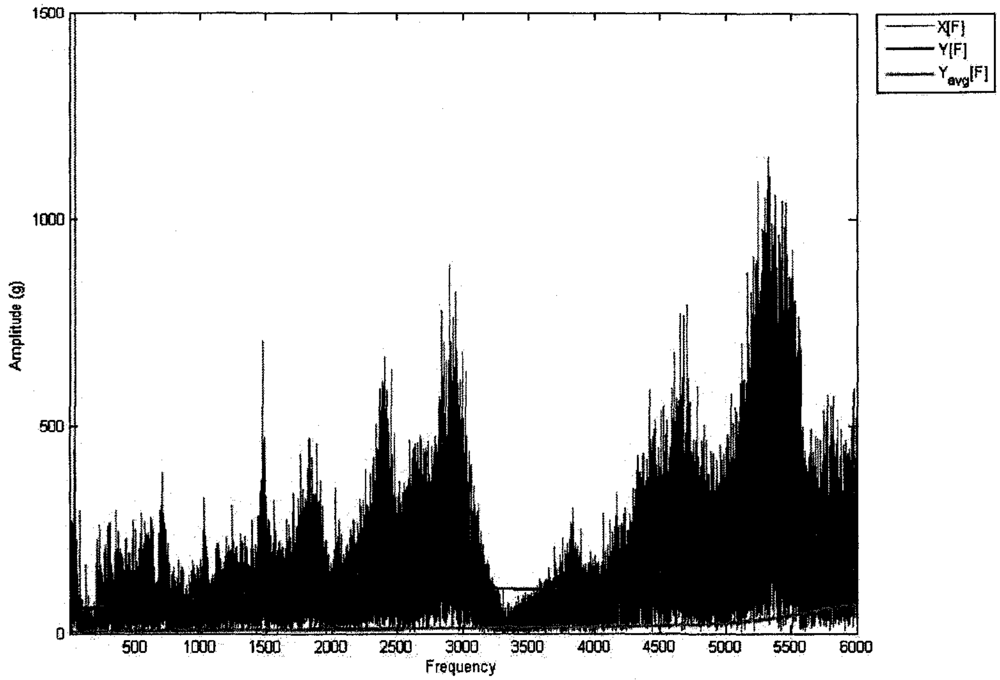


Figure B.21: Filtered ARMA - Comparison of a 5.4L 3V Engine to the Baseline Average

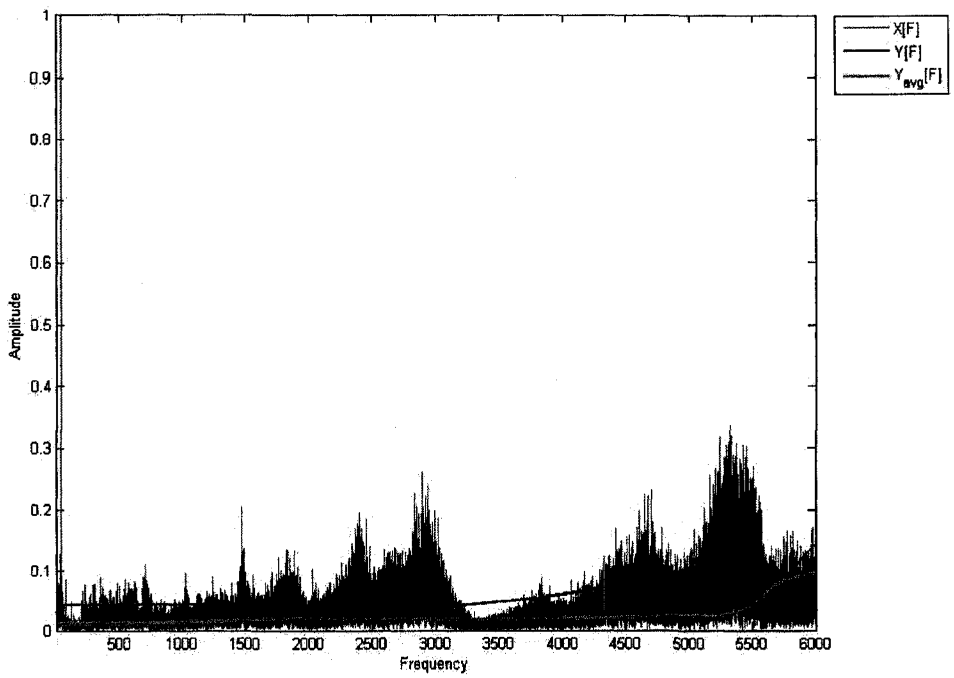


Figure B.22: Filtered Normalized ARMA - Comparison of a 5.4L 3V Engine to the Baseline Average

C. BASELINE RESULTS

The data summarized in this appendix is the baseline data which consists of thirty QOS 5.4L 3V engines. Each table provides the radius of variability of each accelerometer from the average using the different analysis methods. Both raw and filtered data were examined using the multiple investigational techniques. A bandpass filter was used to focus the frequency range to between 3 Hz and 6000 Hz in the filtered data.

The coefficient of variation was calculated from the average and standard deviation derived from the thirty engines. This number is unitless and allows the different data methods to be compared on an equal plane.

Table C.1: Angle Domain Cycle Average - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**58.3673**	6.1825	7.3895	5.1485	5.9919	41.6457	33.8495	13.3029	13.9419
Engine2	**33.1260**	7.2667	8.0420	6.4852	7.0689	14.7260	15.6091	17.4631	11.0618
Engine3	**24.4627**	6.0041	6.8377	5.2045	5.0563	9.9284	12.0208	11.4989	9.3632
Engine4	**26.4311**	6.8174	5.7988	4.8410	5.4146	10.8773	13.0927	13.6906	9.4118
Engine5	**25.9434**	6.0504	6.2506	5.6422	6.2606	10.5870	14.8959	11.2083	8.1705
Engine6	**28.2003**	7.1592	6.7876	5.4802	5.0488	9.6120	14.8614	15.4607	9.4932
Engine7	**37.5444**	6.5845	14.1812	6.1594	5.7343	22.2824	13.3414	18.8917	7.9315
Engine8	**28.6644**	7.5645	7.3462	6.2390	6.0201	10.3263	12.7433	16.1275	10.3042
Engine9	**28.8025**	5.6750	9.7589	5.8376	5.3552	9.3343	12.9507	16.9457	9.8679
Engine10	**25.1149**	6.1674	6.2661	5.3521	5.1352	8.3927	9.8996	16.3572	7.9022
Engine11	**31.6351**	6.0711	8.7449	6.3756	5.8970	10.1894	16.0113	18.0715	11.1920
Engine12	**29.3648**	9.1247	9.0369	6.1264	6.5971	9.5579	13.3530	14.9461	11.1025
Engine13	**26.9270**	7.1220	6.3680	5.2943	5.5891	9.7157	12.5099	14.2603	10.9670
Engine14	**26.9332**	6.7583	7.7269	6.0960	5.8455	8.7646	11.7772	15.8186	9.1071
Engine15	**33.3706**	9.4968	8.5665	6.6416	7.3023	11.2339	14.9127	18.8539	12.1872
Engine16	**30.7496**	7.4841	8.6797	6.0739	6.3020	11.2648	15.1532	16.5408	10.3667
Engine17	**24.0618**	5.9757	5.5798	5.2573	5.2256	9.6396	11.3612	12.0760	9.4525
Engine18	**33.3849**	6.4920	6.0542	6.0830	5.6209	21.6486	11.7753	15.4625	10.9883
Engine19	**27.2636**	6.4523	7.1531	6.9128	6.5424	9.5337	11.4941	15.5107	9.8146
Engine20	**26.5263**	6.5649	5.9568	5.7074	5.6750	8.9943	11.5019	16.7621	8.1318
Engine21	**38.0453**	6.5732	8.2396	5.5500	6.5217	21.7908	15.1910	21.1156	10.5613
Engine22	**27.8829**	6.0377	6.2879	5.9962	6.9840	9.5458	14.8048	14.1396	10.3196
Engine23	**29.1755**	7.0392	7.4666	5.9416	5.9658	10.3997	13.4657	17.0467	9.7439
Engine24	**27.7434**	6.1247	7.9584	5.5594	5.7332	10.7947	11.9071	15.5327	10.2716
Engine25	**32.9792**	10.5745	7.6806	6.5366	6.9917	11.0577	14.6249	20.3936	8.5524
Engine26	**30.9472**	7.0935	7.6301	6.3095	7.3914	11.4281	13.8153	18.7979	8.9402
Engine27	**28.8545**	6.0621	9.9620	6.1772	7.6254	10.7493	11.1074	16.7276	9.0307
Engine28	**29.0587**	7.3369	6.8943	7.5048	6.8124	10.8821	10.2885	17.9894	9.6135
Engine29	**40.4348**	2.3274	6.0733	6.1605	5.4673	12.1700	28.4476	21.0403	11.1697
Engine30	**32.1983**	7.5017	5.9738	6.1878	5.5519	11.3772	13.8061	21.5582	9.5316
Average	**30.8065**	6.7895	7.5564	5.9627	6.0909	12.6150	14.3524	16.4530	9.9497
Std Dev	**6.5465**	1.3866	1.7223	0.5730	0.7392	6.6099	4.8968	2.7150	1.3167
Coef Var	**0.2125**	0.2042	0.2279	0.0961	0.1214	0.5240	0.3412	0.1650	0.1323

Table C.2: Angle Domain - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**564.2272**	139.6780	128.6226	127.9891	137.0990	318.3876	278.9184	188.4164	180.1510
Engine2	**596.5422**	140.7519	128.8311	163.6358	126.1353	326.3486	223.2639	225.3416	263.8906
Engine3	**455.2317**	125.6153	111.4365	129.6984	114.2377	214.2932	175.1823	165.4506	212.5615
Engine4	**467.0296**	142.6216	94.6895	118.5892	134.6221	227.7959	185.0075	190.3703	185.1039
Engine5	**481.2459**	135.6910	121.5469	138.0467	132.9110	207.9517	207.0887	171.6853	214.6723
Engine6	**460.5015**	146.1862	153.9401	136.5731	93.6083	149.9404	191.1928	187.3224	213.1957
Engine7	**460.2309**	131.9399	140.3947	134.9946	98.0744	183.8302	189.9236	205.8575	186.0370
Engine8	**411.7981**	130.1364	124.1010	101.2718	90.7327	147.5709	186.5945	193.3214	157.4323
Engine9	**424.9585**	132.6493	116.8572	103.9527	87.0185	131.7889	182.2478	199.0753	201.8574
Engine10	**403.3754**	137.2091	106.9785	117.9135	90.6120	129.4960	148.7902	206.5710	169.5509
Engine11	**542.3158**	135.9419	135.5519	112.4556	111.5211	183.4288	262.6014	250.7696	258.2203
Engine12	**516.7134**	157.6140	132.5543	127.2179	120.7151	225.0743	224.5619	187.5941	239.8862
Engine13	**557.3310**	174.5939	135.3684	141.1653	129.9217	200.0789	247.2270	222.6598	272.5304
Engine14	**477.8757**	145.7239	98.9005	129.9723	106.8148	169.7017	201.9198	239.2567	205.5048
Engine15	**538.2363**	163.7535	175.8207	141.9710	136.9468	182.1380	218.4401	235.9013	237.7398
Engine16	**507.9063**	159.3569	132.3287	124.7970	107.8672	202.3105	223.0439	223.2308	217.5858
Engine17	**461.6905**	136.2833	121.7150	121.6269	120.2966	159.3425	203.6914	177.8040	228.0607
Engine18	**457.2640**	133.9073	91.3613	124.5523	114.7124	192.5049	189.5660	186.6534	215.1912
Engine19	**437.6904**	115.0614	120.6230	129.9601	97.3606	152.4431	157.0514	215.1040	207.9455
Engine20	**448.3781**	149.0125	108.1960	119.9615	111.1583	155.6697	182.0659	211.0709	196.0942
Engine21	**551.5179**	170.4360	129.6842	137.4685	107.7137	228.4697	263.5412	237.5717	222.9644
Engine22	**496.5560**	148.6311	120.2048	135.5632	119.8211	160.6925	214.2588	214.8629	243.7171
Engine23	**472.2426**	145.5956	121.1793	135.5500	105.4090	152.4824	181.6127	224.6762	225.6817
Engine24	**462.6816**	125.0618	126.4447	128.0733	113.7332	158.2957	174.2415	208.8319	232.5493
Engine25	**527.1545**	146.3191	138.4150	143.2403	121.2460	179.6201	245.0143	281.8138	174.3305
Engine26	**499.2075**	134.9018	116.6322	142.9750	133.3506	173.7479	217.5725	251.2907	196.2377
Engine27	**483.1333**	104.3490	166.0948	145.2189	98.2570	172.2158	197.9428	242.0360	191.7748
Engine28	**521.1819**	121.3229	125.1378	176.0427	136.4320	188.7889	191.4593	263.1489	223.8345
Engine29	**514.6563**	30.3441	121.6594	130.3017	106.8785	193.7921	276.1183	243.5468	218.2570
Engine30	**475.0699**	142.1712	112.2669	142.3855	116.8623	163.7341	213.4567	237.1370	174.1776
Average	**489.1315**	136.7620	125.2512	132.1055	114.0690	187.7312	208.4532	216.2791	212.2245
Std Dev	**46.8240**	25.1891	18.3998	15.1959	15.0622	45.2709	33.4039	28.4714	28.3254
Coef Var	**0.0957**	0.1842	0.1469	0.1150	0.1320	0.2411	0.1602	0.1316	0.1335

Table C.3: Detrended Angle Domain - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**480.3177**	138.8262	126.8818	127.2907	136.0589	219.6619	220.9923	187.8544	168.0482
Engine2	**592.8742**	139.4693	126.1051	163.4890	126.1088	326.0333	217.1130	224.7078	263.7881
Engine3	**452.8390**	125.0863	109.4840	129.6923	113.9449	214.1965	171.4057	165.0064	212.4596
Engine4	**463.7548**	142.0427	92.8876	118.4003	134.0151	227.4117	179.5991	189.9401	185.0308
Engine5	**478.7278**	135.6248	121.2564	137.7441	131.3300	207.9137	202.7812	171.5614	214.6636
Engine6	**459.5086**	146.1459	153.9254	136.5093	93.4097	148.4438	191.1626	186.4219	213.0832
Engine7	**441.5424**	131.8481	140.2372	134.3495	98.0581	142.2957	189.7708	198.6121	185.8395
Engine8	**410.5540**	130.0666	124.0703	101.1256	90.4268	145.4517	186.5150	192.6574	157.4151
Engine9	**422.2563**	130.0507	116.7524	103.3968	86.7961	128.6310	182.0048	198.0011	201.6320
Engine10	**402.4054**	137.1221	106.9607	117.7325	90.3049	127.5775	148.7322	206.2324	169.5347
Engine11	**541.7028**	135.9231	135.5235	112.1736	111.1951	182.3310	262.5940	250.6104	258.1614
Engine12	**514.6963**	157.5169	132.4839	126.9678	120.4083	221.8225	224.4274	186.7385	239.7615
Engine13	**555.3587**	172.9116	135.2287	140.9104	129.6282	198.1107	247.0093	221.7063	272.3301
Engine14	**477.1617**	145.2441	98.4670	129.9450	105.7393	169.1584	201.9185	239.2478	205.4265
Engine15	**536.9349**	163.7030	175.7745	141.8652	136.7948	179.6614	217.9615	235.7288	237.5115
Engine16	**505.6758**	159.1441	132.0211	124.3516	107.2347	199.6182	222.4443	222.5107	217.1385
Engine17	**460.2619**	136.2326	121.7048	121.5180	120.1193	156.6283	203.4948	177.0384	228.0115
Engine18	**440.5772**	133.8455	91.3345	124.4496	114.5208	156.9670	189.5361	180.0457	215.1046
Engine19	**436.8426**	114.8237	120.5424	129.6945	96.9459	151.0775	157.0462	214.9275	207.8836
Engine20	**447.6577**	148.9615	108.1593	119.8898	111.0675	154.3530	181.9924	210.7406	196.0669
Engine21	**538.2394**	170.3958	129.6603	137.3778	107.5343	199.2793	263.5393	233.5683	222.9339
Engine22	**495.4453**	148.4722	120.0643	135.2801	119.4244	158.9221	214.1618	214.3526	243.6704
Engine23	**471.1420**	145.5510	121.1632	135.4388	105.1915	150.3896	181.5370	224.0867	225.6383
Engine24	**459.7656**	124.4526	125.6462	127.6130	113.3462	152.6168	173.5092	208.6583	232.4671
Engine25	**522.9380**	145.2681	137.0059	142.2649	120.1630	174.6010	243.5724	280.8702	173.8135
Engine26	**495.0534**	134.0051	115.2267	142.2336	132.7644	167.9372	216.1543	250.3247	195.9554
Engine27	**479.9800**	103.6706	165.4900	144.7818	97.8380	167.2963	196.8431	241.3371	191.6597
Engine28	**517.0019**	119.9137	123.8858	175.2206	135.6972	184.2589	190.4052	261.3234	223.5007
Engine29	**489.8178**	28.3525	121.0009	129.8938	106.5608	189.8836	236.3627	238.2173	218.1242
Engine30	**471.8418**	141.7300	111.3872	141.9782	116.6083	158.3136	212.3471	236.5498	173.9960
Average	**482.0958**	136.2133	124.6777	131.7859	113.6412	178.6948	204.2311	214.9859	211.6883
Std Dev	**44.2800**	25.4473	18.5175	15.1195	14.9286	39.2001	28.5374	28.5030	28.8819
Coef Var	**0.0918**	0.1868	0.1485	0.1147	0.1314	0.2194	0.1397	0.1326	0.1364

Table C.4: FFT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**132825**	38040	33611	33532	38260	57630	66960	48691	47977
Engine2	**170983**	36421	40476	44787	44310	102790	64251	56243	66664
Engine3	**120362**	32911	33382	33648	31055	54877	51702	42747	51778
Engine4	**126806**	37613	25733	27300	37995	60515	49136	46582	59730
Engine5	**124936**	34760	33286	36847	42015	54929	48738	47021	50659
Engine6	**130661**	39000	57305	50655	26705	36326	49480	49264	52855
Engine7	**122577**	37889	55145	34340	24093	40263	47761	53948	44455
Engine8	**117921**	32288	33363	35636	28656	37564	47647	55467	53860
Engine9	**119354**	37820	33201	30068	26354	41217	45805	62046	49673
Engine10	**106782**	36358	28266	28431	24672	35784	42422	54304	42843
Engine11	**136950**	37036	36243	30307	28038	41945	69376	60855	63950
Engine12	**141204**	45213	37122	31509	35507	73153	57132	45588	59743
Engine13	**143896**	55069	35396	36057	33982	48564	64329	52027	69009
Engine14	**121501**	39287	28770	29421	27333	39017	50859	66049	48033
Engine15	**145571**	50133	57206	34192	38587	42906	56449	65848	58170
Engine16	**137467**	44601	38266	34211	29748	49579	53425	72292	53384
Engine17	**115491**	33884	32271	29836	31116	40422	48479	43187	58659
Engine18	**123607**	34768	32175	29172	33689	43498	49610	56676	59019
Engine19	**117847**	37329	31202	32667	28439	37781	42643	62418	50030
Engine20	**113597**	46220	27841	28497	28104	38742	47935	50631	45042
Engine21	**143681**	48908	35717	33489	32290	49433	75233	58640	57185
Engine22	**127951**	39384	30635	36128	36946	37009	58838	52307	60365
Engine23	**120460**	38138	32827	34664	26945	39567	49861	55578	53946
Engine24	**117407**	29746	35594	30946	30617	39403	45261	52078	58519
Engine25	**146133**	48787	36679	37365	32382	43126	73443	75675	46948
Engine26	**133740**	35186	33653	38922	34985	44939	58049	71062	48353
Engine27	**138714**	42794	59732	37798	41223	44918	46419	64352	48999
Engine28	**136993**	36439	34309	48331	38228	44134	44944	73857	55155
Engine29	**134552**	46929	34142	39414	29225	45973	59805	60975	54041
Engine30	**126948**	42715	35841	35173	31950	39363	54195	61685	49570
Average	**129897**	39856	36646	34778	32448	46846	54006	57270	53954
Std Dev	**13059**	6003	8846	5560	5367	13465	9003	9061	6522
Coef Var	**0.1005**	0.1506	0.2414	0.1599	0.1654	0.2874	0.1667	0.1582	0.1209

Table C.5: Normalized FFT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**50.2381**	18.6249	16.7940	19.2334	17.3843	24.1959	16.5993	12.0959	14.6805
Engine2	**48.4741**	20.6322	19.8746	20.0194	20.3376	11.8966	14.1704	13.3383	13.9432
Engine3	**61.9867**	25.1262	28.7482	28.8756	15.7549	23.2291	15.9691	14.5367	17.2228
Engine4	**46.5796**	15.8867	16.8610	16.8592	15.7440	22.2381	14.9229	13.9402	13.7593
Engine5	**83.8875**	38.6337	33.3036	37.4585	46.2661	18.4007	13.2108	13.0316	14.4497
Engine6	**94.9975**	43.4625	54.3572	47.9820	33.7224	11.1259	14.1534	13.2870	15.5147
Engine7	**64.2693**	35.9535	20.8150	18.0034	40.5433	10.7628	9.8710	10.5812	10.5592
Engine8	**39.0537**	14.2410	13.7968	16.5416	15.2393	10.3480	12.1123	13.3699	13.9150
Engine9	**47.4100**	21.2772	17.8452	20.6739	19.3431	13.9755	11.6436	13.1326	13.1004
Engine10	**35.1132**	13.4777	14.0015	14.3274	14.8429	9.6834	10.1055	10.6930	10.9285
Engine11	**44.0275**	14.6006	13.9181	14.0474	13.0871	14.6666	11.7993	17.5364	22.3846
Engine12	**41.4645**	15.3232	14.2612	13.7685	15.1648	16.9855	15.7714	9.6322	15.2170
Engine13	**45.3942**	21.4247	17.5758	19.4914	18.2195	12.4829	11.3515	12.0872	12.2503
Engine14	**36.9475**	14.4378	15.5415	13.5105	14.4944	9.5260	12.1575	12.4410	11.3657
Engine15	**46.2520**	19.7042	17.1515	19.6073	18.5589	13.4227	11.2699	15.0885	13.8959
Engine16	**48.3072**	19.9406	18.8446	20.8929	19.8042	13.4428	12.4807	14.1900	14.6384
Engine17	**96.4267**	34.2501	46.7500	44.8474	37.4307	22.3110	25.9054	18.9804	31.5914
Engine18	**90.4045**	56.2935	26.3082	36.6300	47.3413	12.0906	12.2521	13.6063	15.7327
Engine19	**71.4624**	28.2758	39.1888	33.8868	30.7399	10.5263	10.1724	16.1034	14.3085
Engine20	**41.6013**	16.1952	13.1847	13.3831	12.9628	13.9611	15.2735	15.9470	16.2760
Engine21	**61.4636**	32.5311	19.3241	20.0048	17.4241	19.2880	25.7256	12.7676	21.1055
Engine22	**45.9442**	20.7692	12.3067	17.9887	15.6965	11.8442	12.8819	15.9888	19.9051
Engine23	**75.4028**	35.0337	41.8585	25.0593	38.5716	10.4422	11.5747	12.9769	13.3767
Engine24	**59.3175**	24.2823	27.0706	25.4882	22.1807	13.8675	14.3872	16.5169	19.5547
Engine25	**48.1244**	20.8672	18.1613	20.0815	19.2237	15.1253	12.9935	11.8003	15.5246
Engine26	**48.0064**	20.2075	19.1017	20.3074	18.7731	14.3032	12.9688	12.9912	15.0015
Engine27	**75.7410**	32.0672	20.1084	39.3330	32.6941	20.3339	19.9166	20.8261	21.0760
Engine28	**98.7909**	39.0488	63.1728	36.8233	39.2088	16.2020	14.4017	22.9920	18.7672
Engine29	**79.5654**	20.5417	36.7736	44.2731	37.4238	17.2018	19.0371	15.9310	16.8414
Engine30	**69.2776**	32.9954	24.0914	27.0219	35.8349	13.8151	19.8404	17.7705	14.6860
Average	**59.8644**	25.5368	24.7030	24.8807	24.8004	14.9232	14.4973	14.4727	16.0524
Std Dev	**19.2766**	10.3775	12.9974	10.3629	10.9640	4.2546	4.0547	2.9888	4.1949
Coef Var	**0.3220**	0.4064	0.5261	0.4165	0.4421	0.2851	0.2797	0.2065	0.2613

Table C.6: DCT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	340.8256	98.2319	88.2621	88.6204	98.1019	150.4153	165.8515	128.3261	121.0197
Engine2	428.5934	94.6667	97.8229	114.2116	103.6455	249.9804	160.0064	149.3610	175.9931
Engine3	313.5251	85.8661	82.3379	88.2963	79.9446	145.0765	128.3290	113.3940	139.9441
Engine4	325.5778	97.5086	65.5024	75.1672	95.8631	156.8791	126.3515	126.2008	144.4304
Engine5	327.2718	91.6840	85.1426	95.4281	101.5718	143.2790	132.1753	121.1241	139.1330
Engine6	330.3922	101.0694	132.7871	117.4342	67.3181	97.9061	129.8314	128.3842	141.6500
Engine7	313.3161	95.3961	126.1100	91.0665	64.5986	102.4525	127.2758	138.6763	121.5318
Engine8	296.6417	86.0382	85.9919	83.6931	69.2177	98.7305	125.9835	139.4995	127.7648
Engine9	302.7855	94.5676	84.0323	75.7398	65.2568	100.0055	121.7591	151.5340	133.7563
Engine10	278.0076	94.5556	73.7737	76.7519	63.3143	91.4208	107.4698	141.9178	113.8296
Engine11	363.1279	95.0628	93.2573	77.8657	74.2419	115.9055	180.6344	164.1700	171.8674
Engine12	362.3770	113.9406	94.2803	84.2460	88.7910	175.0391	151.4747	124.1402	159.5950
Engine13	378.5574	133.8658	92.8302	95.6420	89.2654	131.3348	168.0381	143.4869	183.2441
Engine14	321.0409	100.6588	71.8455	82.1439	71.9391	108.2921	135.2720	168.6641	131.8224
Engine15	374.2068	123.0749	137.7140	92.0468	97.4597	116.6750	147.7999	167.5839	156.2206
Engine16	352.3680	112.7563	95.2088	87.0410	75.1679	131.7485	144.4565	174.2129	143.4666
Engine17	307.6978	90.6134	83.9906	80.1951	81.7492	106.2129	131.8710	117.1254	154.6256
Engine18	314.3955	91.0314	75.7294	80.1578	84.2092	111.0279	129.9209	138.6964	151.2054
Engine19	304.5660	90.0775	81.8046	86.7180	71.0440	100.7896	110.3987	156.9432	135.6824
Engine20	299.9593	112.9588	73.0668	77.6308	74.4730	103.0886	124.7977	136.6699	124.1933
Engine21	372.3909	123.0934	91.0843	89.9781	79.7271	132.4538	190.2189	156.2393	150.4534
Engine22	335.7476	102.3372	80.2782	93.4243	90.4767	101.9041	150.4176	140.4704	161.7187
Engine23	318.1733	99.5785	84.6520	91.1057	70.9378	103.5806	127.9162	148.9863	146.7362
Engine24	309.9438	80.7299	89.9310	83.3119	78.8708	103.6741	118.9975	138.4732	155.6125
Engine25	370.9503	116.0263	94.5175	96.9696	83.0040	115.8944	181.5514	194.7497	120.8131
Engine26	343.8217	91.5467	83.6794	99.5030	90.7564	116.0104	150.0325	178.9808	129.1914
Engine27	348.4691	96.8593	139.5960	98.5727	92.7845	116.2544	127.3107	166.5972	129.4553
Engine28	356.3596	90.0542	87.3664	123.3418	96.8713	120.0579	123.6517	187.1733	148.0366
Engine29	344.7210	94.1638	86.5565	97.2634	74.8826	124.4093	158.8772	160.6693	144.4710
Engine30	327.4773	105.5821	86.8029	93.9837	82.0296	105.3628	143.0671	160.6850	124.9323
Average	335.4429	100.1199	91.5318	90.5850	81.9171	122.5287	140.7246	148.7712	142.7465
Std Dev	31.5739	12.4449	18.6282	11.8854	11.7751	31.2440	21.2336	20.7780	17.2852
Coef Var	0.0941	0.1243	0.2035	0.1312	0.1437	0.2550	0.1509	0.1397	0.1211

Table C.7: Normalized DCT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	37.4399	12.9024	12.4090	13.4932	13.0099	16.6321	15.6901	8.6915	11.4723
Engine2	34.0961	13.6041	14.0877	13.4597	14.4026	9.1153	10.7709	9.4280	10.1203
Engine3	53.0212	22.2711	25.3061	29.2514	17.6827	13.4519	10.6611	9.3963	11.1187
Engine4	40.2976	11.0226	11.8286	11.0911	11.1920	24.0588	16.5132	12.1144	10.7675
Engine5	66.3958	25.2119	28.7823	28.8089	38.6958	14.7437	11.2267	10.9412	12.4055
Engine6	83.7307	33.6460	47.8013	39.8971	29.5679	14.1282	17.1433	15.9603	19.4820
Engine7	55.4531	33.0257	15.4132	12.5871	35.3481	8.9239	9.0455	9.4166	9.4200
Engine8	33.2770	12.3875	11.8749	12.7434	12.1048	9.6763	11.1673	11.9390	11.9621
Engine9	33.8493	14.0937	12.8786	14.1822	13.9544	10.3122	9.3335	9.4099	10.1697
Engine10	29.2502	10.9936	10.9868	10.9077	11.4629	8.5041	9.3665	10.3849	9.7843
Engine11	32.0826	12.6162	12.0646	11.2157	10.6183	9.0896	11.5588	11.0810	12.1250
Engine12	32.5706	11.8081	11.3549	10.7930	11.9347	12.0893	12.2222	8.2819	13.0166
Engine13	31.7949	14.0807	12.3401	13.1054	12.9137	9.1139	8.9667	8.3949	9.3763
Engine14	30.3689	11.3422	11.6448	10.4449	11.2270	8.7875	10.8515	10.8744	10.4716
Engine15	33.2754	12.9557	12.1584	13.0317	13.1299	9.5948	9.2510	13.0206	10.1083
Engine16	33.2418	13.1459	13.0659	13.9274	13.8823	9.4452	9.2346	9.6578	10.3456
Engine17	90.2971	29.6307	40.6358	37.3478	30.8387	26.4439	25.5848	18.8229	39.6267
Engine18	72.3569	36.3818	27.9529	28.9283	41.3082	10.9958	11.2918	11.9397	14.0121
Engine19	60.3227	25.4751	33.2208	26.6650	27.0193	8.9918	8.9029	12.2677	11.5996
Engine20	37.5594	12.2479	11.2599	11.9046	11.4124	14.1422	14.9103	13.2132	16.2802
Engine21	48.6707	20.5794	14.3066	13.7058	12.9886	19.0171	21.1725	12.4641	20.4649
Engine22	41.0391	17.8522	10.8058	15.3433	12.6737	11.1438	15.0715	14.2538	17.2682
Engine23	65.1168	32.8145	28.9840	23.0427	34.1157	10.2425	11.1388	14.0929	14.1741
Engine24	49.3821	20.3926	21.6422	19.7130	17.4382	12.8690	12.8286	12.8942	19.1104
Engine25	33.6487	13.7548	12.4379	13.2101	13.3462	12.5497	9.8419	8.1337	10.7330
Engine26	33.5447	13.3421	13.4269	13.7046	13.3380	10.2726	9.7918	9.0643	10.8474
Engine27	65.1712	26.9071	18.2526	36.1301	26.7465	16.6738	16.4636	17.4279	17.7929
Engine28	82.4249	30.1045	45.0052	31.2607	33.6454	21.3245	19.3101	19.1954	23.5964
Engine29	68.0050	13.7095	35.0777	34.6291	30.0052	16.9478	18.0162	14.8064	16.6058
Engine30	55.7674	25.3201	19.1249	18.9793	30.1179	12.6106	17.0678	14.6941	13.0225
Average	48.7817	19.4540	19.8710	19.4501	20.2040	13.0631	13.1465	12.0754	14.2427
Std Dev	18.2436	8.2521	11.0317	9.4209	10.0021	4.6935	4.2232	3.0567	6.0928
Coef Var	0.3740	0.4242	0.5552	0.4844	0.4951	0.3593	0.3212	0.2531	0.4278

Table C.8: MA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**377.0963**	98.6278	106.8771	155.9280	104.1244	145.3223	169.8076	162.3492	97.9057
Engine2	**464.9311**	117.7412	107.9572	110.9803	110.2915	231.4742	209.7959	162.1224	205.6307
Engine3	**356.1586**	94.1926	68.0415	100.3170	121.6358	144.7557	140.3253	132.3346	174.1565
Engine4	**364.2730**	120.1413	69.5361	58.8786	121.7102	168.6535	155.1340	168.1899	119.7794
Engine5	**385.5082**	95.9656	105.1950	109.6836	112.0014	205.9316	135.6478	133.3582	158.6627
Engine6	**376.5221**	107.3318	144.6666	123.4084	69.2510	72.1209	147.9176	156.2498	194.4222
Engine7	**330.8342**	110.6851	116.2176	86.4881	73.6844	63.4217	124.0524	161.3180	159.2141
Engine8	**346.2748**	97.3004	97.3232	107.6964	67.5714	149.1211	160.7423	167.3511	93.3869
Engine9	**299.5307**	91.2003	58.8373	68.8311	82.5371	75.0930	126.8871	144.4570	154.2144
Engine10	**293.0639**	109.5092	78.4434	54.6628	63.9099	51.1488	124.4637	154.6918	136.4966
Engine11	**452.2280**	140.5493	88.2990	76.2139	97.9387	172.8811	231.4583	199.1126	196.0922
Engine12	**347.1853**	106.2281	75.7523	100.9211	99.6786	98.0175	175.6899	136.5418	155.8071
Engine13	**404.6422**	114.2591	107.5009	90.4857	90.3797	149.7906	170.1515	184.7898	192.9547
Engine14	**353.6303**	130.2226	54.8075	93.0084	71.8672	85.9909	160.9550	184.1797	155.0937
Engine15	**379.4826**	125.7420	145.4042	86.9050	120.4487	86.6707	147.0680	177.2670	156.2975
Engine16	**415.7363**	137.7781	112.0292	144.0265	84.0870	115.2924	201.5819	187.8514	155.7989
Engine17	**374.7741**	108.0947	101.5569	76.0439	86.6479	113.7086	187.3684	151.8922	184.5510
Engine18	**340.4476**	115.1714	84.9107	74.2190	103.8006	122.3379	143.0531	155.9590	139.2599
Engine19	**312.1612**	98.0877	88.8992	93.1815	65.8508	95.4225	125.6168	175.8813	105.2710
Engine20	**312.0541**	132.1172	68.7447	73.4921	82.5463	83.1047	117.3704	171.3926	113.6852
Engine21	**408.7764**	126.1234	78.7087	90.0022	84.6056	154.3017	216.4952	180.7877	162.4010
Engine22	**357.2075**	113.9020	81.3626	86.2477	88.6811	108.0284	156.8984	168.6766	167.2173
Engine23	**365.1916**	107.1407	100.0788	110.0481	84.1372	141.2020	136.9842	189.8639	133.9005
Engine24	**348.7512**	90.7906	83.4861	147.8152	80.1069	142.5302	132.6741	156.3673	125.6188
Engine25	**379.3317**	105.8238	95.9324	86.6973	83.5462	95.0041	208.6261	222.6607	82.8615
Engine26	**345.3334**	107.6179	66.9855	89.4677	88.0090	115.0575	179.8168	179.6984	97.8398
Engine27	**369.0112**	87.2041	104.3012	117.9361	101.3747	117.6585	154.5762	210.0603	107.8776
Engine28	**401.6733**	103.7590	95.1234	139.0721	95.5882	182.8787	151.9670	208.2812	114.5828
Engine29	**419.0393**	50.6342	99.8469	107.2946	75.9573	202.4934	170.7102	208.4795	179.3594
Engine30	**334.0827**	115.9056	82.3505	83.5895	92.9623	70.2271	152.0006	197.3593	93.6999
Average	**367.1644**	108.6616	92.3059	98.1181	90.1644	125.3214	160.5279	172.9841	143.8013
Std Dev	**40.8436**	17.6718	21.6787	25.3815	16.5054	45.6056	30.0949	23.4604	35.2404
Coef Var	**0.1112**	0.1626	0.2349	0.2587	0.1831	0.3639	0.1875	0.1356	0.2451

Table C.9: Normalized MA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**0.1045**	0.0236	0.0247	0.0330	0.0293	0.0699	0.0315	0.0189	0.0395
Engine2	**0.0649**	0.0221	0.0277	0.0284	0.0252	0.0212	0.0188	0.0095	0.0251
Engine3	**0.1753**	0.0749	0.0718	0.0712	0.0737	0.0623	0.0292	0.0512	0.0461
Engine4	**0.1129**	0.0346	0.0226	0.0296	0.0192	0.0621	0.0351	0.0501	0.0469
Engine5	**0.1990**	0.0869	0.0841	0.0902	0.1061	0.0521	0.0202	0.0433	0.0246
Engine6	**0.2192**	0.1010	0.1218	0.1090	0.0801	0.0345	0.0295	0.0429	0.0282
Engine7	**0.1451**	0.0886	0.0495	0.0224	0.0940	0.0227	0.0095	0.0246	0.0143
Engine8	**0.1089**	0.0289	0.0404	0.0439	0.0368	0.0397	0.0209	0.0447	0.0458
Engine9	**0.0604**	0.0247	0.0200	0.0243	0.0251	0.0216	0.0185	0.0133	0.0207
Engine10	**0.0872**	0.0297	0.0206	0.0277	0.0182	0.0223	0.0518	0.0276	0.0355
Engine11	**0.1108**	0.0514	0.0274	0.0165	0.0219	0.0585	0.0300	0.0492	0.0375
Engine12	**0.0668**	0.0252	0.0217	0.0221	0.0275	0.0172	0.0250	0.0253	0.0236
Engine13	**0.0618**	0.0290	0.0217	0.0273	0.0232	0.0175	0.0138	0.0182	0.0200
Engine14	**0.0849**	0.0451	0.0315	0.0288	0.0236	0.0341	0.0175	0.0329	0.0155
Engine15	**0.0740**	0.0276	0.0242	0.0233	0.0210	0.0132	0.0118	0.0467	0.0256
Engine16	**0.0669**	0.0310	0.0250	0.0321	0.0255	0.0169	0.0154	0.0107	0.0238
Engine17	**0.2451**	0.0974	0.1160	0.0999	0.0958	0.0636	0.0890	0.0520	0.0573
Engine18	**0.2131**	0.1289	0.0721	0.0877	0.1102	0.0324	0.0177	0.0407	0.0272
Engine19	**0.1770**	0.0732	0.0947	0.0748	0.0832	0.0352	0.0203	0.0497	0.0188
Engine20	**0.1029**	0.0300	0.0341	0.0486	0.0335	0.0418	0.0251	0.0439	0.0273
Engine21	**0.1573**	0.0851	0.0503	0.0589	0.0444	0.0611	0.0518	0.0376	0.0412
Engine22	**0.1261**	0.0654	0.0308	0.0583	0.0301	0.0421	0.0308	0.0467	0.0383
Engine23	**0.1891**	0.0832	0.0951	0.0754	0.1012	0.0295	0.0332	0.0392	0.0191
Engine24	**0.1755**	0.0852	0.0657	0.0987	0.0653	0.0398	0.0236	0.0459	0.0309
Engine25	**0.0864**	0.0294	0.0238	0.0301	0.0205	0.0483	0.0330	0.0134	0.0333
Engine26	**0.0588**	0.0278	0.0221	0.0242	0.0191	0.0130	0.0165	0.0094	0.0266
Engine27	**0.1766**	0.0755	0.0368	0.0911	0.0776	0.0562	0.0454	0.0526	0.0429
Engine28	**0.2282**	0.0893	0.1434	0.0864	0.0898	0.0524	0.0258	0.0575	0.0359
Engine29	**0.1950**	0.0227	0.0935	0.1100	0.0922	0.0518	0.0362	0.0538	0.0357
Engine30	**0.1799**	0.0847	0.0575	0.0641	0.0952	0.0411	0.0401	0.0543	0.0498
Average	**0.1351**	0.0567	0.0524	0.0546	0.0536	0.0391	0.0289	0.0369	0.0319
Std Dev	**0.0586**	0.0312	0.0353	0.0308	0.0335	0.0172	0.0157	0.0156	0.0110
Coef Var	**0.4337**	0.5492	0.6747	0.5640	0.6244	0.4388	0.5442	0.4221	0.3447

Table C.10: ARMA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**52.6516**	32.3940	8.7384	24.8503	9.9608	25.9226	6.4788	3.6615	14.2250
Engine2	**50.2788**	8.2373	16.0485	12.1667	3.5630	36.4419	6.3371	5.4403	25.3784
Engine3	**39.3286**	17.4053	15.9551	14.6989	10.2284	13.6158	9.5367	4.2463	19.3437
Engine4	**62.4462**	35.7176	24.6959	20.2077	21.5079	25.1963	15.8220	4.1910	15.4985
Engine5	**42.5100**	23.9591	17.2255	17.5982	6.9354	14.3349	9.7913	11.4967	12.0422
Engine6	**55.2721**	14.0033	22.5724	22.2635	16.5127	5.6268	10.5339	3.5708	37.7583
Engine7	**53.8074**	14.8483	11.1999	13.9891	27.3634	30.4198	20.8013	5.3729	14.7633
Engine8	**54.9633**	20.6601	31.0544	15.9000	9.1103	11.6999	32.7405	2.6411	8.8396
Engine9	**66.6483**	19.4749	19.6582	23.6183	20.5679	16.0016	8.2976	44.8495	18.9484
Engine10	**39.9297**	11.6118	16.0054	17.9320	12.6320	11.5853	8.4596	9.6218	20.5886
Engine11	**45.1981**	24.4146	9.2992	4.4190	15.4213	11.2607	26.1333	5.4664	16.2277
Engine12	**58.7865**	23.3072	37.0290	14.8437	19.6404	9.4282	4.0992	10.2063	26.9358
Engine13	**68.4717**	25.1484	39.0007	21.3710	9.7889	28.0999	30.1840	5.0973	15.9901
Engine14	**50.3154**	33.2727	8.3864	11.0447	12.5170	17.9041	14.1129	18.7860	14.2452
Engine15	**58.2663**	14.6007	46.7750	9.0648	9.6736	12.3568	18.9753	6.5429	16.2040
Engine16	**50.7963**	25.2310	23.6386	27.0159	10.8685	15.9515	10.9868	3.5222	12.2201
Engine17	**44.8075**	17.2114	18.4564	16.6096	12.8479	7.7240	9.8734	5.9394	27.1564
Engine18	**43.3269**	18.4043	12.5767	16.0660	11.0580	14.5332	8.6111	3.7734	26.4638
Engine19	**53.1835**	23.1829	19.0279	28.4775	15.6840	21.5211	9.9511	6.3788	16.4058
Engine20	**95.0560**	18.1172	13.5333	4.8386	35.8139	9.3820	18.1445	3.4907	82.3940
Engine21	**38.8524**	10.3462	11.9154	18.4363	22.9522	11.2031	10.8576	4.0079	11.5899
Engine22	**41.5182**	17.8226	11.2072	16.8378	9.7705	9.8476	9.1563	3.8072	26.5751
Engine23	**70.7091**	5.9394	13.0705	17.8576	18.2386	12.8119	13.3347	7.1285	61.2320
Engine24	**80.9783**	2.9315	11.3718	14.6754	9.2256	36.3812	9.9938	6.0447	68.2575
Engine25	**52.1642**	13.1590	22.5701	22.1909	12.6587	10.8871	13.7717	7.8282	31.8808
Engine26	**51.6703**	16.3017	10.6985	7.3263	27.9864	10.5698	18.4368	6.3627	30.9933
Engine27	**52.0411**	19.0305	11.6992	19.0396	7.8826	35.1184	18.6152	4.6332	13.5390
Engine28	**74.8042**	10.4686	44.4359	42.9322	11.9442	27.1559	3.4481	4.5250	27.4933
Engine29	**54.5329**	15.7273	16.2657	11.6227	38.2214	3.8974	11.9227	6.8532	25.7225
Engine30	**58.2395**	41.9959	18.5344	22.0574	6.9198	8.8805	14.9462	11.2563	17.9246
Average	**55.3852**	19.1642	19.4215	17.6651	15.2498	16.8586	13.4785	7.5581	25.2279
Std Dev	**12.9052**	8.7670	10.4585	7.6376	8.3837	9.3658	7.0682	7.7804	17.1407
Coef Var	**0.2330**	0.4575	0.5385	0.4324	0.5498	0.5555	0.5244	1.0294	0.6794

Table C.11: Normalized ARMA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**1.8065**	0.5344	1.0901	0.4407	0.7507	0.5048	0.4294	0.6526	0.4079
Engine2	**2.3136**	0.8446	0.9482	0.7657	1.0549	0.8031	0.7550	0.6996	0.5802
Engine3	**1.9724**	0.5312	0.8214	0.9469	0.8556	0.4421	0.5671	0.7468	0.4796
Engine4	**2.4045**	0.4641	0.5166	0.7624	1.1041	1.1431	0.7488	0.7828	1.0094
Engine5	**2.2490**	1.0418	1.0074	0.9339	0.7680	0.6171	0.7914	0.4949	0.4939
Engine6	**2.1090**	0.6776	0.9100	0.7862	0.8570	0.5424	0.8041	0.7665	0.5291
Engine7	**2.3541**	0.8960	0.8909	0.9366	1.0274	0.7706	0.7595	0.6252	0.6714
Engine8	**1.9659**	0.6105	0.7241	0.7683	0.4997	0.4295	0.7080	0.9268	0.7634
Engine9	**2.0183**	0.6588	0.8474	0.9078	0.5236	0.6868	0.7974	0.7244	0.4369
Engine10	**1.8052**	0.8690	0.5630	0.7081	0.4930	0.5145	0.5842	0.7572	0.5127
Engine11	**2.0663**	0.5162	0.8173	0.6177	0.5960	0.8886	0.8616	0.8288	0.6160
Engine12	**2.1893**	0.8821	0.9853	0.9460	0.5551	0.6876	0.8525	0.5023	0.6240
Engine13	**2.1007**	0.8637	0.6467	0.4901	1.1373	0.7001	0.7053	0.5980	0.6082
Engine14	**2.1996**	0.6243	0.8747	0.9215	0.7213	0.8579	0.8341	0.4257	0.8372
Engine15	**2.0713**	0.8210	1.0099	0.7747	0.4890	0.5707	0.7282	0.4235	0.8496
Engine16	**2.1349**	0.5558	0.6690	0.5269	0.9843	0.6860	0.7504	0.8180	0.9232
Engine17	**1.9908**	0.5398	0.8005	0.6018	0.6958	0.6665	0.7393	0.7486	0.7958
Engine18	**2.0500**	0.7839	0.7216	0.6798	0.8730	0.6973	0.6561	0.7781	0.5666
Engine19	**1.9944**	0.8956	0.6315	0.6775	0.7284	0.5539	0.6799	0.6480	0.7734
Engine20	**2.1851**	0.7813	0.5620	0.6471	0.6408	1.2873	0.8003	0.7559	0.3871
Engine21	**2.5642**	1.0779	0.7670	0.8587	0.9342	0.5847	1.0563	0.7624	1.0844
Engine22	**2.0094**	0.7940	0.7228	0.6395	0.6610	0.6984	0.6381	0.7224	0.7888
Engine23	**2.2295**	0.9115	0.8947	0.7992	0.7465	0.4826	0.7566	0.7966	0.8387
Engine24	**2.0106**	0.7312	0.5252	1.0218	0.6409	0.6157	0.7158	0.8090	0.4809
Engine25	**2.2407**	0.8107	0.7519	0.6981	1.1787	0.4589	0.7992	0.7852	0.6752
Engine26	**1.9924**	0.8136	0.5465	0.6902	0.6804	0.5402	0.6723	0.7297	0.8906
Engine27	**2.4056**	1.1440	1.1353	0.8186	0.5616	0.7598	0.7838	0.8569	0.5271
Engine28	**2.5500**	0.9876	0.9758	0.9965	1.1578	0.4775	0.6864	0.8467	0.9085
Engine29	**2.0743**	0.9763	0.8502	0.6438	0.5267	0.8186	0.6765	0.7628	0.4746
Engine30	**2.2235**	1.0439	0.9584	0.9842	0.7248	0.4542	0.6719	0.6375	0.6144
Average	**2.1427**	0.7894	0.8055	0.7663	0.7723	0.6647	0.7336	0.7138	0.6716
Std Dev	**0.1885**	0.1853	0.1721	0.1562	0.2153	0.1985	0.1092	0.1241	0.1889
Coef Var	**0.0880**	0.2348	0.2136	0.2039	0.2788	0.2986	0.1489	0.1739	0.2812

Table C.12: Filtered Angle Domain Cycle Average - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**25.2058**	3.8425	5.9297	3.8698	3.6666	9.4096	15.7844	12.7586	7.5177
Engine2	**26.9983**	5.4197	6.2877	3.5440	6.8096	10.2717	11.7648	16.7514	8.7489
Engine3	**20.0114**	4.1760	5.2465	3.0575	3.4349	8.1040	9.2968	10.7853	8.1191
Engine4	**21.9531**	4.9276	4.5757	3.1965	3.2423	8.9017	9.5380	13.0871	8.6318
Engine5	**21.2926**	4.2360	4.9936	2.9222	3.2498	8.8245	12.3497	10.7836	6.6874
Engine6	**25.0483**	5.4413	4.5928	3.1875	3.9599	8.1093	14.3489	14.7788	7.7981
Engine7	**27.9427**	3.5847	13.9201	3.5449	4.4538	8.8056	12.6898	16.1684	6.4643
Engine8	**26.0153**	6.0463	6.0177	5.4362	5.3239	8.4105	11.8690	15.5428	9.6406
Engine9	**26.1645**	3.2851	9.4117	4.8762	4.7961	7.3313	12.2513	16.1948	8.5038
Engine10	**22.5798**	3.5438	5.7292	3.6589	4.1645	6.8271	9.3607	15.9177	6.7915
Engine11	**28.5835**	4.4963	8.3342	5.2571	4.5873	8.3894	14.6913	17.3787	9.5092
Engine12	**25.9525**	7.8671	8.4547	3.4654	5.7981	7.9463	12.1873	14.2250	8.9726
Engine13	**22.8696**	6.0995	5.5861	3.6113	4.4563	7.3313	11.0313	13.3490	8.2509
Engine14	**23.2763**	4.3982	7.1801	3.4145	3.8306	7.1552	10.6726	15.0258	7.3267
Engine15	**29.3125**	8.5130	5.7100	4.2880	5.4971	8.9002	13.8453	18.1930	10.1811
Engine16	**27.3806**	5.5687	8.2315	4.7416	5.6696	8.4487	14.0135	15.8544	8.7852
Engine17	**20.0150**	4.1354	4.5344	3.5406	3.6696	7.2273	10.1407	11.3271	7.3189
Engine18	**22.6994**	3.6849	5.1245	3.6250	3.8336	8.9576	10.9481	12.3692	9.7206
Engine19	**24.4298**	5.2003	5.9759	4.8063	5.8122	7.9762	11.0395	14.9776	8.2070
Engine20	**23.5839**	3.2827	5.2109	4.1317	4.3435	7.3864	10.8018	16.3366	6.6492
Engine21	**29.0352**	3.7512	7.7871	3.5111	6.0342	8.5020	13.6830	19.4547	9.0331
Engine22	**25.0653**	4.3172	5.6301	4.5522	6.4439	7.8401	14.0725	13.4929	8.6099
Engine23	**25.8245**	4.1452	6.2625	3.6803	4.8052	8.5223	12.8033	16.4682	8.1311
Engine24	**23.9552**	4.4883	7.0252	2.9498	4.3667	6.8071	11.1330	15.0851	8.8739
Engine25	**29.1295**	9.8383	6.6085	4.6219	5.9479	7.0143	12.8065	19.5458	7.4887
Engine26	**26.5783**	5.0910	6.3713	4.0951	6.2335	7.4385	12.3237	17.8969	7.5341
Engine27	**25.3128**	5.4110	9.4066	4.2594	7.3219	6.7854	9.5031	15.9171	7.8435
Engine28	**23.4660**	5.7486	4.9643	3.2961	5.0523	6.7346	8.4998	16.5580	8.0501
Engine29	**27.6432**	1.0982	4.3431	5.0150	4.6866	8.9931	12.8707	18.7326	9.9764
Engine30	**28.8184**	6.5100	4.4250	3.6433	4.1315	7.8883	12.3881	21.0526	8.9047
Average	**25.2048**	4.9383	6.4624	3.9266	4.8541	8.0413	11.9569	15.5336	8.2757
Std Dev	**2.6731**	1.7006	2.0189	0.7059	1.0968	0.8868	1.7993	2.5731	1.0053
Coef Var	**0.1061**	0.3444	0.3124	0.1798	0.2260	0.1103	0.1505	0.1656	0.1215

Table C.13: Filtered Angle Domain - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**340.3494**	68.0240	90.5301	77.4991	51.7438	132.3390	187.2575	153.3376	135.0548
Engine2	**392.5863**	86.2192	102.9527	56.9147	106.2371	187.1432	154.0528	189.1731	164.3901
Engine3	**296.9018**	67.3901	89.3246	45.1306	47.9531	129.1137	117.8463	136.3623	148.7995
Engine4	**319.4448**	89.4057	73.6207	56.5871	47.9420	142.9462	119.4173	164.2489	146.4897
Engine5	**309.3633**	68.3326	82.5847	46.3439	43.9366	114.8298	154.4827	146.9261	146.6282
Engine6	**303.0214**	83.0992	54.4046	35.0110	42.7607	103.8612	146.8775	163.4486	140.8076
Engine7	**319.9046**	44.5499	130.7000	50.5850	53.8509	114.3129	140.7282	174.9236	119.7617
Engine8	**312.8295**	76.1960	82.9691	77.4195	73.4761	101.5730	136.8969	170.1243	125.6184
Engine9	**313.1001**	45.0741	99.2725	63.5104	65.0518	95.7258	131.1269	173.1445	146.7752
Engine10	**295.7377**	56.3932	85.4020	57.1862	58.9997	89.6167	112.5444	189.0161	117.5218
Engine11	**392.9775**	80.3077	117.9844	73.1876	56.4918	123.9000	180.2051	214.1879	178.3602
Engine12	**351.7568**	115.8473	112.3581	45.5411	99.2365	113.8618	151.1107	160.3681	155.7214
Engine13	**371.2946**	109.0391	92.2077	72.2377	73.8643	137.5754	159.5029	185.7088	167.1459
Engine14	**315.7411**	76.7582	81.9327	52.1387	55.1790	112.7473	132.6332	183.7221	131.4046
Engine15	**351.6758**	126.9162	71.8451	54.3190	62.3210	115.6719	147.1774	199.0242	144.6380
Engine16	**349.3314**	83.1936	107.5865	77.1428	75.2800	126.8911	150.0084	181.9932	142.1020
Engine17	**317.7532**	74.6723	78.5937	66.4177	61.4282	112.2866	145.7893	158.0995	148.8999
Engine18	**295.7775**	51.8075	50.7987	55.3816	43.8915	118.2950	137.8028	151.7708	145.6313
Engine19	**320.1234**	73.5920	86.6245	71.8854	78.1653	107.4019	124.9597	179.6131	137.3721
Engine20	**316.2241**	43.2377	81.2720	67.3389	63.0607	104.9339	136.7835	191.1670	129.4072
Engine21	**373.3197**	67.9845	103.5716	61.4157	91.6185	123.0395	171.2216	210.8489	151.4595
Engine22	**368.6568**	85.3054	87.1997	80.6534	102.2750	107.5399	167.7881	188.6355	169.5902
Engine23	**329.0443**	63.4068	77.9539	57.8702	68.3747	104.0673	138.6012	193.5844	150.4450
Engine24	**331.9685**	75.8446	94.5605	49.8892	57.0384	103.6249	136.4114	184.2882	162.6603
Engine25	**378.4373**	116.1885	107.2819	81.5774	81.5970	112.6172	160.6678	228.6864	118.7368
Engine26	**352.9867**	81.4252	83.8895	71.3990	88.2099	101.4233	155.9124	217.1799	127.6355
Engine27	**375.5023**	93.0080	155.7197	81.0726	93.2871	105.0862	135.8013	213.6313	133.0569
Engine28	**359.4310**	86.4748	72.3811	58.3123	71.6666	113.7698	122.0995	229.6854	165.3180
Engine29	**359.2199**	17.1492	68.2161	94.2427	83.4316	129.9899	156.4497	211.5845	148.6843
Engine30	**358.7020**	114.5647	56.8128	59.3454	54.4864	111.2428	161.3401	218.2129	140.7169
Average	**339.1054**	77.3802	89.3517	63.2519	68.4285	116.5809	145.7832	185.4232	144.6944
Std Dev	**29.6057**	24.2945	22.1320	13.6250	18.3126	18.1406	18.1459	24.9771	15.6194
Coef Var	**0.0873**	0.3140	0.2477	0.2154	0.2676	0.1556	0.1245	0.1347	0.1079

Table C.14: Filtered Detrended Angle Domain - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**340.3480**	68.0240	90.5299	77.4990	51.7438	132.3372	187.2566	153.3375	135.0547
Engine2	**392.5860**	86.2192	102.9527	56.9146	106.2371	187.1429	154.0527	189.1730	164.3899
Engine3	**296.9017**	67.3899	89.3246	45.1306	47.9531	129.1137	117.8463	136.3623	148.7994
Engine4	**319.4443**	89.4056	73.6205	56.5870	47.9420	142.9462	119.4171	164.2488	146.4892
Engine5	**309.3632**	68.3326	82.5847	46.3439	43.9366	114.8298	154.4827	146.9261	146.6281
Engine6	**303.0213**	83.0991	54.4045	35.0110	42.7606	103.8612	146.8775	163.4485	140.8075
Engine7	**319.9040**	44.5499	130.6991	50.5850	53.8509	114.3127	140.7281	174.9235	119.7617
Engine8	**312.8293**	76.1959	82.9687	77.4195	73.4760	101.5730	136.8969	170.1242	125.6183
Engine9	**313.0993**	45.0693	99.2725	63.5104	65.0517	95.7258	131.1268	173.1445	146.7752
Engine10	**295.7376**	56.3931	85.4018	57.1862	58.9997	89.6167	112.5444	189.0161	117.5218
Engine11	**392.9774**	80.3077	117.9843	73.1875	56.4918	123.9000	180.2050	214.1878	178.3602
Engine12	**351.7556**	115.8473	112.3580	45.5411	99.2362	113.8594	151.1104	160.3679	155.7212
Engine13	**371.2944**	109.0390	92.2076	72.2375	73.8642	137.5754	159.5029	185.7088	167.1457
Engine14	**315.7410**	76.7582	81.9327	52.1387	55.1789	112.7470	132.6332	183.7221	131.4046
Engine15	**351.6755**	126.9159	71.8449	54.3188	62.3210	115.6719	147.1774	199.0241	144.6380
Engine16	**349.3310**	83.1934	107.5865	77.1427	75.2796	126.8909	150.0083	181.9931	142.1017
Engine17	**317.7530**	74.6721	78.5936	66.4177	61.4282	112.2865	145.7892	158.0994	148.8998
Engine18	**295.7767**	51.8075	50.7986	55.3811	43.8915	118.2941	137.8028	151.7707	145.6309
Engine19	**320.1233**	73.5920	86.6245	71.8854	78.1652	107.4019	124.9597	179.6130	137.3721
Engine20	**316.2238**	43.2377	81.2720	67.3388	63.0607	104.9339	136.7835	191.1666	129.4072
Engine21	**373.3195**	67.9842	103.5715	61.4157	91.6185	123.0395	171.2216	210.8487	151.4594
Engine22	**368.6564**	85.3051	87.1996	80.6533	102.2748	107.5399	167.7881	188.6351	169.5902
Engine23	**329.0442**	63.4068	77.9539	57.8702	68.3746	104.0672	138.6010	193.5843	150.4449
Engine24	**331.9684**	75.8445	94.5605	49.8892	57.0384	103.6248	136.4114	184.2882	162.6602
Engine25	**378.4362**	116.1884	107.2819	81.5774	81.5970	112.6171	160.6672	228.6852	118.7367
Engine26	**352.9858**	81.4247	83.8892	71.3985	88.2096	101.4227	155.9122	217.1795	127.6354
Engine27	**375.5019**	93.0080	155.7193	81.0726	93.2871	105.0862	135.8013	213.6311	133.0568
Engine28	**359.4306**	86.4747	72.3811	58.3123	71.6665	113.7697	122.0995	229.6849	165.3180
Engine29	**359.2198**	17.1492	68.2160	94.2427	83.4316	129.9898	156.4497	211.5843	148.6843
Engine30	**358.7017**	114.5646	56.8127	59.3453	54.4864	111.2427	161.3400	218.2127	140.7168
Average	**339.1050**	77.3800	89.3516	63.2518	68.4284	116.5807	145.7831	185.4231	144.6943
Std Dev	**29.6056**	24.2947	22.1319	13.6250	18.3125	18.1405	18.1458	24.9769	15.6193
Coef Var	**0.0873**	0.3140	0.2477	0.2154	0.2676	0.1556	0.1245	0.1347	0.1079

Table C.15: Filtered FFT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**67430**	10624	16912	15405	9193	23268	42379	29101	25335
Engine2	**80908**	15727	23225	8207	25307	41269	36712	32673	30549
Engine3	**57966**	9933	19346	8268	9120	22097	28985	25458	27552
Engine4	**61370**	17646	13274	7735	9326	24230	22356	28531	35084
Engine5	**58126**	10644	17805	8684	9573	21775	27479	29024	26639
Engine6	**58567**	13502	15213	9988	10282	17465	28576	31077	26898
Engine7	**65967**	11900	35529	9605	9419	20098	26441	34553	21675
Engine8	**64327**	13327	16531	16364	13140	18651	26895	35729	29981
Engine9	**64462**	11121	20164	12415	11060	20581	23583	39989	27742
Engine10	**55043**	10546	16238	8112	9622	16918	22167	35334	21687
Engine11	**70865**	12732	22853	13734	9944	20839	33844	36609	33617
Engine12	**67264**	25947	22934	7882	21875	19852	29172	27951	27536
Engine13	**65935**	23247	17052	8956	10421	24762	29702	30311	30221
Engine14	**57027**	11530	15465	7711	8954	18582	25394	34723	23333
Engine15	**69029**	29432	12685	8569	11728	20005	29415	40366	25142
Engine16	**67098**	14438	22866	13177	13974	22880	25954	39468	25437
Engine17	**55162**	11673	14375	10624	9345	19398	25169	26331	28224
Engine18	**65369**	10509	17027	7765	9709	23478	27582	36647	32608
Engine19	**60824**	15730	16353	11754	14753	18868	22411	37026	24490
Engine20	**56547**	12138	14018	11991	11197	18914	26268	32461	21981
Engine21	**69462**	9678	20880	7785	18415	21145	33830	38109	29183
Engine22	**68483**	13009	15669	13304	22678	17385	34903	32690	31541
Engine23	**58981**	9776	13986	8527	11137	18507	27897	33952	26784
Engine24	**60533**	12092	19404	7728	10234	18674	24998	33029	30209
Engine25	**74308**	26946	20131	13621	15567	17791	37461	41457	22891
Engine26	**70437**	15623	18050	9687	17093	20190	32450	44986	22829
Engine27	**78701**	21076	39490	15745	23210	22209	23275	41601	25259
Engine28	**68088**	16114	12299	8375	12585	18317	21494	47605	30541
Engine29	**69428**	18183	13196	21453	15975	21653	28237	39084	28395
Engine30	**67092**	25133	12960	8361	9818	18446	29925	39856	26669
Average	**65160**	15333	18531	10718	13155	20942	28498	35191	27334
Std Dev	**6556**	5673	6126	3384	4792	4389	5010	5460	3571
Coef Var	**0.1006**	0.3700	0.3306	0.3157	0.3643	0.2096	0.1758	0.1551	0.1306

Table C.16: Filtered Normalized FFT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**23.6325**	7.6486	8.0182	5.3690	7.9378	9.5921	10.6625	7.5881	8.9773
Engine2	**21.1846**	7.5531	9.2446	6.6097	7.6602	5.6493	7.3735	8.1401	7.1669
Engine3	**27.0354**	6.5470	18.0308	5.0720	4.6604	9.2335	8.7596	8.2615	9.2333
Engine4	**20.7329**	5.5341	7.2819	5.4087	7.5420	8.9410	6.6676	8.6128	7.8412
Engine5	**27.2892**	11.1171	17.2192	6.4510	7.5530	6.7077	7.5496	8.0621	7.6783
Engine6	**26.9790**	16.3197	10.4314	6.3091	8.6671	5.7276	8.3486	8.4892	7.9515
Engine7	**23.2749**	5.3707	11.7116	6.2884	14.5545	4.6283	5.2222	6.7747	5.4544
Engine8	**19.0862**	5.8154	6.7509	6.3766	5.4159	5.1840	6.8683	8.6577	8.1174
Engine9	**20.2233**	8.5960	7.9574	6.2271	7.3221	6.2619	5.7343	8.2026	6.3249
Engine10	**16.1054**	6.0473	6.4325	4.5587	5.6505	4.5565	5.4478	6.7980	5.6635
Engine11	**21.4933**	5.2139	6.6983	4.9146	5.6213	7.3482	5.7796	10.5177	11.6679
Engine12	**18.6232**	6.7485	6.2366	4.8782	5.5383	7.8923	7.8721	5.9024	6.9871
Engine13	**19.7470**	7.8450	8.3663	6.1117	7.6877	5.4860	5.9331	7.4204	6.4492
Engine14	**16.4818**	5.6379	6.5059	4.8617	6.4468	4.4668	5.9915	6.6747	5.6514
Engine15	**21.1949**	6.5221	9.2989	6.5803	8.0058	6.2393	5.9815	9.2163	7.2920
Engine16	**20.9672**	7.4714	8.7524	6.0337	7.8054	6.2620	6.3708	8.6131	7.4752
Engine17	**40.3803**	11.7030	20.1591	17.4593	10.2905	12.0038	13.4248	12.1770	14.2795
Engine18	**24.4983**	10.3384	9.7262	8.0774	9.5655	6.7441	6.8080	8.7660	8.5596
Engine19	**37.2014**	13.9542	21.1077	13.3146	19.1500	5.4889	5.6437	9.4720	6.9275
Engine20	**20.9412**	7.3194	5.9430	5.3854	5.3532	7.0453	8.5736	10.4173	7.7664
Engine21	**25.3339**	5.1721	11.2352	4.2313	9.6550	8.1061	11.4729	8.3269	10.5371
Engine22	**21.6635**	6.9804	5.6262	6.6314	6.6865	5.6967	7.6032	10.0831	10.4072
Engine23	**29.3066**	6.4234	17.8641	6.1314	16.9037	4.9436	6.5572	7.9626	6.6578
Engine24	**27.4180**	10.5564	15.2105	4.9764	6.7897	7.0973	8.5410	10.5411	10.1810
Engine25	**20.4353**	7.2166	8.3088	6.0057	7.7852	6.1319	6.9501	7.2809	7.8033
Engine26	**21.1375**	7.3922	8.9963	6.4359	7.5983	6.7655	6.6409	8.0212	7.6058
Engine27	**41.9679**	20.4616	11.3608	16.7114	21.5319	9.0182	9.6794	13.4209	10.7486
Engine28	**40.3662**	21.4957	23.9795	5.1873	12.4307	6.5077	6.4867	14.6896	10.5217
Engine29	**42.0197**	7.3634	12.9328	26.6473	22.5452	8.2461	8.7812	10.2459	8.7024
Engine30	**31.2317**	21.2252	6.3390	5.5897	8.2606	6.8104	11.1235	11.7402	8.7919
Average	**25.5984**	9.2530	10.9242	7.4945	9.4205	6.8261	7.6283	9.0359	8.3140
Std Dev	**7.6271**	4.7723	5.0901	4.8348	4.7716	1.7175	2.0033	2.0123	1.9761
Coef Var	**0.2980**	0.5158	0.4659	0.6451	0.5065	0.2516	0.2626	0.2227	0.2377

Table C.17: Filtered DCT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**181.4495**	19.1336	20.1259	15.1093	18.7182	60.9538	131.7111	89.1268	50.6688
Engine2	**183.4857**	20.1308	44.2669	16.6072	40.7030	71.5554	104.9269	107.6256	40.7010
Engine3	**137.4323**	16.7794	20.4423	15.4718	17.7055	45.6786	81.7677	79.1743	50.9339
Engine4	**143.0068**	19.2764	21.1078	14.9057	17.4671	54.0404	61.4677	95.0340	58.1071
Engine5	**142.6136**	19.5641	24.3471	15.4095	18.5414	56.2895	82.6231	86.2254	36.7689
Engine6	**143.4530**	18.6485	20.1009	15.4535	18.9190	39.1661	88.7468	93.0590	34.0629
Engine7	**172.5795**	15.0537	101.1225	25.8665	19.4568	46.7807	71.3389	99.2683	33.9382
Engine8	**160.9882**	28.1489	22.0623	19.1204	19.6066	48.1567	84.0529	111.2904	46.0282
Engine9	**146.4677**	15.0132	49.5578	26.0993	18.2754	36.4703	67.3096	102.9624	35.9769
Engine10	**139.7556**	14.9257	19.8527	15.1938	18.1940	38.3332	61.2419	109.0617	35.1907
Engine11	**162.6362**	16.0967	40.9512	26.7948	22.2789	43.4478	91.9832	106.0025	41.4122
Engine12	**146.3920**	21.4111	24.7793	14.8174	20.4353	52.2857	90.9188	84.8978	38.9020
Engine13	**150.8745**	50.7638	29.7918	15.5503	23.1242	42.4405	81.4558	93.9639	35.4486
Engine14	**141.5037**	15.2900	34.2929	14.0917	17.4143	37.5578	67.8848	104.2126	35.1067
Engine15	**176.4478**	23.5560	23.1022	18.2585	29.0732	48.5777	90.6872	129.2933	39.5712
Engine16	**150.6292**	17.9764	22.0883	17.5892	26.0257	40.4384	77.0131	110.2658	34.1551
Engine17	**133.7891**	17.9091	28.3188	14.4907	19.3044	42.7103	72.3157	84.3548	44.9969
Engine18	**134.7519**	15.4573	28.5577	14.4605	17.6637	49.0499	61.7101	85.7297	54.9444
Engine19	**143.2375**	19.6068	21.3217	19.5311	22.8217	41.6199	66.7531	106.3620	35.7012
Engine20	**149.8712**	15.0412	22.1901	15.8575	22.5535	47.8498	74.0980	109.0969	36.0605
Engine21	**181.4446**	15.8025	47.0292	14.6453	33.7482	50.3811	100.1833	122.9050	37.7713
Engine22	**170.1347**	16.2389	33.4133	24.4145	44.9795	41.6166	108.0415	97.1339	45.8972
Engine23	**143.5338**	15.2301	29.7587	14.7281	18.0307	39.5606	77.4771	98.0737	41.9070
Engine24	**144.3317**	17.0741	31.3742	13.5694	24.9222	36.1406	70.3080	104.3140	40.2464
Engine25	**193.7995**	60.0991	25.3093	16.5258	34.4393	39.0411	105.6251	132.2940	40.7928
Engine26	**169.3498**	17.2255	39.8615	18.9286	33.5082	50.2453	82.5655	119.4277	41.3279
Engine27	**153.8615**	24.6659	23.4412	18.3711	50.5053	39.2269	59.8017	110.3064	48.4221
Engine28	**156.1337**	29.6541	20.4065	14.7857	31.8825	37.6053	55.9010	118.7128	56.7012
Engine29	**167.1928**	20.5926	21.4507	15.7801	18.1371	51.3608	74.5266	116.7738	68.2862
Engine30	**165.6088**	21.0293	22.2197	15.4635	20.6169	40.4097	64.3161	129.2736	57.8358
Average	**156.2252**	21.2465	30.4215	17.2630	24.6351	45.6330	80.2917	104.5407	43.2621
Std Dev	**16.4414**	10.0960	15.8784	3.7515	8.8590	8.0408	17.3083	14.2595	8.8649
Coef Var	**0.1052**	0.4752	0.5219	0.2173	0.3596	0.1762	0.2156	0.1364	0.2049

Table C.18: Filtered Normalized DCT - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**17.9137**	2.9785	4.0898	2.6502	4.2544	6.6051	12.6727	6.2690	5.1628
Engine2	**12.3076**	2.9984	4.2599	2.7077	4.0992	3.6206	5.9227	6.4616	3.2037
Engine3	**14.6386**	4.2982	5.5895	5.2487	3.5829	4.1897	6.8368	6.6123	4.0209
Engine4	**16.3789**	2.3420	3.6063	2.1299	3.7550	8.0109	8.2131	9.3828	3.3875
Engine5	**17.5864**	5.3074	7.9184	4.8260	6.5171	5.7390	7.0397	7.6970	3.3032
Engine6	**22.7420**	6.3583	6.5782	5.9424	8.3825	5.8178	12.2119	11.3067	4.1355
Engine7	**18.0180**	4.4123	9.7558	2.6353	10.3222	3.8060	5.1032	6.8951	2.9056
Engine8	**15.3325**	3.8921	3.2199	2.5868	3.0747	4.7789	7.5009	9.5864	4.7352
Engine9	**11.7837**	3.2550	3.6517	2.5650	4.2028	3.6825	4.8000	6.6285	3.1853
Engine10	**12.1779**	2.4008	3.4092	2.0764	3.4617	3.5256	5.3877	7.9848	3.0669
Engine11	**12.4325**	2.3054	4.4797	3.0329	3.2195	3.5684	5.9566	7.1632	3.1771
Engine12	**12.1590**	2.3351	3.1749	2.1441	3.4398	4.4858	7.2931	5.6843	3.2026
Engine13	**11.3027**	2.9293	3.9268	2.6019	4.0067	3.5362	4.9432	5.9017	3.0259
Engine14	**11.4374**	2.4196	3.4605	2.1264	3.6255	3.1748	5.4815	6.8119	2.9647
Engine15	**14.0132**	2.7205	4.1832	2.5982	4.0855	3.6443	4.9328	10.0390	3.1036
Engine16	**11.9951**	2.9966	4.1328	2.6384	4.1795	3.8173	4.9632	6.6458	3.1658
Engine17	**31.3206**	5.3822	14.1210	6.7945	7.1094	11.2649	14.1608	14.0957	11.3921
Engine18	**20.2599**	5.3192	12.5316	4.8887	8.5288	4.9692	5.2959	7.0154	5.1510
Engine19	**18.0643**	5.9232	6.6496	6.2479	9.4128	3.6974	5.2473	8.2835	3.0915
Engine20	**17.3551**	2.4742	3.2860	2.3742	3.5281	7.0649	8.8460	10.8340	4.5450
Engine21	**19.5547**	2.5638	7.1257	2.2190	4.7942	7.1085	11.0962	9.8901	5.0657
Engine22	**18.0755**	2.7631	4.1601	3.9627	4.9305	4.6998	10.9957	9.7652	4.8389
Engine23	**19.1882**	4.4518	10.7104	3.6318	7.5292	4.0243	6.8310	9.2059	4.0214
Engine24	**17.7071**	4.0885	7.7206	3.0174	5.6771	4.4668	7.7063	9.7594	4.6152
Engine25	**11.7809**	2.6326	3.9819	2.6546	4.0363	4.2050	5.7968	5.6338	3.1051
Engine26	**12.1348**	2.9968	4.1447	2.6719	4.2420	3.9252	5.2528	6.5460	3.1799
Engine27	**26.6413**	9.1071	3.1868	6.7862	17.2810	5.7114	7.3142	11.6639	7.0576
Engine28	**25.9217**	11.0755	10.0856	3.4997	10.9926	5.9420	7.5990	12.0329	8.7533
Engine29	**20.3462**	3.1975	6.2592	6.0953	5.8599	7.0270	8.1156	10.8181	7.7975
Engine30	**19.5430**	5.3348	4.6599	3.0373	7.3686	4.9194	7.4326	12.0643	6.5760
Average	**17.0037**	4.0420	5.8020	3.5464	5.8500	5.0343	7.3650	8.6226	4.4979
Std Dev	**5.0142**	2.0532	2.9797	1.5266	3.1186	1.7623	2.5309	2.2851	2.0113
Coef Var	**0.2949**	0.5080	0.5136	0.4305	0.5331	0.3501	0.3436	0.2650	0.4472

Table C.19: Filtered MA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**6047.77**	1065.00	1143.54	346.15	871.02	3574.62	4301.21	804.31	1153.21
Engine2	**5018.55**	480.82	4025.05	163.79	748.58	2367.13	1012.44	485.33	1141.29
Engine3	**1929.72**	539.69	801.63	98.42	503.39	480.46	783.16	312.98	1258.86
Engine4	**3379.67**	929.98	1815.75	304.48	1012.96	1485.39	1082.28	414.83	1609.89
Engine5	**3450.95**	1302.25	643.32	66.92	547.39	2277.97	644.74	754.95	1822.21
Engine6	**2540.46**	813.02	1469.10	98.27	562.83	323.67	794.12	745.66	1420.17
Engine7	**3069.29**	409.77	877.87	753.43	504.92	2496.09	684.80	816.65	541.33
Engine8	**4150.92**	488.22	2514.58	711.01	867.15	954.82	1431.59	2126.79	1388.10
Engine9	**3868.06**	1739.25	404.29	548.79	1599.93	503.57	1031.55	645.38	2679.24
Engine10	**5868.25**	750.98	3159.90	84.35	1652.48	3423.69	2952.39	708.08	458.13
Engine11	**4568.63**	1205.70	1813.62	400.80	556.39	2869.06	1101.73	797.88	2361.62
Engine12	**6697.46**	1550.48	4174.10	160.32	1106.92	418.72	1281.76	1096.95	4555.92
Engine13	**4787.85**	274.85	484.70	193.00	1240.55	3803.40	1804.14	636.66	1706.10
Engine14	**4804.17**	928.26	857.02	186.49	1065.29	3085.28	1260.02	314.70	3018.05
Engine15	**5082.45**	1365.11	576.02	679.77	868.12	1967.55	1560.22	1072.16	3868.48
Engine16	**10078.56**	228.39	606.71	415.51	2190.11	5334.02	840.43	4842.61	6601.43
Engine17	**5529.16**	3446.43	2095.77	142.55	1039.75	533.72	1081.83	465.94	3395.25
Engine18	**4252.04**	290.62	436.02	68.05	1056.90	1576.76	1661.01	3070.90	1417.04
Engine19	**6088.22**	537.15	450.66	362.79	1455.18	834.65	1541.79	5475.28	1128.36
Engine20	**4310.30**	954.64	3462.38	154.12	1325.71	372.79	1775.94	191.77	753.83
Engine21	**5972.96**	236.63	538.17	79.78	1383.55	2650.02	2879.84	731.36	4190.35
Engine22	**8045.50**	2150.58	442.42	1213.52	666.73	1321.15	1104.62	601.01	7393.60
Engine23	**2273.55**	179.98	518.67	71.60	1146.62	1097.82	867.05	585.23	1117.26
Engine24	**3536.89**	1414.55	1383.15	627.70	1086.83	1016.64	1316.12	1682.33	1193.48
Engine25	**4826.15**	775.15	635.15	980.14	3604.74	2405.03	939.84	611.11	1136.53
Engine26	**6036.89**	373.49	2974.95	464.45	1465.08	2532.41	3160.69	1174.77	2703.50
Engine27	**7742.81**	1378.39	1890.37	259.48	611.38	7128.36	1179.65	916.10	996.07
Engine28	**6510.12**	1385.85	352.65	306.84	3020.23	3001.93	610.13	4226.83	1967.47
Engine29	**3542.05**	652.49	869.76	613.35	2850.30	517.44	851.78	672.99	1190.48
Engine30	**6498.25**	922.30	502.91	501.63	1769.24	681.81	4303.53	662.90	4279.86
Average	**5016.92**	959.00	1397.34	368.58	1279.34	2034.53	1528.01	1254.81	2281.57
Std Dev	**1806.10**	687.51	1151.75	292.80	765.37	1588.03	996.40	1354.14	1721.64
Coef Var	**0.3600**	0.7169	0.8242	0.7944	0.5983	0.7805	0.6521	1.0792	0.7546

Table C.20: Filtered Normalized MA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**1.8662**	0.1033	0.4369	0.0515	0.4078	1.2660	1.0139	0.1349	0.6807
Engine2	**0.7686**	0.1063	0.4255	0.0854	0.2320	0.0819	0.3625	0.1881	0.4048
Engine3	**1.7987**	0.4163	0.9384	0.1317	0.2760	0.1911	0.8047	0.9843	0.6596
Engine4	**0.8999**	0.0848	0.3291	0.0963	0.1672	0.3771	0.5274	0.2976	0.3849
Engine5	**3.7671**	1.0676	2.5313	0.1219	2.3096	0.7528	0.2176	0.5537	0.6117
Engine6	**1.7838**	0.7283	1.1641	0.1376	0.4218	0.1285	0.2436	0.9152	0.4317
Engine7	**1.1983**	0.1077	0.5746	0.1090	0.5914	0.6608	0.1981	0.4552	0.2222
Engine8	**1.6780**	1.0334	0.4035	0.2528	0.8169	0.2316	0.5987	0.4799	0.4595
Engine9	**0.7671**	0.0571	0.3843	0.2469	0.2252	0.1001	0.4063	0.2572	0.2909
Engine10	**1.6283**	0.0821	0.8668	0.0594	0.8108	0.9060	0.5623	0.0424	0.3057
Engine11	**1.2888**	0.3710	0.6030	0.1759	0.5368	0.5139	0.1553	0.2101	0.7130
Engine12	**1.5163**	0.4145	0.5965	0.0910	0.3576	0.0649	0.3072	0.1669	1.2284
Engine13	**0.8404**	0.0839	0.3823	0.0798	0.2163	0.3715	0.3837	0.1803	0.4267
Engine14	**1.3284**	0.1356	0.7599	0.0945	0.3035	0.7025	0.3618	0.1792	0.6412
Engine15	**0.7435**	0.0864	0.4375	0.0821	0.1475	0.3079	0.2770	0.3688	0.1335
Engine16	**1.1766**	0.0873	0.3920	0.0703	0.4670	0.4208	0.2733	0.8457	0.1819
Engine17	**2.8658**	0.9725	1.7635	0.9519	0.6834	0.3951	0.2817	0.4954	1.5176
Engine18	**2.4062**	1.0632	0.5888	0.3041	1.6306	0.3906	0.6866	0.8998	0.3573
Engine19	**3.7985**	1.7577	0.6304	0.8473	2.7931	0.4784	0.3240	1.4066	0.3320
Engine20	**1.7540**	0.0888	1.4462	0.0783	0.6366	0.2614	0.6060	0.2155	0.2894
Engine21	**1.9933**	0.3169	0.5859	0.0649	0.6719	0.8810	0.8201	0.0635	1.2732
Engine22	**2.5971**	0.8842	0.4759	0.5447	0.2319	0.5002	0.2503	0.1617	2.2465
Engine23	**3.8630**	0.3146	2.4200	0.0649	0.8891	0.2532	0.9931	0.0736	2.6678
Engine24	**1.6960**	0.7286	0.9305	0.2214	0.6707	0.5696	0.3033	0.6372	0.3980
Engine25	**1.0072**	0.1241	0.2825	0.0997	0.1241	0.7723	0.3496	0.1670	0.3838
Engine26	**0.9646**	0.0876	0.3094	0.2068	0.2151	0.1037	0.4307	0.6533	0.3390
Engine27	**4.9614**	1.2158	0.4608	0.8289	0.6235	1.5541	3.9230	1.5998	1.2184
Engine28	**3.1587**	0.6015	0.4884	0.1956	1.4657	1.4178	0.4366	2.0737	0.8304
Engine29	**3.1427**	0.6482	1.0456	0.8099	2.6699	0.4090	0.2204	0.2814	0.5322
Engine30	**2.7579**	0.6035	0.3462	0.3189	1.2409	0.2390	1.6968	0.8223	1.3667
Average	**2.0005**	0.4791	0.7667	0.2474	0.7611	0.5101	0.6005	0.5270	0.7176
Std Dev	**1.1038**	0.4456	0.5798	0.2660	0.7269	0.3867	0.7059	0.4916	0.6039
Coef Var	**0.5517**	0.9302	0.7562	1.0752	0.9550	0.7581	1.1756	0.9328	0.8416

Table C.21: Filtered ARMA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**69.2902**	16.3746	16.4048	37.3154	12.0973	41.8291	13.2461	19.0251	20.9287
Engine2	**86.3107**	13.0458	30.2899	12.6971	12.0740	72.8934	14.0433	11.4865	20.3042
Engine3	**53.7818**	10.6674	14.9295	12.0633	14.8112	35.6564	10.5728	12.3742	25.5855
Engine4	**37.2539**	23.6869	10.6510	10.5813	10.2079	10.2241	12.2116	12.8112	8.9102
Engine5	**46.6042**	14.8130	19.7917	13.5342	9.9225	24.2740	8.6671	7.4218	23.6591
Engine6	**44.8918**	13.9398	16.9564	11.1109	9.4624	14.3966	12.8120	16.6163	25.9410
Engine7	**48.2479**	18.4784	15.3497	13.0159	14.1098	19.8354	11.2117	15.5407	24.9326
Engine8	**51.8421**	17.7290	21.4634	27.1533	11.1027	17.3573	18.5502	16.9244	10.9644
Engine9	**57.4366**	15.1712	16.2983	27.3957	7.0817	35.9895	7.2198	21.4857	13.9098
Engine10	**67.5940**	9.4259	21.7047	15.8311	14.9824	10.3736	12.9355	18.1261	54.1333
Engine11	**75.0754**	11.7003	19.4300	25.0565	7.2457	46.9358	11.7896	34.6700	29.9600
Engine12	**73.4462**	6.0376	25.3527	12.3409	32.8489	35.0367	32.3943	16.1970	30.7325
Engine13	**49.9036**	10.3188	15.9002	21.1277	5.5497	31.2436	7.2738	5.5287	24.3774
Engine14	**62.0449**	24.1733	10.5838	7.2684	7.6220	16.3145	6.5182	4.7345	52.0694
Engine15	**39.4578**	16.7185	15.9508	11.5417	8.6920	16.6852	14.1411	15.9524	9.0207
Engine16	**57.1382**	23.2280	23.2699	20.7303	11.2760	33.7714	11.8510	17.8097	5.3581
Engine17	**75.5958**	37.1029	14.3863	11.5180	10.4198	14.0064	16.5261	13.9954	56.7867
Engine18	**41.9292**	14.8760	14.9067	6.7059	17.7515	13.1382	15.4536	6.5632	22.3599
Engine19	**83.9547**	59.8927	22.4266	12.8886	26.6648	37.7729	7.4414	8.0596	23.1095
Engine20	**62.1245**	16.3072	13.3827	25.1309	10.3660	24.4230	22.7630	26.5857	29.2229
Engine21	**61.3309**	13.8898	13.1204	14.8218	26.2606	25.2700	11.6153	9.4119	40.3117
Engine22	**66.8486**	24.5583	29.2890	12.5296	11.3360	12.7935	11.7892	11.4170	47.8464
Engine23	**68.1668**	22.7948	8.3930	19.3625	41.9077	26.6645	13.0203	10.0458	30.7257
Engine24	**54.1233**	14.9986	10.8722	10.1327	9.4603	15.0424	12.3850	10.4660	43.6441
Engine25	**90.6234**	19.6409	19.7250	25.4021	11.1104	78.5780	11.2367	15.4715	11.3542
Engine26	**49.0256**	9.6997	16.0241	11.0393	14.9211	11.8823	11.7185	14.6484	34.8577
Engine27	**57.1652**	27.2811	25.2997	26.7486	15.1303	19.7964	10.2174	10.4757	18.2505
Engine28	**65.7914**	22.5381	19.1993	9.6942	18.2051	29.7602	12.2492	19.2256	40.2640
Engine29	**53.9756**	21.1732	14.0534	33.0309	20.7101	15.0349	11.9158	11.1346	15.9876
Engine30	**40.1571**	27.7570	14.2709	12.3255	13.6669	7.7314	11.0530	5.3982	9.4178
Average	**59.7044**	19.2673	17.6559	17.0031	14.5666	26.4904	12.8274	13.9868	26.8309
Std Dev	**14.1187**	10.1548	5.4135	7.9738	8.0653	17.0024	4.9636	6.4517	14.2175
Coef Var	**0.2365**	0.5270	0.3066	0.4690	0.5537	0.6418	0.3870	0.4613	0.5299

Table C.22: Filtered Normalized ARMA - Baseline Calculation Summary

	Overall	Accel 1	Accel 2	Accel 3	Accel 4	Accel 5	Accel 6	Accel 7	Accel 8
Engine1	**2.8089**	1.2759	0.9759	0.9509	0.8836	0.9779	0.7461	0.8772	1.1585
Engine2	**3.0513**	1.3310	1.1571	0.9590	1.3280	1.0864	0.7567	0.8733	1.0007
Engine3	**3.3677**	1.3982	1.2040	1.8920	1.1691	0.4668	0.9000	0.9494	1.0301
Engine4	**2.8050**	1.2924	0.8053	1.1822	0.9982	0.6607	0.7560	0.8659	1.1821
Engine5	**3.0789**	1.1654	1.0433	1.4347	1.1010	1.0879	0.4885	0.7092	1.3553
Engine6	**3.4672**	1.7690	1.4307	1.1497	1.1465	0.9077	0.6905	1.2355	1.1756
Engine7	**3.1258**	1.0281	1.1719	1.1136	0.8389	0.7998	1.5567	1.1649	0.9880
Engine8	**3.1770**	1.0382	1.3352	0.7908	1.6048	0.9727	0.6455	0.8334	1.4053
Engine9	**3.1796**	1.3384	1.0879	0.9551	1.2599	0.9495	1.1033	1.3145	0.8880
Engine10	**2.8099**	1.0974	1.2369	0.9199	0.9290	0.8400	0.7059	0.6172	1.3665
Engine11	**3.0446**	1.1410	1.2735	1.0223	1.1030	0.9507	0.7661	1.3176	0.9262
Engine12	**2.6964**	1.0013	0.8560	1.2300	1.1873	0.6485	0.6263	1.0535	0.8306
Engine13	**2.7512**	0.9063	1.1405	0.9391	0.8395	0.8622	1.0801	0.9858	0.9890
Engine14	**2.7751**	0.9451	1.0995	0.9125	1.0883	0.6237	1.4610	0.8393	0.5949
Engine15	**2.7500**	0.9184	1.1995	1.2348	1.0287	0.7276	0.6567	0.9113	0.9517
Engine16	**2.7528**	0.9902	1.0914	0.8256	0.9590	0.9582	1.2533	0.9162	0.6904
Engine17	**4.2188**	1.3232	2.3063	1.8713	1.1886	0.8316	0.8134	1.2130	1.7289
Engine18	**3.5603**	1.2799	1.3062	1.3188	1.2973	1.1397	0.8315	1.2645	1.5232
Engine19	**3.6248**	0.9079	1.3242	0.8913	2.4247	0.5731	1.2456	0.8766	1.1130
Engine20	**2.5334**	1.1922	1.1048	1.0311	0.6446	0.5222	0.7241	0.8711	0.8613
Engine21	**2.9956**	0.9282	1.2072	0.8566	0.8635	1.1332	0.7084	0.8386	1.6389
Engine22	**2.6083**	1.0481	0.9577	1.0091	0.7737	0.5667	0.7297	1.1705	0.9731
Engine23	**3.2902**	1.2139	1.2373	0.9578	1.6663	1.2102	0.7314	1.2192	0.8010
Engine24	**3.4855**	1.2082	1.9233	0.9376	1.0531	1.2004	0.7210	1.4194	1.0132
Engine25	**3.0459**	0.9863	1.1862	1.3337	1.2405	1.2296	0.8052	0.7589	0.9190
Engine26	**3.3509**	0.9769	1.1449	1.3635	1.2235	1.1153	1.2115	1.2700	1.1327
Engine27	**4.5722**	2.0668	1.3855	2.1678	1.4361	1.6258	1.6396	1.3571	0.8825
Engine28	**4.5309**	2.1578	2.6499	0.9774	1.1337	1.2816	1.1589	1.5129	1.1557
Engine29	**3.5132**	1.1459	1.0914	1.1842	2.0343	0.7480	1.6163	0.7678	0.7321
Engine30	**4.0885**	2.1771	1.2629	1.3778	1.3332	1.1579	1.8841	0.8973	1.0049
Average	**3.2353**	1.2416	1.2732	1.1597	1.1926	0.9285	0.9671	1.0300	1.0671
Std Dev	**0.5411**	0.3559	0.3853	0.3311	0.3671	0.2675	0.3635	0.2365	0.2697
Coef Var	**0.1672**	0.2866	0.3026	0.2855	0.3078	0.2881	0.3759	0.2296	0.2527

D. COMPARISON GROUP RESULTS

The tables in this appendix summarize the variability in the three comparison sets. In each group the six engines are analyzed and the average found in the same process as the baseline evaluation.

In Table D.1 a comparison of variability of each of the groups is displayed. The coefficient of variation of the overall results was used here as a comparison term.

Table D.1: Summary of the Analysis Methods of Each Engine Group

Analysis Method	Raw Data				Filtered Data - 3Hz to 6000Hz			
	Baseline	Compare Internal			Baseline	Compare Internal		
	5.4L 3V	Faulted	6.8L 3V	4.6L 2V	5.4L 3V	Faulted	6.8L 3V	4.6L 2V
Cycle Average	0.2125	0.2440	0.0610	0.4605	0.1061	0.1938	0.0641	0.0840
Angle Domain	0.0957	0.2738	0.0708	0.1389	0.0873	0.3680	0.0544	0.0816
Detrended Angle Doma	0.0918	0.2699	0.0708	0.0812	0.0873	0.3680	0.0544	0.0816
FFT	0.1005	0.4008	0.0672	0.0911	0.1006	0.5141	0.0608	0.0940
Normalized FFT	0.3220	0.0904	0.2385	0.0542	0.2980	0.1636	0.2541	0.0984
DCT	0.0941	0.3565	0.0692	0.0854	0.1052	0.4552	0.0591	0.1253
Normalized DCT	0.3740	0.0960	0.2647	0.1175	0.2949	0.0873	0.2670	0.0679
MA	0.1112	0.2283	0.1387	0.0809	0.3600	0.5192	0.1164	0.2368
Normalized MA	0.4337	0.0760	0.3609	0.2146	0.5517	0.3984	0.4938	0.3946
ARMA	0.2330	0.3075	0.2201	0.2527	0.2365	0.1061	0.1679	0.0840
Normalized ARMA	0.0880	0.1018	0.0267	0.0984	0.1672	0.0636	0.0654	0.1256

Results from each of the comparison group's engines and the overall results are compiled in the following tables. The overall radius of variability of each engine is listed along with its average, standard deviation and coefficient of variation.

Table D.2: Angle Domain Cycle Average - Internal Calculation Summary

	Raw Data			**Filtered Data**		
	Faulted	**6.8L 3V**	**4.6L 2V**	**Faulted**	**6.8L 3V**	**4.6L 2V**
Engine1	45.3365	20.6932	15.1183	34.0840	17.1526	9.3148
Engine2	31.0245	19.2659	39.3020	26.0549	15.8088	9.4461
Engine3	27.1120	18.9414	15.4008	21.9669	15.7254	9.5534
Engine4	26.3308	19.2567	15.5175	20.8895	16.4589	9.7831
Engine5	25.4246	17.9593	21.8840	22.1826	14.5010	11.2642
Engine6	28.4855	17.3843	16.5139	25.0376	14.7254	10.9847
Average	30.6190	18.9168	20.6227	25.0359	15.7287	10.0577
Std Dev	7.4698	1.1540	9.4976	4.8510	1.0081	0.8451
Coef Var	0.2440	0.0610	0.4605	0.1938	0.0641	0.0840

Table D.3: Angle Domain - Internal Calculation Summary

	Raw Data			**Filtered Data**		
	Faulted	**6.8L 3V**	**4.6L 2V**	**Faulted**	**6.8L 3V**	**4.6L 2V**
Engine1	895.0437	537.9337	285.5857	706.2039	379.9234	209.2431
Engine2	523.9478	510.5963	411.0770	346.6518	365.4825	265.5490
Engine3	559.2013	523.0146	307.6167	372.1265	382.1461	238.0527
Engine4	496.3012	478.4920	295.1681	318.6416	353.2498	220.2651
Engine5	485.4617	478.2129	332.6336	332.0421	334.5943	237.8213
Engine6	502.1302	442.9090	321.2203	351.8173	342.5844	235.7229
Average	577.0143	495.1931	325.5502	404.5805	359.6634	234.4423
Std Dev	157.9748	35.0398	45.2230	148.8738	19.5504	19.1296
Coef Var	0.2738	0.0708	0.1389	0.3680	0.0544	0.0816

Table D.4: Detrended Angle Domain - Internal Calculation Summary

	Raw Data			**Filtered Data**		
	Faulted	**6.8L 3V**	**4.6L 2V**	**Faulted**	**6.8L 3V**	**4.6L 2V**
Engine1	885.1642	537.7754	279.1389	706.2032	379.9233	209.2430
Engine2	520.4161	510.5277	350.0413	346.6514	365.4824	265.5487
Engine3	557.3942	522.5417	301.5163	372.1261	382.1460	238.0526
Engine4	492.9418	478.3787	288.7494	318.6415	353.2498	220.2650
Engine5	484.5747	478.1624	316.9170	332.0419	334.5942	237.8209
Engine6	500.9954	442.5745	314.7784	351.8170	342.5843	235.7228
Average	573.5811	494.9934	308.5236	404.5802	359.6633	234.4422
Std Dev	154.8329	35.0360	25.0475	148.8736	19.5504	19.1295
Coef Var	0.2699	0.0708	0.0812	0.3680	0.0544	0.0816

Table D.5: FFT - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	314318	137707	78055	183495	71001	40860
Engine2	145729	130603	97000	69405	66551	52107
Engine3	162846	130903	77837	74773	69571	43807
Engine4	144517	116948	77823	69731	61743	42806
Engine5	132870	123357	87271	66880	64430	49142
Engine6	141595	116634	83901	73441	61357	43865
Average	173646	126025	83648	89621	65776	45431
Std Dev	69603	8472	7622	46078	3998	4271
Coef Var	0.4008	0.0672	0.0911	0.5141	0.0608	0.0940

Table D.6: Normalized FFT - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	68.6240	44.3986	36.0086	29.4786	23.6799	17.9819
Engine2	63.9980	58.1996	41.3410	22.6311	29.5956	22.2107
Engine3	77.7054	56.6220	38.6199	33.1690	28.8311	22.8118
Engine4	78.5150	88.1218	36.8310	27.5008	45.3580	19.0726
Engine5	64.0707	72.4281	40.7026	22.4926	32.8938	22.8294
Engine6	72.0482	75.3412	39.3827	23.5991	43.4769	21.9144
Average	70.8269	65.8519	38.8143	26.4785	33.9725	21.1368
Std Dev	6.4038	15.7050	2.1031	4.3310	8.6332	2.0805
Coef Var	0.0904	0.2385	0.0542	0.1636	0.2541	0.0984

Table D.7: DCT - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	739.0219	363.3616	198.8880	387.2360	138.4293	95.3966
Engine2	370.1521	344.8219	247.3831	165.8187	139.4283	105.7232
Engine3	407.4625	349.6712	205.0098	166.4113	148.2992	94.6031
Engine4	361.4853	314.4366	200.7841	157.7430	135.6750	93.1582
Engine5	340.7384	323.9966	224.0766	153.6565	149.7588	126.5698
Engine6	358.9792	303.1530	217.8501	175.4803	127.4948	112.3142
Average	429.6399	333.2401	215.6653	201.0576	139.8476	104.6275
Std Dev	153.1596	23.0464	18.4283	91.5224	8.2686	13.1072
Coef Var	0.3565	0.0692	0.0854	0.4552	0.0591	0.1253

Table D.8: Normalized DCT - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	56.8434	38.1929	32.9782	19.4251	14.0518	15.1256
Engine2	57.0987	42.8667	38.3418	17.2193	15.7470	16.1830
Engine3	58.8793	40.9066	42.9649	20.9391	15.3206	16.3233
Engine4	71.2145	71.4511	37.1900	20.5687	26.0806	15.0678
Engine5	58.7395	62.1526	34.0598	16.9999	24.1162	15.1764
Engine6	55.7569	62.6527	31.3187	19.7265	23.1768	13.4400
Average	59.7554	53.0371	36.1422	19.1464	19.7488	15.2193
Std Dev	5.7382	14.0397	4.2449	1.6717	5.2725	1.0341
Coef Var	0.0960	0.2647	0.1175	0.0873	0.2670	0.0679

Table D.9: MA - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	644.02	362.98	223.84	11859.80	6244.98	5768.01
Engine2	451.44	308.90	280.78	6892.04	4633.98	5619.48
Engine3	427.90	445.13	233.82	9749.06	5819.86	5073.08
Engine4	425.60	378.17	235.72	4773.95	6284.42	2617.17
Engine5	348.00	347.52	247.29	3512.85	5101.68	5148.10
Engine6	392.90	314.32	241.73	3426.72	5503.26	4801.53
Average	448.31	359.50	243.86	6702.40	5598.03	4837.89
Std Dev	102.35	49.88	19.74	3479.63	651.71	1145.47
Coef Var	0.2283	0.1387	0.0809	0.5192	0.1164	0.2368

Table D.10: Normalized MA - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	0.1953	0.0991	0.0955	3.8467	2.3768	1.7431
Engine2	0.1680	0.0951	0.1062	1.7937	1.7902	2.2010
Engine3	0.1954	0.0928	0.1311	4.9380	1.7688	3.0701
Engine4	0.1992	0.1929	0.1027	2.5555	5.6388	2.9738
Engine5	0.1681	0.1740	0.1133	3.1520	3.0247	1.4217
Engine6	0.1846	0.1968	0.0649	1.9205	4.4817	1.0672
Average	0.1851	0.1418	0.1023	3.0344	3.1802	2.0795
Std Dev	0.0141	0.0512	0.0219	1.2089	1.5705	0.8205
Coef Var	0.0760	0.3609	0.2146	0.3984	0.4938	0.3946

Table D.11: ARMA - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	81.5315	49.3162	30.8310	59.1263	64.2127	40.8792
Engine2	40.3279	49.1178	48.2716	51.8109	77.7873	48.0163
Engine3	42.2193	35.7513	26.3216	60.1891	76.8479	48.5124
Engine4	67.0888	26.6385	35.0798	60.4747	47.5611	45.5763
Engine5	42.1760	36.6774	24.9335	50.3824	66.6537	39.4171
Engine6	52.6883	43.8004	33.8691	47.0009	74.5478	43.5349
Average	54.3386	40.2169	33.2178	54.8307	67.9351	44.3227
Std Dev	16.7084	8.8511	8.3951	5.8178	11.4090	3.7232
Coef Var	0.3075	0.2201	0.2527	0.1061	0.1679	0.0840

Table D.12: Normalized ARMA - Internal Calculation Summary

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	2.3603	2.0800	2.3510	3.2781	2.9003	2.9100
Engine2	2.0193	2.1327	1.8547	2.9223	2.7229	2.3081
Engine3	2.0776	2.0340	2.2717	3.3205	2.7072	3.0676
Engine4	2.3136	2.1014	1.9215	3.2340	3.1882	2.5014
Engine5	1.8259	1.9895	2.0161	2.9653	2.9434	3.2233
Engine6	1.9233	2.0145	1.9480	2.8847	3.0809	3.0256
Average	2.0867	2.0587	2.0605	3.1008	2.9238	2.8393
Std Dev	0.2125	0.0550	0.2027	0.1972	0.1912	0.3565
Coef Var	0.1018	0.0267	0.0984	0.0636	0.0654	0.1256

E. BASELINE TO COMPARISON GROUPS RESULTS

The tables included in this appendix convey the correlations between the baseline and the comparison groups. In each comparison group the six engines were analyzed and compared to the baseline average. The overall radius of variability of each engine from the baseline is listed in these tables along with its average, standard deviation and coefficient of variation.

Table E.1: Angle Domain Cycle Average - Comparison of Engine Groups to the Baseline

	Raw Data			**Filtered Data**		
	Faulted	**6.8L 3V**	**4.6L 2V**	**Faulted**	**6.8L 3V**	**4.6L 2V**
Engine1	54.8708	26.7171	15.7268	40.3037	20.5256	11.8671
Engine2	32.6260	26.1003	51.4937	28.2148	20.5307	11.7740
Engine3	32.7173	24.8484	15.1729	24.8048	19.8090	11.6874
Engine4	27.3943	25.0619	16.2539	22.2638	20.2884	12.1291
Engine5	26.9538	23.8720	32.0188	23.0731	18.3567	14.1211
Engine6	32.5764	22.7852	17.2097	28.3843	19.2990	13.9160
Average	34.5231	24.8975	24.6459	27.8408	19.8016	12.5825
Std Dev	10.3227	1.4353	14.6299	6.6153	0.8524	1.1241
Coef Var	0.2990	0.0576	0.5936	0.2376	0.0430	0.0893

Table E.2: Angle Domain - Comparison of Engine Groups to the Baseline

	Raw Data			**Filtered Data**		
	Faulted	**6.8L 3V**	**4.6L 2V**	**Faulted**	**6.8L 3V**	**4.6L 2V**
Engine1	1053.9649	612.2663	314.4641	836.6098	426.8289	231.3005
Engine2	556.6849	577.5677	493.4941	357.4629	411.4547	305.5497
Engine3	615.2654	589.1410	342.8023	398.9746	431.5403	269.4102
Engine4	520.7391	532.2671	327.5988	319.9223	393.0359	246.3460
Engine5	505.6413	530.9232	395.2690	335.5612	366.8368	270.0569
Engine6	533.1018	481.5188	359.9316	369.2472	378.1467	267.6082
Average	630.8996	553.9474	372.2600	436.2963	401.3072	265.0452
Std Dev	210.7728	47.8407	65.6991	198.0124	26.3112	25.2179
Coef Var	0.3341	0.0864	0.1765	0.4538	0.0656	0.0951

Table E.3: Detrended Angle Domain - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	1039.7557	608.7941	311.0378	836.6091	426.8288	231.3004
Engine2	554.7951	574.4862	403.4405	357.4626	411.4547	305.5494
Engine3	609.4272	586.0426	340.3732	398.9744	431.5402	269.4101
Engine4	518.2338	529.3330	323.8533	319.9222	393.0359	246.3459
Engine5	503.9659	528.0637	361.8327	335.5610	366.8367	270.0563
Engine6	530.5738	479.5299	356.9827	369.2470	378.1466	267.6081
Average	626.1252	551.0416	349.5867	436.2960	401.3071	265.0450
Std Dev	205.9857	47.3777	32.6742	198.0122	26.3112	25.2179
Coef Var	0.3290	0.0860	0.0935	0.4538	0.0656	0.0951

Table E.4: FFT - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	386325	170750	139573	223661	88638	76469
Engine2	156750	153539	153874	70911	81133	85572
Engine3	181656	161713	145362	82018	86355	81699
Engine4	146364	144275	139226	61740	78206	78494
Engine5	135140	143025	143937	61688	74424	80929
Engine6	150651	133713	145230	74116	75128	82767
Average	192814	151169	144534	95689	80647	80988
Std Dev	96055	13556	5321	63169	5862	3204
Coef Var	0.4982	0.0897	0.0368	0.6601	0.0727	0.0396

Table E.5: Normalized FFT - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	76.9963	42.5995	52.0905	35.6004	19.8968	28.8916
Engine2	79.4408	42.8190	55.5656	26.2021	18.6993	30.1025
Engine3	88.6063	43.4991	56.1914	42.3234	18.2874	33.0409
Engine4	102.9163	110.0428	52.4211	32.8481	57.8638	30.0160
Engine5	81.9317	93.0595	55.7650	25.5449	42.9477	32.1152
Engine6	92.1972	97.4524	49.2610	26.4676	55.6687	21.9431
Average	87.0148	71.5787	53.5491	31.4977	35.5606	29.3515
Std Dev	9.6522	31.8300	2.7476	6.7027	18.8911	3.9332
Coef Var	0.1109	0.4447	0.0513	0.2128	0.5312	0.1340

Table E.6: DCT - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	896.8781	433.4854	310.4303	460.8652	165.2153	171.3681
Engine2	397.1084	395.8179	354.4331	164.3058	161.6152	174.4111
Engine3	451.0884	413.9290	326.4286	173.3764	169.3697	173.7996
Engine4	371.0945	370.1162	312.0247	145.9087	164.2971	170.3338
Engine5	350.0905	367.8295	328.1724	149.7082	184.1841	191.3592
Engine6	381.0407	339.7298	330.4047	193.5213	152.7393	192.1207
Average	474.5501	386.8180	326.9823	214.6143	166.2368	178.8988
Std Dev	209.6883	34.2072	15.9040	121.8599	10.3949	10.0627
Coef Var	0.4419	0.0884	0.0486	0.5678	0.0625	0.0562

Table E.7: Normalized DCT - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	62.9391	40.1615	43.0150	21.8140	14.3010	23.1397
Engine2	68.9534	31.3284	47.2974	19.3073	11.5822	21.0785
Engine3	64.4246	31.5459	54.4410	23.6888	11.2308	24.1032
Engine4	88.6148	87.1222	47.0555	24.1115	32.2440	22.8043
Engine5	71.6454	77.1283	43.8579	19.1942	30.4899	22.0869
Engine6	64.7617	77.7195	35.5405	23.2345	28.6568	13.6678
Average	70.2231	57.5010	45.2012	21.8917	21.4174	21.1467
Std Dev	9.5749	25.8100	6.2148	2.1873	10.0307	3.8022
Coef Var	0.1363	0.4489	0.1375	0.0999	0.4683	0.1798

Table E.8: MA - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	778.54	444.99	243.97	14120.91	7392.65	7192.25
Engine2	464.56	391.80	329.16	5567.30	5723.53	7189.95
Engine3	461.55	491.00	308.06	11944.17	7178.85	6840.91
Engine4	420.86	380.13	316.95	2909.52	7540.73	4841.67
Engine5	385.11	411.46	280.05	3645.02	5015.47	5199.09
Engine6	397.15	329.41	318.10	2794.75	5933.04	4874.21
Average	484.63	408.13	299.38	6830.28	6464.04	6023.01
Std Dev	147.61	55.65	31.83	4953.87	1045.10	1165.50
Coef Var	0.3046	0.1364	0.1063	0.7253	0.1617	0.1935

Table E.9: Normalized MA - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	0.1914	0.0890	0.1151	4.4093	2.4267	2.7285
Engine2	0.1986	0.0572	0.1388	1.6750	0.7101	2.3330
Engine3	0.2034	0.0649	0.1408	5.2092	0.9539	2.9445
Engine4	0.2460	0.2551	0.1387	2.6731	6.5602	3.8931
Engine5	0.2000	0.2268	0.1298	3.1609	3.1321	1.7873
Engine6	0.2184	0.2223	0.0744	1.7168	5.0905	1.0249
Average	0.2096	0.1525	0.1229	3.1407	3.1456	2.4519
Std Dev	0.0199	0.0913	0.0256	1.4341	2.3106	0.9888
Coef Var	0.0951	0.5986	0.2086	0.4566	0.7346	0.4033

Table E.10: ARMA - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	98.3188	57.6440	44.2606	57.5221	59.6080	48.0296
Engine2	36.1790	58.2218	61.1343	57.8930	104.5030	62.6163
Engine3	61.2337	44.4883	30.2729	62.7748	92.7004	65.3700
Engine4	78.6032	36.7846	50.7710	71.2808	76.7517	57.5901
Engine5	41.4805	45.7762	30.9104	50.3101	68.0703	53.7582
Engine6	58.0107	45.8344	43.8443	54.8041	70.9336	58.4574
Average	62.3043	48.1249	43.5322	59.0975	78.7612	57.6369
Std Dev	23.2312	8.3085	11.8151	7.2324	16.7535	6.2067
Coef Var	0.3729	0.1726	0.2714	0.1224	0.2127	0.1077

Table E.11: Normalized ARMA - Comparison of Engine Groups to the Baseline

	Raw Data			Filtered Data		
	Faulted	6.8L 3V	4.6L 2V	Faulted	6.8L 3V	4.6L 2V
Engine1	2.4871	2.3749	2.7705	3.4969	3.2364	4.0056
Engine2	2.4552	2.4063	2.4863	3.0567	3.3689	3.8818
Engine3	2.2198	2.5555	2.6668	4.4145	3.3020	4.0487
Engine4	2.6372	2.1254	2.3232	4.0076	3.6870	4.0341
Engine5	2.2724	2.2887	1.8926	3.6106	2.9411	4.0071
Engine6	2.1717	2.7826	2.3976	3.1631	3.8613	3.6506
Average	2.3739	2.4222	2.4228	3.6249	3.3995	3.9380
Std Dev	0.1809	0.2263	0.3086	0.5143	0.3296	0.1527
Coef Var	0.0762	0.0934	0.1274	0.1419	0.0970	0.0388

F. SUMMARY GRAPHS

The graphs in this appendix are a summary of the baseline analysis and of the correlation between the baseline and the comparison groups. To clarify the contents a brief outline regarding each plot is included.

In Figure F.1 the coefficient of variation of each analysis method is displayed; this is derived from the comparison of the standard deviation to the average of each technique. A dimensionless value is provided by the coefficient of variation to relate the outcome of each method. Results from the investigation of the 30 engine 5.4L 3V baseline is the source of the presented findings. The original data from the engines was collected at a sampling rate of 33.3 kHz, which is the limiting factor of the frequency content. To provide a deeper understanding of the analysis involved the computation time of each method is also displayed. The length of the computation time is the additional time required above and beyond the current testing procedure and includes the analysis of 30 engines.

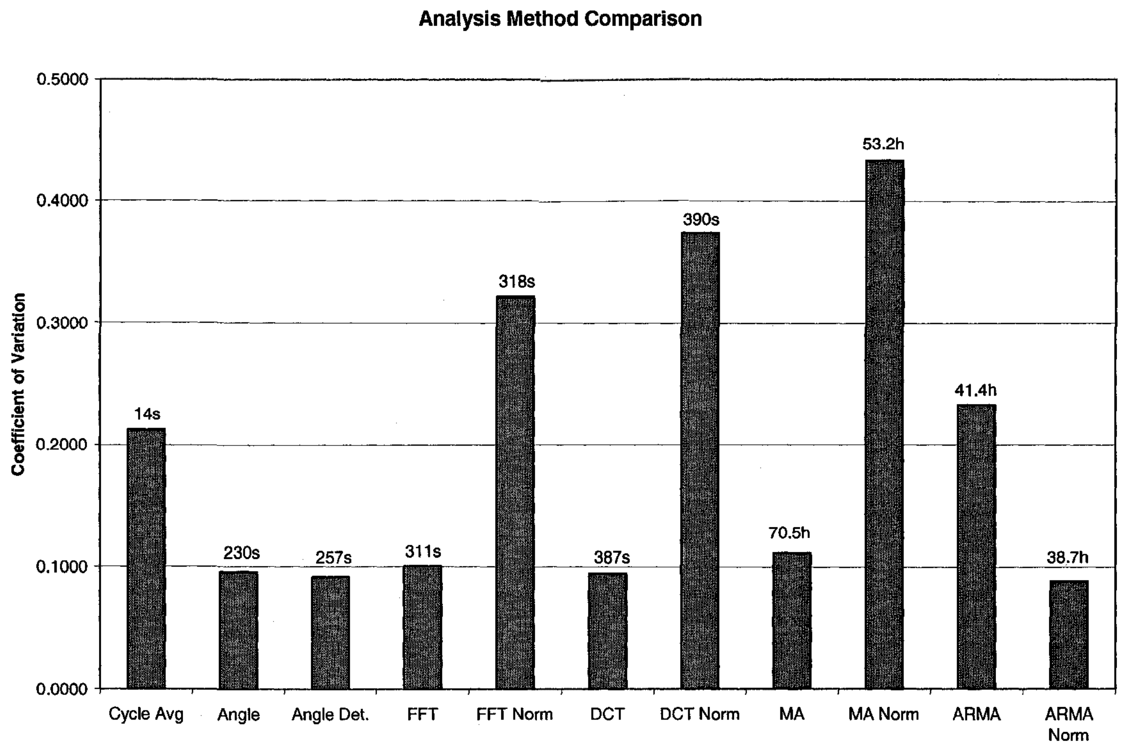


Figure F.1: Comparison of Data Analysis Methods utilizing the Baseline Data

A comparison of the coefficient of variation and calculation time of the filtered baseline data is displayed in Figure F.2. The band of the frequencies of interest was filtered from the original data before the further calculations were performed. The computation was carried out in the same manner as the results of Figure F.1. A range of 3 to 6000 Hz was focused upon to reflect the limitations of the equipment and to concentrate on the pertinent engine noise and vibration information.

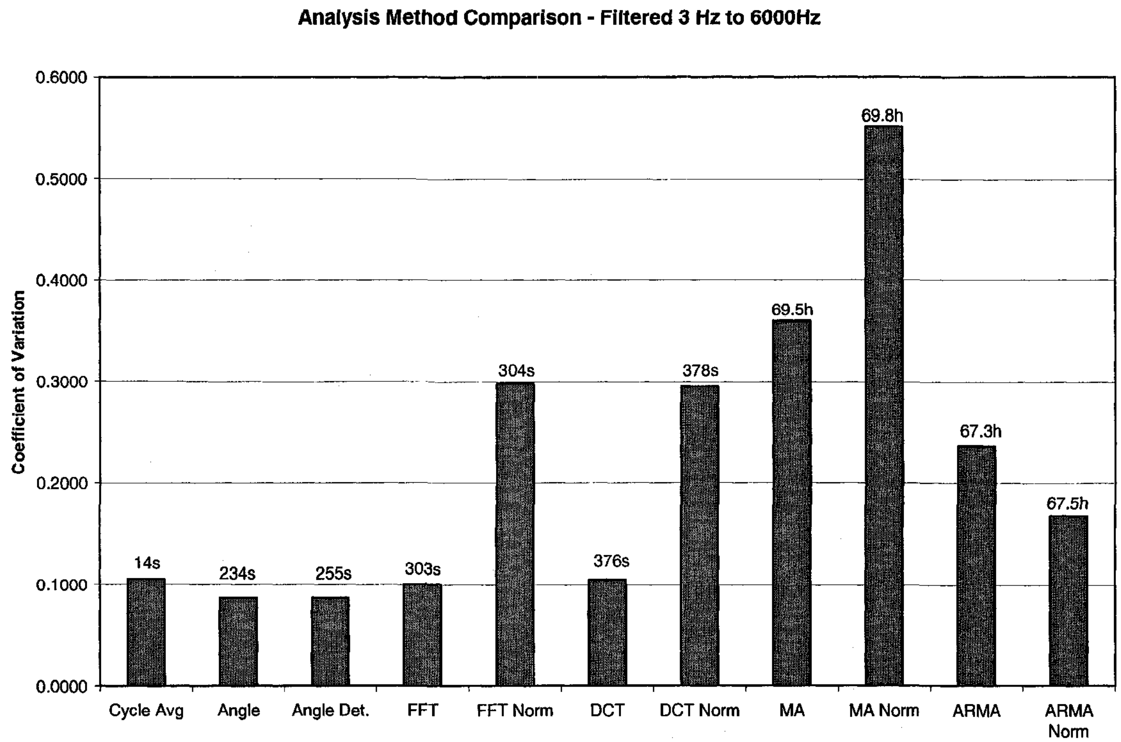


Figure F.2: Comparison of Data Analysis Methods utilizing the Filtered Baseline Data

Figure F.3 depicts the correlation between the baseline and each of the engines in the faulted engine comparison group. Engines from the faulted set were considered to be acceptable at the time of production and later were found to be defective. The engines are listed in the order of severity of defects; the first three engines have significant faults and final three possess minor defects. A coefficient of variation for each engine was calculated by finding ratio of the baseline average to the difference between the results of the baseline average and the faulted engine. The plot compares the baseline coefficient of variation to the individual engines of the faulted group.

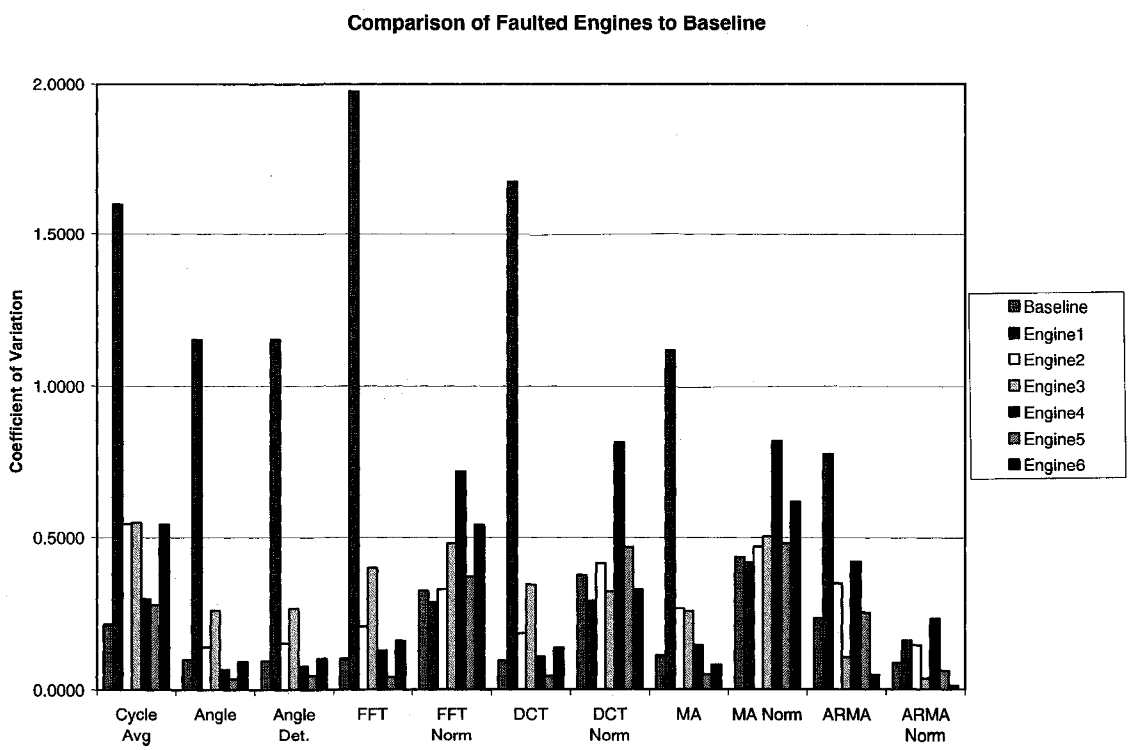


Figure F.3: Comparison of Data Analysis Methods in the Correlation of the Faulted Engine Group to the Baseline Data

Results of the correlation between the filtered data from the baseline and each of the engines in the faulted engine comparison group are given in Figure F.4. The data from both the faulted engine group and the baseline was filtered to include only the 3 to 6000 Hz frequency range. From this point the data was processed in the same manner as that of Figure F.3.

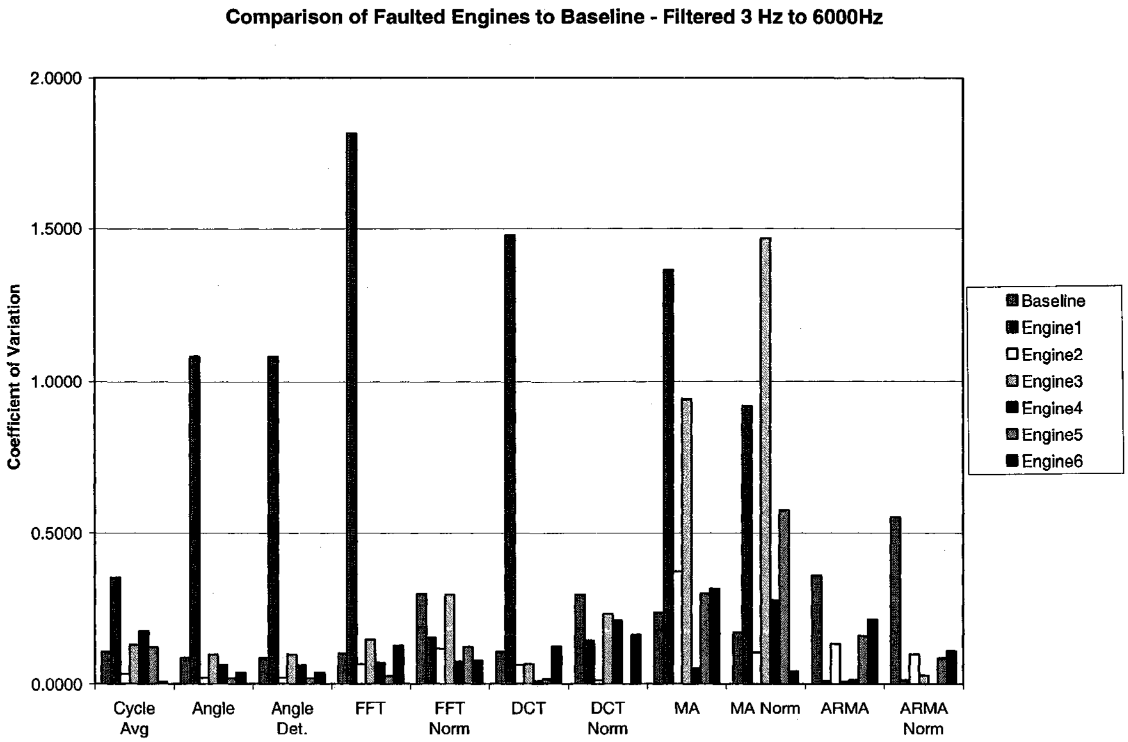


Figure F.4: Comparison of Data Analysis Methods in the Correlation of the Filtered Faulted Engine Group to the Baseline Data

In Figure F.5 the correlation between the baseline data and each of the engines in the QOS 6.8L 3V engine comparison group is displayed. Engines in the comparison set along with the baseline engines were part of a quality of service test and are considered a representative sample of the production engines. This plot depicts the similarities of the engine signatures when evaluated using the different analysis techniques.

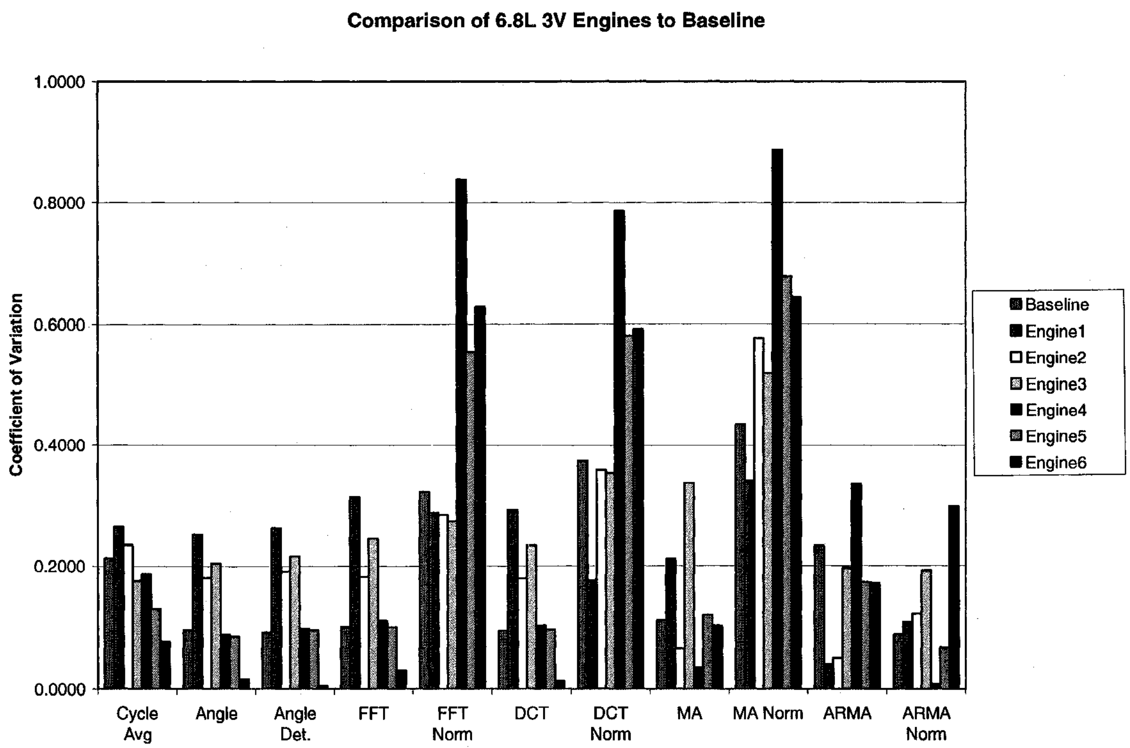


Figure F.5: Comparison of Data Analysis Methods in the Correlation of the QOS 6.8L 3V Engine Group to the Baseline Data

The correlation between the filtered data from the baseline and each of the engines in the QOS 6.8L 3V engine comparison group is illustrated in Figure F.6. The data from both the comparison group and the baseline was filtered to include only the 3 to 6000 Hz frequency range. Following the filtration data was analyzed in the same method as that of Figure F.5.

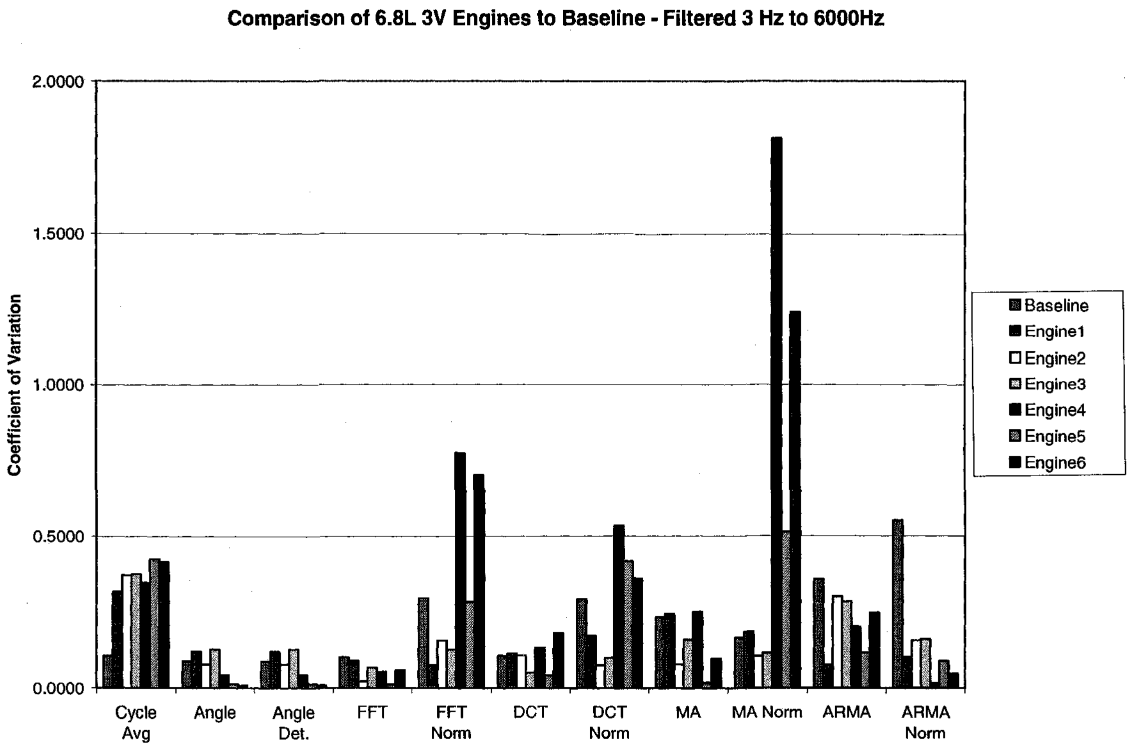


Figure F.6: Comparison of Data Analysis Methods in the Correlation of the Filtered QOS 6.8L 3V Engine Group to the Baseline Data

Depicted in Figure F.7 is the correlation between the baseline data and each of the engines in the QOS 4.6L 2V engine comparison group. These 4.6L 2V engines are a sample set utilized in the quality of service testing. The following graph illustrates the measure of variation of the engine signatures between the sample group and the baseline.

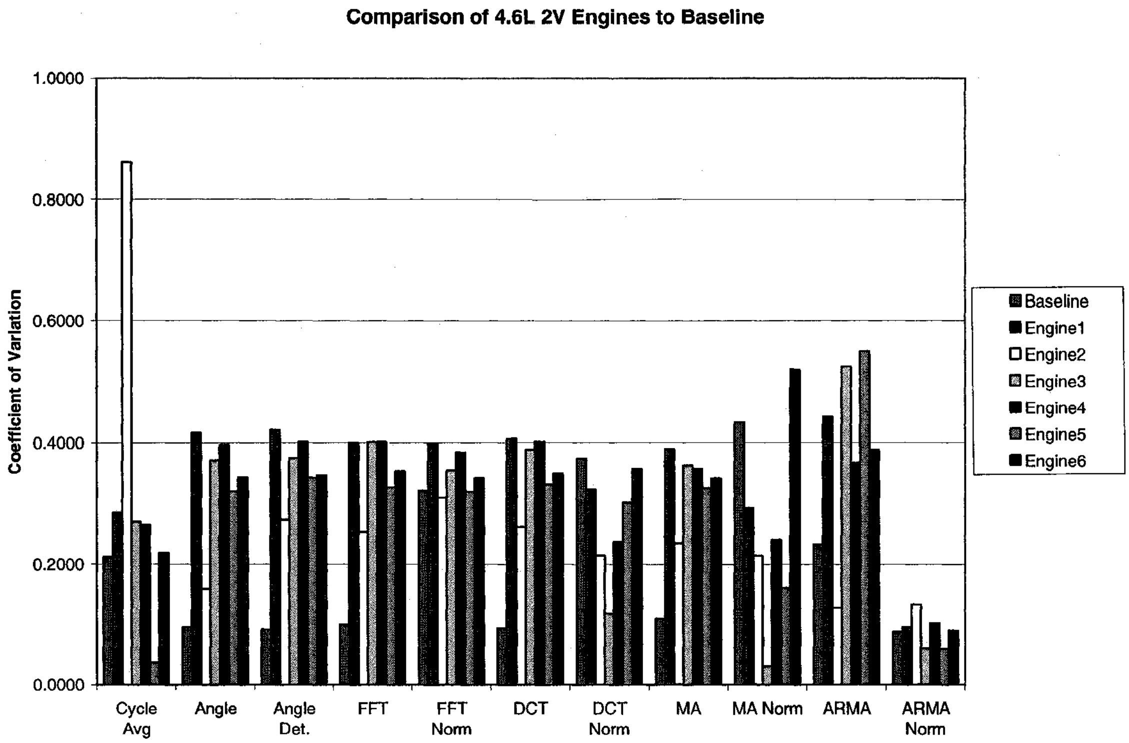


Figure F.7: Comparison of Data Analysis Methods in the Correlation of the QOS 4.6L 2V Engine Group to the Baseline Data

Figure F.8 depicts the correlation between the filtered data from the baseline and each of the engines in the QOS 4.6L 2V engine comparison group. The data from both the comparison group and the baseline was filtered to include only the 3 to 6000 Hz frequency range. After the original data was filtered the results were obtained though the same method as that of Figure F.7.

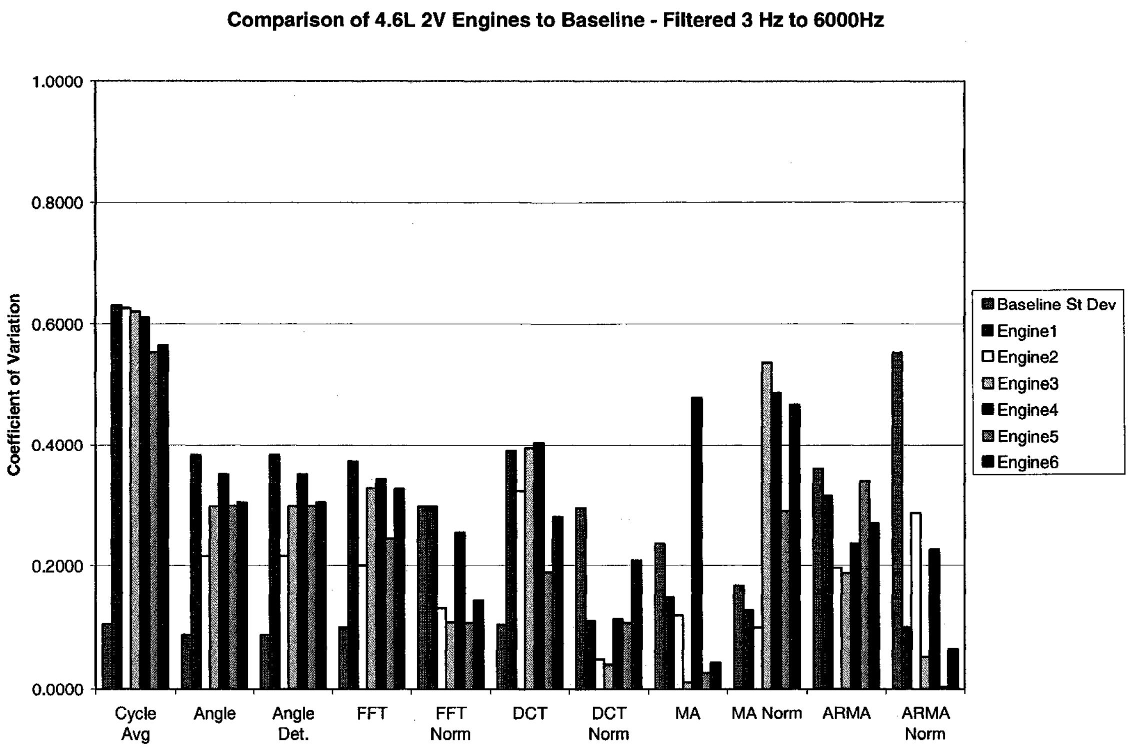


Figure F.8: Comparison of Data Analysis Methods in the Correlation of the Filtered QOS 4.6L 2V Engine Group to the Baseline Data

G. SELECTION OF THE FREQUENCY RANGE OF INTEREST

The filtered frequency range utilized spans from 3 Hz to 6000 Hz. Many different factors influenced the selection of this range and will be discussed in detail.

The frequency range of the Brüel & Kjær type 4366 charge accelerometer was the most limiting factor. Per the specifications found in Appendix A, the resonant frequency is 16 kHz and the range of five percent error in amplitude response had a maximum limit of 5 kHz. The actual calibration charts denoted that the real mounted frequency in all of the utilized accelerometers was greater than 20 kHz. Further the amplitude response in the selected frequency range was generally flat with some the accelerometer's error starting to increase just before 6000 Hz. The maximum observed error at 6000 Hz was only 3.5 % which was well within acceptable limits. Also suggestions from the manufacturer noted that the upper limiting frequency should not be greater than a third of the mounted resonance frequency [34].

The lower frequency limit was selected to include half order vibration. Sub-harmonics are generally not of interest but a half order disturbance in an engine denotes a problem that occurs once every engine cycle. Such events can indicate a misfire or camshaft issue. The idle speed of the engines under study is approximately 600 rpm; this means that the half order frequency is 5 Hz.

Combustion and structure borne vibration are the areas of key concern. In the engine the frequency spectrum of interest of combustion vibration ranges from the half order up to the twentieth order frequency. Audible noise due to structure borne vibration is focused between 1 kHz and 5 kHz. This is because the human ear is most sensitive in this range. In this experiment extending the upper end of this selected scope is to ensure the audible noise range is encompassed.

VITA AUCTORIS

Carol Lynn Deck was born on December 24, 1978 in Windsor, Ontario, Canada. She graduated from St. Thomas of Villanova Secondary School in 1996 and also achieved a French Immersion diploma. She went on to complete her Ontario Academic Credits and gained entrance into the University of Windsor engineering program. During her first year of University she selected Electrical Engineering as her program of study and graduated from the undergraduate program in the summer of 2001. After working in the automotive industry she decided to return to university to pursue her Master's. While she continued her education she also worked for prominent automotive companies in the field of noise and vibration. She is currently a candidate for the Master's of Applied Science degree in Mechanical Engineering at the University of Windsor.