VEHICLE AIR-CONDITION COMPRESSOR MONITORING USING VIBRATION SIGNAL ANALYSIS (VSA)

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BACHELOR OF MECHANICAL ENGINEERING TECHNOLOGY (MAINTENANCE TECHNOLOGY) WITH HONOURS

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DEDICATION

To my loving family and dedicated project supervisor, I am profoundly grateful for your unwavering support, encouragement, and belief in me throughout this final year project. My family, you have been my constant source of inspiration, providing love, understanding, and motivation during the highs and lows of this journey. Your sacrifices and encouragement have fuelled my determination to succeed. To my project supervisor, Ts. Dr. Nor Azazi Bin Ngatiman, your guidance, expertise, and valuable insights have been instrumental in shaping this project. Your dedication and mentorship have pushed me to explore new horizons and reach my full potential. I am indebted to both my family and supervisor for their invaluable contributions. This project is dedicated to all of you, with heartfelt gratitude for your unwavering support and belief in my abilities.

ABSTRACT

This research study focuses study on the monitoring of vehicle compressors using vibration signal analysis. Vehicle compressors are critical components in automotive air conditioning systems, and their reliable performance is essential for passenger comfort and safety. By analysing the vibration signals generated during compressor operation, valuable insights can be obtained regarding its health condition, operational efficiency, and potential faults. The proposed methodology involves the installation of vibration sensors on the compressor housing to capture the vibration signals during operation. These signals are then processed using advanced signal processing technique to extract relevant features and patterns. Machine learning algorithms are employed to classify the extracted features and identify normal operating conditions, as well as various types of anomalies, including compressor misalignment, worn bearings, and valve leaks. To evaluate the effectiveness of the proposed approach, extensive experimental tests were conducted on a range of vehicle compressors with varying models and conditions. The collected vibration data was labelled and utilized to train and validate the machine learning models. The results demonstrate high accuracy in detecting and categorizing compressor faults, enabling timely maintenance actions, and mitigating the risk of unexpected system failures. The implementation of this vibration-based monitoring system offers several advantages. Firstly, it provides real-time monitoring capability, allowing for early detection of potential issues and the initiation of proactive maintenance strategies. Secondly, it facilitates optimized maintenance schedules by enabling condition-based maintenance, thereby reducing costs and downtime. Lastly, it enhances passenger safety by ensuring the reliable and efficient functioning of the vehicle's air conditioning system. In summary, the research highlights the potential of vibration signal analysis as a robust and effective method for monitoring vehicle compressor. By employing advanced techniques, it offers a proactive to maintenance, improving the reliability, performance, and longevity of automotive air conditioning systems.

ABSTRAK

Kajian penyelidikan ini memberi tumpuan kepada pemantauan kompresor kenderaan menggunakan analisis isyarat getaran. Kompresor kenderaan adalah komponen penting dalam sistem penghawa dingin automotif, dan prestasi yang boleh dipercayai adalah penting bagi keselesaan dan keselamatan penumpang. Dengan menganalisis isyarat getaran yang dihasilkan semasa operasi kompresor, maklumat berharga boleh diperoleh mengenai keadaan kesihatannya, kecekapan operasi, dan kecacatan berpotensi. Kaedah yang dicadangkan melibatkan pemasanagn sensor getaran pada penempatan kompresor untuk merakam isyarat getaran semasa operasi. Isyarat ini kemudian diproses menggunakan teknik pemprosesan isyarat terkini untuk mengestrak ciri dan corak yang relevan. Algoritma pembelajaran mesin digunakan untuk mengklafikasikan ciri-ciri yang diekstrak dan mengenalpasti keadaan operasi normal, serta jenis anomaly, termasuk ketidakselarasan kompresor, galas yang haus, dan kebocoran injap. Untuk menilai keberkesanan pendekatan yang dicadangkan, ujian eksperimen yang meluas dijalankan pada pelbagai jenis dan keadaan kompresor kenderaan. Data getaran yang dikumpulkan diberi label dan digunakan untuk melatih dan mengesahakan model pembelajaran mesin. Hasilnya menunjukkan ketepatan yang tinggi dalam mengesan dan mengkategorikan kecacatan kompresor, membolehkan tindakan penyelenggaraan yang tepat pada masanya dan mengurangkan risiko kegagalan sistematik yang tidak dijangka. Perlaksanaan sistem pemantauan berdasarkan getaran ini menawarkan beberapa kelebihan. Pertama, ia menyediakan keupayaan pemantauan secara masa nyata, membolehkan pengesanan awal isu berpotensi dan pelaksanaan strategi penyelenggaraan proaktif. Kedua, ia memudahkan jadual penyelenggaraan yang dioptimumkan dengan membolehkan penyelenggaraan berdasarkan keadaan, dengan itu mengurangkan kos dan masa tidak beroperasi. Terakhir, ia meningkatkan keselamatan penumpang dengan memastikan sistem penghawa dingin kenderaan berfungsi dengan boleh dipercayai dan efisien. Kesimpulannya, kajian ini menyoroti potensi analisis isyarat getaran sebagai Kaedah yang kukuh dan berkesan untuk memantau kompresor kenderaan. Dengan menggunakan Teknik terkini, ia menawarkan pendekatan penyelenggaraan proaktif, meningkatkan kebolehperacayaan, prestasi dan jangka hayat sistem penghawa dingin automatif.

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LIST OF SYMBOLS AND ABBREVIATIONS

V	-	Velocity values
N	-	Number of samples, or data points
M	-	Mass
K	-	Spring constant
F	-	Force
C	-	Damping constant
X	-	Linear displacement
R^2	-	Coefficient of determination
f	-	Frequency
a	-	Acceleration
d	-	Displacement
W	-	Weight
wn	-	Natural Frequency
t	-	Time

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CHAPTER 1

INTRODUCTION

1.1 Background

A vehicle's climate control system regulates the temperature inside the vehicle and plays an important role in passenger comfort. Air conditioning compressor provide efficient cooling by circulating and compressing refrigerant. A failed compressor can be expensive to repair, increase energy consumption, and cause inconvenience to passengers in the vehicle.

To ensure that your air conditioning compressor is working optimally and to avoid unexpected failures, it is important to continuously monitor the condition of your compressor. Previous maintenance strategies usually rely on regular check-ups or temperature detectors, which may not be able to detect any early signs of compressor damage or any potential failures.

Vibration signal analysis has become a powerful technique for monitoring rotating machinery such as air conditioner compressors. Analyzing the vibration signal can provide valuable information about the mechanical condition of the compressor. This analysis enables early detection of a variety of failures such as bealting tension, bealting wear, bealting misalignment and lack of lubrication.

1.2 Problem Statement

The air conditioning compressor has an important part in ensuring passenger comfort in the context of vehicle air conditioning systems. If it fails, there might be a significant amount of discomfort, expensive repais, and higher enerygy use. For the early identification of possible compressor breakdowns, traditional maintenance techniques like routine inspections and temperature monitoring are frequently insufficient. These techniques could miss early warning indicators of damage or imminent failure, such as wear, misalignment, belt tension, or lack of lubrication. As a result, monitoring the condition and effectiveness of car air conditioning compressors requires a more comprehensive and proactive strategy.

Vibration signal analysis offers a possible fix for this issue. Nevertheless, there isn't much experience using this method specifically for maintaining monitoring for car air conditioner compressors. Comprehensive techniques for efficiently analysing the vibration signals produced by these compressors, identifying failures in real-time, and using machine learning techniques for detailed fault categorization are lacking. Therefore, the goal of this research is to guarantee that car air conditioning compressors operate at their best by creating and testing an alternative monitoring system that combines machine learning approaches with vibration signal analysis. This objective of this technology are to save maintenance costs, increase passenger comfort in cars, and increase compressor dependability.

1.3 Research Objective

The main aim of this research is to monitor of vehicle air-condition compressor monitoring using vibration signal analysis. Specifically, the objective are as follows:

a) To analyze the vibration generated by the compressor during operation. The algorithm should be capable of extracting relevant features from the signals to assess the health and performance of the compressor.

b) To detect and diagnose compressor ,belting and refrigerant faults. Design a fault detection and diagnosis system that can identify abnormal vibration patterns in real-time.

c) To validate the analyze data by using machine learning method. Collect and pre-process enough vibration signal data from the compressor during its operation.

1.4 Scope of Research

The scope of this research are as follows:

- Measure the effectiveness of wireless sensors for vibration measurement.
- Analyze the vibration signals obtained from the air conditioning compressors.
- Investigate and apply suitable machine learning or pattern recognition algorithms for the diagnosis and classification of bealting faults based on the extracted vibration features.
- Develop and apply signal processing techniques and algoritms measured to bealting fault detection.
- Conduct extensive testing and validation of the developed monitoring system using a variety of simulated or real-world bealting fault scenarios.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the past few years, given the improvements in socioeconomic situations and the growing consciousness increasing environmental awareness. To protect the environment for future generations and lessen air pollution, there has been an increase in the demand for less-polluting cars (such as hybrid electric vehicles, plug in hybrid electric vehicles, pure electric vehicles, and hydrogen fuel cell vehicles). Pure electric vehicles will be the most popular among the vehicles mentioned above as environmental awareness among people increases due to its minimal pollution and low energy usage. However, in addition to the noise and vibration issues related to standard vehicles, it's required to identify and fix major problems, such as strange noises coming from air conditioning (AC) compressors. Usually, the noise is having a low frequency. A lot of complaints have been made regarding the unpleasant sensation this gives users of these cars, and since these noises are usually avoidable without the use of acoustic material, it's possible that the only way to stop them is to improve the structural design. The ability of the complainants' low-frequency hearing and the distinctiveness of the unpleasant sound have already been the subject of extensive research by several acoustic experts of Northern Europe. One of the most crucial aspects of a vehicle's performance is its comfort, and this is one of the factors that initial research, conceptual design, product development, simulation analysis, experiment evaluation and continuous improvement everything use into consideration. In an overview, comfort is a characteristic that is monitored and considered from the beginning of a vehicle's design until the end of its use, as well as for subsequent revisions. Users think about noise and vibration performance when choosing a car because it's a crucial part of comfort in a vehicle.

Vehicles with conventional engines produce more noise than electric vehicles, therefore the noise of the electrical system is more emphasized. In the product design and development process of one type of pure electric vehicle, the start-up phase of the AC compressor is accompanied by 'clicking' and 'whooping' sounds, neither of which are admissible. The source must be located first and foremost. Two methods can be used to approach this. System the AC compressor differently and continually evaluate the outcomes to create fresh versions of the design to maximize it. Generating noise goal levels by comparing your car to those of competitors. Analyzing the body frame vibration mode frequency and form as well as the interior vehicle body sound pressure field distribution is required to confirm the noise transfer path and vibration response responsible for the abnormal noise in the AC compressor. Over the last few years, there have been some advances in acoustic numerical calculation methods, such as the smoothed finite element method (S-FEM), the stable node-based smoothed finite element method (SNS-FEM) and the element decomposition method (EDM) have all seen some advancements during the past several years. There is also gradient smoothing technique (GST), which is employed to simulate both highly deformed models and local geometry. Higher precision, computational efficiency, dependability and stability, and a significantly faster convergence rate are the benefits. This indicates that the goal might be met while cutting back on expenses and development time. All these techniques can be used for engineering acoustic simulation prediction and for the structural-acoustic properties of vehicle bodies in the design and development of the automotive industry. In this paper, the aim to analyze the vibration generated by the compressor during operation, to detect and diagnose compressor and bearing faults and to validate the analyze data by using machine learning method.

2.2 Condition Monitoring of Vibration

Monitoring a resource's condition using data is the process of condition monitoring. Vibration sensors, temperature sensors, and oil analysis are just a few examples of the sources from which this information may be gathered. Condition monitoring to foresee prospective issues in advance so that preventative measures can be done before a failure takes place (Tiboni M, Remino C, Bussola R, Amici C, See fewer, (2022). Predictive maintenance can assist to avois unplanned downtime and expensive repairs by using the essential instrument of condition monitoring.

2.2.1 Vibration Amplitude

The distance between an object's equilibrium position and its peak displacement is shown by the vibration amplitude, which is an essential indicator of an object's greatest displacement. Its dimensions can be expressed in terms of millimetres, inches, or micrometres(m) . A movement of micrometers from the object's equilibrium position, for example, is indicated by a vibration amplitude of 100m. In vibration analysis, this metric is important since it helps to spot possible problems with spinning machinery (Zhiwei, C., & Yigang, L 2018). High vibration amplitudes may indicate bearing wear or machine imbalance, allowing for prompt action to avoid unplanned downtime and costly repairs. Vibration sensors can transform vibrations into electrical impulses, which may then be amplifies and monitored, as one technique of measuring vibration amplitude. Laser vibrometers also use laser beams to examine the reflected beam and gauge the vibrations amplitude. Assessing vibration amplitude enables the early dicovery of mechanical issues leading to better maintenance procedures and operating effectiveness.

2.2.2 Vibration Frequency

Vibration frequency, expressed in hertz (Hz), is the rate at which a vibrating item completes one cycle of motion per second. Fir instance, an object's frequency is 100 Hz, which denotes 100 vibrations per second, if it completes a cycle once every 0.01 seconds. In vibration analysis, this value is important for identifying possible problems with spinning machinery. High vibration frequencies may indicate bearing degradation or machine imbalance. The vibrating frequency of an item in the absence of outside forces is represented by its natural frequency, which is dictated by its mass and stiffness. The frequency at which an item vibrates in response to a periodic force is known as the resonant frequency, which is equivalent to the natural frequency (Zinkovskyi A. P. Savchenko K. V. , 2023). Vibration sensors that transform vibrations into electrical impulses, which are then amplified and analysed, are on way to monitor vibration frequency. It is also possible to use laser vibrometers, which use laser beams to examine the reflected beam and establishthe vibration frequency, early detection of equipment issues is made feasible, allowing for the development of preventative measures to avoid unacticipated downtime and expensive repairs.

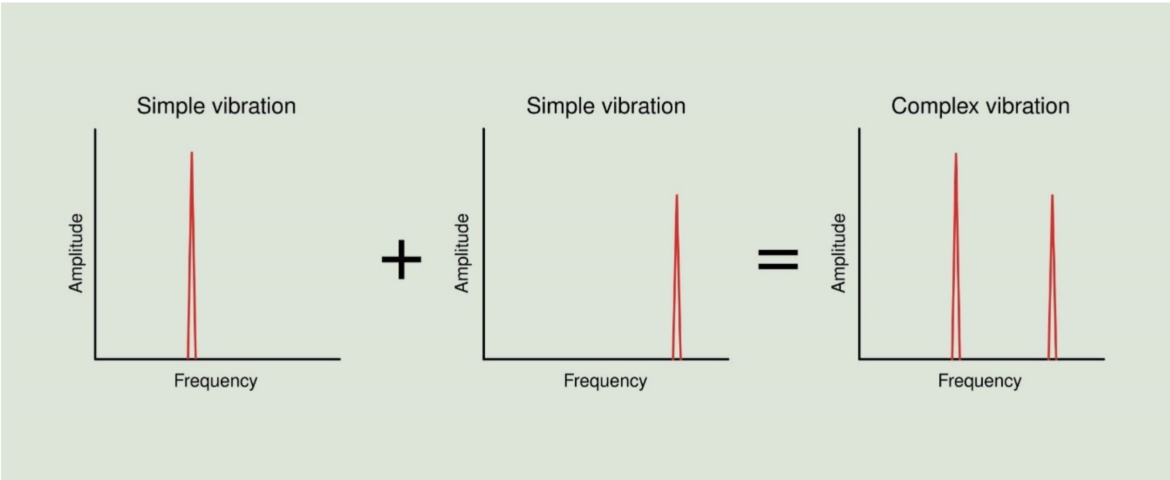

Figure 2.1 Vibration Frequency

2.2.3 Vibration Spectrum

A vibration signal's frequency content is graphically represented as the vibration spectrum, which sheds light on various frequencies and their accompanying amplitudes. It aids engineers in analysing a systems or machine's vibrational properties. The power spectrum is a popular tool for displaying squared amplitudes at each frequency component. It is a frequency domain plot where frequency is on the horizontal axis and amplitude is on the vertical axis. With the use of this spectrum, vibration sources such as rotational speeds, harmonics, bearing flaws, gear meshing, and resonance frequencies may be located, and prominent frequencies and their amplitudes can be determined. When compared to reference spectra, anomalous peaks or patterns in the spectrum can be used to identify flaws, defects, or imbalances early on (Hady, H. A.2023). For condition monitoring, preventive maintenance, and maximising machinery performance and longevity, this analysis is essential, the vibration spectrum provides a through visual representation of frequency content and amplitudes, supporting efficient defect identification, diagnosis, and maintenance techniques.

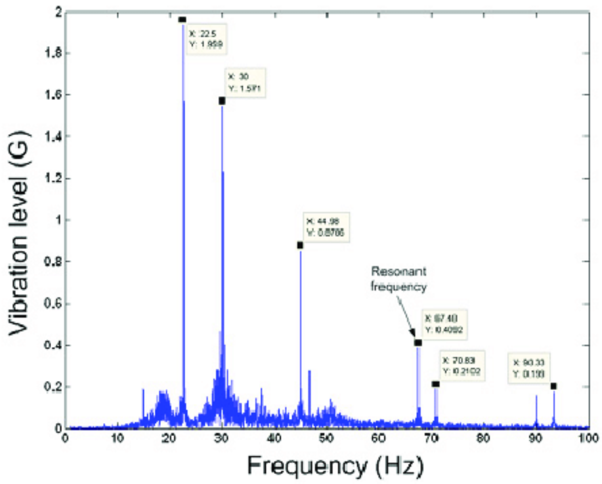

Figure 2.2 Vibration Spectrum With Multiple Peaks at Different Frequencies

2.2.4 Root Mean Square (rms) Velocity

The average vibrating object's root mean square (RMS) velocity is a scalar quantity that may be computed by calculating the square root of the mean square of the vibration velocity. RMS velocity has magnitude but no direction, unlike vibration velocity, which is a vector quantity (Kudryavtseva I.S, Naumenko A.P, Bardanov V.E, 2019). Due to its capacity to reveal the object's average energy since the square of the velocity is proportional to the object's energy, it is a useful parameter in vibration analysis. RMS velocity measurement identifies possible problems with rotating machinery, such as imbalance or bearing wear, allowing for early intervention to avoid unanticipated downtime and expensive repairs. The formula for RMS Velocity is:

$$RMS\ velocity = \sqrt{\Sigma(\frac{v^2)}{n})}$$

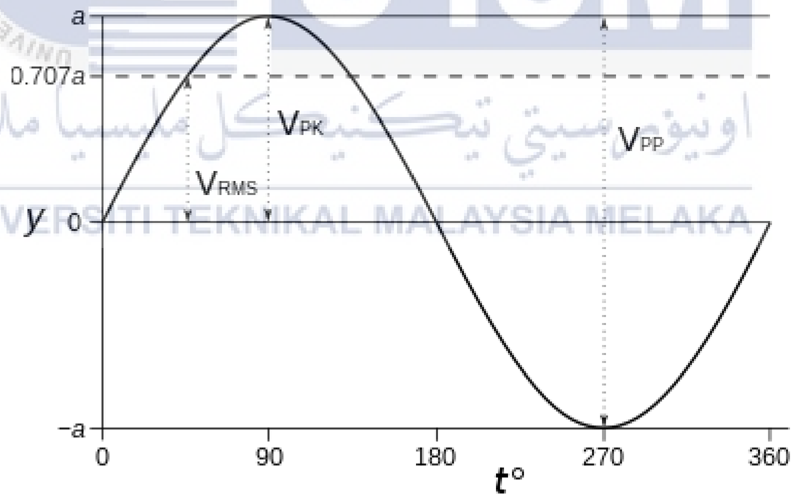

Figure 2.3 Root Mean Square Amplitude

2.2.5 Overall Vibration Severity (OVT)

entire vibration severity (OVT) is a single numerical measurement that measures and assesses the entire intensity of vibration in a machine or system. It incorporates vibration amplitudes from several frequency bands into a thorough analysis. Sensors are used to acquire vibration data, which allows for the capture of motion along many axes (Armstrong E.K, Stevenson R.E, (2023) . To extract frequency information, frequency analysis methods like Fourier or wavelet analysis are used. To get the OVT value, amplitudes within frequency bands are assessed, weighted according to their significance, and added. Potential problems or anomalies in the system can be found by analysing OVT against predetermined criteria. Early failure identification is made possible by tracking patterns in OVT. OVT offers a standardised depiction of vibration levels, permitting rapid tests, upkeep choices, and risk reduction. For creating acceptable thresholds and reaction strategies, it is advised to contact pertinent standards and specialists as interpretation might differ.

Table 2.1 Vibration Severity

VIBRATION SEVERITY PER ISO 10816-1						
	Machine		Class I	Class II	Class III	Class IV
	in/s	mm/s	Small Machines	Medium Machines	Large Rigid Foundation	Large Soft Foundation
Vibration Velocity Vrms	0.01	0.28				
	0.02	0.45				
	0.03	0.71		GOOD		
	0.04	1.12				
	0.07	1.80				
	0.11	2.80		SATISFACTORY		
	0.18	4.50				
	0.28	7.10		UNSATISFACTORY		
	0.44	11.20				
	0.70	18.00				
	1.10	28.00		UNACCEPTABLE		
	1.77	45.90				

2.3 Classification of Vibration

The wide range of vibrations in structures, devices, and human activities makes them a subject of several studies. Vibrations are an ongoing danger to structures and machinery, whether they come from operational issues like rotating or reciprocating imbalances or environmental issues like earthquakes and wind loads. The systems may experience wear and perhaps failure because of these vibrations powerful effects. The structural integrity and durability of the systems depends on an understanding of and control over these vibrations (Liu F, Ye Z, Wang L, 2022).

In addition, vibration also has different forms in involving human activities. Vision is based on electromagnetic waves, while speech and hearing depend on sound vibrations. ergonomic issues bring about negative effects of vibration on humans. Therefore, human well-being is important in considering the effects of vibration on humans.

Different strategies are being used by engineers and research to track vibrations. To protect structures, machines, and human occupants the main goal is frequently to minimize or reduce vibration levels. In some instances, it could be necessary to change the system's design so that it can resist the anticipated vibrations (Martinez-Rioz E.A, Bustamante-Bello M.R, Arce-Saenz L.A, 2022). However, there are situations where vibrations are purposefully used or improved for specific objectives. Examples include sound systems, accelerometers, vibratory conveyors, and clocks. Achieving these goals requires a thorough understanding of vibration mechanics and how they affect physical variables.

There are multiple methods to categorize vibrations, and each one provides information about their characteristics and behaviors. Engineers can more accurately analyses, model, and minimizes vibrations by classifying them.

2.3.1 Structure in Vibration

The three main elements of a vibrating systems affect by its three main properties is mass, stiffness, and damping. The quantity of substance in the system is represented by mass, which offers inertia and resistance to changes in motion. The system stiffness affects its resistance to deformation as stiffness rises, movement requires more force to move it

(Kumar, A., Sathujoda, P., & Bhalla, N. A. 2022). The pace at which vibrations stop can be controlled by damping, which is the dissipation of energy in the system. The natural frequency at which the system vibrates without the assistance of outside forces is represented by the natural frequency, which is dictated by mass and stiffness. The system vibrates close to its native frequency in response to an external stimulation, which could result in resonance and a large rise in vibration amplitude.

2.3.2 Airbone in Vibration

The term "airborne vibration" describes the movement of vibrations from one object to a different one through the atmosphere. It can come from various sources, including equipment, traffic, earthquakes, and it can be annoying and harm property. The inconvenience brought on by jackhammer vibrations, structural damage brought on by automobile engine vibrations, and extensive damage brought on by airborne vibration during an earthquake are a few examples of airborne vibration. To reduce airborne vibration, a variety of techniques can be used. It is possible to stop vibrations from travelling through the air by using vibration isolation mounts, which isolate vibrating objects from the ground. Additionally, by absorbing sound waves, the use of soundproofing materials contributes to reducing the transmission of airborne vibration. The best method for decreasing or eliminating airborne vibration depends on the unique situation (Yi Zong, Jianxin Li, Mingliang Duan, Guoliang Chen, Wenqian Lu, Rihong Zhu, and Lei Chen. 2019).. However, the effects of airborne vibration on people and things can be reduced by using vibration isolation mounts and soundproofing materials. When attempting to comprehend airborne vibration, it is important to consider its frequency (stated in hertz), amplitude (stated in meters), and power (stated in watts). To measure airborne vibration, devices like vibrometers, accelerometers, and sound level meters are used. This information is used to determine the source of the vibration, evaluate how severe it's, and develop mitigation plans. Applications of airborne vibration encompass vibration monitoring for assessing the condition of machinery and structures, vibration control to mitigate noise and prevent structural damage, and vibration sensing for object and event detection. Given the complexity and potential impact of airborne vibration, comprehension of its causes and effects allows for the development of strategies to minimize or eliminate its adverse effects on individuals and assets.

2.4 Type of Vibration

Free vibration, forced vibration, and damped vibration are types of vibration. A system vibrates naturally when it is set in motion and allowed to follow its natural frequency, which is defined by its mass and stiffness. When a system is subjected to a periodic force, it vibrates at the forces frequency, with the amplitude depending on the strength of the applied force and the damping of the system. Contrarily, damping causes a system to experience damped vibration, which eventually results in a reduction in the amplitude of the vibration. The rate of amplitude reduction is controlled by the damping ratio. For analyzing and managing the dismiss of vibrating systems, it is essential to comprehend these kinds of vibrations.

2.4.1 Free and Natural Vibration

When a system is set in motion and left to vibrate on its own to accord, following the natural frequency specified by its mass and stiffness, this is known as free vibration. An example of free vibration is a swing, which after an initial push imparts displacement and velocity oscillates at its natural frequency until all energy is lost. The natural frequency is the system's fundamental vibration frequency that is unaffected by outside forces and depends on the mass and stiffness of the system. The stiffness defines the system's resistance to deformation, requiring more effort for displacement, whereas the mass identifies the system's amount of matter, affecting its inertia and resistance to motion changes.

The highest deviation of the system from its equilibrium position is the amplitude of free vibration. Due to damping, the amplitude of free vibration gradually diminishes. Damping refers to the process of energy dissipation in a system. If a system has higher damping, it will stop vibrating more rapidly. Method how to increase the damping of a system:

- Adding mass to the system
- Increasing the stiffness of the system
- Using damping materials

If the damping of a system is increased, it can decrease the amplitude of free vibration. This can be beneficial in preventing harm to the system and enhancing the comfort of passengers or operators.

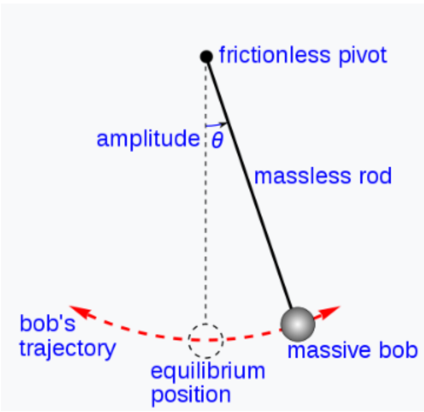

Figure 2.4 Example of Natural Frequency: A Pendulum

2.4.1.1 Theoretical Calculations of Natural Frequency

Considering first the free vibration of the undamped system, Newton's equation is written for the mass m. The force mx exerted by the mass on the spring is equal and opposite to the force kx applied by the spring on the mass:

$$mx + kx = 0 \tag{2.1}$$

Where $x = 0$ defines the equilibrium position of the mass.

The solution of the equation:

$$x = A \sin \sqrt{\frac{k}{m}} t + B \cos \sqrt{\frac{k}{m}} t$$

(2.2)

Where the term $\frac{\sqrt{k}}{m}$ is the angular natural frequency defined by

$$\omega n = \frac{\sqrt{\frac{k}{m}} rad}{sec} \tag{2.3}$$

sinusoidal oscillation of the mass repeats continuously, and the time interval to complete one cycle is the period:

$$\tau = \frac{2\pi}{\omega n} \tag{2.4}$$

The reciprocal of the period is the natural frequency:

$$fn = \frac{1}{\tau} = \frac{\omega n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{kg}{W}} \tag{2.5}$$

Where W= mg is the weight of the rigid body forming the mass of the system show.

2.4.2 Forced Vibration

Forced vibration is a type of vibration that occurs when an external force is applied to a system, causing it to vibrate at a specific frequency. The system can be anything from a simple mass-spring system to a complex mechanical structure such as a bridge or a building. The frequency of the forced vibration is determined by the frequency of the applied force. If the frequency of the applied force is equal to the natural frequency of the system, then the system will vibrate at a large amplitude (Kang S.H, Kim Y, Cho H, Shin S.J, See Fewer, 2022). This is known as resonance. If the frequency of the applied force is not equal to the natural frequency of the system, then the system will vibrate at a smaller amplitude.

Forced vibrations can be used to control the motion of a system. For example, a car's suspension system uses forced vibrations to dampen the effects of bumps in the road. Forced vibrations can also be used to generate sound. For example, a guitar string vibrates when a musician plucks it, and this vibration is amplified by the body of the guitar to produce sound. Here are some examples of forced vibrations: a child on a swing being pushes by an adult, a car driving over a bumpy road, a tuning fork vibrating when struck, a guitar string vibrating when plucked, and a loudspeaker vibrating when an electrical signal is applied.

Forced vibrations can be beneficial or harmful, depending on the situation. For example, forced vibrations can be used to control the motion of a system, but they can also cause damage to structures if the forces are too great. Vibration control is one of the applications of forced vibrations. It can be used to control the motion of a system by applying a force that cancels out the natural frequency of the system. This can be used to reduce vibration in bridges, buildings, and other structures. Sound generation is another application of forced vibrations. Forced vibration can be used to generate sound by applying a force that causes a structure to vibrate. This is how musical instruments such as guitars and drum work. The frequency of forced vibrations can also be used to measure the properties of materials, such as their stiffness and damping. Finally, force vibrations can be used to detect problems with machines, such as unbalanced rotors and worn bearings (Zhang S, Xing Y, Xu H, Pei S, Zhang L (2020).

There are many benefits to using vibration measurement equipment. By highlighting the root causes, it makes early problem detection possible, enabling prompt action and failure prevention, saving time, and assuring safety. It also enables proactive failure prevention efforts, reducing disruptions and related expenses. Furthermore, detecting vibration levels and lowering them improve performance, maximizing output, energy use, and product quality. In total, the reliability, safety, and efficiency of various sectors are significantly increased by vibration measurement equipment.

2.5 Equipment to Measured Vibration

Equipment vibration measurement uses sensor to measure the vibration of spinning machinery and collects information on its amplitude, frequency, and intensity. These measures help to pinppoint potential equipment problems such imbalance, looseness, misalignment, or bearing wear. Vibration measurement is a crucial instrumennt for condition monitoring since it enables the early diagnosis of issues before they result in failures, saving time and money by avoiding expensive downtime and repairs. Vibration can be measured using a variety of sensors, including accelerometers, velocity sensors, and displacement sensors. The obtained vibration data is often recorded using a data collecting device, which achives the data for further analysis using software.

It is possible to identify a number of problems, including imbalance, looseness, misalignment, and bearing wear, by analysing vibration data collected from rotating machinery. High-frequency vibrations are caused by an imbalance, which is the uneven distribution of the rotating mass. Low frequency vibrations are caused by looseness, which signals excessive movement between equipment parts. A misalignment is an incorrect alignment of spinning shafts that results in a mix of gigh and low frequency. High frequency vibrations are caused by worn out bearings inside the machinery, which is what bearing wear indicates.

Equipment vibration assessment involves the use of sensors to monitor the vibration of rotating machinery, analysing amplitude, frequency, and intensity to find potential problems such imbalance, looseness, misalignment, or bearing wear. Regular vibration monitoring allows for early problem detection, which prevents failures and expensive repairs, saving time and money. Vibration is typically measured using accelerometers, velocity sensors, and displacement sensors. Recorded data is gathered using a data acquistion device for later analysing using different software applications. Early problem identification enables prompt corrective action, averting failures and reducing downtime and maintenance costs. Additionaladvantages of equipment vibration measurement include improved safety through the detection of dangers and increased efficiency through improved equipment performance and lower operating expenses.

If you are in charge of rotating equiment maintenance, it is highly advised that you apply vibration measurement as a condition monitoring tool. Vibration measurement allows you to spot possible problems at an early stage, reducing the chance of failure and ultimately saving time and money. Futhermore, it helps the safety and effectiveness of your operations.

2.5.1 Tranducer to Measured Vibration

A transducer is a device that transfers one type of energy into a different type of energy. In the case of vibration transducers, mechanical vibrations are converted into electrical signals. This may be used for a multitude of applications, including monitoring the state of machinery, detecting vibration intensity, and producing sound.

Accelerometers and velocity sensors are the two most common categories of vibration transducers. While velocity sensors monitor the object’s velocity, accelerometers measure the object’s acceleration. A vibration transducer’s output signal may be used to determine the vibration’s amplitude, frequency, and phase.

Vibration transducers are essential in many applications and provide a variety of advantages. These tools make it possible to detect vibration intensity, sound production, and machinery condition. One of the main benefits is the early diagnosis of issues, allowing for prompt intervention before they worsen and necessitate expensive repairs, saving both time and money. By spotting possible dangers like loosened machinery parts or uneven rotating shafts, vibration transducers can help to increased safety. Accidents and injuries can be avoided by quickly resolving these problems (Sandoval, Oscar R, Machado, Luiz Henrique Jorge, Hanriot, Vitor Mourao Troysi, Fernanda, Faria, Marco tulio C, 2022). By locating and fixing issues that lead to downtime, these transducers also improve productivity by maximizing operational effectiveness.

Figure 2.5 Tranducer

2.5.2 Sensor of Vibration

A vibration sensor is a tool that monitors an object's oscillating motion, or vibration, which can be caused by a variety of things, including spinning equipment, earthquakes, or explosions. These sensors are widely used in a variety of industries. By tracking vibration lexels, they are used in equipment condition monitoring to evaluate the health of engines, pumps, and compressors, allowing for the early detection of possible problems before they result in damage. Vibration sensors are used to monitor the structural health of structures like buildings and bridges. Vibration analysis enables the identification of issues like fractures or damage. Vibration sensors are used in earthquake engineering to monitor ground vibrations during earthquake occurrnces, giving crucial information for determining the extent of damage and formulating mitigation plans. In order to identify possible issues and improve component performance, vibration sensors are also used in the automobile engineering industry to monitor the vibrations of engines, gearboxes and other components. Vibration sensors are widely used in many different sectors, and they are essential for performance, safety, and monitoring.

Accelerometers and velocity sensors are the two primary categories for vibration sensors. While velocity sensors measure the object's velocity, accelerometers measure the object's acceleration when it vibrates. The output signal from these sensors may be used to determine vital vibrational properties including amplitude, frequency, and phase. Vibration sensors have a wide range of application in several sectors due to their capacity to monitor vibrations. They act as a flexible instruments for evaluating vibrations in a range of applications, and they are essential to safety and performance monitoring systems. Vibration sensors are essential for guaranteeing safety and maximizing performance, whether they are used for structural health monitoring, equipment condition monitoring or other monitoring systems.

Common vibration sensors include accelerometers, velocity sensors, and strain gauges, each of which has a specific function for monitoring and analysing vibrations. In order to calculate variables like amplitude, frequency, and phase accelerometers monitor acceleration. Velocity sensors concentrate on monitoring velocity to offer information about kinetic enery. Strain gauges assess material strain to determine stress levels and spot possible issues. For evaluating and tracking vibrations in many applications, these sensors are fundamental.

Figure 2.6
Accelerometer Sensors

Figure 2.7
Velocity Sensor

2.6 Measurement of Vibration

The method of measuring a vibrating object's motion is known as vibration measurement. It is used to evaluate the state of equipment, buildings, and other items and to spot possible issues before they result in failure. Vibration measurement is calculating the acceleration, velocity, or displacement of a vibrating item to quantify its motion. By finding issues like misalignment, looseness, and wear that might cause an early failure, it is used to evaluate the state of machinery, buildings, and items. Continuous vibration monitoring enables the early identification of possible problems, offering significant advantages in terms of time, expense, and safety.

Several industries, including oil and gas, manufacturing, and transportation, depend on vibration measurement. By keeping an eye on the state of infrastructure, tools, and spinning machinery, failures, downtime, and risks may be avoided. Vibration measurement allows business to proactively identify and fix problems, enhancing safety, increasing productivity, and lowering costs. Vibration measurement is a useful technique that may be applied in many different sectors to increase efficiency, safety and save costs.

2.6.1 Displacement

The distance an object moves away from its resting position is known as displacement. It is measured in length units such meters, millimeters, or micrometers. The displacement of vibrating objects is measured using displacement sensors. They may be contact or non-contact sensors. Non-contact sensors monitor the displacement of the object without meeting it, whereas contact sensors establish physical contact with the vibrating object.

Applications for displacement measurement are many and varied across sectors. It is used to monitor the state of machinery, allowing for the early identification of possible problems with rotating shafts and bearing. Displacement measurement assists in spotting possible issues in bridges and buildings during structural health monitoring, reducing the danger of collapses. Displacement measurement is useful for vibration analysis as well since it makes it possible to identify the sources of vibration and gauge their intensity. Overall, displacement measurement is a flexible instrument that helps numerous industry sectors increase safety, efficiency, and cost effectiveness.

2.6.2 Velocity

The method of measuring a vibrating object's motion is known as vibration measurement. It is used to evaluate the state of equipment, buildings, and other items and to spot possible issues before they result in failure.

Vibrations in buildings are frequently measured using velocity, which is defined as the rate of change of position. This is accomplished by using velocity sensors, which translate velocity into an electrical output. These sensors are normally made of a piezoelectrical material, which when distorted produced an electrical signal, the degree of which is directly inversely related to the measured velocity. Due to their detection of positional change rather than absolute location, velocity sensors exhibit reduced susceptibility to noise as compared to acceleration sensors. As a result, they are more resistant to little tremors or problems. Nevertheless, it should be emphasized that due to their smaller range of measurement values, velocity sensors are less accurate than acceleration sensors.

Velocity sensors are used for a variety of things and have several uses. They are used in vibration analysis to monitor the vibrations of buildings and bridges, helping to identify problems like loose bolts or broken parts. Additionally, velocity sensors are used to monitor machines, allowing for the evaluation of machine performance including that of engines and the early detection of possible issues like wear and tear, preventing malfunctions. Additionally, these sensors are important for traffic monitoring since they make it possible to assess the pace and flow of the traffic, which improves traffic management and safety measures. These numerous applications benefit from the adaptability of velocity sensors, which allows for vital measurements and enhances performance and safety in a variety of settings.

2.6.3 Acceleration

Acceleration sensors are frequently used to measure the rate of change in velocity, especially in the study of machinery vibration, however they may also be used to diverse objects like bridges and buildings. These sensors make use of a piezoelectric material, the degree of which is directly related to the acceleration of the item being measured. When exposed to deformation, the piezoelectric material produces an electric signal.

Since the acceleration caused by gravity is measured in units of g, there is a direct relationship between acceleration and the output signal in volts. It is essential to consider an acceleration sensors frequency response when choosing it for a certain application since it shows how well it can measure vibrations at various frequencies. Usually, acceleration sensors are used to monitor vibrations between 10Hz and 10000Hz. The accuracy of some sensors, however, allows them to measure vibrations at up to 1 MHz of frequency.

When using an acceleration sensor, it’s important to consider its sensitivity, which establishes the sensor’s lowest observable acceleration. Usually, acceleration sensors work in conjunction with a data collecting system to gather and store sensor data for later analysis. This information may be used to spot possible problems with the equipment, including loose bolts or broken parts. It also makes it possible to track the performance of the machinery to make sure it runs within the parameters defined by its design.

Acceleration sensors provide several benefits, including their adaptability in monitoring vibrations in various objects and their capacity to sense vibrations over a broad frequency range. In comparison to other vibration sensors, they are very inexpensive. They do, however, have drawbacks, such as noise sensitivity, potential installation issues, and less precision in comparison to other type of vibration sensors.

2.6.4 Relating Acceleration, Velocity and Displacement

The crucial measures in vibration analysis are displacement, velocity, and acceleration. The distance an item has moved from its resting position is known as displacement, while the rate at which displacement changes is known as velocity changes is known as acceleration.

In vibration, have three measurements are related by the following equations:

Velocity and displacement magnitudes can be defined as follows for a given acceleration magnitude A:

$$velocity, V = \frac{a}{2\pi f} \tag{2.6}$$

$$displacement, d = \frac{V}{2\pi f} = \frac{a}{(2\pi f)^2} \tag{2.7}$$

Where f is the frequency of vibration

Given velocity magnitude V, the acceleration and displacement magnitudes can be defined as:

$$Acceleration, a = V(2\pi f) \tag{2.8}$$

$$Displacement, d = \frac{V}{2\pi f} \tag{2.9}$$

Given displacement, the acceleration and velocity magnitudes can be defined as:

$$velocity, V = d(2\pi f)$$

(2.10)

$$acceleration, a = V(2\pi f) = d(2\pi f)^2 \tag{2.11}$$

2.7 Analysis of Vibrations

The technique of detecting and examining the vibrations of a machine or building to spot possible issues is known as vibration analysis. Misalignment, looseness, bearing wear, and structural damage are only a few of the causes of vibrations. Engineers can locate the source of the disturbance by analyzing the vibration signature and take action to fix the issue before it results in harm.

The two primary forms of vibration analysis are time domain and frequency domain. In contrast to frequency domain analysis, which separates the signals throughout time. Every analysis type has the potential to reveal important details regarding the condition of the device or building.

2.7.1 Statistical Analysis

Patterns in data vibration data can be found using the potent instrument of statistical analysis. Engineers can spot possible issues before they cause harm by examining the statistical features of the vibration signal.

Several well used statistical approaches are used in vibration analysis. Among these ways is computing the mean, which indicates the average value of a series of data points and as well as in determining the central the primary trend of a vibration signal. Furthermore, the variance is used to calculate the deviation of the data points from the mean, offering insight into the amount of vibration variability. Another extensively used statistic is the standard deviation, which is the square root of the variance and provides a more intuitive grasp of vibration variability. These statistical approaches help enable the full analysis of vibration data by assisting in the discovery of patterns, trends, and anomalies.

Additional statistical approaches often employed in vibration analysis include peak to peak and root mean square (RMS). The difference between the highest and minimum values in a vibration signal provides a measurement of the oscillation's amplitude. It helps in determining the amount of the vibration excursion. The square root of the mean of the squares of the vibration signal, on the other hand, is used to determine RMS. It indicates the whole energy in the vibration signal, providing information about the vibration's total strength or intensity. Peak to peak and RMS statistical metrics are critical in quantifying and analyzing vibration properties, allowing for thorough study and understanding of vibration

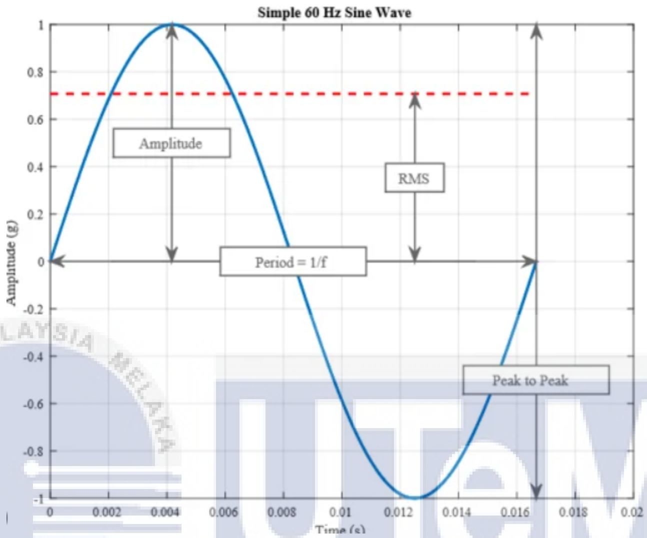

Figure 2.8 Root Mean Square & Peak to Peak

behaviors.

Root Mean Square formula:

$$x_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_{i^2}} = \sqrt{\frac{x_{1^2}+x_{2^2}+\cdots+x_{n^2}}{n}} \tag{2.12}$$

2.7.2 Time-domain Analysis

In vibration analysis, time domain analysis entails looking at vibration data over a period of time. Plotting the vibration data on a graph with time on the x-axis and vibration amplitude or velocity on the y-axis is required for this study. Time domain analysis may be used to identify a variety of problems with machines and structures. Vibration levels that rise over time could be an indication of machinery or building wear and tear or a potential issue (Hochong Park and Joo-Hiuk Son, 2021). Uneven vibration levels may point to a problem with the equipment or structure's equilibrium. Additionally, the existence of peaks and trought in the vibration levels might be an indication of alignment issues with the machine or structure. Time domain analysis provides insightful information on the dynamic behaviour of vibrations, enabling the early identification and diagnosis of possible problems for maintenance and performance enhancement.

Time domain analysis in vibration analysis plays a significant part in locating the cause of vibration problems in addition to assisting in the identification of difficulties with equipment and buildings. It is possible to spot distinct patterns in the vibration levels over time, such as increased vibration levels during particular times of the machine's operation. The core reasons of the vibration issue, such as problems with the machine's working speed, may be better understood with the use of this information. Potential issues can be identified at an early stage, enabling prompt remedial action to be done and averting serious damage or failures, by using time domain analysis as a routine monitoring technique for machines and structures. Time domain analysis is a strong and useful method for guaranteeing the best performance and lifetime of equipment and structures due to its capacity to identify a variety of issues.

Time domain analysis is a useful method for tracking the levels of vibration in machines and buildings since it has a number of advantages. First of all, it's simple to comprehend even for those without prior knowledge of vibration analysis, enabling greater accessibility and use. Time domain analysis is a useful diagnostic technique because it is adaptable and capable of detecting a broad variety of issues in machines and buildings. Additionally, it is a cost-effective startegy that offers an effective and affordable way to monitor vibration levels. One may proactively evaluate the health of machinery and buildings by using time domain analysis for monitoring, thereby saving a lot of money and avoiding costly repairs in the future.

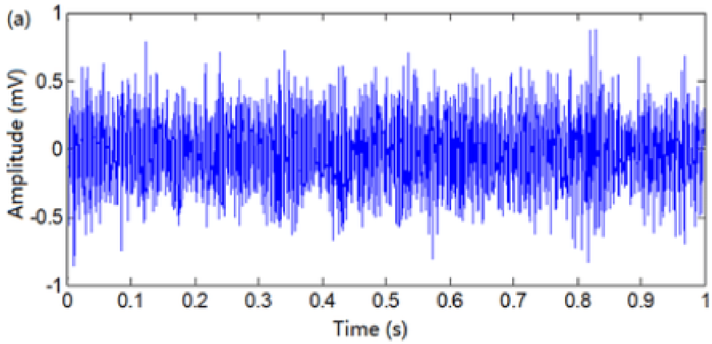

Figure 2.9 The Raw Vibration Signal: Time Domain Waveform

2.7.3 Frequency-domain Analysis

A form of vibration analysis known as frequency domain analysis examines the vibration data in terms of frequency. This may be achieved by transforming the vibration data into a frequency spectrum using a Fourier transform. The vibration data manu frequencies are depicted in the frequency spectrum, along with each frequency's amplitude (Hochong Park and Joo-Hiuk Son, 2021).

Using frequency domain analysis, it is possible to find issues with machines and buildings. It helps in the detection of harmonic vibrations that occur at speeds gretaer than the machines's working speed and are brought on by problems like imbalanced rotors or misalignment. Additionally, it identifies the natural frequencies where forces might result in large vibration amplitudes and possible harm. The frequency domain study also examines the resonance and damaging vibrations that emerge from the interaction between the vibrations of the machine and the structure. These issues may be successfully detected and fixed by using this analysis, resulting in the best performance and safety.

In addition to detecting concerns like harmonic vibrations and natural frequencies, frequency domain analysis may also helps in locating the cause of vibration problems. If there is a peak in the frequncy spectrum at the machine's working speed, a balancing issue may be present (Jianhui, Caiming, Wengui ,2019). This demonstrates how frequency domain analysis may be used to diagnose a variety of issues with machines and buildings. This method of routine vibration level monitoring allows for early deection of possible problems, prompt remedial action, and little damage. As a result, frequency domain analysis is a potent tool for preserving the fuctionality and integrity of machines and structures.

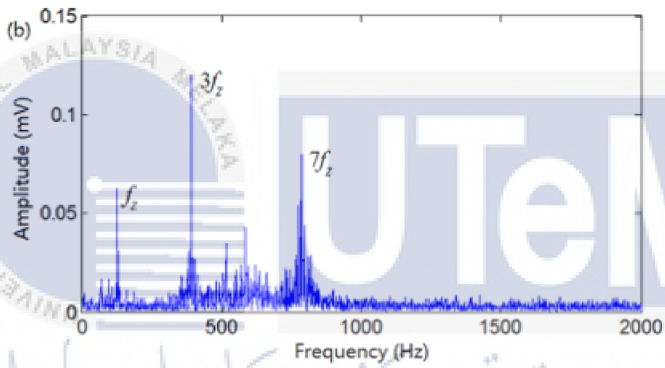

Figure 2.10 The raw vibration: Frequency Spectrum

2.8 V-Standard

The Verein Deutscher Ingenieure (VDI) developed the V-standard, a set of vibration standards for assessing the condition of rotating machinery such motors, turbines, and generators. This standard divide vibration severity into three categories. The warning level denotes possible problems with the equipment, while it is still capable of operating safely, while the normal level reflects acceptable vibration for everyday operation. This critical amount of vibration, on the other hand, signals an impending risk of machine failure and calls for an emergency shutdown to save additional damage. For determining vibration levels and guaranteeing the secure and dependable operation of rotating machinery, the V-standard is an invaluable reference.

The V-standard stipulates limitations for the acceleration and velocities of vibrations at different frequencies while considering the nature of the machine, its working speed, and the surrounding environment. By recording the machine's acceleration, which indicates the force of vibration, accelerometers are used to assess vibration levels. The vibration velocity and acceleration may be determined from these readings. Engineers can use the V-standard to discover possible problems with spinning machinery by tracking vibration levels over time and seeing patterns that could point to concerns. Thos proactive strategy enables prompt interventions before the machine sustains and harms. In the end, the V-standard is a crucial instrument for guaranteeing the dependability and safety of rotating gear since it enables engineers to avoid expensive repairs and save downtime by following its rules.

2.8.1 ISO 10816

General recommendations are provided by ISO 10816 for the measuring of machine vibration on non-rotating components. To measure and classify mechanical vibration of reciprocating compressors, this part of ISO 10816 specifies unique standards and processes. It generally refers to vibration of the compressor's primary structure, including the foundation, pulsation dampers, and associated piping system . The definition of the guiding values for these vibrations is done largely to categorise the vibration and to prevent issues with the auxiliary equipment put on these structures. This section of ISO 10816 provides recommendations for measurements and assesstement criteria.

The oscillating masses, the cyclically variable torque, the pulsing forces in the cylinders and cylinder strecth, pulsation dampers, and the pipe system are typical characterictics of reciprocating compressors. The compressor system cibrates as a result of all these features, which also place alternate strains on the primary supports. Reciprocal compressor systems often have higher vibration values than rotating compressor systems, but since the design characteristics of the compressor play a bigger role in determining these values, they tend to be more stable throughout the course of the system's lifetime.

2.8.2 ANSI/ASME B11.18

The ANSI/ASME B11.18 standard is essential for assuring the security of equipment used to process or slice coils of metal or non-coils. It includes a wide variety of equipment, such as slitting, press feed, and cut to length lines. The standard includes thorough guidelines for machine guarding, electrical security, personal safety gear, instruction, and upkeep. It seeks to reduce any dangers and hazrads related to these equipment in order to promote a secure workplace. The standard has had two updates since its first publication in 2006, with the most recent revision occuring in 2020, ensuring that it is current with changing industry practises and improvements in safety measures.

A few important additions to ANSI/ASME B11.18 were made with the 2020 edition. Improved electrical safety requirements that comply with current industry standards, updated requirements for machine guarding that provide better injury prevention measures, more appropriate requirements for personal proactive equipment considering the risks associated with metal processing, thorough training requirements that cover the new standard provisions, and improved maintenance requirements to prevent hazards are a few examples. For anyone working with equipment used in the processing or slitting of coiled or non-coiled metal, ANSI/ASME B11.18 is a crucial safety standard. To protect the safety of machine operators and staff, it is critical to have a thorough grasp of the standards requirements and to ensure compliance.

2.8.3 DIN 4150

The German standard DIN 4150 describes how to measure and assess how vibration affects structure developed primarily for static loads. It is applicable to structures that are not required to be developed in accordance with certain standards or codes of practice for dynamic loads.

The standard defines two types of vibration, impact vibration and continuos vibration. Impact vibration is brought on by quick and light loads. Numerous events, like explosions, pile drives, or falling objects, may result in these loads. Impact vibrations may harm structures through mechanisms including cracking and aging. They may also give patiens headaches, nausea, and other unpleasant symptoms.

Repetative loads are the source of continuos vibration. Numerous factors, like traffic, machinery, or building activities, might contribute to these loads. Constant vibration can also weaken and break a structures through a variety of methods. They may also give patiens headaches, nausea, and other unpleasant symptoms.

2.9 Machine Learning

Support vector machines (SVMs), neural networks, and random forests are a few machine learning techniques frequently utilised for vibration analysis. SVMs are supervised learning algorithms that can categories or forecast data, making them excellent for finding patterns in vibration data. It is possible to analyse the complicated correlations between vibrations and machine or structural states using neural networks, which were inspired by the functioning of the human brain. Even in the presence of noisy or insufficient vibration data, the ensemble learning system known as random forests combines decision trees to produce precise predictions (Kota Prashanth, M Elagovan, 2019).

Vibration analysis makes use of machine learning in several different methods. By analyzing vibration data, it can among other things, forecast when a machine will break, allowing for preventative maintenance and reducing expensive downtime and repairs. Second, by using vibration analysis, it may find structural deterioration like fractures in structures, helping to prevent catastrophic disasters. By detecting flaws in produced parts and streamlining manufacturing procedures based on vibration data analysis, machine learning also helps to improve product quality (Wang et al., 2014). Finally, it enhances safety by using machine learning to detect dangerous circumstances like excessive vibration or noise, guaranteeing a safer workplace for personnel and equipment.

2.9.1 Supervised Learning

A machine learning technique called supervised learning uses labelled data, where each data point has a corresponding right output, to train a model. Classification and regression challenges frequently use this kind of learning. The input data and their related outputs are given to the model, allowing it to understand the relationship between the two. The model may iteratively update its parameters to increase the accuracy of its output prediction by using an approach that minimises prediction error. Machines may learn from labelled examples and make precise predictions based on fresh, unused data using the fundamental approach of supervised learning.

2.9.1.1 Logistic Regression

For binary classification problems, where the output might have one of two potential values, logistic regression is a frequently used approach. It uses a logistic or sigmoid function to represent the data, converting real numbers to probabilities between 0 and 1. This function is used to calculate the likelihood that a data point belongs to a particular class. By figuring out the logistic function's parameters, which minimise the difference between the model's predictions and the actual labels, the model is trained. Despite its simplicity, logistic regression is very successful for binary classification problems and is preferred by machine learning practitioners for its simplicity of understanding.

2.9.1.2 Support Vector Machines (SVMs)

The capacity of support vector machines (SVMs), a form of supervised learning algorithm, to spot patterns in vibration data that are hard to see visually, makes them a frequent choice for vibration analysis. To separate two classes of data from one another in an n-dimensional space, SVMs look for a hyperplane that can be seen, for instance, as a line separating two groups of points in a two-dimensional situation. SVMs main goal is to identify a hyperplane that maximizes the margin between the hyperplane and the nearest points in each class. Improved predicted accuracy in vibration analysis is achieved using SVMs by maximizing the margin.

2.9.1.3 Decision Trees

Decision trees are a potent yet simple algorithm that is frequently used for classification applications. The procedure entails recursively dividing the data into smaller subsets based on characteristics and the values assigned to them, producing subsets that eventually only belong to a single class. The criteria used to choose the features and values provide the most uniform class distributions within the subsets. Until each subgroup is clearly categorised, this splitting procedure is repeated. A popular option among machine learning practitioners, decision trees are praised for their clarity, interpretability, and efficiency in handling categorization issues.

2.9.1.4 Random Forests

A potent method that advances decision trees is called random forests. They entail training several decision trees on various subsets of the data and merging their predictions to get a final prediction. This strategy has various benefits. First off, it lessens the possibility that a model may memorise the training data, hence minimising the danger of overfitting. Random forests improve generalisation to unknown data by utilising numerous decision trees. Second, given that the variety of the tree subsets helps reduce the influence of random fluctuations, random forests show resistance to noisy data. Last but not least, random forests offer insights into feature significance, assisting in model refinement and the identification of key features for future research. For many machine learning applications, random forests provide a powerful and adaptable tool.

2.10 Summary

To summarize this chapter, vibration is oscillations about an equilibrium point are a mechanical phenomenon. The word's root is vibration, which means "shaking, brandishing" in Latin. The oscillations might be random like a tire rolling over gravel or periodic, like the swinging of a pendulum. Vibrations such as those made by a tuning fork, a woodwind instrument or harmonics reed, a mobile phone, or a loudspeaker cone can be pleasing to the ear.

The efficacy of mechanical connections in conveying vibrations changes as vibrations travel in mechanical waves. While active vibration isolation makes use of sensors and actuators to create disruptive interference that cancels out incoming vibrations, passive vibration isolation uses materials and mechanical connections to absorb and dampen these waves.

Vibration has negative impacts on both humans and machines. Vibration in people can result in several health problems, including whole body vibration syndrome (WBVS), which affects the entire body, and Hand-arm vibration syndrome (HAVS), which affects the hands, arms, and shoulders. Additionally, noise-induced hearing loss can be brought on ny the high-frequency noise that is frequently connected to vibration.

2.11 Table Summary

Table 2.2 Summary of Research

No.	Literature Title	Strength	Weakness	Notable Features	Reference
1.	Diagnosis and analysis of abnormal noise in the pure electric vehicle's air condition compressor at idle.	a. Help prevent abnormal noise. b. Preserving the environment for future generations and reducing atmospheric pollution.	a. Pure electric vehicles do not create the same amount of noise as vehicles with conventional engines, the noise of the electrical system is more emphasized. b. Cannot identify target sound sources with complicated shapes accurately and locate sound sources on the frequency spectrum.	a. Professional evaluators carry out set evaluations and the abnormal noise-generation mechanism and its transfer path are analysed. b. The mode shape and sound pressure distribution are both simulated using the finite element method. c. The AC compressor's sound source is identified and located in the main frequency domain using the acoustic array and image formation method.	Cheng, Zhiwei ; Lu, Yigang (2018)

2.	Vibration based fault monitoring of a compressor using tree-based algorithm.	a. Accuracy: Tree-based algorithms are known for their high accuracy and are commonly used in predictive modelling. They can accurately predict the health status of a compressor based on vibration data. By using a tree-based algorithm, you can increase the accuracy of fault diagnosis and reduce the chances of false alarms or missed faults. b. Efficiency: Tree-based algorithms can handle large amounts of data quickly and efficiently. They can process data in parallel and can be implemented on low-cost, low power	a.Overfitting: One potential disadvantage of tree-based algorithms is that they csn be prone to overfitting, which means the model is too closely fitted to the training data and does not generalize well to new data. This can happen when the algorithms are overly complex or when there is not enough data available to train the model effectively. b.Data pre-processing: Tree-based algorithms require a certain level of data pre-processing to handle missing values, outliers, and categorical variables. This can be time-consuming and may require domain expertise to perform effectively.	a. Research do make attempts to find a suitable device that is profoundly welcome by the industry. b. Diagnosis of the fault that recommends a remedial action. c. A study was attempted and vibration signals were collected.	Kota Prashanth , M Elagovan (2019)

		hardware, making them suitable for real-time fault monitoring applications.			
3.	Validation of Clicking Type Noise and Vibration in Automotive HVAC System			a. The characteristics of clicking-type noise and vibration occurring in the automotive heating, ventilation, and air conditional (HVAC) systems are investigated. b. Three different sensors namely as tachometer, accelerometer, and micro	M.H.A. Satar, A.Z.A. Mazlan, M.H. Hamdan, M.S. Md. Isa, M.A.R. Paiman, and M.Z. Abd. Ghapar
4.	A vibration subassembly and vibration sensor for vibration sensor	a. The vibration subassembly can also modify the vibration damper between the fixed component and the vibration section and the vibration range. b. An innovative vibration subassembly		A new vibration subassembly and vibration sensor for a vibration sensor are described in the study. A vibrating diaphragm with a how supporting part, a quality piece laminated on the diaphragm, an edge, and a fixed portion of connection on	Li Xinliang, Duanmu Luyu

		and vibration sensor for a vibration sensor are presented in the paper.		the supporting part make up the vibration subassembly. The vibrating diaphragm's damping characteristic, vibrating diaphragm amplitude, and vibration sensor sensitivity may all be improved by the vibrating subassembly.	
5.	Vibration Analysis for Machine Monitoring and Diagnosis	a. By emphasizing the potential costs brought on by premature breakdowns, the reseacrh highlights the need of regular machinery maintenance. The demonstrates how applicable study is in real life. b. In the study, fault identification in vibration analysis is covered in relation to the application of artifical intelligence (AI) techniques like deep learning. The	a. Although vibration analysis is the main emphasis of research, alternative diagnostic methods for machine monitoring are not covered in great detail. A more thorough grasp of the subject may be obtained by a wider discussion and comparison of other strategies. b. The study does not dive into specifics or breakthroughs in this field, just briefly mentioning	Machines are essential for factory operation and can be diagnosed using a variety of methods, such as oil analysis, particle analysis, corrosion monitoring, acoustic signal analysis, and wear debris analysis. Acoustic analysis has advantages such as short analysis time, high recognition efficiency, and nondestructive testing, while vibration analysis has limitations such as noise contamination and proper	Mohamad Hazwan Mohd Ghazali, Wan Rahiman (2021)

		automation of feature extraction from raw vibration signals through the use of Ai in vibration analysis has the potential toimprove defect detection's effectiveness and precision.	data collecting methods such analyzers and sensors. The comprehension of the research issue could be improved by further investigation of data collection techniques.	mounting position of vibration sensor.	
6.	Vibration Signal analysis of a rotor-bearing system through wavelet transform and empirical mode decomposition	a. Decomposing vibration signals into intrinsic mode functions enables effective fault identification. b. The suggested strategy for research utilising WT and EMD methodologies improves fault detection in the rotor-bearing system, resulting in more precise and reliable identification of defects, which is essential for optimal maintenance	a. The research lacks thorough data analysis since it doesn't give precise information regarding the utilised data analysis methodologies, such as characteristics or parameters extracted, which restrics understanding of the research finding.	Vibration analysis is used to monitor the health of rotatong machinery, and this research explores the feasibility of using WT and EMD to decompose sophisticated vibrations signals into a finite number of intrinsic mode functions. The analysis result showed that the proposed approach can diagnose the faults of the rotor baring system.	Ashutosh Kumar, 2022

		and the averting of machine breaksowns			
7.	Vehicle vibration safety estimation area	a. The chalenge to identifying the parameters and properties of nonlinear dynamic systems is explored using both the frequency domain and the time domain as possible solution regions. This makes it possible to analyse and compare the analysed system's quality and accuracy in great detail. b. The purpose of the study is to determine if it is possible to pick the best parameters for research by employing similar properties of the analysed system. For further investigation and decision-		The problem of mathematical modeling of the car vibration isolation system can be solved in the frequency and time domain.to estimate the adequacy of solutions, it is necessary to make a choice of the method of statistical linearization from the known in practice design of automatic control systems. Four methods of statistical linearization are considered, using which calculations in the frequency domain have been carried out. It is shown that the first method of statistical linearization is the most flexible, according to the amplitude-frequency response of the system. The results of the research are	Zheglov, A Fominykh (2020)

		making, this offers insights on the appropriateness and applicability of certain features.		separate frequency and integral parameters. The last ones do not give any priority in the choice of the calculation field, under the condition of vehicle movement safety.	
8.	Simulation Analysis of Electromagnetic Vibration of Rotor Compressor Motor based on Modal Superposition Method	The simulation findings and test results match up well, according to the abstract, demonstrating the validity of the analytical method. The validity of the study is increased by this.	There is no background information or study context provided in the abstract. A succinct introduction outlining the significance and relevance of researching the electromagnetic vibration of inverter compressor motors would be helpful.	The research object is a 6-pole 9-slot permanent magnet synchronous motor. Analytical methods are used to obtain the radial electromagnetic force wave generated by the air gap magnetic field. Modal superposition is used to combine the electromagnetic force with the motor modal mesh, and a bench test is conducted to measure the vibration spectrum.	Mingxu Ren,Hui Shen, WanjieSun, Haishui Jin (2019)
9.	Active vibration control of an Inertia-type Piezoelectric Actuator based	provide outcomes, such as the decline in handle accelerations and the percentage of	The construction of three distinct controllers and the characterisation of the	AVC, or active vibration control, is a useful technique for reducing vibrations	Cheah Cheng Theik and Ahmad Zhafran Ahmad

	suspended handle using PID-AFC Controller	vibration reduction attained following controller activation. This provides a crystal-clear indicator of how well the controls reduce vibration.	piezoelectric actuator are briefly mentioned in the abstract, but no information regarding the experimental setup, measurement methods, or assessment standards are given. The research's credibility and understanding would both be improved by providing more information about the methods.	caused by various stimulation frequencies. In this research, an inertia-type piezoelectric actuator was used to reduce the vibration of a hanging handle. In this work, a piezoelectric actuator is characterised in order to assess its performance using various inertia masses. Following the investigation, three distinct controllers—PID manual tuning, PID auto-tuning, and PID-AFC controllers—were developed. According to the findings, engaging the controller causes the accelerations at the handle to drop from 7.54 m/s to 3.79 m/s (a total reduction in vibration of 49.7%). Experimental results show that PID-AFC controller, followed by PID manual	Mazlan (2020)

				tuning and auto-tuning, provides the optimum vibration attenuation.	
10.	Study on vibrations modes of large type vertical motor	No possible restrictions or disadvantages of utilising Msc.nastran for dynamic simulation are mentioned in the texts. A more balanced viewpoint would be presented by offering insights into the method's drawbacks or difficulties.	Because to Msc.nastran's excellent computation accuracy, simulation results can be more accurate and trustworthy. When examining the dynamic behaviour of vertical motors, this precision is essential.	The paper presents a method for dynamic simulation of a vertical motor based on Msc.nastran, which has advantages such as simple analytical model, high calculation accuracy, and easy to combine with vibration modes.	Jianhui, Caiming, Wengui (2019)

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CHAPTER 3

METHODOLOGY

3.1 Introduction

This thesis focused on monitoring and analyzing vibration signals in vehicle air conditioning compressors to detect bearing faults, deflection of bearing and speed of belting to run the compressor. Vibration analysis is a powerful technique for evaluating the mechanical condition of rotating machinery, and applying vibration analysis to air conditioning compressors can provide valuable insight into the condition and performance of these critical components. By concentrating on one axis within the compressor system, identifying specific problems that may affect compressor operation and efficiency growth.

The results obtained from this methodology will contribute to a better understanding of the compressor mechanical condition, facilitate timely maintenance interventions, and ultimately improve the reliability and performance of the air conditioning system .This was done to determine and diagnose the vibration magnitude of faults cause on a compressor earlier and to prevent the compressor and bearing vibration to deteriorate further causing more problems to the system or machinery it is in. vibration signals analysis was carried out through the DigivibeMX 11 software to monitor and capture relevant vibration data analyses the vibration signals, process it to enhance signal quality, extract meaningful features related to bearing faults deflection, speed belting , and on/off compressor states, and employ dedicated algorithms for fault detection of the compressor during its operation.

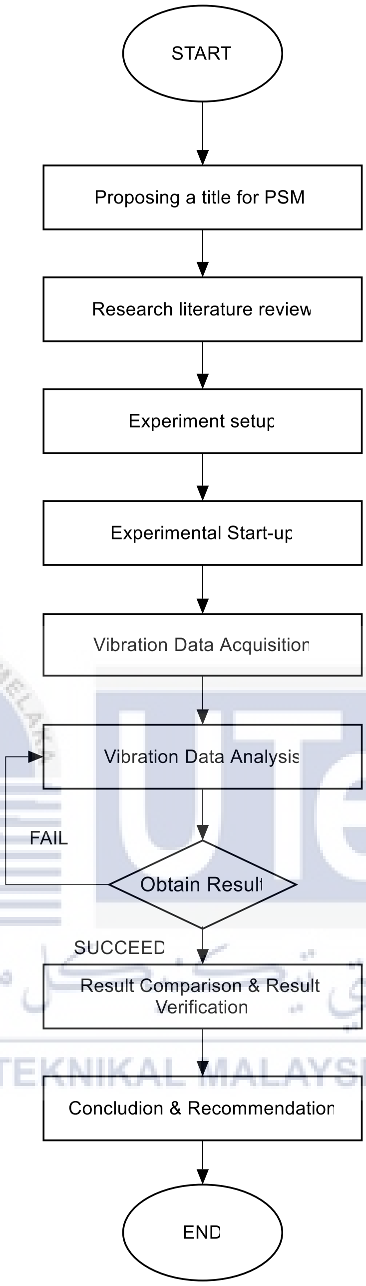

Figure 3.1 Project Flow Chart

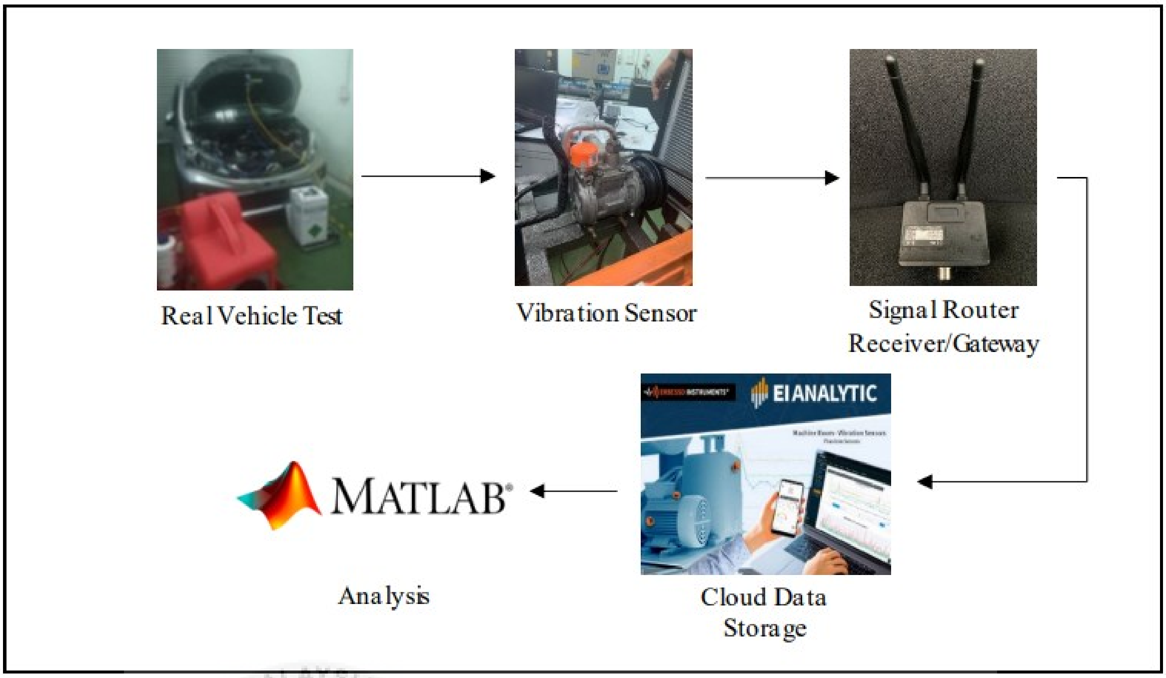

Figure 3.2 Experiment Setup

3.2 Research Design

The investigation into the correlation between vibration signals and various factors in vehicle air conditioning compressor, such as bearing problems, deflection of belting, speed of belting and ON/OFF compressor states, this study will use a mixed-methods research approach. To attain the research goals, the research methodology will comprise of experiment data collection and analytic methodologies.

Using the proper vibration sensors, vibration data will be gathered from a selected axle within the axle of the air conditioning compressor within the vehicle. The compressor will be used to collect data under a variety of settings, including standard operation, compressor ON/OFF transitions, speed belting variations, and conditions that could result in deflection or bearing failures. The data that has been gathered will be entered and saved for future examination.

The vibration data that has been gathered will be subjected to preprocessing procedures to get rid of any unwanted noise or artifacts and increase the signal quality. To find pertinent traits related to belting defect, belting speed, belting deflection and ON/OFF compressor system, feature extraction approaches will be used. To examine the retrieved features and find patterns or anomalies suggestive of circumstances, statistical and pattern recognition algorithms will be used. To evaluate the accuracy and efficacy of the analytical procedures, the data will be evaluated and contrasted with known fault conditions or pre-established benchmark.

3.3 Proposed Methodology

The proposed methodology for this study involves collecting vibration data from a selected axle of the vehicle air conditioning compressor under varying speed value (1000RPM, 1100RPM, 1200RPM, 1300RPM, 1400RPM and 1500RPM), the normal condition on test Rig and different quantity of refrigerant on vehicle compressor (280g, 300g, 320g, 340g and 360g). The collected data will undergo preprocessing to remove noise and artifacts, followed by feature extraction to identify relevant characteristics associated with belting fault, deflection, and speed belting anomalies. Statistical analysis and pattern recognition techniques will be utilized to analyze the extracted features and assess their relationship with specific fault conditions or established benchmarks to evaluate the accuracy and effectiveness of the analytical procedures in detecting and diagnosing faults in the vehicle air conditioning compressor under different operating conditions.

3.3.1 Experimental Setup

The vibration analysis of the compressor was carried out while operating it at varying speeds and with different belt deflection levels. The belting was subjected to six varying rotational speeds, namely 1000rpm, 1100rpm, 1200rpm, 1300rpm, 1400rpm and 1500rpm, with each deflection 0.5mm (normal), 1.0 mm, 1.5mm and 2.0mm being tested under all these speeds. Initially a wireless Phantom sensor was used to link the Phantom Gateway 2.0 to Wi-Fi. Data entered through the Phantom will be sent to the DigivibeMX software. Before doing the experiment, the first thing that should be done is to determine the normal gas setting that needs to be entered according to the specifics of the vehicle.

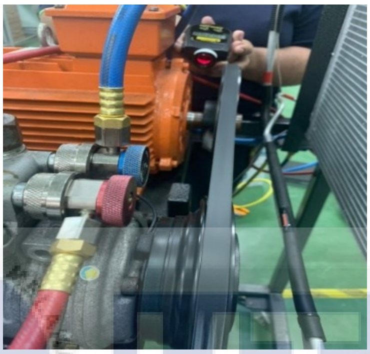

Figure 3.3 Measured Compressor Speed Using Tachometer

Figure 3.4 Manifold Gauge to Measured Amount of Refrigerant

Figure 3.5 Tensioning Gauge to Measured Deflection Belting

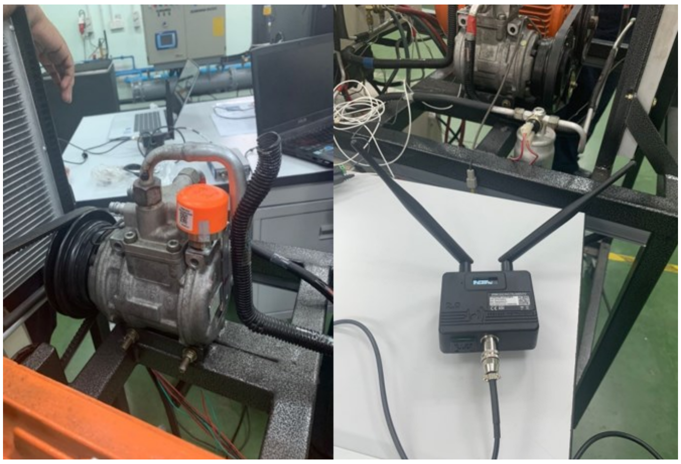

Figure 3.6 Experiment Setup

3.3.2 Parameters

The parameters which were used in the experiments were the types of deflection of bearing and speed of the compressor, rotating speed, and the duration of data collection. There are four different types of belting deflection employed in this project. The rotating speeds were set to six speeds. The duration of the data collected was set to ten (10) seconds by setting automatically in EI Analytic software. The experiment was run three (3) times for each speed and each condition to find the average value of data.

3.3.3 Equipment and Software

This part shows that there were many pieces of equipment and software used to achieve the desired output of the project. The types of equipment that will be used in this project is Phantom Gateway 2.0 to Wireless Phantom converter, EI Analytic and DigivibeMX Phantom software.

3.3.3.1 Reliability PHANTOM-GW Gateway 2.0

The Phantom Gateway 2.0 is a wireless data collection and monitoring system made to gather information from up to 100 phantom sensors. It has the flexibility of operating in offline or online mode and has a range of up to 100 meters line of sight. This system excels in condition monitoring, offering capabilities like mass configuration for simultaneous setup of numerous sensors, simultaneous data collection from various sensors for a thorough machine condition analysis, and cloud connectivity for data access anywhere in the world. Additionally, the Phantom Gateway 2.0 supports Modbus TCP/IP connection, providing simple integration with current automation systems, while its compatibility with the MQTT protocol promotes interaction with a variety of systems. Additionally, it supports OPC communication, enhancing its compatibility and integration potential.

The Phantom Gateway 2.0 is a robust, adaptable, and user-friendly data monitoring and collecting device that is ideal for a wide range of applications. It is a fantastic option for businesses looking to keep tabs on the health of their equipment since it combines simplicity, dependability, and scalability. Notably, the Phantom Gateway 2.0 adds more capabilities including repeater functionality, expanding the range of sensors for improved coverage. Additionally, it offers direct control of Phantom Gen 3 sensors, making it possible to do operations like starting and stopping data collecting, setting alarm thresholds, and changing firmware. Additionally, the device has a substantial storage capacity that can hold up to 100,000 waveforms, allowing continual data collecting over long periods of time without worries about storage constraints.

Figure 3.7 Phantom Gateway

3.3.3.2 DigivibeMX 11 Phantom Software

DigivibeMX is a flexible, multi-functional program that can analyze machine vibration in real time and collect traditional data. The software features accessible to the user are determined by the DigivibeMX model purchased. Figure 3.8 shows the DigivibeMX software.

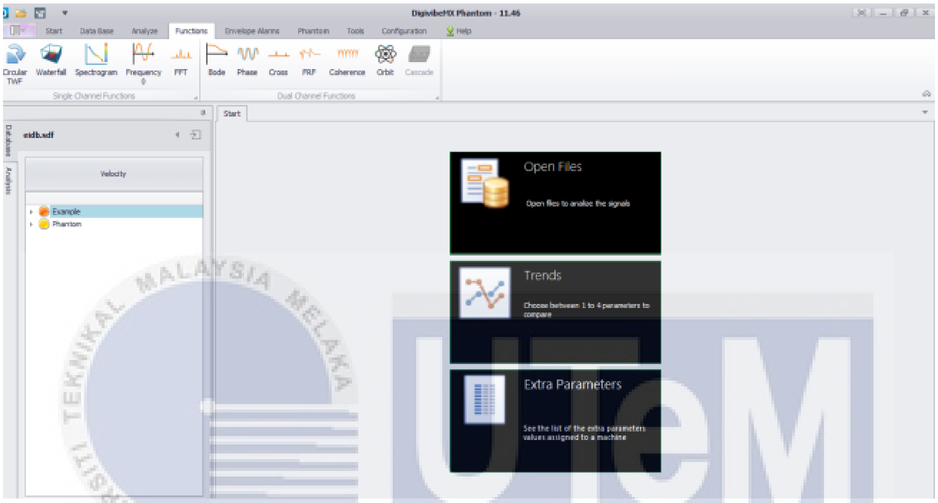

Figure 3.8 DigivibeMX11 Phanto Software to Collect Data

3.3.3.3 EI Analytic Software

The EI Analytic gateway offers two main methods for internet connections and is created to provide a smooth link between our cloud service and the extremely powerful Gateway 2.0 in the first technique, an ethernet cable is used to directly link the Gateway and modem, establishing a secure and direct connected connection to the network. Wi-fi may also be used to join the Gateway to a wireless network, enabling freedom and mobility while yet keeping an internet connection. To fully utilize the EI Analytic gateway's capabilities, guarantee peak performance, and provide access to cloud services, network connectivity must be established.

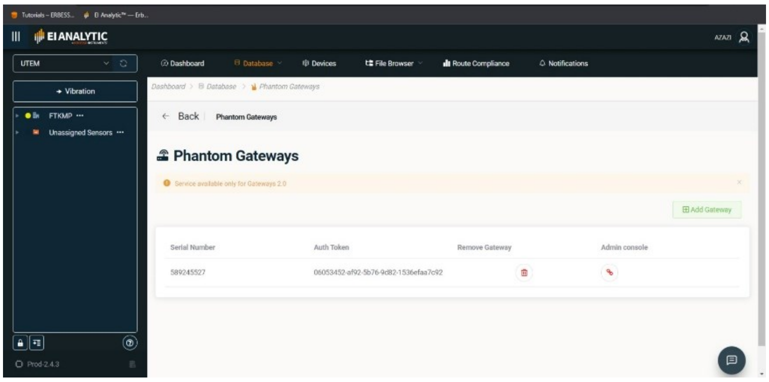

Figure 3.9 EI Analytic Software

3.4 Vibration Measurement

The most crucial step in this study is measuring the vibration signal, since it allows research to determine how well the rotor performs in various environments (Rivera-Guillen et al., 2019). This project employed the Phantom converter.

The phantom gateway has to be WiFi connected. Remember that the EI-Analytics or 4G-module PC should be on the same network as the Gateway. Phantom gateways connect phantom condition monitoring sensors to a local database or the internet (the cloud).

3.4.1 Phantom Gateway Configuration Steps

Phantom gateways include Ethernet connectivity in addition to two wireless protocols (Wi-fi and BLE 5.0). the phantom gateway will function as an access point with the SSID “PHANTOM01” the first time it switched on, with “01” denoting the serial number of the phantom gateway. Put a paperclip on the tiny pinhole next to the screen while the device is on and wait for it to click if the gateway must be reconfigured, need to be configured already or does not enter access point mode. Figure 3.10 shows, the example of putting a paperclip on the little pinhole located right next to the screen to reset the phantom gateway.

Figure 3.10 Inserting a Paperclip on the Little Pinhole

The EI-Gateway Access Point Mode will then be activated. Open the used device's Setting app and tap Network and Internet option. Tap listed network and there will be Phantom gateway network. Use "88888888" (8 times number 8) as the password to access it from a computer or a device. Figure3.11 shows, how to connect the EI-Gateway Access Point Mode with a smartphone.

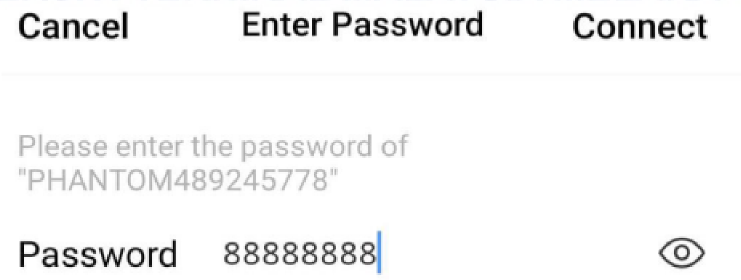

Figure 3.11 Connecting The EI-Gateway Access Point Mode with Smartphone

3.4.2 Phantom Manager Application Setup

Install Phantom Manager app in the mobile phone (iOS or android) from App Store or PlayStore. It’s vital to remember that getting the update requires being close to the device. The magnetic key is necessary for Phantom devices. There are 5 primary parts on the home screen:

1. Options
2. Node Update
3. Gateway Update
4. EI Monitor Module Update
5. Gateway Configurations

Connect the user’s smartphone to the same network after configuring the gateway’s Wi-Fi network, then open the phantom manager app. Choose Gateway configuration option. The following steps must be taken to choose a Wi-Fi connection:

i. Select an option from the list in SSID.

ii. Enter the Wi-Fi network’s password in the box provided.

iii. Select save Settings.

Keep in mind that the computer with EI-Analytics or the 4G-Module should be on the same network as the Gateway (Miniserver). Figure below displays the Wi-Fi configurations of Phantom Manager application.

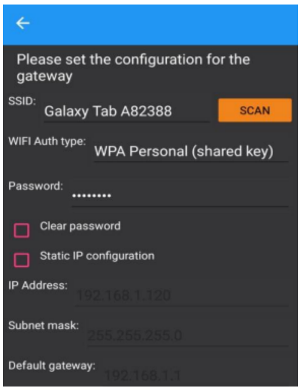

Figure 3.12 Send Data to Cloud Option

With the phantom gateways, users may now transfer the data directly to EI-Analytic account. When "Send data to Cloud" is chosen, the gateway established a connection with the cloud services of EI-Analytic. Change the time zone to Asia/Kuala Lumpur and simply click the box to save the settings without the requirement for a monitor service. Figure 3.13, displays the send data to Cloud option in Phantom Manager app.

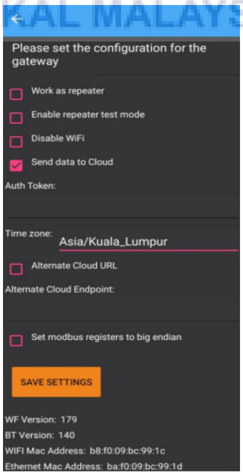

Figure 3.13 Wi-Fi Connection in Phantom Manager App

Once all these steps are done, the gateway screen shows the current date and time as Figure 3.14 below.

Figure 3.14 Gateway Screen with Date and Time

3.4.3 Sensor Installation

Phantom tool that enables step-by-step sensor setting in DigivibeMX software. Open the Wizard main window by clicking the Wizard button, then click Next to access the Phantom configuration. Phantom configuration will be displayed as shown in Figure 3.15.

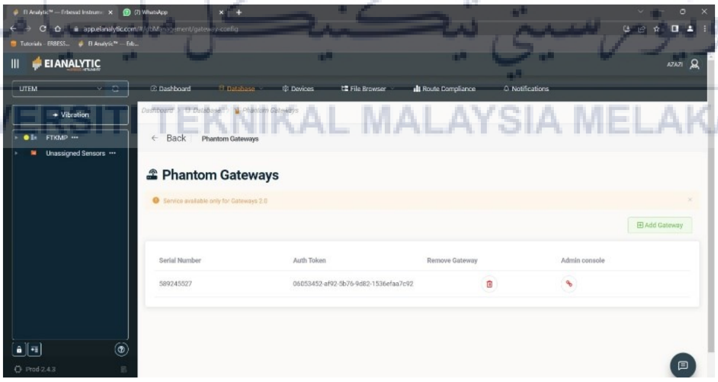

Figure 3.15 Phantom Configuration in DigivibeMX Software

Sensors can be added to the software by clicking Add Phantom button and add the information of the sensor such as name, description of the sensor, axes configuration of the sensor and finally the alarms for the sensor to wake up according to our own use.

3.4.4 Wiser Vibe Pro

The Vibration Analysis App, like the WiSER Vibe Pro from Erbessd Instruments, is crucial for tracking, identifying, and carrying out preventive maintenance programmes for rotating machinery. This programme offers all the capabilities required to maintain the health and durability of your equipment, including time-based waveforms, FFT analysis, circular time waveform, orbits analysis, and routes-based records. You may avoid unexpected production shutdowns, reduce negative economic effects, increase equipment longevity, and accurately detect a variety of abnormalities by using this useful and portable tool. Start utilising this sophisticated vibration analysis app to prioritise the performance and well-being of your equipment.

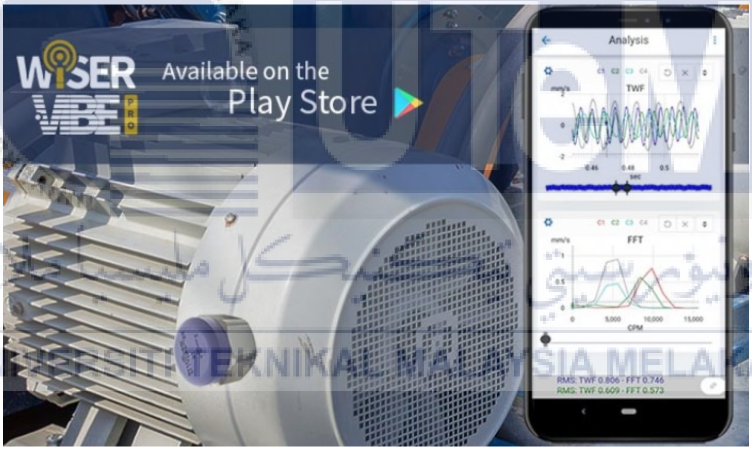

Figure 3.16 Wiser Vibe Pro

3.5 Technique

This part shows that there many pieces of machine learning used to achieve the desired output of the project. The types of equipment that will be used in this project is MATLAB software to analyze data, conduct research, and develop programming skills.

3.5.1 Machine Learning

Machine learning is a branch of artificial intelligence (AI) that focuses on creating algorithms and models that let computers learn from data and form hypotheses or judgements based on that data. It includes creating systems that explicit programming, can automatically pick up new skills and get better over time.

3.5.1.1 MATLAB

The high-level programming environment and language MATLAB were created especially for scientific research and numerical computing. The acronym MATLAB, which stands for "MATrix LABoratory," emphasises the software's potent matrix manipulation capabilities, which are crucial to many calculations in science and engineering. For data analysis, visualisation, and algorithm creation, MATLAB offers a complete collection of tools, functions, and libraries.

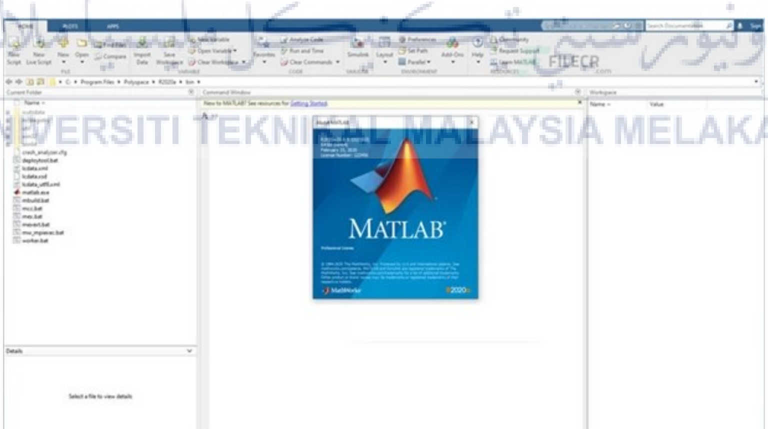

Figure 3.17 MATLAB Software

3.6 Summary

This conclusion of the methodology is it focuses on the importance of implementing the proper methods of analysis and regulatory planning in the process of materializing as efficiently. This proposed framework is followed by several steps to make sure the outcome of the project. In this chapter, it is also discussed the platform of the tool to be used to obtain the desired data which is important to the objective of executing this PSM title. The chapter is analyzed correctly to gain an effective approach to obtaining the exact result. This chapter presents the proposed methodology for monitoring the vibration analysis of compressors using Phantom Gateway Configuration and Phantom Sensor. The vibration analysis was conducted using different types of vibration analysis techniques. A software called DigivibeMX11 was used to analyze the data collected. The software was so helpful to compare the vibration analysis graphs. During the monitoring process, the speed of the compressor and defflection of the belting was set up under different conditions. The data was then transferred to Microsoft Excel to easy to study the data collected, make comparisons and finally conclude the project.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, we unveil insights from our experiment on vehicle air conditioning compressors, examining vibration signals under diverse conditions. The study encompasses a spectrum of compressor speeds, ranging from 750rpm(idle) for compressor off and 950rpm(idle) for compressor on to 2000rpm, operational states (on and off), and varied refrigerant amounts spanning 280g to 360g. the data, meticulously collected to reflect real-world scenarios, facilitates a detailed understanding of the compressor's performance. Beginning with an overview of the experimental setup, the results section systematically presents patterns in vibration signals, highlighting the nuanced impact of different compressor speeds and refrigerant quantities. The ensuing discussion interprets findings within the context of our research objectives, exploring how variations in compressor speed and refrigerant quantity manifest in variation signals, and benchmarking against standard conditions enables a meaningful assessment of deviations. The practical implications emphasize the advancement of predictive maintenance strategies for air conditioning compressors, targeting enhance reliability, reduced costs, and improved passenger comfort.

4.2 Normal Condition on Test Rig

Figure below, displays the vibration result which in an acceleration (m/s^2) of normal condition on test rig for six different speeds which are 1000rpm, 1100rpm, 1200rpm, 1300rpm, 1400rpm and 1500rpm. When the compressor is run in a low speed, the vibration becomes low and when the speed increases the vibration becomes increase too. Significant vibration will occur as the speed of the compressor increases. Thus, the value of vibration indicates that the machine is still in good condition and no defect occurred. The amplitude of the time domain graph increases together with compressor speed where amplitude increased approximately five times compared to low speed. At this stage, obviously the rig is in an unstable position. There is a peak in every frequency domain graph which indicates the speed of the compressor and other sub peaks which were produced from the vibration of other components. The quantity of refrigerant and compressor oil is also one of the causes of vibration. The component that causes vibration and produced sub peaks are hard to predict because there were so many components of the machine vibrating during the experiment been carried out.

The time domain waveform for 1000rpm and 1500rpm reveal different acceleration patterns. In the 1000rpm scenario, the accelerometer starts at rest and experiences a sudden acceleration of around 8m/s^2 at 0.1 seconds, followed by a relatively constant acceleration period at 2 m/s^2 before returning to rest 0.4 seconds. This suggests a single, abrupt event, possibly caused by the accelerometer being dropped or experiencing a sudden change in motion.

On the other hand, the 1500rpm graph portrays a more dynamic scenario. It begins with the accelerometer at rest and registers a sudden upward acceleration of about 1.25m/s^2 at 0.1 seconds, followed by a downward acceleration of -1m/s^2 at 0.2 seconds. Subsequently, the graph displays a series of smaller acceleration peaks, indicating potential bouncing or vibration, before eventually settling back to rest at 0.6seconds. This pattern implies a more complex motion scenario, possibly involving the accelerometer being subjected to various forces and movements.

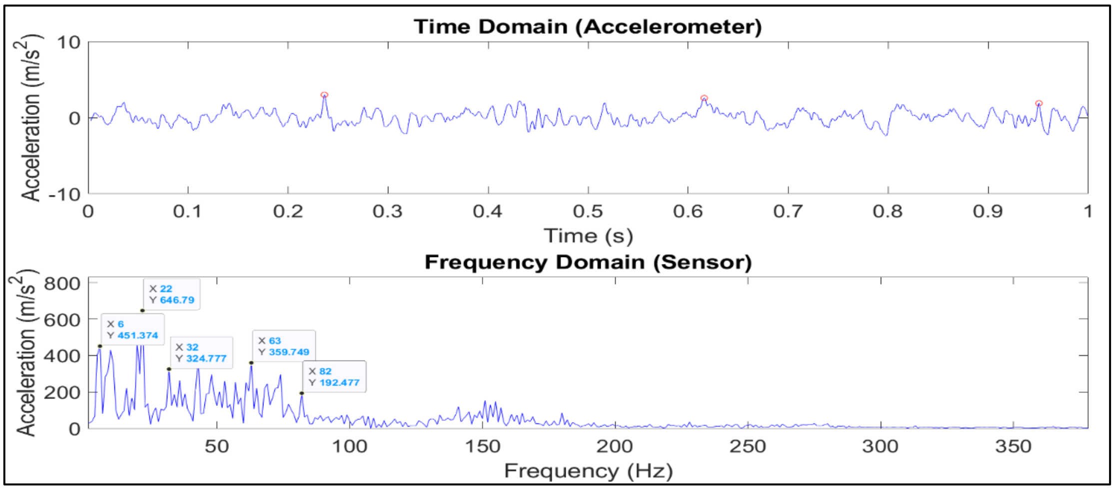

Figure 4.1 Time-domain & Frequency-domain on Compressor Speed 1000rpm

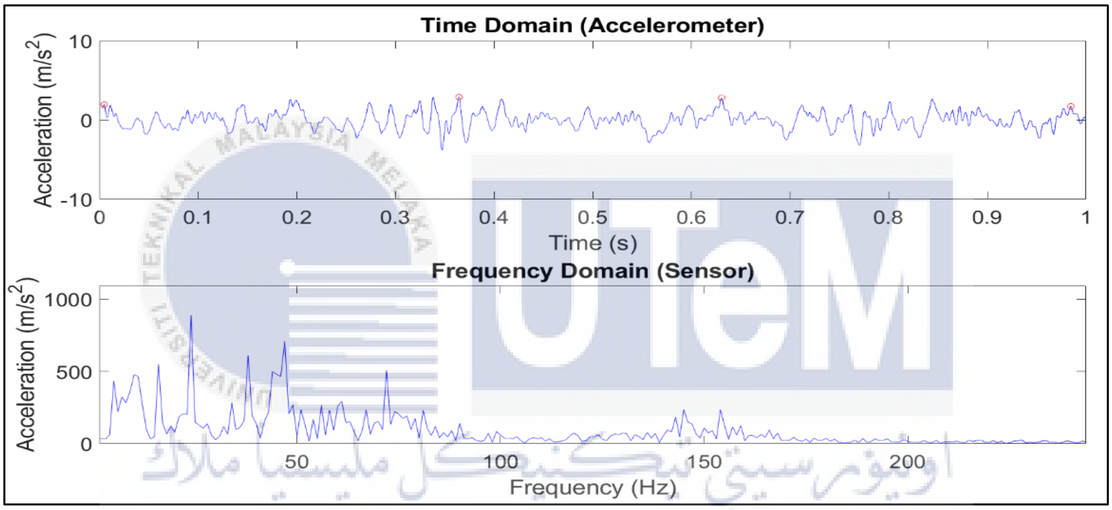

Figure 4.2 Time-domain & Frequency-domain on Compressor Speed 1100rpm

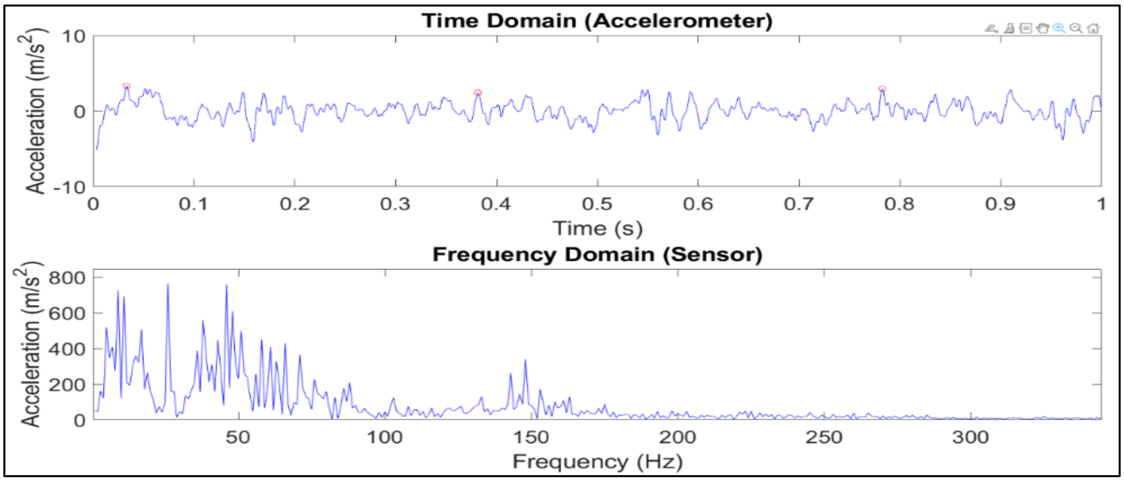

Figure 4.3 Time-domain & Frequency-domain on Compressor Speed 1200rpm

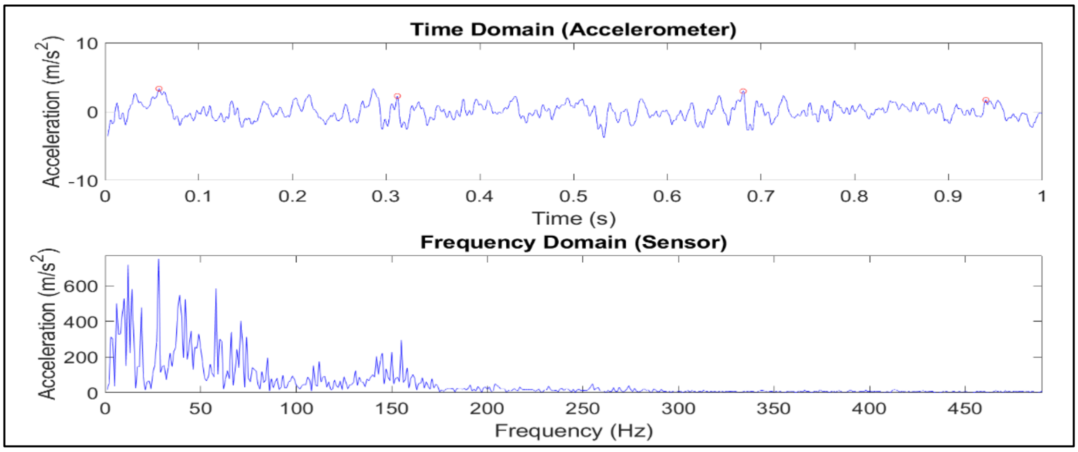

Figure 4.4 Time-domain & Frequency-domain on Compressor Speed 1300rpm

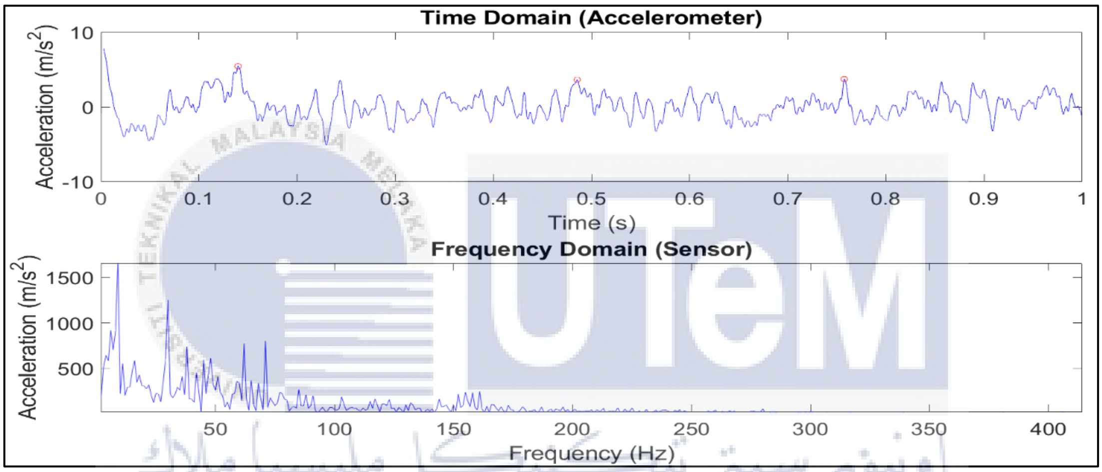

Figure 4.5 Time-domain & Frequency-domain on Compressor Speed 1400rpm

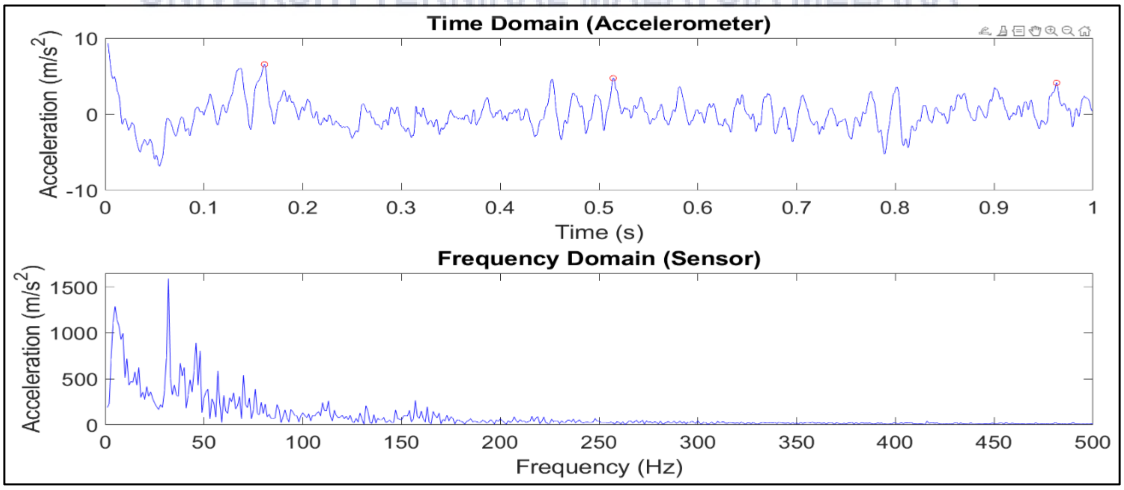

Figure 4.6 Time-domain & Frequency-domain on Compressor Speed 1500rpm

4.3 Normal Condition of Engine

Figure shows the data scattering of Z-freq coefficient for the compressor speed of 900rpm and 2000rpm together with the time frequency domain for each clearance size.

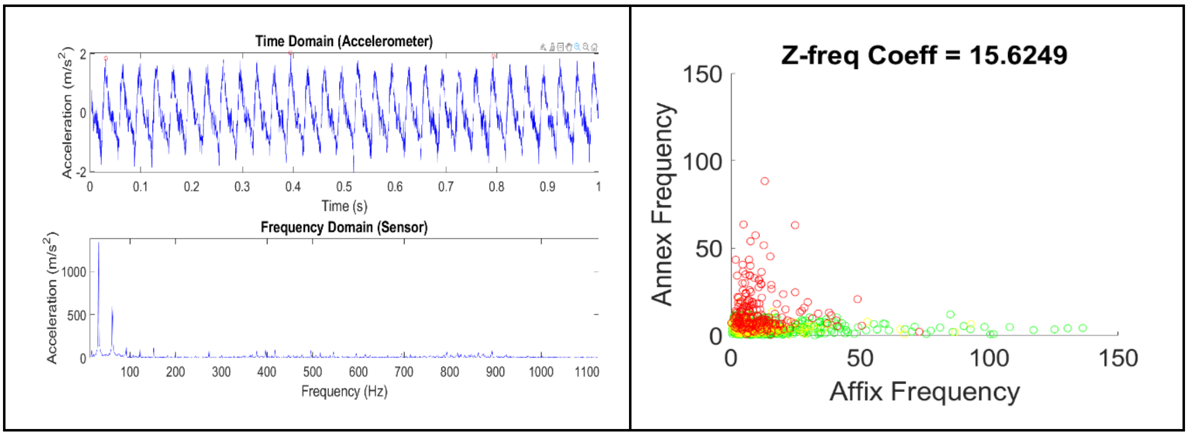

Figure 4.7 900rpm Compressor Speed

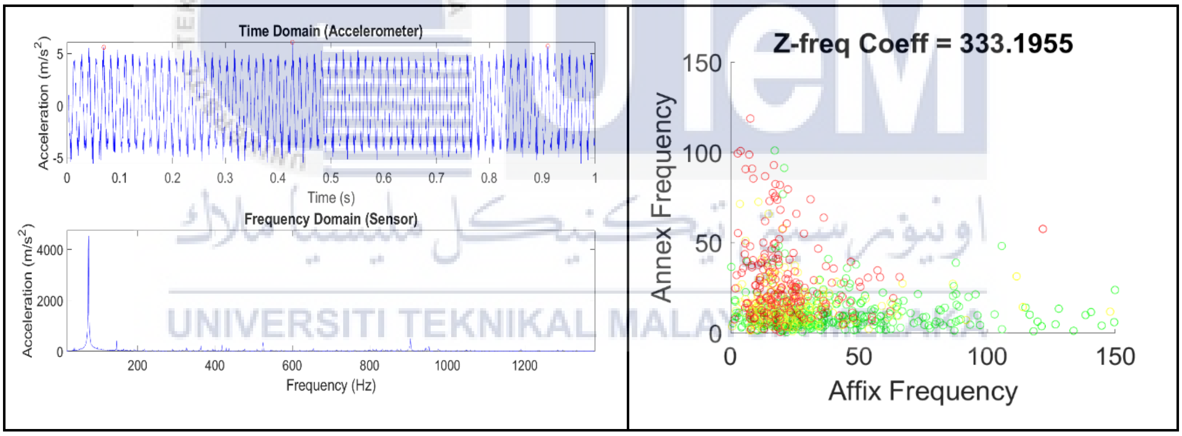

Figure 4.8 2000rpm Compressor Speed

In the experiment, the characteristics of a compressor operating at 900 rpm and 2000 rpm are examined through the analysis of vibration patterns. At 900 rpm, the compressor demonstrates a natural frequency of around 15 Hz and a corresponding fundamental frequency linked to its rotational speed. The vibration spectrum indicates potential issues, such as imbalance or misalignment, with an emphasis on monitoring the unspecified max amplitude to identify any excessive position. Conversely, at 2000 rpm, the compressor exhibits an increased natural frequency of approximately 33.33 Hz, reflecting the higher operational speed. The vibration spectrum at 2000 rpm reveals a broader peak at the natural frequency and a smaller peak at the fundamental frequency, suggesting a shift in the compressor vibration profile at elevated speeds.

Z-freq coefficient obtained from the data of each compressor speed from 900 rpm to 2000 rpm. The Z-freq coefficient can be seen to be almost constant across the compressor speed between 900rpm to 2000rpm. The z-freq coefficient shows the red and yellow dots are spreading across the affix frequency. all the dots can also be seen to separate from each other at high affix frequency across the annex frequency.

4.4 Z-Freq

4.4.1 Z-Freq in Compressor Active

The amount of gas is also one of the factors that cause vibration. If seen on the graph, the less gas the higher the resulting vibration at the Zfreq value. The quantity of refrigerant 280g is one example that can be shown. This is because inside the compressor there is a space that must be compressed by the refrigerant. If there is no refrigerant only the piston will move empty and thus the vibration will increase. If compared to the quantity of refrigerant 320g to 340g the amount of vibration is normal. This is because the compressor is filled with space and the piston can move perfectly.

Table 4.1 Data Z-freq of Compressor in Active Condition

Quantity of Refrigerant (g)	280	300	320	340	360
RPM	Z-freq				
900	44.9658	7.9948	15.6249	17.2979	13.6274
1000	96.314	23.2427	33.0747	21.5986	19.27
1250	144.4348	33.36	32.1847	25.1186	23.9713

1500	246.7724	78.5609	41.2346	49.6253	34.0297
1750	448.9114	147.654	104.2007	95.7425	95.6702
2000	1223.778	394.0494	333.1955	221.609	241.6452

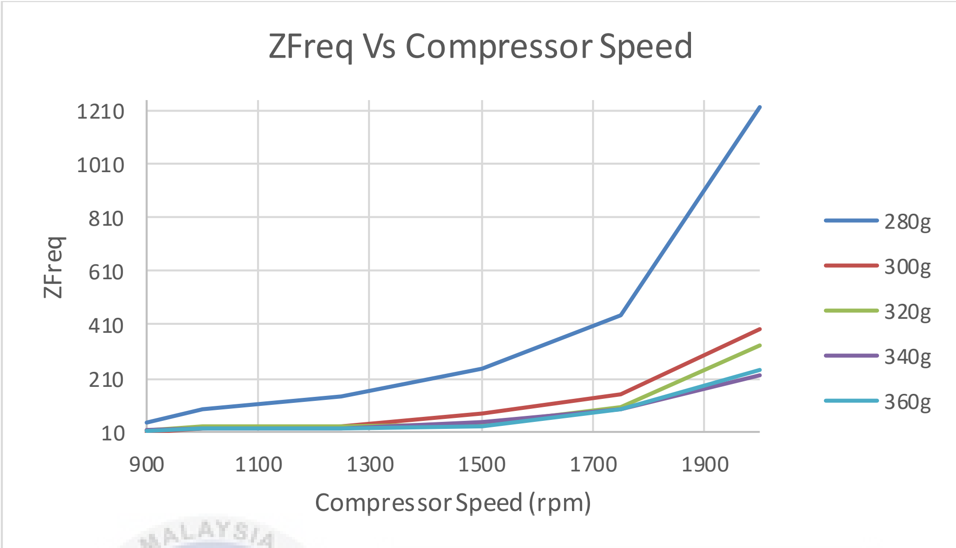

Figure 4.9 Comparison Data for Z-Freq

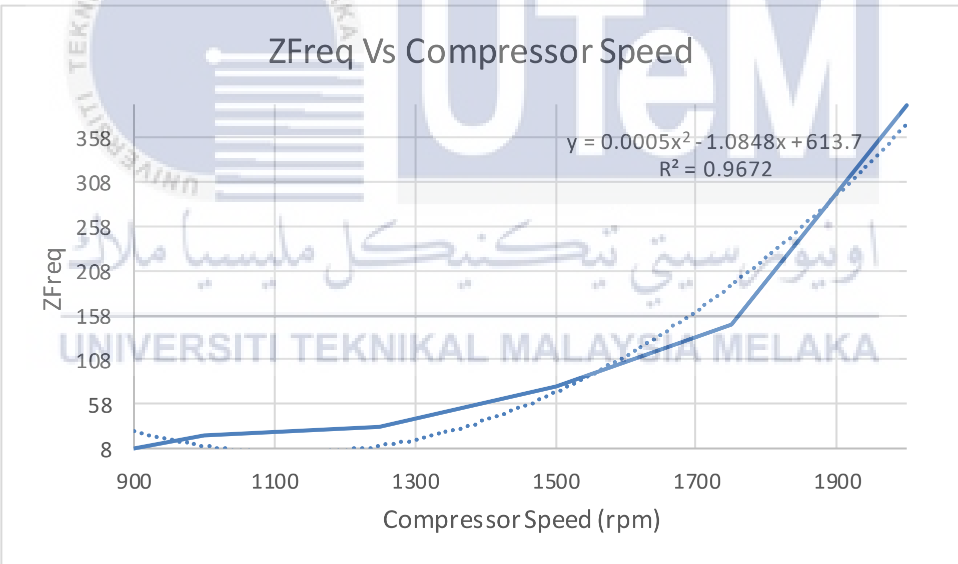

Figure 4.10 Coefficient of Determination for Z-Freq

The term 'Zfreq' may pertain to a frequency that relates to a certain attribute or behavior inside the compressor system. These attributes may include vibration frequency, acoustic frequency, or any operational feature that is dependent on compressor speed.

$$y = 0.0005x^2 - 1.0848x + 613 \quad (4.1)$$

Zfreq is represented by 'y' in this case, while compressor speed (in rpm) is by 'x'. Zfreq does not grow at a consistent rate with compressor speed, indicating that the connection between these two variables is nonlinear, as shown by the inclusion of the x^2 component. Rather, the acceleration is proportional to the square of the compressor speed, less an offset and a linear term.

The statistical measure of how well the regression line approximates the actual data points is the coefficient of determination, or $R^2 = 0.9672$. with a very high R^2 value of 0.9672, the model supplied by the quadratic equation can explain roughly 96.72% of the variance in Zfreq by the variation in compressor speed. There may be a substantial association between these two variables based on this high correlation.

The graph showing the quadratic connection between Zfreq and compressor speed may be a sign of resonant behavior, variations in the system's operating efficiency, non-linear thermodynamic reaction of the refrigerant gas, or rising mechanical stress.

4.4.2 Z-Freq Compressor Stop

The vibration will still originate from the closed compressor, but it will be lessened compared to the operating compressor. Like how a gas value of 280g will result in a strong vibration. As the refrigerant set quantity is insufficient compared to the standard.

Table 4.2 Data Z-Freq of Compressor in Stop Condition

Quantity of Refrigerant (g)	280	300	320	340	360
RPM	Z-freq				
750	27.4441	1.4903	1.9931	2.3116	2.9452
1000	97.0925	18.4029	17.736	17.8186	19.3936
1250	116.2773	42.0001	25.3577	26.2249	30.1375
1500	229.4311	96.249	71.7721	68.0119	72.6772
1750	609.2595	292.4598	126.1843	126.5137	83.613
2000	1057.096	448.3302	306.953	169.7692	292.9283

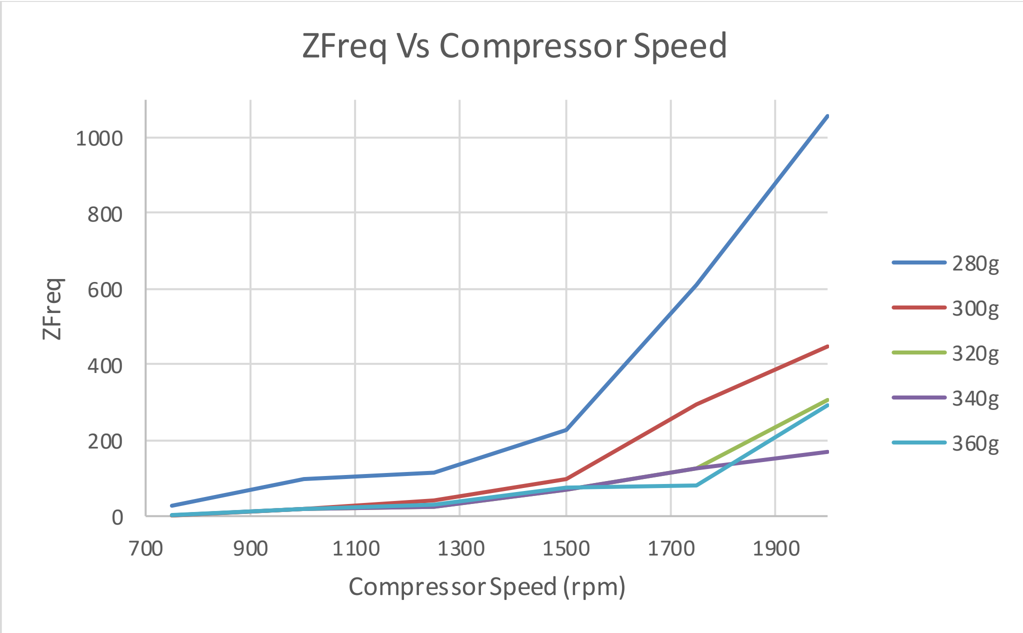

Figure 4.11 Comparison Data for Z-Freq

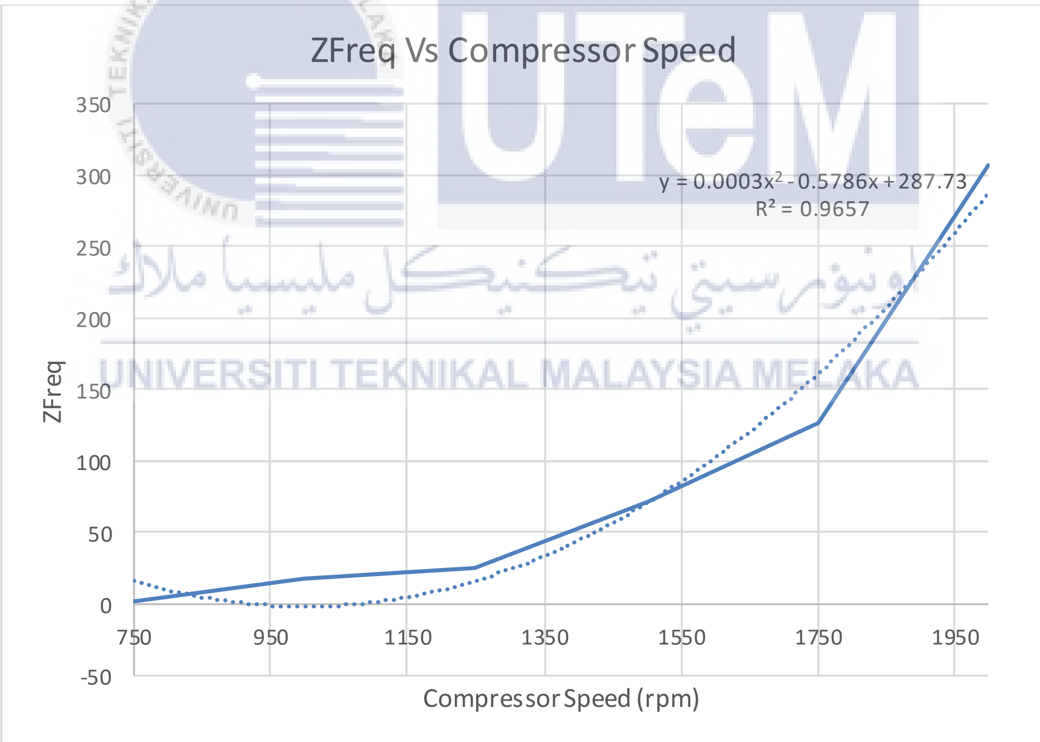

Figure 4.12 Coefficient of Determination for Z-Freq

With the compressor turned off, the scatter plot graph presented illustrates the connection between Zfreq and compressor speed. This kind of graph is frequently used to show the relationship between one variable and another; in this example, the relationship between Zfreq and the compressor speed (measured in revolutions per minute).

There is a quadratic pattern in the connection between the two variables, not a linear one, as seen by the solid line representing a fitted quadratic regression model and the dotted line representing the data points. The quadratic model's equation is as follows:

$$y = 0.0003x^2 - 0.5786x + 287.73$$

(4.2)

Where y is the Zfreq and x is the compressor speed.

The coefficient of determination, represented as R^2 is 0.9657, indicating a near value of 1. This implies that significant amount of variance in the Zfreq data may be explained by the quadratic model. That is, a high correlation is shown by the fact that variations in compressor speed explain around 96.57% of the variance in Zfreq.

The data which shows that the compressor is off may be displaying passive frequencies that are created by other machinery or outside sources, such as vibration frequencies. Such a pattern is rare for an off-state compressor and might be caused by resonances or background vibrations. When the curve first begins to approach the origin, it indicates less motion and a lower frequency at lower speeds or in non-operational conditions. But even when the speed is off, the Zfreq climbs increasingly faster, and the quadratic model captures this trend. It is important to know exactly what Zfreq means, particularly if it is a vibration frequency, since this information may be important for predictive maintenance. Higher frequencies at specific speeds might indicate wear or misalignment, which could cause a malfunction when the device is operating. The model's positive quadratic component

$(0.0003x^2)$ shows a faster rise in frequency beyond the speed range indicated by the negative linear term (-0.5786x), which suggests a less marked speed range for frequency growth.

4.5 Root Mean Square (rms)

4.5.1 RMS in Compressor Active

Table 4.3 Data RMS of Compressor in Active Condition

Quantity of Refrigerant (g)	280	300	320	340	360
RPM	RMS				
750	1.2815	0.5531	0.7841	0.7915	0.6905
1000	1.9231	0.9332	1.1096	0.9056	0.8834
1250	2.1969	1.0793	1.1232	0.9523	0.9576
1500	2.823	1.5502	1.2517	1.3127	1.0964
1750	3.5973	2.1023	1.7774	1.684	1.679
2000	5.9081	3.3135	3.0381	2.5653	2.7285

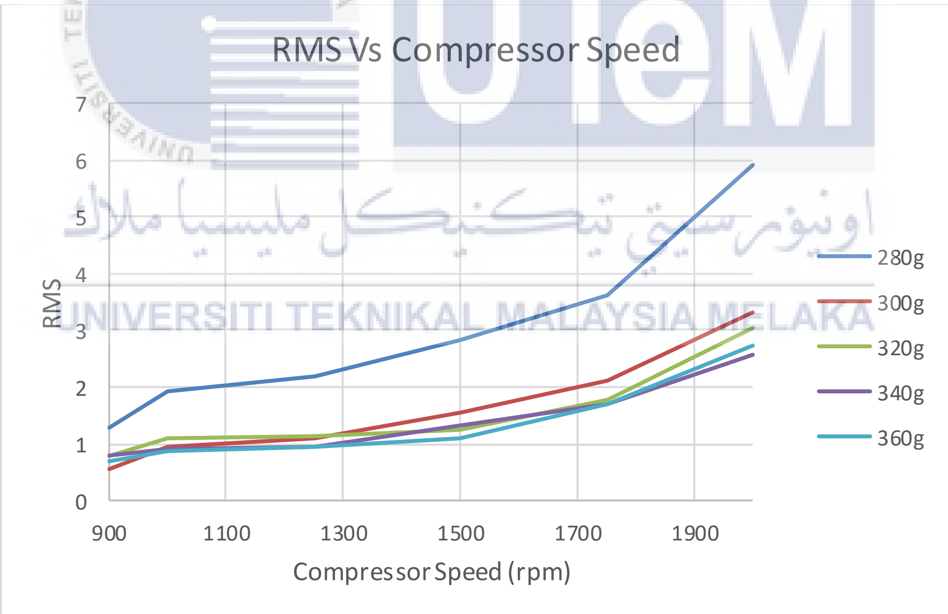

Figure 4.13 Comparison Data for RMS

The RMS (Root Mean Square) coefficient is shown versus compressor speed, expressed in revolutions per minute (rpm), for a range of refrigerant weights, from 280g to 360g, on this graph. The term "RMS coefficient" most usually refers to a measurable attribute of the system that has a root mean square value. Examples of such attributes are vibration amplitude, electrical current, and acoustic pressure level, which are frequently measured quantities in physics and engineering.

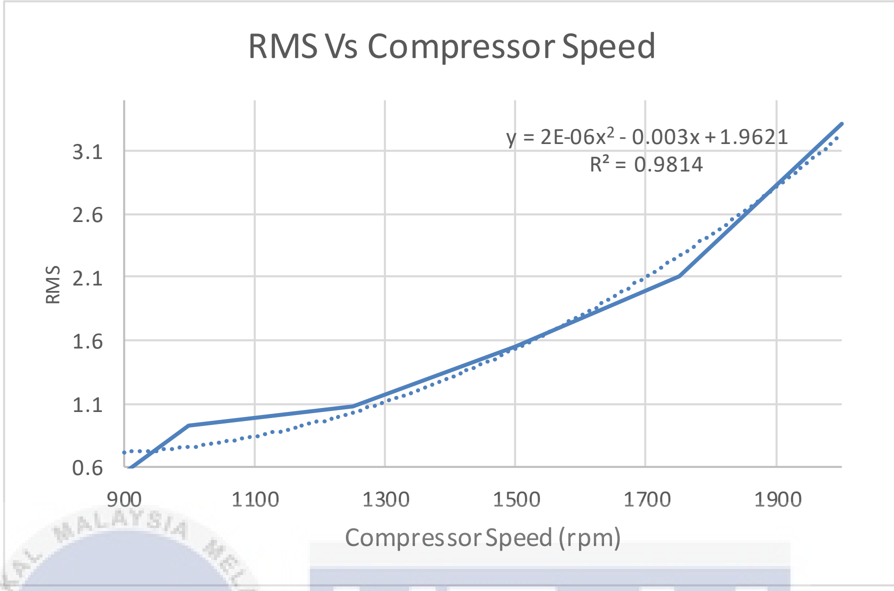

Figure 4.14 Coefficient of Determination for RMS

The display graph is a scatter plot that contrasts RMS (root Mean Square) values with compressor speed (measured in rpm) when the compressor is operating. When it comes to machinery such as compressors, vibration levels are frequently measured using the root mean square (RMS) value, which generally denotes the magnitude of a variable amount.

Using the formula y = 2E-06x^2 - 0.003x + 1.9621 (4.3), which represents the analysis of the quadratic regression model and y is the RMS value, there is a significant link between these variables, where x is the compressor speed. With a coefficient of determination R^2 of 0.9814, this model accounts for 98.14% of the variability in the RMS values. The graph that displays a solid line for the model closely coinciding with the dotted line of data points further demonstrates the model's effectiveness in fitting the data points, as indicated by the high R^2 value. The graph indicates a pattern whereby the RMS value gradually rises as compressor speed increases. This pattern might be explained by things like increased mechanical vibrations or the appearance of resonant frequencies at faster velocities, which become more noticeable and possibly significant.

For predictive maintenance and compressor health monitoring, it’s essential to comprehend this connection in practice. Components that may be under stress or malfunctioning as speed are highlighted by the growing RMS value in association with speed, which may signal wear or impending failure. Importantly, the regression equation’s coefficient must be interpreted. As the compressor speed increases, the RMS rise appears to be accelerating rather than linear, as indicated by the positive quadratic component 2 E-0.6x^2. A bit decrease in the rate of change at particular speeds is shown by the negative linear coefficient -0.003x. RMS readings often show an increasing trend as compressor speed increases; however, the quadratic component has a greater overall influence.

The RMS values most likely represent real mechanical vibrations or acoustic emissions from the compressor as it works at various speeds given the operating status of the compressor (on). Such data must be tracked and analyses to comprehend compressor performance and maybe spot problems before they become fatal. The speeds at which the RMS starts to climb more quickly would be the main areas of concern since they could hint to crucial thresholds for the machinery.

4.5.2 RMS in Compressor Stop

Table 4.4 Data RMS of Compressor in Stop Condition

Quantity of Refrigerant (g)	280	300	320	340	360
RPM	RMS				
750	1.1756	0.2425	0.331	0.3072	0.3261
1000	1.715	0.7915	0.7942	0.7432	0.7832
1250	1.9338	1.1224	1.0013	0.9233	0.9368
1500	2.5882	1.6478	1.5898	1.3785	1.4258

1750	4.026	2.7836	1.8978	1.8435	1.5109
2000	5.2902	3.4292	3.4016	2.2216	2.9164

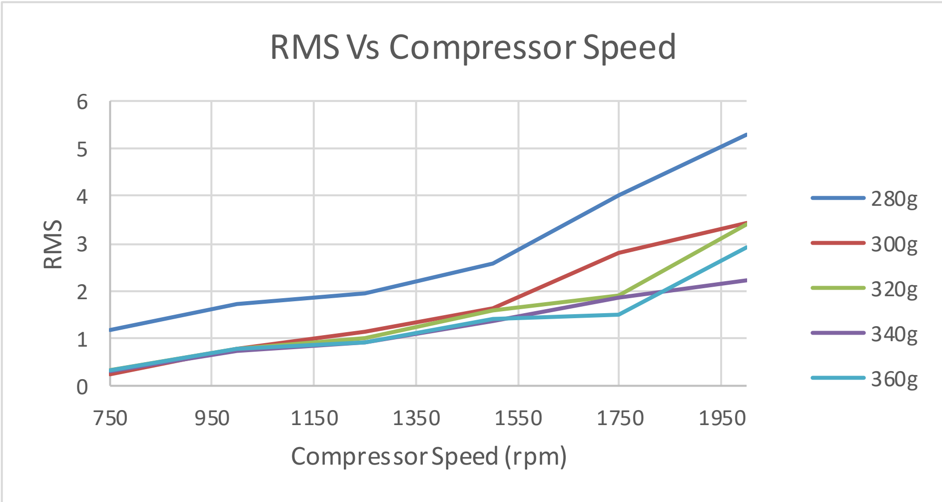

Figure 4.15 Comparison Data for RMS

The relationship between the RMS coefficient and compressor speed under various refrigerant volumes is seen in the RMS VS Compressor Speed graph. All curves start at 0rpm, meaning that there are no meaningful RMS values while the compressor is not operating. The RMS coefficient grows with compressor speed, first gradually and later significantly, indicating a non-linear connection. At lower speeds, the effect of refrigerant quantity on RMS is negligible but, at 1500rpm, it becomes considerable, especially for the 360g amount, suggesting increased sensitivity. Sharp increases in RMS, particularly above 2000rpm, might indicate the approach of a crucial operating threshold and possible instability in the system. In the research, the studies are visible at the 320g refrigerant quantity in regular RMS circumstances.

When the compressor is turned off, the graph illustrates the relationship between RMS values and Compressor Speed (in rpm). This scatter plot is supported by a quadratic regression model, which, like the previous graph we looked at, suggests that there is a non-linear relationship between the two variables.

A quadratic regression model is used in the graph analysis to explain the link between the RMS values and the compressor speed. According to the model equation, RMS values are affected by both the quadratic and linear components of the compressor speed, as shown by:

$$y = 2E - 06x^2 - 0.0022x + 1.2138$$

(4.4)

This indicates that when the compressor speed rises, the RMS values show a complicated behavior, with negative linear terms having a decreasing impact and the quadratic term driving an accelerating increase.

The coefficient of determination (R^2) value of 0.9616 suggests that the model explains a substantial 96.16% of the variance in RMS data. This indicates a robust relationship between the compressor speed and RMS values.

The unexpected increase in RMS values as the compressor speed increases even while the compressor is off is a fascinating feature of the data. This anomaly shows that RMS values may be collecting passive vibrations or resonances connected to adjacent equipment, even though they are normally indicative of active machinery vibrations. This research emphasizes the need to comprehend external impacts on equipment, even while it is idle, and has significant consequences for industry. To find out if the off-state compressor maintains standby modes with active components or is susceptible to vibrations from nearby tools, more research is necessary. These insights are essential for protecting equipment and performing industrial maintenance.

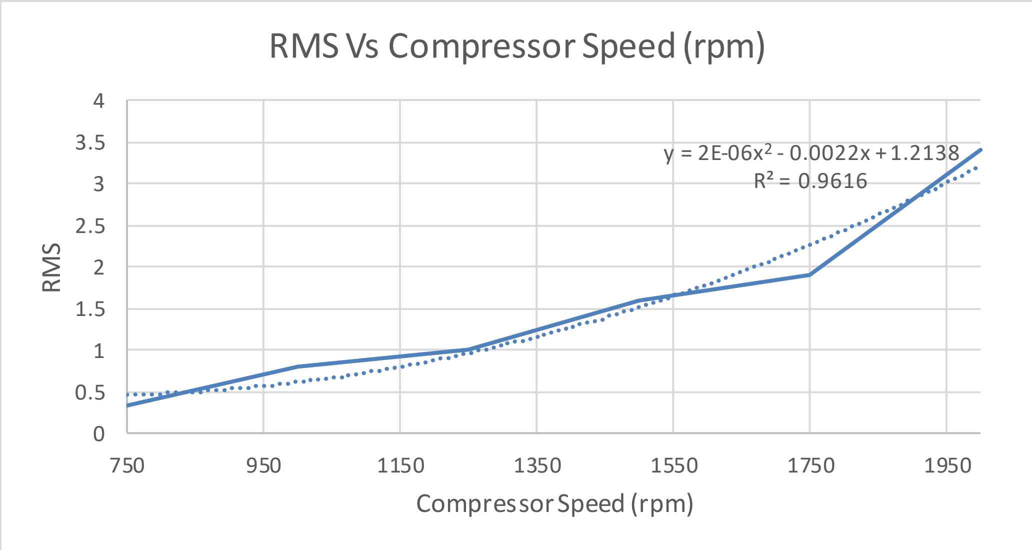

Figure 4.16 Coefficient of Determination for RMS

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the thesis on “Vehicle Air-Condition Compressor Using Vibration Signal Analysis” has throen light on the reliability and effectiveness of vehicle compressors for air conditioning. An in depth analysis of compressor behavior at a range of operating speeds from 750rpm to 2000rpm both with compressor on and off of the study. The analysis of typical conditions, including refrigerant and oil levels, also gave the inquiry more depth.

The Z-freq graph’s importance in properly analyzing vibration impacts is one of the study’s most natable findings. Particularly when used in conjuction with vibration analysis, this graph has shown to be a trustworthy resource for tracking and assessing compressor performance. As a result, it is advised that the Z-freq graph be used as the primary technique for evaluating compressor health and spotting any problems in future research and commercial applications.

The behavior of the car air conditioner compressor and the significance of vibration signal analysis have both been improved by the thesis, all things considered. This might lead to improved efficiency and dependability of vehicle air conditioning systems by laying the groundwork for future research and real-world application in the automotive sector.

5.2 Recommendations

With the knowledge gained from this thesis, a number of important suggestions for improving the upkeep and functionality of car air conditioner compressors come to light.

Above all, it is highly recommended that Z-freq graph analysis be in incorporated into regular maintenance and monitoring procedures by both automakers and repair facilities. This approach of frequently evaluating compressor vibration data allows for the early identification and resolution of any problems. This proactive strategy increases system efficiency overall ehile also extending the compressor's lifespan. In addition, it is advisable to contemplate the deployment of advanced real-time monitoring systems can furnish prompt input about vibration patterns and intensities. Manufacturers and car consumers could benefit from this technology's capacity to increase compressor reliability and lower the frequency of unplanned failures.

Furthermore maintaining the lifetime and effective opeartion of air conditioning compressors requires optimising working conditions. Maintaining compressor speeds within the specified range and keeping an eye on refrigerant and lubricant levels are two examples of suggeste operating parameters that may have a big impact on the lifespan and overall efficacy of the compressor. To optimize the life span of their air conditioning compressors, car owners should carefully adhere to the manufacturer's explicit advice regarding the optimal working parameters.

Finally, this thesis highlights how important vibration signal analysis is for assessing compressor conditions, particularlywhen using the Z-freq graph. Further study in this area needs to concentrate on improving analysic methods, creating more accurate prediction models, and investigating new diagnostic instruments. Academic industry collabrations are crucial for supporting innovation and creatung cutting edge techniques and technologies that improve the efficiency and dependability of car air conditioner compressors. This joint project promises significant advantages for automakers and customers in the form of increased air conditioning system efficiency and dependability.

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(Armstrong & Stevenson, 1960; Kudryavtseva et al., 2019; Tiboni et al., 2022)

APPENDICES

APPENDIX A PSM 1 Gantt Chart

PSM 1 PLANNING GANTT CHART																
2023																
MONTH	FEB		MARCH				APRIL				MAY				JUNE	
ACTIVITY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Proposed Project	PSM 1 BRIEFING								MID SEMESTER BREAK							SEMESTER BREAK
Find Supervisor																
Decide Project Title																
Identify objective, problem statement, and literature review																
Thesis for Instrumentations and Software																
Plan experimental setup																
Method of Component																
Project Costing																
Identify instrumentations and software																
Selection of Instrumentations and Software																
Final selection of suitable system																
Finalize the project experimental setup																
Project Deliverable (PSM1)																
Chapter 1,2 and 3 draft submission																
Chapter 1,2 and 3 final submission																
Submission Final Report																
Presentation																
Slide Presentation																

APPENDIX B PSM 2 Gantt Chart

PSM 2 PLANNING GANTT CHART																
2023																
BIL	TASK	PLAN/ ACTUAL	WEEK													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Briefing	Plan														
		Actual														
2	Experimental setup	Plan														
		Actual														
3	Data Collection	Plan														
		Actual														
4	Result Analysis	Plan														
		Actual														
5	Result Verification	Plan									MID SEMESTER BREAK					
		Actual														
6	Conclusion and Recommendation	Plan														
		Actual														
7	Weekly BDP Reporting (Logbook)	Plan														
		Actual														
8	Project Reporting	Plan														
		Actual														
9	4 Pages Summary	Plan														
		Actual														
10	Presentation & Poster	Plan														
		Actual														