UNIVERSITI TEKNIKAL MALAYSIA MELAKA

WIRELESS A/C COMPRESSOR VIBRATION DIAGNOSTICS USING MACHINE LEARNING-BASED SIGNAL ANALYSIS Z-FREQ 2D WITH REFRIGERANT AND OIL AS FAULTS

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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A dissertation submitted
in partial fulfillment of the requirements for the degree of
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2024

DECLARATION

I declare that this thesis entitled “Wireless A/C Compressor Vibration Diagnostics Using Machine Learning-Based Signal Analysis Z-Freq 2D With Refrigerant And Oil As Faults“ is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :.....

Name : Muhammad Yuszairie Bin Yusri

Date : …….14 April 2025.....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality as a partial fulfillment of Master of Science in Mechanical Engineering

Signature :.....

Supervisor Name : Ts. Dr. Nor Azazi Bin Ngatiman

Date :……14 April 2025.....

DEDICATION

This work of thesis I would like to dedicate my whole love to both beloved late parents Zaiton Binti Shamsudin and Yusri Bin Harun. Although both of them are no longer with us, their advice, wisdom, love, unwavering support, and encouragement patiently supported me through life's struggles, believing I could achieve great success both personally and academically. Undoubtedly, without their prayer, I will never be at where I am now. I wish both of you still with us, and the memories with you will always stay in my heart.

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ABSTRACT

Advanced diagnostic monitoring and fault detection in vehicle A/C systems are critical for the automotive and A/C industries to accurately identify system anomalies and enable early detection of mechanical failures, particularly in compressor health and performance. Key components of automotive A/C systems—compressor, condenser, evaporator, thermal expansion valve, and receiver drier—are essential for optimal functionality. A primary factor contributing to poor compressor performance is insufficient oil lubricant and refrigerant R134a. This study aims to develop the Z-Freq 2D coefficient as a novel statistical method for detecting faults in vehicle compressors by analyzing vibration data influenced by refrigerant and lubricant levels, using a wireless diagnostic approach and validating findings through machine learning, simulation, and experimental testing. Fault conditions were simulated by varying the speed of the compressor, refrigerant amounts, and lubricant volumes. Vibration data was collected using a Phantom Vibration Sensor attached to the compressor of a Myvi 1.5L X vehicle with a registered air conditioning system. Data analysis was performed using MATLAB, where the Z-Freq 2D coefficient was applied to generate graphical representations and validate results using machine learning models, specifically Support Vector Machine (SVM) and k-Nearest Neighbors (kNN). The experimental parameters included compressor speeds ranging from 750 to 2000 RPM, refrigerant levels from 280g to 360g, and lubricant volumes from 40ml to 120ml. Industry-recommended benchmark values were 320–330 g of refrigerant and 80–90 ml of lubricant. Results indicate that the Z-Freq 2D coefficient, combined with the Phantom Vibration Sensor, effectively identifies compressor faults. The SVM model outperformed kNN, achieving 87.1% accuracy and 98.6% sensitivity, compared to kNN's 82.9% accuracy and 88.6% sensitivity. Additionally, an increase in compressor RPM resulted in higher Z-Freq 2D data distribution, correlating with elevated vibration levels while excluding noise from the vehicle frame. The study also highlights a limitation in the wireless diagnostic method, which depends on stable network connectivity for transmitting data to cloud-based platforms such as DigivibeMX or EI Analytic. The findings demonstrate the reliability of the Z-Freq 2D coefficient as a diagnostic tool for fault detection in automotive compressors. This method, validated through experimentation and machine learning, offers significant potential for enhancing the accuracy of HVAC system diagnostics. The research underscores the importance of maintaining optimal refrigerant and lubricant levels to ensure compressor efficiency and overall system reliability.

ABSTRAK

Pemantauan diagnostik yang maju dan pengesanan kerosakan dalam sistem penyaman udara kenderaan adalah kritikal untuk industri automotif dan penyaman udara bagi mengenal pasti anomali sistem dengan tepat serta membolehkan pengesanan awal kegagalan mekanikal, terutamanya berkaitan kesihatan dan prestasi pemampat. Komponen utama sistem penyaman udara kenderaan—pemampat, kondensor, penyejat, injap pengembangan terma, dan penerima pengering—adalah penting untuk memastikan fungsi optimum. Faktor utama yang menyumbang kepada prestasi pemampat yang lemah ialah kekurangan pelincir minyak dan penyejuk R134a. Kajian ini bertujuan membangunkan pekali Z-Freq 2D sebagai kaedah statistik baharu untuk mengesan kerosakan pemampat kenderaan dengan menganalisis data getaran yang dipengaruhi oleh tahap penyejuk dan pelincir, menggunakan pendekatan diagnostik tanpa wayar serta mengesahkan dapatan melalui pembelajaran mesin, simulasi, dan ujian eksperimen. Keadaan kerosakan disimulasikan dengan memvariasikan kelajuan pemampat, jumlah penyejuk, dan isipadu pelincir. Data getaran dikumpul menggunakan Phantom Vibration Sensor yang dipasang pada pemampat kenderaan Myvi 1.5L X dengan sistem penyaman udara berdaftar. Analisis data dilakukan menggunakan MATLAB, di mana pekali Z-Freq 2D diaplikasikan untuk menghasilkan perwakilan grafik dan mengesahkan keputusan menggunakan model pembelajaran mesin, khususnya Support Vector Machine (SVM) dan k-Nearest Neighbors (kNN). Parameter eksperimen termasuk kelajuan pemampat antara 750 hingga 2000 RPM, tahap penyejuk dari 280 g hingga 360 g, dan isipadu pelincir dari 40 ml hingga 120 ml. Nilai penanda aras yang disyorkan oleh industri ialah 320–330 g penyejuk dan 80–90 ml pelincir. Keputusan menunjukkan bahawa pekali Z-Freq 2D, apabila digabungkan dengan Phantom Vibration Sensor, berkesan dalam mengenal pasti kerosakan pemampat. Model SVM mengatasi kNN, dengan ketepatan 87.1% dan sensitiviti 98.6%, berbanding kNN yang mencapai ketepatan 82.9% dan sensitiviti 88.6%. Tambahan pula, peningkatan RPM pemampat menghasilkan taburan data Z-Freq 2D yang lebih tinggi, yang berkorelasi dengan peningkatan tahap getaran sambil mengecualikan bunyi daripada kerangka kenderaan. Kajian ini juga menonjolkan had kaedah diagnostik tanpa wayar, yang bergantung kepada kekuatan isyarat rangkaian untuk menghantar data ke platform berasaskan awan seperti DigivibeMX atau EI Analytic. Penemuan ini membuktikan kebolehpercayaan pekali Z-Freq 2D sebagai alat diagnostik untuk pengesanan kerosakan pemampat automotif. Kaedah ini, yang disahkan melalui eksperimen dan pembelajaran mesin, menawarkan potensi besar dalam meningkatkan ketepatan diagnostik sistem penyaman udara. Kajian ini menekankan kepentingan mengekalkan tahap penyejuk dan pelincir yang optimum bagi memastikan kecekapan pemampat dan kebolehpercayaan keseluruhan sistem.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

$UTeM$	-	Universiti Teknikal Malaysia Melaka
A/C	-	Air Conditioning
HVAC	-	Heating, Ventilation, And Air Conditioning
RPM	-	Revolution Per Minute
i-Kaz	-	Integrated Kurtosis Algorithm
SVM	-	Support Vector Machines
k-NN	-	k-Nearest Neighbors
CFC	-	Chlorofluorocarbon
HCFC	-	Hydrochlorofluorocarbon
HFC	-	Hydrofluorocarbon
ML	-	Machine Learning
MATLAB	-	Matrix Laboratory
PVS	-	Phantom Vibration Sensor
HEV	-	Hybrid Electric Vehicle
PMSMs	-	Permanent Magnet Synchronous Motors
OCR	-	Oil Circulation Rate
GWP	-	Global Warming Potential
COP	-	Coefficient Of Performance
NMS	-	Network Management Systems
IoT	-	The Internet of Things
AUC	-	Area Under the Curve

LIST OF SYMBOLS

δ	-	Voltage angle
n	-	The number of sample
f	-	frequency
σ	-	The Square Standard deviation value
x	-	value of data point
μ	-	mean of the data
Z_2^f	-	z frequency 2D at second central moment

LIST OF APPENDICES

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this dissertation paper:

Muhammad Y., Azazi N., Shamsul A., Muhammad N.O. 2024. Wireless HVAC compressor diagnostics using machine learning-based signal analysis Z-Freq 2D. Journal of Physics: Conference Series, Volume 2688, 7th International Conference on Mechanical Engineering Research 2023 (ICMER 2023) 12-13 september 2023 Kuantan, Malaysia

CHAPTER 1

INTRODUCTION

1.1 Background

Diagnostic monitoring and fault detection in vehicle HVAC systems have become crucial for both the automotive and HVAC industries to detect faults and prevent mechanical failures or breakdowns (Zhan and Makis. 2006). The information obtained from the diagnostic performed, is capable of providing an early planning strategy when there are early warning signs of machine faults which preventing any further critical damage to the machine components in the future. Statistical diagnostics is an effective method for mechanical applications involving high vibration signals, which can lead to significant failures in machine performance, such as in wind turbines, aircraft motors, and building HVAC systems..

In many industrial applications, compressors are essential components because they supply the power required for a wide range of operations. Efficiency is essential for these systems to function optimally and have a long lifespan. However, preventive maintenance and the avoidance of costly downtime still rely on the early identification and diagnosis of potential problems, particularly those related to vibration. This work investigates the application of wireless diagnostics, with a focus on utilizing newly developed Z-freq 2D coefficients, to obtain unparalleled understanding of the vibration dynamics of compressors.

Since vibration analysis reflects wear, misalignment, and mechanical imbalances, it has long been acknowledged as a critical machinery health indicator. One of the drawbacks of traditional wired monitoring systems is their geographical and installation complexity. In addition to overcoming these obstacles, the use of wireless technologies creates opportunities for real-time diagnostics and monitoring, offering a more thorough grasp of compressor health.

The specific objective of this study is to introduce a new method for vibration analysis, known as Z-freq coefficients. According to Ngatiman N., et al (2021) Z-freq is a technology that uses vibration sensors to evaluate signals and convert auditory data into signal features. It is also used to monitor engines. The Integrated Kurtosis-based Algorithm (i-Kaz), which divides a time-domain signal into frequency ranges, is one of the simplified and effective statistical signal assessment approaches used in this method (Ngatiman N., et al. 2021). Our objective is to formulate a new statistical-based signal data analysis using Z-Freq 2D and to understand the distribution of compressor vibrations and their frequency components through this advanced statistical method. In addition, to examining and evaluating experimentation data in order to identify the relationship between vibration on the compressor and experimental parameters.

The following sections will cover our study's methodology, results from our Z-freq 2D coefficient analysis, and implications for the compressor health monitoring field. We will also examine the literature that has already been written on wireless diagnostics and vibration analysis. With potential applications spanning beyond compressors, the knowledge gathered from this study is expected to make a substantial contribution to the development of wireless diagnostics in industrial settings.

This study aims to rigorously assess the impact of different amount of refrigerants and the amount of oil on the performance and efficiency of vehicle air conditioning (A/C) systems. Employing Z-freq 2D statistical analysis alongside machine learning validation techniques, the research aims to explain the optimal refrigerant choices that enhance A/C functionality while ensuring environmental sustainability. This approach promises to contribute significantly to the field, offering a comprehensive evaluation of refrigerant efficacy within vehicular contexts.

1.2 Problem statement

It is crucial to assess and monitor the performance of the compressor in vehicle air conditioning (A/C) systems to ensure both the quality of the A/C and the comfort of the users. Wireless diagnostics using state-of-the-art machine learning-based signal analysis with Z-freq 2D is a method for monitoring the performance of vehicle compressors remotely, eliminating the need for close-up physical inspections to detect system faults.

In this research, the coefficients in the formula are derived from the standard notation of 2D Z-frequencies. In another words new formula based on a coefficient system for 2D Z-frequencies defined notation has been put forth. For two-dimensional digital signal processing applications, this method shows potential in streamlining calculations and analysis. Nonetheless, there is still much to learn about the formula's efficiency, especially with regard to how quickly and accurately the standard notation and coefficient representation may be converted.

Using a wireless diagnostic approach, vibrations from a car compressor were evaluated in an early exploratory experiment. But the study's concentration on a single

issue or a small sample size meant that its breadth was constrained. With the goal of improving the wireless technique and proving its effectiveness for thorough compressor vibration analysis, this preliminary study lays the groundwork for future research.

This innovative study represents a paradigm shift in the identification of car compressor problems. It offers an innovative methodology that breaks from conventional practices and provides a new viewpoint on locating compressor problems. By gaining a greater understanding of defect causes and enabling more accurate and efficient identification, this novel technique has the potential to completely transform the field of compressor diagnostics. The study lays the groundwork for additional investigation and advancement, which may result in the development of cutting-edge diagnostic instruments for car compressors.

Hence, the three problem statement of this research can be stated as follow;

i) The current efficiency of the formula, derived from the standard notation of 2D Z-frequencies, is under investigation, highlighting the need for further optimization and validation,

ii) The existing evaluation of vehicle compressor vibration using a wireless diagnostic technique has been limited in scope, indicating the necessity for a more comprehensive and detailed study,

iii) This research proposes a novel and innovative approach to diagnosing vehicle compressor faults, offering a fresh perspective that addresses the limitations of current diagnostic methods.

1.3 Research question

The main aim of this research is to propose a new statistical diagnostic methodology focusing on the implementation of wireless HVAC compressor diagnostics using state-of-the-art machine learning-based signal analysis with Z-freq 2D. In this section of the proposal, there are several research questions that can be define. Specifically, the research question are as follows:

i) Is there enough foundation in the vibration sensitivity found in this study to create a fault detection system that can identify and isolate specific compressor faults?.

ii) Could the wireless Phantom Vibration Sensor (PVS) provide better defect detection performance than connected cable sensors, producing quantifiably separate data sets?.

iii) Is it possible to determine the accuracy level attained by using 2D Z-Frequency analysis as a trustworthy tool for identifying compressor faults?.

1.4 Research objective

The primary goal of this study is to develop new statistical diagnostic techniques that are more organized and efficient for accurately estimating the likelihood of malfunctions or defects in a car's HVAC system, thereby preventing further damage. Specifically, the objectives are as follows:

i) To formulate a new statistical - based signal data in Z-freq 2D for accurate wireless system fault diagnosis and improve the fault detection in the HVAC,