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QUANTITATIVE ASSESSMENT OF REFRIGERANT IMPACT ON VEHICLE AIR-CONDITIONING SYSTEMS VIA Z-Freq 2D STATISTICAL ANALYSIS

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ABSTRACT

In this study, the impact of refrigerant types on the performance and efficiency of vehicle air-conditioning (AC) systems was quantitatively assessed using a novel two-dimensional Z-Freq 2D statistical analysis method. Wireless vibration accelerometers, capturing both horizontal and vertical vibrations, were utilized to measure the dynamic response of the air-conditioning compressor. Before data collection, meticulous calibration of sensors was conducted to ensure the accuracy and reliability of measurements. The introduction of the Z-Freq 2D statistical analysis technique, developed specifically for this research, allowed for a comprehensive examination of the vibrational data, facilitating a deeper understanding of the effects of different refrigerants on AC system performance. To validate the effectiveness and reliability of the Z-Freq 2D analysis, machine learning techniques were employed. These techniques provided a robust framework for the analysis of the statistical data, with performance evaluation indicators demonstrating the efficacy of the newly developed method. The experimental setup was based on an actual vehicle air-conditioning test rig, designed to simulate real-world operating conditions accurately. The findings of this research offer significant insights into the selection of refrigerants for vehicle AC systems, highlighting the potential for enhanced system performance and efficiency through the application of advanced statistical analysis and machine learning validation techniques. This study not only contributes to the field of automotive thermal management but also paves the way for future research in the optimization of vehicle AC systems.

Keywords: fault diagnostics, statistical methods, Z-Freq 2D, vibration monitoring, machine learning.

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INTRODUCTION

In the case of hybrid electric vehicles (HEVs), a comprehensive inspection of the vehicle's compressor as part of an annual maintenance program can help prevent potential problems for drivers, such as car breakdowns or distracted driving caused by hot air. The "Engine Management Light" system is now utilized to detect engine issues in automobiles. It doesn't pinpoint the exact flaw that is causing the issue, but it illuminates anytime "something" seems wrong with the engine, indicating that there might be a problem.

Some automotive problems may also go unnoticed due to inadequate vehicle diagnostics. Would ultimately be detrimental to the vehicle and its occupants. Among the incidents is the HVAC system leaking gas into the vehicle. This scenario is concerning from a medical and dangerous viewpoint and has the potential to be fatal, even if it might not seem alarming to the typical individual. Although the HVAC system was intended to supply the cabin with safe, clean air, a bad diagnosis led to a leak that let harmful gases like carbon dioxide (CO2) escape. These gases can cause several adverse effects, such as nausea, migraines, and even fatalities. [11].

Currently, problems with compressors or HVAC systems are detected by measuring the temperature coming from the vehicle's air conditioner. The main indication that the car's air conditioning system is broken is inadequate air chilling, and the AC vault's hot air implies that the HVAC system may be having problems due to its high temperature. A 2016 book states that slugging and lubrication loss are the most common causes of compressor failure [10] Not the Compressor's Fault.
With the use of cutting-edge machine learning-based signal analysis Z-freq 2D, this research study aims to implement wireless HVAC compressor diagnostics by correlating the volume of oil, the amount of R134a refrigerant, the speed of the compressor, and other characteristics.

RESEARCH STUDY LITERATURE REVIEW

Vehicle air conditioning systems, which use parts like compressors and refrigerants for effective heat management, are essential for guaranteeing the comfort and safety of passengers. New developments emphasize the incorporation of heat pump air conditioning with vapor injection for improved heating efficiency, which is critical for the range of electric vehicles and the safety of batteries in different scenarios. [9].

The significance of refrigerant type in vehicle AC systems is paramount, affecting performance, efficiency, and environmental impact. As the automotive sector evolves towards electrification, the choice of refrigerants becomes crucial in optimizing thermal management strategies, directly influencing the efficiency and environmental sustainability of these systems [2]. This underscores the need for ongoing research to identify refrigerants that strike an optimal balance between cooling efficiency and environmental sustainability.

Assessing the performance of automotive air conditioning systems, especially the dynamic reactions of parts like compressors, is quite difficult. The subtleties of monitoring operational states and performance characteristics are brought to light by recent research, such as that conducted by Kim and Kang (2023), which demonstrates the difficulties of evaluating sensor data to analyze piston air compressors in railway vehicles. In addition to providing a window into the larger issues facing all automotive AC systems, this dynamic study is essential for improving safety, dependability, and maintenance procedures. [3].

The ability to precisely measure both horizontal and vertical vibrations has allowed wireless vibration accelerometers to completely change the way air conditioner compressors are monitored. This technical development is essential for identifying possible problems, improving efficiency, and extending the life of equipment. To guarantee the precision and dependability of the information gathered, the calibration of these sensors is essential. This will enable efficient maintenance plans and operations.

The advent of Z-Freq 2D statistical analysis heralds a significant leap forward in the realm of vibrational data analysis, addressing the limitations inherent in traditional methods. Existing analytical techniques often fall short of comprehensively understanding the nuances of vibrational data, particularly in the context of AC system performance. The novel Z-Freq 2D method, through its innovative use of a Z-notch frequency domain filter and the Phantom Vibration Sensor, offers a more nuanced and accurate analysis of AC compressor vibrations. This advancement is crucial for early detection of compressor malfunctions, thereby mitigating potential long-term maintenance challenges [4].

The integration of machine learning techniques in performance evaluation, particularly through Z-Freq 2D analysis, marks a significant advancement in the analysis of complex datasets. This approach, as highlighted by Muhammad Y. *et al*. (2024), employs state-of-the-art machine learning-based signal analysis to enhance diagnostic capabilities for vehicle A/C compressor malfunctions. The use of Z-freq 2D, augmented by machine learning, facilitates the early detection of faults, thereby preventing extensive maintenance and offering a more accurate interpretation of data, leading to actionable insights [4].

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

MACHINE LEARNING: MATRIX LABORATORY (MATLAB)

When analyzing an A/C compressor malfunction or malfunction that is related to any number of criteria, such as a lack of refrigerant or oil in the system, etc., the machine learning approach is a mathematical and statistical methodology that is very helpful. This experiment analysis method involves calculating and identifying any data changes using the coefficient formula. MATLAB stands for Matrix Laboratory, which is a high-level programming language and computing environment developed by a company known as MathWorks. Machine learning (ML) is a subfield of artificial intelligence (AI) that uses algorithms and data to enable software programs to anticipate outcomes with accuracy. Additionally, machine learning algorithms can mimic how people learn by using past data as input to forecast new output values [5]. The ability of a machine to mimic intelligent human behavior is the general definition of machine learning. The Z-Freq 2D data will be analyzed using Machine Learning using the MATLAB software.

METHODS AND MATERIAL

Experimental Setup

The key aspect of this research is utilizing the Z-Freq 2D method to identify the existence of faulty in the vehicle A/C (air conditioning) system, which in this research focuses on the vibration produced by the compressor. In this research, an experiment was conducted on the new car generation in Malaysia, namely Myvi 1.5L X. The experiment is set with two different kinds of parameters, one with different percentages of oil in the vehicle A/C system and another with different amounts of refrigerant gas in the system. The standard amount for the vehicle A/C system, according to the automotive industry specific to this type of car, is about 320 g to 330 g of refrigerant and 80 ml to 90 ml of oil in the compressor, which is the best amount to obtain the best performance result for the A/C system of the vehicle.

There are several main components in the air conditioning system of a vehicle's A/C system, which include the compressor, condenser, evaporator, thermal expansion valve, and receiver drier. These components are the basic and standard components in building a functional vehicle A/C system, and the compressor is the heart of the A/C system [12 and 13]. Figure-1 shows the experimented vehicle, Myvi 1.5L X, and Figure-2 shows the illustration of the vehicle A/C system.

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Figure-1. Experimental vehicle Myvi 1.5L X.

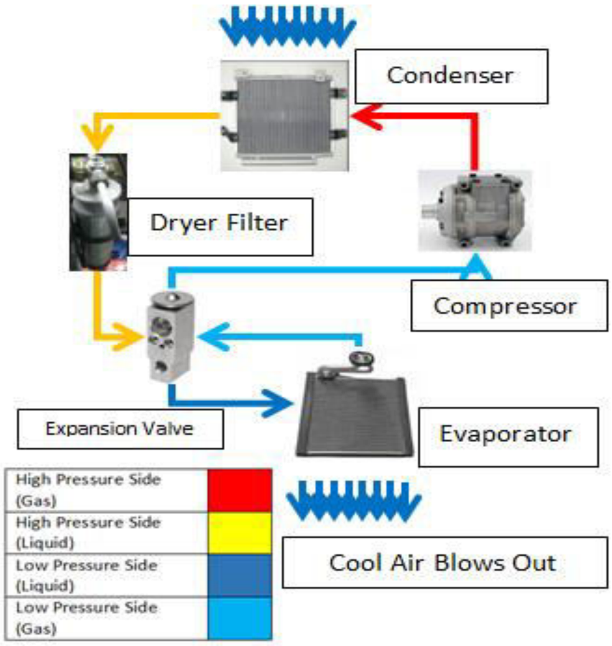

Figure-2. Vehicle air conditioning system [1].

The amount of R134a refrigerant is one of the different parameters used in the experiment. With a 5-second time record, the parameters are examined at various compressor speeds (RPMs), ranging from the lowest 750 RPM to 2000 RPM. Figure-3 illustrates how the Phantom Vibration Sensor, which is installed at the vehicle compressor, is utilized to record and monitor the data gathering. Over about 5 seconds of recording, the sensor is set up to generate 16, 384 samples per channel at a sampling rate of 3.2 kHz and a resolution of 6400 lines. Using this method, every event that happened while the vibration signal was being recorded may be found and examined.

Figure-3. Phantom vibration sensor at vehicle compressor.

The experiment parameters are set up from the lowest amount of refrigerant gases to the highest amount of refrigerant: 280g, 300g, 320g, 340g, and 360g. Each of the different gas amounts is tested at different speeds of the compressor, starting from idle speed (which has a different RPM value during compressor off and compressor on) until the highest speed: 750 RPM (compressor off idle speed), 900 RPM (compressor on idle speed), 1000 RPM, 1250 RPM, 1500 RPM, 1750 RPM, and 2000 RPM. All this experiment was conducted with 80 mL of the same amount of compressor oil for each parameter of refrigerant. Figure-4 shows the parameters setup for the experiment, and Figure-5 shows the overall experiment overflow.

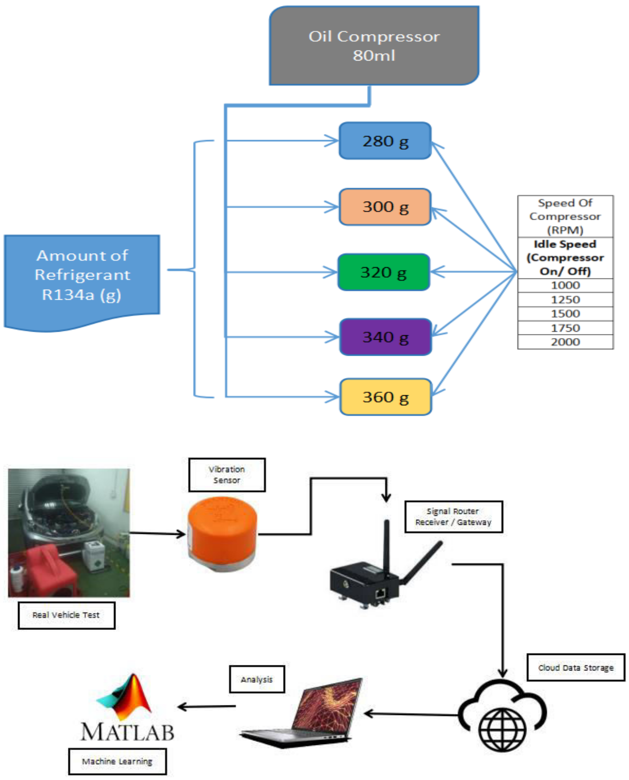

Figure-4. The illustration of experiment parameters setup and overflow.

MATHEMATICAL FORMULA

The primary purpose of the Integrated Kurtosis Algorithm (I-kaz) is to measure the data collected concerning the data centroid of dynamic signal analysis and to identify any alterations in the data signal in the experiment. With a distinct magnitude distribution for each axis, the I-kaz algorithm analysis yields a three-dimensional graphic representation of the data, where each axis denotes the frequency range of the data distribution. [6].

$$\text{I-kaz} = \left(\frac{1}{N}(M_4^L) + \frac{1}{N}(M_4^H) + \frac{1}{N}(M_4^V)\right)^{\frac{1}{2}} \quad (1)$$

Where,
N = number of data
M4 = 4th order moment of signal in LF, HF, and VF range respectively.

The mean, standard deviation, root mean square (RMS), skewness, and kurtosis are the formulas typically used in statistical parameters [7]. As the fourth moment of global signal statistics, the statistical moment for kurtosis (K) is sensitive to the spikiness of the data. In the equation, the kurtosis value is expressed as follows. (2):

$$K = \frac{1}{n\sigma^4}\sum_{i=1}^{n}(f_i - \bar{f})^4 \quad (2)$$

Where,
K: Kurtosis,
n: The number of samples,
f: frequency,
σ: The Square Standard deviation value

For a Gaussian distribution, the kurtosis value is roughly 3.0. According to Nuawi *et al*. (2008), higher kurtosis values indicate the presence of extreme values in a Gaussian distribution. The standard deviation value s for a signal with n data points can be obtained using the following formula. (3):

$$s = \left(\frac{1}{n}\sum_{i=1}^{n}(x_1 - \mu)^2\right)^{\frac{1}{2}} \quad (3)$$

Where,
x: value of data point,
μ: mean of the data,
n: number of samples

Equation (4) defines the coefficient of Z-Freq 2D based on the previous equation. The x- and y-axes locations, which represent x and y, respectively, are the two data frequency points that are used to determine the Z frequency.

$$Z_2^f = \frac{1}{n}\sqrt{K_x S_x^4 + K_y S_y^4} \quad (4)$$

Where:
Z_2^f: z frequency 2D at the second central moment,
n: number of samples,
K: kurtosis values,
S: standard deviation,
x: x-axis location,
y: y-axis location.

RESULTS AND DISCUSSIONS

Experimental Results

The experiment data obtained from the app DigivibeMX, which is a way to download the vibration data from the cloud, is then analyzed through Matlab with the formula Z-freq 2D as the core of the analysis to find the patterns of the vibration. Each of the vibrations will give different results in the scatter data pattern, which can be used to identify if the vehicle has a low volume of refrigerant in the HVAC system. Due to the high temperature within the car caused by low refrigerant gas volume, the compressor will have to work harder to keep the interior temperature of the cabin cool. There is no doubt that this is bad for the compressor's health, and it may be avoided with the use of this mathematical technique.

At each speed of the compressor, more than three (3) times the data are taken to ensure the data are the best possible data signal for obtaining the best possible analysis results. The vibration sensor records three (3) different axes, namely the horizontal (H) axis, the vertical (V) axis, and the axial (A) axis. Each axe represents the direction of the vibration signal, and the significant vibration indicates that this is the actual vibration signal to be captured and analyzed. In this case, vibrations on the horizontal and vertical axes have significant vibration values.

Experimental Result: Idle Compressor State

The experiment began with collecting the vibration signal at the idle speed of the compressor, which was conducted in two different states: compressor on and compressor off. Compressor off means that the vehicle is tested without running the compressor, while compressor on means that the compressor is running and working to cool the cabin. The reason behind this is to find out and compare the vibration present between a running compressor and a non-running compressor since a non-working compressor is considered faulty in the HVAC system. The idle speed during compressor off is around 750 RPM, while during compressor on it is 900 RPM.

As mentioned earlier, this research paper discussed the experiment of different amounts of refrigerant R134a with the same amount of compressor oil which is 80 ml. Figure-5 and Figure-6 show the results of the time domain and frequency domain for idle speed at 280 g of refrigerant for both states of the compressor respectively.

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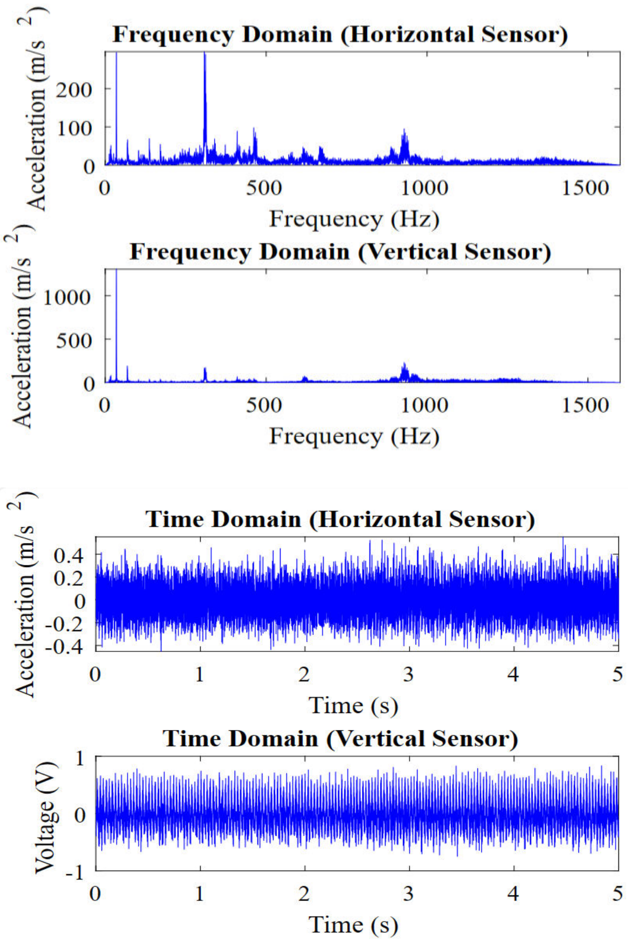
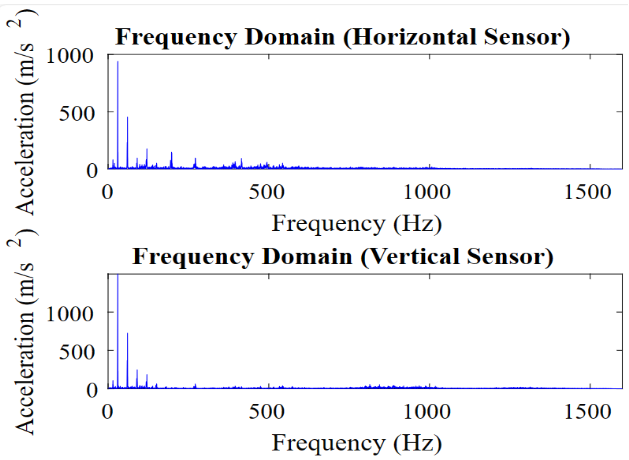


Figure-5. Time and frequency domain at idle speed for 280 g refrigerant (compressor off).



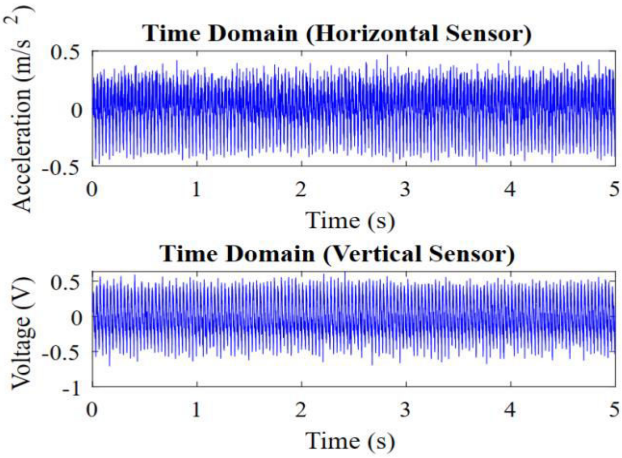


Figure-6. Time and frequency domain at idle speed for 280 g refrigerant (compressor on).

Figure-7 and Figure-8 show the results of the time domain and frequency domain for idle speed at 360 g of refrigerant for both states of the compressor respectively.

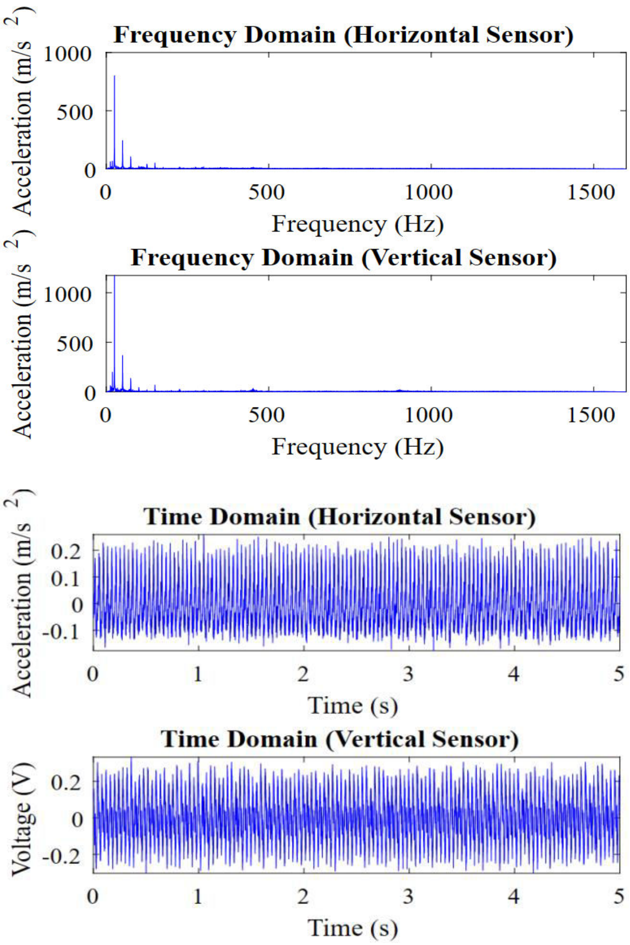


Figure-7. Time and frequency domain at idle speed for 360 g refrigerant (compressor off).

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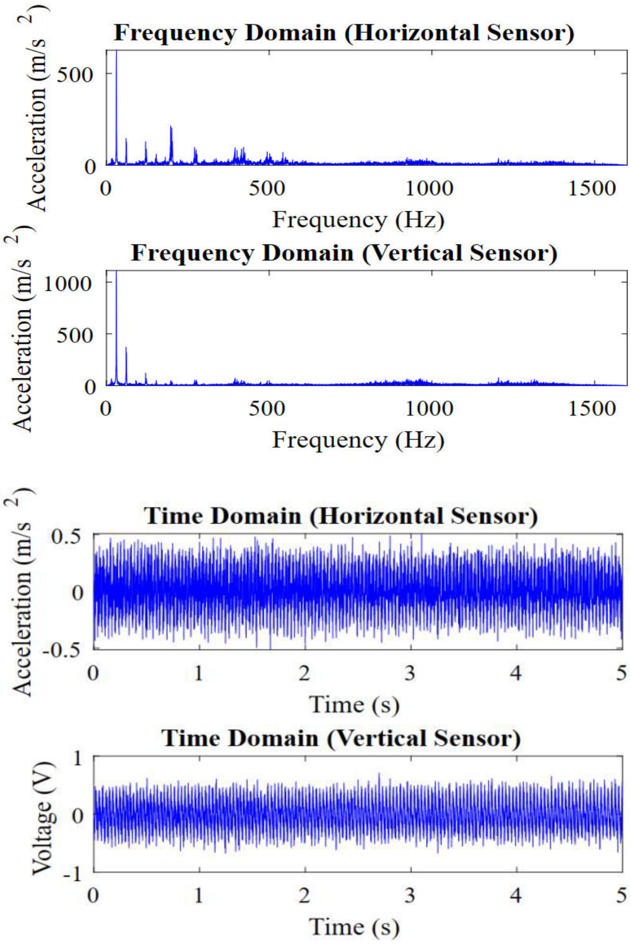
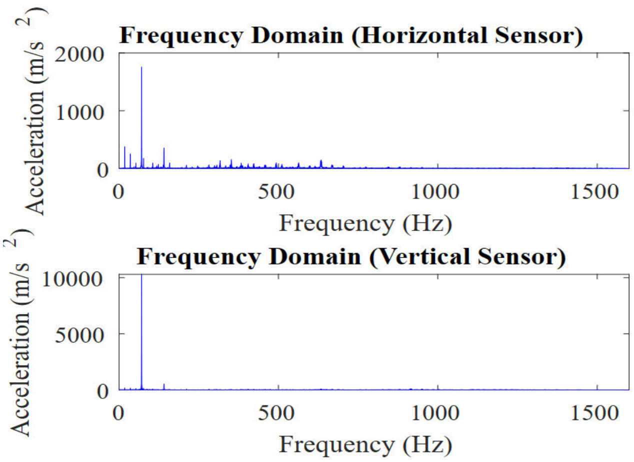


Figure-8. Time and frequency domain at idle speed for 360 g refrigerant (compressor on).

Experimental Result: Compressor Speed 2000 RPM

Figure-9 and Figure-10 show the results of the time domain and frequency domain for speed 2000 rpm at 280 g of refrigerant for both states of the compressor respectively.



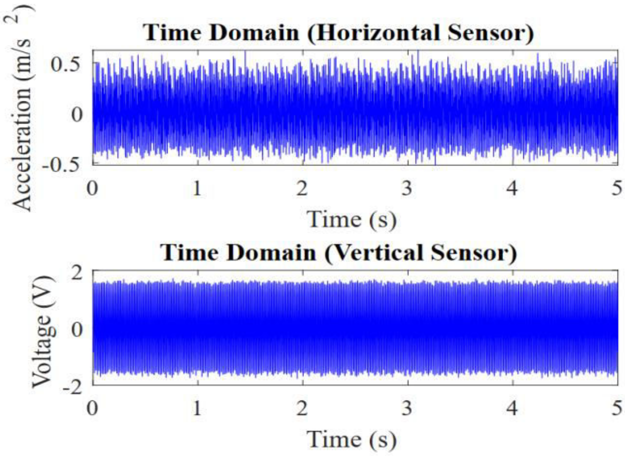


Figure-9. Time and frequency domain at 2000 RPM for 280 g refrigerant (compressor off).

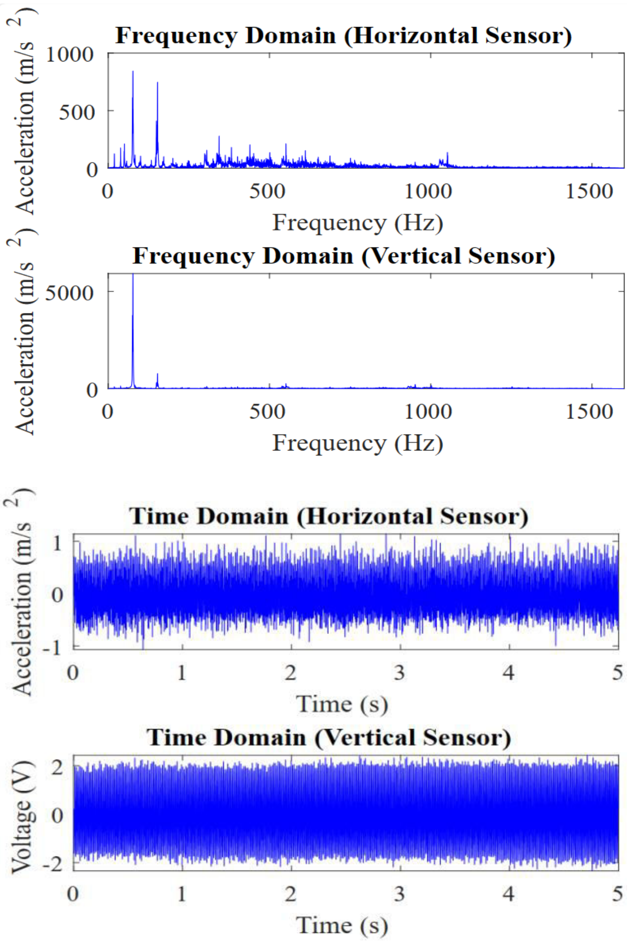


Figure-10. Time and frequency domain at 2000 RPM for 280 g refrigerant (compressor on).

Figure-11 and Figure-12 show the results of the time domain and frequency domain for speed 2000 rpm at 360 g of refrigerant for both states of the compressor respectively.

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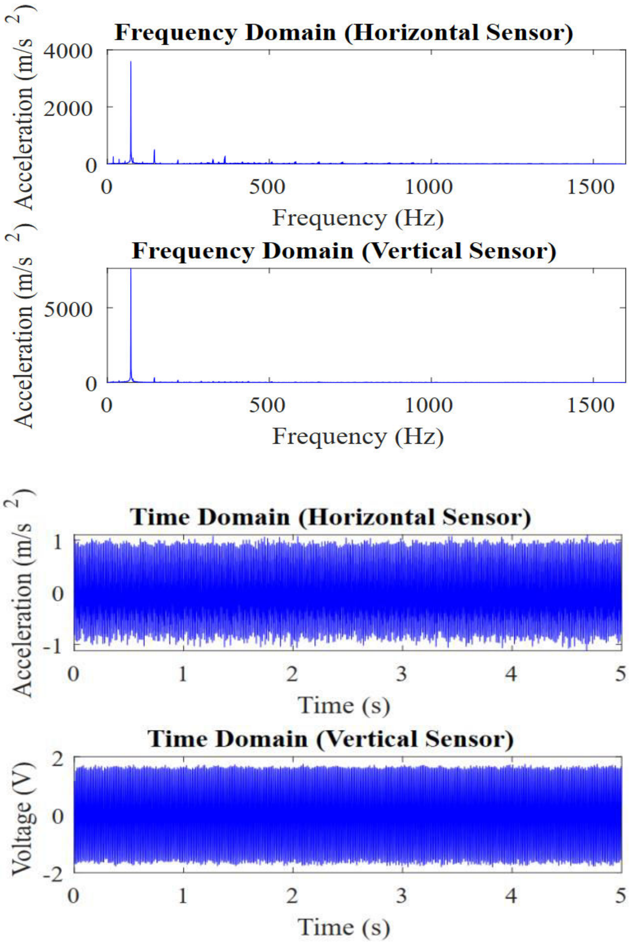
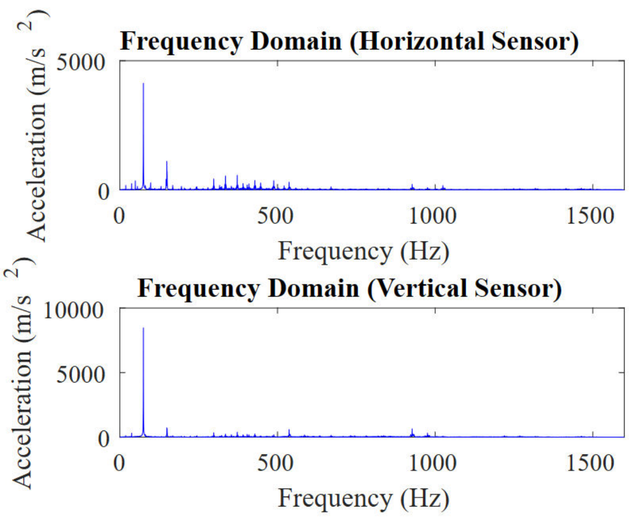


Figure-11. Time and frequency domain at 2000 RPM for 360 g refrigerant (compressor off).



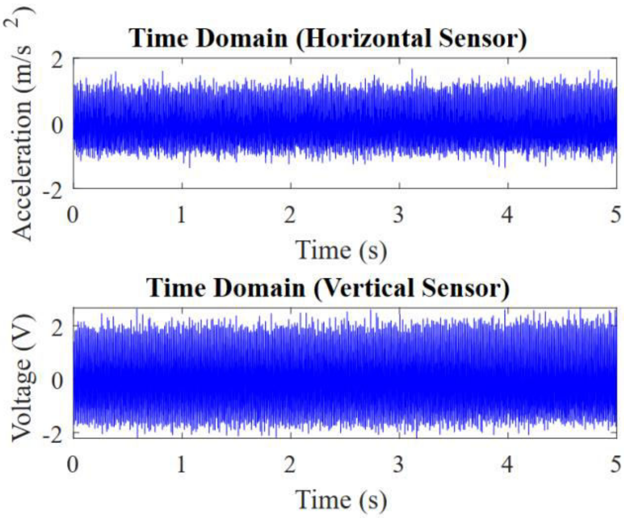


Figure-12. Time and frequency domain at 2000 RPM for 360 g refrigerant (compressor on).

Experimental Result: Z-FREQ 2D Graph

Once the data for both states of the compressor was collected, the data was transformed into an axial graph, where the graph represented the value of Z-FFreq 2D versus the speed of the compressor (RPM). The vibration data for both of the Z-FFreq 2D compressors off and on are stacked together in one axial graph to further analyze the effect of the parameters presented in the experiment against the speed of the compressor (revolution per minute) and the amount of refrigerant in vehicle air conditioning as the manipulated parameters. From these results, we will be able to identify which conditions are considered faulty for the vehicle's air conditioning by using Z-FFreq 2D coefficient values.

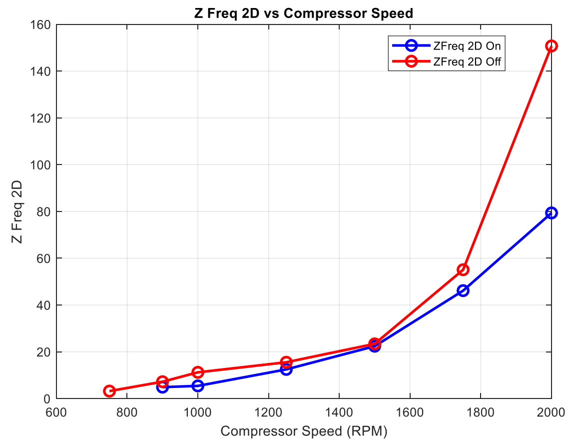


Figure-13. Graph line of Z-Freq 2D versus compressor for refrigerant 280g.

Figure-13 shows a graph line for refrigerant at 280g for both the compressor off and the compressor on. From the graph line, as the compressor speed increases from 650 RPM to 2000 RPM, the Z-FFreq 2D value also increases. However, it is quite obvious in the graph that the graph line for Z Freq 2D during compressor on is a

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smoother increase compared to compressor off. This indicates a possible correlation between the compressor speed and Z-frequency 2D values, with the effect being amplified when the compressor is in an active state. This also means that the vibration produced by the compressor shows that the compressor is working perfectly fine. However, at 1500 rpm, both the Z-Freq 2D values coincide with each other, reaching the same value of the Z-Freq 2D coefficient. Around 750 RPM and 1250 RPM, the lines are closely related and almost intersect with one another, meaning that the Z-Freq 2D value is not that far apart from the value of vibration during compressor on and compressor off.

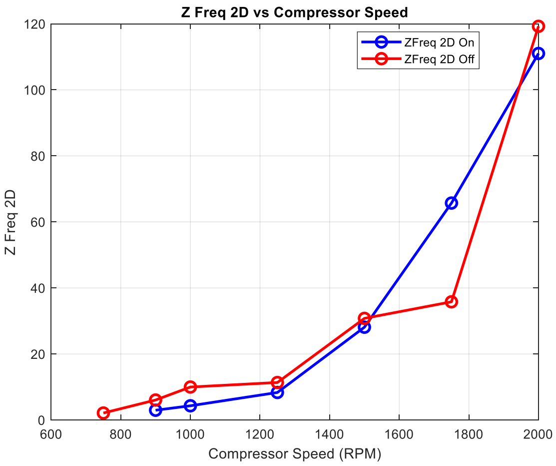

Figure-14. Graph line of Z-Freq 2D versus compressor for refrigerant 360g.

Figure-14 shows the result of the experiment using refrigerant with an amount of 360 g and oil in 80 ml. When the compressor is turned off, there are huge, significant drops in the Z-FFreq 2D value, showing that the vibration that appears in the compressor is in fact not stable. At 1500 RPM, the value of the Z-FFreq 2D is 30.7894, and at 1750 RPM, the value of the Z-- Freq 2D is around 35.8062. Even though the value does show that the Z-FFreq 2D value is increasing over the speed of the compressor, the value does fall below the Z-FFreq 2D value of the compressor, which in theory means that the value of Z-FFreq 2D for both compressor states should increase consistently along the speed of the compressor without intersecting one another. This means that the vibration is not stable and the amount of refrigerant in the vehicle air conditioning is possibly over the optimum level.

Machine Learning Results

A primary concern of this research is to investigate and analyze experimentation data as well as to validate the data gained. To prove this research, the machine learning method is used to analyze 2D Z-Freq as it provides great potential as well as essential for a wide range of technologies, especially in the automotive industry.

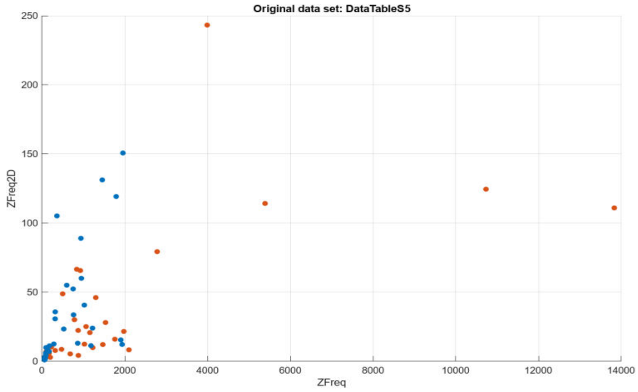

Figure-15. Scattered data prediction model of Z-Freq 2D.

A confusion matrix of all the Z - Freq 2D coefficient values has been summarized as shown in figure 16 and Figure-17. This can prove that the coefficient can be used for prediction methods, especially for speed and amount of refrigerant activity.

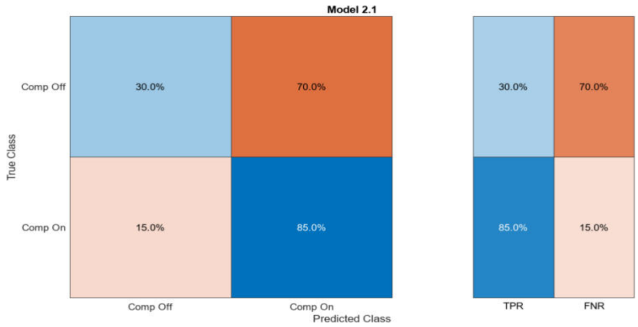

Figure-16. SVM confusion matrix for Z-freq coefficient.

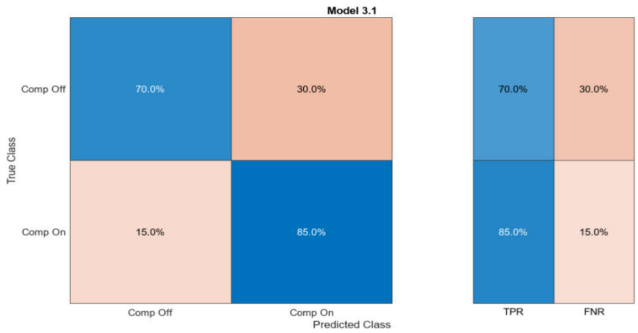

Figure-17. kNN confusion matrix for Z-freq coefficient.

Figures 16 and 17 show the true positive rate (TPR) and false positive rate (FPR) of the respective classifiers. It shows that at support vector machines (SVM), the true positive rate is 85% with an accuracy validation of 57.5%, while the k-nearest neighbor has accuracy validation results of 77.5% with a true positive rate of 85%. From the confusion matrix compared to SVM, the value for kNN is higher than that of SVM, which is because kNN is typically simpler and easier to implement. Because of its lazy learning strategy, the algorithm requires few tuning parameters and small training datasets. kNN also makes fewer assumptions than SVMs because it uses the data points closest to each query point for predictions rather than assuming any distribution or making generalizations about the data set [8]. However, from this research, it is also necessary to further research studies of the Z-FFreq 2D coefficient to verify the accuracy and consistency of the coefficient for future and real-time prediction in the automotive industry, especially.

CONCLUSIONS

In conclusion, this study has successfully quantitatively assessed the impact of different refrigerant types on the performance and efficiency of vehicle air-conditioning systems using a novel two-dimensional Z-Freq 2D statistical analysis method. The use of wireless vibration accelerometers and meticulous calibration of sensors ensured the accuracy and reliability of measurements. The newly developed Z-Freq 2D statistical analysis technique allowed for a comprehensive examination of the vibrational data, providing a deeper understanding of the effects of different refrigerants on AC system performance. The validation of the Z-Freq 2D analysis using machine learning techniques demonstrated its effectiveness and reliability. The experimental setup, based on an actual vehicle air-conditioning test rig, accurately simulated real-world operating conditions. The findings of this research offer significant insights into the selection of refrigerants for vehicle AC systems, highlighting the potential for enhanced system performance and efficiency through the application of advanced statistical analysis and machine learning validation techniques. This study not only contributes to the field of automotive thermal management but also paves the way for future research in the optimization of vehicle AC systems.

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