Hybrid Vehicle Engine Misfire Detection using Piezo-film Sensors and Analysing with Z-freq

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ABSTRACT

This paper explores the application of standard deviation and kurtosis to formulate a new statistical method for hybrid electric vehicle (HEV) engine misfire detection named as Z-freq. Existing engine management system is unable to evaluate the performance of each individual piston of the internal combustion engine. Eventually, it will affect the whole hybrid system especially charging or cruising. The principal objective of this research is to diagnose the engine wall vibration and identify the combustion strokes. Furthermore, the primary advantages of this technique are the simple, accurate and fast computation of the algorithm such it can be processed rapidly using a low-cost controller. This investigation involves two phases of the procedure including signal measurement using data acquisition equipment as well as signal analysis using the MatLab. At the first phase, a piezoelectric-based sensor called piezo-film is attached to each engine wall, run the hybrid engine at different speeds and also run with misfire spark plug and record the signal measured. While the second phase is signal measurement using data acquisition, filtering and analysis using Z-freq method. The advantage of the proposed method is this technique able to identify different combustion strokes. This technique is also can be applied for engine technical expert who requires

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simple, fast yet accurate results. These findings provide a solid evidence base on pattern representation which easier to the investigator to categorise the measured parameters.

Keywords: *Engine Misfire Diagnostic, Piezo-film Sensors, Z-freq Technique.*

Introduction

The utilisation of the Hybrid Electric Vehicle (HEV) is an options approach to diminish fuel consumption in transportation. It likewise ensures emissions reduction and guarantees great performance such as increasing power or lessening vibration [1][2][3]. A few countries have executed restrictive standards and stringent regulations to limit energy usage and emission produced by vehicles on the road [4]. The automobile division worldwide is moving its consideration towards insignificant consumption of petroleum resources on the one hand while trying to achieve the most effective use of electrical power accessible on board [5]. Thus, it has turned into the most imperative innovation and a vital concern of the researchers in this field studied [6][7][8]. In a hybrid vehicle, two independent movers are usually used which three-phase motor and internal combustion engine (ICE) that can be coupled in different ways referred to as hybrid architectures with various drive operating modes. Furthermore, ICE plays an important function which it will support during the high voltage battery charging, vehicle acceleration assisting, hill climbing or boosting the car [9].

The most common architecture in the hybrid system is series, parallel or combination of both series and parallel architectures. In ICE, the combustion process involves oscillating piston to deliver torque to powertrain which effects the components endurance, produce noise, vibration and also create discomfort to driver’s feeling simultaneously. These restrictions require an appropriate investigation to engine torque control which is an essential performance factor of an ICE [10].

Vibration is an oscillating or another periodic movement of an object as it is forced out of a state of equilibrium, any transducers that measure any of these parameters can be utilised [11]. Vibration signals is a well-known input in fault diagnosis and have been studied successfully by many researchers. Vibration condition monitoring technique is widely utilised for fault identification [12]. Time domain determines an analysis display of the vibration signal as a component of time. The study visually observes the segments of the time domain representation or by analysing some statistical parameters with respect to time domain analysis. Various time domain statistical parameters have been utilised as trend parameters to identify the occurrence of identical component faults. The most common analysis technique utilised are a peak occurrence, RMS value, crest factor value and kurtosis value [13].

The diagnostic exercises should not be neglected from any deficiencies and defects happened [14]. Most of the ICE fault issue tracked because of vibration produced through friction between the cylinder liner and piston ring. Statistical technique exhibits that it can be applied by executing signal analysis to the test equipment. Assessment of statistical parameters provides a diagnostic sign of errors or failures of the existing components in a machine, for instance, rotating or vibrating components. The signal analysis for engine condition monitoring can be explored by using Integrated-Kurtosis-based Algorithm for Z-filter (I-kaz™) [15]. I-kaz™ is an alternatively great option of statistical analysis method which was developed by the researcher to measure the degree of data scattering with respect to the data centroid for dynamic signal analysis. Furthermore, it has another application utilised as effective monitoring for tool life, bearings, and automotive gearbox [2]. In extension to further analysis of the time domain is an application of frequency domain data into the signal analysis by utilising statistical methods called Integrated-Kurtosis-Frequency based on Z-filter (Z-freq™). This technique has been explored to extracted more information from a raw signal acquired through experimentally using data acquisition equipment.

In ICE, emission, engine efficiency, vibration and durability during ignition period spark timing have a significant influence on engine spark timing. Control and monitor spark timing to achieve optimal combustion without ignoring the existing constraint is crucial for engine performance while maintaining consistency of the function [15]. Condition monitoring has to turn out to be critical in many industrial sectors, such as power generating units, automobile industries and aeronautics industries. Most current research demonstrated a new method to condition monitoring of engine wall. Strain sensor has been utilised for signal measurement from the engine block and statistical method has used for signal analysing [2].

Currently, there are many issues such as the engine is the main part that needs to be reviewed to guarantee the best performance and minimize the load on the environment [16]. Eventually, this system monitoring in the automobiles is crucial. Generally, condition monitoring is doing some practice to monitor machinery condition, such that a significant change is indicative of a developing failure and this is the main factor of predictive maintenance. The reason for condition monitoring is it allows maintenance to be scheduled, or actions to be taken to prevent the consequences of failure before the failure occurs. This event can ensure the long lifespan of an engine [2]. Three effective key elements in condition monitoring are (1) Data acquisition, (2) Data processing, and (3) Decision making. Basically, while the fault diagnosis is detected at an early stage, it would be an efficient engine monitoring. In the automobile, the maintenance of engine is a must to replace the defect parts and overhauls. In any case, if we have a good engine monitoring, it can save the cost of the hybrid engine maintenance and keeps the engine performance to an optimum level and extend its lifecycle [9].

Recent researches have been conducted by investigators shown there is no correlation between statistical parameters and condition of the engine installed on a hybrid vehicle [4].

The time domain representation records what happens to parameters such as magnitude, voltage, current, velocity or acceleration of the system versus time. By selecting the amplitudes, frequencies and phases of waves correctly, the desired signal can be produced from the waveform. From the frequency domain graph of the signal, it is called the spectrum of the signal. When these components are split in the frequency domain, the small components are easy to see because they are not overridden by larger ones. The frequency domain provides an important tool for analysing these little, but vital impacts.

Regardless of the possibility that the quick issue is not electrical, the fundamental parameters of interest are regularly changed into electrical signals using transducers. Basic transducers include accelerometers, strain gauge and load cells in mechanical work. The powerful measurement and analysis capabilities of these instruments can lead to a rapid understanding of the system under investigation. In this application note, it presents the ideas of the time and frequency. Importantly, it is observed that there are three main areas in fault diagnosis: 1) fault detection; 2) fault isolation; and 3) fault identification.

The condition monitoring of the engine relied on the experience of experts, yet the decision-making process was very subjective. In other cases, it has also been observed that dealing in the time domain poses many drawbacks such as lacking information and noise embedding in certain frequency envelope. This is solved by considering analysis in the frequency domain such as Fourier transform [17].

Materials and Methods

Z-freq Analysis Method

Amplitude, frequency, phase and energy variation can be determined by signal measurement. All signals can be classified into two parts which deterministic and non-deterministic. For a deterministic signal, it determines by a mathematical relationship between the value of time domain and frequency domain. Many signals in daily life application contain random or non-deterministic signal which gives the challenge to analyse using signal processing methods [1].

Firstly, the random signals are frequently classified into *r*-th order of moment about mean M_r. The *r*-th order of moment about mean, M_r for the discrete signal in the frequency band can be written as equation (1):

$$M_r = \frac{1}{N}\sum_{i=1}^{n}(f_i - \bar{f})^r \qquad (1)$$

Where *N* is the number of data, *r* is the order of the moment, f_i is frequency at *i*-th and $\bar{f}$ is average frequency. Kurtosis, which is the signal 4th statistical moment, is a global signal statistic which is highly sensitive to the spikiness of the data. For discrete data sets the kurtosis value is defined as equation (2):

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

Where σ standard deviation and *K* is Kurtosis value.

The value of kurtosis is about 3.0 for a Gaussian distribution. Higher kurtosis values determine the existence of more extreme values that should be found in a Gaussian distribution. Kurtosis is utilised in engineering application for detection of fault symptoms because of its sensitivity to high amplitude events. Based on kurtosis, Z-freq method provides a two-dimensional graphical representation of the measured signal frequency distribution. The time domain signal is decomposed into two frequency mob, which are; *x*-axis, which is low frequency (*affix*), *y*-axis which is high frequency (*annex*). Affix mob consists of frequency mob from 0 to $0.5f_{max}$ and annex mob consists of frequency mob $0.5f_{max}$ to f_{max}. In order to measure the scatter of data distribution, the Z-freq coefficient calculates the distance of each data point from the signal centroid. Z-freq coefficient is defined as equation (3):

$$Z^f = \frac{1}{n}\sqrt{K_{afx}s_{afx}^4 + K_{anx}s_{anx}^4} \qquad (3)$$

Where K_{afx}, s_{afx} is the kurtosis and standard deviation for low-frequency range and K_{anx}, s_{anx} is the kurtosis and standard deviation for high-frequency range respectively. Z^f coefficient was formulated base on the normal order of Daubechies signal decomposition. The signal monitoring activities can be illustrated in the flowchart as shown in Figure 1.

This study is divided into two phases, which the first phase is focusing on data collection while the second phase is performing a signal analysis for measured data. During the first phase, all four piezo-film sensor is located at each engine cylinder wall using recommended glue in order to prevent error signal measurement due to high-temperature operation. Every cylinder also tagged as a channel to help technical expert identify every sensor. Measurement activity involves both normal conditions and also a faulty condition to prove the effectiveness of the developed method.

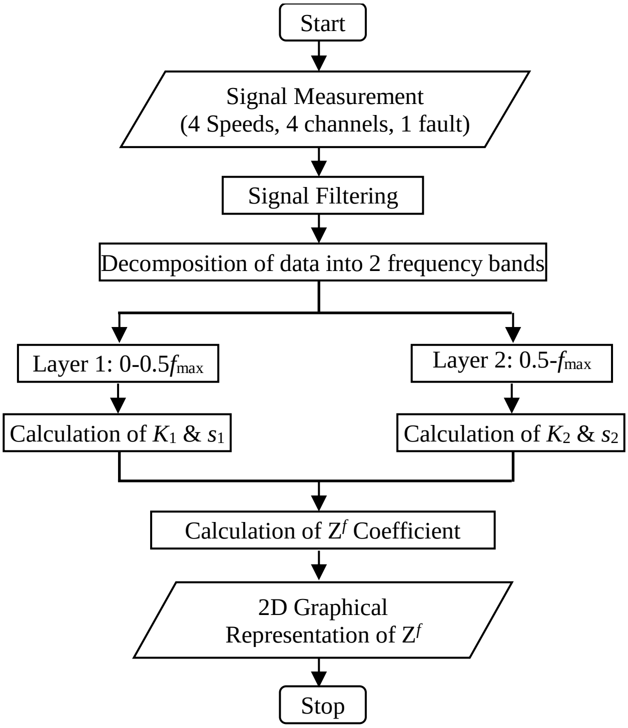

Figure 1: Hybrid vehicle engine monitoring flowchart using Z-freq.

A raw data from the data acquisition need to be filtered from unwanted noise produced by testing equipment or connected components. A filtered signal data will be decomposed into two main categories in which low frequency named affix and high frequency named annex. These categories are important to study the pattern of every condition studied. For the second phase, the analysis method is used to calculate Z-freq coefficient and also 2D representation graph for further understanding on the correlation between affix and annex frequency.

During experimental on high voltage battery, calibrated measurement equipment, and other factors that affect the signal monitoring activities, all standard of the procedure will be followed. Electrical work on high-voltage systems must be performed only after protective measures against electric shock, short circuits and arc faults have been understood. The task should not be conducted on live electrical parts and equipment. The overall monitoring process is presented into the flowchart as shown in Figure 1.

The monitoring process is illustrated as shown in Figure 2. Four piezo-film sensors are attached to engine wall by following a standard procedure that has been set as per previous researchers. Then these sensors are connected to vibration analyser using BNC cables. Finally, the output from vibration analyser is recorded using data acquisition software installed on the computer. The filtered signal will be analysed using the proposed new statistical technique by using the MatLab software.

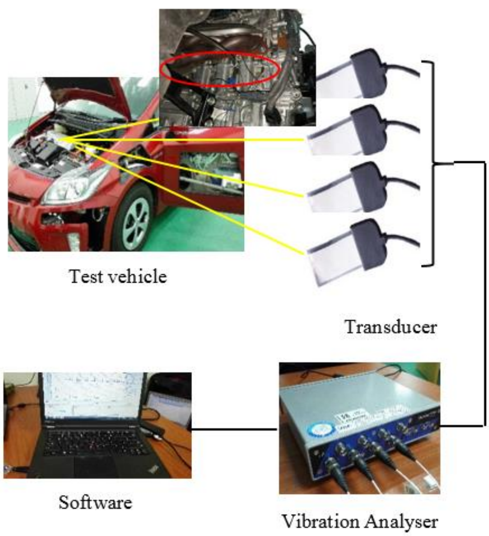

Figure 2: HEV engine signal acquisition process flow diagram.

Piezo-film Sensor Installation

Transducers used for this experimental is piezo-based called piezo-film. This sensor is a rectangular shape with 18” coaxial link. This sensor surface is printed with silver ink and it has a wide frequency response [18]. It is recommended to use an x10 probe to increase the low-frequency range. Furthermore, the light weight of the sensor, thin shape and high sensitivity to vibration become a key indicator to catch the signal with non-resonant conduct.

This sensor has a similarity characteristic to a strain gauge, but it has a higher yield. The sensor performs well at low frequencies where the wide range and low acceleration, also at high frequencies where small displacement and high acceleration as shown in Figure 3.

The initial activity has been done with transducer installation by using the tape-assisted technique to stick into the engine wall. The piezo-film sensor with detail specifications is depicted in Table 1. The size of the sensor is fully fitted to the engine wall.

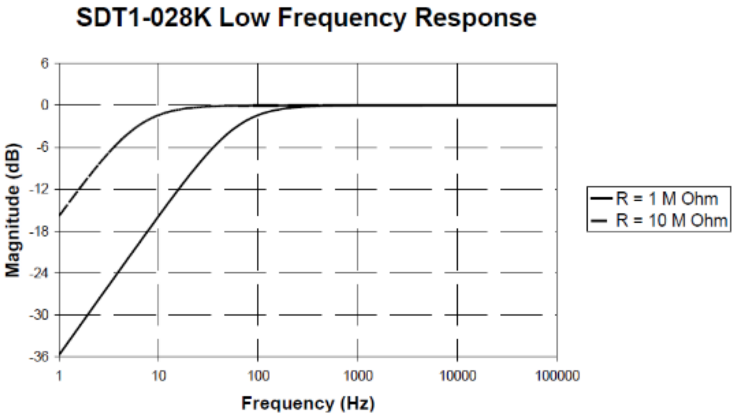

Figure 3: Low-frequency response of the piezo-film sensor.

Table 1: Piezo-film sensor specifications.

Parameters	Specifications
Type	SDT shielded piezo sensors
Min Impedance	1mΩ
Preferred Impedance	10mΩ
Output voltage @ 10mΩ	Min 15V
Storage temp	-40 ºC to +70 ºC
Running temp	0 ºC to + 70 ºC
Connection	Braided Wire-Ground
Dimension	LxWxH: 28.6×11.2×0.13

Vibration Analyzer

This vibration analyser able to perform measurement on noise, vibration and harshness of the test sample. Its interface presents a time domain recording, frequency domain recording, acoustics analysis, modal analysis and shock analysis. It will support technical expert to conduct a signal analysis judgement due to pre-set databases format. This analyser also supports various types of transducers such as piezo-film, accelerometer, micro-fibre composite and proximity sensor for all channels.

In these applications, RMS, peak and peak-peak measurements of acceleration, velocity and displacement become input to machine condition monitoring activity. This analyser meets the requirements of the numerous standards such as ISO 13373, ISO 7919, ISO 10816, VDI 2056, ISO 2372, NF 90-300/310, BS 4675 or the API acceptance testing series.

Hybrid Vehicle Test Setup

A hybrid vehicle is classified by its drive configuration and there are three main high voltage systems which determine the level of performance as follows [21]:

- Micro-hybrid with maximum motor power 2 to 4 kW
- Mild-hybrid with maximum motor power 10 to 15 kW
- Strong hybrid with maximum motor power more than 15 kW

Hybrid vehicles also can be differentiated by their drives variety as follows [21]:

- Serial hybrid with a series drive connection
- Parallel hybrid with a parallel drive connection
- Serial/parallel hybrid with combination drive connection

These two main prime movers, the internal combustion engine and three-phase motor play an important role depending on its operating modes as follows:

- Hybrid operation mode running with engine and motor combined interaction for certain torque required
- Purely electric operation mode running with three-phase motor only and at medium or low speed
- Generator operation mode running with high voltage battery state of charge (SOC) being monitored in order to divert part of engine output for charging operation
- Boosting operation mode running with both engine and motor to achieve maximum torque performance during driving
- Regenerative braking operation mode running with the utilization of motor generator braking moment instead or normal service brake's friction moment to slow down or stop the vehicle

During the experimental activity, test equipment used is a specific hybrid vehicle with engine number and other specifications as depicted in Table 2. Vibration analyser is used to collect signal from transducers which located for every cylinder wall. In handling a vehicle with high voltage battery, proper safety procedure must be followed and all precautions must be considered. A class A glove up to 1000 V is used, insulated high voltage cable is tagged, conduct the experiment in the natural environment and always assisted by well-trained technicians.

All the hybrid system fully functions so that any disturbances are taken into consideration during measurements. This vehicle is a 2015 model with the third generation of the hybrid system developed by the manufacturer.

Table 2: Hybrid vehicle test specifications.

Items	Specifications
Engine number	ZVW30-196651
ICE	1.8L Atkinson cycle, 4 cylinders inline
Engine compression	13.0:1
Engine maximum	73kW @ 5200 rpm
Engine maximum	142Nm @ 4000 rpm
Maximum motor	650VAC
Maximum motor	60kW
Maximum motor	207Nm

Signal Data Analysis

Piezo-film sensor is very sensitive to vibration and heat because of its material construction. During actual measurement, the engine wall temperature can go up to 90ºC due to material friction occurred and it leads to inaccurate reading. Because of that constraint, a rigid layer will be used to dissipate heat for stable data collection. A raw voltage signal in the time domain will be recorded for further analysis and classification. This data will be converted into the frequency domain using a Fast Fourier Transform (FFT) in order to decompose the signal into two categories in which low frequency and high-frequency contents. These frequency data will be used for Z-freq coefficient calculation.

Results and Discussions

The new statistical analysis was used by implementing kurtosis application into the frequency domain of the converted signal acquired from the data acquisition. Four type of engine speed was recorded in order to study the characteristic of the analysis result. Each test conducted uses 51200 sampling rate so that it is able to detect every event occurred during signal capturing processes. For instant in this internal combustion engine for a hybrid vehicle, there are four-stroke involved which intake, compression, power and exhaust. From the data in Figure 4, it presents signal collected and plotted into the time domain, converted into the frequency domain and zoomed in to measure the four-stroke process quantitatively. As can be seen from the Figure 4a, engine speed with 1000 rpm will result in 0.06 s/rev in simulation and experimentally shows a correct desired value of each revolution time.

The most interesting aspect from this graph is samples that acquired from the vibration analyser able to distinguish different engine speed by observing and calculating the peak-to-peak time value. In overall, it can be summarised the result that 1000 rpm will get 0.06 s/rev, 1500 rpm is 0.04, 2000 rpm set out 0.03 s/rev, and lastly for 2500 rpm presented 0.024 s/rev. Another interesting part that can be observed is for each power stroke, the signal will create a peak and it is repeating harmonically after all four-stroke processes happened. The second lower peak can be seen as the stroke for exhaust because the valve is opened while the cylinder location is at the top position. The calculation for the revolution time is shown in Table 3. There was a significant positive correlation referring time domain on the random graph pattern which it is easier to see the peak signal at low speed and the peak becomes closer as the speed increased.

The representation as shown in frequency domain random graph pattern, it can be concluded that the magnitude of frequency was increased significantly as the hybrid engine speed increased at low frequency. It also can be traced that magnitude of frequency power at high frequency slowly increased as speed increased which contribute to Z-freq value.

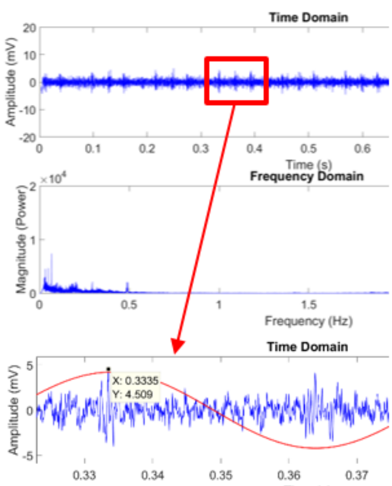

Figure 4a: 1000 rpm experimental data C1.

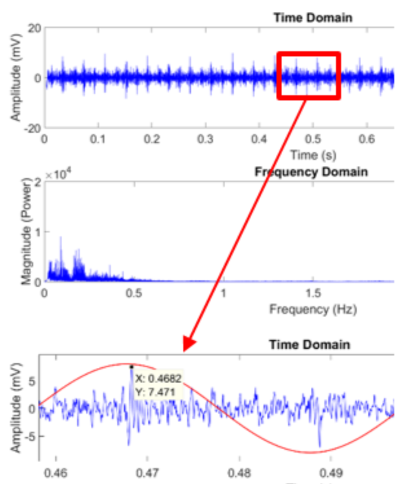

Figure 4b: 1500 rpm experimental data C1.

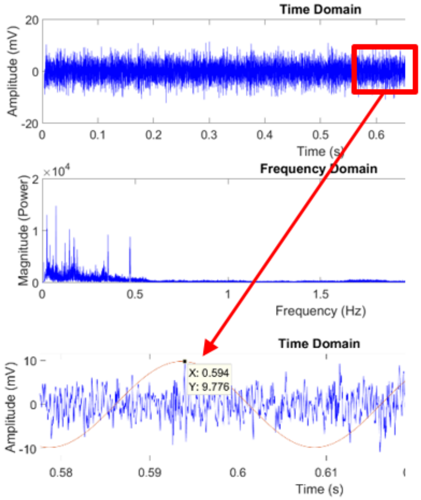

Figure 4c: 2000 rpm experimental data C1.

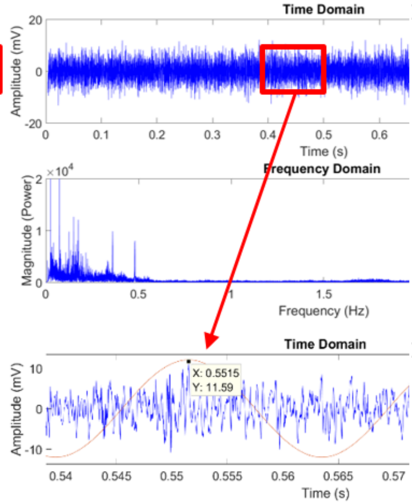

Figure 4d: 2500 rpm experimental data C1.

As mentioned in the previous finding, a pattern of hybrid vehicle engine pattern also can be displayed in the scatter diagram as shown in Figure 5(a-d). The significant pattern was presented in the graph below. There is two axis which *x*-axis represent low-frequency distribution and the *y*-axis represents the high-frequency distribution. It was hypothesised that the scattering of the frequency magnitude become wider for both low and high frequency as the engine speed increased.

Table 3: Total time per revolution for simulation and experimental.

rpm	rev/s	s/rev Simulation	Time Experiment	x2	x1
1000	16.67	0.060	0.060	0.3933	0.3335
1500	25.00	0.040	0.040	0.5079	0.4682
2000	33.33	0.030	0.029	0.6230	0.5940
2500	41.67	0.024	0.024	0.5751	0.5515

It is because of in the frequency domain, distribution of high-frequency data appears slowly increase in frequency magnitude. The scatter is clearly can be seen as per what is discussed in the Figure 5a for 1000 rpm to Figure 5d for 2500 rpm. From this figure, H for *y*-axis represent high-frequency mob and L for *x*-axis represent low frequency mob.

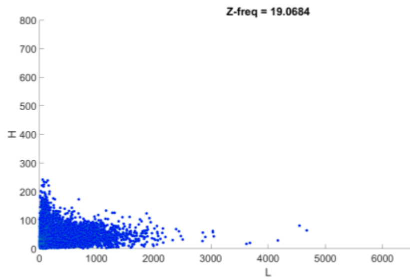

Figure 5a: 1000 rpm Z-freq representation.

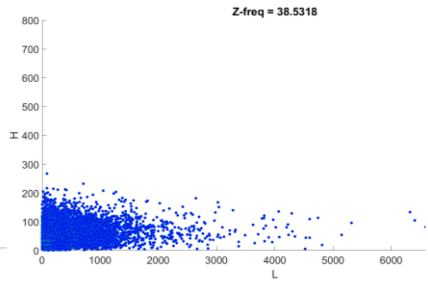

Figure 5b: 1500 rpm Z-freq representation.

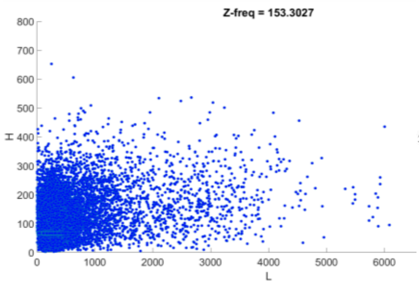

Figure 5c: 2000 rpm Z-freq representation.

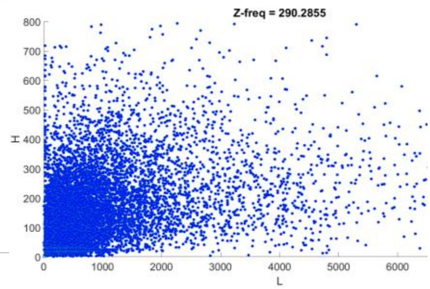

Figure 5d: 2500 rpm Z-freq representation.

The current study found that the Z-freq values increase significantly over engine speed and the value also identical for each speed in a certain average as shown in Figure 6. On the other hand Z-freq coefficient showing the downward pattern from channel 1 (cylinder 1) to channel 4 (cylinder 4) because of effect from the nearby timing chain. The experiment did not detect any effect except timing chain rotation at the moment.

Figure 7 compares the Z-freq value obtain from the measures of each sensor channel for all different speed from 1000 rpm, 1500 rpm, 2000 rpm to 2500 rpm. It is apparent from this figure that the coefficient value increases as per speed increases. It also shows a slow increment in Z-freq coefficient for 1500 rpm because of the engine able to run in smooth condition and become noisy during the observation phase.

Looking at Figure 8, the most interesting aspect of the graph is the experiment purposely to inspect the condition of the Z-freq value coefficient observation during misfires one of the engine cylinders, in this case, the spark voltage of channel 2 or cylinder 2 has been opened. This graph quite revealing how the Z-freq value dropped to half compared to the average value of the previous coefficient. The other three Z-freq value remain on average while channel 2 dropped because of no combustion process occurred due to no voltage supplied. The effect on that situation, the vibration level of the engine wall become slightly damped.

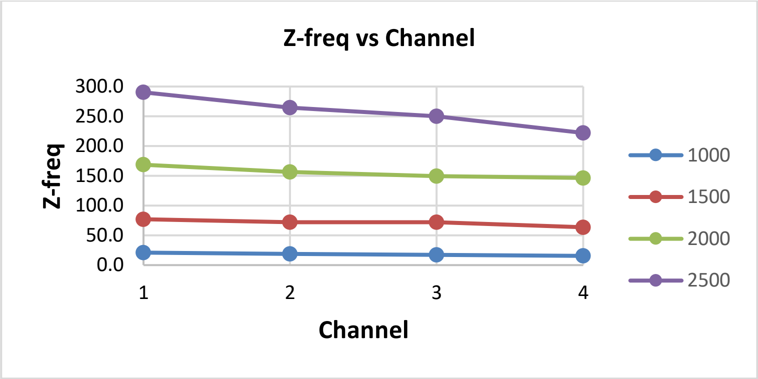

Figure 6: Z-freq plot for a different speed.

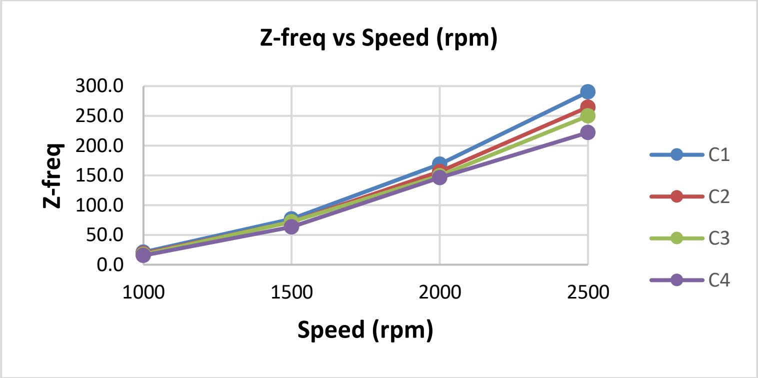

Figure 7: Z-freq plot for different engine speed.

The value for Z-freq coefficient during misfire test run are shown in Table 4, and it can be observed that combustion process without firing from spark plug at cylinder 3 will result in half of the average value from other cylinders.

Table 4: Z-freq values with channel 3 misfire.

Sensor's Channel	**Z-freq coefficient values** 1000 rpm
C1	22.6
C2	20.6
C3	10.4
C4	18.5

The overall result for Z-freq values is presented in Table 5. The correlation for every speed and also every channel clearly state that the coefficient will increase as the speed increased. From this new statistical analysis, it also shows that the coefficient remains in the range of respective average for each channel. The most important are the pattern can be seen from the table to predict the condition of the current situation.

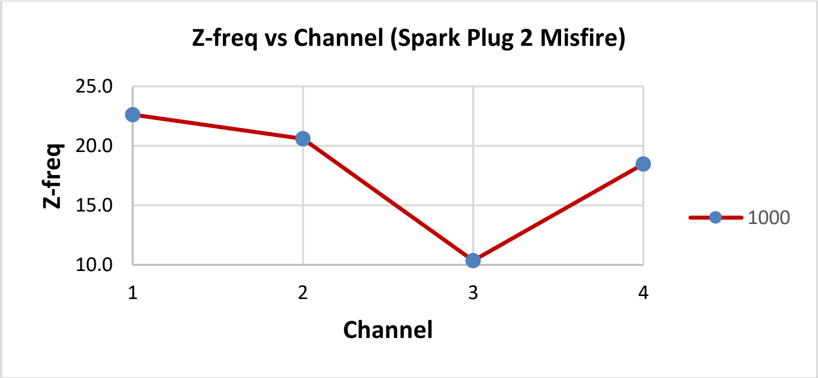

Figure 8: Z-freq plot for channel 3 misfire.

Table 5 Summary of Z-freq values vs speed.

Sensor's Channel	Z-freq coefficient values			
	1000 rpm	1500 rpm	2000 rpm	2500 rpm
C1	21.0	77.1	168.6	290.2
C2	18.8	71.9	156.7	264.7
C3	17.3	71.8	149.5	249.9
C4	15.5	63.6	146.4	221.9

Conclusion

The aim of the present research was to apply signal analysis method with the utilization of statistical technique for hybrid prime mover called internal combustion engine diagnostic using piezo-based has been successfully achieved. Initially, from the time domain representation, it reviews in detail the available information on four-stroke processes because of the high-frequency sampling rate. The analysis result produced by applying frequency domain into Kurtosis calculation named Z-freq was successfully implemented. The research findings proved that hybrid engine diagnostic using piezo-film sensors able to identify the normal and faulty condition of every cylinder during actual operation. The signal generated from the sensor successfully recorded and filtered from unwanted noise for further analysis with developed Z-freq method. The coefficient values calculated from the analysis shows an identical pattern and consistently with the engine condition. This result is used to differentiate which cylinder is faulty due to spark plug misfire. In summary, from this analysis it can be concluded that every cylinder monitoring is crucial because it will affect the whole charging system and driving performance.

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