

Monitoring Valve and Spark Plug Failures using Z-Freq Statistical Analysis

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ABSTRACT

Engine problems such as spark plug misfire, valve clearance and valve cracks are the failures that lead to engine malfunction if engine continues in operation and require early detection. Machine learning can be used to automatically diagnose engine problems, but a high success rate is still a barrier because a significant amount of training data is needed. Therefore, in order to examine the specific frequency characteristics, this new fault analysis approach will take into frequency content throughout the Fast Fourier Transform (FFT) procedure. Z-freq, a dynamic vibration signal analysis for non-deterministic data that focuses on frequency domain rather than time data, is a new statistical signal-based analysis that can easily be used to improve these vibration-induced faults studies at this stage for further enhanced investigation. This examination examines the time and frequency domain of data acquired from Proton, Toyota, and BMW engines operating at various speeds between 750 and 3000 rpm. In order to replicate the real effect, the fracture fault was made using a wire cut method for 0.25, 0.5, and 1.0 mm, while the clearance fault was set using a screw and sheet gauge for clearance thicknesses of 0.0, 0.2, 0.3 mm during experimental tasks. The voltage applied to a particular spark plug will be cut to simulate a misfire issue. High sensitivity, space-saving, and long-lasting piezo-based sensors are used to assess vibration caused by spark plug misfire, valve clearance and valve crack. Piezo-film, micro-fiber composite, and accelerometer sensors are employed in this experiment. To guarantee precise and accurate observation, all of these sensors were calibrated using the Bruel and Kjaer type 4294 calibration exciter. The main finding is that the distribution of Z-freq data for normal, misfire, valve clearance, and valve crack shows a notable pattern in the coefficient value.

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INTRODUCTION

In the automotive industry, valve and spark plug failures are crucial problems because they can have a big influence on emissions, fuel economy, and engine performance. In order to preserve vehicle dependability and lower maintenance expenses, these problems must be quickly identified and fixed. Using Z-freq statistical analysis, a potent method for identifying odd patterns in failure data, this research study offers a thorough method for tracking valve and spark plug failures.

The study uses a variety of sources, such as a review of maintenance records to determine the reliability of diesel engines [1], research on evaluating the operating status of cards in real-time [2], and a comprehensive examination of engine failure analysis and its causes [3].

The intricacy of the engine itself and the difficulty of acquiring signals while the engine is running make it difficult to diagnose and identify engine flaws early on [4]. However, while putting safety first, engine fault identification is essential for avoiding engine damage and, thus, reducing maintenance costs. Premature engine flaws in gears, bearings, pistons, valves, and other components can result in major losses and serious harm [5, 6].

In an engine component defect monitoring system has been developed in this study to enable monitoring while the engine runs at different speeds. Z-frequency signal analysis was used to optimize engine condition monitoring utilizing three sensors: a micro-fibre composite, a piezoelectric film, and an accelerometer. The benefits of each sensor were compared under a range of engine situations, including normal operation, spark plug failures, and valve crack flaws.

Existing research on engine reliability and failure analysis has highlighted the importance of robust monitoring and analysis techniques. Liu et al. [1] discusses the classification of faults in maintenance records to better understand the impact of different failures on engine operation. Yanhong et al. [2] emphasizes the need for accurate real-time data to enable reliable fault diagnosis and early warning systems in automobiles. Furthermore, Lukášik [7] outlines the importance of monitoring engine oil degradation and the potential for life predictions in combustion engines, which can provide valuable observations into the underlying causes of valve and spark plug failures.

STATISTICAL ANALYSIS USING Z-FREQ

Referencing the idea of Kurtosis, the frequency distribution of a recorded signal can be represented graphically in two dimensions using the Z-freq approach. 2 frequency clusters are formed from the decomposition of the time-domain signal: the y-axis shows high frequencies (annex), and the x-axis represents low frequencies (affix). This chapter's methodology is breaking down into five primary sections: (i) the creation of the Z-freq statistical analysis, (ii) the installation of piezo-film sensors, (iii) vibration analyzers, (iv) the setup of vehicle engine tests, and (v) the analysis of signal data.

Frequency ranges between 0 and 0.5f_{max} are found in the affix frequency cluster, while those between 0.5f_{max} and 1.0f_{max} are found in the annex frequency cluster. The distance between each data point and the centroid, or central point, of the signal is used to compute the Z-freq value, which is used to measure the frequency distribution. Equation 1 below describes the Z-freq coefficient,

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

where the kurtosis and standard deviation for low-frequency range are represented by K_{afx} and S_{afx} , and for high-frequency range by K_{anx} and S_{anx} . Z^f is formulated from the normal order of Daubechies signal decomposition. The testing related to signal monitoring can be depicted in Figure 1. The first step involves gathering data from the hybrid electric vehicle (HEV) engine using four piezo-film sensors for each cylinder. The data is then acquired using a vibration analyzer, and the data is divided into High Frequency (Annex) and Low Frequency (Affix).

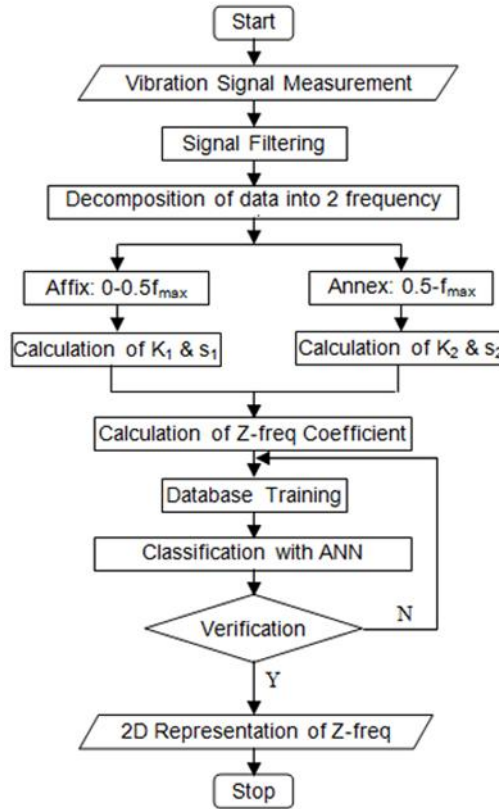


Figure 1. Process for HEV Engine misfire diagnostics.

EXPERIMENTAL SET UP

The standard operating procedure should be adhered to when handling the calibrated measurement equipment and high voltage battery. Electrical work on high-voltage components can only be done when precautions against arc faults, electric shock, and short circuits have been utilized. Live electrical components should never be used for tasks.

The sensor's handbook specifies a standard approach for attaching piezo-film sensor transducers to the engine wall of hybrid electric vehicles. Following that, BNC cables are used to connect these sensors to the vibration analyzer. Lastly, use the computer's inbuilt data collecting program to record the vibration analyzer's output. MatLab software will be used to filter and analyze the signal using the proposed statistical

method. Figure 2 below displays the flow diagram for the hybrid vehicle engine signal acquisition procedure used in this experiment.

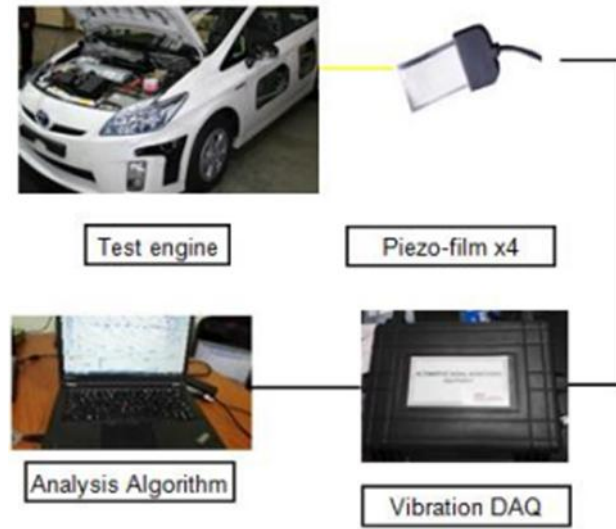


Figure 2. Flow diagram for the process of acquiring engine signal for HEV.

Shielded piezo sensors are the most widely used among the piezoelectric transducers. This 18" coaxial link rectangular piezo film component has a contoured plastic housing. The sensor's film component is printed with silver ink, which is then folded over itself. To guarantee accurate data measurement, EMI surroundings are used [8].

The transducer functions similarly to a "dynamic" capacitor. Therefore, it is necessary to consider the signal stacking caused by the measurement device's information impedance. The associated capacitance may be sufficient to provide enough low-frequency feedback into conventional 1 mΩ loads due to the thinness of the films. The low-frequency range will be extended by years with the use of X10 probe.

The transducer's low mass contribution and non-resonant conduct are compulsory. It is necessary to refine the relationship between the film's frequency feedback and its relative behaviour, such as piezoelectric accelerometers, which react to acceleration by producing low-frequency flexing to generate high signal levels.

The way the piezo-film sensor responded to strain explained why it resembled a strain gauge but had a much higher yield. The sensor works well at low frequencies with an extensive range and little acceleration, as well as at high frequencies with a small displacement and a strong acceleration [8]. Figure 3 below shows the low-frequency response characteristic for the piezo-film sensor used.

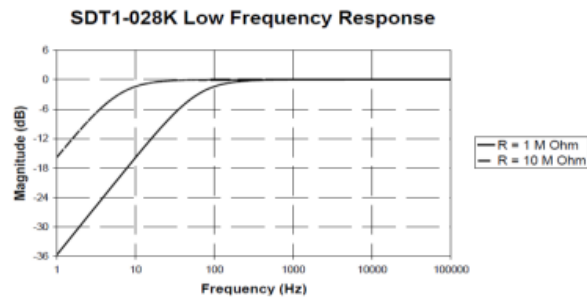


Figure 3. Graph of low frequency response characteristics for piezo-film sensor.

The preliminary step of the task involved installing the transducer into the body wall of the hybrid internal combustion engine utilizing the most widely used tape-assisted technique. The size of the sensor suited the engine wall well. Table 1 shows the parameters of a piezoelectric vibration transducer known as a piezo-film sensor.

Table 1. Piezo-film sensor parameters.

Parameters	Specifications
Type	SDT shielded piezo
Output voltage @ 10mΩ	Min 15V
Operating temperature	0°C to + 70°C
Sensor dimension	LxWxH : 28.6x11.2x0.13

All common noise, vibration, and harshness measurements are covered by the vibration analyzer program known as SO Analyzer. For example, time recording to disk, spinning equipment, and general spectrum analysis. It shows how managers, engineers, technicians, other staff members exchange analysis and report data using a uniform structure [9]. Significant findings can be obtained from the collecting and analysis of engine speed vibration data that is just time-based, particularly in cases where the engine speed rise or drop is relatively stable across time. RMS, peak, peak-peak acceleration, velocity, and displacement measurements are useful evidence of machine health in these applications.

Software processing choices give acceleration, velocity, and displacement that come from the same input channel, whereas the input sensors can be proximity (displacement) probes, accelerometers, velocity, or piezoelectric-based. These processing choices, when combined with pre-filtering, satisfy the requirements of the several standards in this field, including NF 90-300/310, BS 4675, ISO 2372, ISO 7919, ISO 2056, VDI 10816, ISO 13373, and the API acceptance testing series. Depending on the vehicle's operating conditions and needed torque level, the electric machine and combustion engine contribute differently to its propulsion. The way the combustion engine, electric machine, and energy store interact determines the various working modes.

In order to measure signal data using vibration analyzer, the most popular hybrid electric vehicle (HEV) with vehicle identification number (VIN) stated has been utilised. The test vehicle is set up according to the correct safety protocols and all precautions are considered, including using high voltage Class A synthetic glove up to 1000V, insulated cable tagged, standard setting, and assistance of skilled technicians. Table 2 shows the specifications of test hybrid vehicles. In order to account for any interruptions during measurements, the hybrid system operates in its full form. This 2015 model has the third iteration of the hybrid technology the company has created.

Table 2. Test system for hybrid vehicle specifications.

Items	Details
Vehicle identification	ZVW30-196651
Engine	1.8L Atkinson cycle, 4 cylinders
Electric motor voltage	650VAC
Electric motor power	60kW
Electric motor torque	207Nm
Engine compression ratio	13.0:1
Engine maximum power	73kW @ 5200 rpm
Engine maximum torque	142Nm @ 4000 rpm

Piezo-film is overly sensitive to vibration and heat when measuring the engine monitoring operations. However, when the hybrid electric vehicle engine is operating, friction between engine components might cause the engine wall temperature to rise above 90°C, which will result in unstable data recording. Since this heat impact cannot be avoided, an extra stiff plate was employed to separate some heat. Furthermore, a filtering method was applied to reduce unwanted noise generated by the measurement device. The Fast Fourier Transform (FFT) is then used to convert the signal from the collected data into the frequency domain. The Z-freq coefficient value may then be obtained by analyzing the signal using the recommended statistical approach [10].

RESULTS AND DISCUSSION

In this topic, the results of the first stage of analysis utilizing the developed technique, Z-freq are presented in detail for all types of test materials and test conditions. In terms of the coefficient values and graphical representation, this section also compares the methods with those previously produced by other researchers. As previously mentioned, Z-freq is the result of extracting information from the frequency domain into two frequency clusters.

The Proton Iswara engine generates the time-domain and frequency-domain graphs for vibration measurements at 1000 RPM, which are shown in Figure 4 (a). According to the graph, several peaks are clearly observed, generated by the engine cycle process with 4 m/s², which means that each peak represents an explosion or power stroke process, as these explosions cause strong vibrations. In the frequency-domain graph, the peak with the highest magnitude occurs at the fundamental frequency, roughly 5500 Hz.

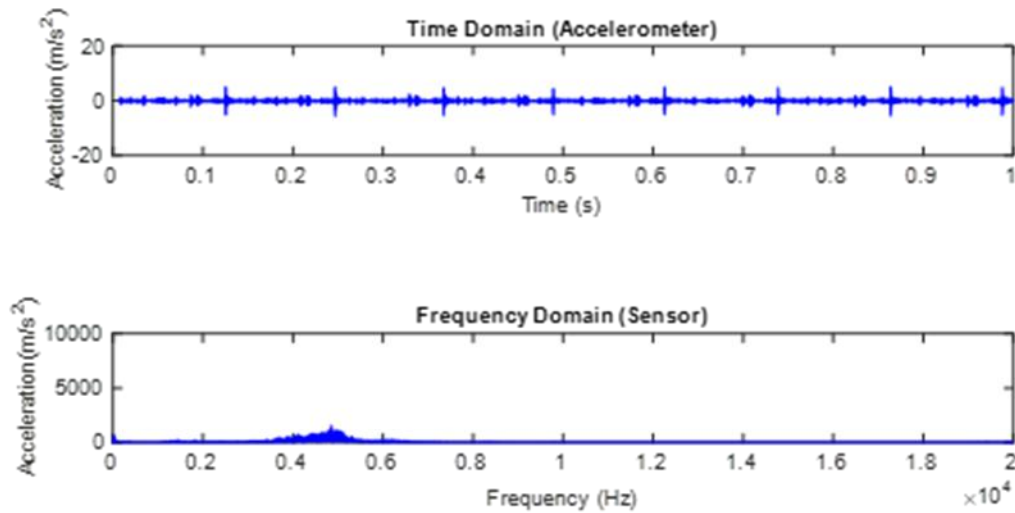


Figure 4 (a). Speed 1000 RPM (Proton Iswara)
Time-domain and frequency domain.

Figure 4 (b) below depicts the 2D Z-freq representation, with the y-axis representing high frequencies and the x-axis representing low frequencies. Each point on the graph stands for the vibration frequency value of the entire test that occurs over a one-minute period, with the color of each data point representing the data range based on the Daubechies distribution. For the Z-freq distribution plot, color-coded data is used to differentiate and identify patterns based on the frequency domain graph ranges. These

ranges are as follows: (1) 1 Hz–6400 Hz for Affix frequency and 19201 Hz–25600 Hz for Annex frequency, colored green; (2) 6401 Hz–9600 Hz for Affix frequency and 16001 Hz–19200 Hz for Annex frequency, colored yellow; and (3) 9601 Hz–11200 Hz for Affix frequency and 14401 Hz–16000 Hz for Annex frequency, colored red. The color representation corresponds to the following L-H pairs: (1) green - low pair; (2) yellow - medium pair; and (3) red - high pair. From the Z-freq representation results, it is found that at 1000 RPM, the Z-freq coefficient value is 1.96, and the data distribution for all four L-H pairs is more focused around their original axes.

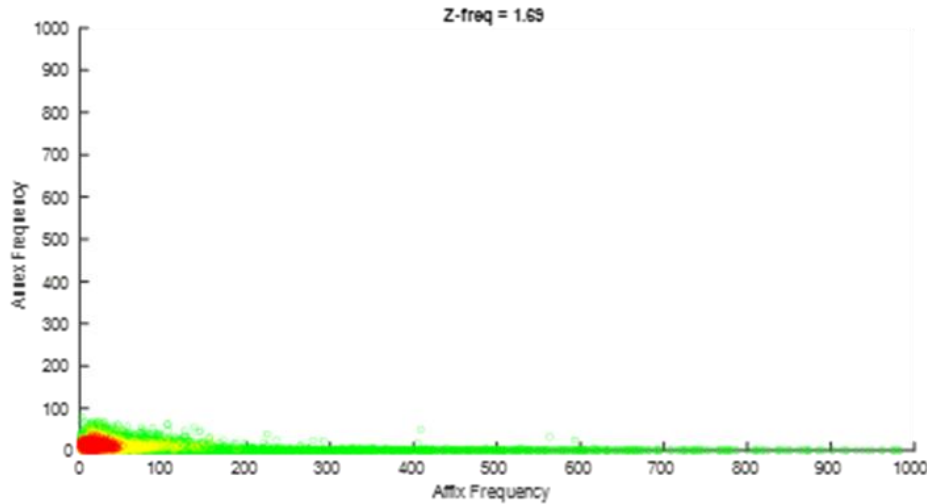


Figure 4 (b). Speed 1000 RPM (Proton Iswara)
Z-freq domain.

CONCLUSIONS

To sum up, the suggested Z-freq statistical analysis method has proven to be successful in tracking and identifying spark plug and valve problems in automobile engines. The Z-freq statistical method has been successfully used to construct a vibration analysis technique for the three vehicles of petrol engines, including the BMW 1 Series, Toyota Prius Hybrid, and Proton Iswara. With the use of the coefficient values and 2D graphical representation, this method can effectively differentiate between each sort of fault. Three types of piezo-based sensors: an accelerometer, a piezoelectric film, and a micro-fiber composite have been effectively used to identify engine faults such as spark plug defects, valve cracks, and valve clearance concerns.

The findings show that the Z-freq technique delivers a precise and dependable way to identify engine problems, which can greatly improve the service and performance of automobile engines. Future work would focus on developing real-time monitoring systems that incorporate the Z-Freq method could enhance the early detection of engine faults. This would involve integrating the method with onboard diagnostics (OBD) systems and Internet of Things (IoT) technologies to provide continuous monitoring and instant alerts.

In addition, incorporating machine learning and artificial intelligence (AI) techniques could further enhance the fault detection capabilities of the Z-Freq method. Developing predictive models that learn from historical data to predict potential failures before they occur would be a valuable.

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