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A STUDY ON GASOLINE ENGINE FUEL OCTANE NUMBERS USING ACCELEROMETER ANALYZING AND STATISTICAL MEASUREMENT

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Abstract— Octane numbers are considered as one of the most important things element in fuel to ensure the performance of the engine. Octane numbers are also can be the cause of failure to the engine. This study is present about the performance of the engine that relates to the octane numbers and compression ratio. The experimental procedure was performed by using three specimen fuels within the specific range of speed at the engine. Data acquisition involved the vibration signal recorded by the accelerometer sensor. The vibration signal that produced by dynamic response of combustion engine has been analyzed using Fast Fourier Transform (FFT). All the data recorded are filtered using the MATLAB to get the valid data. The data obtained from the experiment were analyzed using statistical analysis method to make the interpretation of the data obtained. Mean absolute percentage error and root mean square error has been showing the suitable fuel for the engine N43B20. Correlation process has been proved that it can be used as a standard for determining the suitable fuel for the engine through statistical analysis which is non-destructive, low cost and efficient method.

Keywords: *RON, Performance, RMS, Standard Deviation, Kurtosis, Skewness*

I. Introduction

In a vehicle, vibration can occur in overall body part especially engine. Gasoline engine is a type of internal combustion engine that almost all vehicle used on road compared to electrical engine. The concept of a gasoline engine is mainly burn gasoline for fuel to generate energy. The gasoline engine is also referred to as petrol engine. When the vehicle starts running, it can produce vibration on the engine. Unexpected vibration can generate faults in the engine. Many faults in the engine can be listed, such like clogged radiator that caused the engine close to overheat if the radiator contaminated with dirty coolant. Dirty oil can produce and leave the molecules on vehicle components like spark plugs, valves and combustion chambers. It also damages car bearing by leaving dirty molecule or oil that can become embedded in the oil filter which produced clogged. Usually, the possibility of engine fault because of the component that always operated in-vehicle systems such as pistons, bearings, gaskets, cracks rings and many more. All these possibilities occurred because of spark knock and it can be detected by using vibration analysis. Spark knock called as premature ignition that occurred because of the fuel used is not suitable to the engine. Unexpected fault in engine can cause higher cost for corrective maintenance. To find and eliminate the fault, there were several methods to diagnose the condition of the engine.

Condition monitoring is a technique used to monitor the vibration and noise in engine. In order to diagnose the failure, a good understanding regarding the strategy and vibration parameters is required. Condition monitoring is often placed as a maintenance technique to diagnose the failure. Fuel properties and compression ratio can affect the performance of the internal combustion engine.

The compression ratio is related to the knocking sound [1]. Using higher compression ratio can improve efficiency to reduce the knock but it can give an effect to high temperature and pressure for unburned mix fuel-air which can lead to more knock at high load. Spark ignition is related to research octane number (RON) and motor octane number (MON) [2]. Fuel resistance is linked with the auto-ignition that can produce carbon in an internal combustion engine [3].

Research octane number is the number that measures the quality and performance of fuel that has been used in vehicle. The higher the octane number, the probability to knock ignition occur is low. In gasoline, the fuel has been mixed with heptane and octane. The characteristics between these elements are heptane can handle the compression very low and it can compress the cylinder slightly and spontaneously ignited. Otherwise, the octane can handle the compression operation very well and it can compress the cylinder a lot and nothing can happen [4, 5].

The fuel with low octane number to the high compression engine can produce side effect to the engine. Using non-suitable fuel to the engine can reduce the efficiency and performance of the engine and also can build up the carbon in the combustion chamber [6]. Thus, by knowing the relation of gasoline octane number and compression ratio, the performance of the engine and causes of engine failure can be investigated.

II. Methodology

The accelerometer is used to observe the vibration signals that generated by combustion engine system by placing the sensor at fixed position on the engine N43B20. Fuel octane number is measured using vibration signal record by data acquisition. Simultaneous data acquisition process involves various types of signal that require multi-channel software. The software is capable in observing the data for up to 4 channels simultaneously [7]. Figure 1 illustrates the experimental design on the engine.

The system was set up at the engine N43B20 in the automotive laboratory at Factory 3 UTeM. These fuels are filled sequentially from RON 95 to RON 100 into the BMW tank to ensure the data is orderly. The details steps of conducting the experiments are explained in the points below:

- To ensure the data was effective and function, the accelerometer sensor is calibrated using calibration exciter. The sensor can detect 159.4Hz which is the value of frequency calibration exciter.
- The output from the sensor accelerometer is connect with cables to input channel 1 until channel 4 of data acquisition. The fuel RON 95 followed by RON 97 and RON 100 were filled to the fuel tank before running the engine. The start button then is pushed at the engine and both data acquisition software and data acquisition process to acquire the waveform on the screen. When the engine started, the shape of the signal is produced and saved in .txt in acquisition data software. The speed was increased from 1000 rpm to 1500 rpm, 2000 rpm, 2500 rpm and 3000 rpm respectively. Off the engine before changing with another fuel. Remove the fuel using a hand siphon pump from the fuel tank. Start the engine and let the engine run until the engine is automatically off to ensure the tank is totally empty.

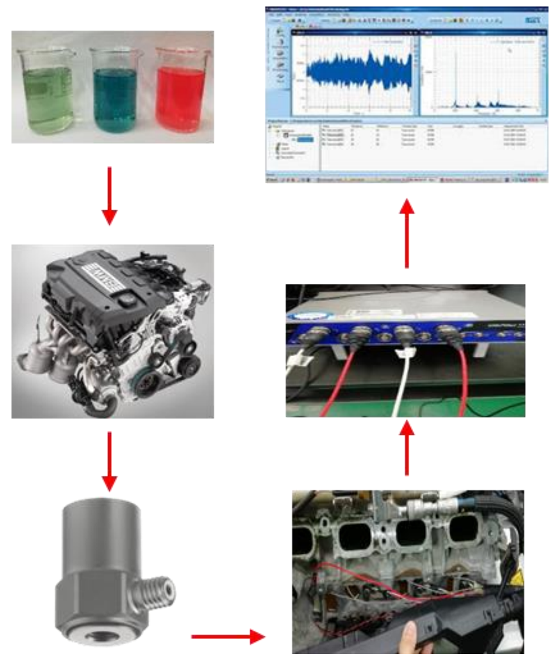


Figure 1: Experimental design of an engine

Table 1 and Table 2 show the specification of engine BMW N43B20 and accelerometer sensor.

Table 1: Accelerometer specification

Specification	Unit	Value
Sensitivity	PC/g	6/10
Frequency response	KHz	0.01 ~ 10
Operating temperature	0C	-50 ~ 250
Weight	g	4

Table 2: Specification engine N43B20

Technical specs	Type
Manufacturer	BMW Plant Hams Hall
Called as	BMW N43
Production	2007-2011
Cylinder block alley	Aluminum
Valvetrain	DOHC 4 valves per cylinder
Piston stroke, mm (in)	90 (3.54)
Cylinder bore, mm (in)	84 (3.3)
Compression ratio	12
Displacement	1995 cc (121.7 cu in)
Fuel type	Gasoline
Turbocharger	Naturally aspirated

III. Data Analysis

The global signal statistics are frequently used to classify random signals and the most commonly used statistical parameters are the mean, standard deviation, root-mean-square (RMS), skewness and kurtosis. In this work, statistical analysis is used in order to achieve the objectives of this paper. The statistical analysis method is used to identify the fault and measure the performance of machine [8]. The statistical measurement method such as standard deviation, root mean square, skewness and kurtosis are used in this experiment to interpret the data obtained. Below is the specific equation (1) and (2) for standard deviation and RMS respectively.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{\mu})^2} \qquad (1)$$

The σ can be expressed as standard deviation, x_i is discrete data value of i-th is a significant sample, N is value of data in a signal and $\bar{\mu}$ is a mean for the population. The term of $(x_i - \bar{\mu})$ can be expressed by how many long the i-th sample can be stray from normal path of mean.

$$RMS = \sqrt{\frac{1}{N}\sum x_i^2} \qquad (2)$$

The abbreviated RMS is an additionally called the average of quadrate, it could be mathematical in measuring the magnitude of a variable data. Where RMS is the root mean square of the signal, x_i is various value of i-th data in a signal and N is a number of observation in the signal.

In statistic, the measurement of shape like kurtosis tend to describe the relative peakedness or flatness of the signal. Kurtosis is the 4th statistical moment of the signal, is a global signal statistic that is highly sensitive to the density of data. Higher kurtosis values indicate that more extreme values than a Gaussian distribution should be found. Kurtosis is used to detect fault symptoms in engineering due to its sensitivity to high amplitude events. Kurtosis formula is shown as below:

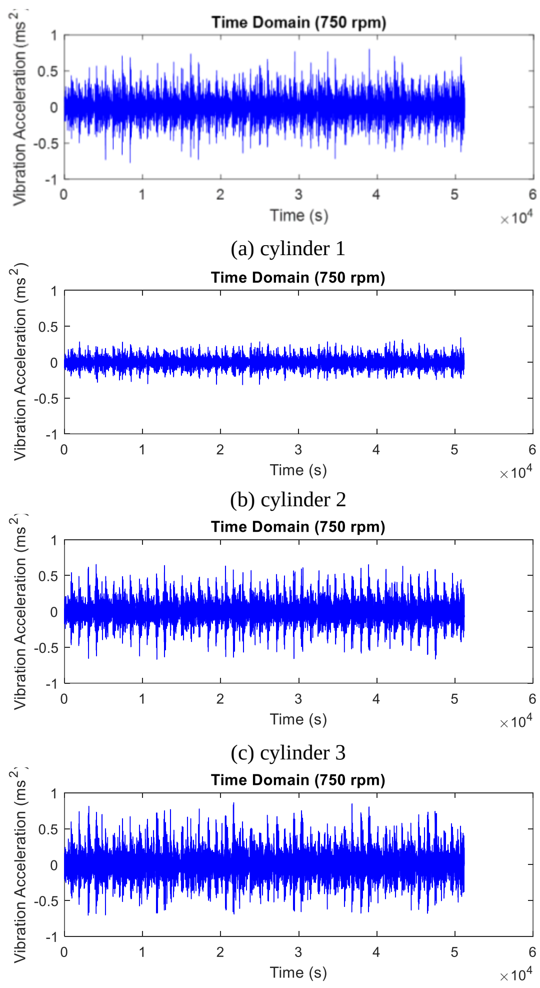
$$b_2 = \frac{\sum(X_i - \bar{X})^4/n}{(\sum(X_i - \bar{X})^2/n)^{2\prime}} \qquad (3)$$

The symbol in the equation can be expressed as b_2 is a sample of kurtosis, $\bar{X}$ is a sample of mean n is a number of sample.

The statistical of shape for skewness is to measure the symmetry of the signal. One of the characteristic of normal distribution is symmetric shape. A symmetric normal produced when a tail has been balanced between both sides. It can be observed as a normal distribution. The sample skewness is defined by equation (4) [9]:

$$skew = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{\mu})^3 / \left[\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{\mu})^2\right]^{3/2} \qquad (4)$$

The vibration signal of the engine is then analysed in time domain and frequency domain signals. The original time domain for every fuel were presented in figures. All the signals were sampled at 250,000 Hz for 5 sec record length that record 3 times for every fuel and speed. Figure 2-4 display time domain signal and Figure 5-7 display frequency domain signal.



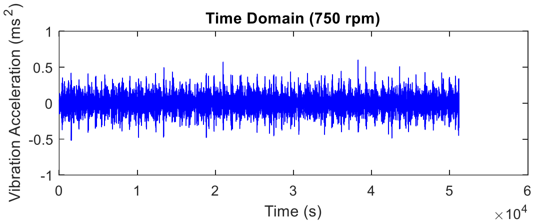
(a) cylinder 1

(b) cylinder 2

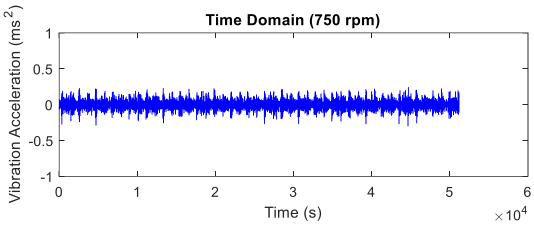
(c) cylinder 3

(d) cylinder 4

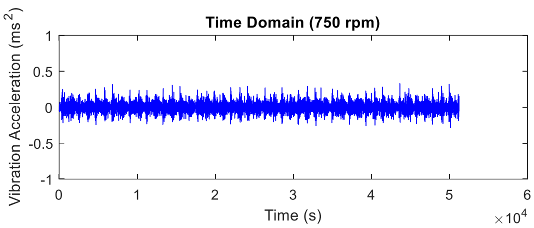
Figure 2: Signal time domain for fuel 95



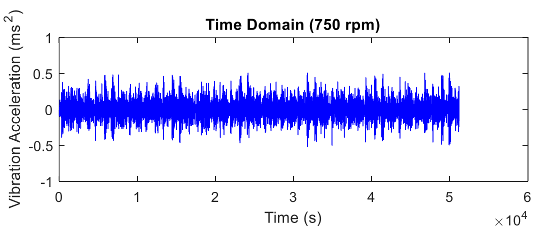
(a) cylinder 1



(b) cylinder 2

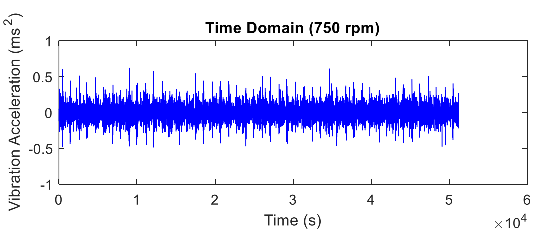


(c) cylinder 3

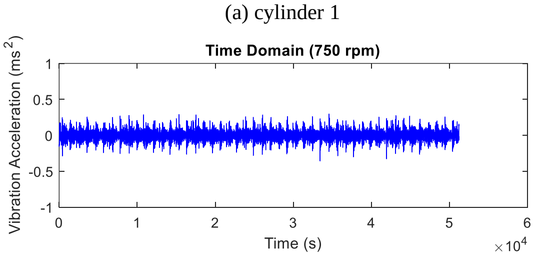


(d) cylinder 4

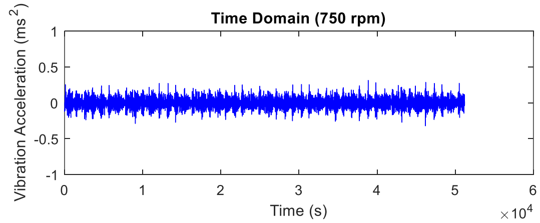
Figure 3: Signal time domain of fuel 97



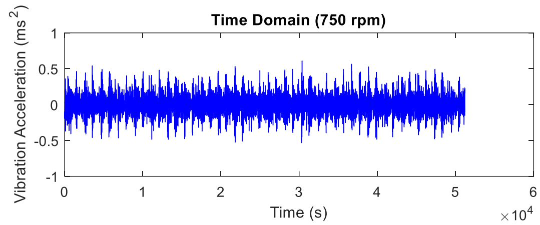
(a) cylinder 1



(b) cylinder 2

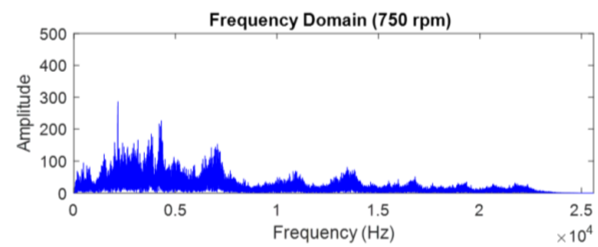


(c) cylinder 3

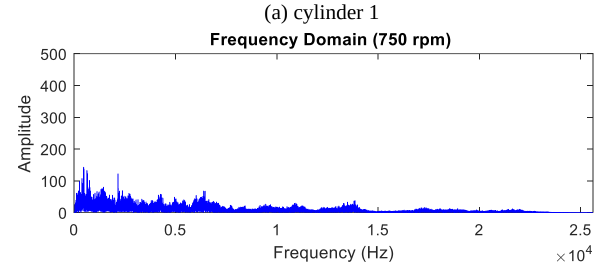


(d) cylinder 4

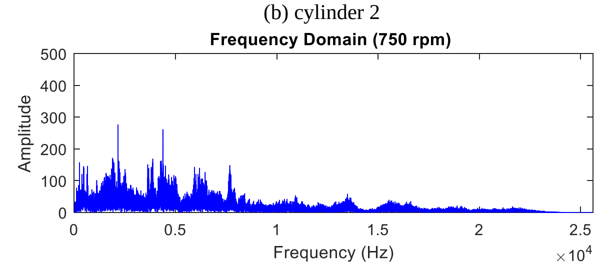
Figure 4: Signal time domain for fuel 100



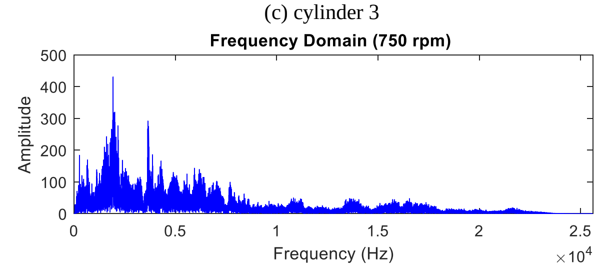
(a) cylinder 1



(b) cylinder 2

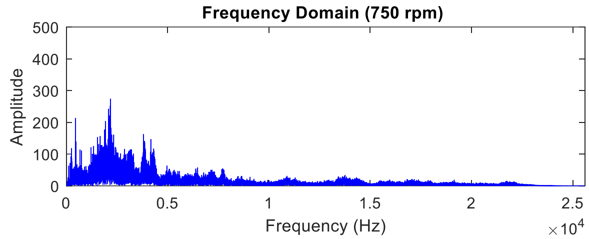


(c) cylinder 3

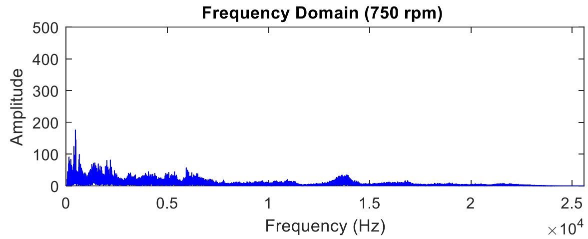


(d) cylinder 4

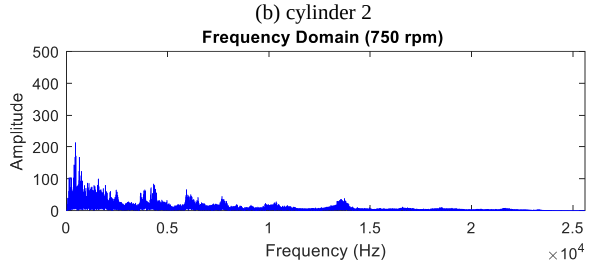
Figure 5: Signal frequency domain for fuel 95



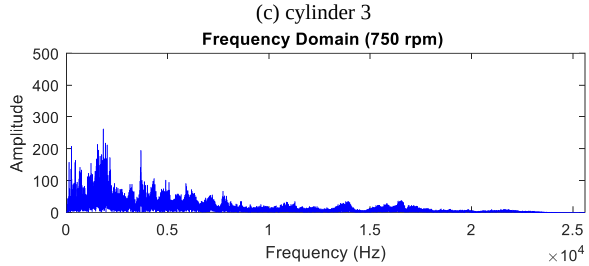
(a) cylinder 1



(b) cylinder 2

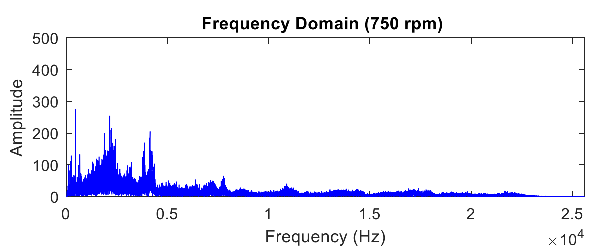


(c) cylinder 3

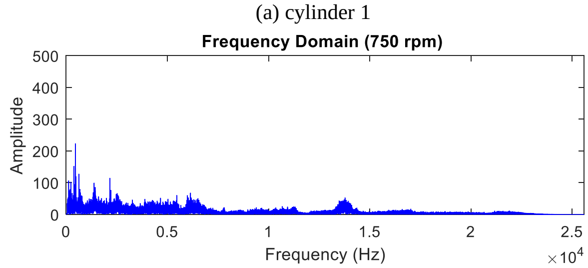


(d) cylinder 4

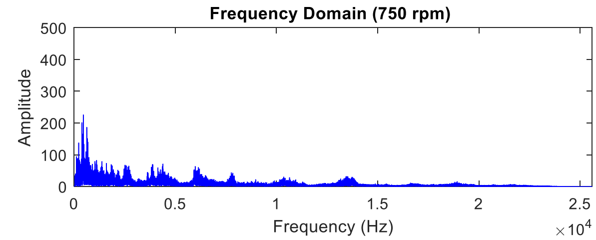
Figure 6: Signal frequency domain for fuel 97



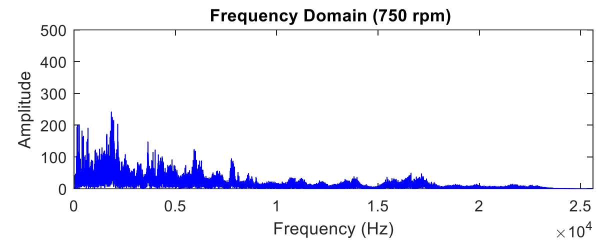
(a) cylinder 1



(b) cylinder 2



(c) cylinder 3



(d) cylinder 4

Figure 7: Signal frequency domain for fuel 100 (a) cylinder 1 (b) cylinder 2 (c) cylinder 3 (d) cylinder 4

The time domain and frequency domain result produced by a vibration signal that contains the characteristics of materials records by the accelerometer and piezo-film sensor [10]. This study shows the capability of the accelerometer sensor to characterize the engine condition using different fuels. From Figure 5(a), graph frequency domain at the first peak is due to the combustion process and the amplitude is highly depends on the combustion conditions. The vibration acceleration is increased with increasing speed [11]. The vibration occurred when the engine is in run condition. When the vibration is high, the amplitude also high. Figure 2 to Figure 4 are clearly show that the amplitude movement resulting from time domain graph appear as a vibration signal when the combustion engine is operated. From time-domain it can be understood that the vibration acceleration increased because of the effect of octane number. Furthermore, when the engine running, the amplitude increased rapidly, most clearly at cylinder 1 and cylinder 4 for three types of fuel, then the amplitude of the signal were slowly decreased until the signal disappears to zero amplitude at the frequency domain (Figure 5, 6, 7).

The trending for these three fuels (increasing and decreasing amplitudes) of a vibration signal for each cylinder might be a certain effect of the mechanism during operation. Fuel 97 and fuel 100 shown as a good fuel gasoline to the engine by referring to the graph above.

IV. Result and Discussion

In this experiment, the statistics are presented in the definite form for easier converted to the important figures for analysis. The data are presented in the form of table, graph and figure through parameter measured. The total data recorded by data acquisition in one second are 256,000 data. Every raw data will be recorded in five seconds to get the accurate value for each fuel.

All the data are filtered by MATLAB for validation. Table 3 to Table 8 are filtered data for every speed.

Table 3: Validation statistical data for 750 RPM

Fuel	Cylinder	RMS	Std Deviation	Kurtosis	Skewness
95	1	0.139037	0.13079	0.129063	4.816147
	2	0.079194	.06643	-0.00928	4.079715
	3	0.133721	0.121604	0.144928	4.797429
	4	0.161122	0.154072	0.274621	4.834626
97	1	0.108963	0.101009	-0.02808	4.346766
	2	0.077139	0.058788	-0.09165	3.693285
	3	0.084722	0.065723	0.068011	3.706738
	4	0.119782	0.110213	0.142347	3.981925
100	1	0.106641	0.098336	0.051717	4.518169
	2	0.081247	0.065595	-0.02374	3.699238
	3	0.08266	0.066191	0.009734	3.459198
	4	0.120738	0.112346	0.077434	3.972101

Table 4: Validation statistical data for 1000 RPM

Fuel	Cylinder	RMS	Std Deviation	Kurtosis	Skewness
95	1	0.166229	0.160025	0.156023	3.855834
	2	0.090893	0.081375	0.121885	3.429999
	3	0.139399	0.128490	0.094983	3.802508
	4	0.177692	0.172007	0.098043	4.073829
97	1	0.113862	0.106276	0.006861	3.366793
	2	0.081475	0.064273	0.110728	3.390515
	3	0.095611	0.076022	0.057632	3.372147
	4	0.132394	0.123383	0.127183	3.474905
100	1	0.165038	0.159912	0.026637	3.422085
	2	0.107695	0.097914	0.085526	3.708605
	3	0.108329	0.094685	0.022347	3.331222
	4	0.182401	0.176888	0.090542	3.551979

Table 5: Validation statistical data for 1500 RPM

Fuel	Cylinder	RMS	Std Deviation	Kurtosis	Skewness
95	1	0.391981	0.389567	0.111810	3.506818
	2	0.172320	0.167882	0.138660	3.292523
	3	0.314554	0.309721	0.039935	3.180241
	4	0.363247	0.360638	0.060288	3.321920
97	1	0.162053	0.156687	0.131587	3.054232
	2	0.118175	0.107343	0.241741	3.049705
	3	0.137072	0.126805	0.164528	2.803768
	4	0.196389	0.190920	0.129050	3.043759
100	1	0.219685	0.215152	0.048619	3.112508
	2	0.148632	0.139880	0.165362	3.204594
	3	0.150195	0.142116	0.190597	3.078421
	4	0.252505	0.248851	0.055759	3.210777

Table 6: Validation statistical data for 2000 RPM

Fuel	Cylinder	RMS	Std Deviation	Kurtosis	Skewness
95	1	0.551449	0.549591	-0.00322	3.251802
	2	0.274762	0.271991	0.139689	3.263156
	3	0.455176	0.451788	0.074428	3.020461
	4	0.532761	0.530931	0.043187	3.141470
97	1	0.260432	0.256732	0.005019	3.044186
	2	0.197429	0.191824	0.135076	3.067827
	3	0.216316	0.210373	-0.06379	2.807606
	4	0.325976	0.323011	0.172393	3.144750
100	1	0.329754	0.327064	0.042299	3.179429
	2	0.224088	0.218731	0.023395	3.078843
	3	0.226066	0.219996	0.144730	2.861089
	4	0.392439	0.390025	0.114462	3.182619

Table 7: Validation statistical data for 2500 RPM

Fuel	Cylinder	RMS	Std Deviation	Kurtosis	Skewness
95	1	0.665804	0.664127	0.028375	3.176509
	2	0.353067	0.350601	0.269240	3.286941
	3	0.527801	0.524921	0.233913	3.288406
	4	0.709084	0.707640	0.080760	3.035421
97	1	0.373496	0.371017	0.032307	2.914453
	2	0.324512	0.320520	0.366953	2.923554
	3	0.326125	0.322807	0.046444	2.617796
	4	0.501962	0.500267	0.125262	2.729210
100	1	0.440506	0.438447	0.036117	2.976362
	2	0.356274	0.352840	0.486324	3.431970
	3	0.338114	0.334660	0.334125	2.962895
	4	0.549592	0.547821	0.161386	3.149764

Table 8: Validation statistical data for 3000 RPM

Fuel	Cylinder	RMS	Std Deviation	Kurtosis	Skewness
95	1	0.869767	0.868532	0.019303	3.110602
	2	0.485528	0.483848	0.196387	3.167282
	3	0.660226	0.658368	0.093589	3.200658
	4	0.898366	0.897372	0.100866	3.209294
97	1	0.468864	0.466997	-0.10095	3.035511
	2	0.434200	0.431327	0.178176	2.843329
	3	0.399888	0.396410	0.178531	2.842825
	4	0.660981	0.659455	0.123338	3.132875
100	1	0.556456	0.554764	-0.05028	3.038831
	2	0.448354	0.445536	0.417302	3.489537
	3	0.420233	0.417300	0.251684	3.190762
	4	0.710466	0.709090	0.011319	3.081890

As shown in tables data statistical for fuel 95 is quite high compared to fuel 97 and fuel 100. Only relying on the tables was insufficient to analyse the performance of fuel because the characteristics of the statistical parameter are not shown. The data were summarised in graph statistical of the speed performance for all fuels and cylinders. Figure 8 to Figure 11 illustrate the statistical data for root mean square, standard deviation, skewness and kurtosis.

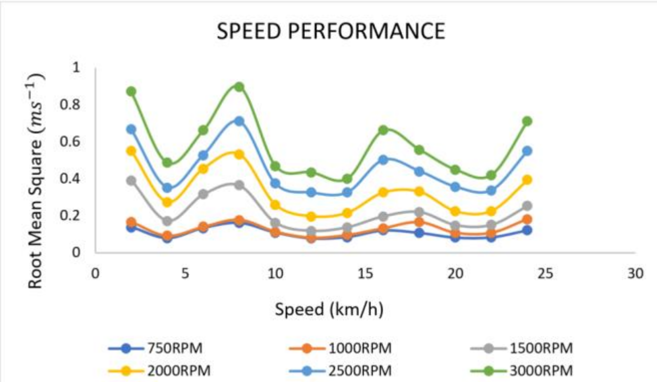


Figure 8: Root mean square for speed performance

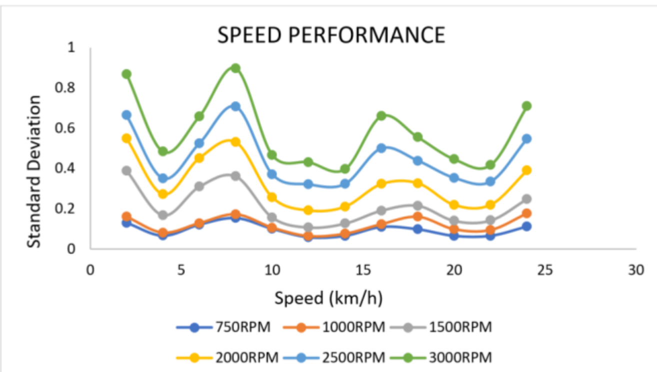


Figure 9: Standard deviation for speed performance

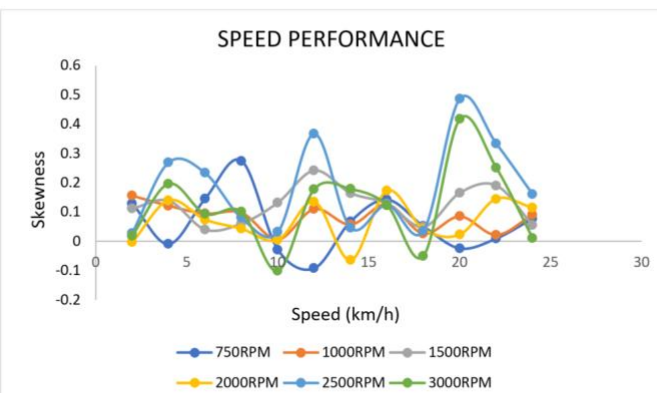


Figure 10: Skewness for speed performance

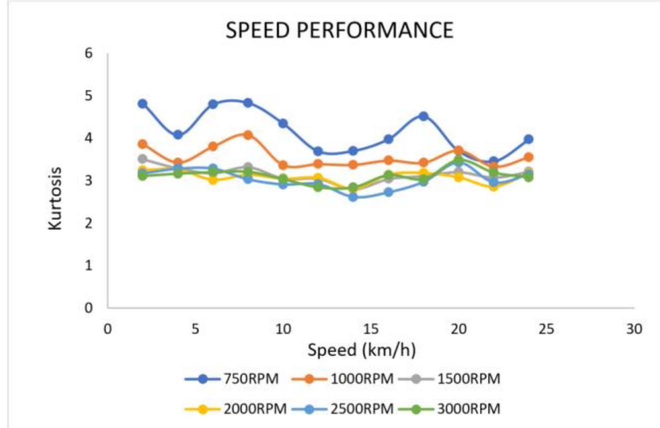


Figure 11: Kurtosis for speed performance

From Figure 8 and Figure 9, the design is similar between root mean square and standard deviation. According to these figures, statistical parameters assumed as a vibration response for all cylinder in a combustion engine. From result in Figure 1 to Figure 4, assumption obtained are as follows:

First, each individual cylinder has different vibration response from the same fuel. For example, cylinder 1 and cylinder 4 showed highest vibration response compare to cylinder 2 and cylinder 3.

Second, each individual cylinder vibration effect at 750 rpm and 1000 rpm remained constant because these two speeds were still in the range of idle speed where they remark no force given at the combustion engine.

Third, refer to the figure of standard deviation and root mean square, fuel 97 was in the best lines followed by fuel 100 compare to fuel 95 that have a fluctuated line.

Forth, the vibration response for each cylinder increases with the increasing of speed. For example, vibration in cylinder 1, cylinder 2, cylinder 3 and cylinder 4 increased rapidly from speed 1500 rpm to 3000 rpm.

Fifth, the figure for kurtosis and skewness are not valid and it is difficult to analyse. The graphs did not show the characteristics of kurtosis and skewness. To summarise the information about these two statistical parameters, further techniques have been conducted to ensure the validation of the data.

Coefficient of determination

A linear trendline fitting was used for the calibration of coefficient determination. All linear equations for the fuels result with high-value correlation coefficient (R^2) between range 0.9065 to 0.9602 which mean high precision for linear fitting. The linear equation and the value of correlation coefficient is shown in Table 9 for RON 95, RON 97 and RON 100.

Table 9: Correlation and coefficient for fuel RON 95, RON 97 and RON 100

Fuel	Linear equation	Correlation coefficient (R^2)
95	y = 0.0834x - 0.0494	0.9602
97	y = 0.0741x - 0.0539	0.9065
100	y = 0.0759x - 0.038	0.9394

From the result of correlation coefficient, it is understood that RON 97 has a lower value compared to RON 95 and RON 100. The linear trendline was chosen because the correlation coefficient of the fuels was in good value at range between 0 and 1.

RMSE and MAPE

RMSE (Root Mean Square Error) and MAPE (Mean Absolute Percentage Error) analysis can measure how well the fuels perform and predict which are suitable fuel for the engine. Table 10, 11, 12 and 13 show the value of RMSE and MAPE for root mean square, standard deviation, kurtosis and skewness.

Table 10: RMSE and MAPE value for root mean square

Fuel	RMSE	MAPE
95	0.195126	0.757553
97	0.118096	0.677735
100	0.133750	0.719733

Table 11: RMSE and MAPE value for standard deviation

Fuel	RMSE	MAPE
95	0.148971	0.975864
97	0.137269	0.687221
100	0.137646	0.844116

Table 12: RMSE and MAPE value for kurtosis

Fuel	RMSE	MAPE
95	0.59033	0.126353
97	0.292793	0.078652
100	0.312724	0.077669

Table 13: RMSE and MAPE value for skewness

Fuel	RMSE	MAPE
95	0.062135	0.585442
97	0.017148	0.096417
100	0.035022	0.530850

From the tables above, the value for MAPE is not precision at fuel 95, fuel 97 and fuel 100. For instance, value MAPE for root mean square at fuel 95, fuel 97 and fuel 100 are 0.757533, 0.677735 and 0.719733 while value MAPE for kurtosis at fuel 95, fuel 97 and fuel 100 are 0.126353, 0.078652 and 0.077669. It shown that the value of MAPE at root mean square and kurtosis for fuel 97 and fuel 100 have higher value fluctuating compared to fuel 95. Thus it was quite difficult to analyze the performance for both fuels. The different value of MAPE are not depend on the developed system and database, but also affected by the condition of the recorded cutting force signal and vibration [12] at the component that close to the engine.

The RMSE reading for fuel 97 and fuel 100 are nearly similar. The RMSE of standard deviation at Table 11 for fuel 97 and fuel 100 is 0.137269 and 0.137646. The value has 0.0004 difference between them. RMSE for fuel 95 is always high for all statistical analysis. It showed that fuel 95 is not suitable for the engine and can cause fault and engine break down.

The higher the octane number, the higher the performance occurred and the higher compression ratio improves efficiency in the absence of knock [5]. Octane called as an anti-knocking because of the ability to resist knocking when used in the engine. Engine N43B20 required a high compression ratio as shown in the result obtained. It also is shown that fuel 95 give a lower ignition resistance during a combustion processed. This shows that fuel 95 is not suitable for the engine with high compression ratio. Putting a lower octane fuel to the high compression engine can produce a premature ignition that can create a knocking sound from time to time. Knock is a fundamentally chemical process initiated by pre-flame reactions leading to auto ignition. Using the lower octane fuel can reduce the efficiency and performance of the engine. It is also can damage the engine with carbon deposits [13].

From the results, it shows fuel 100 having a problem to the engine N43B20. The performance of fuel 97 is better for the engine compare to fuel 100. Figure 8 and Figure 9 show the fuel 97 is more suitable compared to fuel 100. To prove that, Table 12 and Table 13 show the value of RMSE and MAPE for fuel 97 are smaller compared to fuel 100. This proved that the compression ratio of engine N43B20 is not fitted with the fuel 100.

V. Conclusion

With the different number of octanes, it can give an impact to the vibration acceleration. The amplitude of the frequency shows something wrong with the engine when running the unsuitable fuel in the engine. Engine durability, fuel consumption and power density, as well as noise and emission performance, are related to the spark ignition. The ‘knock’ ignition is one of the main causes that can give effect to the high amplitude [14, 15]. To support the statement, the result of RMSE and MAPE show the performance error between these fuels.

In conclusion, the evaluation by using vibration analysis is not only to measure the performance of the engine, but it is also having the potential to detect faults when the engine is under full running. From MAPE values, it is clearly indicated that RON 97 and RON 100 is the best fuel types for engine N43B20 due to the smallest error generated. By comparing the RMSE result, it is proven that RMSE value for RON 97 is suitable compared to RON 95 and RON 100. By considering the analysis of RMSE and MAPE, the result is more valid to decide that RON 97 is the most suitable for best engine performance due to smaller error occurred [16, 17, 18].

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