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Preliminary Study of Condition-Based Monitoring (CBM) on Automotive Gearbox Using Ultrasonic Signal

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Abstract: This paper discusses the outcomes from a preliminary investigation of a condition based monitoring using ultrasonic signal on a 5-speeds automotive manual transmission. A high frequency ultrasonic sensor was used as the transducer for the data collected which was based on engine speed and gear positions. The data was analyzed using MATLAB software and translated into figures of the signal. These figures show all the possible conditions during the gearbox operation. Signal was filtered within the ultrasonic range to avoid noise and other unnecessary interference. The signal was clustered to identify the point of transient generated by any fault in the gear box based on statistical analysis.

Key word: Statistical Analysis · Ultrasonic signal · Condition-Based Monitoring · I-kaz · Gear Box,

INTRODUCTION

Condition Based Monitoring (CBM) is used as a tool for engineers and technicians to monitor the state of health of moving parts by indentifying the faulty symptoms during the operation. If faulty symptoms were found, the parts can be replaced before failure or otherwise it will be allowed to continue running. Rotating machines such as gearboxes often failed due to heavy loads. A study found that 60% of gearbox damage is due to faults in the gears itself and in details about 90% of the gear faults were due to localized gear defects such as forced fractures, fatigue fractures and incipient cracks [1].

The advantages of an effective gear condition monitoring program include avoidances of; hazards, degraded product quality, loss of production, cost of collateral damage, as well as the cost to replace or repair the faulty gear. In critical applications such as in helicopters, the detection of incipient failure in the gear system may save lives and money [2]. Vibration is one of measuring technique but this technique has the disadvantages especially when measuring the fundamental frequency at low speed. Typically, vibration analysis is not capable of measuring the fundamental frequency of operation at rotational speed below 300rpm [3].

Theoretical Background

Gear Box Diagnosis: Gearbox is the main component in the transmission system. A gearbox consists of various sizes of gears to give the engine a mechanical advantage over the driving wheels. Without the mechanical advantage the gearing provides, an engine can generate only limited torque at low speeds and the vehicles need sufficient torque to move from a standing start. The condition of the gearbox is very important to make sure the vehicle can move smoothly. Thus, a lot of study and research of condition monitoring for gearbox were made to find the best way of preventing gearbox damage. Rautert and Kollman[4] presented a computer simulation of the generated force in gear mesh and the resulting noise radiation.N. Saravanan and K.I Ramachandran[5] used the wavelet transform to represent all possible type of transients in the vibration signal generated by faults in a gear box. Furthermore, The earlier study of gearbox monitoring also used the Fourier analysis to analyzed the vibration signal, but there are some crucial restrictions of the Fourier transforms, which the signal to be analysed must be periodical or stationary but in contrast the vibration signal of gearbox was not stationary [6]. Even though, the ultrasonic sound was better than vibrations method to monitoring the operating equipments. Alan S. Bandes said in his article, research by

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National Aeronautic and Space Administration (NASA) has demonstrated that ultrasound can locate incipient failure in bearings long before traditional heat and vibration method [7]. Preventing the gearbox from suffering any damage requires a good method of condition monitoring. Thus, the ultrasonic sound is one of the methods that can be used to monitor the condition of gearbox [3].

Ultrasonic Signal: There three main types of sound wave, categorized by its frequency value. Infrasonic wave has frequency below 20Hz. Frequency value ranging between 20Hz to 20 kHz is call audio wave. While ultrasonic wave have frequency lying between 20 kHz to 100 kHz [14]. This study was concentrates on ultrasonic wave i.e. the study of sound propagate at frequency beyond the audible range that is detectable by human ears.

Ultrasonic technique is one of widely used for non-destructive testing (NDT) of materials [8, 9]. The ultrasonic sound wave, generated by piezoelectric transducer propagated through the materials and is reflected by the defects and back surface of the sample. According to previous study, Saka M *et al.*, The signals reflected by defect possess information about defect size and orientation [10].

Usually the ultrasonic signal processing was used for detection of defect in materials. For examples, D.Pagodinas was used this method for detection of defects in composite materials [11]. While Stanullo J. *et al.* used the ultrasonic signal analysis to monitor damaged development in short fiber reinforced polymer [12]. However, in this paper the ultrasonic signal processing was applied to gearbox for detection of the condition during operation.

Statistical Analysis: A measured signal commonly consists of variations in amplitude, frequency, phase and energy. Signals can be divided into two main categories which are deterministic and nondeterministic. A deterministic signal can be described by a mathematical relationship between the value of the function and time. Many signals in nature exhibit random or nondeterministic characteristics which provide a challenge to analyse using signal processing techniques.

The skewness, which is the signal 3rd statistical moment, is a measure of the symmetry of the distribution of the data points about the mean value. The skewness of a signal is given by

$$S = \frac{1}{n(r.m.s.)^3}\sum_{i=1}^{n}(x_i - \bar{x})^3 \qquad (1)$$

where n is No. of data, $r.m.s$ is root mean square, x_i is the value of data point and $\bar{x}$ is the means of data.

The skewness for a symmetrical distribution such as a sinusoid or a Gaussian random signal is zero. Negative skewness values indicate probability distributions that are skewed to the left, while positive skewness values indicate probability distributions that are skewed to the right, with respect to the mean value[13].

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:

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

where n is no. of data, ó is standard deviation, x_i is the value of data point and $\bar{x}$ is the means of data.

The kurtosis value is approximately 3.0 for a Gaussian distribution. Higher kurtosis values indicate the presence of more extreme values than should be found in a Gaussian distribution. Kurtosis is used in engineering for detection of fault symptoms because of its sensitivity to high amplitude events [13].

The crest factor (CF), which is commonly encountered in engineering applications, is defined as the ratio between the maximum value in the time history and the r.m.s. value:

$$CF = \left|\frac{x_{i\max}}{r.m.s.}\right| \qquad (3)$$

The crest factor value for sinusoidal time histories is 1.41 and the value approaches 4.00 in the case of a Gaussian random signal of infinite length [13].

Integrated Kurtosis-Based Algorithm for Z-filter (I-kaz): Integrated Kurtosis-based Algorithm for Z-filter (I-kaz) is an alternative statistical approach as supplement to the existing statistical method. This technique has viability in forming an effective condition monitoring system which both descriptive and inferential statistics were utilised in the I-kaz method [14].

Based on kurtosis, I-kaz method [14] provides a three dimensional graphical representation of the measured signal data distribution. The time domain signal is decomposed into three frequency bands which are, x-axis, which is for low frequency (*LF*) range of 10-20 kHz, y-axis, which is high frequency (*HF*) range of 20-50 kHz and z-axis, which is very high frequency (*VF*) range of 50-100 kHz. In order to measure the scatter of data distribution, the I-kaz coefficient calculates the distance of each data point from signal centroid [14]. I-kaz coefficient is defined as:

$$Z^{\infty} = \frac{1}{n}\sqrt{K_L s_L^4 + K_H s_H^4 + K_V s_V^4} \quad (4)$$

where n is the number of data, K_L, K_H, K_V are the kurtosis of signal in *LF, HF* and *VF* range and s_L, s_H and s_V are the standard deviation of signal in *LF, HF* and *VF* range respectively.

MATERIALS AND METHOD

Experiment Set up: For the experimental work, the manual engine gearbox system was used as the test rig. The unit consists of a coated manual gearbox, a driving motor, a breaking motor and a control console, all mounted on an epoxy-coated steel base frame. The manual gearbox system is a modern design, with 5 forward speeds and one reversed speed. The data was captured based on the input speed (RPM) and the number of gear speeds (including the reverse gear). The signal of the gearbox was measured using the VS 1000 sensor during the operation. Sensor was positioned at center of the gearbox case which possible to measure every gear speed data. The VS 1000 sensor wills connect from the PCI Extensions for Instrumentation (PXI) (data acquisition) through the AEP 4 pre-amplifier. The data was stored in the computer and the MATLAB software was used to analyze the data. The MATLAB software was used to get the frequency of the signals using the FFT function and statistical analysis of the clustering. Before collecting the data, various parameters such as sampling frequency, maximum and minimum voltage and band pass filter should be set. All configurations were set in the NI CAIDMARK software in the computer. Figure 1 shows the experiment set-up which mainly consist of gearbox, VS 1000 sensor, AEP 4 pre-amplifier, data acquisition (PXI) and computer.

Experiment Process: In this study, a manual gear box test rig was used to simulate the actual gear box system. The test-rig consists of a control console, a manual gearbox set and an input and output motor. In the test rig, the input motor was connected to the front of the gear box which it is represents an engine in an actual gear box system. The speeds of the motor were controlled by the control console. The maximum speed for the motor is 1300 RPM and the minimum speed is 800 RPM. The signal was measured at five RPMs within the specified range i.e. 800, 1000, 1100, 1200 and 1300 RPMs for each number of gears. The gear box system was run step by step according to the gear number starting from gear 1 until 5 and then the reverse gear.

During the gearbox running, the time domain signal was displayed on the computer by using the NI CAIDMARK software. Since the minimum rpm of 800 was considered in this study for the signal measurement process, so that 0.075 s was needed for one complete gear rotation. In order to study the variation of signals within a few rotations, the duration of each signal measurement was set to 0.75s.

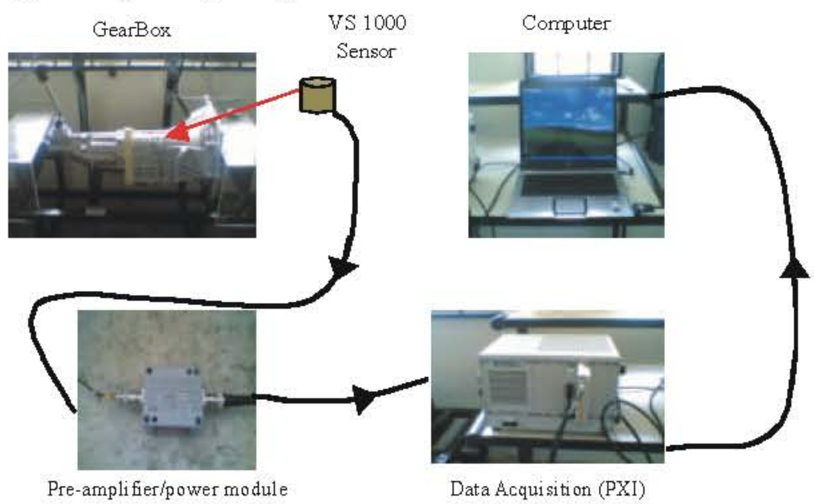


Fig. 1: Equipments set up

RESULTS AND DISCUSSION

Table 1 and Table 2 show the statistical analysis results including value of frequency for each number of gears and RPM. Four statistical parameters shown in both tables were calculated in MATLAB environment. Both skewness and kurtosis parameters from Table 1 were calculated by existing MATLAB functions (kurtosis using KURTOSIS (data) and skewness using SKEWNESS (data)). Meanwhile I-kaz coefficient parameter and Crest Factor parameter was generated by authors MATLAB codes. Figure 2 shows the example of time domain graph for signal that has been measured on all number of gears at 800 rpm. Basically, the time domain graph shows how the signals change over time. The duration of each signal measurement was set to 1.5 seconds. For this sampling period, total number of data has been measured is 300000 and the data was varies with time. Utilising the FFT algorithm, the time domain signal was transformed into frequency domain. Frequency domain graph on figure 3 shows how much of the signal lies within each given frequency band over a range of frequencies. During the experiment, the frequency band was set from 20 kHz to 100 kHz. Using this range of frequency the ultrasonic signal was measured from automotive gear box. The ultrasonic signal was proved can monitor the condition of machine [15, 16]. Based on the frequency domain, the dominant frequency of signal can then be obtained.

The statistical parameter values from Table 1 and 2 were used to produce a scattering plot graph. The pattern of data that scattered in the plotted graph according to the gear condition during operation was observed. The clustering results were presented in Figure 4, 5 and 6. Based on the three clustering graphs, I-kaz vs Kurtosis (Figure 4), I-kaz vs Crest Factor (see figure 5) and I-kaz vs Skewness (see figure 6) the pattern of the statistical data can be observed. From the three graphs, the similar trend of clustering can be observed. It can be seen that the clustering areas was divided into three regions according to its statistical value. Since the I-kaz coefficient was plotted as the responding variable, the region of data clustering was influenced by the I-kaz coefficient value. Gear 2 covers the higher region and Gear 1 covers the lower part of graph. These separated region shows that the signal produced by the gear 2 has relatively higher amplitude and frequency component compared to the gear 1, as it has higher value of I-kaz coefficient. The signal feature in terms of amplitude and frequency that represents by the I-kaz coefficient was discussed further in the previous study [14].

Table 1: Statistical result of signal obtained from each rpm for different Number of gear: Gear 1, Gear 2, Gear 3,

Gear 1					
rpm	800	1000	1100	1200	1300
Kurtosis	3.892927	3.949873	3.873867	3.827283	3.810529
Skewness	0.025542	0.005514	0.008406	0.012219	0.016538
CF	8.599849	7.910132	6.891671	8.312114	7.164637
I-kaz	9.42E-14	9.35E-14	9.49E-14	9.38E-14	9.27E-14
Dominant Frekuensi	64404.3	81640.63	41894.53	80126.95	48339.84
Gear 2					
rpm	800	1000	1100	1200	1300
Kurtosis	4.389722	4.549146	4.303711	4.144899	4.231348
Skewness	0.026223	0.004998	0.01506	0.022434	0.020869
CF	8.222672	9.845944	8.126685	8.624518	8.030083
I-kaz	1.05E-13	1.07E-13	1.03E-13	9.98E-14	1.01E-13
Dominant Frekuensi	42089.84	87988.28	85595.7	88183.59	70654.3
Gear 3					
rpm	800	1000	1100	1200	1300
Kurtosis	4.19904	4.243328	4.16671	4.192261	4.201573
Skewness	0.017399	-0.00453	0.018479	0.019443	0.025885
CF	8.318752	8.616901	7.359443	8.748425	7.566309
I-kaz	1E-13	1.02E-13	1E-13	1.02E-13	9.85E-14
Dominant Frekuensi	66406.25	33447.27	72705.08	57128.91	83789.06

Table 2: Statistical result of signal obtained from each rpm for different Number of gear: Gear 4, Gear 5, Reverse Gear

Gear 4					
rpm	800	1000	1100	1200	1300
Kurtosis	4.336239	4.277515	4.181868	4.213303	4.311741
Skewness	0.012875	0.0084	0.035543	0.021806	0.02088
CF	9.583787	8.370212	8.579633	8.143892	8.514522
I-kaz	1.02E-13	1.01E-13	9.96E-14	1.02E-13	1.01E-13
Dominant Frekuensi	71777.34	63232.42	87109.38	57568.36	13037.11
r.m.s	0.000154	0.000154	0.000153	0.000154	0.000154
Gear 5					
rpm	800	1000	1100	1200	1300
Kurtosis	4.20964	4.074097	4.043821	4.150771	4.247285
Skewness	0.018201	0.012675	0.026218	-0.00423	0.019218
CF	8.094601	8.336396	9.914128	9.95096	10.16192
I-kaz	1.01E-13	9.86E-14	9.77E-14	1.01E-13	9.9E-14
Dominant Frekuensi	31542.97	96093.75	74462.89	30810.55	53222.66
r.m.s	0.000154	0.000153	0.000153	0.000154	0.000153
Reverse Gear					
rpm	800	1000	1100	1200	1300
Kurtosis	4.232343	4.024964	4.031413	4.060152	4.201565
Skewness	0.013579	0.010325	-0.00383	0.014391	0.025279
CF	9.540465	6.911979	7.684432	8.590208	9.480701
I-kaz	9.96E-14	9.64E-14	9.6E-14	9.73E-14	9.65E-14
Dominant Frekuensi	49121.09	55859.38	80664.06	40673.83	98779.3
r.m.s	0.000153	0.000152	0.000152	0.000153	0.000151

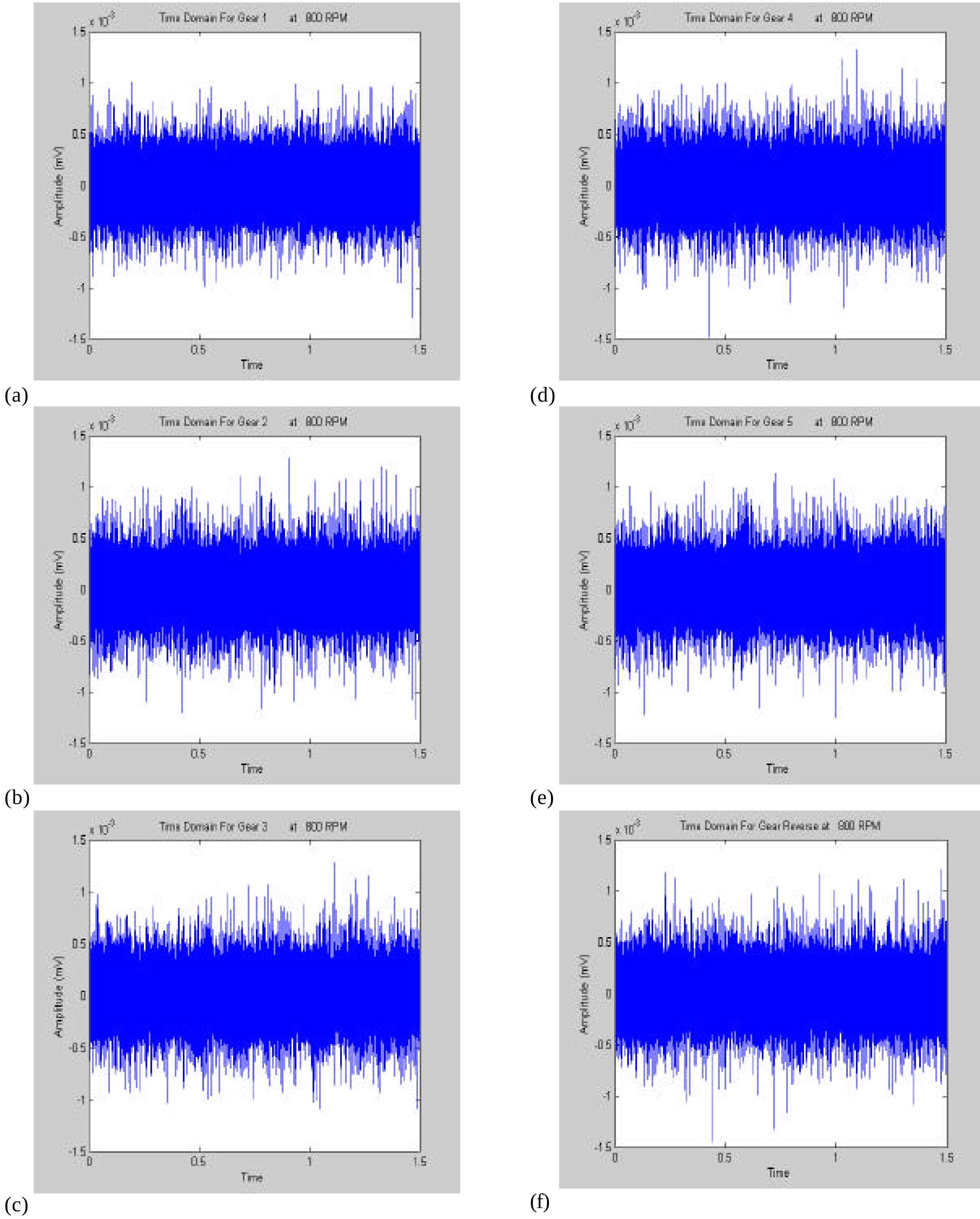
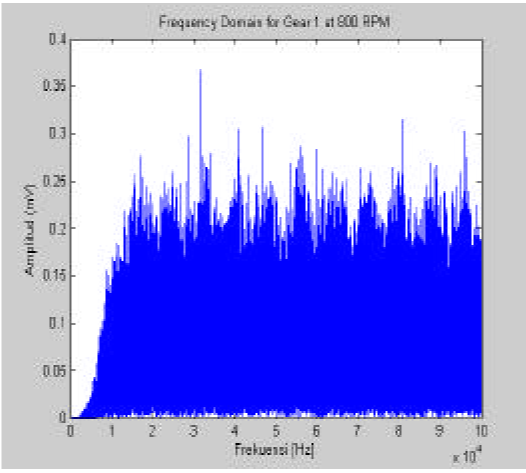
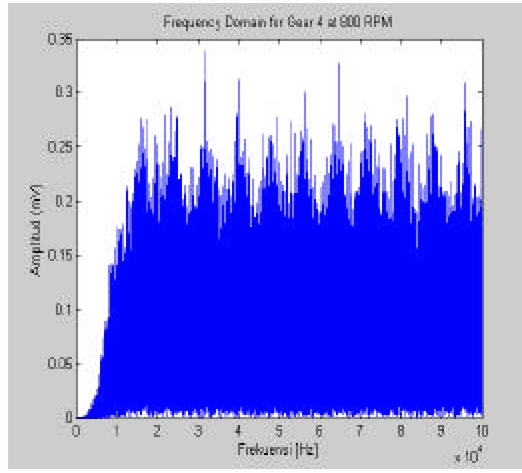


Fig. 2: Time domain for 800 rpm from gear 1 to reverse gear: (a) Gear 1, (b) Gear 2, (c) Gear 3, (d) Gear 4, (e) Gear 5. (f) Reverse Gear



(a)



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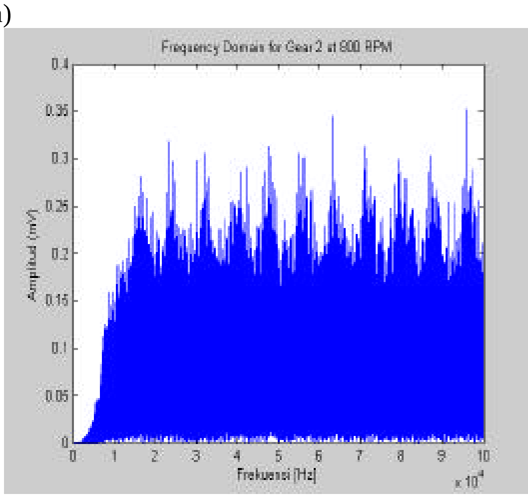
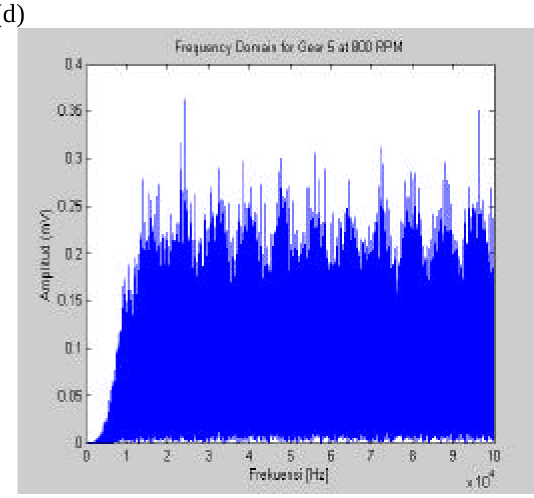
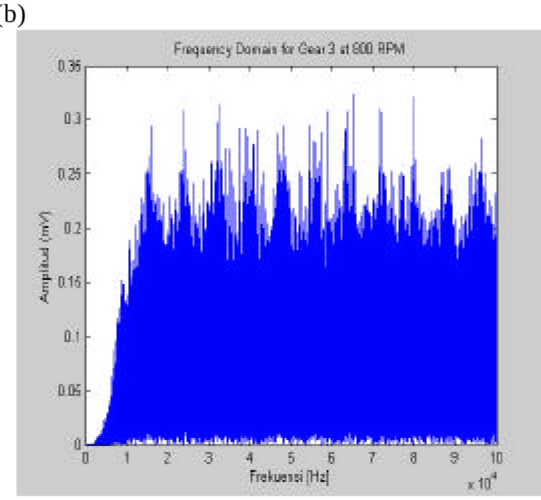


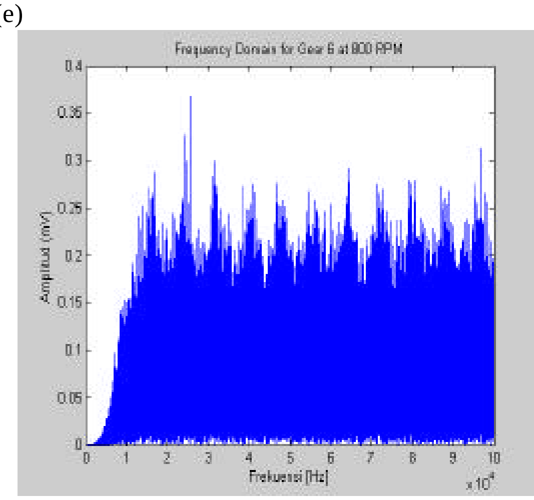
(b)



(e)



(c)



(f)

Fig. 3: Frequency domain for 800 rpm from gear 1 to reverse gear: (a) Gear 1, (b) Gear 2, (c) Gear 3, (d) Gear 4, (e) Gear 5, (f) Reverse Gear

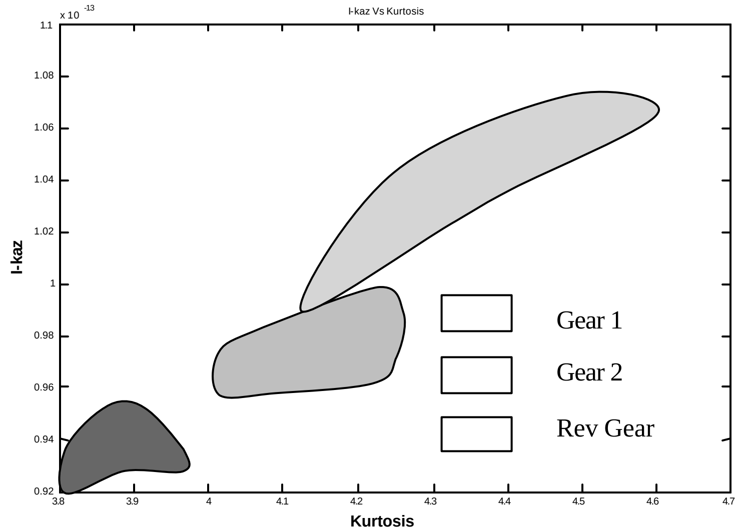


Fig. 4: Clustering I-kaz vs Kurtosis for gear 1, gear 2 and reverse gear

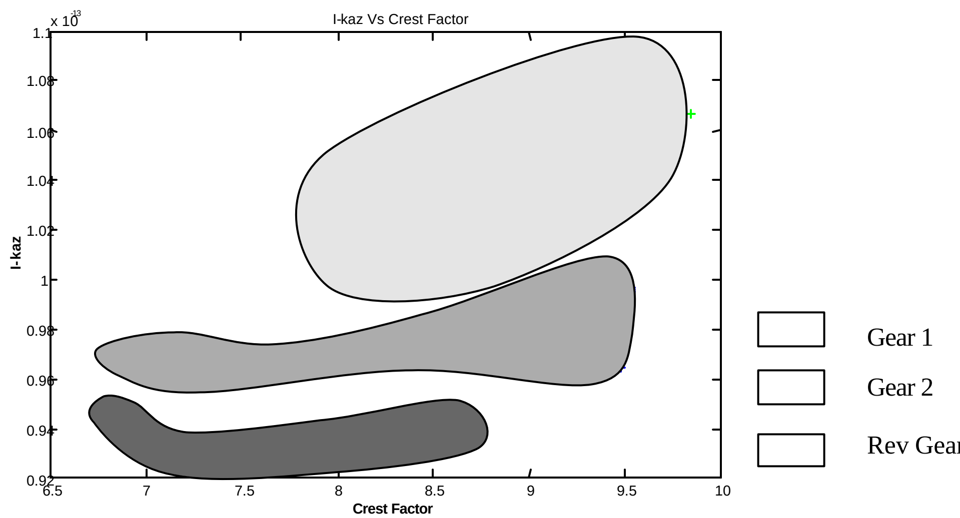


Fig. 5: Clustering I-kaz vs Crest Factor for gear 1, gear 2 and reverse gear

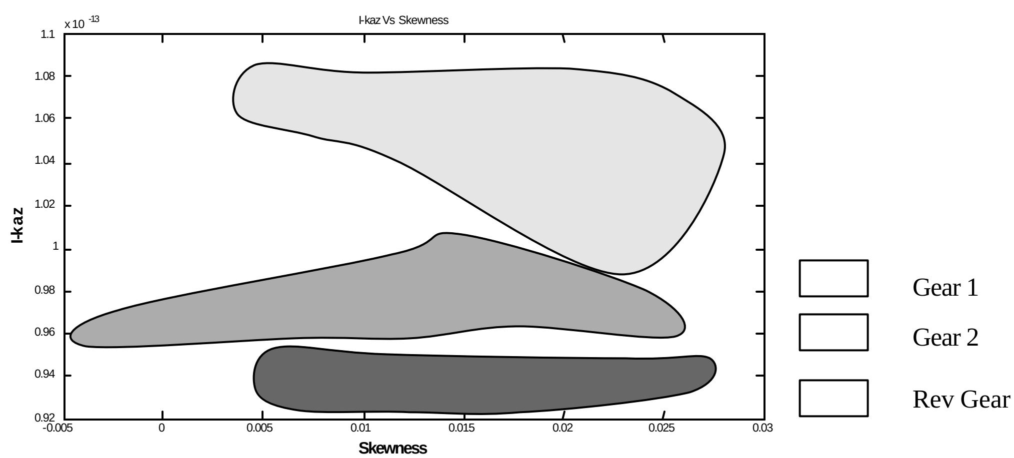


Fig. 6: Clustering I-kaz vs Skewness for gear 1, gear 2 and reverse gear.

Meanwhile, the region of signal produced by the reverse gear was located between gear 2 and gear 1. The region shows that the I-kaz coefficient value for reverse gear was higher than gear 1 and less than gear 2. Based on the observation during the experiment, the value of input and output speed obtains for gear 1 and reverse gear was similar. This result exhibits that the size of both gears are almost the same. Ideally, the statistical parameter for signal generated by both gears will be scattered in the same region as it has the similar gear size but the regions for both gears still can be differentiated by this clustering approach. The difference of gear 1 and reverse gear region may be caused by the switch of gear rotation from the forward to reverse condition and the long operation period of forward gear. These graphs were useful to monitor the condition of gearbox. Furthermore, the three graphs can be used as a reference for further study in future.

The values of statistical parameter for gear 3, 4 and 5 are almost the same and the pattern of the statistical data point while plotting a graph are very close and some points are overlapping. These three gears cannot be clustered by this clustering approach because the data scattering was not classified into different groups. Further clarification for this problem statement would be remarked for future study.

CONCLUSIONS

This paper demonstrates that using the scattering of the statistical data, the clustering were obtainable to differentiate the region of data for each gear. From the three graphs, the similar trend of clustering can be observed. The role of I-kaz coefficient as the responding variable gave significant difference of gear 1 and gear 2. The I-kaz value for gear 2 was higher than gear 1. The variation of I-kaz coefficient value was influenced by the value of amplitude and frequency of each gear. The results of this experiment give some prediction of the condition for the automotive gearbox. Contribution of statistical parameter such as crest factor, skewness, kurtosis and I-kaz is the vital role in signal clustering for the gearbox operation.

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