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Value Prediction of Materials Mechanical Properties Using I-kaz Analysis Method during Impact Test: Experimental Study

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Abstract

The specific mechanical constant of a material can be determined by examining in detail its dynamic pulse response or dynamic resonance. This paper proposes the use of the Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz multilevel) signal analysis method which is used on dynamic resonance signals to predict the value of specific mechanical properties of the test materials. Four rectangular bars made from four different materials were excited in an anechoic room by an impact test which produces transient sound radiation and vibration responses. The sound and vibration signals were recorded using microphones and accelerometer sensors respectively. An alternative Z-stem filtering technique was used on the captured signals for noise removal purpose which may have been captured by the sensor equipment during the impact test. The filtered signals were analysed using the I-kaz multilevel analysis method to determine the pattern of the signal and to estimate the significant differences between the four materials. The experimental power curve equations of mechanical loss coefficient vs. linear coefficient and compressive strength vs. linear equation can be used to predict the unknown values of the mechanical loss coefficient and compressive strength of the test material.

Keywords: Impact test; Material property; I-kaz™ method; Signal features; Sound; Vibration

INTRODUCTION

In recent years, many techniques have been proposed to identify the mechanical properties, specifically the elastics properties, of both orthotropic and isotropic materials [1, 2]. Under these methods, the samples under study were applied to various experimental setups. The vibration and acoustic signals produced were picked up and analysed to distinguish the changes in the vibration and acoustic properties [3-6].

This paper deals with the dynamic characterization of materials by measuring the vibration and sound signals from the impact tests which used simple method and calculation, fairly cheap equipment and non-destructive material. Thus, measurements could be repeated on the same specimen. The signal feature (SF) of the captured sound and vibration signals was analysed using the Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz multilevel) statistical analysis method. The I-kaz multilevel coefficient values calculated from the signals were analysed and then correlated with the specific mechanical properties of the work pieces.

Dynamic signal filtering

Sound and vibration signals were filtered using a Z-stem filter algorithm based on the frequency components to remove unwanted noise. In the next stage, the recorded signals were transformed to the frequency domain using a Fast Fourier Transform (FFT) algorithm. The values of the frequency components for sound and vibration signals were compared to observe the same and different dominant frequencies. The effectiveness of the Z-stem noise filtering technique in removing unwanted noise can be proven by finding the correlation between both signals before and after the filtering process. For that reason, the correlation coefficient was utilized to quantify the similarity of the filtered and unfiltered signal against noise. Eq. (1) shows the correlation coefficient, R which represents the normalized measure of the strength of the linear relationship between variables [7-9].

$$\mathrm{R} = \frac{\sum_{t=1}^{N} (x_t - x)(x_{t+k} - \bar{x})}{\sum_{t=1}^{N} (x_t - \bar{x})^2} \tag{1}$$

The effectiveness of the Z-stem filter de-noising technique can be observed by the value of *e* as shown in Eq. (2) [10].

$$e = \frac{R_{filtered} - R_{measured}}{1 - R_{measured}} \tag{2}$$

The filtered vibration and sound signal was analysed using the new I-kaz multilevel analysis method to observe the information characteristic contained in the signal.

I-kaz multilevel method

Signals captured in time domain need to be analysed and extracted using specific signal features (SF) in order to describe the signal sufficiently and maintain the relevant information [11-14]. SFs such as standard deviation, kurtosis, average values, root mean square (rms) and variance are commonly used to extract information in any signal in time domain [15-17].

The average value of $\bar{x}$ is defined as in Eq. (3) where n is the number of points and x_i is the value of each individual item in the list of points being averaged.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n}(x_i) \tag{3}$$

The standard deviation value, s is defined as in Eq. (4):

$$s = \left(\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right)^{\frac{1}{2}} \tag{4}$$

Where $\bar{x}$ is the mean of the data and x_i is the value of the data point. The value of kurtosis, for discrete data sets is defined in Eq. (5).

$$\mathrm{K} = \frac{1}{ns^4}\sum_{i=1}^{n}(x_i - \bar{x})^4 \tag{5}$$

Kurtosis values which are capable of detecting the high amplitude in signals are commonly used in industries for the purpose of defect detection [18]. It was also used in a study as one of the coefficients to predict the fatigue life reliability of a stub axle [19].

The maximum frequency span in a signal is described in Eq. (6):

$$f_{\max} = \frac{f_s}{2.56} \tag{6}$$

Where $F_{\max}$ is the maximum frequency, f_s the sampling frequency and 2.56 is the Nyquist number which was chosen to be more than 2 in order to avoid the content of the sampling signal to be misinterpreted [20].

Previous studies show that the I-kaz™ coefficient was used as the parameter to translate the signal features on the captured signals. J.A. Ghani in her study used the I-kaz™ coefficient to analyse the tool wear in a turning machining process to predict the tool wear status during machining [21-23]. The I-kaz™ coefficient also has been used to predict the internal pipe surface condition by analysing the acoustic signal emitted when knocking the two sample pipes, the rough pipe and smooth pipe surfaces [13]. This coefficient in another study was used to identify the three typical wear curves in a machining process for certain cutting parameters [24].

The new I-kaz multilevel coefficient ($^{L}Z^{\infty}$) which is more sensitive towards amplitude and frequency changes in a signal was developed base on the original I-kaz™ (Z^{∞}) [10, 25, 26]. The related I-kaz multilevel coefficient can be calculated as in Eq. (7):

$$^{L}Z^{\infty} = \frac{1}{n}\sqrt{K_1 s_1{}^4 + K_2 s_2{}^4 + K_3 s_3{}^4 \ldots + K_L s_L{}^4} \tag{7}$$

where K is the kurtosis, s is the standard deviation and L is the number of order of signal decomposition.

The purpose of this study is to identify the mechanical values of four different materials by analyzing the vibration and sound signal captured during the impact test. The signals will be analysed using I-kaz multilevel method.

METHODOLOGY

Design of experiment

In this impact test experiment, four rectangular bars were used, medium carbon steel S50C, brass, stainless steel AISI 304 and cast iron FCD 500 with the size of 250mm, 50mm and 10 mm for their length, width and thickness respectively.

Process parameters and their levels for this experiment are shown in Table 1.

Table 1: Process parameters and their levels

Materials	Medium carbon steel S50C	Brass	Stainless steel AISI 304	Cast iron FCD 500
Impact force (N)	0	0	0	0
	420	420	420	420
	640	640	640	640
	890	890	890	890
	1080	1080	1080	1080
	1290	1290	1290	1290

EXPERIMENTAL PROCEDURE

The experiment set-up is shown in Fig. 1. The mechanical properties of the specimens or work pieces are given in Table 2. The force applied during the impact was generated by an impact hammer model Endevco 2302-10 which was connected to the computer through the pulse analyzer to measure the magnitude of the force during the impact. Six different impact force, 0 N, 420 N, 640 N, 890 N, 1080 N and 1290 N will be applied on each material. A small size microphone model GRAS 40SC was placed 5 mm from the edge of the material to capture the sound signal. The microphone was connected to its amplifier module and then to the data acquisition equipment, NI PXI-1031DC. An accelerometer model DJB A/23/E was placed as far from the nodal point as necessary, to pick up the vibration signals during and after the impact. The experiment was conducted in an anechoic room and the procedure was in accordance with ASTM E1876 [27]. The specimen was elastically impacted by the impact hammer without plastic deformation at the impact area. The impact was located at the centre position of the test materials. The vibration, force and sound signals were recorded at the same time and stored in the computer. The signals stored in the computer were analysed using MATLAB to find the I-kaz multilevel coefficient values at the analysis stage.

RESULTS

Z-stem filter for removing unwanted modes

The transient sound radiation and vibration responses were obtained in this experiment and plotted brass cast iron FCD 500 as shown Figure 2 and Figure 3. The selected signals were based on 90 percent attenuation from the maximum amplitude of the signal. The time domain characteristics for both sound and vibration signals were similar for all materials, with high oscillation as a result of the dynamic response of the impact testing interaction between the hammer tip and the specimen surface.

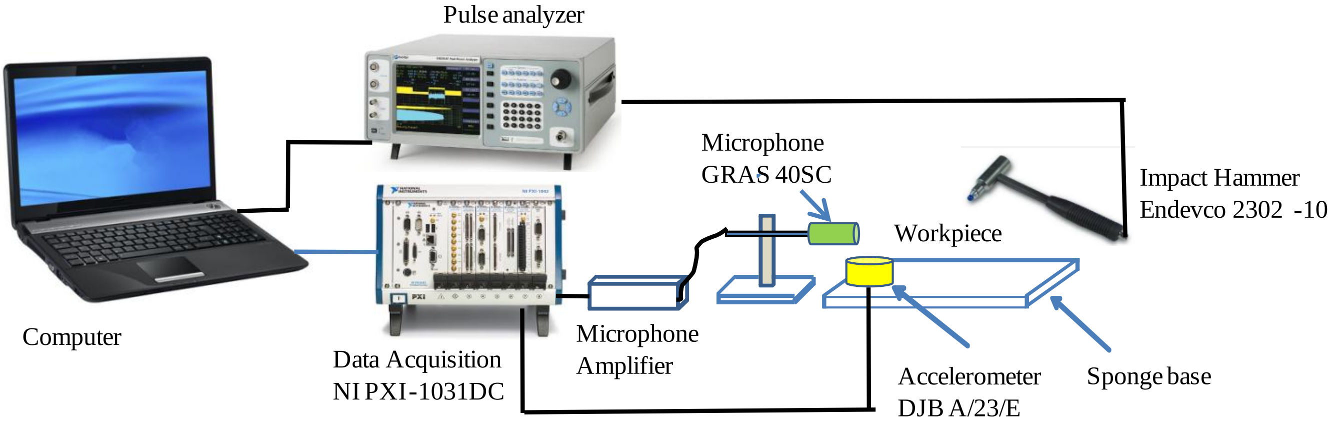
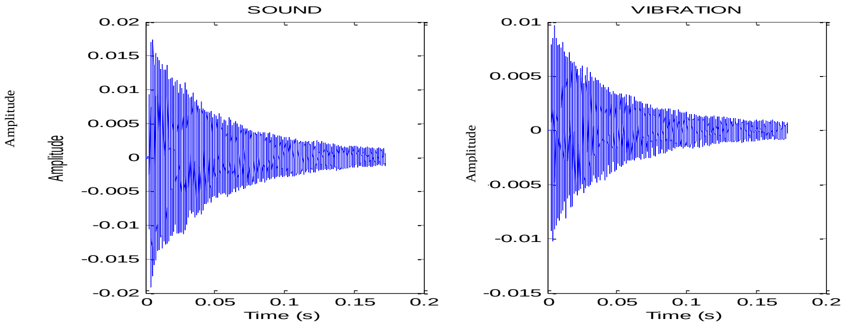


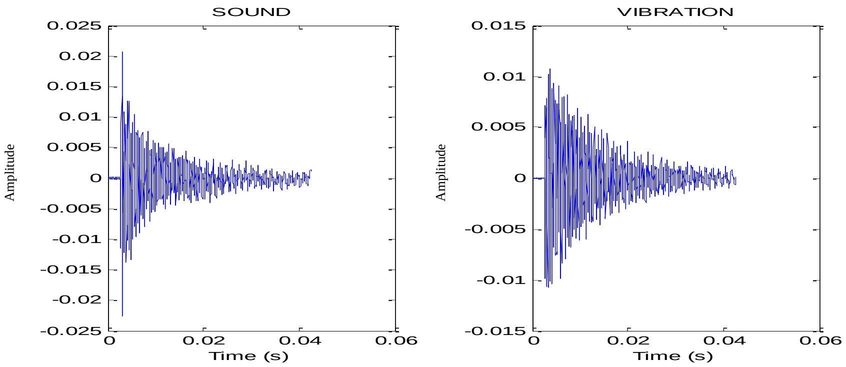
Figure 1: Experimental set-up

Table 2: Mechanical property of the specimens

Material	Poisson Ratio	Mechanical Loss Coefficient	Compressive Strength (Mpa)	Modulus of Rupture (Mpa)
Brass	0.345	5.74×10^{-4}	89.98	89.98
Medium Carbon steelS50C	0.290	8.80×10^{-4}	365.00	365.00
Stainless steel AISI 304	0.270	1.13×10^{-3}	257.52	257.52
Cast iron FCD 500	0.260	2.25×10^{-2}	164.99	95.01

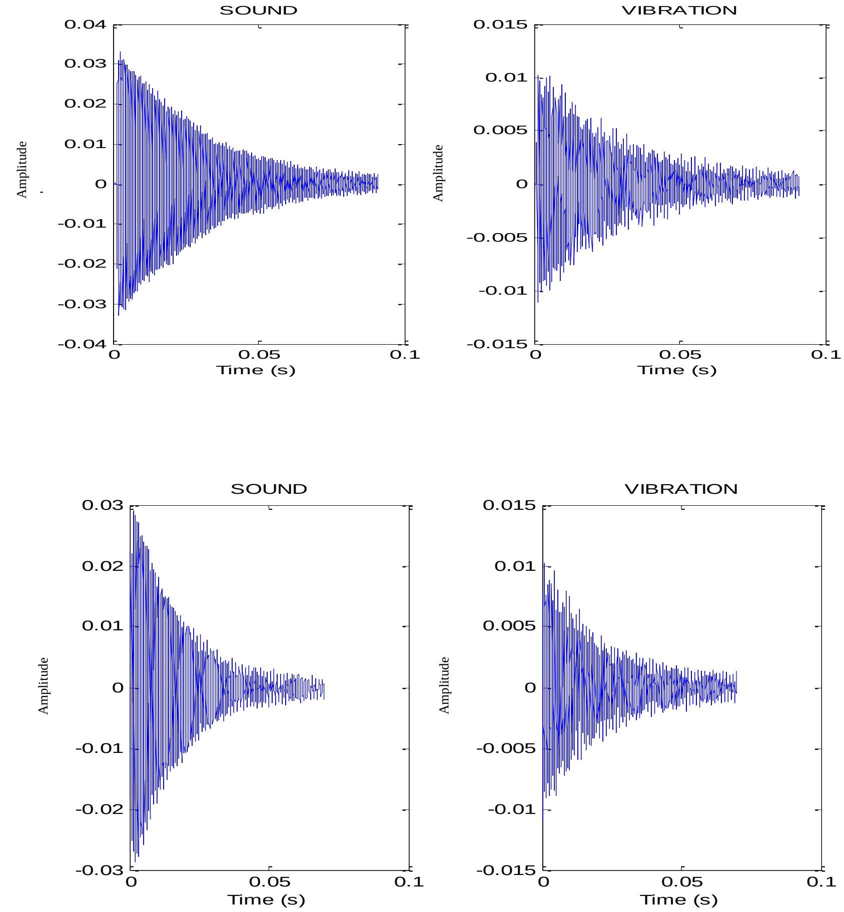


(a)



(b)

Figure 2: Time history record (a) brass; (b) cast iron FCD 500

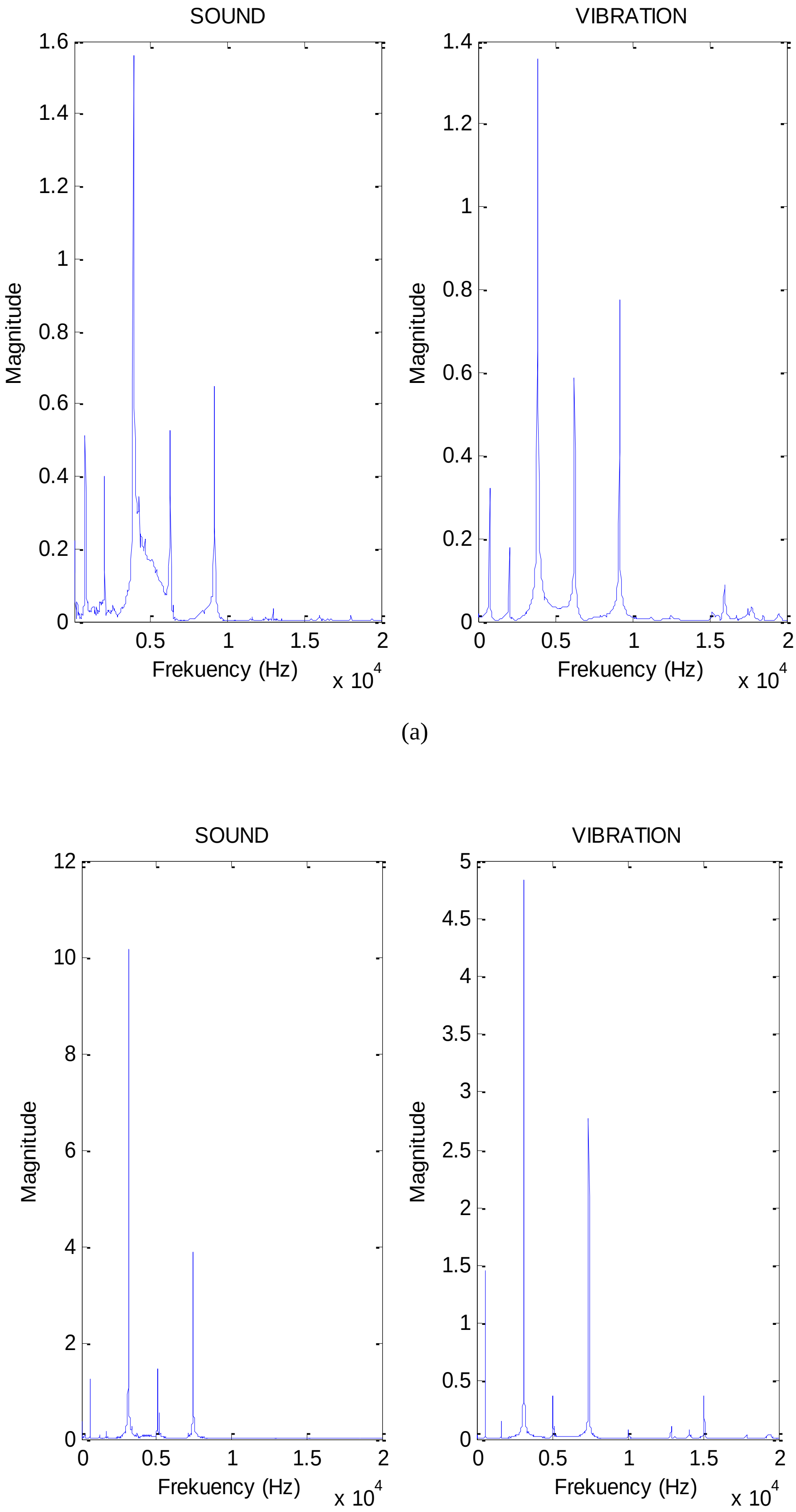


(a)

(b)

Figure 3: Time history record (a) medium carbon steel S50C; (b) stainless steel AISI 304

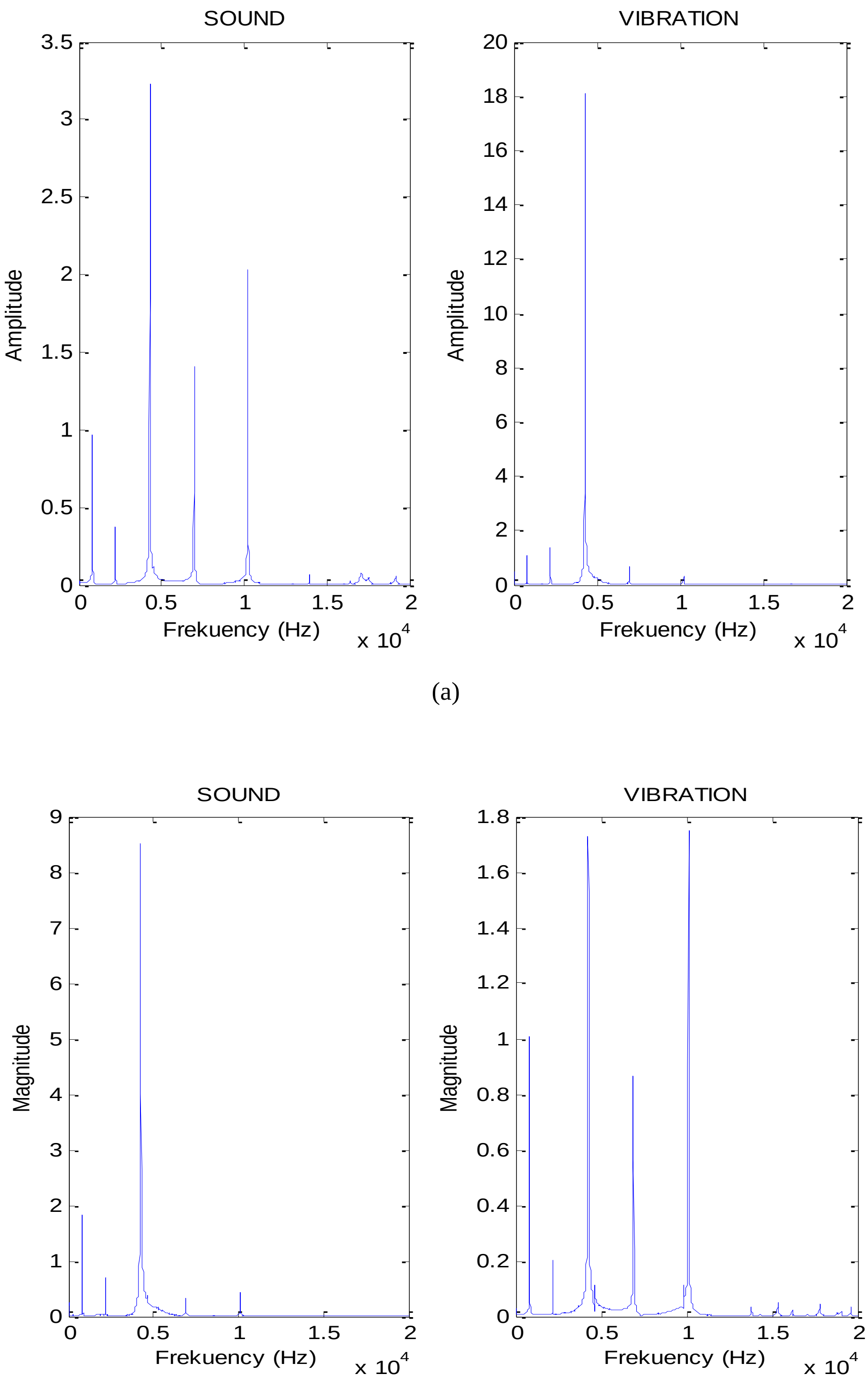
The plot of sound and vibration signals in the frequency domain after the Fast Fourier Transform (FFT) shows the same modes generated during the impact excited process (Figure 4 and Figure 5). However, different modes also exist between the sound and vibration signals for a particular material. These unwanted modes need to be filtered by treating the vibration modes as the reference to obtain a precise sound signal for analysis purposes.



(a)

(b)

Figure 4: Raw data plotted in frequency domain (a) brass; (b) cast iron FCD 500



(a)

(b)

Figure 5: Raw data plotted in frequency domain (a) medium carbon steel S50C; (b) stainless steel AISI 304

The Z-stem noise filtering technique was applied to remove the unwanted modes contained in the raw sound signal. In the case of the cast iron FCD 500, the five modes frequency components were retained in the filtered signal, as shown in Fig. 6 (a). The five frequencies of 750 Hz, 2025 Hz, 3875 Hz, 6275 Hz and 9175 Hz were unchanged by this filtration technique and maintained the same magnitudes, similar to the raw signal. This means that the unwanted noise frequency components were eliminated by the Z-stem noise filtering technique without eliminating the original frequency modes and the original amplitude of the signals.

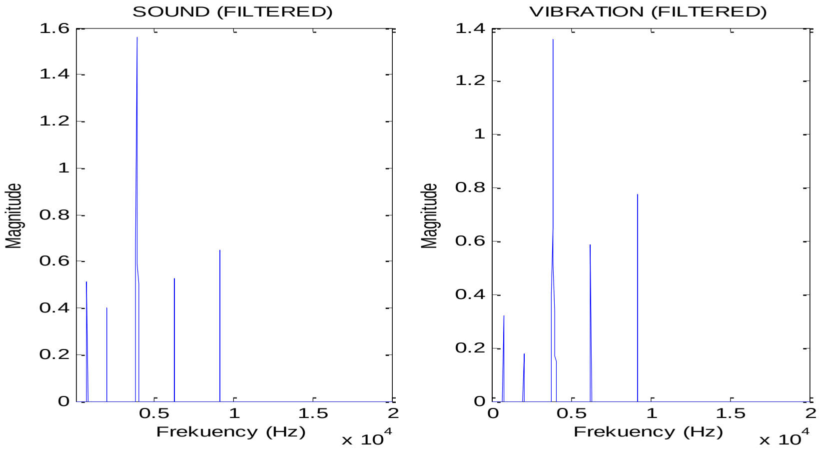


Figure 6: Filtered sound and vibration signals for cast iron FDC 500 in frequency domain

Table 3: Correlation coefficient of the raw and filtered signals for the materials

Material	Signal type	Correlation coefficient
Brass	Raw	-0.1239
	Filtered	0.9840
Cast iron FCD 500	Raw	-0.5913
	Filtered	0.9234
Medium carbon steel S50C	Raw	0.7944
	Filtered	0.8847
Stainless steel AISI 304	Raw	0.3956
	Filtered	0.8635

The correlation between the unfiltered and the filtered signals is important to quantify the effectiveness of the Z-stem filter technique. The value of the correlation coefficient, R, was calculated for the unfiltered and filtered signals. The smaller R value obtained for the signals in the correlation test means less similarity between the signals. Using Eq. (2), the R value of the raw and filtered signals for all test samples are shown in Table 3. The effectiveness of the Z-stem filter was quantified by the deviation between the filtered and raw signal against noise. The effectiveness for the medium carbon steel S50 is 0.4392. This effectiveness indicates that 43.92% of the overall unwanted noise had been removed from the raw signal.

I-kaz multilevel signal analysis for the filtered signals

The filtered vibration and sound signals were analysed using the I-kaz multilevel method as described in Eq. (7) to calculate the value of the coefficients for each data set. The coefficient values for each data set are shown in Table 4 and Table 5. It can be seen that as the impact force on the specimen increases, the I-kaz multilevel coefficient, ${}^{7}Z^{\infty}$, also increases.

Table 4: I-kaz multilevel coefficient (${}^{7}Z^{\infty}$) of the filtered vibration and sound signals for brass and cast iron FCD 500

Impact force (N)	Brass		Cast iron FCD 500	
	Vibration	Sound	Vibration	Sound
0	0	0	0	0
420	4.2232×10^{-10}	1.8222×10^{-9}	4.88×10^{-9}	8.43×10^{-9}
640	1.4884×10^{-9}	6.2744×10^{-9}	1.07×10^{-8}	1.86×10^{-8}
890	2.4679×10^{-9}	1.0178×10^{-8}	1.91×10^{-8}	3.12×10^{-8}
1080	2.9794×10^{-9}	1.2566×10^{-8}	2.01×10^{-8}	2.97×10^{-8}
1290	4.1459×10^{-9}	1.6202×10^{-8}	2.85×10^{-8}	5.48×10^{-8}

Table 5: I-kaz multilevel coefficient ($^7Z^\infty$) of the filtered vibration and sound signal for medium carbon steel S50C and stainless steel AISI 304

Impact force (N)	Medium Carbon steel S50C		Stainless steel AISI 304	
	Vibration	Sound	Vibration	Sound
0	0	0	0	0
420	1.35×10^{-9}	3.27×10^{-8}	1.8986×10^{-9}	3.02×10^{-8}
640	4.08×10^{-9}	1.01×10^{-7}	4.9234×10^{-9}	6.40×10^{-8}
890	6.72×10^{-9}	1.44×10^{-7}	8.4800×10^{-9}	1.52×10^{-7}
1080	8.37×10^{-9}	1.84×10^{-7}	1.0592×10^{-8}	2.03×10^{-7}
1290	1.27×10^{-8}	3.52×10^{-7}	1.5976×10^{-8}	2.98×10^{-7}

The value of coefficient $^7Z^\infty$ increasing with the increase of the force applied is similar to the other types of material under testing in this experiment. Vibration and sound amplitude increased as higher impact force was applied on the specimen. The I-kaz multilevel coefficient, $^7Z^\infty$ also increased as it is very sensitive to the small changes of amplitude in the vibration and sound signal. The increase of amplitude in vibration and sound signals are different from one material to another. Thus, the $^7Z^\infty$ values will also show different values depending on the type of material tested during the impact test. Referring to Table 3 and Table 4, at impact force equal to 640N, the values of $^7Z^\infty$ for the vibration signals are 1.4884×10^{-9} and 4.08×10^{-9} for brass and medium carbon steel S50C, respectively. This is because different materials have different mechanical properties and will respond differently towards impact force applied on their surface.

The plotted graphs of the I-kaz multilevel versus impact force for vibration and sound signals as shown in Figure 7 and Figure 8 were used to further investigate the relationship between the I-kaz multilevel coefficient ($^7Z^\infty$) values and the impact force.

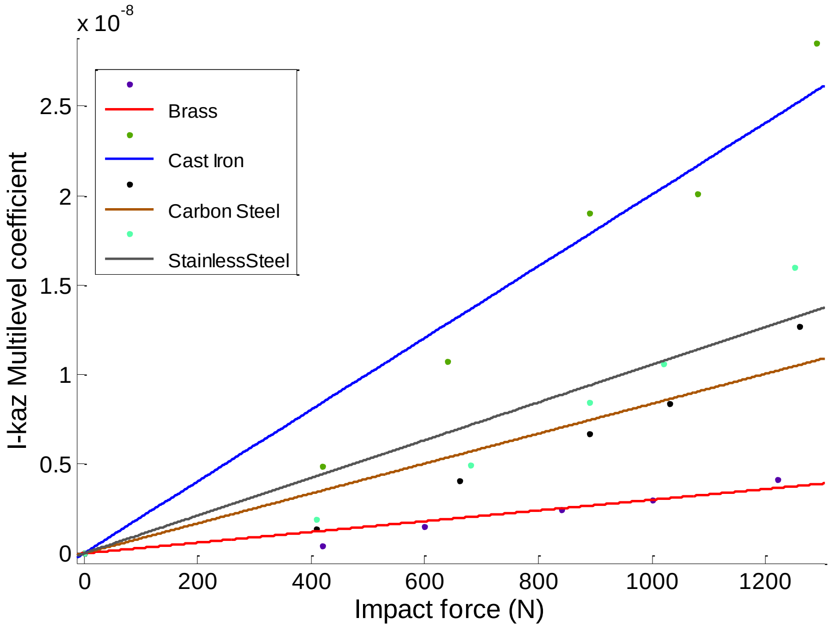


Figure 7: I-kaz multilevel coefficient for vibration signal vs. force

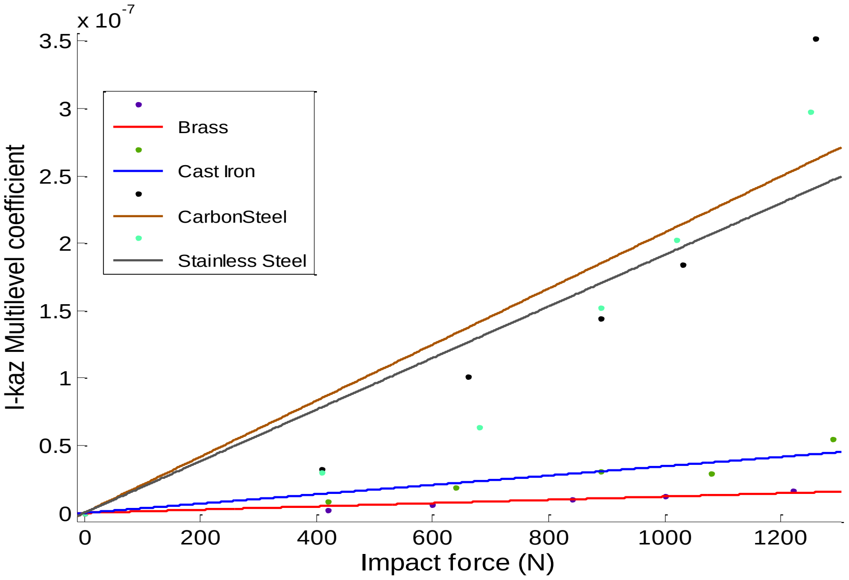


Figure 8: I-kaz multilevel coefficient for sound signal vs. force

Using the curve fitting tool feature in the MATLAB, both plots are identified as in the form of linear equations with the average R^2 values equal to 0.913 and 0.867 for vibration signals and sound signals respectively. The linear equations for vibration and sound signals for each type of material are as listed in Table 6 below. This table shows that different materials have different linear equations for both types of signal analysis on vibration signals and sound signals. From the above linear equation, it can be therefore concluded that the linear equation can provide a simple and effective method to study the relationship between the material mechanical properties versus the vibration signals and sound signals.

In comparing the material mechanical properties in Table 1 and the coefficient of linear equations in Table 6, two findings have been made. Firstly, the linear coefficient values for the vibration signals are directly related to the mechanical loss coefficients of the materials. Secondly, the linear coefficients for the sound signals are directly related to the compressive strength of the materials. These two findings are summarized in Table 7 and Table 8 as shown below.

Table 6: Curve fitting equation for vibration and sound signals

	Material	Linear Line Equation
Vibration	Medium carbon steel S50C	$y = 8.360 \times 10^{-12}x$
	Stainless steel AISI304	$y = 1.054 \times 10^{-11}x$
	Cast iron FCD 500	$y = 2.005 \times 10^{-11}x$
	Brass	$y = 2.997 \times 10^{-12}x$
Sound	Medium carbon steel S50C	$y = 2.080 \times 10^{-10}x$
	Stainless steel AISI304	$y = 1.915 \times 10^{-10}x$
	Cast iron FCD 500	$y = 3.468 \times 10^{-11}x$
	Brass	$y = 1.219 \times 10^{-11}x$

Table 7: Linear coefficients of vibration signal and mechanical loss coefficients

Material	Linear coefficient	Mechanical loss coefficient
Cast iron FCD 500	2.005×10^{-11}	2.25×10^{-2}
Stainless steel AISI304	1.054×10^{-11}	1.13×10^{-3}
Medium carbon steel S50C	8.360×10^{-12}	8.80×10^{-4}
Brass	2.997×10^{-12}	5.74×10^{-4}

Table 8: Linear coefficients of sound signal and compressive strength

Material	Linear coefficient	Compressive strength (Mpa)
Medium carbon steel S50C	2.080×10^{-10}	365.00
Stainless steel AISI304	1.915×10^{-10}	257.52
Cast iron FCD 500	3.468×10^{-11}	164.99
Brass	1.219×10^{-11}	89.98

Base on the information in Table 7, the value of the linear coefficient increases proportional with the increase in the value of the mechanical loss coefficient. Materials with lower mechanical loss coefficients will produce lower linear coefficients whereas materials with higher mechanical loss coefficients will produce higher linear coefficients. The plot of mechanical loss coefficient versus linear coefficient is shown in Figure 9.

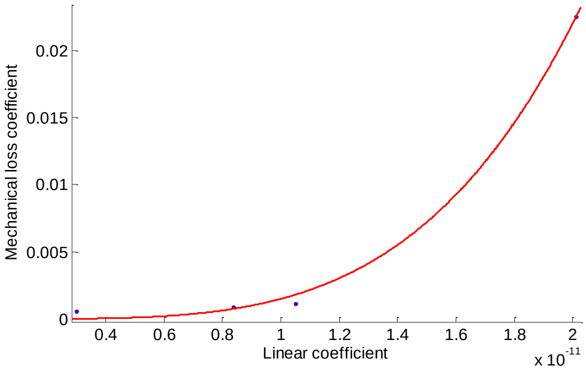


Figure 9: Mechanical loss coefficient vs. linear coefficient

The curve fitting in Fig. 9 is in the form of a power equation with the average R2 values equal to 0.9978. The graph was plotted using the power regression method because it is the simplest approach and it gives the highest value of R2. The relationship between mechanical loss coefficient and linear coefficient can be written as in Equation 8.

$$y = (7.994 \text{ X } 10^{39})\,(x)^{3.884} \tag{8}$$

where y is the mechanical loss coefficient and x is the linear coefficient. Equation 8 can be used to predict the value of an unknown mechanical loss coefficient of a material when the experiment is repeated using the same method on the material.

Table 7 shows the relationship between the linear coefficients of the sound signal and the compressive strength of the materials. As in Table 7, Table 8 also shows that the linear coefficients of the sound signals increase proportional with the increase in the value of the compressive strength. Materials having higher compressive strength values will produce higher linear coefficients and materials with lower compressive strength will produce lower linear coefficients.

From the information in Table 8, it can be therefore inferred that the use of the I-kaz multilevel signal analysis on the vibration and sound signals could characterized the mechanical loss coefficient and the compressive strength of the material, respectively. The plot of compressive strength versus linear coefficient is shown in Figure 10.

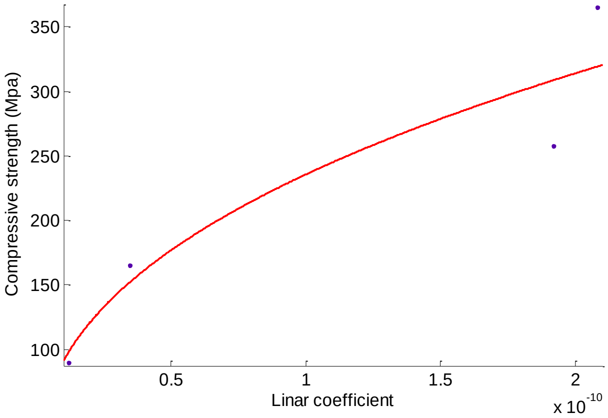


Figure 10: Compressive strength vs. linear coefficient

The curve fitting in Fig. 10 is in the form of a power equation with the average R^2 values equal to 0.8827. The power regression method was chosen to plot the graph since it is the simplest approach and it gives the highest value of R^2. The relationship between the compressive strength and the linear coefficient can be written as in Eq. (9).

$$y = (3.337 \text{ X } 10^{6})\,(x)^{0.4151} \tag{9}$$

where y is the compressive strength and x is the linear coefficient. Materials with unknown value of compressive strength can be predicted by using Eq. (9) when the experiment is repeated on the material with the same methodology. Similar finding was reported by Alfano, M. and Pagnotta in their study to identify the Poisson's ratio and the dynamic Young's modulus by analysing two of the first four frequencies of natural vibration in thin rectangular plates [28]. These results are also in agreement with the study done by M.Z. Nuawi et al. in determining the Poison’s ratio and thermal conductivity of materials by analysing the sound and vibration signals during impact test using Mesokurtosis Zonal Nonparametric Signal Analysis method [29].

CONCLUSION

In this paper, a new procedure is presented for the dynamic characterization of materials using the multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz multilevel) signal analysis. The procedure requires the measurement of transient sound radiation and the vibration response captured using a microphone and an accelerometer. The Z-stem signal filtering technique successfully removes noise or unwanted signals from the raw signals of sound and vibration. In the case of stainless steel AISI 304, noise removal effectiveness is 43.92%. The I-kaz multilevel signal analysis method was used to analyse the filtered signals of both sound and vibration. The experimental power curve equations of mechanical loss coefficient vs. linear coefficient and compressive strength vs. linear equation with R^2 value of 0.9978 and 0.8827, respectively, can be used to predict the unknown values of the mechanical loss coefficient and the compressive strength of a material. More accurate power regression equations could be achieved if more points are considered or more materials are tested in the impact test in plotting the prediction equation. Therefore, it can be concluded from these results that the use of the I-kaz multilevel signal analysis on vibration and sound signals could predict the mechanical loss coefficient and the compressive strength of a material, respectively.

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