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Material Mechanical Property Correlation Study Using Vibration Signal Analysis

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Abstract: The identification of material's specific mechanical properties can be achieved by analyzing its dynamic resonance or dynamic pulse response. This paper proposes a method to find the correlation between a specific material mechanical property and the specific coefficient ($^7Z^\infty$) by the application of an alternative statistical analysis method called Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz Multilevel). In this study, four rectangular bars with different materials were excited by impact test. An impact hammer was used as the impactor which connected to the pulse analyzer and then to the computer to measure the force applied during the impact. The test was conducted in an anechoic room and an accelerometer sensor was used to capture the vibration responses generated during the impact test. The signals were analyzed using I-kaz Multilevel signal analysis to determine value of $^7Z^\infty$ coefficients for each impact test for the four materials. The plot of I-kaz Multilevel coefficients versus impact forces reveals a quadratic curve with the average R squared values equal to 0.998. The coefficient value of the quadratic equation for each curve that represents each material can be used to correlate the mechanical loss coefficient of the material mechanical properties for vibration signal analysis.

Key words: Material mechanical property, I-kaz, correlation, vibration

INTRODUCTION

1.1. Elastic Properties of materials:

Elastic properties of materials can be determined by two different methods, static method and dynamic method. A dynamic method is a well known method and can be classified into two groups: resonance and pulse methods (Alfano and Pagnotta, 2006). Resonance methods consist of a sample which is set into mechanical vibration in various vibrational modes at various frequencies that produce resonance. The vibration is excited by drivers having continuously variable frequency output or by impact. The sample's vibration is captured using transducers which need be monitored and analyzed to determine the characteristic frequencies. Knowing the vibrational mode, frequency, dimensions and mass of the samples, the elastic constant of the material can be calculated (Radovic *et. al*., 2004). The pulse method is based on the time spent for the ultrasonic pulse to travel through the specimen from the transmitting to the receiving transducer or called transit time. Using the transit time for longitudinal and transversal ultrasonic waves together with the dimensions and the density of the samples, the shear modulus and the Young's modulus can be identified (Plachy *et. al*., 2009).

Recently, a great number of techniques for the identification of the mechanical properties particularly the elastics properties of both isotropic and orthotropic materials have been proposed. In these techniques, the measurements of acoustics and vibration signals were mainly used to identify the changes in the acoustics and vibration properties when the sample materials under study were applied under different experimental set-up (Najib *et. al*., 2011; Chunhua *et. al*., 2012). These methods however are involving expensive equipment, difficult set up and time consuming

This paper proposes an alternative method to correlate certain mechanical properties of material by the measurement of vibration signals from the impact test. This method is using fairly cheap equipment, simple calculation and most important is non-destructive. The new alternative statistical analysis method called Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz Multilevel) will be used to analyze the captured vibration signals. The calculated I-kaz Multilevel will be used to correlate with certain mechanical properties of the test materials.

1.2. I-kaz Multilevel method:

Signal features (SF) from captured signals in time domain need to be derived so that they can describe the signal adequately and maintain the relevant information (Teti *et. al*., 2010). Some common SFs that can be used for extraction from any time domain signal are average value, standard deviation, variance, skewness, kurtosis and root mean square (rms) (Sick *et. al*., 2002; Ghosh *et. al*., 2007; Dong *et. al*., 2006).

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For a signal with n-number of data points, the mean value $\bar{x}$ is mathematically defined trough equation 3 where x_i is the value of the data point. The mean value is one of the most important and often used parameters in indicating the tendency of the data toward the center.

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

The standard deviation value is given by :

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

Where x_i is the value of the data point and $\bar{x}$ is the mean of the data.

The signal 4th statistical moment, Kurtosis (*K*), is an important global signal statistic that is very sensitive to the spikeness of the data. The value of Kurtosis, for descrete data sets is defined in equation 5.

$$K = \frac{1}{ns^4}\sum_{i=1}^{n}(x_i - \bar{x})^4 \tag{3}$$

Kurtosis value was used frequently in industries in which defect symptoms can be identified due to its sensitivity towards the occurance of high amplitude (Pontuale *et. al*., 2003).

I-kaz™ coefficient was used in previous researches as the parameter to analyze the flank wear during turning process for tool wear prediction purpose (Ghani *et. al*., 2011). Nuawi *et. al*. (2009) in his study used I-kaz™ for the correlation of structure-borne acoustic signal and internal piping surface condition to differentiate between the smooth and rough pipe surface.

The development of I-kaz Multilevel coefficient ($^{L}Z^{\infty}$) was inspired by the original I-kaz™ (Z^{∞}) which was pioneered by M.Z. Nuawi *et. al*. (2008). The new symbol used is $^{L}Z^{\infty}$, in which *L* is referring to the number of frequency bands in the signal decomposition.

The Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz Multilevel) coefficient ($^{L}Z^{\infty}$) is proven more sensitivity with the change of amplitude and frequency. The I-kaz Multilevel algorithm was summarized as presented in Fig. 1 (Z. Karim *et. al*., 2011).

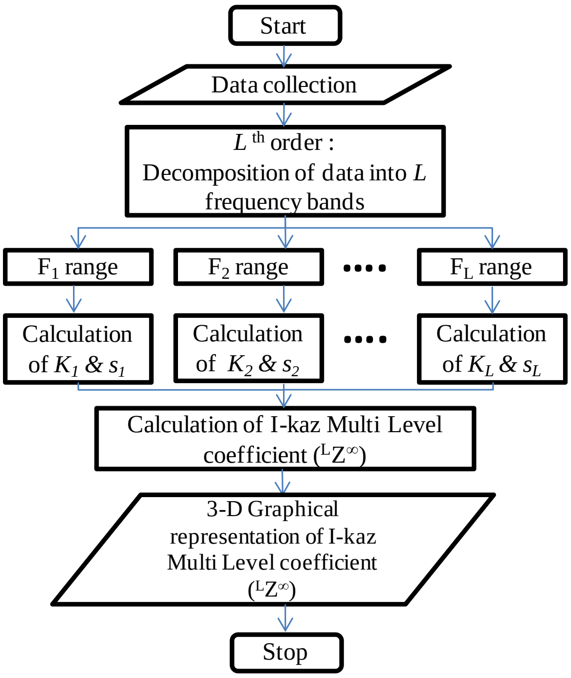


Fig. 1: Flowchart of the I-kaz Multilevel method

The related I-kaz Multilevel coefficient can be calculated as:

$$^{L}Z^{\infty} = \frac{1}{n}\sqrt{K_1 s_1^{\ 4} + K_2 s_2^{\ 4} + K_3 s_3^{\ 4} ... + K_L s_L^{\ 4}} \qquad (4)$$

Where *L* indicates the order of signal decomposition. The I-kaz coefficient $^{L}Z^{\infty}$, which is more sensitive than other I-kaz™ coefficient family can be used for analyzing dynamic signals (Z. Karim *et. al*., 2011).

Experimental Set-Up And Procedures:

The experimental set-up for this impact test study is shown in Fig. 2. This set-up uses four rectangular bars, brass, cast iron FCD 500, medium carbon steel S50C and stainless steel AISI 304 with a size of 250 x 50 x 10 mm (length x width x thickness). Table 1 shows the mechanical properties of the test materials. The impact during the test was generated using an impact hammer model Endevco 2302-10. The hammer was connected to the pulse analyzer and to the computer to measure the force applied during the impact. The vibration during the test was measured using an accelerometer model DJB A/23/E which was placed at the top end of the plate. The accelerometer was connected to the data acquisition box model NI PXI-1031DC and then to the computer system. The experiment set up was in accordance with ASTM E1876 and was conducted in an anechoic room (ASTM E1876). The specimen was impacted elastically at the center position without plastic deformation. The resultant force and vibration readings were recorded simultaneously and stored in the computer. A MATLAB computing software was used to analyze the captured data in the computer.

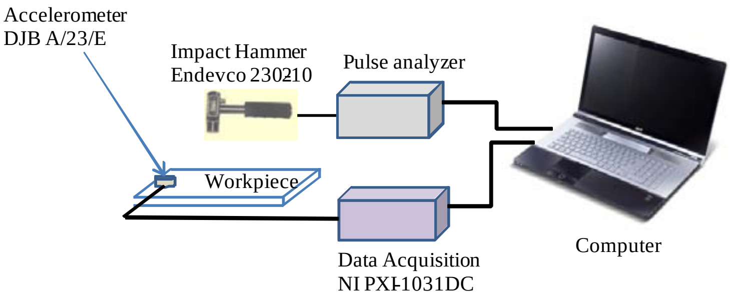


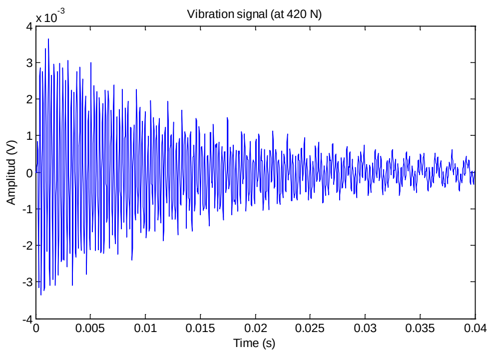
Fig. 2: Experimental Setup for the impact test

Table 1: Mechanical property of the specimens

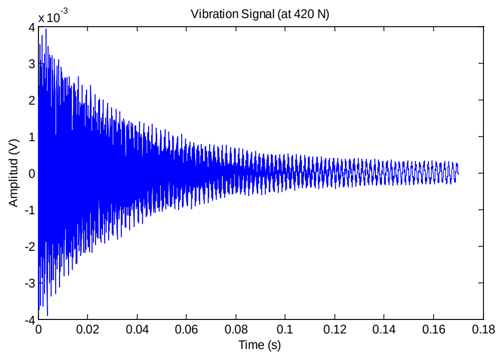
Material	Poisson Ratio	Mechanical Loss Coefficient	Compressive Strength (Mpa)	Modulus of Rupture (Mpa)
Brass	0.345	5.74×10^{-4}	89.98	89.98
Medium Carbon steel S50C	0.290	8.80×10^{-4}	365.00	365.00
Stainless steel AISI 304	0.270	1.13×10^{-3}	257.52	257.52
Cast iron FCD 500	0.260	2.25×10^{-2}	164.99	95.01

RESULTS AND DISCUSSION

I-kaz Multilevel signal analysis was performed on the filtered vibration signals. Eq. 4 was used to calculate the coefficient value for each set of data. Fig 3(a) and 3(b) show the plot of vibration signal in time domain and the I-kaz Multilevel coefficient values for cast iron and brass respectively. The calculated coefficients values for all values of forces and materials are presented in Table 2. It can be seen that the I-kaz Multilevel coefficient increases with the increases of the impact force excited on the specimen.



(a)



(b)

Fig. 3: Vibration signal (a) cast iron with calculated $^{7}Z^{\infty} = 9.52 \times 10^{-10}$ (b) brass with calculated $^{7}Z^{\infty} = 1.17 \times 10^{-10}$

Table 2: I-kaz Multilevel coefficient ($^7Z^\infty$) of the vibration for four type of materials at different force

Impact force (N)	Cast iron FCD 500	Stainless steel AISI 304	Medium carbon steel S50C	Brass
0	0	0	0	0
420	9.52×10^{-10}	3.66×10^{-10}	2.49E-10	1.17×10^{-10}
640	2.17×10^{-9}	1.00×10^{-9}	7.55E-10	2.83×10^{-10}
890	4.09×10^{-9}	1.74×10^{-9}	1.28×10^{-9}	5.30×10^{-10}
1080	5.81×10^{-9}	2.30×10^{-9}	1.72×10^{-9}	7.31×10^{-10}
1290	8.03×10^{-9}	3.54×10^{-9}	2.55×10^{-9}	$1.08\text{E} \times 10^{-9}$

From Table 2, the values of I-kaz Multilevel coefficients, $^7Z^\infty$, increase with respect to the increase in the force applied to the specimens. The increment trend of coefficient $^7Z^\infty$ to the increase of the force applied is consistent with every type of the material tested in this experiment. Higher impact force applied on the specimen will result in the increase of vibration amplitudes. The I-kaz Multilevel coefficient, $^7Z^\infty$ which is very sensitive in detecting amplitude change in a signal will therefore increase with respect to the increase in amplitude of vibration signals. The values of $^7Z^\infty$ calculated on vibration signals are also varies depending on the type of the material tested for the same range of force applied to the materials. For example, at impact force equal to 890N, the values of $^7Z^\infty$ for vibration signals are 4.09 $\times 10^{-9}$, 1.74 $\times 10^{-8}$, 1.28 $\times 10^{-9}$ and 5.30 $\times 10^{-9}$ for materials brass, cast iron FCD 500, medium carbon steel S50C and stainless steel AISI 304 respectively. This is due to the distribution of discrete values for a particular type of signal is at the different position for each different material.

The relationship between I-kaz Multilevel coefficient ($^7Z^\infty$) values and the impact force was further analyzed by plotting two different graphs of I-kaz Multilevel versus impact force for vibration signal.

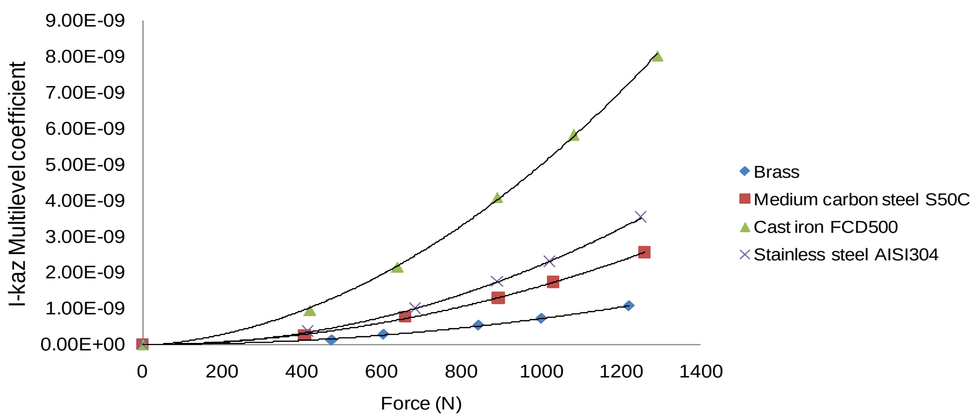


Fig. 4: I-kaz Multilevel coefficient for vibration signal vs. force

The curve fitting in the above figure is in the form of quadratic equation with the average R^2 values equal to 0.998. The quadratic equations for each type of material for the two different types of signals are summarized as in Table 3 below:

Table 3: Curve fitting equation for vibration

Material	Quadratic equation	R squared (R^2)
Medium carbon steel S50C	$y = 1.560 \times 10^{-15} x^2 + 5.540 \times 10^{-14} x$	0.999
Stainless steel AISI304	$y = 2.384 \times 10^{-15} x^2 - 1.585 \times 10^{-13} x$	0.999
Cast iron FCD 500	$y = 4.360 \times 10^{-15} x^2 + 6.400 \times 10^{-13} x$	0.999
Brass	$y = 7.492 \times 10^{-16} x^2 - 2.097 \times 10^{-15} x$	0.996

Table 3 shows that different materials have different quadratic equation for signal analysis on vibration signals. From the above quadratic equation, it can be therefore concluded that the quadratic equation can provide a simple and effective method to study the relationship between the material mechanical properties versus the vibration signals. Comparing between the material mechanical properties in Table 1 and the coefficient of quadratic equations in Table 3, one finding has been made. The quadratic coefficient values for vibration signals are directly related to the mechanical loss coefficient of the materials. This finding is summarized in Table 4.

Table 4: Quadratic coefficients of vibration signal and mechanical loss coefficients

Material	Quadratic coefficient	Mechanical loss coefficient
Cast iron FCD 500	4.360×10^{-15}	2.25×10^{-2}
Stainless steel AISI304	2.384×10^{-15}	1.13×10^{-3}
Medium carbon steel S50C	1.560×10^{-15}	8.80×10^{-4}
Brass	7.492×10^{-16}	5.74×10^{-4}

Base on the information in Table 4, the value of quadratic coefficient increases in quadratic with the increase in the value of mechanical loss coefficient. Material with lower mechanical loss coefficient will produce lower quadratic coefficient whereas material with higher mechanical loss coefficient will produce higher quadratic coefficient. From the information in Table 4, it can be therefore inferred that the use of I-kaz Multilevel signal analysis on the vibration signals could characterized the mechanical loss coefficient of the four different material respectively.

Conclusion:

In this paper, a new procedure is presented in finding the correlation of specific mechanical material property using Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz Multilevel) signal analysis. The measurement of transient vibration response captured using the accelerometer produce I-kaz Multilevel coefficient. The plot of I-kaz Multilevel coefficient versus impact force revealed quadratic curve for each material. In the I-kaz Multilevel coefficient for vibration signal versus force curves, the value of quadratic coefficient can be correlated with one of the materials mechanical properties. Thus, it can be concluded that the use of I-kaz Multilevel signal analysis on vibration signals can produce a strong correlation to the mechanical loss coefficient of the material mechanical property. This result is in the agreement with the quadratic coefficient value and mechanical properties of the materials presented in Table 4.

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