Modulus of Rupture Correlation Study by Acoustic Signal Analysis during Impact Test

Z. Karim, A.Y.M. Said, A.S. Ramli, A.R. Bahari, J.A. Ghani, M.Z. Nuawi

Abstract—**The identification of material's specific mechanical properties can be achieved through a series of standardized mechanical tests. This paper proposes a method to find the correlation between modulus of rapture 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, 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 impact test was performed on four rectangular bars with different materials but with the same dimension. The test was conducted in non-echoing or echo-free room and a microphone used to capture the acoustic 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 on the acoustic signal versus impact forces reveals a linear line with the average R squared values equal to 0.998. The coefficient value of the linear equation for each plot can be used to correlate the modulus of rupture of the material mechanical properties for acoustic signal analysis.**

Index Terms—**Material mechanical property, I-kaz Multilevel, correlation, acoustic**

I. Introduction

The mechanical properties of a material show how it reacts to physical forces and it is determined through a series of standardized mechanical tests. The tests have been documented by the respective user communities and published through ASTM International. These test however require expensive equipments and destructive.

This paper proposes an alternative method on characterization of materials by the measurement of acoustic signals from the impact test that apply simple method, fairly cheap equipment and non-destructive. The signal feature (SF) of the captured acoustic signals will be analyzed using the new alternative statistical analysis method called Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz Multilevel). The I-kaz Multilevel coefficients calculated from the signals will be used to correlate with certain mechanical properties of the test materials such as tensile strength, mechanical loss coefficient, density and modulus of rupture.

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 [1]. 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) [2-4].

For a signal with n-number of data points, the mean value $\overline{x}$ 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.

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

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 4[th] 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 3.

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

The kurtosis value for a normal or Gausian distribution is approximately 3.0. The presence of more extreme value or amplitude than should be found in a Gaussian distribution can be detected when the kurtosis value is higher than 3.0.

Kurtosis value was used frequently in industries in which defect symptoms can be identified due to its sensitivity towards the occurance of high amplitude [5].

I-kaz[TM] coefficient was used in previous research as the parameter to analyze the flank wear during turning process for tool wear prediction purpose [6]. Nuawi in his study used I-kaz[TM] for the correlation of structure-borne acoustic

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signal and internal piping surface condition to differentiate between the smooth and rough pipe surface [7].

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 [8]. The new symbol for I-kaz Multilevel coefficient is defined as $^{L}Z^{\infty}$ in which *L* is referring to the number of frequency bands in the signal decomposition.

The new developed Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz Multilevel) coefficient ($^{L}Z^{\infty}$) is expected to have more sensitivity towards amplitude and frequency change in a signal. In I-kaz Multilevel method, signal decomposition using L^{th} order of Daubechies theorem will result in *L* number of frequency bands. This algorithm is summarized as in Fig. 1 [9].

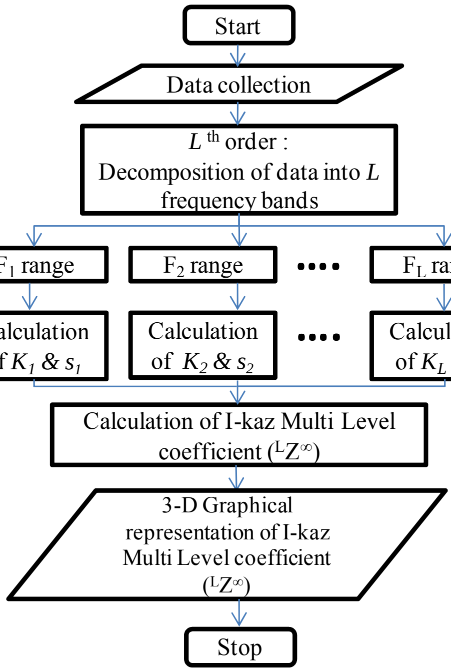

Fig 1: Flowchart of the I-kaz Multilevel method

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

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

Where *L* indicates the order of signal decomposition. The optimized level of I-kaz coefficient $^{L}Z^{\infty}$, which is more sensitive than the current I-kaz™ coefficient Z^{∞}, can be used for analyzing dynamic signals [14].

II. METHODS AND EXPERIMANTAL SET-UP

The experimental set-up for this study is shown in Fig. 2. This set-up consists of 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). The mechanical properties of the specimens or workpieces are given in Table I. An impact hammer model Endevco 2302-10 was used as the impactor. The hammer was connected to the pulse analyzer and to the computer to measure the force applied during the impact. A small size microphone model GRAS 40SC was placed 5 mm from the edge of the material to capture the acoustic signal during and after the impact. The experiment was conducted in an anechoic room and the procedure was performed base on ASTM E1876 [10]. The specimen was impacted elastically using the impact hammer at the center position without plastic deformation at an impacted area during the contact period. The resultant force and acoustic readings were recorded simultaneously and stored in the computer. Technical computing software, MATLAB was used to analyze the captured data in the computer.

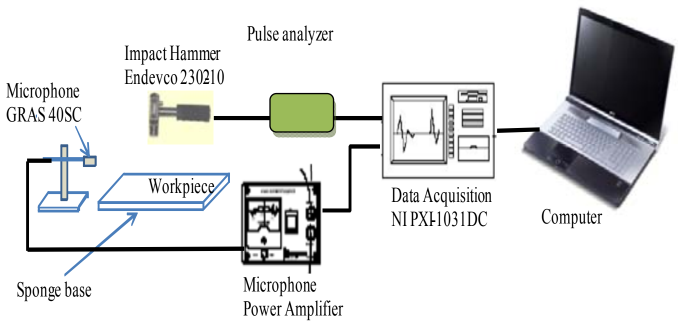

Fig.2: Experimental Setup for the impact test

Table I: Mechanical property of the specimens

[redacted]

III. RESULTS AND DISCUSION

I-kaz Multilevel signal analysis was performed on the filtered acoustic 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 acoustic 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 II. It can be seen that the I-kaz Multilevel coefficient increases with the increases of the impact force excited on the specimen.

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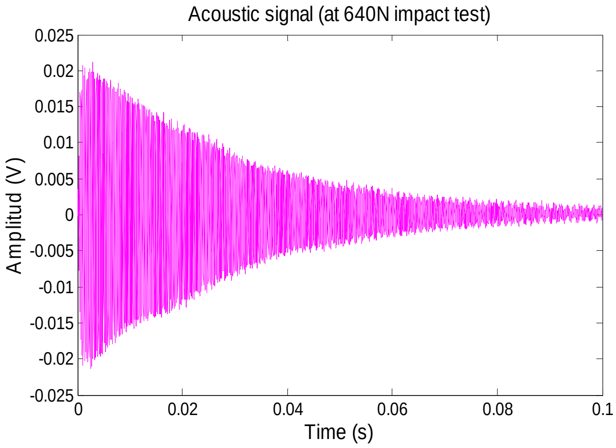
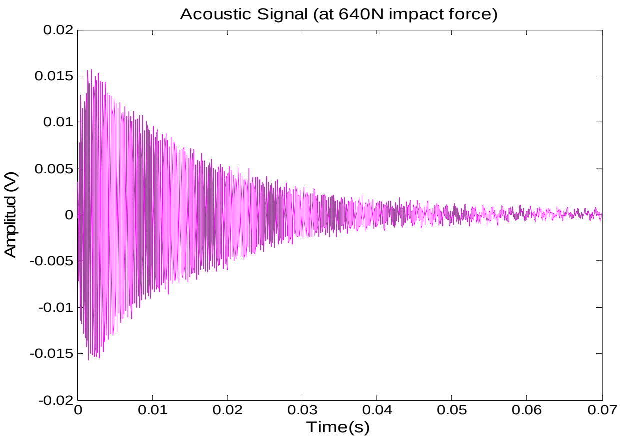


(a)



(b)

Fig 3: Acoustic signal in time domain
(a) carbon steel S50C with calculated ${}^{7}Z^{\infty} = 1.01 \times 10^{-7}$
(b) stainless steel AISI304 with calculated ${}^{7}Z^{\infty} = 6.40 \times 10^{-8}$

Table II: I-kaz Multilevel coefficient (${}^{7}Z^{\infty}$) of the acoustic signal for four types of materials at different force

	Impact force (N)					
	0	420	640	890	1080	1290
Brass	0	1.82×10^{-9}	6.27×10^{-9}	1.02×10^{-8}	1.26×10^{-8}	1.62×10^{-8}
Medium carbon steel S50C	0	3.27×10^{-8}	1.01×10^{-7}	1.44×10^{-7}	1.84×10^{-7}	3.52×10^{-7}
Cast iron FCD 500	0	8.43×10^{-9}	1.86×10^{-8}	3.12×10^{-8}	2.97×10^{-8}	5.48×10^{-8}
Stainless steel AISI 304	0	3.02×10^{-8}	6.40×10^{-8}	1.52×10^{-7}	2.03×10^{-7}	2.98×10^{-7}

From Table II, the values of I-kaz Multilevel coefficients, ${}^{7}Z^{\infty}$, increase with respect to the increase in the force applied to the specimens. The increment trend of coefficient ${}^{7}Z^{\infty}$ 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 acoustic amplitudes. The I-kaz Multilevel coefficient, ${}^{7}Z^{\infty}$ which is very sensitive in detecting amplitude change in a signal will therefore increase with respect to the increase in amplitude of acoustic signals. The values of ${}^{7}Z^{\infty}$ calculated on acoustic 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 ${}^{7}Z^{\infty}$ for acoustic signals are 1.02×10^{-8}, 1.44×10^{-7}, 3.12×10^{-8} and 1.52×10^{-7} for materials brass, medium carbon steel S50C, cast iron FCD 500 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 (${}^{7}Z^{\infty}$) values and the impact force was further analyzed by plotting a graph of I-kaz Multilevel versus impact force for acoustic signal as shown in Fig 4.

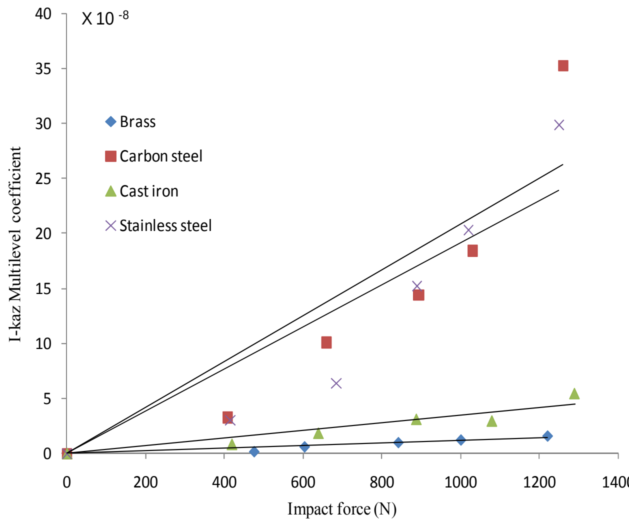


Fig 4: I-kaz Multilevel coefficient for acoustic signal vs. force

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

Table III: Curve fitting equation for acoustic signal

Material	Equation
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	$y = 1.219 \times 10^{-11}\, x$

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Table III shows that a different material has a different linear equation for the signal analysis on the acoustic signal. 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 acoustic signals. Comparing between the material mechanical properties in Table I and the coefficient of linear equations in Table III, one finding has been made. The linear coefficient values for acoustic signals are directly related to the modulus of rupture of the materials. This finding is summarized in Table IV.

Table IV: Linear coefficients of acoustic signal and modulus of rupture

Material	Linear coefficient	Modulus of rupture (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}	95.01
Brass	1.219×10^{-11}	89.98

Base on the information in Table IV, the value of linear coefficient increases in linear with the increase in the value of modulus of rupture. Material with lower modulus of rupture will produce lower linear coefficient whereas material with higher modulus of rupture will produce higher linear coefficient. From the information in Table IV, it can be therefore inferred that the use of I-kaz Multilevel signal analysis on the acoustic signals could characterized the modulus of rupture of the four different materials respectively.

IV. Conclusion

In this paper, a new procedure is presented for the dynamic characterization of material using Multilevel Integrated Kurtosis Algorithm with Z-notch Filter (I-kaz Multilevel) signal analysis. The procedure requires the measurement of acoustic signal captured using a microphone. The filtered signals of acoustic are used to be analyzed by I-kaz Multilevel signal analysis. The experimental linear equations of the I-kaz Multilevel coefficient for different materials have been plotted versus the applied force to determine the correlation to the mechanical properties of the test materials. In the I-kaz Multilevel coefficient for acoustic signal versus force curves, the value of linear coefficient can be correlated with the modulus of rupture of the materials. From this result, it can be concluded that the use of I-kaz Multilevel signal analysis on acoustic signals could characterized the modulus of rupture of the material respectively. This result is in the agreement with the mechanical properties of the materials presented in Table I.

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