Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 15 (1): 138-145, 2015
ISSN 1812-5654 / DOI: 10.3923/jas.2015.138.145

Characterisation of Polymer Material Using I-Kaz™ Analysis Method under Impact Hammer Excitation Technique

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Abstract: During the design and engineering applications, the characteristics of the material are regarded as one of the most significant aspects of the process. This is to prevent any component or structure failure. This study employs the implementation of a newly devised method for characterising the property of a material based on the non-destructive testing concept which uses vibrational signals. Experimental procedure was carried out by elastically triggering a specimen using an impact hammer following ASTM C 1259-01 standard within the specific range of impact force. The polymer material specimen tested were of four types: Polycarbonate (PC), Polyoxymethylene (POM), Polyvinyl chloride (PVC) and Cast nylon (MC). Data obtained involved three forms of signals which are vibrational signals recorded by accelerometer sensor, the vibration signal recorded by piezofilm sensor and the impact force signal using the impact hammer. An alternative statistical analysis of Integrated Kurtosis-Based Algorithm for Z-Filter (I-kaz^{TM}) method was used to analyse and interpret the time domain of vibrational signal obtained from the experiment. The results are two correlation processes between the material properties (Bulk modulus and hardness-Vickers) and the I-kaz^{TM}, Z^8 coefficients of vibration signal that are recorded by the piezofilm sensor and accelerometer sensor. The findings prove that there is a relationship between the I-kaz^{TM} coefficients of vibration signal and the properties of certain materials based on statistical analysis approach used in this study.

Key words: Material properties, vibration signal, statistical analysis, I-kaz^{TM} method

INTRODUCTION

Material characterization denotes a complete description of the structure and composition of a particular material. It involves an analysis of the properties of the material, the fabrication of the material and the usage of the said material (Groves and Wachtman Jr., 1986). An analysis on the properties of the material used is in designing and engineering applications is very vital as disastrous engineering failures could be avoided. Hence, a research on material characterization is vital so as to have a better understanding on the performance of materials. Therefore, the materials can be used in a variety of ways to bring out their utmost potentials (Tan *et al.*, 2011). A successful approach of this procedure relies upon:

- The information that is available on the analysis of material characterization using different methods
- Availability of equipment to carry out a particular method of material characterization
- In depth understanding of the process involved inthe application whereby only the characterization of materials which can be practically used in engineering materials are done

A basic analysis and advancement in materials characterization can contribute to the creation of new materials.

A lot of methods have been experimented to determine the elasticity of materials which is very important in designing and engineering applications. Generally the methods can be categorized into static methods and dynamic methods (Bunshan, 1971).

Static method relies upon direct measurements of strain and stress using standard mechanical tests of compressive, flexural tensile and tensional. The samples used for testing must be of a particular size and shape and Young's and Shear moduli can be ascertain from the slope of linear region of the stress-strain curve (Young and Budynas, 2002). Dynamic method is a constructive economic technique whereby the ease and

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straightforwardness in executing plus the accurateness of the stipulated findings caused it to be popular among the industries and researchers. Dynamic method can be divided into two techniques namely: Resonance technique means a sample is set in one or more mechanical vibration modes, at different frequency whereby the vibrations are at a maximum resonance (Nuawi *et al.*, 2013). Excitation is made by drivers with uninterrupted variable frequencies outputs or by impact (Alfano and Pagnotta, 2007). Transducers are utilized to monitor the vibrations of the sample and analyse them so that the characteristic frequencies of the sample can be identified. The elasticity of the sample material can be calculated if the vibrational mode, frequency, dimension and mass of the sample is known (Radovic *et al.*, 2004).

Pulse technique depends on transit time which is the time taken by the ultrasonic pulse to pass through the sample from the transmitting transducer to the receiving transducer.

This study highlights the dynamics of material characterization by measuring the vibration signals from an impulsive excitation test. It gives a detailed explanation on the set-up and process involved.

METHODOLOGY

Experimental design and process: An experiment was carried out using four kinds of polymers namely Cast nylon (MC), Polycarbonate (PC), Polyvinylchloride (PVC) and Polyoxymethylene (POM). The shape and measurement of the sample is in accordance to the American Society for Test and Material ASTM C 1259-01 standard (ASTM C 1259-01, 2001). A disc shaped sample which was 120 mm in diameter and 20 mm thickness were used. Table 1 shows the specifications of sample materials tested in compliance with the Cambridge Engineering Selector software CES-2011. Figure 1 shows the lay out of the experimental design which was made of a piezofilm sensor, an accelerometer sensor and an impact hammer and data acquisition device to measure force of impact and vibration signals. The experiment had to be carried out in a semi anechoic room. The accelerometer sensor and piezofilm sensor were placed in contact with the test sample. The centre of the sample was banged at specific range of applied force (200-300, 300-400, 400-500, 500-600, 600-700, 700-800, 800-900 and 900-1000 N) using an impact hammer. The resulting force of impact and vibration readings were noted concurrently.

Table 1: Material properties

Materials	Young's modulus (GPa) CES	Shear modulus (GPa) CES	Poisson's ratio (μ) CES	Bulk modulus (GPa) CES	Hardness-vickers (HV) CES
Polycarbonate (PC)	2.060	0.736	0.40	3.70	19.7
Polyoxymethylene (POM)	3.128	1.142	0.37	4.50	19.6
Polyvinylchloride (PVC)	2.793	1.004	0.39	4.80	13.1
Cast nylon (MC)	2.610	0.967	0.35	3.80	27.1

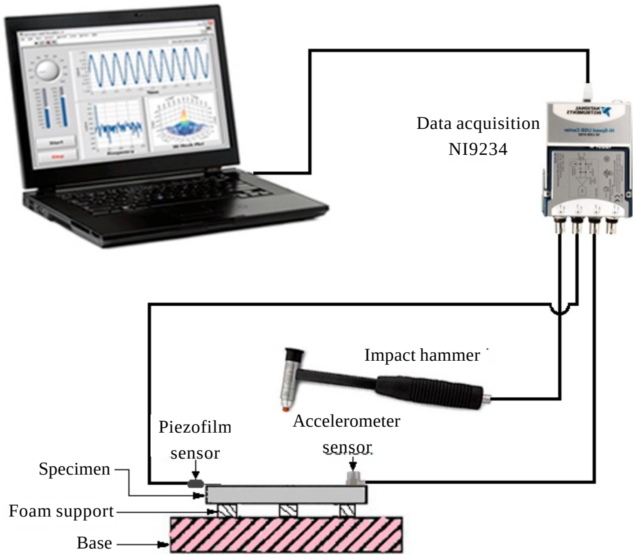

Fig. 1: Schematic of the experimental design

I-kaz™ analysis method: The statistical analysis of Integrated Kurtosis-Based Algorithm for Z-Filter (I-kaz™) technique is constructed on the theory of scattering data to a central value (Nuawi *et al*., 2008). The time domain of a signal or any data of time series is divided into three frequency range as illustrated in Fig. 2.

Three frequencies ranges as set on the three axis of graphical representation of I-kaz are:

- **X-axis:** Represents Low Frequency (LF) range of 0 - 0.25 f_{max}
- **Y-axis:** Represents High Frequency (HF) range of 0.25 f_{max}-0.5 f_{max}
- **Z-axis:** Represents very high frequency (VF) range of 0.5 f_{max}-f_{max}

f_{max} denotes the maximum frequency set in the signal measurement. Specifically, this value is half of the sampling frequency used during the process of recording a signal built on the sampling theorem (Figliola and Beasley, 2001). Equation 1 shows the degree of dispersion of the data measured using the variance parameters σ^2:

$$\sigma_L^2 = \frac{\sum_{i=1}^{N}\left(x_i^L - \mu_L\right)^2}{n}; \sigma_H^2 = \frac{\sum_{i=1}^{N}\left(x_i^H - \mu_H\right)^2}{n}; \sigma_V^2 = \frac{\sum_{i=1}^{N}\left(x_i^V - \mu_V\right)^2}{n} \quad (1)$$

While Eq. 2 shows how the I-kaz coefficient, Z^∞ is calculated:

$$Z^\infty = \sqrt{\frac{\sum_{i=1}^{N}(X_i^L - \mu_L)^4}{n^2} + \frac{\sum_{i=1}^{N}(X_i^H - \mu_H)^4}{n^2} + \frac{\sum_{i=1}^{N}(X_i^V - \mu_V)^4}{n^2}} \quad (2)$$

N is the total number of data. x_i^L, x_i^H, x_i^V are the value of distinct data in low, high and very high frequency range, respectively at i-sample of time. $\mu||_L$, $\mu||_H$ and $\mu||_V$ are the corresponding mean value of distinct data at low, high and very high frequency ranges.

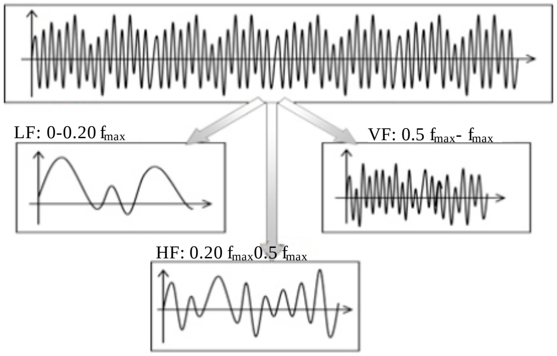

Fig. 2: Frequency range of I-kaz™ method source (Nuawi *et al*., 2008)

RESULTS AND DISCUSSION

The time domain of vibration signals collected from the accelerometer sensors and piezofilm are analysed using the Integrated Kurtosis-Based Algorithm for Z-Filter (I-kaz™) technique by observing the information characteristic contained in the signal. In comparison to previous study which use frequencies of the vibrations to characterise types of material such as metal, stones (Yoshida *et al*., 2010; Dos Santos *et al*., 2013) this study shows the I-kaz capability to characterise other different type of material which is polymer). Figure 3-6 show the transient vibration signal obtained from Polycarbonate (PC), Polyoxymethylene (POM), Polyvinylchloride (PVC) and Cast nylon (MC), respectively.

The value of I-kaz coefficient calculated using Eq. 1, has a low value of 10^{-4} to 10^{-5}. All I-kaz coefficients are multiplied by the power of 10^5. Table 2 display the values

Table 2: I-kaz coefficients of accelerometer and piezofilm sensors for PC, POM, PVC and MC

Impact force (N)	I-kaz coefficient Accelerometer (10^{-5})	I-kaz coefficient piezofilm (10^{-5})
PC		
0	0	0
221	0.48552	1.3181
320	0.97144	2.2422
425	1.3711	2.8498
524	2.1831	4.3349
640	3.0466	5.7816
731	4.0527	7.5518
838	4.5638	8.2480
987	5.0823	13.4650
POM		
0	0	0
221	0.6944	0.93796
325	1.5283	2.0424
431	2.1167	3.2843
520	3.0357	4.4415
620	4.3700	5.7397
730	4.9924	8.2245
817	5.7268	9.4745
917	6.4911	11.2880
PVC		
0	0	0
232	0.4123	0.50283
331	0.74795	0.79209
426	1.11	1.3338
536	1.5669	1.8857
631	2.3809	2.8917
725	2.8725	3.6435
828	3.2631	4.4317
934	4.7968	5.6863
MC		
0	0	0
224	0.60001	1.3055
324	1.1544	2.7975
425	1.7598	4.3811
538	2.2568	7.3499
634	3.2034	9.3257
713	3.7551	11.1160
826	4.5625	13.3340
905	4.8780	16.1370

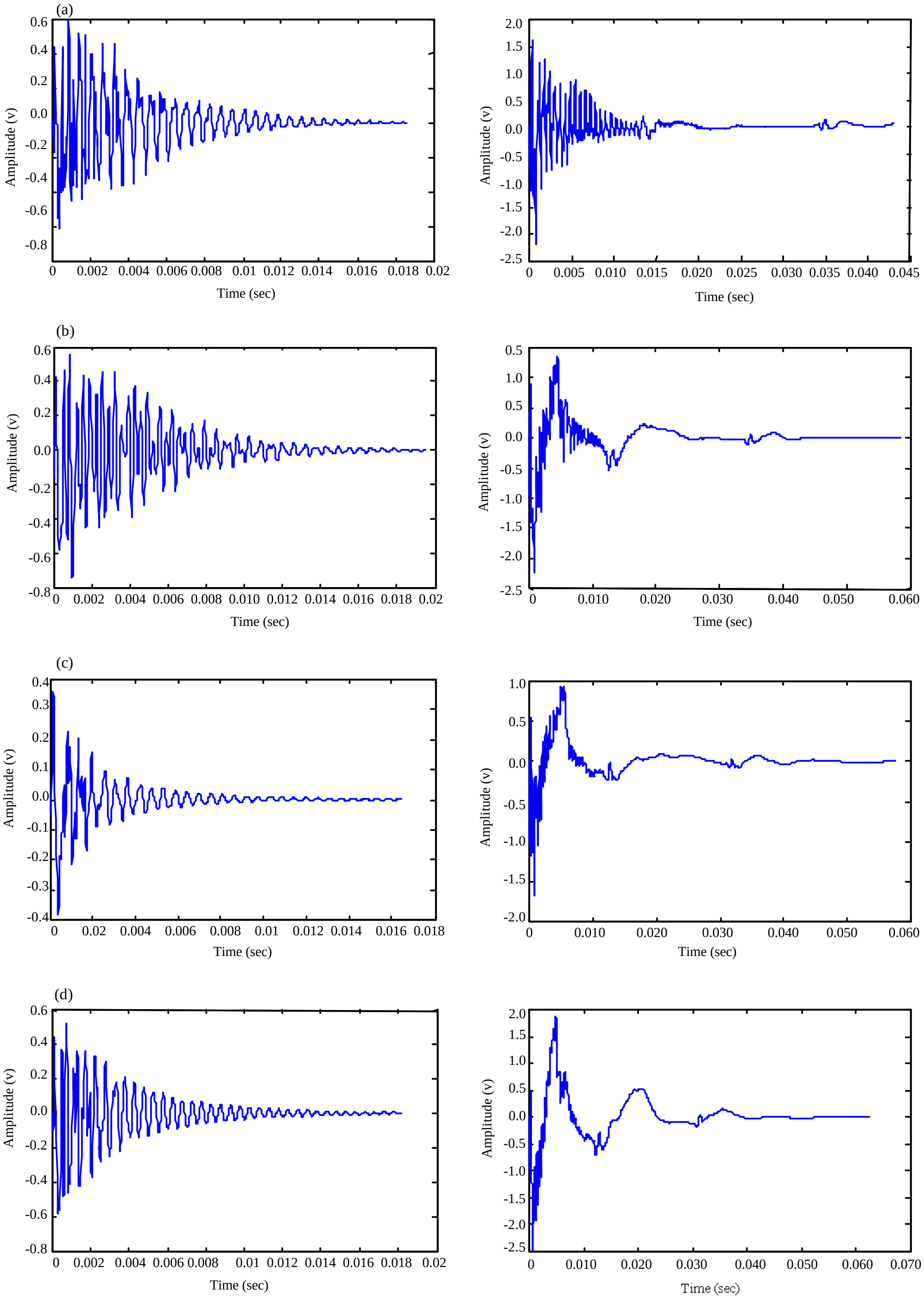

Fig. 3(a-d): Transient vibration signals of (a) Time domain Polycarbonate PC 987 N, (b) Polyoxymethylene POM 917 N, (c) Polyvinylchloride PVC 921 N and (d) Cast nylon MC 905

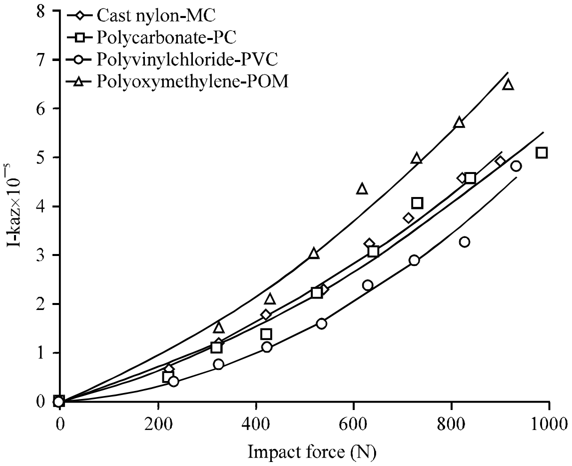

Fig. 4: I-kaz coefficient captured by accelerometer sensor against impact force

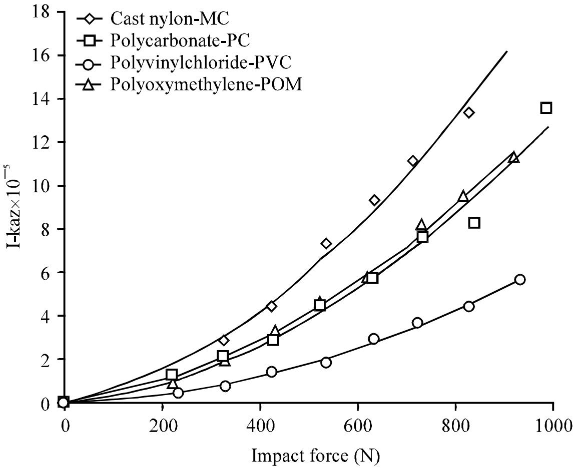

Fig. 5: I-kaz coefficient of piezofilm sensor against impact force

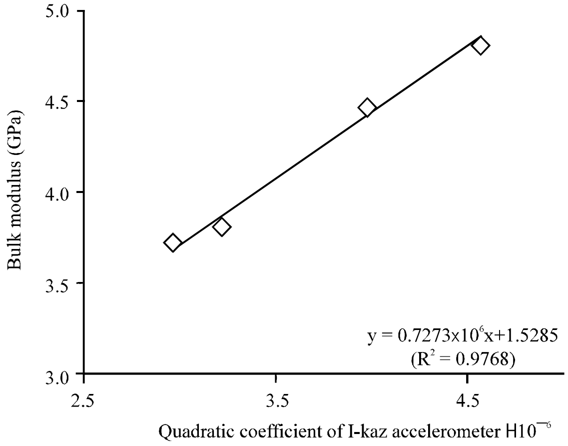

Fig. 6: Bulk modulus vs. I-kaz quadratic coefficient (accelerometer)

of I-kaz coefficient of vibration signal produced by the accelerometer sensor and piezofilm sensor for each type of polymer material and the corresponding impact force that had been used in the experiment.

Based on the findings, two important properties had been recognized. Firstly, the I-kaz coefficients of vibration signal which was captured by accelerometer and piezofilm sensors for all kinds of materials increased when the force of impact applied to the sample was increased. Secondly, the I-kaz coefficient of vibration signal for all types of materials at the same range of impact force were different from each other. This showed that the distribution of the vibration signals to the centroid was different for each type of material.

Figure 4 and 5 show the changes in the I-kaz coefficients of vibration signal captured by the accelerometer sensor and piezofilm sensor which were listed in Table 2 for four types of polymer materials.

A quadratic polynomial curve fitting was used for the calibration of I-kaz coefficients. All quadratic equations which resulted from quadratic polynomial curve fitting had a high value of correlation coefficients (R^2) that ranged between 0.974 and 0.998 which means a high precision of curve fitting. The quadratic equation and the value of its correlation coefficients (R^2) for accelerometer sensor is shown in Table 3 and for piezofilm sensor in Table 4.

The quadratic equation for each of the polymer material in Table 3 is for accelerometer sensor and Table 4 for piezofilm sensor. The difference between these quadratic equations (y = ax2+bx) can be characterized from its quadratic coefficient (a). The quadratic coefficient (a) denotes the degree of the curve curvature. The quadratic coefficient (a) of quadratic equations of I-kaz coefficients were examined in order to find out the relationship between the vibration signal of accelerometer sensor and piezofilm sensor and the mechanical properties of the materials. Hence, the quadratic coefficients of I-kaz curves were listed in ascending order. A comparison is made between quadratic coefficients (a) with the sequence arrangement of the material properties in Table 1. The sequence order of the quadratic coefficient of I-kaz of accelerometer sensor was similar to the sequence order of the bulk modulus of the materials. Apart from that, the sequence order of the quadratic coefficient of I-kaz of piezofilm sensor was similar to the sequence order of the hardness-Vickers of the materials. Table 5 shows the quadratic coefficient (a) of I-kaz vibration for accelerometer sensor and bulk modulus for the four types of polymer materials. Table 6 shows the quadratic coefficient (a) of I-kaz vibration for piezofilm sensor and Hardness-Vickers for the four types of polymer materials.

Table 3: Quadratic equation and quadratic coefficients (R^2) of accelerometer

Materials	Quadratic equation	Correlation coefficients (R^2)
Polycarbonate (PC)	$y = 2.9580\times10^{-6}x^2+2.6654\times10^{-3}x$	0.974
Polyoxymethylene (POM)	$y = 3.9394\times10^{-6}x^2+3.7617\times10^{-3}x$	0.987
Polyvinylchloride (PVC)	$y = 4.5704\times10^{-6}x^2+6.2135\times10^{-4}x$	0.987
Cast nylon (MC)	$y = 3.2252\times10^{-6}x^2+2.7223\times10^{-3}x$	0.993

Table 4: Quadratic equation and quadratic coefficients (R^2) of piezofilm

Materials	Quadratic equation	Correlation coefficients (R^2)
Polycarbonate (PC)	$y = 10.62\times10^{-6}x^2+2.3906\times10^{-3}x$	0.983
Polyoxymethylene (POM)	$y = 10.33\times10^{-6}x^2+3.1011\times10^{-3}x$	0.997
Polyvinylchloride (PVC)	$y = 5.810\times10^{-6}x^2+6.6368\times10^{-3}x$	0.998
Cast nylon (MC)	$y = 14.33\times10^{-6}x^2+4.9236\times10^{-3}x$	0.995

Table 5: Quadratic coefficients (α) and bulk modulus of materials for accelerometer

Materials	Quadratic coefficients (α)	Bulk modulus (GPa) from CES
Polycarbonate (PC)	2.9580×10^{-6}	3.7
Cast nylon (MC)	3.2252×10^{-6}	3.8
Polyoxymethylene (POM)	3.9394×10^{-6}	4.5
Polyvinylchloride (PVC)	4.5704×10^{-6}	4.8

Table 6: Quadratic coefficients (α) and Hardness-Vickers of materials for piezofilm

Materials	Quadratic coefficients (α)	Hardness-vickers (HV) from CES
Polyvinylchloride (PVC)	0.581×10^{-6}	13.1
Polyoxymethylene (POM)	1.033×10^{-6}	19.6
Polycarbonate (PC)	1.062×10^{-6}	19.7
Cast nylon (MC)	1.433×10^{-6}	27.1

Based on the data of Table 5 and 6, it can be seen that there are a relationship between the vibration signal of the accelerometer sensor and the bulk modulus and the vibration signal of the piezofilm sensor and the hardness-Vickers of the four tested of polymer materials. (In previous study, I-kaz characterise only young's modulus of metallic material (medium carbon steel S50C, stainless steel AISI 304, brass and cast iron FCD 500) (Nuawi *et al*., 2014) while this study expand the capability of I-kaz statistical analysis method to characterise other different material properties (bulk modulus and hardness-Vickers). The manner of the relationship is that the polymer which has highest bulk modulus and hardness-Vickers, will have the highest quadratic coefficient of I-kaz of vibration signal of accelerometer and piezofilm sensors. To obtain a mathematical expression for correlation between quadratic coefficient of I-kaz and bulk modulus and hardness-Vickers, the graph of the quadratic coefficient of I-kaz for four types of polymers, versus bulk modulus and hardness-Vickers has been plotted as shown in Fig. 6 and 7.

Based on Fig. 6, the polynomial linear trendline is chosen to matching the data. Linear equation for the linear trendline is of the form of (y = ax + b). Linear trendline is chosen because its correlation coefficient (R^2) has a good value of 0.9768. The mathematical expression for correlation process is based on a resulting linear equation of Fig. 6.

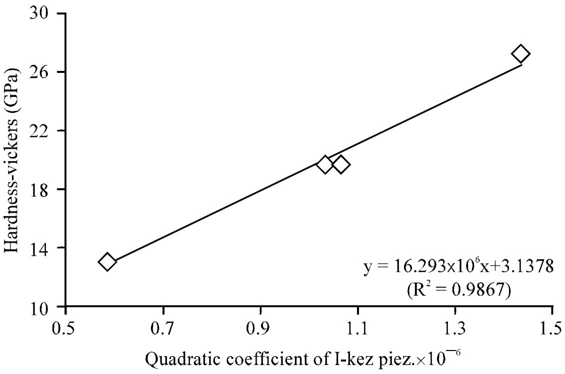

Fig. 7: Hardness-Vickers verse I-kaz quadratic coefficient (piezofilm)

$$y = 0.7273\times10^{6}x+1.5285 \tag{3}$$

By using Eq. 3, it can be conclude that the mathematical expression for correlation process between the vibration signal of accelerometer sensor and the bulk modulus is as the Eq. 4:

$$B = 0.7273\times10^{6}\ \text{(quardatic ficient of I-kaz of accelerometer)}+1.528 \tag{4}$$

While from Fig. 7, the linear equation ($y = 16.293\times10^{6}x+3.1378$) obtained from the linear trendline has a good value of correlation coefficient (0.9867) that can be depended for calibrating data. Based on the resulting equation the mathematical expression for correlation can be expressed as Eq. 5 below:

$$H = 16.293\times10^{6}\ \text{(quadratic coefficient of I-kaz of piezo film)}+3.1378 \tag{5}$$

Table 7 and 8 show the calculated bulk modulus and hardness-Vickers for all tested material from the correlation Eq. 4 and 5, respectively and the percentage error of these calculated properties were compared with the average value of Bulk modulus and hardness-Vickers

Table 7: Calculated bulk modulus and CES bulk modulus of tested materials

Materials	Bulk modulus (GPa) from correlation	Bulk modulus (GPa) from CES	Error (%)
Polycarbonate (PC)	3.68	3.70	0.54
Cast nylon (MC)	3.87	3.80	1.84
Polyoxymethylene (POM)	4.39	4.50	2.44
Polyvinylchloride (PVC)	4.85	4.80	1.04

Table 8: Calculated Hardness-vickers and CES Hardness-vickers of materials

Materials	Hardness-Vickers (HV) from correlation	Hardness-Vickers (HV) from CES	Error (%)
Polycarbonate (PC)	20.44	19.7	3.76
Cast nylon (MC)	26.49	27.1	2.25
Polyoxymethylene (POM)	19.97	19.6	1.88
Polyvinylchloride (PVC)	12.60	13.1	3.82

obtained from the Cambridge Engineering Selector software CES-2011. In compared to other studies which use the frequencies of the vibration signals to determine Young's modulus, shear modulus and Poisson's ratio (Alfano and Pagnotta, 2007; ASTM Standard E1876, 2007; Dos Santos *et al*., 2013; Radovic *et al*., 2004) this study contribute to expand the functionality of the frequencies of the vibration signals of the materials to characterise the other type of material properties which are hardness-Vickers and bulk modulus). The percentage error of the difference between the two values are ranged between (0.54-2.44%) which can be consider as an accepted value of error especially for engineering purposes.

CONCLUSION

The I-kaz coefficients for vibration signal that has been recorded in the experiment using the accelerometer and piezofilm sensors are obtained using I-kaz^{TM} method. It is found that the I-kaz coefficient for vibration signals increased when the specimen is subjected to higher impact and forms a quadratic curve y||ax2||bx. Through the characterization of quadratic curves and the properties of tested materials, it is found that there is a relationship between I-kaz coefficient of vibration signals that recorded by the accelerometer sensor and the bulk modulus and I-kaz coefficient of vibration signals that recorded by the piezofilm sensor and the hardness-Vickers of tested materials. However, the correlation expression in the form of a mathematical representation obtained for these two relationships. The mathematical expression for the correlation between the I-kaz of accelerometer vibration signal and the bulk modulus obtained is bulk modulus, B = 0.6842×106 (quadratic coefficient)+1.6963. While the mathematical expression for the correlation between the I-kaz of piezofilm vibration signal and the hardness-Vickers obtained is hardness-Vickers, H = 1.6388×106 (quadratic coefficient)+3.2889. The correlation equations of correlation processes can be used as standards for determining these properties through I-kaz^{TM} analysis of vibration signal.

ACKNOWLEDGEMENT

The authors wish to acknowledge ERGS/1/2013/TK01/UKM/02/2, for the research Grant.

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