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Data-Driven Impulse Excitation Technique via Statistical Signal Analysis for Determining Materials' Elastic Properties

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Abstract

Characterising materials' mechanical properties is vital in engineering applications to ensure the components' performance. This study emphasised the Impulse Excitation Technique (IET), a non-destructive dynamic testing to determine the materials' elastic properties. It comprised the standard resonant-frequency-measurement IET and alternative statistical signal data analytic method via Integrated Kurtosis-based Algorithm for Z-notch Filter (I-kaz™). The equipment included an impact hammer as an exciter, a piece of piezoelectric film patch as a sensor, a data acquisition device for signals recording, and six materials with the same geometry as samples. They comprised 6582 alloy steel, bronze, T250 cast iron, copper, P20 plastic mould steel and SKD-11 cold work tool steel. The experiment setup was designed based on ASTM E1876 standard for flexural test mode. Raw data were processed through MATLAB software, involving two different signals: impact nd vibration. I-kaz™ was utilised to decrypt the data statistically and generate a relationship by correlating the vibration and impulse signals with tabulated Young's Modulus of respective materials. The result indicated that the standard IET achieved a mean error value of 7.6%. In contrast, I-kaz is at 13.1% with approximately 5.5% differences. Although the latter was inferior, improvement could be done as it was driven and relied upon the exploited data. Obtain relevant features through multivariate analysis, adding more materials, and undergoing signal filtration in the pre-processed stage could remove irrelevancy and significantly boost the accuracy. Yet, this alternative method opens a new avenue to advance material characterisation and offering flexibility to researchers with an additional instrument for analysing data other than the standard IET.

1. Introduction

Material properties characterisation and criteria selection are vital in material science and engineering applications. Engineers need to consider a lot of factors when analysing and selecting materials. They are divided into six categories, namely mechanical, optical, electrical, magnetic, thermal, and deteriorative characteristics. Many aspects affect the material selection process; however, the most prominent are those describing a particular mechanical performance. It could be deciphered in terms of mechanical properties, which are essentially needed in any engineering design phase for a specific application, such as in the automotive industry. A good selection of these automotive components' materials enables designers to improve durability against load–bearing requirements while retaining necessary conditions or criteria such as lightweight, economical, safe, and recyclability [1]. The material's mechanical performance focusing on plasticity and elasticity could be derived empirically through static and dynamic methods.

Static methods depend on direct local stress and strain measurement during lab testing, such as four-point bending, nanoindentation, and tension or compression tests [2]. On the other hand, dynamic methods involve indirect measurement using transducers to acquire particular signals, such as sound and vibration. They were analysed using theoretical equations to reveal and quantify a specific mechanical property. The impulse excitation technique (IET) is a dynamic test that exploits the resonant frequencies of materials obtained from impulse response signals to determine the material's elastic properties. It is accomplished by tapping the material using an exciter to produce impulse while the sensor acquires the resultant response signals, which are collected as signal data. The data are processed using Fast Fourier Transform (FFT) to convert from time domain signal to spectral form in the frequency domain. Natural frequencies are identified by observing the spectra's peaks. The elastic properties of materials, such as Young's modulus, shear modulus, and Poisson's ratio, are determined by applying and deriving the Euler-Bernoulli beam theory. Despite the widespread use of static tests over dynamics in many industries, the latter has several advantages: cheaper equipment, quicker operation, simple experimental setup, and non-destructive nature [3]. Furthermore, the accuracy is high with uncertainty up to 0.1%, and temperatures-wise testing ranges from -50 to 1700 ℃ [4,5].

The rapid growth of technology and extensive practice of signals in various fields, including biomedical, geology and communication, have led to the advancement of signal processing. They allow practitioners to analyse, interpret, optimise, and modify signals to inspect components of interest. Over the decades, statistical parameters have been vastly utilised in signal analysis. The statistical signal analysis uses particular techniques to quantify data such as mean, kurtosis and covariance. The main advantage of statistical methods lies in their ability to decrypt and measure signals in particular phenomena with several levels of detail and decent understanding. To cope with the growth, an alternative statistical signal analysis method for non-deterministic signals was developed by Nuawi et al. [6], namely Integrated Kurtosis-Based Algorithm for Z-Notch Filter (I-kaz™). Afterwards, it has been optimised and utilised in several fields of study. For instance, Gao et al. [7] improved the accuracy of tool wear monitoring by incorporating the I-kaz with Kernel Extreme Learning Machine, with an increment of over 10% over other methods. Othman et al. [8] used I-kaz as the signal feature on pitch-hitting vibration signals for detecting automotive bearing defects and showed as high as 96% efficiency. The I-kaz method was also implemented in Magnetic Flux Leakage (MFL) by analysing the hall sensors' signals [9]. The result showed that it provided a good indicator and was suitable for detecting small changes of material lost for non-destructive tests (NDT).

Engineering problems are commonly solved using conventional experiments, physics-based solutions, and simulation models, such as the finite element method, as tools for material characterisation. As modern technologies grow exponentially, they open the door to a data-driven approach regarded as a fourth paradigm of science after empirical, theoretical and computational [10]. It utilises statistics, informatics and data analytics with related techniques and theories drawn from many fields to understand certain phenomena via the input datasets. Lately, there have been several attempts to adapt data-driven methods to impulse excitation-based techniques. The recent one by Shen et al. [11] introduced the integration of IET and comprehensive regression neural network to predict the coatings' elastic moduli and demonstrated high accuracy of determination coefficients between 0.958 and 0.979. Besides that, principal component analysis (PCA) was also implemented on acoustical response signals in spectral forms to classify materials' types by clustering visualisation, proving reliable [12]. In addition, there was also an attempt to correlate the materials' mechanical properties with statistical features extracted from impulse responses via sensor fusion technique, which was later verified with low uncertainties [13].

Hence, this study focuses on the alternative of characterising dynamic material's elastic properties by using impulse excitation and exploiting the I-kaz statistical analysis technique in the signal processing phase. Analytical data was realised by correlating the signal features with material properties and extracting relevant information. Piezoelectric film patch and impact hammer were used as sensors and exciters. Standard impulse excitation via natural frequency measurement was done to validate and compare the accuracy of the alternative technique. Detailed explanations of the setup and process are provided in the methodology section.

2. Methodology

The study's methodology was divided into three main parts: experimental setup and operation, standard resonant-frequency-measurement IET, and alternative statistical signal data analysis. Figure 1 shows the summarised process flow for the whole study. IET experimental design, configuration or layout system, and implementation with signal acquisition are in the first part. The second part involved converting time domain signals to frequency spectral forms, extracting the resonant frequency's first peak and calculating Young's modulus. Conversely, the final part included the I-kaz statistical signal analysis method, regression models through the correlation between statistical features with impulses and tabulated Young's modulus, and the estimation of Young's modulus via established mathematical models.

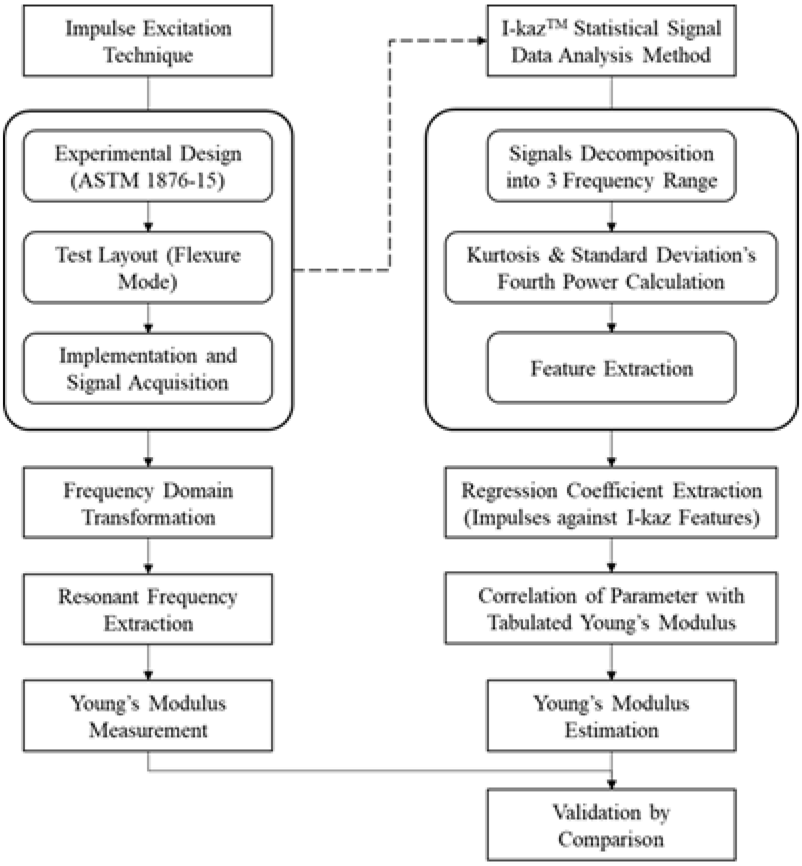

Fig. 1 *Process flow of the whole study*

2.1 Experimental Design and Operation

The experimental setup involved equipment comprised of a low-cost SDT1-028K piezoelectric film patch as a sensor, an impact hammer as an exciter and NI 9234 data acquisition device (DAQ). The sensor has a flat response in a wide frequency range with above 10 MHz of resonant frequency. Its preferred impedance is 10 MΩ, producing a 15 V minimum output voltage with 10 mΩ.

Six metallic materials were chosen as samples. They comprised 6582 alloy steel, bronze, T250 cast iron, copper, P20 plastic mould steel and SKD-11 cold work tool steel. All samples have the same geometry and shape: a rectangular bar with a dimension of 250 mm in length, 50 mm in width and 10 mm in thickness. The theoretical Young's modulus, designated as tabulated values of every material sample, was gathered using CES EduPack software. By referencing the available properties through the mill certificate for each material, an interpolation technique was done to get the approximate values of Young's modulus property, as the software only gave them in range.

For example, by taking alloy steel 6582 as an example, the mill certificate gave a value of 1337 MPa for tensile strength but with no value of Young's modulus. Fortunately, CES EduPack gave a range of value of 190 – 210 GPa for it, with 1200 – 1400 MPa of tensile strength. The interpolation formula is shown in Equation 1.

$$y = \frac{(y_2 - y_1)(x - x_1)}{x_2 - x_1} + y_1 \quad (1)$$

By assuming and inserting the unknown value of Young's modulus as y,190 and 210 GPa as y_1 and y_2, 1337 MPa of tensile strength as x, and 1200 and 1400 MPa as x_1 and x_2 in the formula, we will get as below.

$$y = \frac{(210 - 190)(1337 - 1200)}{(1400 - 1200)} + 190 = 203.70 \quad (2)$$

Thus, we get 203.70 GPa of Young's Modulus for the steel. The steps were repeated for other materials, and the tabulated properties and their mass are presented in Table 1.

Table 1 *Mass and theoretical Young's modulus of samples*

Material	Mass (kg)	Theoretical Young's Modulus (GPa)
Alloy Steel 6582	0.969	203.70
Bronze	1.050	78.80
Cast Iron T250	0.900	113.80
Copper	1.100	123.00
Plastic Mold Steel P20	0.980	205.80
Cold Work Tool Steel SKD-11	0.970	208.80

The samples were placed on the support before impact tests were carried out. The placement position of the support on the rectangular bar is at the node points of 0.224 L (L refers to the length of the specimen) from both ends of the samples. The excitation point was marked on the centre of the samples, while the sensor placement point was marked at one of the ends. These support and excitation positions activate the bending mode configuration, per ASTM E1876-15 standard [14]. It is because of the bending motion associated with flexural vibration. The material's fibres stretch and compress while it vibrates in this mode, which is related to its elastic properties.

Young's modulus describes the material's stiffness in response to stretching or compressing forces. At these points, samples will experience resonance with a constant zero displacement value. The position was fixed, and experiments were done in a non-resonant room to obtain accurate and precise measurements across each sample. The impact hammer and piezoelectric film patch were connected to the same DAQ but with a different channel. The apparatus was checked accordingly to ensure optimal condition before the test.

Figure 2 depicts the experimental design and operation. The sampling frequency was 25.6 kHz, with Nyquist frequency at 12.8 kHz. The frequency contents of the vibration signals were expected to be lower than 10 kHz. Thus, the chosen sampling rate could avoid the aliasing effect, which can severely distort the data and make them unreliable.

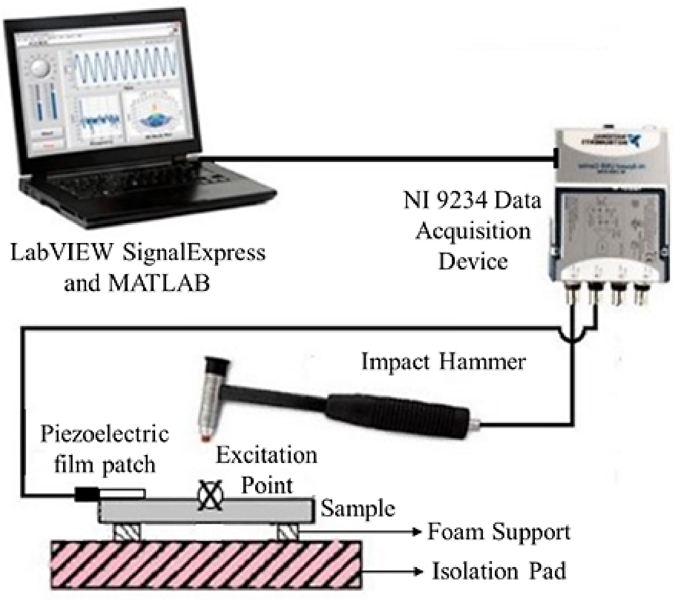

Fig. 2 *Setup and design of experiment*

The sample was tapped on its centre point using the impact hammer to excite and produce impulse signals. These were done repetitively within the specified range of 100 - 1100 N to make variations of excitation forces. The impulses exerted on the sample simultaneously created the vibration responses of the sample's structure as the output reaction. The piezoelectric patch sensed the waveform signals of the responses and subsequently sent them to DAQ, which was connected to a computer for signal conditioning and data acquisition.

The signal conditioning included the high-pass filter with a setting at 60Hz as the piezoelectric sensor was susceptible to that particular noise, which was a hum from the AC power line frequency. The monitoring and signal data recording of the impulses and responses were done using LabVIEW SignalExpress software and afterwards extracted in text files (.txt) for further analysis.

2.2 Standard Impulse Excitation Analysis

Conventionally, IET analysis requires the determination of resonant frequencies from particular vibration modes to calculate the desired elasticities of materials. This study's experiment setup and operation stimulated the flexural mode, which could be used to find the material's Young's modulus value. The acquired vibration response signals due to impulse excitation were directly analysed using Fast Fourier Transform (FFT). The first highest peak in the spectra distribution was the resonant or the natural frequency. It will be used to determine Young's modulus. The process used MATLAB programming software, which converted the time-domain signals into frequency-domain forms.

Equation 3 gives the elasticity property of a test piece with a pre-defined rectangular beam shape or bar vibrating in the flexure mode support.

$$E = 0.9465\left({mf_f^2}/{b}\right)(L^3/t^3)T \tag{3}$$

Where E is the Young Modulus, m is the mass, b is the width, L is the length, t is the thickness of the specimen, f_f is the resonant frequency in flexural mode, and T is the correction factor. Since the ratio of length to thickness of the sample is higher than 20 ($L/t \geq 20$), T is simplified and determined as follows.

$$T = 1.000 + 6.585({t}/{L})^2 \tag{4}$$

A comparison between theoretical, conventional and alternative IET was made to validate the efficiency of the applied methods.

2.3 Alternative Statistical Signal Analysis Method

Apart from relying on theoretical equations to find the material property, the other way was through manipulating and establishing the relationship between data by extracting relevant information and obtaining the mathematical models, which can be used to calculate the property. In this regard, the response signal data were initially subjected to the statistical signal analysis method of I-kaz™ to quantify them to descriptive statistics with meaningful values.

I-kaz™ emphasised the concept of signal data scattering and distribution in discrete time against a given centroid value. The signal amplitudes in the time domain were decomposed and separated into three frequency ranges and later combined for feature extraction. According to Nuawi et al. [6], the method could be simplified and presented as the I-kaz coefficient as in Equation 5.

$$Z^{\infty} = \frac{1}{n}\sqrt{K_L {s_L}^4 + K_H {s_H}^4 + K_V {s_V}^4} \tag{5}$$

K_L, K_H and K_V are the kurtosis values of low, high and very high frequency, while s_L, s_H and s_V are the standard deviation for each frequency band of decomposed signals, respectively. The distribution of the signals is as follows;

- Low frequency (L) range: 0 – 0.25 f_{max}
- High frequency (H) range: 0.25 – 0.50 f_{max}
- Very high frequency (V) range: 0.50 – f_{max}

Where f_{max} is the maximum frequency, half of the sampling rate, and the Nyquist is set to a value of 2. The calculation was done using MATLAB. Each response signal produced from impulse variations will have its I-kaz coefficient value representation.

The I-kaz coefficients depicted the statistical signal feature used in the study, whose values were used to build a relationship with the independent variable. Thus, a correlation was done between signal features and impulse forces to establish suitable regression through curve fitting for all the samples. Model equations for each sample derived from the correlation and fitting were acquired, and the regression coefficients were extracted as variables.

Each regression coefficient was paired with tabulated Young's modulus of the same material and afterwards correlated to bring out the final linear regression models. For each material of interest, that particular material's pair was excluded in the correlation phase. The established model will estimate Young's modulus of the excluded material by inserting the discarded regression coefficient value into the equation.

3. Result and Discussion

The result was organised into four sections: evaluating impulse and vibration responses, measuring elastic property via the conventional method (resonant frequency), predicting the property through I-kaz statistical parameters, and validating the outputs.

3.1 Impulse and Vibration Response Signals

Two types of data acquired: impulses due to the impact forces and response signals due to the emitted vibrations after excitations. Figures 3 and 4 illustrate the impulses and responses acquired at minimum and maximum values for alloy steel 6582. An impact force higher than the maximum designated value could cause the sample to bounce and fall from the support, making the piezoelectric film detach from the mounting position and simultaneously giving an inaccurate reading.

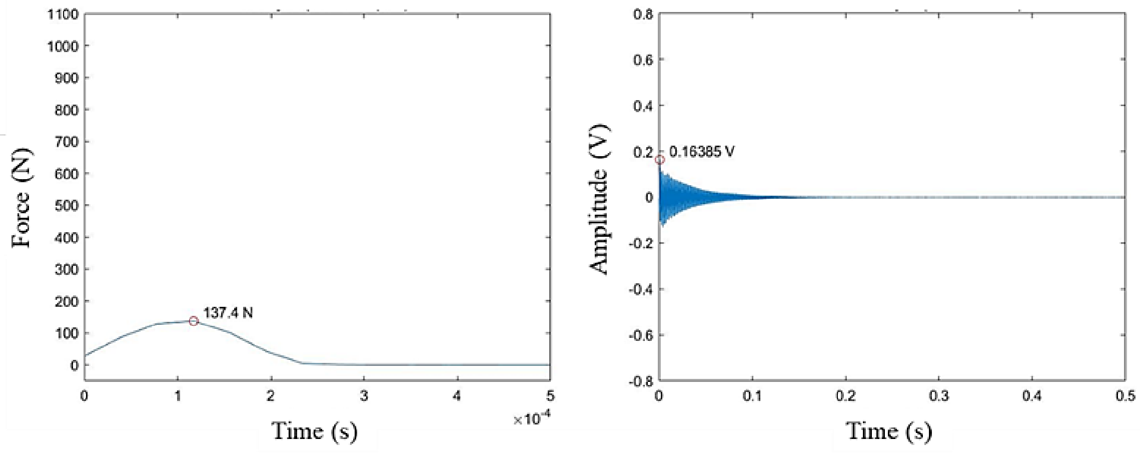

Fig. 3 *Impulse and response signal at minimum impact force*

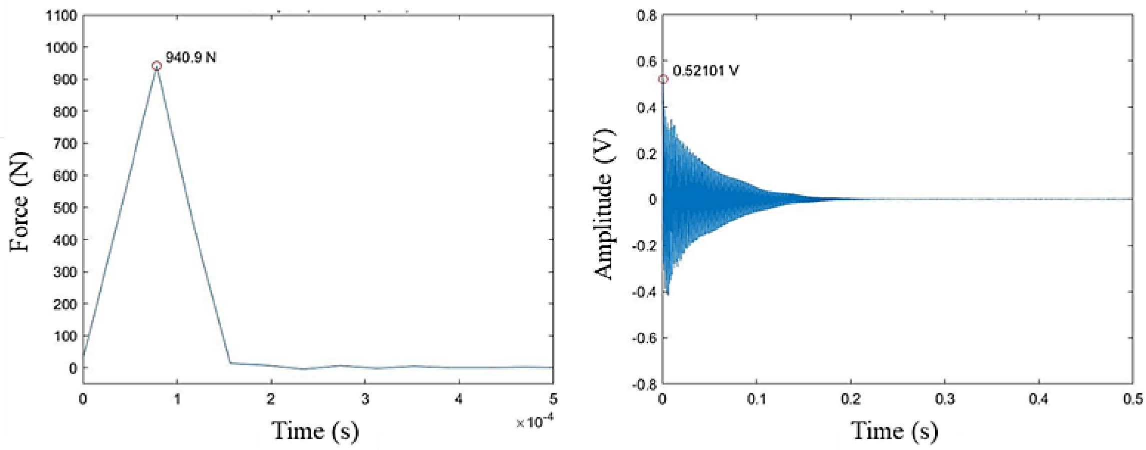

Fig. 4 *Impulse and response signal at maximum impact force*

The impulses implied brief input signals, which increase to peak value and decrease to zero drastically in a short period. Likewise, the vibration responses exhibited transient signals in an exponential decay form, starting with maximum amplitude and attenuating to zero over time. The lowest data set describes the impact force at 137.4 N with a response signal of 0.16385 V maximum amplitude. On the other hand, the highest set shows 940.9

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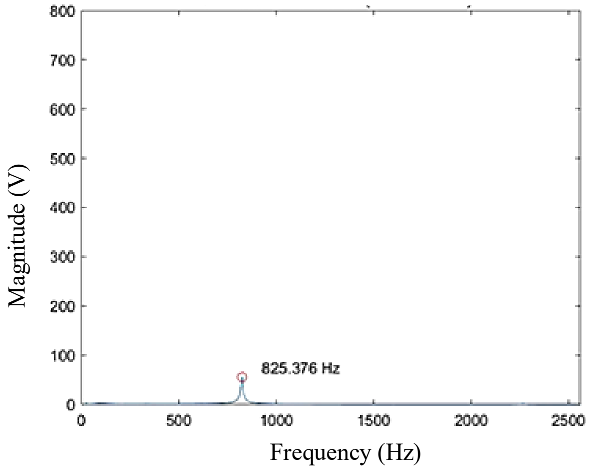
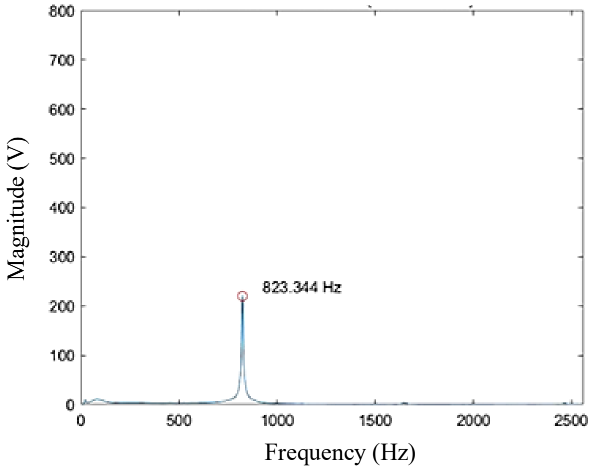
N of force and 0.52101 V of maximum response. The relationship could be formed where a higher degree of impulse will produce a larger amplitude of response signal as output. The hypothesis was the same across all other samples, which suggested the data acquired were in good agreement.

3.2 Elastic Property Measurement Through Resonant Frequency

The conventional measurement needed the resonant frequency value as the primary input, and this was done by observing the frequency domain of vibration response. Figure 5 display the spectral forms in the frequency domain at minimum and maximum impact force whose signals are converted from vibration responses in Figures 3 and 4.



(a)



(b)

Fig. 5 *Vibration response in the frequency domain at (a) Minimum impact force; (b) Maximum impact force*

The fundamental frequency, the first peak of magnitude, depicts the flexural mode's resonant or natural frequency. The peak for the lowest force was at 825.376 Hz of frequency, whereas the highest impulse produced 823.344 Hz. There was a slight difference in value between them; therefore, mean values were found to apportion the data equally across each element. Table 2 shows the average natural frequency obtained across every sample.

Table 2 *Mean natural frequency for each material*

Materials	Average Natural Frequency (Hz)
Alloy Steel 6582	823.03
Bronze	529.76
Cast Iron T250	698.94
Copper	593.56
Plastic Mould Steel P20	849.91
Cold Work Tool Steel SKD-11	873.89

The natural frequency, mass and geometry concerning its material were substituted into Equation 3 to calculate Young's modulus property. Table 3 denoted the elastic property across all samples obtained through the theoretical equation. SKD-11, P20 and 6582 steel bars were recorded as the top three in values, while bronze was the lowest, indicating a good agreement with the theoretical values in Table 1.

Table 3 *Calculated Young's Modulus from resonant-frequency-measurement IET*

Material	Mass (kg)	Dimension, $L \times b \times t$ (m)	Correction factor, T	Natural frequency, f_f (Hz)	Young's Modulus, E (GPa)
6582 Steel	0.969	0.25 x 0.05 x 0.01	1.010536	823.03	196.192
Bronze	1.050			529.76	88.0801
T250 Cast Iron	0.900			698.94	131.416
Copper	1.100			593.56	115.835
P20 Steel	0.980			849.91	211.588
SKD-11 Steel	0.970			873.89	221.415

3.3 Elastic Property Prediction Through I-Kaz Statistical Signal Data Analysis

The statistical information in the vibration response was successfully extracted by quantifying the signal using I-kaz coefficients, which signified the signal feature extraction phase. Table 4 until Table 9 presents the I-kaz coefficients found as a product of vibration signal processing under respective impact forces.

Table 4 *Impact forces and I-kaz coefficients for 6582 alloy steel*

Impact Force (N)	I-kaz Coefficient
137.4	8.17528E-08
229.0	6.57331E-08
235.6	7.60134E-08
328.3	9.19231E-08
410.8	1.40975E-07
518.7	1.95490E-07
523.3	1.90963E-07
585.2	2.31367E-07
599.6	2.04677E-07
619.0	2.90347E-07
632.1	2.00523E-07
635.2	1.92787E-07
712.9	3.18157E-07
727.0	3.37694E-07
748.1	2.91257E-07
763.8	4.58077E-07
816.5	4.48210E-07
940.9	4.65389E-07

Table 5 *Impact forces and I-kaz coefficients for bronze*

Impact Force (N)	I-kaz Coefficient
137.6	7.79963E-08
156.1	1.87724E-07
214.4	1.27749E-07
261.1	1.49526E-07
385.2	2.41514E-07
409.2	1.94210E-07
413.5	2.45721E-07
475.6	2.91304E-07
477.2	2.72467E-07
520.6	3.19015E-07
521.7	3.83343E-07
620.5	3.92384E-07
635.3	4.28199E-07
655.9	4.28199E-07
671.9	4.39000E-07
690.0	4.05392E-07
732.0	6.94091E-07
933.9	5.52646E-07

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Table 6 *Impact forces and I-kaz coefficients for T250 cast iron*

Impact Force (N)	I-kaz Coefficient
188.6	3.22177E-08
218.2	4.12194E-08
233.7	3.51447E-08
262.9	6.28145E-08
294.1	6.42522E-08
398.9	1.58407E-07
410.4	1.40450E-07
415.7	1.76703E-07
455.6	1.44226E-07
472.5	2.91420E-07
510.2	1.44859E-07
584.0	3.86867E-07
672.3	4.05085E-07
684.4	3.86993E-07
702.2	5.39444E-07
837.4	6.70546E-07
890.3	5.29495E-07
911.4	5.61832E-07

Table 7 *Impact forces and I-kaz coefficients for copper*

Impact Force (N)	I-kaz Coefficient
227.3	1.06250E-07
255.7	1.13979E-07
298.5	1.11534E-07
311.6	1.16269E-07
352.8	1.89941E-07
448.8	2.45506E-07
450.2	2.81720E-07
478.9	2.41433E-07
488.2	2.91583E-07
610.0	2.65136E-07
610.8	3.58226E-07
631.3	3.65528E-07
740.0	2.91548E-07
743.7	4.60582E-07
866.6	4.51602E-07
894.1	4.58793E-07
900.4	5.78650E-07
988.8	6.50933E-07

Table 8 *Impact forces and I-kaz coefficients for P20 plastic mould steel*

Impact Force (N)	I-kaz Coefficient
31.8	2.16293E-09
224.5	1.17117E-08
242.4	3.69237E-08
301.2	4.87720E-08
310.4	6.44371E-08
354.8	5.97009E-08
359.9	6.96526E-08
424.4	8.95946E-08
437.2	1.29940E-07
561.4	1.78339E-07
690.8	1.73608E-07
720.8	2.11433E-07
788.8	2.58692E-07
880.9	3.54466E-07
906.0	4.64829E-07
990.6	5.78463E-07
970.7	5.55755E-07
1001.5	5.52239E-07

Table 9 *Impact forces and I-kaz coefficients for SKD-11 cold work tool steel*

Impact Force (N)	I-kaz Coefficient
167.4	1.08083E-07
297.8	1.22098E-07
298.1	1.56804E-07
310.6	1.53037E-07
325.5	1.21953E-07
336.4	2.01521E-07
343.0	1.42568E-07
410.8	1.63777E-07
414.8	2.12771E-07
449.7	2.52698E-07
516.1	1.84432E-07
519.1	2.39282E-07
644.3	3.05136E-07
646.7	2.53230E-07
739.0	4.24464E-07
885.5	5.15861E-07
890.9	4.66273E-07
1034.3	6.78008E-07

The relationship of the data set was derived by observing the rising trend between impact force and I-kaz coefficient. Correlation and curve fitting between the pairs were done to obtain the best data fit for each material and tabulated as in Figure 6.

The polynomial function of the second degree was outlined across all graphs, and the quadratic polynomial equation was defined as part of the regression analysis. The curves with the quadratic model showcased a good agreement between vibration signal features and impact forces, as acknowledged by previous studies [15,16].

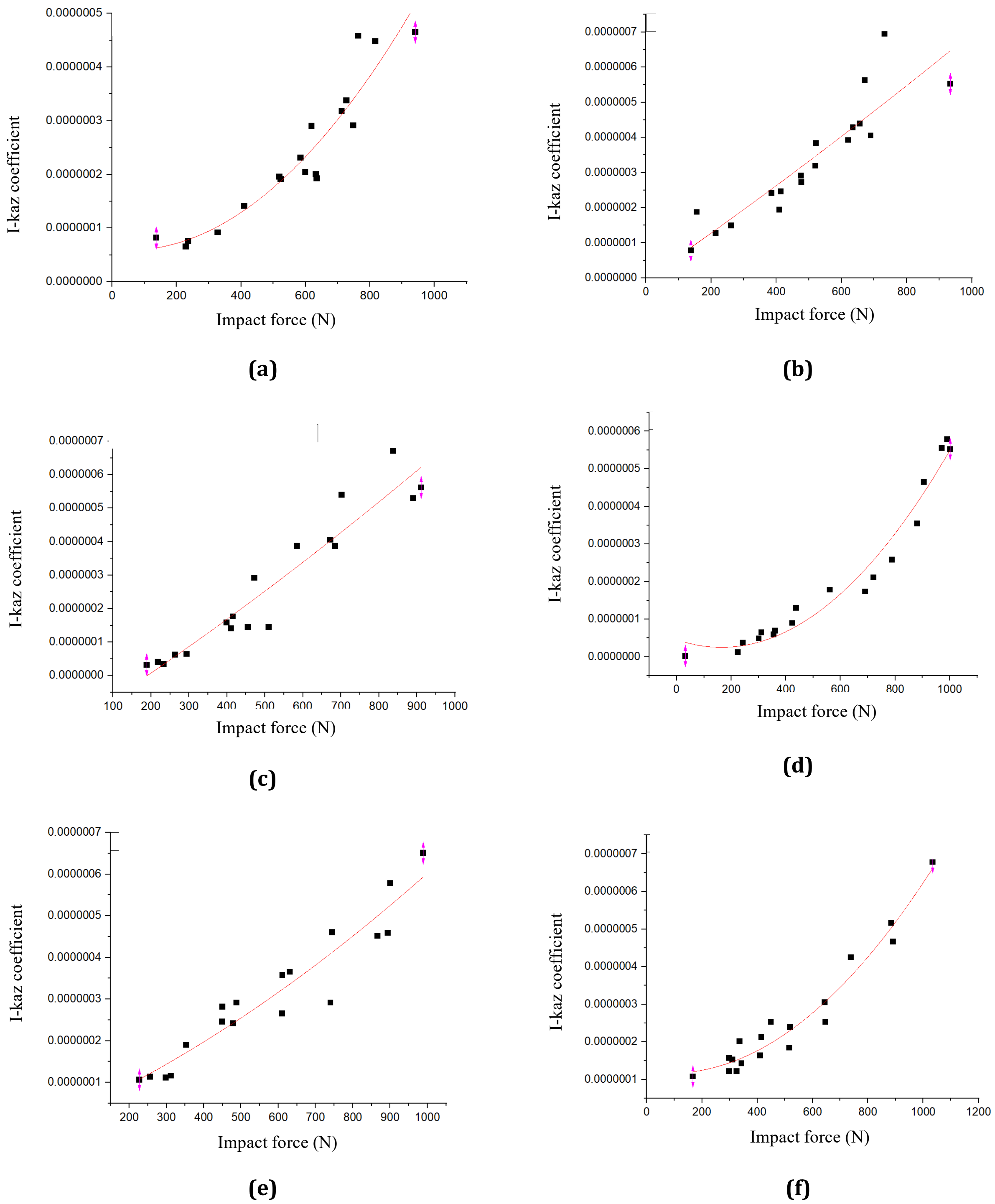

Fig. 6 *Correlation and best-fit curve for (a) 6582 alloy steel; (b) Bronze; (c) T250 cast iron; (d) P20 plastic mould steel; (e) Copper; (f) SKD-11 cold work tool steel*

The quadratic equations for all materials were obtained from the regression assessment. The equation from the resulting curve fitting was in the form of ax^2+bx+c. The value of a was extracted for each sample and wholly signified as I-kaz quadratic coefficients. They were then paired with theoretical Young's modulus of respective materials and later tabulated as shown in Table 10.

The I-kaz quadratic coefficients were then correlated with Young's modulus' theoretical values by discarding one material per regression graph. The material's property will be estimated using the established regression model. Figure 7 illustrates the correlation and the best curve fit for materials of interest. A linear fit was defined as the model function and later utilised to predict the property of previously discarded material.

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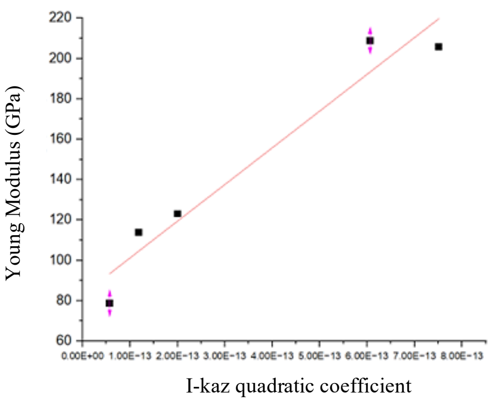
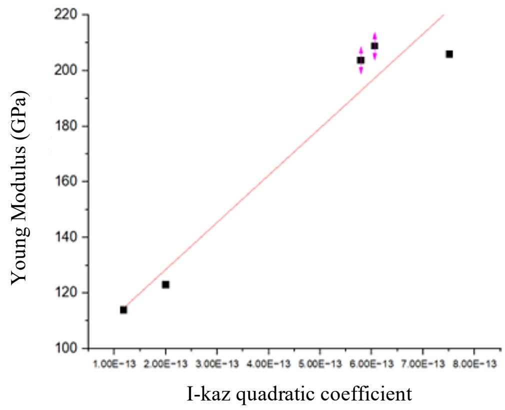
Table 10 *The I-kaz quadratic coefficients with theoretical Young's modulus of each material*

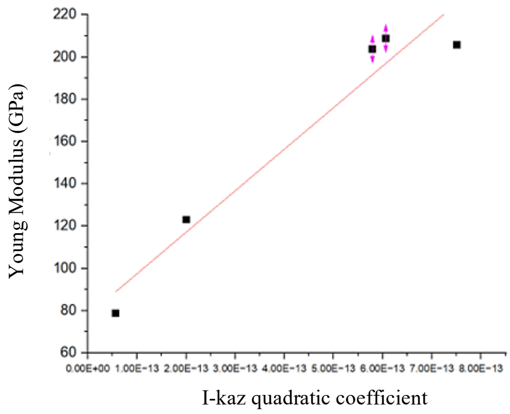
Material	Polynomial quadratic equation, $y = ax^2+bx+c$	I-kaz Quadratic Coefficient, a	Young's Modulus from CES (GPa)
6582 Steel	$y = 5.79 \times 10^{-13}x^2 - 5.98 \times 10^{-11}x + 6.04 \times 10^{-08}$	5.79×10^{-13}	203.7
Bronze	$y = 5.70 \times 10^{-14}x^2 + 6.42 \times 10^{-10}x - 3.11 \times 10^{-09}$	5.70×10^{-14}	78.8
T250 Cast Iron	$y = 1.18 \times 10^{-13}x^2 + 7.33 \times 10^{-10}x - 1.44 \times 10^{-07}$	1.18×10^{-13}	113.8
Copper	$y = 2.00 \times 10^{-13}x^2 + 3.95 \times 10^{-10}x + 7.40 \times 10^{-09}$	2.00×10^{-13}	123.0
P20 Steel	$y = 7.51 \times 10^{-13}x^2 - 2.48 \times 10^{-10}x + 4.56 \times 10^{-08}$	7.51×10^{-13}	205.8
SKD-11 Steel	$y = 6.06 \times 10^{-13}x^2 - 1.03 \times 10^{-10}x + 1.21 \times 10^{-07}$	6.06×10^{-13}	208.8



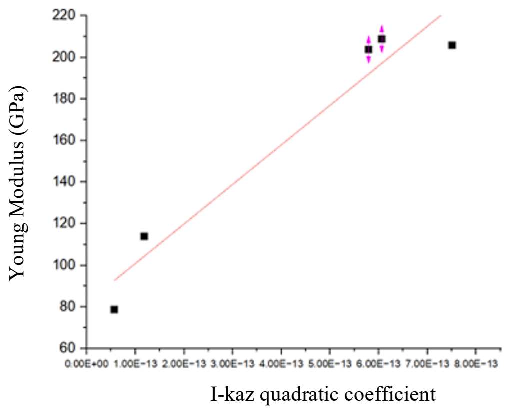
(a)



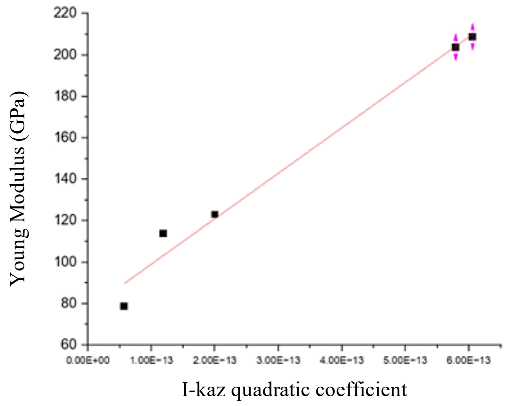
(b)

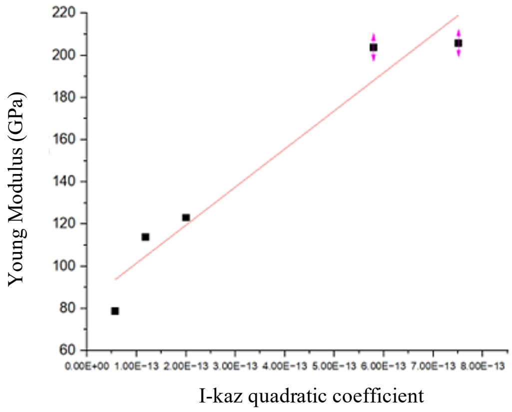


(c)



(d)





(e) **(f)**

Fig. 7 *Young's modulus against I-kaz quadratic coefficient by discarding (a) 6582 steel; (b) Bronze; (c) T250 cast iron; (d) Copper; (e) P20 steel; (f) SKD-11 steel*

The linear equations in the form of $y = ax + b$ were extracted from the graphs and shown in Equation 6 until Equation 11 for the 6582 steel, bronze, T250 cast iron, copper, P20 steel and SKD-11 tool steel.

$$y = 1.81934 \times 10^{14}x + 83.00232 \quad (6)$$

$$y = 1.69536 \times 10^{14}x + 94.57582 \quad (7)$$

$$y = 1.96648 \times 10^{14}x + 77.76698 \quad (8)$$

$$y = 1.90114 \times 10^{14}x + 81.89649 \quad (9)$$

$$y = 2.19296 \times 10^{14}x + 77.18828 \quad (10)$$

$$y = 1.80683 \times 10^{14}x + 83.38605 \quad (11)$$

y is the output of Young's modulus value, and x is the I-kaz quadratic coefficient for the material of interest. Using a statistical estimation approach, the quadratic coefficient values were substituted into the linear equations to obtain the elastic property values. Table 11 tabulates the result.

Table 11 *Quadratic coefficients, linear model equations and estimated Young's modulus of materials*

Material	Quadratic coefficient, x	Model equation	Young's modulus, y (GPa)
6582 Steel	5.79×10^{-13}	$y = 1.81934 \times 10^{14}x + 83.00232$	188.348
Bronze	5.70×10^{-14}	$y = 1.69536 \times 10^{14}x + 94.57582$	104.232
T250 Cast Iron	1.18×10^{-13}	$y = 1.96648 \times 10^{14}x + 77.76698$	101.048
Copper	2.00×10^{-13}	$y = 1.90114 \times 10^{14}x + 81.89649$	119.920
P20 Steel	7.51×10^{-13}	$y = 2.19296 \times 10^{14}x + 77.18828$	241.924
SKD-11 Steel	6.06×10^{-13}	$y = 1.80683 \times 10^{14}x + 83.38605$	192.859

The charted results showed some disagreements with theoretical values. Bronze material was supposed to be the lowest, with a value below 100 GPa, whereas SKD-11 should be the highest. However, the estimated result showed otherwise. Therefore, the result must be validated to calculate the error and devise a conclusion.

3.4 Validation of Standard and Statistical Analysis Technique

The validation phase adopted the theoretical Young Modulus via CES Edupack software as a reference to compare the standard and statistical methods. Observation between data sets was done to build inferences between pairs. The final result with percentage error is shown in Table 12.

The lowest from the standard method is P20 steel with a 2.8% error, whereas the maximum is 15.5 % on T250 cast iron material. On the contrary, the alternative method of I-kaz statistical analysis scored the lowest error of only 2.5 % on copper but the highest at 32.3 % on the bronze sample, which was more than double the maximum value of the standard approach.

The table disclosed two materials with high errors for both methods: bronze and T250 cast iron. Bronze materials exhibit 11.8% and 32.3% errors, while cast iron gives 15.5% and 11.2% for standard and alternative methods, respectively. The discrepancies mainly occurred due to the complex microstructure and characteristics of the materials. Bronze has a mixture of alpha and beta phases with various intermetallic phases, while cast iron has flakes-shaped graphite or nodules embedded in ferrite or pearlite matrixes. These microstructural features affected the material's stiffness, inherently making higher damping than others. Their vibrations dissipate faster with a shorter ringing time and reduce the response towards impulse. This makes it harder to identify accurate modal frequency. It also leads to weaker signals, which makes feature extraction less reliable.

Table 12 *Elastic modulus and percentage errors for standard and alternative approach*

Material	Young's modulus via CES, E^t (GPa)	Young's modulus via standard method, E^f (GPa)	Young's modulus via I-kaz method, E^z (GPa)	Error for standard method (%)	Error for alternative method (%)
6582 Steel	203.700	196.192	188.348	3.7%	7.5%
Bronze	78.800	88.080	104.232	11.8%	32.3%
T250 Cast Iron	113.800	131.416	101.048	15.5%	11.2%
Copper	123.000	115.835	119.920	5.8%	2.5%
P20 Steel	205.800	211.588	241.924	2.8%	17.6%
SKD-11 Steel	208.800	221.415	192.859	6.0%	7.6%
			Average	7.6%	13.1%

The mean error values of both methods were calculated to finalise the result. The average error for the standard approach was 7.6%, whereas it was 13.1% for the alternative. The difference was approximately 5.5%. The main reason behind the lower efficiency on the alternative part was that the statistical method depends on time-domain signals, which contain transient responses, damping effects, and possible artifacts from the impact hammer and sensor. They directly affected the extracted signal features. Meanwhile, the standard IET highlights that the frequency-domain method primarily focuses on the dominant resonant frequency, which is more stable and inherently linked to Young's modulus. Therefore, it was less affected by noise and transient effects.

Hence, it can be deduced that standard IET measurement was better than statistical data analytics. However, as this was an early attempt to exploit the statistical signal data over conventional IET, it was still a promising result. Moreover, it opens a new branch of techniques for gathering, measuring, and exploring IET signal data, especially in academic areas.

4. Potential Refinements and Extensions

The proposed alternative technique relied heavily on the input data to establish relationships and models for estimating the output. It could be enhanced to a higher degree by improving the underlying aspect of input data via the feature engineering phase. Instead of only I-kaz as a feature, applying multivariate analysis could utilise multiple signal features, such as the global statistics (mean, variance, kurtosis, crest factor, etc.) to support and balance the offset parameters. Besides that, features derived from time-frequency analysis could also be incorporated, such as wavelet transforms, short-time Fourier transforms (STFT), or Hilbert-Huang transforms (HHT). These could capture non-linear behaviour and frequency-dependent damping that statistical features might miss. The correlation technique would be sufficient to test and examine the linear relationships between pairs and identify highly correlated features that may be redundant.

In addition, the other resolution is by testing and analysing additional samples with different metallic materials. The gaps with massive errors in data could be reduced as they were considerably filled. Thus, the connectivity and discrepancy between data sets become more apparent. Optimisation on the pre-processing phase could also be implemented by performing a signal filtering step to attenuate noise and discard insignificant data samples in specific signals. This indirectly improves the signals and reveals the actual behaviours when quantifying the vibration responses toward impulses. By executing these solutions with suitable techniques, the statistical approach could outperform the conventional method as the useful data technically drives it.

The potential application for extension or future direction would be material science and engineering research in the academic field, where the IET work is still underrated. It is mainly confined to quality control checks in many industries but remains scarce in academics [10]. IET is rich with information, and with proper materials and methods, the content can be extracted and used in advanced material characterisation. The data could be used to investigate the relationship and discrepancy between dynamic mechanical properties, frequency contents, non-linear behaviour and material damping through statistical signal feature extraction and selection. They allow for extensive dataset analysis from material synthesis and processing experiments. Rather than measuring the standard properties, it could be explored in pattern recognition and prediction systems to optimise the IET technique and thereby indirectly contribute to the academic world.

5. Conclusion

The standard measurement IET and statistical signal analysis method was successfully applied. The acquired data comprised variations of impact forces, which were the upper limit of impulse signals and vibration responses with different amplitudes produced from the force excitation on the material. The vibration responses, which were the output signals, were converted to frequency domain data and resonant frequencies were determined. They were also subjected to the I-kaz statistical signal analysis method to reveal the individual signal information regarding I-kaz coefficients.

The average resonant frequencies of every material under study were used to calculate Young's modulus through the standard theoretical formula for a rectangular beam under flexural mode. I-kaz coefficients were correlated with impact forces, and curve fitting was done. Quadratic coefficients of the graphs were taken out and later paired with theoretical Young's modulus obtained from the CES Edupack platform to obtain the best curve with linear equations. They were used to estimate the elastic property of all materials and then validated to measure the performance. Concisely, the alternative statistical method showed lower competency than the conventional IET approach. Still, the former could be revised and improved with an appropriate solution that resolves data relevancy.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhamad Arif Fadli Ahmad, Mohd Zaki Nuawi;* ***data collection:*** *Meor Iqram Meor Ahmad;* ***analysis and interpretation of results:*** *Muhamad Arif Fadli Ahmad, Mohd Zaki Nuawi, Shahrum Abdullah;* ***draft manuscript preparation:*** *Muhamad Arif Fadli Ahmad, Mohd Faizal Mat Tahir. All authors reviewed the results and approved the final version of the manuscript.*

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