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AN IMPULSIVE EXCITATION APPROACH FOR FATIGUE STRENGTH PROPERTY CHARACTERISATION ANALYSIS OF POLYMERS

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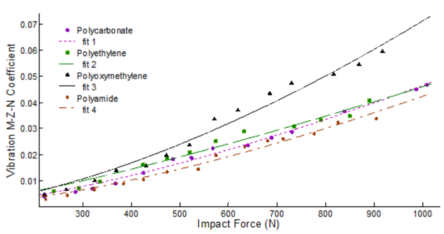
Graphical abstract



Abstract

This paper proposes a method by analysing the free vibration behavior of various polymers for fatigue strength property characterisation. Four disc-shaped specimens with different types of polymer were prepared, namely polyethylene, polycarbonate, polyoxymethylene and polyamide. Experimental dynamic tests were carried out based on ASTM E1876 to measure the transient vibration characteristics using an accelerometer positioned on the flat of the disc close to the outer circumference. The specimen has been lightly striked for pulse loading at the center point using an impact hammer. Using the method of Mesokurtosis Zonal Nonparametric (M-Z-N), the instantaneous data point of the selected decaying signals have been analysed and from the obtained results, the correlation between the M-Z-N coefficient and fatigue strength property has been investigated. It is revealed that the proposed statistical signal analysis method can be applied on the transient impulsive free vibration signal for effectively characterise fatigue strength property of polymers.

Keywords: Fatigue strength; impulsive excitation; statistical analysis; resonant frequency

Abstrak

Kertas kerja ini mencadangkan satu kaedah pencirian sifat kekuatan lesu pelbagai jenis polimer melalui penganalisaan kelakuan getaran bebas. Empat spesimen berbentuk cakera dengan pelbagai jenis bahan polimer telah disediakan, iaitu polietilena, polikarbonat, polioksimetilena dan poliamid. Eksperimen secara ujian dinamik telah dijalankan berdasarkan ASTM E1876 untuk mengukur ciri-ciri getaran fana menggunakan meter pecut yang diletakkan di permukaan rata cakera berhampiran dengan lilitan luar. Spesimen telah diketuk secara perlahan untuk pembebanan denyut pada titik pusat cakera menggunakan tukul impak. Menggunakan kaedah Mesokurtosis Zonal Nonparametric (M-Z-N), titik-titik ketika data pada isyarat tersusut yang dipilih telah dianalisis dan daripada keputusan yang diperoleh, korelasi antara pekali M-Z-N dan sifat kekuatan lesu telah dikaji. Ini menunjukkan bahawa kaedah analisis isyarat statistik yang dicadangkan ini boleh diaplikasikan pada isyarat getaran bebas fana denyut untuk mencirikan sifat kekuatan lesu bahan polimer.

Kata kunci: Kekuatan lesu; pengujaan denyut; analisis statistik; frekuensi salunan

1.0 INTRODUCTION

Material properties characterisation can be classified into two categories: statics and dynamics methods. Statics method refers to the determination of material properties by direct measurement of stresses and strains during mechanical testing such as tensile, compressive and flexural test. The static elastic properties are determined from the stress-strain curve. Using statics method in material testing has some disadvantages such as consists of high cost since this destructive method depend on the use of costly equipments and requiring many samples. This method also results in less accurate determination of material properties and time consuming [1, 2, 3]. Dynamics method applies indirect measurements, where the elastic properties are calculated from sound velocity or vibration frequencies. One example of the dynamics method is the impulse excitation technique (IET). It is based on the mechanical excitation of a solid body by means of a slight impact. For isotropic, homogeneous materials of simple geometry (prismatic or cylindrical bars), the resonant frequency of the free vibration can be easily calculated and directly related to the elastic properties of the materials.

Moreover, the amplitude decay of the free vibration is related to the damping or internal friction of the material. At present, IET is a well-established non-destructive technique for the calculation of modulus elastic and internal friction in monolithic, isotropic materials. There are some advantages of using dynamics method. It has a potential in the scope of reliability, reproducible and cost-effectiveness because it is non-destructive. It also has the capability to characterize quickly, accurately and precisely the mechanical properties of material [4, 5].

Dynamics method has been extensively used for properties characterisation on various types of material. Alves *et al.* [1] use impulsive excitation to obtain the dynamic behaviour for the determination of the transverse Young's modulus of wood species. The experimental method is based on the steady-state power injection method, which is a non-destructive acoustic impact testing on a simply-supported wood plate sample by a small plastic ball. This is for the in-situ determination of dissipation and coupling loss factors of subsystems representing the physical system. Gibson [4] applies the vibration response measurements to characterize the mechanical properties of fiber-reinforced composite materials and structures. Single mode or multiple modes of vibration can be used to determine global elastic constants and damping factors of composites and their constituents under various environmental conditions.

Hauert *et al.* [2] used non-destructive IET to measure Young's modulus of metal matrix composites having a high volume fraction of reinforcement. The
dynamic Young's modulus is measured on defect-free composites of pure aluminium or Al–Cu alloys reinforced with high volume fraction of Al^2O^3 particles. The specimens were excited for the first flexural harmonic and second flexural harmonic for the longitudinal vibration mode. Bossuyt *et al.* [5] investigated the variation of a bulk metallic glass's elastic constants with temperature and thermal history using a non-destructive impulse excitation technique for resonant vibration analysis. The specimen was held by spring-tensioned steel wires in a fixture specially designed to precisely position the wires at the (calculated) nodal lines for the vibration mode being measured.

Besides the vibration dynamics method, there are some other methods for material properties determination. Mršnik *et al.* [6] found the characterization of vibration-fatigue strength that is closely related to structural dynamics, which is generally studied in the frequency domain.

This paper proposes a method for characterising fatigue strength property of various polymers. We describe that property characterization by investigating the transient response of the impulsive vibrational signal. The frequency characteristic, the excitation force and the discrete values of the time domain representation are discussed and obtained the correlation with the fatigue strength property. Young's modulus or the other properties can be identified from resonant frequencies as inverse problem [7].

2.0 EXPERIMENTAL SET-UP AND PROCEDURES

In this section, the specimen involved for the experiment is presented. Then, the experimental set-up and procedures for measuring the free vibration of the specimen under impulsive excitation. Last, the description of the M-Z-N analysis.

2.1 Specimen

The specimen involves 4 types of polymer with the disc-shaped size of 50 mm diameter x 10 mm thickness. This size has been chosen following the guideline from ASTM which is the diameter-to-thickness ratio of at least four. The materials are polyethylene, polycarbonate, polyoxymethylene and polyamide. Table 1 shows the material properties of the specimen [8].

2.2 Experimental Set-up

The schematic of the experimental set-up used for impulse/frequency response test is shown in Figure 1 based on the established standard ASTM E1876 [9]. The vibration signal acquisition system comprises an impact hammer, an accelerometer, a dynamic signal acquisition system and a personal computer. According to the standard, the accelerometer had been mounted on the flat of the disc-shaped specimens close to the outer circumference, in order to measure the second natural resonant frequency (the dynamic response).

Table 1 Parameters of the specimen used in the test [8]

Properties	Polyethylene	Polycarbonate	Polyoxymethylene	Polyamide
Young's Modulus (GPa)	5.2	2.2	3.8	3.4
Density (kg/m^3)	949.5	1175.0	1409.9	0.7
Tensile strength (MPa)	32.8	66.2	74.8	86.3
Fatigue strength at 10^7 cycles (MPa)	22.0	26.5	28.1	34.8
Shear modulus (MPa)	265.9	830.8	1556.1	1275.8
Yield strength (MPa)	23.45	64.50	60.50	88.43

2.3 Experimental Procedures

The specimens were subjected to impulsive force at random impact forces range from 200 N to 1000 N. This range has been chosen because 200 N is the lowest value that data acquisition can detect and 1000 N is the highest force before the accelerometer loss its mounting. The vibration response of the sample was measured using an accelerometer. Both of the impact force and vibration signal were measured and collected simultaneously using a dynamic analyser. The vibration data were processed using the algorithm code that was developed and implemented in MATLAB® for the identification of the natural frequencies. Then the vibration data was analysed using M-Z-N method in order to observe the information characteristic contained in the signal.

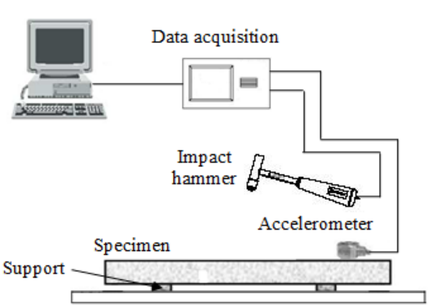


Figure 1 Experimental set-up for impulsive excitation test and measuring system

2.4 M-Z-N Analysis

Formula to calculate M-Z-N coefficient [10] is

$$M-Z-N=\frac{1}{M}\sum_{j=1}^{M}\left[\frac{1}{N}\sum_{i=1}^{N}(x_i-r.m.s)^2\right] \quad (1)$$

where M is the number of segment, N is the number of data point in a segment, x_i is the discrete data value of the i-th sample in a segment and r.m.s is the root mean square value for a segment. The output of this signal analysis method is M-Z-N coefficient. Fatigue strength characterisation will be estimated using this coefficient.

3.0 RESULTS AND DISCUSSION

3.1 Signal Representation

The specimens were subjected to impulsive force at different random impact forces range from 200 N to 1000 N. For each impulsive excitation test, the vibration signal was recorded at the place where the accelerometer was embedded. At first, the prescribe accurate and valid representation of the vibration signal must be defined. Figure 2 shows the typical vibration signal recorded from all the specimens for the impact force in the range of 400 N. It is known that the impulsive excitation load using an impact hammer generates transient-decaying characteristic signal [11]. In all cases, the vibration responses were found to be transient characteristic. This confirms that the waveform is due to the dynamic response of material after excited. The waveform is similar for all cases of impact forces and types of material. By the comparison between materials, it is observed that the influence of excitation force is more apparent in the amplitude of the vibration signal rather than in the signal waveform itself. Noticed that no significant difference can be detected in the time domain as the signals decay to lower amplitude when the maximum amplitude reached after increase drastically [12, 13, 14, 15].

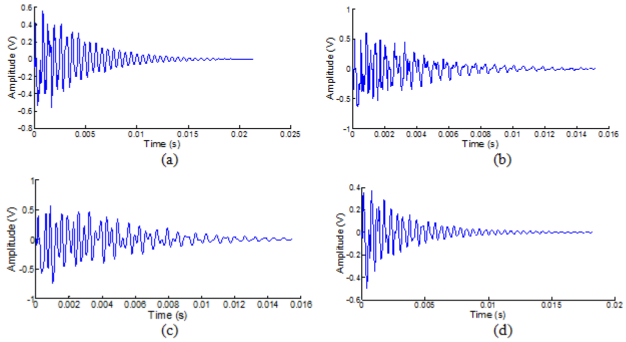


Figure 2 Recorded vibration signal for (a) polyethylene (b) polycarbonate (c) polyoxymethylene (d) polyamide

To obtain further insight into the time domain of vibration pattern from each type of material mentioned above, the signals are converted to the frequency domain. The Fast Fourier Transform method (FFT) is used to obtain the natural frequency components contain in the vibration signal [16]. The Fast Fourier Transform is capable for converting the signal from the time domain to frequency domain. The purpose of this conversion process is to extract the frequency components. Figure 3 shows the frequency domain of the vibration signal for all the materials correspond to the time domain history shown in Figure 2.

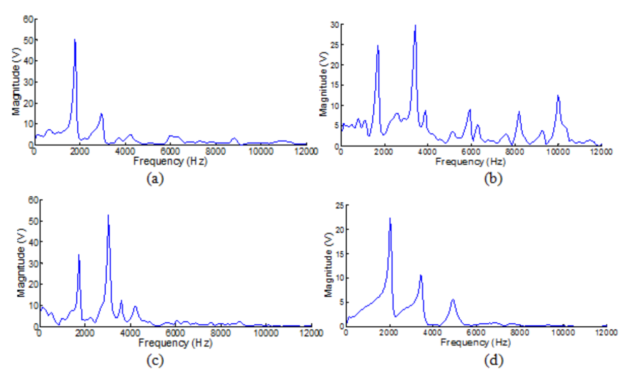


Figure 3 Frequency domain of (a) polyethylene (b) polycarbonate (c) polyoxymethylene (d) polyamide

These frequency domains show that there are several frequency peaks generated during the impact-excited loading between impact hammer and specimen. These peaks represent the natural frequencies information contained in the signal components. The magnitude of each natural frequency component, obtained by FFT processing on the signals, is extracted as the indicator of the vibration pattern. The detail results of the natural frequencies and its magnitude are listed in Table 2.

Two polymers generate three dominant natural frequencies which are polyethylene and polyamide. Polyethylene has three dominant natural frequencies which are 1780 Hz, 2951 Hz and 4263 Hz. Polyamide generates 2020 Hz, 3493 Hz and 4967 Hz. Another two polymers have four dominant natural frequencies. Polycarbonate creates 1680 Hz, 3422 Hz, 5910 Hz and 8212 Hz while polyoxymethylene generates 1721 Hz, 3054 Hz, 3610 Hz and 4220 Hz.

Table 2 Natural frequency values of the test specimens

Material	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	f_4 (Hz)
Polyethylene	1780	2951	4263	-
Polycarbonate	1680	3422	5910	8212
Polyoxymethylene	1721	3054	3610	4220
Polyamide	2020	3493	4967	-

3.2 Vibration M-Z-N Coefficient Curve Pattern

In addition to the time and frequency domain properties discussed in this paper, statistical signal analysis method can yield extra information, for example by analysing the vibration signal using an alternative method known as Mesokurtosis Zonal Nonparametric (M-Z-N). This technique will calculate the M-Z-N coefficient. In these cases, the vibration M-Z-N coefficient is characterised by only two parameters; impulsive excitation force and type of polymer. Table 3 to Table 6 provides the results of the vibration M-Z-N coefficient in increasing order of impact force corresponding to each polymer. One can obtain the vibration M-Z-N coefficient for any impact force and polymer.

Table 3 Vibration M-Z-N coefficient for polyethylene

Impact force (N)	Vibration M-Z-N coefficient
240	6.0782×10^{-3}
292	7.3135×10^{-3}
336	9.5839×10^{-3}
424	1.6072×10^{-2}
474	1.8822×10^{-2}
521	2.0838×10^{-2}
575	2.5143×10^{-2}
633	2.8770×10^{-2}
736	3.0862×10^{-2}
791	3.3255×10^{-2}
850	3.8014×10^{-2}
891	4.0731×10^{-2}

Table 4 Vibration M-Z-N coefficient for polycarbonate

Impact force (N)	Vibration M-Z-N coefficient
221	3.9118×10^{-3}
285	5.8249×10^{-3}
320	7.0585×10^{-3}
368	8.9540×10^{-3}
425	1.2972×10^{-2}
486	1.8344×10^{-2}
524	1.8776×10^{-2}
568	2.2550×10^{-2}
640	2.3594×10^{-2}
689	2.6552×10^{-2}
731	2.8719×10^{-2}
838	3.6591×10^{-2}
987	4.5147×10^{-2}
1009	4.6754×10^{-2}

Table 5 Vibration M-Z-N coefficient for polyoxymethylene

Impact force (N)	Vibration M-Z-N coefficient
221	4.7530×10^{-3}
266	6.6271×10^{-3}
325	1.0012×10^{-2}
369	1.4029×10^{-2}
431	1.5885×10^{-2}
472	1.9704×10^{-2}
520	2.3786×10^{-2}
571	3.3618×10^{-2}
620	4.1095×10^{-2}
685	4.3562×10^{-2}
730	4.7390×10^{-2}
817	5.0763×10^{-2}
869	5.4573×10^{-2}
917	5.9453×10^{-2}

Table 6 Vibration M-Z-N coefficient for polyamide

Impact force (N)	Vibration M-Z-N coefficient
224	3.0026×10^{-3}
269	4.2859×10^{-3}
324	6.5467×10^{-3}
384	8.9112×10^{-3}
425	1.0463×10^{-2}
474	1.3546×10^{-2}
538	1.4467×10^{-2}
575	1.9626×10^{-2}
634	2.2955×10^{-2}
681	2.5334×10^{-2}
713	2.6051×10^{-2}
777	2.8096×10^{-2}
826	3.2392×10^{-2}
905	3.3785×10^{-2}

The pattern of the calculated statistical coefficient is obtained through the fitting curves regarding the vibration M-Z-N coefficient versus impulsive excitation force that are shown in Figure 4. As can be seen from the plot, it is observed that vibration M-Z-N coefficient is significantly increases with the increase of impulsive force applied to excite the specimen. Through analyzing the experimental data, this reason is explained by that higher impulsive excitation force will generate more energy differences between the amplitudes and the root mean square value of the vibration signal. Higher energy difference in all the segments will generate higher M-Z-N coefficient.

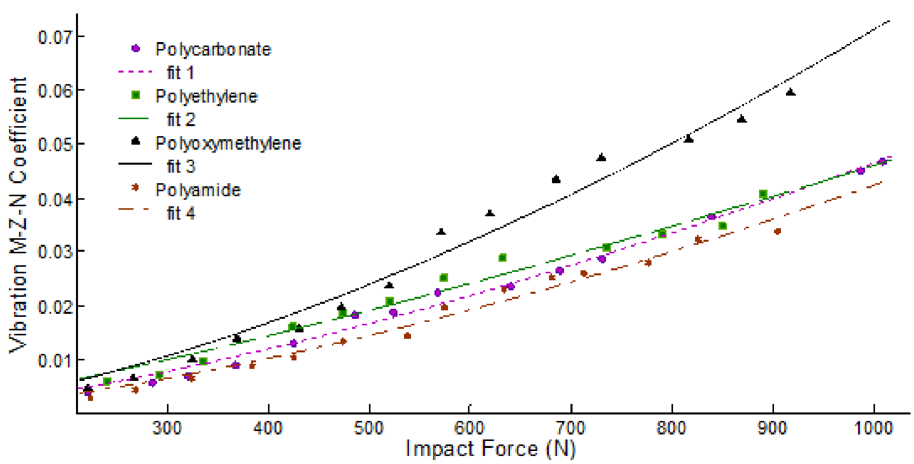


Figure 4 Variation of vibration M-Z-N coefficient based on impulsive excitation force

Another observation for the variation of the vibration M-Z-N coefficient can be drawn. The curve fitting is consistent for all polymers in this paper. The increment of the vibration M-Z-N coefficient is referred to the polynomial characteristic (power equation) with the general form of $y = ax^b$. In comparison of the curve fitting shape, a clearer characteristic of the curve fitting is observed in the polynomial equation. Eq. 2 shows the polynomial equation for polyamide and Eq. 3 shows the polynomial equation for polycarbonate. Eq. 4 shows the polynomial equation for polyethylene and Eq. 5 shows the polynomial equation for polyoxymethylene.

$$y = 9.4888 \times 10^{-7} x^{1.55} \quad (2)$$

$$y = 1.689 \times 10^{-6} x^{1.48} \quad (3)$$

$$y = 7.223 \times 10^{-6} x^{1.268} \quad (4)$$

$$y = 1.358 \times 10^{-6} x^{1.573} \quad (5)$$

Based on the general form of equation, detail analysis on the parameter *a* and *b* in this polynomial (power) equation has been investigated. It is found that the ratio of parameter *b* to the parameter *a* plays a significant role to describe the difference among the polymers as well as shows the material properties pattern.

In the material property characterization process, Table 7 provides the results of the analysis of ratio coefficient and fatigue strength values. The pattern of these ratio coefficient values agrees well with the pattern of the fatigue strength values listed in Table 1. More generally, a good agreement of the experimental impulsive excitation force with the computed signal coefficient using M-Z-N approach was observed in the curve fitting. Finally it can be noted that material with higher fatigue strength value will produce higher ratio coefficient value. The M-Z-N method has become an alternative method for materials research, as well as for characterisation and measurement.

Table 7 Ratio coefficient and fatigue strength property for each polymer

Material	Parameter a	Parameter b	Ratio coefficient b/a	Fatigue strength at 10^7 cycles (MPa)
Polyethylene	7.223×10^{-6}	1.268	1.756×10^{5}	22.0
Polycarbonate	1.689×10^{-6}	1.48	8.763×10^{5}	26.5
Polyoxymethylene	1.358×10^{-6}	1.573	11.58×10^{5}	28.1
Polyamide	0.949×10^{-6}	1.55	16.34×10^{5}	34.8

4.0 CONCLUSION

The reliable non-destructive approach for characterising fatigue strength property of polymer has been addressed. The current work deals with the implementation of an alternative statistical signal analysis known as Mesokurtosis Zonal Nonparametric (M-Z-N) on the vibration signal of the polymer. The specimen was subjected to impulsive excitation loading by an impact hammer and the vibration experiments presented in this paper covered an impulsive force range from 200 to 1000 N. The interest in measuring the dynamic response was achieved using an accelerometer mounted directly to the disc. Overall experimental results have shown that the generated time histories are free oscillations with significant transient-decaying characteristics. Based on the M-Z-N equation, statistical signal analysis has been implemented, following the method by *Nuawi et al.* 2013, regardless of the number of data points in the signal. The calculation results showed that the vibration signal produces significant increment value of M-Z-N coefficients as well as impact force.

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