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AN INVESTIGATION ON LIGHT STRUCTURE MODAL PARAMETER BY USING EXPERIMENTAL MODAL ANALYSIS METHOD VIA PIEZOFILM SENSOR

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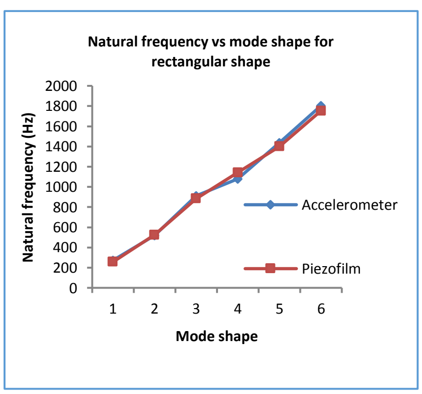
Graphical abstract



Abstract

This study is conducted to determine the modal parameters namely natural frequencies and mode shapes of aluminum 6061 (Al6061). The parameters are done by conducting a free dynamic vibration analysis. Modal analysis study was conducted by both simulation and experimental approaches. The simulation was conducted via ANSYS software while the experimental work was performed through impact hammer testing to determine the vibration parameter. Two sensors i.e. piezoelectric film and accelerometer were used. The result obtained were $y_a = 302.02x – 52.51$ (accelerometer) and $y_p = 295.78x - 41.73$ (piezofilm). y_a (accelerometer) and y_p (piezofilm) is linear equation of the data plotted according to the reading from mode shape versus natural frequency. The relation between natural frequency from accelerometer and piezofilm for the rectangular-shaped specimen was $y_a = 1.02y_p – 9.90$ and can be concluded that the regression ratio of 1.02 was approximately 1.0 which agreed with the status of piezoelectric film sensor that can be used as an alternative sensor for accelerometer. There was a good results agreement between simulation and experimental work outcome.

Keywords: Modal parameters, natural frequency, mode shape, modal analysis, piezoelectric film, accelerometer

Abstrak

Kajian ini dilakukan untuk mengenalpasti parameter modal terdiri daripada frekuensi jati dan bentuk mod bagi aluminum 6061 (Al6061). Kajian untuk mengenalpasti parameter dilakukan dengan analisis getaran dinamik bebas. Kajian analisis modal dilaksanakan dengan simulasi dan eksperimen. Simulasi dijalankan menggunakan perisisan ANSYS manakala ujikaji makmal menggunakan tukul hentaman bagi mengenalpasti parameter getaran. Dua sensor iaitu filem piezoelektrik dan meter pecutan digunakan. Keputusan diperolehi adalah $y_a = 302.02x – 52.51$ (meter pecutan) and $y_p = 295.78x - 41.73$ (filem piezo). y_a (meter pecutan) and y_p (filem piezo) merupakan persamaan garis lurus terhasil dari data diperolehi daripada bentuk ragam dan frekuensi jati. Hubungan antara frekuensi jati untuk meter pecutan dan filem piezoelektrik bagi specimen segiempat tepat adalah $y_a = 1.02y_p – 9.90$ yang mana nisbah regresi

1.02 mendekati 1.0 dan mematuhi status penderia piezoelektrik yang boleh digunakan sebagai alternatif kepada penderia meter pecutan. Satu keputusan yang jitu diperolehi menerusi perbandingan di antara hasil simulasi dan ujikaji.

Kata kunci: Parameter modal, frekuensi jati, bentuk mod, analisis modal, filem piezoelektrik, meter pecutan

1.0 INTRODUCTION

Experimental Modal Analysis (EMA) is done to examine modal parameters which determine natural frequency, mode shape and damping ratio [1, 2]. Modal Analysis is derived originally from Equation of Motion which stated that every motion occurs is incorporated with vibration alongside it [3]. By using signal analysis, the vibration response of the structures to the impact excitation is measure and transformed into Frequency Response Functions (FRF) using fast Fourier Transformation Technique (FFT), hence the measurement of the FRF is the heart of modal analysis [4].

The natural frequency is the rate at which an object vibrates when it is not disturbed by an outside force [5]. Each degree of freedom of an object has its own natural frequency, expressed as ω. This frequency is equal to the speed of vibration divided by wavelength, $\omega = v/\lambda$. Other related equations to find the natural frequency depend on the vibration system involved. Natural frequency can be either damped or undamped [6–8]. The natural frequencies are simple to measure and need a very cheap experimental procedure. Due to this, many study have been conducted by focusing on damage detection [9].

In some occasion, the stiffness and mass of a certain structure play important role in determining the natural frequency of that structure [10, 11]. If frequency of any excitation source coincides with the resonance frequency of a structure, a resonance will occur and can eventually lead to a failure of the entire system. Therefore, the natural frequency is an important parameter that should be precisely analysed to prevent resonance [12[.

Mode shapes can be obtained through displacement (eigenvectors), referred to as mass-normalization with respect to the orthogonality properties of the mass-normalized modal matrix [13]. A mode shape is a specific pattern of vibration executed by a mechanical system at a specific frequency. Different mode shapes will be associated with different frequencies. The experimental technique of modal analysis discovers these mode shapes and frequencies [14, 15].

The mode shape contributes in fixing the desired natural frequency by combining mode shapes to shape i.e. a beam to change its natural frequencies, numerically and experimentally [6, 16]. Mode shape for structure such like bridges can also be estimated by using Frequency Domain Decomposition (FDD) method from numerical investigation [17]. Mode shapes have significant role in detecting the mechanical properties of materials [18]. Practically, the study limited the mode shape not exceeded than 6 modes to obtain a reasonable outcome due to higher mode shape is proportional to lower vibrational speed which is ineffective to collect significant data [19].

2.0 METHODOLOGY

The purpose of this study is to determine the natural frequency and mode shape of Aluminum 6061. The experiment is carried out using the Single Input Single Output (SISO) method. Impact hammer is used to generate signal by exciting on one point to another. Accelerometer and piezoelectric acted as sensors to detect the signal. The resulting signal from the sensors is then sent to the computer for detailed analysis. Simulation testing using ANSYS is conducted via finite element method. See Figure 1.

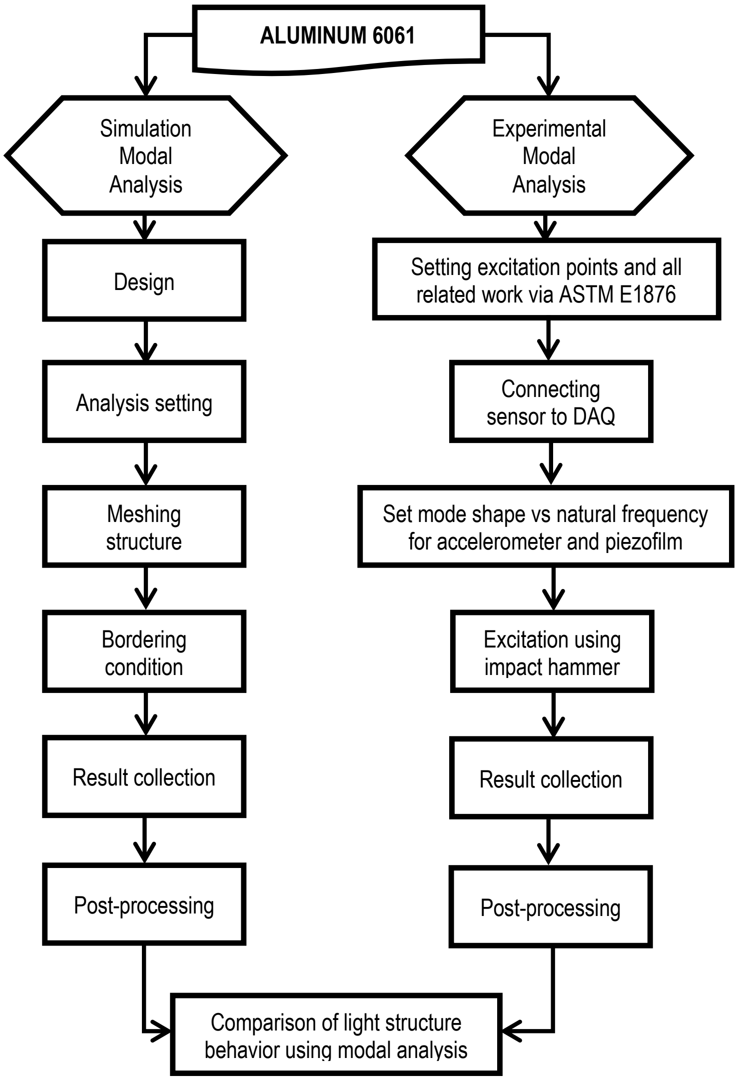


Figure 1 Experimental methodology

2.1 Experimental Set Up

Aluminum 6061 as the experimental specimen of choice is fabricated into rectangular shape:

a) Rectangular (450 x 200 x 1.5mm)

The two types of sensor utilized in the experiment are accelerometer and piezoelectric film.

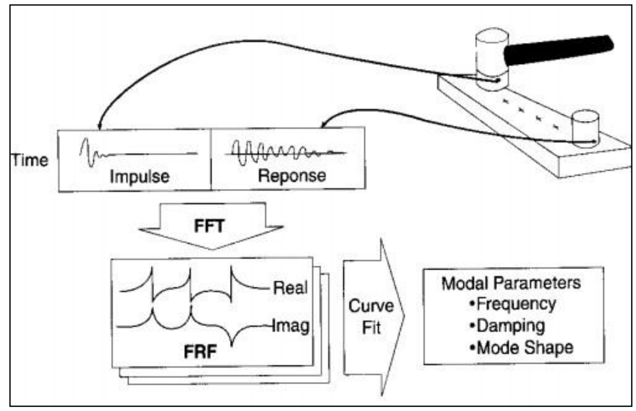


Figure 2 Impact Testing

To perform an impact test, all that is needed is an impact hammer with a load cell attached to its head to measure the input force, a piezofilm sensor to measure the response at a single fixed point, a two channel FFT analyzer to compute FRFs, and post processing software for identifying and displaying the mode shapes in animation. Piezofilm is a transducer with unique capabilities to produce voltage proportional to compressive or tensile mechanical stress or strain. In a typical impact test, the piezofilm is attached to a single point on the structure, and the hammer is used to impact it at points and directions as required to define its mode shapes. FRFs are computed one at a time, between each impact point and the fixed response point. Modal parameters are defined by curve fitting the resulting set of FRFs. Figure 2 depicts the impact testing process.

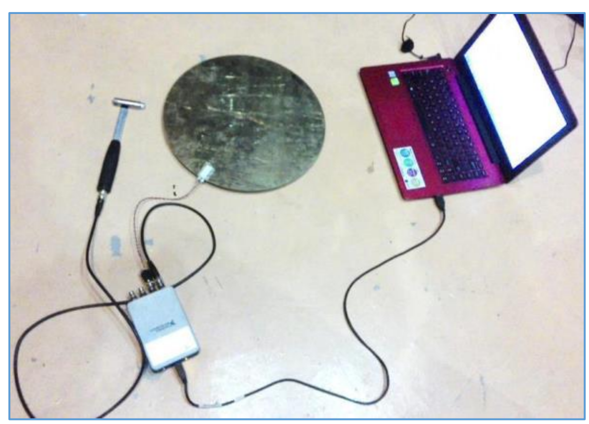


Figure 3 Experimental set up

Impact testing is performed to find mode shapes of the specimen. Modal analysis systems composed of impact hammer, sensor such as transducers (piezofilm sensor), data acquisition system (DAQ) and a host PC. Figure 3 shows the example of experimental set up (in this case, the specimen shape used is circular and used only piezofilm sensor, while in the study the specimen shape is rectangular and used both piezofilm sensor and accelerometer).

2.1.1 Simulation

Firstly, the proposed shape was designed using ANSYS. Next, mesh structure for the shape (eg. selection of size etc.) was generated. Figure 4 displays the mesh structure of the shape. This process can extract shifting magnitude and natural frequency of the structure and also verify mode shapes transition for every natural frequency available in the aluminum structure. The rectangular-shaped design was chosen due to the uniformed in axial distribution and usually applied in industry for completing important area such as in automotive body parts or similar cases involving machinery parts.

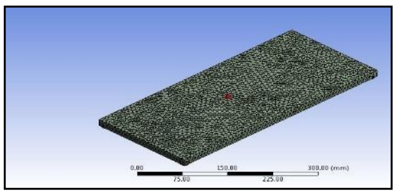


Figure 4 Meshing structure

2.1.2 Material and Method

Initially, points of excitation in the form of knocking point by impact hammer were decided and then spotted using a marker. Channel fixing of impact hammer (called the first channel) was installed on the DAQ. The styrofoam with appropriate size and dimension has been used to support the structure from moving thus avoid unnecessary vibration during the experiment. Next, piezoelectric film was connected to the second channel while accelerometer was connected to the third channel of the DAQ. The DAQ was readily connected to the computer.

Masking tape was applied to the piezoelectric film (masking tape was used to ensure the film from sliding and also due to it lightness, its weight can be neglected) and special glue was put onto the accelerometer upon conducting the experiment. The sensor was positioned at three different points on the specimen shape, as shown in Figure 5. All the works were conducted by following the ASTM E1876 standard procedure.

Figure 5 Sensor three-different position

3.0 RESULTS AND DISCUSSION

To compare between the simulation modal analysis and the experimental modal analysis on dynamic structure characteristics, the percentage error must be clarified first. Percentage error calculations are as follow:

$$\text{Percentage error} = \frac{|f_1 - f_2|}{f_1} \times 100\% \qquad (1)$$

or

$$\text{Percentage error} = \frac{|f_1 - f_3|}{f_1} \times 100\% \qquad (2)$$

Where f_1 represents natural frequency by accelerometer, f_2 stands for natural frequency by piezoelectric film and f_3 represents natural frequency by simulation.

3.1 Simulation result

Table 1 below shows the result of simulation analysis of natural frequency for rectangular-shaped specimen.

Table 1 Simulation analysis of natural frequency for rectangular-shaped specimen

Mode shape	Natural frequency (Hz)
1	291.72
2	647.63
3	841.42
4	1465.00
5	1554.00
6	1952.40

The results showed that natural frequency increased proportionally with the increasing of mode shape. Figure 6 showed the mode shape 1 until 6 for rectangular.

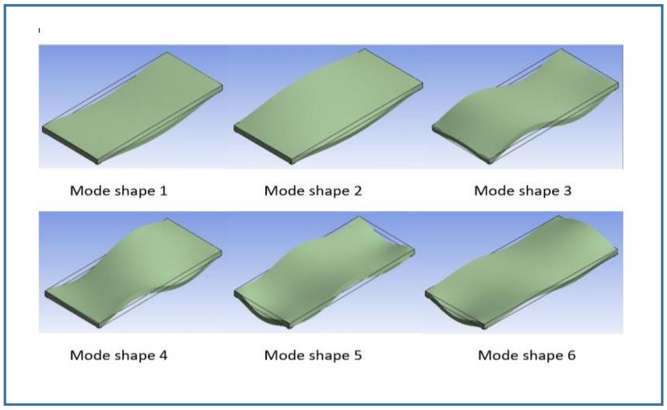


Figure 6 Rectangular mode shape 1 until 6

3.2 Experimental Work Result

Table 2 and Table 3 show the results that describe the natural frequency for every mode shape of piezoelectric film sensor and accelerometer for the rectangular-shaped specimen respectively.

Table 2 Natural frequency from analysis of piezoelectric film sensor for rectangular-shaped specimen

	Natural Frequency (Hz)			
Mode shape	**Point 1**	**Point 2**	**Point 3**	**Average**
1	246	304	225	258.33
2	495	583	496	524.67
3	869	912	872	884.33
4	1132	1185	1108	1141.67
5	1375	1408	1416	1399.67
6	1731	1768	1758	1752.33

Table 3 Natural frequency from analysis of accelerometer for rectangular-shaped specimen

	Natural Frequency (Hz)			
Mode shape	**Point 1**	**Point 2**	**Point 3**	**Average**
1	229	308	279	272.00
2	570	568	426	521.33
3	995	891	853	913.00
4	1119	1112	1011	1080.67
5	1406	1389	1517	1437.33
6	1730	1727	1952	1803.00

Referring to the results showed above, both sensors (piezoelectric film and accelerometer) showed that natural frequency readings captured were the highest at point 2. It can be concluded that according to the position the sensors were located, the natural frequency were clearly detected at the edge position of the structure (refer Figure 5).

3.3 Comparison in Dynamic Structure Characteristics of Modal Analysis Between Simulation and Experimental Work

The comparison in light structure was conducted by finding the difference and error ratio (refer eq. (1) and eq. (2)) between accelerometer versus simulation and accelerometer versus piezoelectric film sensor. Natural frequency for every mode shape transformation was compared for the structure. Accelerometer result acted as the foundation for actual value to compare with. This is because modal analysis experimental work frequently relies on the use of an accelerometer as a sensor due to its accurateness.

The difference between natural frequency for the accelerometer and piezoelectric film is represented by f_1 - f_2 and the difference between natural frequency for the accelerometer and simulation is represented by f_1 - f_3.

Upon obtaining the error between the accelerometer and piezoelectric film sensor, the graph of natural frequency versus each mode for accelerometer and piezoelectric film sensor was plotted. By finding the equation from the graph, the coefficient between the accelerometer and piezoelectric film sensor was obtained. Thus, the relation between the accelerometer and piezoelectric film sensor was successfully determined. Refer Table 4.

Table 4 Comparison between accelerometer, piezoelectric film sensor and simulation for rectangular-shaped specimen

	Natural frequency (Hz)						
M s h p	**Acc (f_1)**	**P.fllm (f_2)**	**Sim. (f_3)**	**Diff. 1 $\lvert f_1 - f_2 \rvert$**	**Diff. 2 $\lvert f_1 - f_3 \rvert$**	**Err. 1 (%) $\frac{f_1 - f_2}{f_1}$**	**Err. 2 (%) $\frac{f_1 - f_3}{f_1}$**
1	272	258	292	14	20	5.00	7.30
2	521	525	648	3	126	0.60	24.20
3	913	884	841	29	72	3.10	7.80
4	1080	1142	1465	61	384	5.60	35.60
5	1437	1400	1554	38	117	2.60	8.10
6	1803	1752	1952	51	149	2.80	8.30

For accelerometer versus piezofilm, the difference of mode shapes (mode 1 to mode 6) based on natural frequency is 14Hz, 3Hz, 29Hz, 61Hz, 38Hz and 51Hz respectively. While the percentage of error for accelerometer versus piezofilm (mode 1 to mode 6) is 5.00%, 0.60%, 3.10%, 5.60%, 2.60% and 2.80% respectively.

For accelerometer versus simulation, the difference of mode shapes (mode 1 to mode 6) based on natural frequency is 20Hz, 126Hz, 72Hz, 384Hz, 117Hz and 149Hz respectively. The percentage of error for accelerometer versus simulation (mode 1 to mode 6) is 7.30%, 24.20%, 7.80%, 35.60%, 8.10% and 8.30% respectively.

Overall, the percentage of error for accelerometer versus piezofilm was satisfying with error less than 10%. The biggest error was at mode 4 with 5.60% error. The smallest was at mode 2 with 0.60% error. As for accelerometer vs simulation, the result was not satisfying. The error percentage average was higher than compared with piezofilm. The highest error was at mode 4 with 35.60%, followed by mode 2 with 24.20% although at mode 1 the error was only 7.30%. The differences were also high at mode 4, mode 6, mode 2 and mode 5 with 384Hz, 149Hz, 126Hz and 117Hz respectively.

Nevertheless, for accelerometer vs simulation, as the mode gets higher, the difference was the highest at mode 4 (384Hz) while the lowest at mode 1 (20Hz). The maximum error is at mode 4 with 35.60% and whilst the smallest error is at mode 1 with only 7.3%. When compared with accelerometer vs piezofilm, it can be concluded that the piezofilm percentage error average is better than simulation percentage error average.

The errors were the highest at mode shape 2 and mode shape 4 mainly because the experiment was conducted manually, there was inconsistency in excitation node developed which affect the second and fourth wave of mode shape.

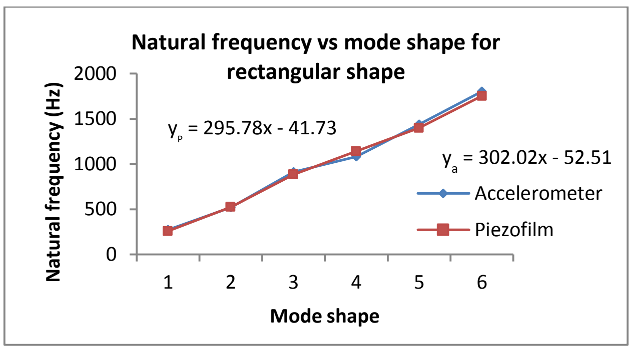


Figure 7 Natural frequency vs mode shape for rectangular-shaped specimen

By referring to Figure 7, the equation of gradient for accelerometer and piezofilm is:

$$\text{Accelerometer: } y_a = 302.02x - 52.51 \quad (3)$$

$$\text{Piezofilm: } y_p = 295.78x - 41.73 \quad (4)$$

Therefore, the relation between the natural frequency of accelerometer and piezofilm for the rectangular-shaped specimen:

$$y_a = 1.02y_p - 9.90 \quad (5)$$

By referring to eq. (5), it can be concluded that the regression ratio of 1.02 was approximately 1.0 which agree with the status of piezoelectric film sensor can be used as an alternative sensor for accelerometer.

4.0 CONCLUSION

In this study, the simulation analysis and experimental work have been successfully carried out to obtain the characteristics of natural frequency and mode shape for the aluminum 6061 that has been fabricated into rectangular shape. The comparison between accelerometer with simulation and the comparison between accelerometer with piezoelectric film sensor have also been successfully executed.

In short, one could understand the relation between accelerometer and piezoelectric film as sensors in determining the natural frequencies and mode shapes in vibration. For rectangular-shaped specimen it was $y_a = 1.02y_p - 9.90$.

By obtaining the relation between the accelerometer sensor and piezoelectric film sensor, one could determine the natural frequency in aluminum components by using piezoelectric film sensor in the future. Thorough understanding of the natural frequency in the components allows for better control on the vibration range. This could assist the design and manufacturing industries by using low cost sensor, thus eliminating the risks of resonance occurrence. There was a good result agreement between simulation and experimental work outcome. As a result, damage control can be applied and potential lost in cost and life will be minimized.

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