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NOVEL TECHNIQUE OF MODAL ANALYSIS FOR LIGHT STRUCTURE VIA PIEZOFILM SENSOR: A COMPARISON STUDY

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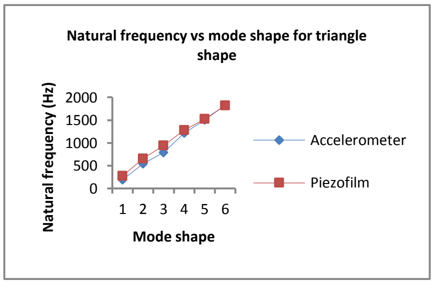
Graphical abstract



Abstract

This study is conducted to determine the modal parameters namely natural frequencies and mode shapes of aluminum 6061 (Al6061). A light and small structure made from Al6061 is chosen as the experimental specimen mainly because of its wide application in industries such as automotive parts or accessories and robotic, mainly in manufacturing of automobile frames. If a component vibrates with a frequency that is coherent with the component's natural frequency, resonance frequency will occur and structural failure might emerge. Two sensors i.e. piezoelectric film and accelerometer were used. The result obtained were $y_a = 329.60x - 142.27$ (accelerometer) and $y_p = 304.98x + 15.18$ (piezofilm). The relation between natural frequency of accelerometer and piezofilm for the triangle-shape specimen was $y_a = 1.08y_p - 158.67$ and can be concluded that the regression ratio of 1.08 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

1.0 INTRODUCTION

The dynamic response of material under excitation force has been proven as one of the most important methods of non-destructive testing of material properties. Until recently, modal testing has become an effective means for identifying, understanding and simulating dynamic behavior and responses of structures [1].

Experimental Modal Analysis (EMA) or modal testing is a non-destructive testing method based on vibration responses of the structures. 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. Subsequently, the series of FRF's are used to extract modal parameters such as natural frequencies, mode shapes and damping ratios [2].

A signal is a pattern of data that representing physical quantity such as voltage, current, pressure or any other variable with respect to second variable (time) to convey messages or information [3].

Currently, piezo material with its properties of high speed and compact size has progressively gaining popularity as core components in many kinds of precision actuators and sensors [4-6]. Actuators with high speed vibration are required in a number of fields including ultra-precision machining [7, 8]. Due to its characteristics, piezo material is imminent in fields that demand large force, fast response, and cost-effective nature of work [9-12].

To some extent, piezo contributes to micro-vibration that can generate large vibration amplitude of up to 100µm at the frequency of 1100Hz [13]. These characteristics prove that in reliable circumstances, piezo possesses the capability to detect tiny vibration. Hence, it can be said that piezo can practically exhibits itself as a sensor [14, 15]. Piezoelectric effect based on its characteristic could therefore give good attribute to modal identification.

The study shall be extended by conducting modal analysis experimentally on the testing component. Finally, comparison will be made between these two outcomes (simulation and experimental work).

2.0 METHODOLOGY

The purpose of this study is to determine the natural frequency and mode shape of Aluminum 6061. Therefore, modal analysis is conducted to investigate the modal parameter of the specimen. By understanding the natural frequency and mode shape of the specimen, further action can be taken to avoid resonant which could damage the specimen, thus ultimately avoiding the structure from potentially harming the end user.

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.

2.1 List of Apparatus

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

a) Triangle (450 x 400 x 1.5mm)

The two types of sensor utilized in the experiment are accelerometer and piezoelectric film. The accelerometer used is of model Endevco 751-100 USA with an output impedance of ≤120Ω, output voltage of ±5V, supply current of 2-20mA and weight of 8g. The piezoelectric film attached to the Aluminium 6061 carries the same function as the accelerometer, with the only difference being the piezoelectric film is laminated to a sheet of polyester. The piezoelectric is made from polymer, commonly from polyvinylidene fluoride (PVDF) of model LDT1-028K, USA, with a minimum impedance of 1MΩ, output voltage of 10mV~100V, storage temperature between -40°C to 70°C and operating temperature between 0°C to 70°C.

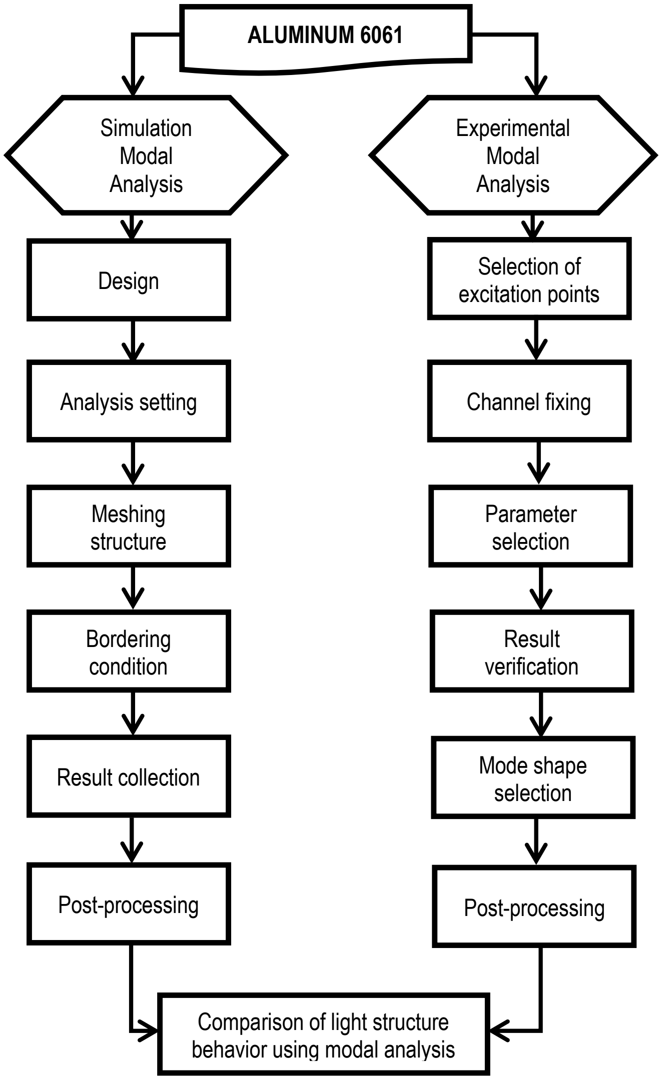


Figure 1 Experimental methodology

The impact hammer which executes impact force onto Aluminum 6061 is of model SN LW31881, PCB 086C03, USA with a force range of 0~22.7kgf, max force of 453.6kgf, sensitivity of 2.25mV/N, resonance frequency of 75kHz, temperature operation range of -73°C~121°C, output voltage of 5V, max impedance of 100Ω, input current range of 2~20mA, input voltage range 18~30VDC and head weight 100g.

Abbreviated as DAQ, the device converts analog waveforms into digital values for processing purpose. DAQ consists of sensor, signal circuit, and analog to digital converter. DAQ is controlled by software programs that are developed using general purpose programming languages such as LabVIEW, Fortran, etc. In this experiment, the DAQ model used is the

National Instrument DAQ, NI9234 4-channel 5V 24 Bit, NI CDAQ-9171 NI COMPACTDAQ with 1 USB slot.

2.1.1 Simulation

Firstly, the proposed shape was designed using ANSYS. Next, mesh structure for every shape (eg. selection of size etc.) was generated. Figure 2 displays the mesh structure of the shapes. 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 triangle- shaped design was chosen due to the uniqueness, disuniformed in axial distribution and usually applied in industry for completing cornered area such as in automotive body parts or similar cases involving machinery parts.

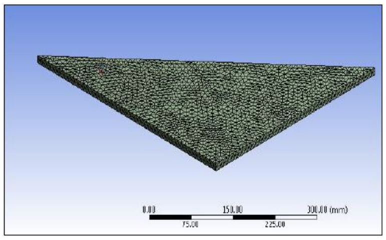


Figure 2 Meshing structure

2.1.2 Experimental work

Initially, points of excitation in the form of knocking point by impact hammer were decided, and then spotted using a marker. The specimen cover was put by base on the floor, and channel fixing of impact hammer (called the first channel) was installed on the DAQ. The hammer was put on sponge while modelling clay with adequate quantity has been used to fix the structure from moving (rather than using sponge which could absorb vibration and affect the reading needed) 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 moving 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 3. All the works were conducted by following the ASTM E1876 standard procedure.

Figure 3 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:

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

or

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

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 triangle-shaped specimen.

Table 1 Simulation analysis of natural frequency for triangle shape specimen

	Natural Frequency (Hz)			
Mode shape	**Point 1**	**Point 2**	**Point 3**	**Average**
1	228	359	244	277
2	506	810	644	653
3	760	1241	817	939
4	1125	1496	1221	1281
5	1454	1631	1488	1524
6	1782	1837	1844	1821

The results showed that natural frequency increased proportionally with the increasing of mode shape.

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 triangle shape specimen respectively.

Table 2 Natural frequency from analysis of piezoelectric film sensor for triangle shape specimen

Mode shape	Natural frequency (Hz)
1	253
2	520
3	700
4	1030
5	1202
6	1786

Table 3 Natural frequency from analysis of accelerometer for triangle shape specimen

	Natural Frequency (Hz)			
Mode shape	**Point 1**	**Point 2**	**Point 3**	**Average**
1	111	225	226	187
2	480	577	564	540
3	798	804	763	788
4	1293	1237	1120	1217
5	1382	1637	1498	1506
6	1846	1861	1782	1830

Referring to the results shown above, both sensors (piezoelectric film and accelerometer) shown 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 actively detected at the peak position of the structure (refer Figure 3).

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.

For accelerometer versus piezofilm, the difference of mode shapes (mode 1 to mode 6) based on natural frequency is 90Hz, 113Hz, 151Hz, 64Hz, 18Hz and 9Hz respectively. While the percentage of error for accelerometer versus piezofilm (mode 1 to mode 6) is 48%, 21%, 19%, 5%, 1% and 0.5% respectively.

For accelerometer versus simulation, the difference of mode shapes (mode 1 to mode 6) based on natural frequency is 66Hz, 20Hz, 88Hz, 187Hz, 304Hz and 44Hz respectively. The percentage of error for accelerometer versus simulation (mode 1 to mode 6) is 35%, 4%, 11%, 15%, 20% and 2% respectively.

Table 4 Comparison between accelerometer, piezoelectric film sensor and simulation for triangle shape 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	187	277	253	90	66	48	35
2	540	653	520	113	20	21	4
3	788	939	700	151	88	19	11
4	1217	1281	1030	64	187	5	15
5	1506	1524	1202	18	304	1	20
6	1830	1821	1786	9	44	0.5	2

Overall, the percentage of error for accelerometer versus piezofilm is not satisfactory at mode 1, mode 2 and mode 3. At mode 3, the difference is at 151Hz. Nevertheless, as the mode gets higher, the difference gradually reduces with the minimum value of 9Hz as presented at mode 6. The maximum error is at mode 1 with 48% and whilst the smallest error is at mode 6 with only 0.5%. As for the comparison between accelerometer and simulation, the result is also not satisfactory. The piezofilm percentage error average is better than simulation percentage error average.

The error were the highest at mode shape 1 and mode shape 2 mainly because the experiment was conducted manually, there was inconsistency in excitation node developed which affect the first and second wave of mode shape.

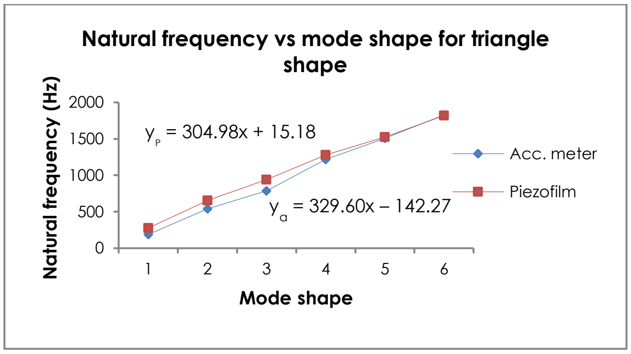


Figure 4 Natural frequency vs mode shape for triangle shape specimen

By referring to Figure 4, the equation of gradient for accelerometer and piezofilm is:

Accelerometer: $y_a = 329.60x - 142.27$ (3)

Piezofilm: $y_p = 304.98x + 15.18$ (4)

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

$y_a = 1.08y_p - 158.67$ (5)

By referring to eq. (5), it can be concluded that the regression ratio of 1.08 was approximately almost 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 triangle 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. The result obtained for accelerometer was $y_a = 329.60x - 142.27$ and for piezofilm was $y_p = 304.98x + 15.18$ respectively. Thus, the relation between natural frequency of accelerometer and piezofilm for the triangle-shaped aluminum 6061 specimen was $y_a = 1.08y_p - 158.67$. It can be concluded that the regression ratio of 1.08 was approximately 1.0 which agreed with the status of piezoelectric film sensor that can be used as an alternative sensor for accelerometer.

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. This could assist the design and manufacturing industries by using low cost sensor while eliminating the risks of resonance occurrence. There was a good result agreement between simulation and experimental work outcome.

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