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Modal Analysis Study on Aluminum 6061 using Accelerometer and Piezoelectric Film Sensor

M.I. Ramli[1,2,a], M.Z. Nuawi[1,b]

[1]Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.

[2]Department of Mechanical Engineering Technology, Faculty of Engineering Technology, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

E-mail: [a]irman@utem.edu.my, [b]zaki@eng.ukm.my

M.R.M. Rasani[3,d], S. Abdullah[3,e], K. K. Seng[3,f]

[3]Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.

E-mail: [d]rasidi@eng.ukm.my, [e]shahrum@eng.ukm.my, [f]shukorme@gmail.com

Abstract

This study is conducted to determine vibration or modal parameters such as natural frequencies and mode shapes of aluminum 6061 (Al6061). If the component vibrates with frequency coherence with the natural frequency, resonance frequency will occur and structural failure might emerge. Modal analysis study is conducted by both simulation and experimental methods. Simulation is conducted via ANSYS software while impact hammer testing is done for experimental work to determine the vibration parameter. Two sensors are used, which are piezoelectric film and accelerometer. Hence, the results obtained from accelerometer showed that frequencies for mode shape 1, 2, 3, 4, 5 and 6 for rectangular shape are 272.00Hz, 521.33Hz, 913.00Hz, 1080.67Hz, 1437.33Hz and 1803.00Hz. The results obtained from piezoelectric film showed that frequencies for mode shape 1, 2, 3, 4, 5 and 6 for rectangular shape are 258.33Hz, 524.67Hz, 884.33Hz, 1141.67Hz, 1399.67Hz and 1752.33Hz. Finally, the results captured from simulation appeared that frequencies for mode shape 1, 2, 3, 4, 5 and 6 for rectangular shape are 291.72Hz, 647.63Hz, 841.42Hz, 1465.00Hz, 1554.00Hz and 1952.40H respectively. The results showed that low cost sensor which is piezoelectric film proved to be reliable in detecting the modal parameter.

Keywords: Modal parameters, natural frequency, mode shape, modal analysis, piezoelectric film, accelerometer, ANSYS, resonance frequency, Al6061

INTRODUCTION

Experimental Modal Analysis (EMA) is done to examine modal parameters which determine natural frequency, mode shape and damping ratio [1]. EMA is a well-known procedure to determine modal analysis [2]. Meanwhile, Operational Modal Analysis (OMA) deals with the identification of modal parameters of a structure using only it output response, without the knowledge of the forces causing the response and useful in determining large structures such as bridges, towers etc. [3, 4].

Piezo materials with their properties of high speed operation and compact size have been more and more applied as core components in many kinds of precision work related with sensors [5]. Due to its character, piezo materials are imminent in fields that require large force, fast response and cost-effective nature of work [6]. In some extent, piezo contribute to micro-vibration that can generate large vibration amplitude up to 100µm at the frequency of 1,100Hz [7]. The character proof that piezo is applicable in detecting tiny vibration in reliable circumstances. This relates with piezo that can practically exhibit itself as a sensor [8]. Piezoelectric effect based on its characteristics could therefore give good attribute to modal identification.

LITERATURE REVIEW

Modal Analysis

Modal Analysis is conducted to acquire two basic modal parameters of which are natural frequencies and mode shapes respectively. Modal Analysis solve for natural tendencies of the structure in the form of motions and frequencies. Two classification of Modal Analysis are Operational Modal Analysis (OMA) and Experimental Modal Analysis (EMA) [9]. Modal Analysis is derived originally from Equation of Motion which stated that every motion occurs is incorporated with vibration alongside it [10]. See Figure 1.

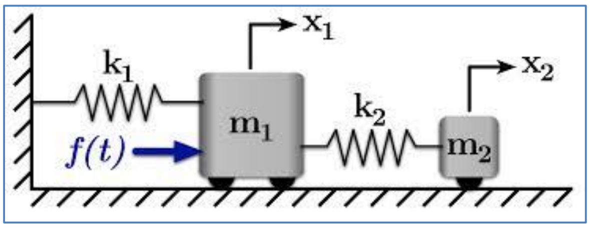

Figure 1: Spring equation of motion [10]

$$m_1\ddot{x}_1 + (k_1 + k_2)x_1 - k_2x_2 = 0 \qquad (1)$$

$$m_2\ddot{x}_2 - k_2x_1 + k_2x_2 = 0 \qquad (2)$$

or in matrix,

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad (3)$$

or

$$m\ddot{x} + kx = 0 \qquad (4)$$

(where

m = mass, k = spring stiffness,
x = displacement from static equilibrium position)

From here, we can derive the natural frequency equation.

$$\omega_n = \sqrt{\frac{k}{m}} \qquad (5)$$

(ω_n = natural frequency, k = spring stiffness, m = mass,

x = displacement from static equilibrium position)

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 [11].

Piezoelectric

Piezoelectric (Fig. 2) is the electric charge that accumulates in certain solid materials (such as crystals and certain ceramics) in response to applied mechanical stress [12]. Piezoelectricity means electricity resulting from pressure [13]. Lead zirconate titanate crystals generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension [14].

Piezoelectricity is the combined effect of the electrical behavior of the material:

$$D = \varepsilon E \rightarrow D_i = \varepsilon_{ij} E_j \qquad (6)$$

where D is the electric charge density displacement (electric displacement), ε is permittivity and E is electric field strength,

and Hooke's Law:

$$S = sT \rightarrow S_{ij} = s_{ijkl} T_{kl} \qquad (7)$$

where S is strain, s is compliance and T is stress.

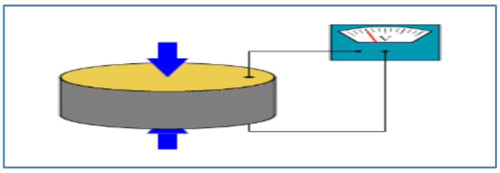

Figure 2: A piezoelectric disk generates a voltage when deformed [13]

Mostly used in engineering application mainly are Piezo Zirconium Titanate (PZT) (synthetic ceramics) and Polyvinylidene Fluoride (PVDF) (polymers). The applications are in high voltage and power sources [12], sensors, actuators, motors among others [15].

PROBLEM STATEMENT

The range in weight for accelerometer is approximately between 40g to 400g. Accelerometer is known for its expensiveness. There is a need to find an alternative sensor that can exhibit low cost operation with character that can overwrite the defect point attached to accelerometer.

SCOPE

The study shall be conducted in two ways:

- Using finite element method via simulation (ANSYS).
- Using vibration test via experiment.

OBJECTIVE

- To verify the result with simulation
- To determine the piezoelectric film sensor data over accelerometer

METHODOLOGY

The experiment technique is Single Input Single Output (SISO) method. Accelerometer and piezoelectric will act as sensor to detect the signal. See Figure 3.

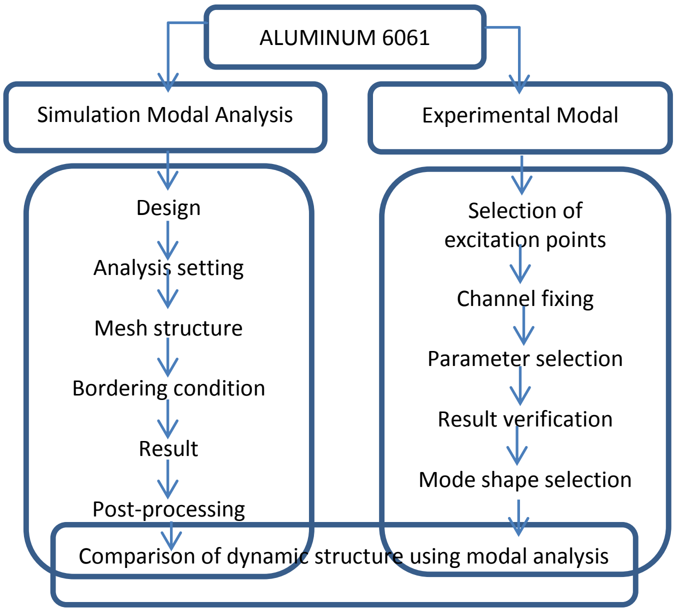

Figure 3: Experimental Methodology

EXPERIMENTAL PROCEDURE

The experimental specimen of Al6061 is shown as follows:

a) Rectangular (450 x 200 x 1.5mm)

Two types of sensors are accelerometer and piezoelectric film. The accelerometer model used was Endevco 751-100 USA with resonance frequency 50kHz. The piezoelectric is from polymer, usually polyvinylidene fluoride (PVDF), with output voltage 10mV~100V. The impact hammer which executes impact force onto Al6061 has force range 0~22.7kgf and output voltage 5V. DAQ, is the device which converts analog waveforms into digital values for signal processing. Here, the model used was National Instrument DAQ, NI9234 4-channel 5V 24 Bit with 1 slot USB.

Modal Analysis Method: Simulation

First, the shape shall be designed using Autodesk Inventor (rectangular shape) (Fig. 4). Next, conduct an analysis setting of basic parameter on the specimen material (aluminum) such as Young Modulus, Poisson ratio and density. As for ANSYS, the first step is selection of material (aluminum) and the parameter shall be fixed automatically. Then, next step is generating mesh structure for every shape (eg. selection of size etc.). Finally, result modification for the best outcome shall be done to obtain natural frequency and mode shape.

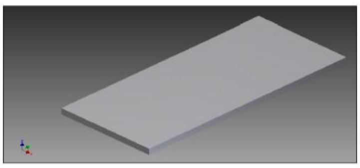

Figure 4: Shape design using Autodesk Inventor

Modal Analysis Method: Experimental work

Connect piezoelectric film to second channel and accelerometer to third channel of DAQ. The excitation point and the sensor (three different locations) showed on Figure 5. The work follows ASTM regulation.

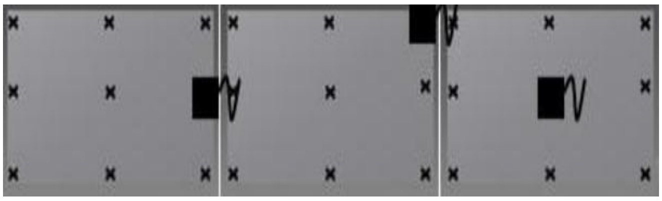

Figure 5: Sensor three-different position

For mode shape selection, MATLab application shall take place. Import the data into 'workplace'. Type the appropriate command to plot the desired graph. From the graph, mode shape and natural frequency for every data can be determined.

RESULT AND DISCUSSION

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

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

or

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

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

Modal Analysis Method: Simulation

In simulation modal analysis, the work shall be analysed using ANSYS WORKBENCH software.

Simulation result for rectangular shape specimen

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

Table 1: Simulation analysis of natural frequency for rectangular shape specimen

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

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Referring to Table 1, analysis simulation result stated that there were 6 natural frequencies and mode shapes exist in rectangular shape aluminum specimen in range 0 to 2000Hz. For mode 1, natural frequency was 291.72Hz and increased from mode 2 to mode 6. At mode 6, natural frequency was 1952.40Hz.

Modal Analysis Method: Experimental work

Parameter for this experimental work is sensor. To ensure the accuracy of the result, excitation on every point shall be done repeatedly to extract the precision reading. This work is conducted following ASTM accordingly.

Experimental result for rectangular shape specimen

From frequency function graph, mode shape and its natural frequency for rectangular shape specimen can be obtained. Refer Table 2 and Table 3.

Table 2: Natural frequency from analysis of piezoelectric film sensor for rectangular shape 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 shape 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

Comparison in dynamic structure characteristics of modal analysis between simulation and experimental work

The comparison in dynamic structure is conducted by finding the difference and error ratio between accelerometer vs simulation and accelerometer vs piezoelectric film sensor. Accelerometer result will act as the foundation for actual value to compare with. This is because modal analysis experimental work is frequently utilized an accelerometer as a sensor due to its accurateness.

The difference between natural frequency for accelerometer and piezoelectric film is represented by $f_1 - f_2$ and difference between natural frequency for accelerometer and simulation is represented by $f_1 - f_3$ (Table 4).

Upon obtaining the error between accelerometer and piezoelectric film sensor, graph natural frequency vs each mode for accelerometer and piezoelectric film sensor will be plotted. By finding the equation from the graph, the coefficient between accelerometer and piezoelectric film sensor will be obtained. Thus, the relation between accelerometer and piezoelectric film sensor will be determined.

Relation between natural frequency of accelerometer and piezoelectric film for rectangular shape specimen

Table 4: Comparison between accelerometer, piezoelectric film sensor and simulation for rectangular shape specimen

	Natural frequency (Hz)						
ModShp.	Acce. meter (f_1)	Piezo film (f_2)	Simul. (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	272.00	258.33	291.72	13.67	19.72	5.00	7.30
2	521.33	524.67	647.63	3.33	126.30	0.60	24.20
3	913.00	884.33	841.42	28.67	71.58	3.10	7.80
4	1080.67	1141.67	1465.00	61.00	384.33	5.60	35.60
5	1437.33	1399.67	1554.00	37.67	116.67	2.60	8.10
6	1803.00	1752.33	1952.40	50.67	149.40	2.80	8.30

As overall, percentage of error for accelerometer vs piezofilm was satisfying with error less than 10%. The biggest error was just at mode 4 with 5.60%. 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 compare 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 384.33Hz, 149.40Hz, 126.30Hz and 116.67Hz respectively.

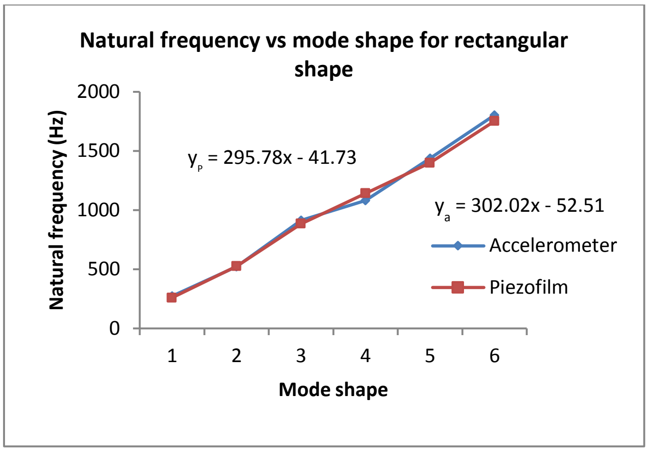

Figure 6: Natural frequency vs mode shape for rectangular shape specimen

Referring to Figure 6, the equation of gradient for accelerometer and piezofilm is:

Accelerometer: $y_a = 302.02x - 52.51$

Piezofilm: $y_p = 295.78x - 41.73$

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

$y_a = 1.02y_p - 9.90$

Factors for result inaccuracy

As overall, the results obtained were satisfying. Nonetheless, there were also error occurred. The error therefore contributed in result inaccuracy. Factors that might be taken into consideration:

a) For inaccuracy in simulation, due to meshing was inappropriate, such like improper type of meshing used. Some mesh may be not suitable for certain shape.

b) For inaccuracy in simulation, the sensor mass was not taken into consideration in simulation for aluminium component. The sensor mass might cause the simulation result in disarray because the component used was light.

c) For inaccuracy in experimental work, this might occur during hammer impact where the force excited for every node was not similar one another. Every excitation manually by hand was difficult to ensure the impact force were the same for every node.

d) For inaccuracy in experimental work, was sensor location on aluminium component. This is because may be the location of the sensor might be not suitable. This could contribute error in average result.

CONCLUSION

In this study, the simulation analysis and experimental work have been successfully done to obtain dynamic characteristics such like natural frequency and mode shape for Al6061 component in rectangular shape. The comparison between accelerometer with simulation and comparison between accelerometer with piezoelectric film sensor have been successfully executed. The frequency range applied in these made shape analysis is 0-2000Hz. Altogether there were 6 natural frequencies and mode shapes were determined in that range.

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

By obtaining the relation between accelerometer and piezoelectric film sensor, one could determine the natural frequency on aluminum component when engage with piezoelectric film sensor in the future. More work need to be done in order to obtain acceptable result for piezofilm to act on behalf of accelerometer in the future.

By understanding the natural frequency in the component, vibration range could be control. This could assist in designing or manufacturing component which can avoid the component from vibrating on its natural frequency thus eliminating the risks of resonance occurrence. As a result, damage control can be applied and lost in cost and life will be minimized.

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