AN INVESTIGATION OF MODAL ANALYSIS FOR AL6061 BETWEEN PIEZOELECTRIC FILM SENSOR AND ACCELEROMETER

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ABSTRACT

An experiment was conducted to determine modal parameters such as natural frequencies and mode shapes of aluminum 6061 (Al6061). A free dynamic vibration analysis was conducted to obtain the parameters. Al6061 was chosen as the experiment component mainly because of its wide application in automotive industries. Theoretically, if the component vibrates and produce frequency coherence with the natural frequency, resonance frequency will occur which can lead to structural failure. Modal analysis study was conducted by using both simulation and experimental method to compare their outcome. Simulation was conducted via ANSYS software while impact hammer testing was done for experimental work to determine the vibration parameter. Piezoelectric film and accelerometer were used as the sensor. The result obtained from simulation showed that frequencies for mode shape 1, 2 and 3 for circle shape were 134.60Hz, 324.73Hz and 727.52Hz. The result obtained from accelerometer showed that frequencies for mode shape 1, 2 and 3 for circle shape were 158.67Hz, 421.33Hz and 625.00Hz. Finally, the result captured from piezoelectric film sensor appeared that frequencies for mode shape 1, 2 and 3 for circle shape were 141.00Hz, 321.00Hz and 504.33Hz. There was a good results agreement between simulation and experimental work outcome.

Keywords: Modal parameters; natural frequencies; mode shapes; Al6061; resonance frequencies; modal analysis; accelerometer; piezoelectric film sensor.

INTRODUCTION

Experimental Modal Analysis (EMA) is applied to determine modal parameters which determine natural frequency, mode shape and damping ratio. The knowledge of structural modal parameters is a must in order to define the natural frequencies, mode shapes and modal damping ratios [1]. EMA is a well-known procedure to determine modal analysis [2]. 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]. 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 and actuators and sensors [4-6]. Due to its character, piezo materials are imminent in fields that require large force, fast response and cost-effective nature of work [7-9]. In some extent, piezo contribute to micro-vibration that can generate large vibration amplitude up to 100μm at the frequency of 1,100Hz [10]. 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 [11]. Piezoelectric effect based on its characteristics could therefore give good attribute to modal identification.

In this study, accelerometer is used as sensor to investigate modal parameter. One of its weak point is accelerometer is heavier compared to other sensor. The range in weight for accelerometer is approximately between 40g to 400g. When testing was to be conducted on small structure, the accuracy of experiment result will be affected. Therefore, the result obtained would be inaccurate.

The objectives of this study are:

- To develop alternative method of modal analysis by using piezoelectric sensor in determining natural frequency of Al6061.
- To obtain dynamic characteristics of natural frequency for Al6061 based on simulation vs accelerometer and piezoelectric film sensor.

Meanwhile, the scope of the study shall be conducted in two ways:

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

The result obtained from ANSYS represent structural dynamic characteristics via simulation comprises of natural frequency and mode shape. The study shall be extended by conducting modal analysis experimentally on the testing component. Finally, comparison shall be made between these two outcomes (simulation and experimental work).

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) [12]. Modal Analysis is derived originally from Equation of Motion which stated that every motion occurs is incorporated with vibration alongside it [13]. See Fig. 1.

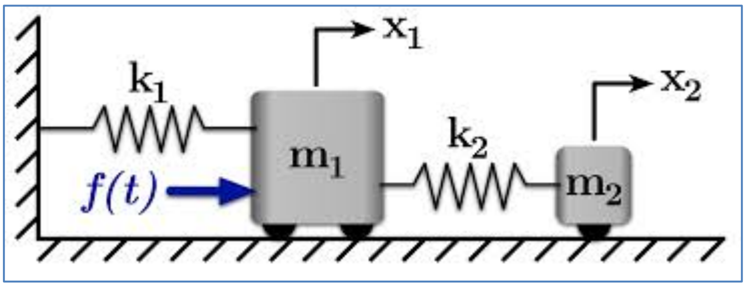


Fig. 1: Spring equation of motion [13].

$$m_1\ddot{x}_1 + (k_1 + k_2)x_1 - k_2x_2 = 0 \quad (1)$$
$$m_2\ddot{x}_2 - k_2x_1 + k_2x_2 = 0 \quad (2)$$

or in matrix,

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

or

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

where,

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

From here, we can derive the natural frequency equation.

$$\omega_n = \sqrt{\frac{k}{m}} \tag{5}$$

where,

ω_n = natural frequency.

Here, natural frequency appears which shall bear with mode shapes once the vibration takes place. Mode shapes on the other hand can be obtained through displacement (eigenvectors) that usually subjected to scaling procedures, which referred to as mass-normalization with respect to the orthogonality properties of the mass-normalized modal matrix [14].

Piezoelectric

Piezoelectric (See Fig. 2) is the electric charge that accumulates in certain solid materials (such as crystals and certain ceramics) in response to applied mechanical stress [15]. Piezoelectricity means electricity resulting from pressure [16]. Piezoelectricity was discovered by French physicist, Jacques and Pierre Curie [17]. The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and electrical state in crystalline materials with no inversion symmetry [18]. Lead zirconate titanate crystals generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension. Conversely, those same crystals will change about 0.1% of their static dimension when an external electric field is applied to the material [19].

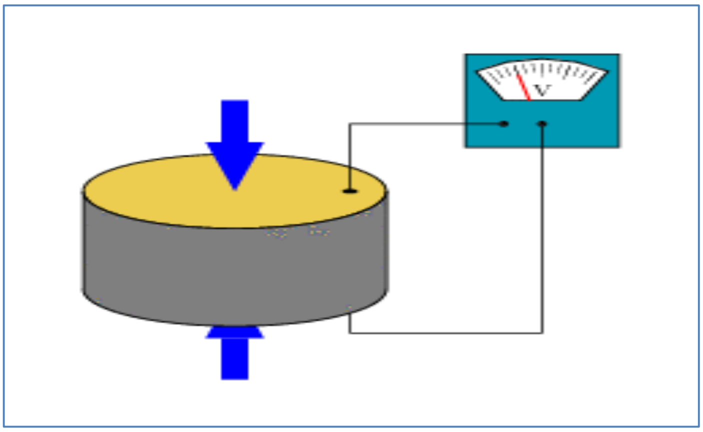


Fig. 2: A piezoelectric disk generates a voltage when deformed [19].

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

$$\boldsymbol{D} = \boldsymbol{\varepsilon E} \rightarrow D_i = \varepsilon_{ij} E_j \tag{6}$$

where,

$\boldsymbol{D}$ is the electric charge density displacement (electric displacement),
$\boldsymbol{\varepsilon}$ is the permittivity,
$\boldsymbol{E}$ is the electric field strength.

Hooke's Law:

$$\boldsymbol{S} = s\boldsymbol{T} \rightarrow S_{ij} = s_{ijkl} T_{kl} \tag{7}$$

where,

$\boldsymbol{S}$ is the strain,
$\boldsymbol{s}$ is the compliance,
$\boldsymbol{T}$ is the stress,
i,j,k,l is the imaginary unit (of linear independence 1, 2,…, n).

There are various materials that exhibit piezoelectricity, but mostly used in engineering application mainly are Piezo Zirconium Titanate (PZT) (synthetic ceramics) and Polyvinylidene Fluoride (PVDF) (polymers).

METHODOLOGY

The purpose of this study is to determine the natural frequency and mode shape of Al6061. Impact hammer shall be used by exciting on one point to another to generate signal. Here, accelerometer and piezoelectric will act as a sensor to detect the signal. The signal shall be sent to computer for analysis and the result from these sensors will be analysed. Furthermore, simulation testing by using ANSYS shall be conducted via finite element method. See Fig. 3.

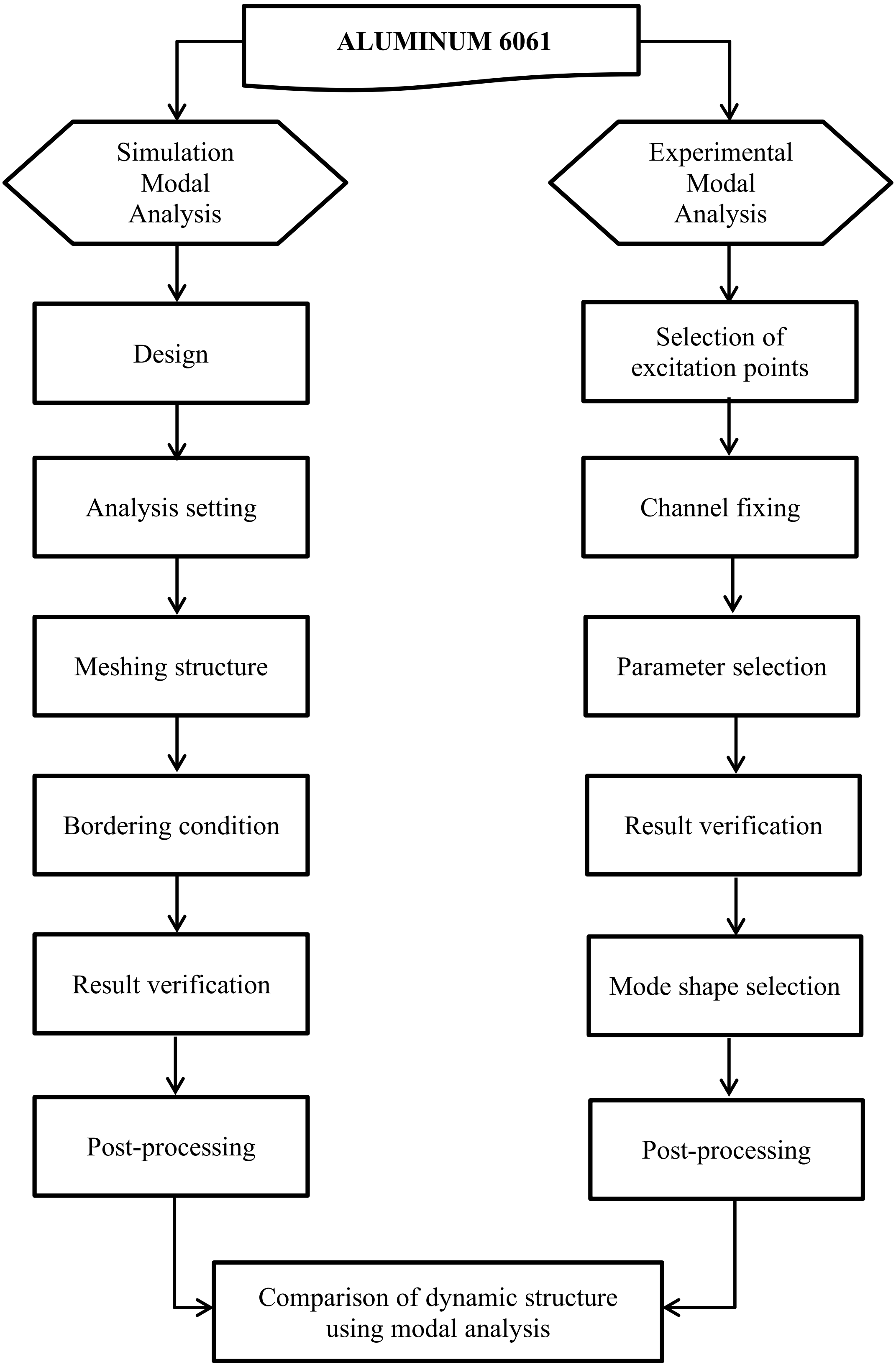


Fig. 3: Experimental Methodology.

Simulation Modal Analysis

First, the circle shape shall be designed using Autodesk Inventor. Next, conduct an analysis setting of basic parameter on the specimen material (Al6061) such as Young Modulus, Poisson ratio and density. As for ANSYS, the first step is the selection of material (aluminum) and the parameter shall be fixed automatically.

Then, the next step is generating mesh structure for the shape (eg. selection of size etc.). Fig. 4 shows the mesh structure of the shape. Furthermore, bordering condition and fixed support were set by assuming the back surface of the specimen. Finally, result modification for the best outcome shall be done to obtain natural frequency and mode shape. Here, the parameter verification such as numbers of mode shapes needed from deformation can be applied. The process can extract shifting magnitude and natural frequency of the structure. It also can verify mode shapes transition for every natural frequency available in aluminum structure.

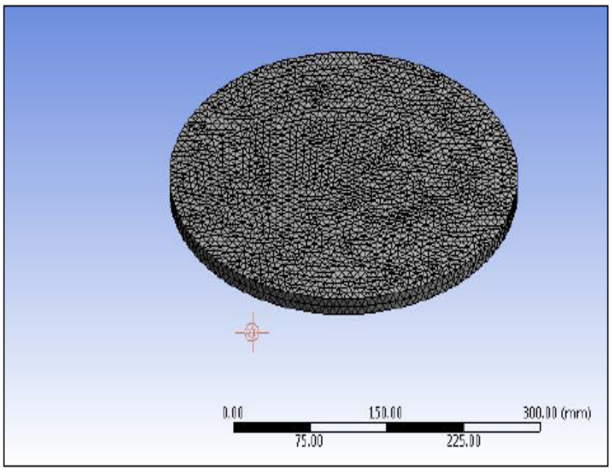


Fig. 4: Mesh structure for every shape.

Experimental Modal Analysis

Initially, points of excitation as knocking point by impact hammer must be decided. Next, by using marker, the excitation point will be spotted (Fig. 5). Channel fixing of impact hammer then shall be installed on DAQ. Then, connect piezoelectric film to the second channel and accelerometer to third channel of DAQ. The DAQ shall be connected to computer. The sensor will be positioned in three different points on the specimen.

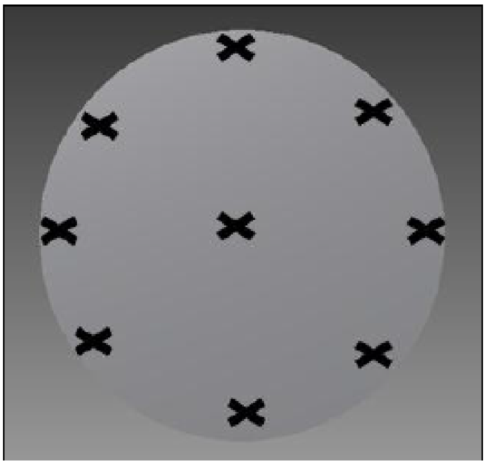


Fig. 5: Excitation point.

For parameter selection, start the Impact Hammer software on computer. Out of four channels, make sure there are only three channels activated (impact hammer, piezoelectric and accelerometer channel). First channel stands for force, second channel represents voltage and third channel stands for acceleration. Set the minimum sample rate and block size to 51200. Determine the project name on the folder. Before first knock, press 'run'. When first excitation starts, the sensor will send the signal and trigger will appear on screen. Amplitude of each trigger will be recorded. 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 result, mode shape and natural frequency for every data can be determined.

Experimental procedure

The experimental specimen of Al6061 was fabricated as follows:

a) Circle (350mm in diameter, 1.5mm thickness)

Two types of sensors are accelerometer and piezoelectric film. The accelerometer model used was Endevco 751-100 USA. The piezoelectric film is laminated to a sheet of polyester. The dual wire lead attached to the sensor allows a circuit to produce the signal. The piezoelectric is from polymer, usually polyvinylidene fluoride (PVDF), model LDT1-028K, USA. The impact hammer which executes impact force onto Al6061 is modelled SN LW31881, PCB 086C03, USA.

Meanwhile, the data acquisition system which processes the sampling signal that measure actual physical condition and converting the resulting sample into digital numeric values. Abbreviated as DAQ, the device converts analog waveforms into digital values for processing. DAQ include sensor, signal circuit, analog to digital converter. DAQ are controlled by software programs developed using general purpose programming languages such as LabVIEW, Fortran etc. Here, the model used was National Instrument DAQ, NI9234.

RESULTS 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:

$$\text{Percentage error} = \frac{|f_1 - f_2|}{f_1} \times 100\% \quad (8)$$

or

$$\text{Percentage error} = \frac{|f_1 - f_3|}{f_1} \times 100\% \quad (9)$$

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

Simulation Modal Analysis

In simulation modal analysis, center plane surface for mesh aluminum, material characteristics clarification shall be processed and analysed using ANSYS software. Here, the analysis result of natural frequency and mode shape for the specimen will be shown.

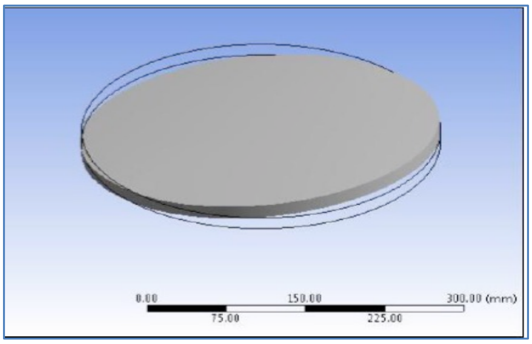
Simulation result for circle shape specimen

Table 1 below shows the result of simulation analysis of natural frequency for circle shape specimen. Fig. 6 showed the mode shape for the same specimen.

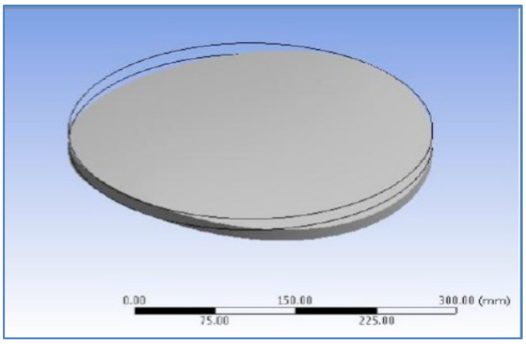
Table 1: Simulation analysis of natural frequency for circle shape specimen.

Mode shape	Natural frequency [Hz]
1	134.60
2	324.73
3	727.52
4	921.26
5	1074.30
6	1491.20

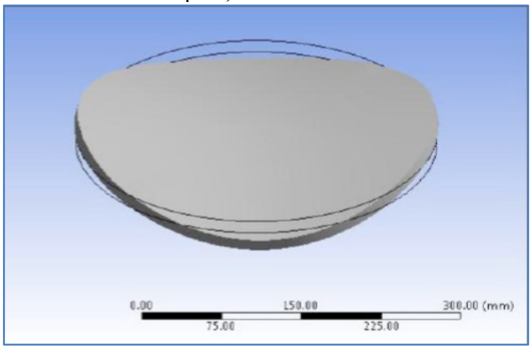
Referring to Table 1, analysis simulation result stated that there were 6 natural frequencies and mode shapes exist in circle shape aluminum specimen in range 0 to 2000Hz. For mode 1 until mode 6, natural frequency obtained was 134.60Hz, 324.73Hz, 727.52Hz, 921.26Hz, 1074.30Hz and 1491.20Hz respectively. The value increased from mode 1 until mode 6.



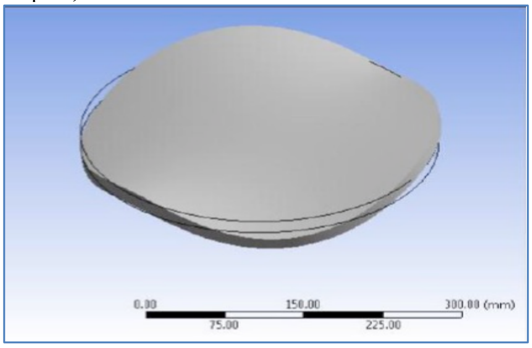
Mode shape 1, 134.60Hz



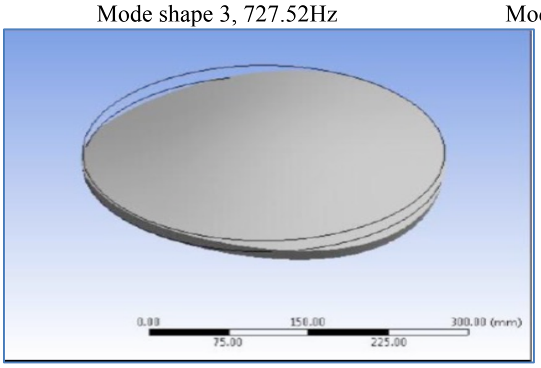
Mode shape 2, 324.73Hz



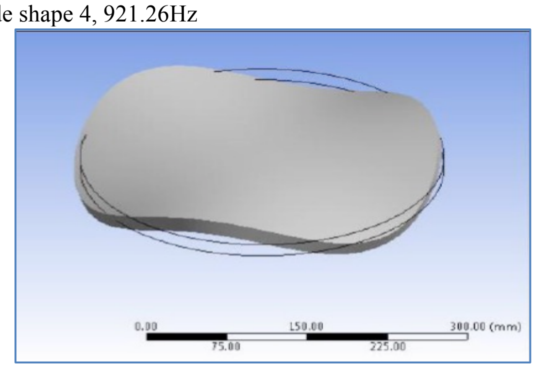
Mode shape 3, 727.52Hz



Mode shape 4, 921.26Hz



Mode shape 5, 1074.30Hz



Mode shape 6, 1491.20Hz

Fig. 6: Mode shape for circle shape specimen.

Experimental Modal Analysis

IMPACT HAMMER software was used to analyse the experimental result. Altogether there were 9 knocking points chosen as excitation point. Parameter for this experimental work is sensor. Therefore, there will be 2 types of sensor namely piezoelectric film and accelerometer to be utilised for the specimen. Hence, to gain average result, the sensors shall be located at 3 different points. The piezoelectric film and accelerometer will be attached to these 3 points for the circle shape. The result obtained will be averaged and analysed to get the final result. To ensure the accuracy of the result, excitation on every point shall be done repeatedly to extract the precision reading. The work is conducted following ASTM accordingly.

Experimental result for circle shape specimen

From frequency function graph, mode shape and its natural frequency for circle shape specimen can be obtained. Table 2 and Table 3 showed the result of natural frequency for every mode shape for piezoelectric film sensor and accelerometer respectively.

Table 2: Natural frequency from analysis of piezoelectric film sensor for circle shape specimen.

Mode shape	Natural Frequency [Hz]			
	Point 1	Point 2	Point 3	Average
1	144	143	136	141.00

2	362	357	244	321.00
3	520	515	478	504.33
4	804	1066	972	947.33
5	1191	1158	1277	1208.67
6	1453	1528	1477	1486.00

Table 3: Natural frequency from analysis of accelerometer for circle shape specimen.

Mode shape	**Natural Frequency [Hz]**			
	Point 1	Point 2	Point 3	Average
1	204	128	144	158.67
2	352	435	477	421.33
3	492	644	739	625.00
4	877	1098	963	979.33
5	1096	1163	1145	1134.67
6	1574	1598	1489	1553.67

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

Natural frequency for every mode shape transformation will be compared for the structure from error ratio. Simulation result will act as the foundation for actual value to compare with. This is because simulation modal analysis is always being based for comparison with experimental work. The natural frequency for simulation is represented by f_1, natural frequency for accelerometer f_2 and natural frequency for piezofilm f_3 respectively (refer Table 4). The difference between natural frequency for simulation vs accelerometer is represented by $f_1 - f_2$ and difference between natural frequency for simulation vs piezoelectric film is represented by $f_1 - f_3$.

Upon obtaining the error between simulation vs accelerometer and simulation vs piezoelectric film sensor, the relation among simulation, accelerometer and piezoelectric film sensor will be determined.

Relation between natural frequency of accelerometer and piezofilm for circle shape specimen

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

Mode shape	**Natural frequency [Hz]**					Error 1 (%)	Error 2 (%)
	Simulation (f_1)	Accelerometer (f_2)	Piezofilm (f_3)	Diff. 1 $\lvert f_1 - f_2 \rvert$	Diff. 2 $\lvert f_1 - f_3 \rvert$	$\frac{f_1 - f_2}{f_1}$	$\frac{f_1 - f_3}{f_1}$
1	134.60	158.67	141.00	24.07	6.40	17.88	4.75
2	324.73	421.33	321.00	96.60	3.73	29.75	1.15
3	727.52	625.00	504.33	102.52	223.19	14.09	30.68
4	921.26	979.33	947.33	58.07	26.07	6.30	2.83
5	1074.30	1134.67	1208.67	60.37	134.37	5.62	12.51
6	1491.20	1553.67	1486.00	62.47	5.20	4.19	0.35

For simulation vs accelerometer, the difference of mode shapes (mode 1 to mode 6) based on natural frequency were 24.07Hz, 96.60Hz, 102.52Hz, 58.07Hz, 60.37Hz and 62.47Hz respectively. Percentage of error for simulation vs accelerometer (mode 1 to mode 6) showed 17.88%, 29.75%, 14.09%, 6.30%, 5.62% and 4.19% respectively.

For simulation vs piezofilm, the difference of mode shapes (mode 1 to mode 6) based on natural frequency were 6.40Hz, 3.73Hz, 223.19Hz, 26.07Hz, 134.37Hz and 5.20Hz respectively. Percentage of error for simulation vs piezofilm (mode 1 to mode 6) showed 4.75%, 1.15%, 30.68%, 2.83%, 12.51% and 0.35% respectively.

As overall, percentage of error for simulation vs accelerometer was satisfying. The highest error was at mode 2 with 29.75% followed by error at mode 1 with 17.88%. The minimum error was at mode 6 with 4.19%. Percentage of error for simulation vs piezofilm was also satisfying. The highest error was at mode 3 with 30.68% followed by error at mode 5 with 12.51%. The minimum error was at mode 6 with 0.35%. Refer Table 4.

Factors for results 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, there is a tendency of error in setting the material characteristics such like Young's modulus, Poisson ratio and density for aluminum. This is because the information for material characteristics installed in software was arranged in range. Therefore, simulation modal analysis by using finite element method via ANSYS software could not guarantee the accurate and precision result.
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. Therefore, the force was inconsistent. This will caused error and affect the quality of coherence function reading. The signals were hard to sustain at each experiment. The data absorbed by piezofilm would become inconsistent. Thus, error occurred in frequency function data collection.
d) For inaccuracy in experimental work, was sensor location on aluminum component. Although the sensor were located at 3 different location and average result were taken, the accurateness could not be guaranteed. This is because may be the location of the sensor might be not suitable. Hence improper readings were taken for analysis. This could contribute error in average result.

CONCLUSIONS

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 of the circle shape. The comparison between simulation with accelerometer and comparison between simulation with piezoelectric film sensor have been successfully executed. The frequency range applied in these mode 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 among simulation as base, accelerometer and piezoelectric film as sensor in determining the natural frequencies and mode shapes in vibration. By obtaining the relation between simulation, accelerometer and piezoelectric film sensor, one could determine the natural frequency on aluminum component when engage with piezoelectric film sensor 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.

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