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Modal And FRF Based Updating Methods For The Investigation Of The Dynamic Behaviour Of A Plate

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ABSTRACT

Accurate finite element models of engineering structures are of paramount importance to dynamicists to be used in predicting the dynamic behaviour of the structures. In order to have a finite element model that can accurately predict the structural behavior, measured data obtained from the test structure can be used to reconcile the finite element model and the procedures involved the reconciliation is model updating. The model updating methods, in general, are classified into two different classes which are the modal based updating and frequency response function (FRF) based updating. This research was aimed to investigate the efficiency, accuracy and economics between the FRF based and the Modal based updating on a thin aluminium plate structure. In this study, the measured results from the structure were obtained from the Experimental Modal Analysis (EMA) via LMS SCADAS. The structure was tested using an impact hammer and roving accelerometers. The test was performed under free-free boundary conditions. The initial finite element model of the aluminum plate was constructed and improved using both model updating methods. Then, the initial finite element results were compared with the experimental results for validation. The comparison of results revealed that the Modal based updating showed better capability to be used in

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reconciling the FE resonance frequencies to the measured counterparts with 6.02 percent of reduction in total error in comparison with the FRF based updating with 8.39 percent. Meanwhile, FRF based updating recorded much better capability to match the FE excitation and resonance frequencies with the measured ones.

Keywords: *finite element method, model updating, modal testing, experimental modal analysis, normal modes analysis*

Nomenclature

K	Stiffness Matrix
M	Mass Matrix
$\boldsymbol{\omega}$	Natural Frequency
$\boldsymbol{f}$	Force Vector
h	Frequency Reponse Function data
p	Updating Parameter

Introduction

Precise description of the dynamic behaviour (natural frequencies and mode shapes) of engineering structures is of paramount importance to the dynamicist community. Usually, there is a great deal of uncertainty about the selection of suitable methods to be used for the analysis. This is because time to market products is shrinking. Experimental analyses usually are very costly and long time consuming to be performed as compared to numerical simulations using the finite element method[1], [2] which is one of the most versatile numerical methods. However, it is found that the finite element results are frequently not in good agreement with experimental counterparts due to the invalid assumptions made in the finite element modelling[3]. One way to refine, correct or update the finite element model through which the dynamic behaviour of a structure is predicted using model updating methods[4]. Model updating methods are a systematic procedure of reconciling a finite element model in the light of measured results[5].

Model updating methods can be classified into two types which are frequency response function (FRF) based updating method and modal based updating[6]. However, it is known that the use of FRF data has advantages over that of modal data, because the former contains information from the complete frequency spectrum, while the latter is usually extracted from a limited number of frequency points around the FRF resonant peaks with the inherent numerical errors[7].

The subject of model updating methods has received much attention of many researchers[8]–[10]. For instance, Abdul Rani [11] investigated the reliable element connector for laser spot welded structure and used modal based updating method to improve the initial finite element results. Lim and Evans [12] proposed model updating by using an incomplete set of measured FRF data directly to update analytical model. Lim and Zhu [13] extended updating methods via FRF based method by including structural damping in the procedure of model updating. However, there is no information available in a direct comparative study regarding the advantages of FRF based updating over modal based updating.

In this paper, a comparative study of the two model updating methods is performed based on the measured and predicted results of an aluminium plate. The main objectives of the comparison are:

i) To investigate the accuracy, efficiency and economics of both methods.

ii) To provide a framework for researchers or engineers.

Modelling and analysis of the plate structure

The finite element model of the plate structure was constructed using NASTRAN software, as shown in Figure 1. In this work, the plate structure was modelled using QUAD4 shell elements with 3000 elements and 3111 nodes. The size of the elements used for plate structure was 5mm and the element type was 2D shell element.

The natural frequencies and mode shapes of the finite element model of the structure were predicted using normal modes analysis in which the model properties of the finite element models were defined as follows: the Young's modulus = 70GPa, Poisson's ratio = 0.35 and density = 2680 kg/m^3. In the normal modes analysis, the modes of interest were the first ten elastic modes, starting from 0 to 1000 Hz.

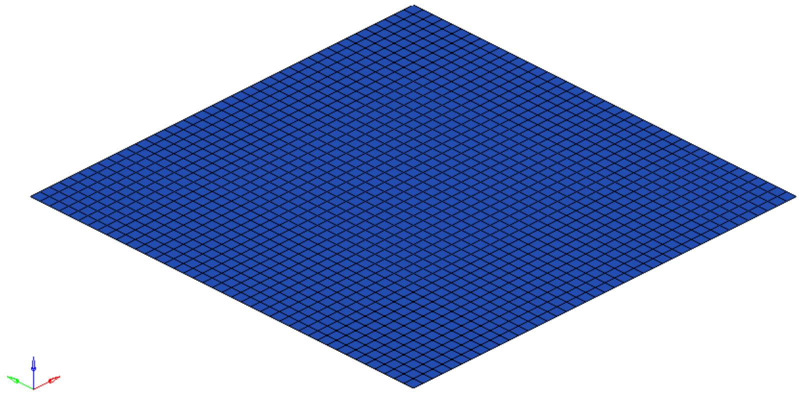


Figure 1: The finite element model of plate structure

FRF based updating method

The dynamic equilibrium equation for the updated model as described by Aimin [6] is

$$\left(\mathbf{K}^{\mathbf{n+1}} - \boldsymbol{\omega}_{\mathbf{i}}^{2}\mathbf{M}^{\mathbf{n+1}}\right)\bar{\mathbf{h}}_{\mathbf{i}} = \mathbf{f} \tag{1}$$

And for the current FE model is:

$$\left(\mathbf{K}^{\mathbf{n}} - \boldsymbol{\omega}_{\mathbf{i}}^{2}\mathbf{M}^{\mathbf{n}}\right)\mathbf{h}_{\mathbf{i}}^{\mathbf{n}} = \mathbf{f} \tag{2}$$

Where **K** and **M** are stiffness matrix and mass matrix; $\boldsymbol{\omega}_{\mathbf{i}}$ denotes the chosen **i** frequency; $\bar{\mathbf{h}}_{\mathbf{i}}, \mathbf{h}_{\mathbf{i}}^{\mathbf{n}}$ are the FRF of the experimental and current models; **f** is the excitation vector. While $\mathbf{K} - \boldsymbol{\omega}^{2}\mathbf{M} = \mathbf{Z}$. From equations (1) and (2) display

$$(\mathbf{Z}_{\mathbf{i}}^{\mathbf{n+1}} - \mathbf{Z}_{\mathbf{i}}^{\mathbf{n}})\bar{\mathbf{h}}_{\mathbf{i}} = \mathbf{Z}_{\mathbf{i}}^{\mathbf{n}}(\mathbf{h}_{\mathbf{i}}^{\mathbf{n}} - \bar{\mathbf{h}}_{\mathbf{i}}) \tag{3}$$

Or

$$\mathbf{H}_{\mathbf{i}}^{\mathbf{n}}\Delta\mathbf{Z}_{\mathbf{i}}\bar{\mathbf{h}}_{\mathbf{i}} = \mathbf{h}_{\mathbf{i}}^{\mathbf{n}} - \bar{\mathbf{h}}_{\mathbf{i}} \tag{4}$$

With

$$\mathbf{H}_{\mathbf{i}}^{\mathbf{n}} = (\mathbf{Z}_{\mathbf{i}}^{\mathbf{n}})^{-1}, \Delta\mathbf{Z}_{\mathbf{i}} = \mathbf{Z}_{\mathbf{i}}^{\mathbf{n+1}}\mathbf{Z}_{\mathbf{i}}^{\mathbf{n}} \tag{5}$$

The updated dynamic stiffness matrix, $\mathbf{Z_i^{n+1}}$, is defined as a function of the updating parameters **p,** and can be expressed as a Taylor expansion of the current dynamic stiffness matrix $\mathbf{Z_i^n}$ as follows:

$$\mathbf{Z_i^{n+1}} = \mathbf{Z_i^n} + \Delta\mathbf{Z_i} = \mathbf{Z_i^n} + \frac{\partial \mathbf{Z_i^n}}{\partial \mathbf{p}}\mathbf{p} + \mathbf{o}(\mathbf{p^2}) \tag{6}$$

Retaining only first order terms and substituting for $\Delta\mathbf{Z_i}$ in (4) lead to

$$\mathbf{A_i p} = \mathbf{b_i} \tag{7}$$

With

$$\mathbf{A_i} = \mathbf{H_i^n}\frac{\partial \mathbf{Z_i^n}}{\partial \mathbf{p}}\bar{\mathbf{h}}_\mathbf{i} = \mathbf{H_i^n}\left[\frac{\partial \mathbf{Z_i^n}}{\partial \mathbf{p_1}}\bar{\mathbf{h}}_\mathbf{i}, \frac{\partial \mathbf{Z_i^n}}{\partial \mathbf{p_2}}\bar{\mathbf{h}}_\mathbf{i}, \dots, \frac{\partial \mathbf{Z_i^n}}{\partial \mathbf{p_{Np}}}\bar{\mathbf{h}}_\mathbf{i}\right] \tag{8}$$

$$\mathbf{b_i} = \mathbf{h_i^n} - \bar{\mathbf{h}}_\mathbf{i} \tag{9}$$

Convergence is performed when the FRF value $\mathbf{h_i^n}$ of the updated model becomes ideally identical or close to the measured $\bar{\mathbf{h}}_\mathbf{i}$, corresponding to a minimization of output residue at any frequencies $\boldsymbol{\omega}_\mathbf{i}$**:**

$$\min_{\mathbf{p}} ||\bar{\mathbf{h}}_\mathbf{i} - \mathbf{h_i^n}||^2 \tag{10}$$

In order to exploit the redundancy of the experimental information, equations 7 until 9 should be repeated for a set of frequencies $\omega_i, \mathbf{i} = \mathbf{1} \dots \mathbf{N_{fr}}$($\mathbf{N_{fr}}$ is the number of chosen frequencies) spanning extensive frequency range. This leads to the following system

$$\begin{bmatrix} \mathbf{A_1} \\ \cdots \\ \mathbf{A_{N_{fr}}} \end{bmatrix} \mathbf{p} = \begin{bmatrix} \mathbf{b_1} \\ \cdots \\ \mathbf{b_{N_{fr}}} \end{bmatrix} \tag{11}$$

which can be simply written as

$$\mathbf{A_h p} = \mathbf{b_h} \tag{12}$$

Here, the index h means updating with FRF data **h**. Each row of the sensitivity matrix **A** in Eq. (8), defines the sensitivity of response at a particular DOF to the updating parameter **p**.

Modal based updating method

Starting from the dynamic equilibrium equation [6] and pre-multiplying it by r-th FE modal shape $\emptyset_r$

$$\boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}[\mathbf{K} - \boldsymbol{\omega}_\mathbf{r}^2\mathbf{M}]\boldsymbol{\emptyset}_\mathbf{r} = \mathbf{0} \tag{13}$$

Differentiating Eq. (13) with respect to updating parameter **p**

$$\frac{\partial \boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}}{\partial \mathbf{P}}[\mathbf{K} - \boldsymbol{\omega}_\mathbf{r}^2\mathbf{M}]\boldsymbol{\emptyset}_\mathbf{r} + \boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}\frac{\partial}{\partial \mathbf{p}}[\mathbf{K} - \boldsymbol{\omega}_\mathbf{r}^2\mathbf{M}]\boldsymbol{\emptyset}_\mathbf{r} + \boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}[\mathbf{K} - \boldsymbol{\omega}_\mathbf{r}^2\mathbf{M}]\frac{\partial \boldsymbol{\emptyset}_\mathbf{r}}{\partial \mathbf{p}} = \mathbf{0} \tag{14}$$

Due to Eq. (13) the first and third terms of Eq. (14) are zero and the term in the middle gives

$$\frac{\partial}{\partial \mathbf{p}}[\mathbf{K} - \boldsymbol{\omega}_\mathbf{r}^2\mathbf{M}] = \frac{\partial \mathbf{K}}{\partial \mathbf{p}} - \frac{\partial \boldsymbol{\omega}_\mathbf{r}^2}{\partial \mathbf{p}}\mathbf{M} - \boldsymbol{\omega}_\mathbf{r}^2\frac{\partial \mathbf{M}}{\partial \mathbf{p}} = \mathbf{0} \tag{15}$$

Finally one finds

$$\frac{\partial \boldsymbol{\omega}_\mathbf{r}^2}{\partial \mathbf{p}} = \boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}\left[\frac{\partial \mathbf{K}}{\partial \mathbf{p}} - \frac{\partial \boldsymbol{\omega}_\mathbf{r}^2}{\partial \mathbf{p}}\mathbf{M}\right]\boldsymbol{\emptyset}_\mathbf{r}/[\boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}\mathbf{M}\boldsymbol{\emptyset}_\mathbf{r}] = \frac{1}{\boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}\mathbf{M}\boldsymbol{\emptyset}_\mathbf{r}}\left[\boldsymbol{\emptyset}_\mathbf{r}^\mathbf{T}\frac{\partial \mathbf{Z}^\mathbf{r}}{\partial \mathbf{p}}\boldsymbol{\emptyset}_\mathbf{r}\right] \tag{16}$$

Similarly, the experimental natural frequency term $\bar{\boldsymbol{\omega}}_\mathbf{r}^2$ may be expressed as a Taylor expansion about the FE solution in terms of the updating parameter **p** (remaining only the first order);

$$\bar{\boldsymbol{\omega}}_\mathbf{r}^2 = \boldsymbol{\omega}_\mathbf{r}^2 + \frac{\partial \boldsymbol{\omega}_\mathbf{r}^2}{\partial \mathbf{p}}\mathbf{p} \tag{17}$$

By substituting Eq. (16) into Eq. (17), one may constitute a system of linear equations in natural frequency data analogue to the previous one Eq. (7) in the FRF data:

$$\mathbf{A}_\mathbf{r}\mathbf{p} = \mathbf{b}_\mathbf{r} \tag{18}$$

With

$$\mathbf{A_r} = -\frac{1}{\emptyset_r^T M \emptyset_r}\left[\emptyset_r^T \frac{\partial Z^r}{\partial p}\emptyset_r\right] = -\frac{1}{\emptyset_r^T M \emptyset_r}\left[\emptyset_r^T \frac{\partial Z^r}{\partial p_1}\emptyset_r, \emptyset_r^T \frac{\partial Z^r}{\partial p_2}\emptyset_r, \dots, \emptyset_r^T \frac{\partial Z^r}{\partial p_{NP}}\emptyset_r\right] \tag{19}$$

$$\mathbf{b_r} = \boldsymbol{\omega}_r^2 - \bar{\boldsymbol{\omega}}_r^2 \tag{20}$$

This may be repeated for $\mathbf{N_\omega}$ chosen modes to form $\mathbf{A_\omega p} = \mathbf{b_\omega}$, where $\mathbf{A_\omega} = [\mathbf{A_1} \quad \cdots \quad \mathbf{A_{N_\omega}}]^T$ and $\mathbf{b_\omega} = [\mathbf{b_1} \quad \cdots \quad \mathbf{b_{N_\omega}}]^T$

The linear equations of Eq. (18) may be inserted in the previous FRF updating equation Eq. (12) to form an enhanced updating system.

$$\mathbf{Ap} = \mathbf{b} \tag{21}$$

With

$$\mathbf{A} = \begin{bmatrix}\mathbf{A_h}\\ \mathbf{A_\omega}\end{bmatrix}, \; \mathbf{b} = \begin{bmatrix}\mathbf{b_h}\\ \mathbf{b_\omega}\end{bmatrix} \tag{22}$$

However, it should be pointed out that such a procedure may lead to numerical problem when solving the equation. It is due to the fact that the matrices A_h, A_ω result from different types of data so that they may be of very different order of magnitude, forcing some equations to dominate. Therefore, a numerical normalisation may be necessary.

The problem defined by Eq. (21) is generally over-determined: the number of equations (Nfr x Nfe + Nw) is usually much larger than that of updating parameters (Np). It can be solved simultaneously in least-squares sense by the application of SVD (singular value decomposition) technique to give a set of updated p-parameters

$$\mathbf{p} = \mathbf{A} + \mathbf{b} \tag{23}$$

Experimental modal analysis set up of the plate

In this study, experimental modal analysis was performed on a simple plate structure with the nominal thickness of 3 mm and the size of the plate 250 mm x 300 mm. The schematic diagram of the experimental modal analysis set-up is shown in Figure 2. The plate was discretized into several small elements. The purpose of the discretization was to have the appropriate number of the location of measuring points. The determination of the number of elements was carried out with the guidance from the results of modal parameters of the plate obtained from the finite element analysis. To simulate free boundary conditions springs and strings were used.

Prior to performing the experimental work, several factors related to the experiments such as the number of accelerometers and measuring points and excitation methods should be considered. In this study, the initial prediction of the dynamic properties of the test plate firstly performed to the test structure. Furthermore, the calculated natural frequencies and mode shapes are then used for the selection of the excitation points and the locations of measurement points of the test structure. The frequency bandwidth of interest was 0 to1000Hz.

In the experimental work, an impact hammer and roving accelerometers were used to measure the dynamic behaviour of the plate. A total of three accelerometers was used with one was fixed at the excitation point and the other two were roved to all measured nodes.

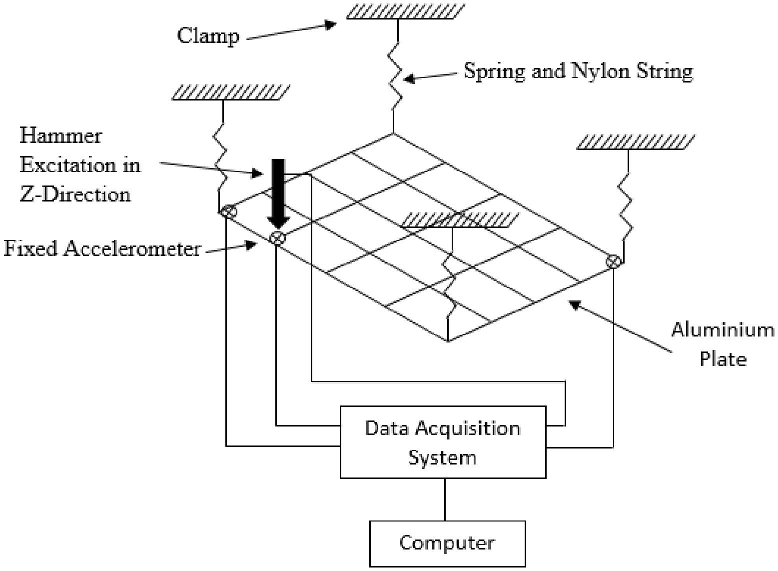


Figure 2: Schematic diagram of the experimental modal analysis setup of the plate

Results and Discussion

Predicted results obtained in previous studies [14]–[16] using the finite element method revealed that analytical results were not in good agreement with the experimental counterparts. As stated by Friswell [4], the disagreement was a result of the invalid assumptions about the model properties used in the finite element model of the structures. Therefore, finite element model updating methods have been widely used by researchers in order to improve the confidence in the analytical models.

In this study, two types of model updating methods which are modal based updating and FRF based updating were used in the attempt to reconcile the initial finite element model in the light of measured data. The predicted results obtained from the two methods and also the direct comparisons of the results are tabulated in Tables 1 and 2 respectively. Figure 3 shows two sets of FRFs obtained from the finite element method and experiment. The information from Figure 3 have been extracted into Table 2 to calculate the total error. Meanwhile, Table 3 depicts a direct comparison between the measured and predicted mode shapes of the plate.

From the comparisons of the results shown in Tables 1 and 2, it can be seen that the natural frequencies were successfully updated by using both model updating methods but the updated results were achieved with the different levels of accuracy. As can be seen from Table 1, all the ten modes obtained from the initial FE model were successfully adjusted in the light of the measured data. The achievement in the adjustment can be clearly seen in columns VI where the total error of the initial FE of 10.89 percent (column IV) was reduced to 6.02 percent. However, a sharp increment in the second mode of the updated FE was observed when each of the modes was compared with the experimental results (column II). The modal based updating method recorded the total error of 6.02 percent in comparison with the measured results. The greatest error was contributed by the second mode with the error of 1.56 percent. The other modes show good agreement with the experimental counterparts with the average error of below 1 percent for every mode. Meanwhile, it was found that the updated finite element model produced from the FRF based updating shows an increment in the total error with 3.2 percent higher than that of recorded from the modal based updating. The greatest error was contributed by the first mode with 2.23 percent and followed by the fourth and seventh modes with 1.52 percent. However, if the comparison of the results

(Table 2) was calculated based on the average error, only 0.92 percent was recorded which is still the acceptable level of accuracy.

Table 1: Comparisons of results of the natural frequencies of the aluminium plate between the measured, initial FE and modal based updating

Mode (I)	EMA (Hz) (II)	Initial FE (Hz) (III)	Error (%) (IV)	Modal Based Updating (Hz) (V)	Error (%) (VI)
1	126.45	129.79	2.64	127.36	0.72
2	173.30	172.78	0.30	170.60	1.56
3	270.57	270.33	0.09	270.08	0.18
4	312.29	318.34	1.94	313.60	0.42
5	360.07	363.54	0.96	358.25	0.51
6	506.76	511.00	0.84	509.61	0.56
7	612.90	624.77	1.94	616.79	0.63
8	621.85	627.54	0.92	619.67	0.35
9	727.46	727.45	0.00	724.38	0.42
10	823.80	834.22	1.26	829.30	0.67
	Total Error		**10.89**		**6.02**

FRF based updating method is very effective in the case of noisy and incomplete experimental data [17], but the direction of excitation is very important to prevent the co-ordinate mismatch. There are several advantages of using FRF based updating as discussed by [18], first, no modal analysis is required and identification errors are thus avoided. In addition, the technique is applicable to the structures with non-modal behaviour such as occurring in the cases of high damping and modal density. In these cases, the accurate determination of a reference modal model is probably at least as difficult as updating the finite element model. Moreover, it is possible to check a given solution by generating another one since the problem is over-determined due to the availability of FRF data of numerous excitation frequencies or frequency points. It is therefore possible to use statistical techniques to determine confidences parameters to interpret the results obtained.

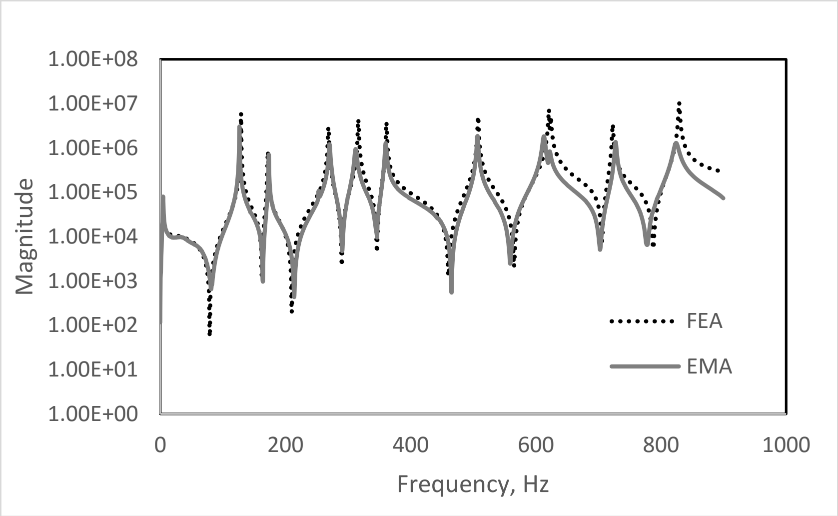


Figure 3: Comparison of measured and FE frequency response function (FRF)

Table 2: Comparisons of results of the natural frequencies of the aluminium plate between the measured, initial FE and FRF based updating

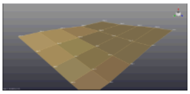
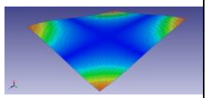
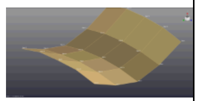
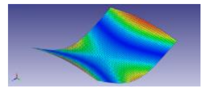
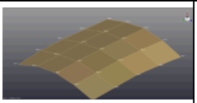
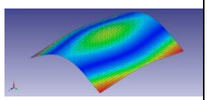
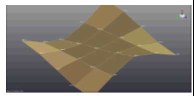
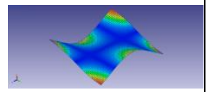
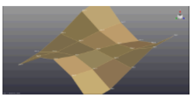
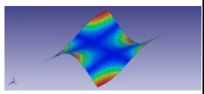
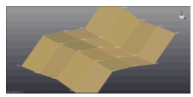
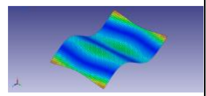
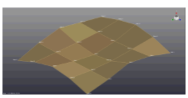
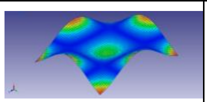
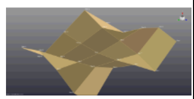
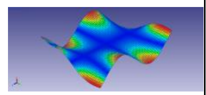
Mode (I)	EMA (Hz) (II)	Initial FE (Hz) (III)	Error (%) (IV)	FRF Based Updating (Hz) (V)	Error (%) (VI)
1	126.45	129.79	2.64	129.01	2.02
2	173.30	172.78	0.30	171.72	0.91
3	270.57	270.33	0.09	268.58	0.74
4	312.29	318.34	1.94	316.40	1.32
5	360.07	363.54	0.96	361.32	0.35
6	506.76	511.00	0.84	507.71	0.19
7	612.90	624.77	1.94	620.92	1.31
8	621.85	627.54	0.92	623.67	0.29
9	727.46	727.45	0.00	722.79	0.64
10	823.80	834.22	1.26	828.92	0.62
	Total Error		**10.89**		**8.39**

The disadvantages or problems which the FRF based model updating methods have to face is incompleteness of the experimental data of FRF. Besides, the difference of the magnitude between the experimental FRF and the analytical FRF due to excitation force during experimental modal analysis. Lastly, when the whole frequency domain of interest is investigated, it will cause the time-consuming.

Modal based updating method has advantage on time consumption, to get the results of model updating. Modal based only required 1.56 seconds to complete all the iteration to get the best results as shown in the table while FRF based required 22.53 seconds to complete the iteration of simple plate structure. In this study, the procedure of modal based was observed to be easier to carry out than that of FRF based in which nodes between measured and predicted structure were required to be matched. Both model updating methods have their own advantages and disadvantages, therefore, the selection of appropriate updating methods should be based on a good physical understanding of the structure itself.

One of the disadvantages of using modal based updating method is the natural frequencies and mode shapes in the experimental and numerical data must relate to the same mode and cannot arranging in ascending order. Furthermore, modal based updating method does not consider damping.

Table 3: Comparison of the mode shapes of the aluminium plate between the measured and predicted

Measured mode shape	**Finite Element mode shape**	**Measured mode shape**	**Finite Element mode shape**
 Mode 1	 Mode 1	 Mode 2	 Mode 2
 Mode 3	 Mode 3	 Mode 4	 Mode 4
 Mode 5	 Mode 5	 Mode 6	 Mode 6
 Mode 7	 Mode 7	 Mode 8	 Mode 8

Conclusions

Numerical investigations of the dynamic behaviour of the aluminium plate were successfully conducted and initial finite element model of the aluminium plate using two types of model updating methods which are modal based updating and FRF based updating also successfully updated in this research. In addition, the dynamic behaviour of the plate using an impact hammer and roving accelerometers have successfully measured. The measured, initial and updated FE results of the dynamic behavior of the plate are presented and discussed.

It was found that modal based updating has shown better capability in terms of reconciling the resonance frequencies of the initial finite element model of the aluminium plate with 6.02 percent reduction in the total error in comparison with FRF based updating with only 8.39 percent. However, FRF based updating which has great capability not to only update the resonance frequencies, but also potential harmful frequencies is seemed much better than modal based updating. This may be as a result of the fact that the inclusion of excitation and resonance frequencies is inherent in the theoretical framework of FRF based updating which has made the method more efficient and economical in updating framework.

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