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Experimental Investigation of Dynamic Behaviour of a Structure with Closely Spaced Modes

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Abstract: The presence of closely spaced modes of vibration in current modern engineering structures seems to be unavoidable and failure in identifying them may lead to inability to accurately derive models for the structures. In this study, a technique for experimental investigation of closely spaced modes of a structure is presented. Free boundary conditions were used in experimental work and simulations. For the validation purposes, the natural frequencies and mode shapes of the structure were measured using three different points and the measured results were compared with those predicted from the finite element method. In this study, the proposed technique was successfully used for accurately identifying the closely spaced modes of the structure.

Key words: Closely spaced modes, dynamic behaviour, finite element model, modal testing, Malaysia

INTRODUCTION

The investigation of repeated or closely spaced modes of engineering structures has received much attention from the experimentalist community due to several difficulties and challenges encountered in identifying the modes (Yang, 2013). Closely spaced modes are when two or more different modes having identical natural frequencies but differ in mode shapes (Balmes and Wright, 1997; Stanbridge *et al*., 2000).

As a direct consequence of these conditions, the structures having such properties can be much more difficult to test than those with distinct modes. Hence, the results of measured modal parameters of the structures are often highly questionable in terms of accuracy and reliability.

The presence of the closely spaced modes in current modern engineering structures is apparently unavoidable, especially in the structures with symmetrical design such as an aeroplane and space shuttle or axisymmetric ones such as discs, cylinders, etc. (Qu, 2004; Mehdigholi, 1991; Royston *et al*., 2000). Therefore, failure in accurately identifying closely spaced modes during the dynamic test can result in inability to derive accurate and reliable models for the structures which may be used for theoretical reconciliations (model updating) (Thonon and Golinval, 2001; Robb and Imregun, 1992; Rani *et al*., 2015).

This study puts forward an experimental technique on how to effectively identify closely spaced modes of a structure with highly reliable results obtained. The presented technique uses an impact hammer testing and roving accelerometers for excitations of the structure and measurements of the modal parameters. The exciting locations and measurements are decided with the help from the finite element results.

MATERIALS AND METHODS

Estimation of modal parameters: A modal analysis provides a set of modal parameters that characterize the dynamic behaviour of a structure. If a structure exist on which measurement can be made, then it can be assumed that a parametric model can be defined that describes that data. The starting point is usually a set of measured data most commonly Frequency Response Function (FRF). The corresponding relation for FRFs is given:

$$h_{ij}(j\omega) = \sum_{k=1}^{N} \left(\frac{r_{ijk}}{(j\omega - \lambda_k)} + \frac{r^{*}_{ikj}}{(j\omega - \lambda^{*}_k)} \right) \quad (1)$$

Where:

$h_{ij}(j\omega)$ = FRF between the response DOF $_?$and reference DOF j

N = Number of modes of vibration that contribute to the structure's dynamic response within the frequency range under consideration

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r_{ijk} = Residual value for mode k
λk = Pole value for mode k
* = Designates complex conjugate

The pole value can be expressed as:

$$\lambda_k = \delta_k + j\omega_{dk} \quad (2)$$

Where:
ω_{dk} = Damped natural frequency of mode k
δ_k = The damping factor of mode k

or:

$$\lambda_k = -\xi_k \omega_{nk} + j\omega_{nk}\sqrt{1-\xi_k^2} \quad (3)$$

Where:
ω_{nk} = The undamped natural frequency of mode k
ξ_k = Damping ratio of mode

Equation 4 shows that the residue can be proven to be the product of three terms:

$$r_{ijk} = a_k v_{ik} v_{jk} \quad (4)$$

Where:
V_{ik} = The mode shape coefficient at response DOF i of mode k
V_{jk} = The mode shape coefficient at reference DOF i of mode
a_k = A complex scaling constant, whose value is determined by the scaling of the mode shapes

If the mode shapes are real, the scaling constant can be expressed as:

$$a_k = \frac{1}{2jm_k\omega_{dk}} \quad (5)$$

where, mk is the modal mass of mode k. The poles, natural frequencies (damped and undamped), damping factors or ratios, mode shapes and residues are commonly referred to as modal parameters (parameters of the modes of the structure).

The fundamental problem of parameter estimation consists of adjusting (estimating the parameters in the model, so that the data predicted by the model approximation or curve-fit) the measured data as closely as possible.

Experimental set up: The structure under investigation is a structure made from a 4 mm-thick aluminium sheet. It is a simplified version of an aeroplane design as shown in Fig. 1. The test model was set-up in free-free boundary conditions. The frequency range of interest was 0~200 Hz.

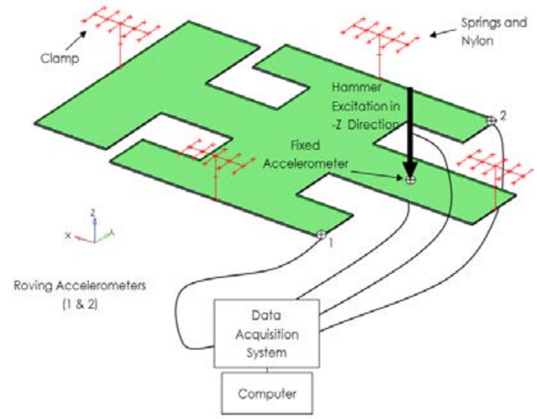


Fig. 1: Schematic diagram of the structure test set up

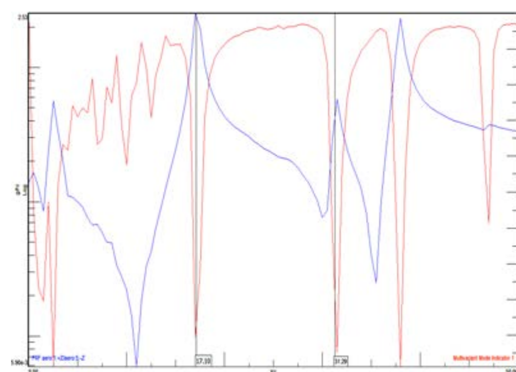


Fig. 2: FRF for excitation at point 5

An impact hammer (transient excitation) and roving accelerometers were used in the investigation of the dynamic behaviour of the test model. The impact hammer which is the most commonly used method of transient excitation for modal testing and has very distinct advantages (Ewins, 2000) was used to excite the tests structure in the Z direction as shown in Fig. 1.

The FE results were used to provide guidance for the test such as the determination of the frequency bandwidth of the testing, the locations of the excitation points, excitation directions and also response measurement points. As a result the test was set up in the way as shown in Fig. 1 in which four springs and nylon strings were used to simulate free-free boundary conditions.

An initial study was performed by hitting the structure using the hammer at several locations in order to identify good excitation points in terms of FRF as shown in Fig. 2-4. The points identified are 5, 58 and 79 as shown in Fig. 5.

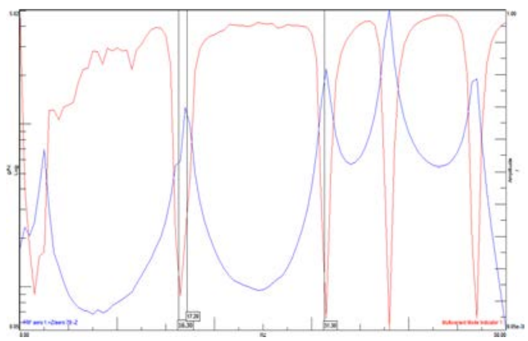


Fig. 3: FRF for excitation at point 79

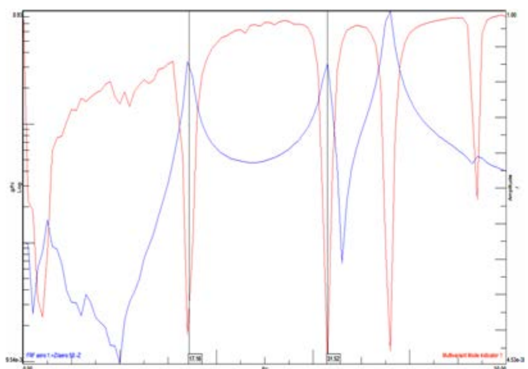


Fig. 4: FRF for excitation at point 58

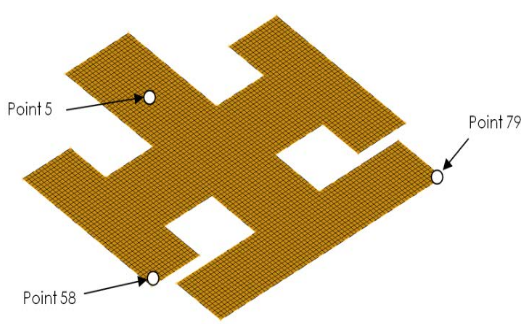


Fig. 5: Simplified aeroplane structure and the excitation points

RESULTS AND DISCUSSION

Identification of closely spaced modes of structures is always a difficult and challenging task. It was reported that to accurately identify the modes, the number of excitation points and their location should be properly studied and selected (Rani *et al*., 2011). In this study, closely spaced modes were identified using three different excitation points. The measured closely space modes were compared with the results predicted from the finite element method. Table 1 and 2 show the results obtained using the proposed technique.

Table 1: Comparisons of natural frequencies between measured and predicted. Obtained from three different excitation points

1	2	3	4	5
Modes	EM analysis (Point 5)	EM analysis (Point 79) (Hz)	EM analysis (Point 58) (Hz)	FE model (Hz)
1	-	16.30	-	16.38
2	17.10	17.20	17.16	17.05
3	31.29	31.30	-	31.24
4	-	-	31.52	31.76

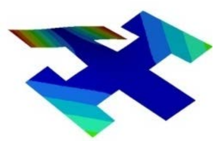
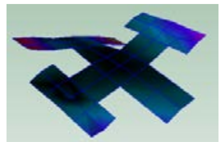
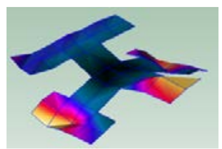
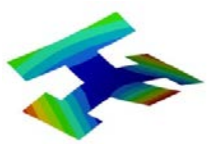
The results show in Table 1 consist of three types of comparisons of measured and predicted natural frequencies obtained from three different excitation points which are points 5, 79 and 58. Column 2 (Point 5) shows the results of the 2nd and 3rd modes (17.05 and 31.24 Hz) as a result of using point 5 as the excitation point. This clearly indicates that the selected excitation point was unable to identify the 1st and 4th modes (16.38 and 31.76 Hz) of the structure.

The next excitation point used in this test was point 79 as illustrated in Fig. 5. The modes obtained from the excitation point are tabulated in Table 1, column 3. It shows that there is additional mode which is the 1st mode (16.38 Hz) obtained from the test. In other words, using point 79 for the excitation point, the number of modes has increased to three modes (16.38 , 17.05 and 31.24 Hz) in comparison with point 5 with only two modes (17.05 and 31.24 Hz). However, the 4th mode could not be identified based on the excitation point.

To solve the issue of the missing mode which is the 4th mode (31.76 Hz), another excitation point was used and it was point 58 as shown in Fig. 5. The results of the natural frequencies identified from the point 58 based tests can be seen in column 4 of Table 1. It is clearly shown that the missing mode has been successfully identified. Despite the success of the identification; the excitation point 58 has failed in identifying the 1st and 3rd modes of the structure which have been successfully obtained from the excitation point 79.

From the results of natural frequencies and mode shapes tabulated in Table 1 and 2, respectively, it clearly indicates that the technique developed in identifying the closely spaced modes has been successfully carried out. However, the accuracy and reliability of the results are largely affected by the excitation points selected and used. Therefore, the number of excitation points which directly will affect the period of measurement process, could be reduced from three (points 5, 79 and 58) to only two which are points 79 and 58. This is because the results shown in Table 1, Columns 2 and 3 in particular have proved that they could be accurately identified based on only those two points.

Table 2: Comparisons of mode shapes of the simplified aeroplane between measured and predicted data

Numerical results	Experimental results
	
Mode 1 : 16.38 Hz	Mode 1 : 16.30 Hz
	
Mode 2 : 17.05 Hz	Mode 2 : 17.10 Hz
	
Mode 3 : 31.24 Hz	Mode 3 : 31.29 Hz
	
Mode 4 : 31.76	Mode 4 : 31.52

CONCLUSION

This study has shown the experimental technique of investigating the dynamic behaviour of a structure with closely spaced modes. It has been shown that the closely spaced modes have been successfully and accurately identified using the proposed technique with the guidance from the finite element data. The comparisons of the results have revealed that the accuracy and reliability of the certain distinct modes and closely spaced modes obtained in the test are highly dependent on the number of, location of excitations and measurement points of the structure.

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