Detection of Surface Crack in Aluminum Alloy 6061 Thin Plate Using Experimental Modal Analysis

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ABSTRACT

A nondestructive detection of surface cracks in aluminum alloy 6061 thin plate using experimental modal analysis is investigated in this paper. Modal testing is performed to obtain the mode shapes of the plate before and after damage under a completely free boundary condition. Modal displacements are then used to compute the strain energy of the laminate beam. Limited by grid points of measurement, a differential quadrature method is adopted to calculate the partial differential terms in strain energy formula. A damage index is then defined based on strain energy ratio of the aluminum plate before and after damage. This damage index successfully predicts the location of surface crack in aluminum plate. A pre-study using a 3-D finite element analysis is also performed to access this approach. It is found that mass effect of accelerometer to the natural frequencies of specimen is significant. Thus, a mass element is assigned to the finite element model. Good correlation between FEA and EMA results is obtained. Only measured mode shapes of the aluminum plate are required in this method, which provides a quick, accurate, inexpensive and flexible approach.

Keywords: surface crack, experimental modal analysis, strain energy, damage index

1. INTRODUCTION

Experimental modal analysis has been increasingly adopted to nondestructively detect damages in engineering structures due to its flexibility of measurement and relatively low cost. The basic theory of this approach is to use the information of modal parameters, such as natural frequencies, mode shapes and damping ratios, to access the structural damage.

Cawley and Adams [1] simply used the frequency shifts for different modes to detect the damage in composite structures. Tracy and Pardoen [2] found that the natural frequencies of a composite beam were affected by the size and damage location. Cornwell et al. [3] utilized the measured mode shapes to calculate the strain energy of a steel plate. In his approach, fractional strain energy of the plate before and after damaged was used to define a damage index, which was used to locate the damage in the steel plate. The method only requires the mode shapes of the structure before and after damage. Choi et al. [4] modified this method by using the changes in the distribution of the modal compliance of the plate structure to detect single and multi-cracks in plate. Nevertheless, the challenge of the above approaches lies in the accuracy of measured modes. A large amount of data points are required for further analysis to locate the damage. To solve this problem, Hu et al. [5-8] adapted differential quadrature method (DQM) to obtain a solution of strain energy of a composite plate, and successfully detect the surface and matrix crack locations in various composite laminate plates. It was reported that the original DQM was first used in structural mechanics problems by Bert et al. [9]. This method is able to rapidly compute accurate solutions of partial differential equations by using only a few grid points in the respective solution domains [10].

The objective of this paper is to nondestructively detect a surface crack in aluminum alloy 6061 thin plate integrating experimental modal analysis and the strain energy method. The measured mode shapes were used to compute strain energy using DQM. Consequently, a damage index was established to locate the surface crack using the fractional strain energy of the plate before and after damaged.

2. THEORY OF DAMAGE INDEX

A plate structures as shown in Figure 1 is subdivided into $N_x \times N_y$ sub-region and denoted the location of each point by (x_i, y_j). The strain energy of plate during elastic deformation is given by

$$U = \frac{D}{2}\int_0^b\int_0^a \left[\left(\frac{\partial^2 w}{\partial x^2}\right)^2 + \left(\frac{\partial^2 w}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 w}{\partial x^2}\right)\left(\frac{\partial^2 w}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2\right] dxdy \tag{1}$$

where w is transverse displacement; D is bending stiffness of the plate. Considering a free-free vibration problem, for a particular mode shape, the total strain energy of the beam associated with the mode shape ϕ_k can be expressed as

$$U_k = \frac{D}{2}\int_0^b\int_0^a \left[\left(\frac{\partial^2 \phi_k}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_k}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_k}{\partial x^2}\right)\left(\frac{\partial^2 \phi_k}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_k}{\partial x \partial y}\right)^2\right] dxdy \tag{2}$$

Cornwell et al. [3] suggested that if the damage is located at a single sub-region then the change of strain energy in sub-region may become significant. Thus, the energy associated with sub-region (i,j) for the k^{th} mode is given by

$$U_{k,ij} = \frac{D_{ij}}{2}\int_{y_j}^{y_{j+1}}\int_{x_i}^{x_{i+1}} \left[\left(\frac{\partial^2 \phi_k}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_k}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_k}{\partial x^2}\right)\left(\frac{\partial^2 \phi_k}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_k}{\partial x \partial y}\right)^2\right] dxdy \tag{3}$$

Similarly, U_k^* and $U_{k,ij}^*$ represent the total strain energy and sub-regional strain energy of the k^{th} mode shape ϕ_k^* for damaged plate. The fractional energies of the plate are defined as

$$F_{k,ij} = \frac{U_{k,ij}}{U_k} \quad \text{and} \quad F_{k,ij}^* = \frac{U_{k,ij}^*}{U_k^*} \tag{4}$$

Considering all measured modes, m, in the calculation, damage index in sub-region (i,j) is defined as

$$\beta_{ij} = \frac{\sum_{k=1}^{m} F_{k,ij}^{*}}{\sum_{k=1}^{m} F_{k,ij}} \quad (5)$$

Equation (5) is used to predict the damage location in thin plate structures. The partial differential terms are calculated using DQM [6].

3. FINITE ELEMENT ANALYSIS

A pre-study was performed by establishing finite element model for thin plate with dimension 246×246×2mm^3. ANSYS, a FEA commercial code, was used in this study. Eight-node linear solid element (SOLID45) was used to simulate the thin plate. A convergence study was performed to obtain a 24×24×2 mesh model, which is sufficient to solve the normal mode problem. A surface crack with 40 mm long, 0.8 mm wide and 1 mm deep was created in the thin plate by separating the nodes at the elements along the crack. Material properties (E = 70 GPa, ν = 0.33, ρ=2735 kg/m^3) of aluminum alloy 6061 were entered into ANSYS. A normal mode analysis with completely free boundary condition was performed to obtain the natural frequencies and the associated mode shapes up to 2 kHz. Hu et al. [5] found that mass effect of accelerometer to the natural frequencies of specimen is significant. Thus, a mass element (MASS21) with 0.0015 kg was assigned to the FE model.

4. EXPERIMENTAL MODAL ANALYSIS

A square thin plate with dimension 246×246×2mm^3 was marked by 13×13 parallel grid points and vertically hung by two cotton strings to simulate a completely free boundary condition. Modal testing was performed by exciting the test plate throughout all grid points using an impact hammer with a force transducer. The dynamic responses were measured by an accelerometer fixing at the corner as shown in Figure 2. Siglab, Model 20-40, was used to record the frequency response functions (FRFs) between measured acceleration and impact force. ME'Scope, a software for the general purpose curve fitting, was used to extract the natural frequencies and mode shapes from the FRFs. A surface crack with 40 mm long, 0.8 mm wide and 1 mm deep was created using a knife.

5. RESULTS AND DISCUSSION

Table 1 lists the first ten natural frequencies of the thin plate before and after damage, respectively. Good correlations between FEA and EMA results are obtained. However, mode 2 and mode 7 are absent in EMA results. It is because that accelerometer is fixed to grid point 1 which is located at the stationary line of mode 2 and 7. Shifting accelerometer location from grid point 1 to grid point 14, these two modes are revealed as shown in Table 2. Unfortunately, the changes in natural frequencies and mode shapes of the plate before and after damage are almost invisible. In fact, it is very difficult to detect the small damage in plate structures based on the changes of natural frequencies and the associate mode shapes.

Figure 3 shows the damage index obtained from the first five mode shapes of FEA results. It is good enough to predict the surface crack location. Since it is possible to lose some mode shapes in EMA due to stationary points and lines, five FEA mode shapes, i.e., 1 and 3-6, are selected to compute damage indices as shown in Figure 4. Consequently, surface crack location is successfully predicted as well.

In EMA result, the first five mode shapes, i.e., 1 and 3-6, were used to compute the damage indices as shown in Figure 5. Peak values occur around surface crack location, and some pseudomorphs in undamaged areas as shown in Figure 5-(a). It is due to the deviation in measurement. Cornwell *et al.* [3] suggested that damage indices with values greater than two are associated with potential damage locations. After truncating the peaks of damage index less than two, the improving outcome is shown in Figure 5-(b). Figures 6-(a), 7-(a) and 8-(a) show the damage indices by using the first six, seven and eight mode shapes, respectively. In these three cases, mode shapes 2 and 7 are absent. However, damage indices still successfully predict the surface crack location. After truncation, damage indices of surface crack become much clearer as shown in Figures 6-(b), 7-(b) and 8-(b).

6. CONCLUSIONS

A surface crack in aluminum alloy 6061 thin plate is successfully predicted by using EMA and strain energy method. Though the challenge still lies in the accuracy of mode shape measurement, significant contributions of this approach are as follows,

- Only a few mode shapes of the plate before and after damage are required.
- Damage location is nondestructively identified.
- Potential damage in overall structure is evaluated.
- Real-time monitor of structure health during the practical service is available.
- Measurement is flexible and cost is relative low.

7. REFERENCE

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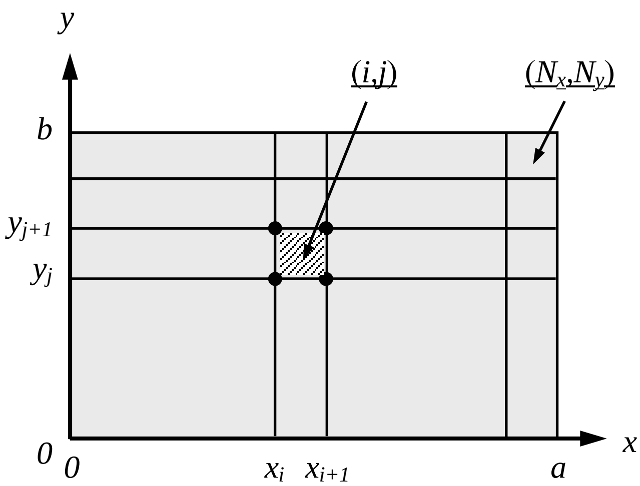


Figure 1 A schematic illustrating of plate

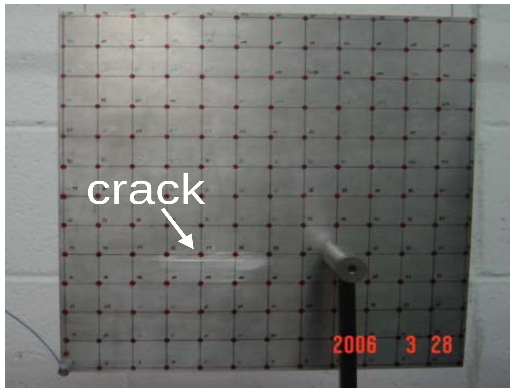


Figure 2 Experimental Set-up

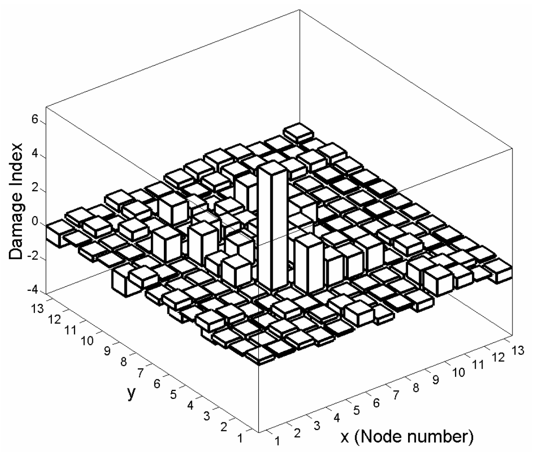


Figure 3 Damage index (FEA: modes 1-5)

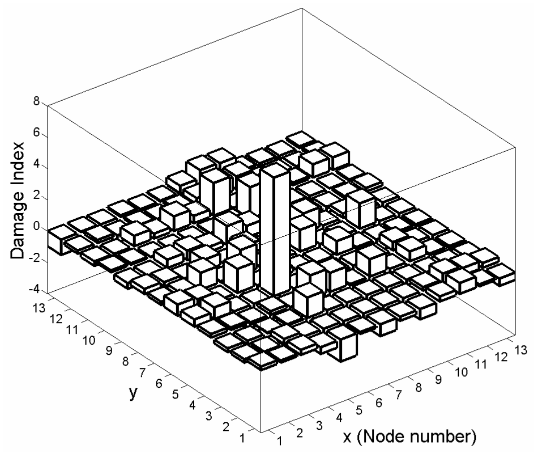
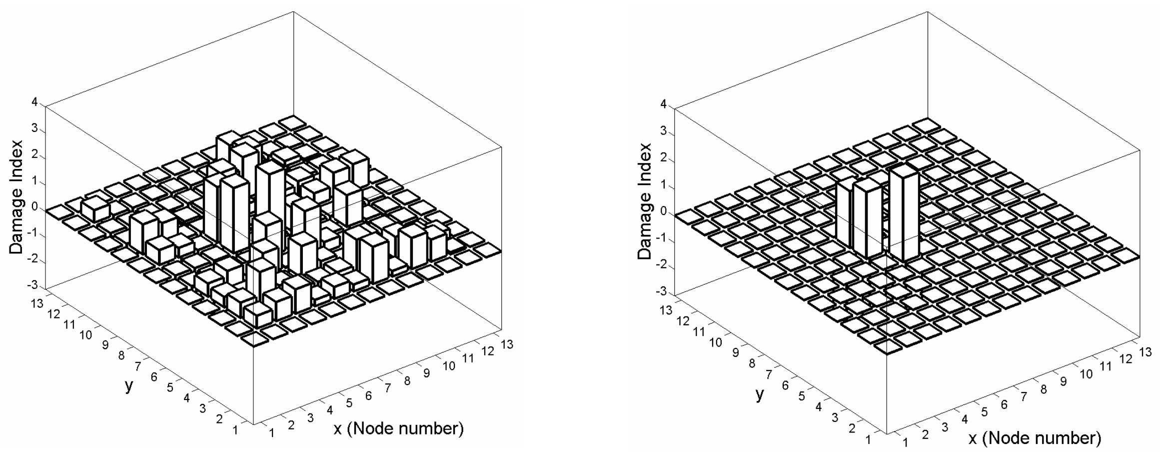
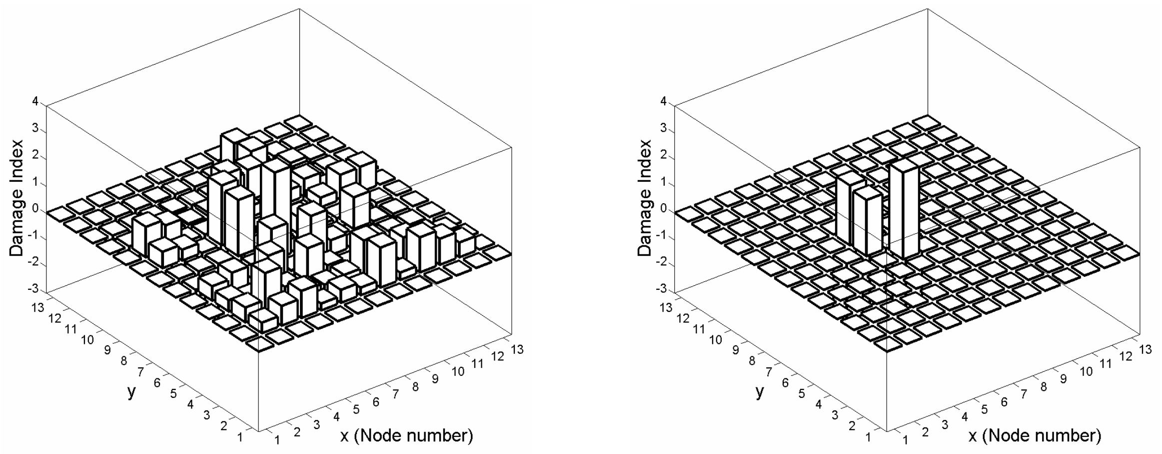


Figure 4 Damage index (FEA: modes 1, 3-6)



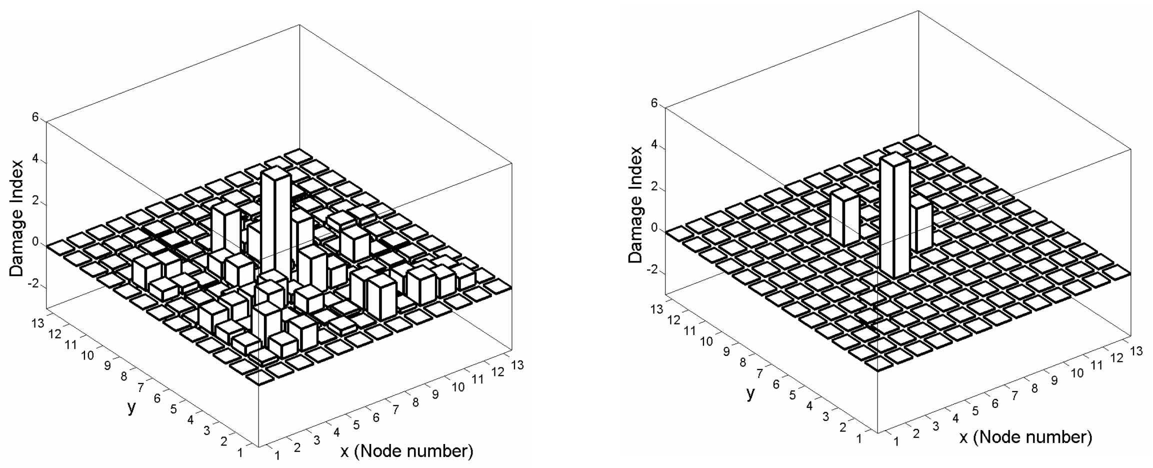
(a) before truncation (b) after truncation

Figure 5 Damage index (EMA: the first five modes)



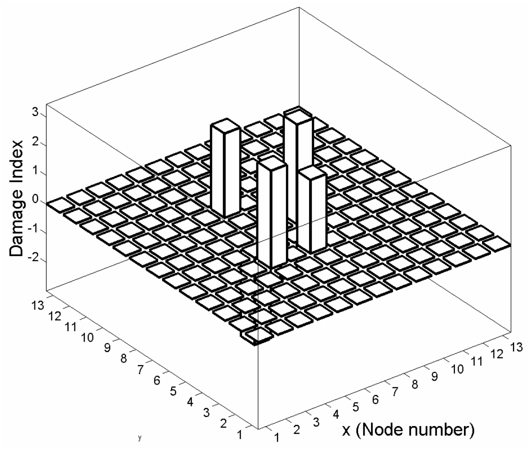
(a) before truncation (b) after truncation

Figure 6 Damage index (EMA: the first six modes)

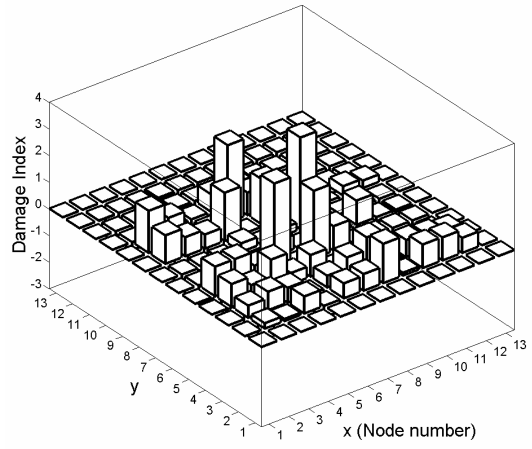


(a) before truncation (b) after truncation

Figure 7 Damage index (EMA: the first seven modes)



(a) before truncation



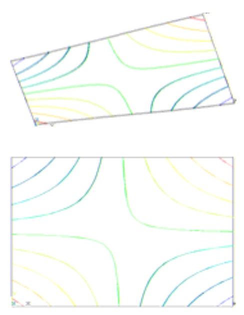
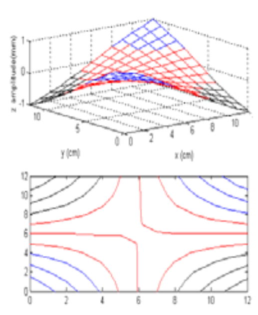
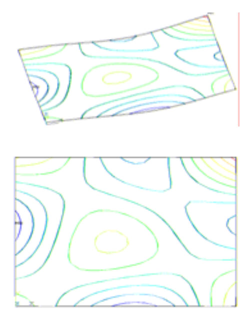
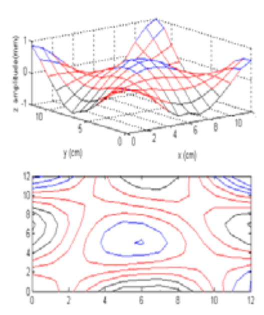
(b) after truncation

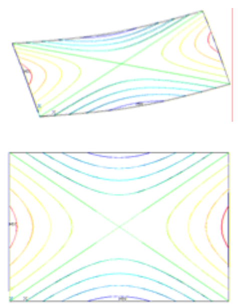
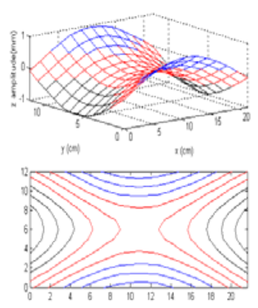
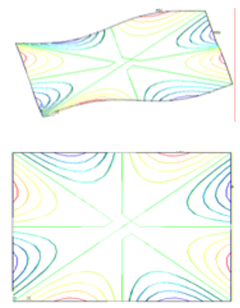
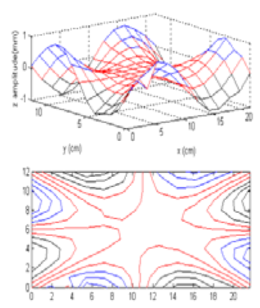
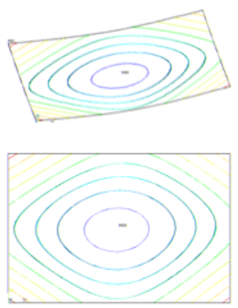
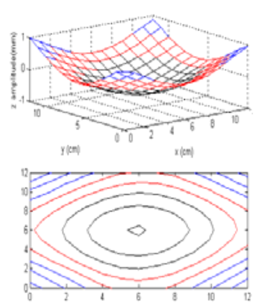
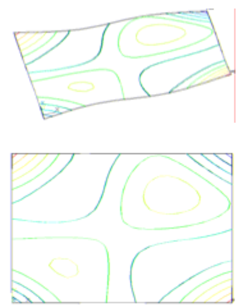
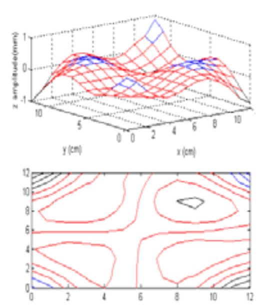
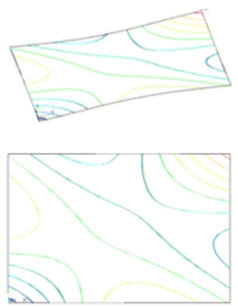
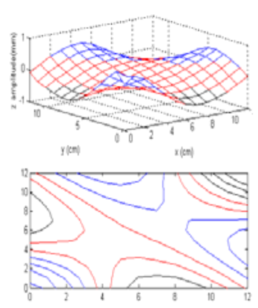
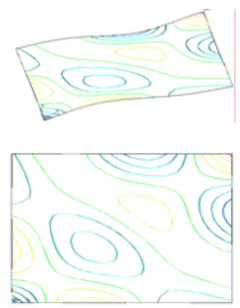
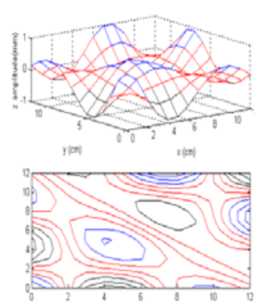
Figure 8 Damage index (EMA: the first eight modes)

Table 1: Natural frequency (Accelerometer at grid point 1)

	Before damage			After damage		
mode	FEA(Hz)	EMA(Hz)	△(%)	FEA(Hz)	EMA(Hz)	△(%)
1	106	108	1.9	106	108	1.9
2	157	—	—	157	—	—
3	196	201	2.6	195	200	2.6
4	272	278	2.2	272	278	2.2
5	484	495	2.3	484	495	2.3
6	512	516	0.8	512	516	0.8
7	563	—	—	563	—	—
8	615	623	1.3	615	623	1.3
9	839	847	1.0	839	847	1.0
10	994	1000	0.6	994	1000	0.6

Table 2: Natural frequencies and mode shapes (Accelerometer at grid point 14)

	FEA	EMA		FEA	EMA
1	106Hz	108Hz	6	514Hz	518Hz
					

2	157Hz	162	7	561Hz	562
					
3	197Hz	202Hz	8	627Hz	631Hz
					
4	275Hz	280Hz	9	856Hz	856Hz
					
5	493Hz	499Hz	10	964Hz	959Hz