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IDENTIFICATION OF DAMAGE FOR A THIN PLATE JOINTED STRUCTURE

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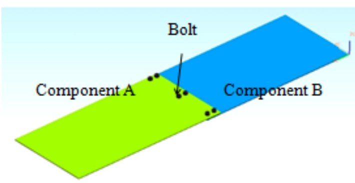
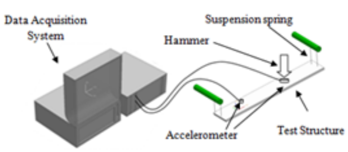
Graphical abstract





Abstract

The dynamic characteristics of automotive structures are largely influenced by joints. The complex structures such as car a body-in-white is made from thin metal sheets and joined together by several types of joints such as spot welds and bolted joints. The integrity and dynamic characteristic of the structure are highly dependent on these joints. The defective and inaccurate tightening of the bolts during the assembly process could degrade the integrity of the structure and alter the dynamic characteristic of the vehicles. Early detection of the presence of damage in the structure is very important so that necessary actions can be taken to prevent further problems to the structure. In this paper, the damage detection via vibration based damage detection is used to identify the presence of damage in a bolted joints structure. In order to check the validity of the proposed method, natural frequencies and mode shapes of the initial finite element model of the undamaged structure and the finite element model of the damaged structure are compared with the experimental counterparts. The model updating method is used to improve the initial finite element model of the undamaged structure and the damaged structure as close as possible to the measured data.

Keywords: Bolted, pre-load, updating, thin plate, connector element

1.0 INTRODUCTION

The bolted joints are widely used in joining mechanical components of automotive structures. The bolted joints have become one of the prevailing joint types in engineering industries due to its versatility. The bolted joints can be easily dissembled, maintained and inspected in comparison with spot welds and glues. For instance, the automotive components are made from thin metal sheets and they are assembled together via mechanical joints such as spot welds and bolted joints. In addition to provide the connections between the components, the bolted joints in the automotive structure also significantly contribute to the vehicle's structural stiffness and dynamic characteristics [1-2].

The loosening of the bolted joints will lead to the alteration of vibration behavior of the structures such as natural frequencies and mode shapes. Furthermore, the reduction of stiffness in the structure can lead to damage to the structure. Therefore, the early detection of the presence of damage is very important, so that necessary actions can be taken to prevent further problems in the structures.

There are wide ranges of damage identification methods that have been widely used to detect damage on structures [3-7]. For instance, the vibration based damaged detection can be used to identify the extent of damage in the structures. This is because the natural frequencies of a structure can be more easily measured than the mode shapes, and the measurement error is usually less than 1%, it would be easier to use the changes in the natural frequencies to detect damage in a structure than the mode shapes [8-9]. Since the damage identification method is model-based, the experimental data is required to establish the relationship between the natural frequencies of the structure and its stiffness so that it can simulate real changes in the natural frequencies caused by particular damage in the structures.

With the advancement of finite element method, it has been widely used to model large and complex structures, structural components and also to perform different types of analyses. The accuracy of a finite element model can be assessed by comparing the initial finite element model with the measured data. However, the results of the initial finite element (FE) model are often differed from the experimental ones due to the inappropriate data inputs. For instance, the material properties and boundary conditions are always based on the assumptions or the nominal values. However, the inaccuracy of the initial FE model of the structure can be improved systematically by a reconciliation technique, which is known as finite element model updating [10].

2.0 EXPERIMENTAL

Experimental modal analysis (EMA) coupled with finite element analysis (FEA) is used to model and to detect damage in structures. A bolted joined structure as shown in Figure 1(a) is used in this work. The structure is made from two thin metal sheets with the nominal thickness of 1.5 mm. The sheets are assembled together by six numbers of bolted joints. The experimental work with free-free boundary conditions is shown in Figure 1 (b). The modal parameters from the both experimental work are obtained via the LMS data acquisition system. The experimental results of the bolted structure are tabulated in Tables 1 and Table 2 respectively.

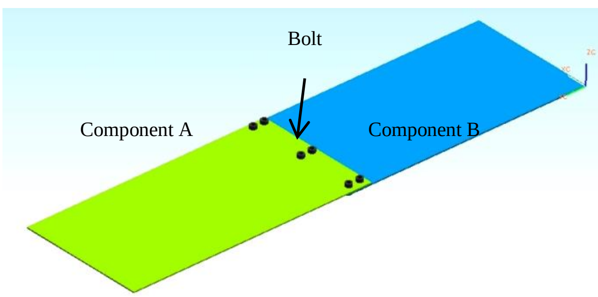


Figure 1 (a) CAD model of the bolted joined structure

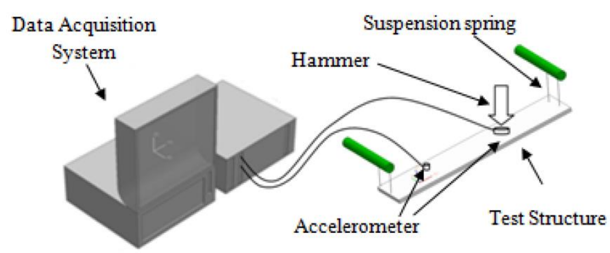


Figure 1 (b) General experimental set-up for free-free boundary conditions

3.0 FE MODELLING AND NORMAL MODES ANALYSIS

The finite element models of the components and the bolted structure are developed using CQUAD4 elements. The, CFAST connector elements are used to represent the bolt joints of the structure (Figure 1(a)) due its versatility [11]. The nominal parameter values such as (Young's modulus 210 GPa; Poisson's ratio 0.3 and Mass density, 7850 kg/m^3) are used in the initial FE model of the components and the bolted structure. Meanwhile the normal mode analysis is performed via NASTRAN SOL 103 to calculate the natural frequencies and mode shapes of the components and the bolted joints structure. The equation of motion for the undamped vibration of the structure can be expressed as [12].

$$(-\lambda\mathbf{M}+\mathbf{K})u=0 \quad \text{(Eq. 1)}$$

where **M** and **K** are n x n mass and stiffness matrices of the structure, and u is the n x 1 modal displacement vector, where n is the number of DOFs of the whole structure and $\lambda=\omega^2$ is the eigenvalue and ω is natural frequency of the structure.

4.0 FE MODEL UPDATING

The process of model updating is divided into two steps; firstly, the FE model of bolted joints is constructed and updated based on the experimental data obtained from the undamaged structure in order to establish a benchmark FE model. In the second step, the benchmark FE model is updated to the modal test data of the damaged structure in order to identify the damage. The choice of updating parameters is obtained through the sensitivity analysis and therefore only the most sensitive parameters are listed as the updating parameters. The approximation used in NASTRAN based optimisation based on first order of Taylor series and the general form of this expansion for λ can be expressed as, [13]

$$\lambda_{i+1}=\lambda_i+\mathbf{S}_i(\delta\theta) \quad \text{(Eq. 2)}$$

where $\mathbf{S}_i$ is an m x n sensitivity matrix at ith iteration, which denotes the rates of change of the structural eigenvalues, λ_i with respect to changes in the updating parameters, $\delta\theta$, defined as [13]

$$\mathbf{S}_i = \frac{\partial \lambda_i}{\partial \theta} = u_i^{\mathrm{T}} \left[\frac{\partial \mathbf{K}}{\partial \theta} - \lambda_i \frac{\partial \mathbf{M}}{\partial \theta} \right] u_i \qquad \text{(Eq. 3)}$$

The expectation of the model updating process is to provide an improvement to the initial FE model that is able to represent the dynamic behaviour of the measured structure. This approach generally depends on minimising the errors between the FE model and the measured data and in this work, an objective function is defined as [10].

$$J = \sum_{i=1}^{n} W_i \left(\frac{\lambda_i^{\mathrm{fe}}}{\lambda_i^{\mathrm{exp}}} - 1 \right)^2 \qquad \text{(Eq. 4)}$$

where, λ_i^{exp} is the i^{th} the experimental eigenvalue and λ_i^{fe} is the i^{th} the predicted eigenvalue from the finite element model, *W* is a weighting and *n* is the number of eigenvalues involved in updating process.

5.0 RESULTS AND DISCUSSION

The normal mode analysis is used to calculate the first five natural frequencies and mode shapes of the initial finite element model of the components and the initial finite element model of the bolted joints structure. The FE models of components (component A and component B) were firstly updated individually to acceptable level based on the measured data. In other words, the errors of the finite element models must be firstly reduced at the components level prior to be assembled by the bolted joints. The parameterization of the components was performed by computing the sensitivity analysis in order to identify the most sensitive parameters of the components. This is to ensure any error that may arise in the finite element model of the bolted joint structure is only due to joint modelling. Then the updated model of the finite element models of the components (component A and component B) were then assembled by six numbers of bolted joints to form the bolted joints structure as shown in Figure 1(a).

Table 1 Three comparisons of the results between the measured, the initial finite element model and updated model of benchmark structure (Bolted joints)

Mode	I	II	III	IV	V	VI
	Experiment (Hz)	Initial FE (Hz)	Error (%) [I-II/I]	Initial FE MAC	Updated FE (Hz)	Error (%) [I-V/I]
1	22.43	23.99	6.95	0.88	22.47	0.18
2	57.25	59.36	3.69	0.83	56.75	0.87
3	63.87	66.34	3.87	0.85	64.29	0.66
4	109.02	113.07	3.71	0.79	110.3	1.17
5	124.56	129.14	3.68	0.83	122.72	1.48
Total Error			21.90			4.36

Table 1 (column II) shows the updated natural frequencies of the finite element model of benchmark structure (bolted joints) are compared with the experimental results as shown in Table 1 (column V) respectively and together with their MAC value. Obviously, it can be seen that the discrepancies of the frequencies of benchmark structure were reduced significantly from 22.0 percent to 4.4 percent. On top of that, the MAC analysis of benchmark structure result shows the mode shapes of the updated FE model was found to have reasonable correlation with the experiment data with more than 0.8.

In this work, the initial stress ratio was used as the updating parameter the representing the damage effect due to the loosening effect of the mating area of the bolted joints. This technique allows the loosing effects of the bolted joints to be modelled in a simple and yet more practical way [14]. Therefore, initial stress ratio was used in the procedure of model updating of bolted joints structure. The first five mode measured frequencies were used in the updating procedure of the finite element model of the bolted joints structure. Then the finite element model of benchmark structure is then updated based on the measured data of the damaged structure. It can be seen, that the selection of the initial stress ratio as the updating parameter were able to improve the correlation between the damaged natural frequencies of the finite element model of the bolted joints structure and damaged structure. The error was significantly reduced from 98 percent (Table 2 column III) to 7.44 percent (Table 2 column VI).

Table 2 Three comparisons of the results between the measured (damaged), the finite element model of damaged structure

Mode	I	II	III	IV	V
	Experiment (Hz)	Initial FE (Hz)	Error (%) [I-II/I]	Updated FE (Hz)	Error (%) [I-IV/I]
1	18.73	22.47	19.97	19.02	1.55
2	48.22	56.75	17.69	49.01	1.64
3	57.83	64.29	11.17	58.23	0.69
4	86.4	110.3	27.66	87.39	1.15
5	101.44	122.72	20.98	103.89	2.42
Total Error			97.47		7.44

6.0 CONCLUSION

In this work the initial stress ratio was used to represent the loosing effect of the FE model of the bolted joints structure. The model updating procedure was used to improve the correlation between the finite element model of the bolted joints structure and experimental data. In addition, this paper has revealed that initial stress ratio can be used as a simple approach to representing the detailed phenomena of the bolted joints such as slip, loosening and clearance effect at the mating areas of the bolts and the surface of the assembled structure. Based on the updated results, the proposed modelling method has given a good insight into the modelling of the assembled structure using the bolted joints especially for structure that is made from thin metal sheets.

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