The Application of Non-deterministic Model Updating method of a Complex Jointed Structure using Central Composite Design based meta-model

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Abstract. Finite element (FE) model of a structure is highly depended on idealising and simplification of model, however, the model may not truly represent the physical structure. The application of FE model updating is advocated to modify FE model of structure in order to acquired better correlation between the predicted and measured structure response. Nevertheless, for complex jointed structure, a FE model is containing a very large degree of freedoms that may contribute to high computational time. Therefore, this paper presents the application of response surface method in non-deterministic model updating using central composite design (CCD) sampling for improving the efficiency of a finite element model of a laser stitch welded structure. In this study, FE model of the structure is developed using CQUAD4 shell elements and ACM2 element connectors been used to representing the laser stitch weld joints. For the measured data, experimental modal analysis was performed using LMS SCADAS and conducted under free-free boundary conditions. In the model updating, the minimisation of uncertainties parameters in the FE model is based on the objective function that is formed from the residuals between the FE and experimental natural frequencies. The results show that the response surface method using CCD sampling is efficient to be used in FE model updating because it is capable of improving the accuracy of the initial FE model.

1. Introduction

In the simulation analysis for structural dynamics problem, finite element (FE) method is an important tool to simulate the dynamic behaviour of complex engineering structures. However, engineers or scientist usually design the FE models by making engineering assumptions. These engineering assumptions generally may not truly embody all the characteristics of a physical structures [1-4]. Consequently, the predicted responses from FE models may extremely inaccurate and differ went comparing with actual structure. The divergences that are produced from FE models basically are originated from the uncertainties in simplifying assumptions of the structural geometry, material properties, mechanical joints and boundary conditions. To improve the accuracy of FE models, the optimisation procedure such as FE model updating is required to adjust uncertainty in parameters that can increase the accuracy of predictions results [5-6].

Inversed method such as FE model updating where used responses such as natural frequency and mode shape to reducing uncertainties in the initial FE model [7]. However, Ren et. al has highlight that setting up of an objective function, selecting updating parameters and applying robust optimisation

algorithm are the most vital procedure in improving the predicted results via model updating [8]. Meanwhile, study showed that, it is very important to ensure the reliability of updated parameter in order to accurately mimic the physical structure [9].

There are a lot of research that used the sensitivity based model updating [10-14]. For example, Russo et. al had mentioned the complexity of the sensitivity based model updating for complex structure in constructions the sensitivity matrices. This is because the FE models must be tuned and recomputed iteratively during optimisation process [15]. Besides, FE model of a complex assembled structure is containing with high degree of freedoms and frequently causing convergence difficulty, ill-conditions and requiring very high computational process [16]. The mentioned problems show that the ineffectiveness of deterministic model updating. Thus, alternative methods such as the used of response surface method in development of meta-model are more efficient in improving the predicted model.

Response surface (RS) methodology is a method to replace FE model using surrogate model. Initially, surrogate model is a simplified form of a FE model. The FE model been replaced statically using design of experiment (DOE) approach. Therefore, RS method is more preferable due to the advantages such as low computation memory needed and low processing time. In RS method, significant parameters are included in predicting the dynamic behaviour and make this method more efficient [17-18].

In this paper, the procedure of FE model updating using RS methodology to improve the correlation between initial predicted in the light of measured data is presented. The structure used to demonstrate the procedure stated is assembled laser stitch welds structure. The structure is selected because of the complexity in the joint development which contribute to the structural uncertainty and thus, non-deterministic procedure can be applied.

2. Structural Testing via Experimental Modal Analysis (EMA)

For the EMA, the structure assembled using laser stitch welds as shown in Figure 1 were tested. The structure was selected as to replicate a sub-structure of car body-in-white. There are 20 laser stitch welds with 10 mm length for each. The structure was fabricated using mild steel.

In this work, frequency of interest was 1 – 1000 Hz. As shown in Figure 2, the structure was setup under free-free boundary conditions using four sets of strings and springs. The free-free boundary conditions setup is essential in this work as to reduce the uncertainty due to the boundary conditions. Meanwhile, impact hammer and roving accelerometers technique was applied to the structure to measure the dynamic behaviour such as natural frequencies and mode shapes (Figure 3). Finally, data acquisition system (DAQ) such as LMS SCADAS were used to processes the output data obtained.
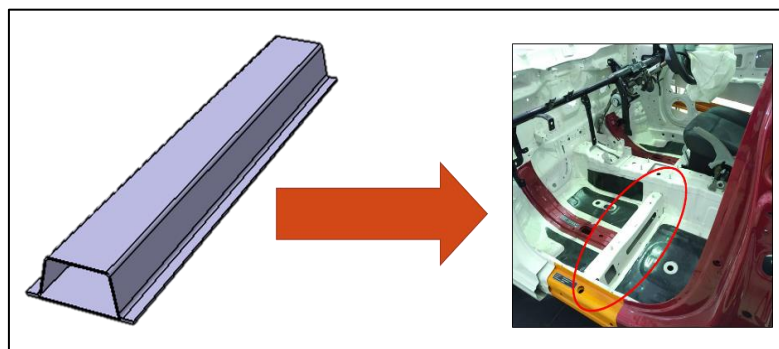

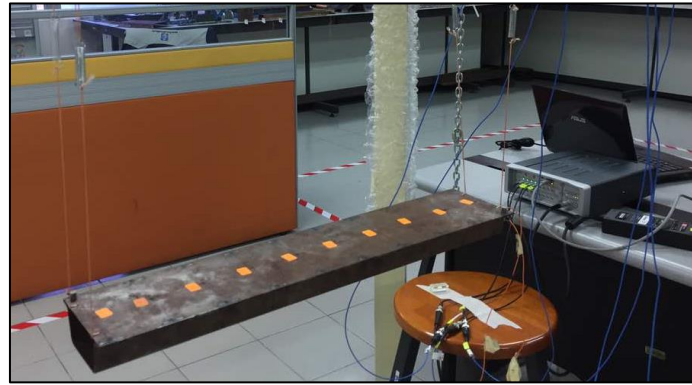**Figure 1.** Simplified model of a car body-in-white

Figure 2. Experimental setup of the structure

3. Finite element (FE) modelling and Analysis

The process of FE analysis for the structure are distinguished into 3 stages which are pre-processing (input model), solver (normal mode analysis) and post-processing (output data). In the pre-processing, the initial FE model was constructed using MSC software. The FE model was constructed using shell elements with 5 mm meshing size. To represent laser stitch weld joints in the FE model, ACM2 element were used [19-21]. Standard properties of mild steel were used as input properties of the FE model.

Table 1. Properties of the welded structure [21]

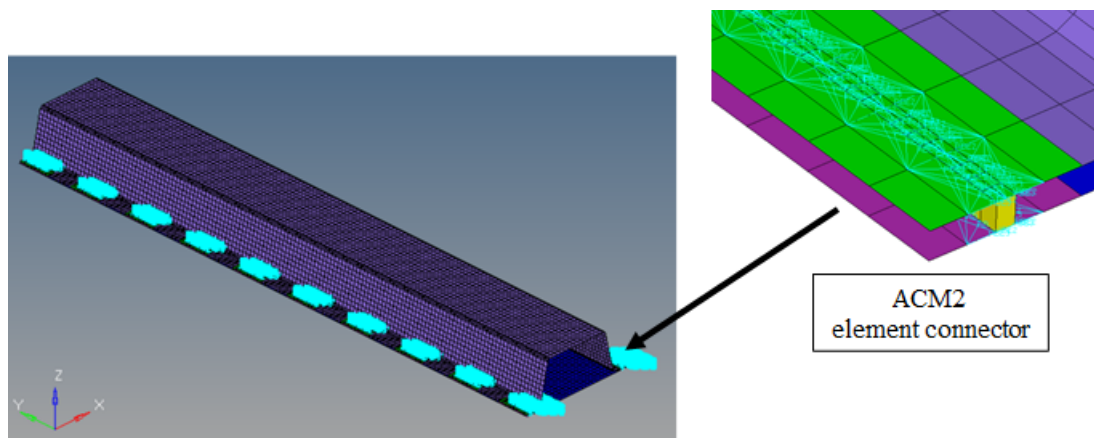|	Parameter	Value	Unit
Mild steel	Young's Modulus	210	GPa
	Poisson's Ratio	0.30	Unitless
	Mass Density	7700	kg/m^3
Laser stitch welds (ACM2)	Young's Modulus	210	GPa
	Poisson's Ratio	0.30	Unitless
	Mass Density	7700	kg/m^3

Figure 3. The FE model of the welded structure

For the solver stage, SOL 103 solver was used to solve the equation of motion. SOL 103 is a solver for normal modes analysis which is to calculate the dynamic behaviour of FE model. The equation of motion is given as

$$(\mathbf{K} - \omega^2\mathbf{M})\phi = 0 \qquad\qquad (1)$$

where **K** and **M** are symmetric matrices of stiffness and mass. Meanwhile ω and ϕ are the natural frequency and mode shape of the system.

4. RS based FE Model Updating

RS methodology based model updating is a method that creating functional evaluation in the design space to globally approximate the response of the structure with comprises objectives and contains. Generally, this method often comprises with a statistical methods to enhancing structures responses [22]. The flowchart of the FE model updating based on RS methodology is shown in Figure 4.
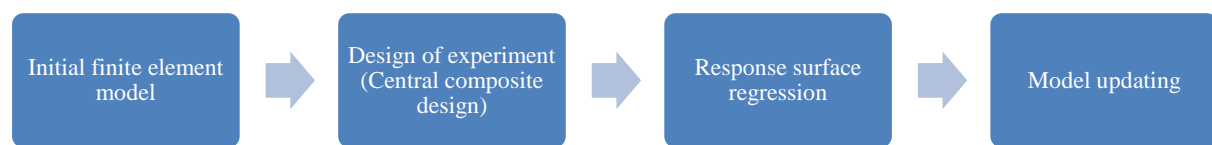

Figure 4. The process of model updating using response surface methodology

4.1. Central Composite Design (CCD) method

One of the basic process to develop a meta-model using response surface (RS) is to calculate predicted response features at numerous points in the design space by solving Eq (1) at selected points using design of experiment (DOE). The values that obtain for solving the Eq (1) at various points are fit with a RS and serve as sampling. However, it is important to understand that, the efficiency and the accuracy of a RS are depending on the selection of sample points. This is because less sampling points may reduce the RS accuracy, meanwhile, high sampling points may improve the response surface accuracy but with high computational time. In this study, CCD method is used in constructing the RS. This method has been found as the most accurate and simple DOE for creation of polynomial surfaces [23-24].

4.2. Parameters selection and identification

In the model updating, the selection of updating parameters to improve the correlation of the predicted data is a crucial part. The potential updated parameters should be selected properly and able to maintain the physical significant of the structure. In the RS model updating, the selected parameters are been used to construct RS and further, the parameters been adjusted to the satisfactory level of accuracy. The parameters such as material properties of geometry or joints can be considered as updated parameters, however it is important to make sure the responses such as natural frequencies are sensitive to the selected parameters.

4.3. RS regression

It is important to develop a meta-model that can represent the dynamic behaviour efficiently. For the structural dynamic problems, second-order polynomials are the most appropriate forms to representing a RS because the calculations are simple and the resulting function is closed-form algebraic expression with less complicity [25]. Polynomials are also capable to approximate the map function between physical parameters and response and thus optimising the responses.

4.4. FE model updating

The intelligent method to increase a confident of predicted responses is FE model updating method. The aim of the method is to improve the correlation of initial FE model in the light of experimental data. The improvement of the initial predicted responses is achieved by altering the assumptions of the predicted

model to an acceptable level. Natural frequencies were used as objective response in this research. The objective function is formulated as in Eq (6).

$$J = \sum_{i=1}^{n} W_i \left(\frac{\lambda_i^{\text{fe}}}{\lambda_i^{\text{exp}}} - 1 \right)^2 \tag{6}$$

where, λ_i^{exp} is the i-th experimental eigenvalue and λ_i^{fe} is the i-th predicted eigenvalue from the FE model and n is the number of eigenvalues involved in the updating procedure.

5. Results and Discussion

Table 2 illustrations the results of the initial FE model and experimental modal analysis (EMA) of laser stitch welded structure in term of natural frequencies. From the results, a vast error was recognised in the initial FE model which is 50.41 percent for the first 6th modes. Meanwhile, the comparison also reveals that the high contribution to the total error is in the mode 2rd, mode 4th, mode 5th, and mode 6th.

The discrepancies in the natural frequencies between FE analysis and EMA were arisen of the inability of the initial FE model to replicate the physical structure accurately. In this work, the initial FE model was developed by idealisation of geometry, nominal material properties, and simplified weld joints [26]. Hence, alteration on the initial FE model must be done to accurately represent the structure.

Parameters such as Young's modulus of mild steel and Young's modulus of weld joints were investigated using sensitivity analysis, to identify significant parameters that need to be updated. However, this study only included the global material properties of the structure since the objective of this work is improving initial FE model by using low computational time based model updating method in which by reducing the complexity of the FE model using meta-model (as shown in Figure5).

RSM based model updating was effectively conducted to the initial FE model. From the result in Table 2, the total error has been managed to reduce from 50.1 percent to 26.84 percent. The result in Table 2 also shows that, the minimisation in the individual error of every mode particularly for the 4th mode, from 15.11 percent to 9.71 percent. Meanwhile, Table 3 shows the comparison of initial and updated value of influential parameters (sensitive) of the structure where the Young's modulus of mild steel and Young's modulus of weld joints were updated from 200 GPa to 206 GPa and 231 GPa respectively. In this work, it was found that, the proposed method has managed to improve the predicted result reasonably.

Table 2. Comparison between EMA, FE and RSM.

	I.	II.	III.	IV.	V.
Mode	EMA (Hz)	FE (Hz)	Error between I & II (%)	RSM (Hz)	Error between I & II (%)
1	521.25	514.11	1.37	526.11	0.93
2	590.04	533.05	9.66	563.20	4.55
3	596.88	561.07	6.00	574.20	3.80
4	672.43	570.82	15.11	607.14	9.71
5	681.01	613.39	9.93	649.40	4.64
6	693.44	635.56	8.35	671.20	3.21
Total Error			50.41		26.84

Table 3. Comparison values of influential parameters of the structure

Parameter	Initial value (GPa)	Updated value (GPa)	Difference (%)
Young's modulus of mild steel	200	206	3.1
Young's modulus of laser welds	200	231	15.5
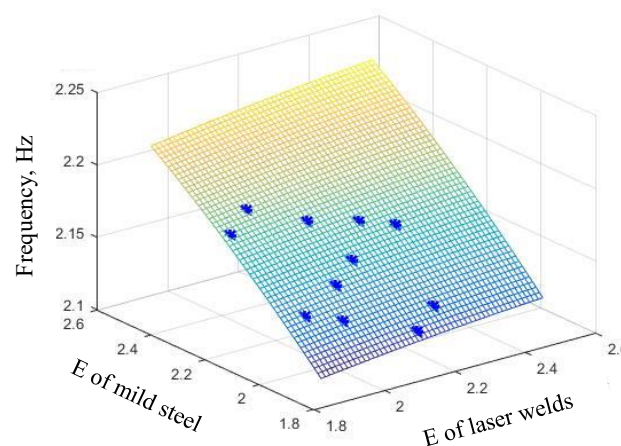
Figure 5. Meta-model of welded structure

6. Conclusions

The procedure of FE model updating using response surface (RS) method for structures that assembled by laser stitch welds has successfully presented in this paper. To improve the correlation of predicted responses with measured data, the meta-model based on RS using second-order polynomial was constructed with central composite design (CCD) as FE statistical sampling. This research show that, the initial FE model can be efficiently and successfully optimise using mentioned procedures.

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