The application of design of experiment method in finite element model updating for estimating uncertainties of Laser Stitch Welded Structure

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Abstract. The sensitivity based finite element model updating is a common method to improve the correlation between the initial finite element model and actual structure. The method is considered to be deterministic to correct the modelling parameters that lead to better predictions of the dynamic behaviour of a structure. However, for a complex jointed structure, there may contains variability and uncertainties that causing the structure become non-deterministic problems. Usually, variability in actual structure may arise from many sources such as geometrical tolerance and manufacturing process. Meanwhile, uncertainties in modelling usually results from the use of nominal material properties and imprecise joint stiffness. Therefore, this paper is intended to propose a novel approach to deal with modelling uncertainties and to perform the model updating of complex jointed structure by using statistical design of experiment (DOE) methods. Initially, the finite element model of the structure was constructed using CQUAD4 shell element and the area contact model (ACM) element connectors was used to represent laser stitch weld joints. Due to the lack of information on the structure and the welds, the input material properties used in the finite element model was based on nominal value of mild steel. Then, DOE methods such as Central composite design (CCD), D-optimal design and Latin hypercube (LHS) were used to estimate the new starting value for the material properties of the model. The results of the finite element models based on DOEs were compared with experimental data in terms of its natural frequencies. The correlations of the nominal FE model, CCD based FE model, D-optimal based FE model and LHS based finite element model with experimental counterpart were improved by using sensitivity based model updating. The results then were compared to identify the feasibility, accuracy and efficiency of the DOE methods in estimating reasonable starting material properties values and further overcome the uncertainties problems. The results show that DOE methods were efficient to be used in FE modelling and model updating since it capable to improve the accuracy of the prediction results.

Keywords. Design of experiment; Uncertainties; Finite element model updating; modal analysis; natural frequencies

1. Introduction

Finite element analysis is the powerful and practical computational tool that capable to provide approximate solutions to the engineering problems. Due to the availability of the finite element technology, the engineering designs such as automotive structures are becoming much complex and
unique. Usually, finite element model of structure is normally constructed on the basis of the idealising and simplifying the designs that makes the finite element model is unable to truly represent the actual characteristics of an actual structure [1]. Consequently, the numerical predictions that are obtained from the finite element model usually can contribute to the high discrepancies of between the predicted results with a real structure. These discrepancies appear because of the assumptions that had been made and also the uncertainties of geometrical modelling, input material and properties as well as structure joints such as bolts, welds and adhesives. Therefore, the initial finite element model with uncertain parameters is required to be corrected in order to obtain a better correlation of the responses with actual structure.

Owing to the fact that finite element model always differs with actual structure, the systematic method such as finite element model updating can be used to reconcile and improve the uncertain parameters so that the realistic finite element model of the structure can be achieved. Basically, finite element model updating is a process that used responses of test structure such as dynamic behaviour that obtained from experimental work to correct and update the uncertain parameters of the initial finite element models of the structure. Previous studies by Ren et. al stated that setting up of an objective function, selecting updating parameters and applying robust optimisation algorithm are the crucial steps in model updating [2]. Moreover, Mottershead et. al has stated that, finite element model updating is not only emphasizing with the satisfactory degree of accuracy of predicted results with actual structure, but the updated parameters must maintain the physical meaning of the structure so that it can mimic the actual structure accurately and reliably [3]. On top of that, Ahmad et. al highlight that, finite element model updating may suffer from ill-conditions, whereas it occurs when the system response is insensitive to some of the updating parameters or when they have similar effects on the system's response [4].

To avoid that, finite element model updating uses sensitivity matrices to guide the iteration steps in minimising objective function until meet the desired convergence criterion. However, by only implementing the sensitivity based updating alone is not suitable and impractical to be used to on a large and complex jointed structure because the structure tends to produce very poor correlation between finite element model and experiment data even after sensitivity based updating procedure has been successfully conducted. The ill-conditioning problem usually appears because the initial finite element model was constructed too simple and the assumptions that are made on the structure and joints are not significantly represent the physical properties of the structure due to a lot of uncertainty exists in the modelling of the structure [5], [6]. For instance, a complex structure such as a car body in white are normally consisted with high amount of the degree of freedom (DOF) that also consists a lot of uncertainties need to be updated and the credibility of the sensitivity based updating are in doubt because the iteration process will increase exponentially. This is because the iteration process will evaluate the objective function based on finite element model and causing high computational time due to the slow convergence problem. Therefore, an alternative procedure to replace the computational expensive method of the iterative finite element model updating has been proposed. The implementation of statistical design of experiment (DOE) methods in model updating, is more preferable since it can effectively provide an accurate, reliable and less running process in comparison to the iterative updating methods.

In general, design of experiment is a statistical approach that is used to sample the design space of a structure based on the analysis of interest in an efficient way. There are lot of methods of DOEs and the most intensively used in structural dynamics problems are Central composite design (CCD), D-optimal design and Latin hypercube sampling (LHS) [7]–[9]. The variability of these methods are particularly depending on the arrangement of sampling points in the design space. In finite element model updating, DOE methods can be used to improve further the credibility of the updating method when the DOE method is implemented to a complex and large jointed structure. The DOE methods can be used to find a set of starting values of the uncertainties parameters that can offer a better result and correlation with the experiment data as the current nominal values. Therefore, this paper is intended to present a DOEs based model updating procedure in structural dynamics for a complex jointed structure which is laser stitch welded structure. The proposed procedure is based on implementation of three (3) different DOEs;
CCD, D-optimal and LHS in the development of finite element models. Those DOEs is used to estimate the starting value of input parameters in the initial finite element model. Then the optimisation procedure based on sensitivity based model updating is conducted to the DOE based the finite element models. The objective function is formed by the residuals between predicted and measured natural frequencies. The results are compared with those obtained from the sensitivity based finite element model updating method to identify the feasibility, reliability and time consuming of DOEs based model updating.

2. Experimental modal analysis

The experimental work was conducted in order to identify structure dynamic behaviour such as natural frequencies and mode shapes. In this work, a complex jointed structure which consist of 2 subcomponents namely hat shape plate and flat shape plate and they were jointed using laser stitch welding technique. There were 20 welds with approximately 20 mm length of each stich. The material properties of the subcomponents are cold rolled mild steel sheets with overall dimension was 560 mm length, 110 mm wide and 15 mm thickness.

In this work, experimental modal analysis was performed to the structure by using an impact hammer as the input source. Meanwhile, the roving accelerometers method was used to extract the structure responses as shown in figure 2. In order to understand the reliability, feasibility and accuracy of the DOE based model updating, the frequency bandwidth of interest was set from 0 – 700 Hz. This is to avoid high number of responses involve and further minimising complexity of the solution[10]. Prior to measure the dynamic behaviour of the structure, the structure was setup under free-free boundary conditions whereby four sets of string and soft springs were used to hang the structure (figure 1) [11]. It is very important to make sure the suspension used can accurately to simulate the free boundary condition because the wrongly selection of suspension will contribute to the poor results of frequency response function (FRF). Finally, all the data obtained were processes using LMS SCADAS data acquisition system.

![Figure 1. Experimental setup of laser stitch welded structure.](image)

![Figure 2. Impact hammer and accelerometers attachment in experiment.](image)
3. Finite element modelling

The finite element model of laser stitch welded structure was used as a case study to illustrate the proposed updating procedure. In the pre-processing stage of the finite element modelling, the MSC PATRAN was used to develop the finite element model. The structure was modelled using CQUAD4 elements and the model was meshed into 5 mm meshing size (figure 3) based on the suitability of the meshes size obtained from mesh convergence test results. The Area Contact Model (ACM) element connectors then were used to represent as laser stitch welds and to connect the hat shape plate and flat shape plate subcomponents as recommended from previous studies [12], [13]. The nominal material properties of mild steel were used in the finite element modelling [14].

![Figure 3. FE model of laser stitch welded structure.](image)

In this research, normal mode analysis was obtained using SOL 103 of MSC NASTRAN to identify the natural frequencies and mode shapes of the finite element model. The generalised of the equation of motion used to discretise the system into a finite element model, also known as 2nd order differential equation is given as

\[ M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \]  

(1)

where \( M, C \) and \( K \) are symmetric matrices of mass, damping and stiffness. Meanwhile \( \ddot{x}, \dot{x} \) and \( x \) represent the vector of accelerations, velocities and displacement respectively and \( f(t) \) is vector of external forces. The structure that been used in this research were considered having light damping and the effect of damping can be theoretically neglected and as a result, for the undamped free vibration analysis, the equation (1) can be simplified as

\[ M\ddot{x}(t) + Kx(t) = 0 \]  

(2)

The equation (2) can be solved by assuming the harmonic solution in the form of

\[ x = \phi \sin\omega t \]  

(3)

where \( \omega \) and \( \phi \) are the mode shape and natural frequency of the system. If the differentiation of the assumed harmonic solution is performed and substituted in equation (2), the equation of motion yields and simplified to the following

\[ (K - \omega^2 M)\phi = 0 \]  

(4)

The natural frequencies and mode shapes of the laser spot welded structure can be predicted by solving the equation (4) using finite element commercial software such as MSC NASTRAN.
4. Design of experiment (DOE)
Practically, finite element analysis is the most essential simulation tool. However, a lot of uncertainty exist in the actual structure making the model become inaccurate and incapable to mimic the physical structure. Current finite element modelling is based on nominal values for input parameters. Extension of the finite element tool with design of experiment methods (DOE) offers a solution to incorporate uncertainty in the model validation and updating process. In general, the main goal of DOEs is to obtain the required information with a minimum number of sampling points, as the evaluation of each sampling point requires and additional run of the FE-model [15-17].

In model updating, DOE techniques can be used to find a set of starting values (e.g. material properties) that result in a better correlation with the experimental data as the current starting values. DOE technique is essential if the correlation between the initial FE model and the experimental data is too poor to perform in a sensitivity based model updating. In this study, three (3) different DOEs which are Central composite design (CCD), D-optimal design and Latin hypercube sampling (LHS) been implemented to identify reasonable starting values for input parameters.

4.1. Central composite design (CCD)
CCD is the most popular DOE and has been widely used among researchers for statistical studied. The design uses the orthogonal table to perform the experimentation in order to determine the sample points of selected parameters. Theoretically, CCD (as shown in figure 4) contains a full factorial design 2k or 2k-1 half replicate (k is the number of independent variables) factorial points (±1,±1, …,±1); 2k axial points of the form (±α, 0,…, 0), (0,±α,… , 0), and 1 centre point (0,0,…,0). In this work, full factorial points will be used for factors k = 5.

![Figure 4. Central composite design with the central point, cube points and axial points.](image)

4.2. D-optimal design
The D-optimal design is a DOE technique that constructed by evaluating a sets number of trials with random sampling points. It only efficient to be used if the set of the sampling having the highest D-efficiency. This is because only sampling points with the high D-efficiency are spread all over the design space and thus providing more information on the parameter relations. It should be noted that there is no guarantee the set of tested designs contained the actual optimal D-efficiency design.

4.3. Latin hypercube sampling (LHS)
In general, the LHS is a design that implemented based on random sampling. The main problem with random type sampling is that the sampling points may be clustered and contribute to the limited information on the influence of input parameters to structure response. However, due to the nature of LHS in which the sampling starts by dividing the parameter bounded range into n intervals with equal probabilities, the design can be assured to spread all sampling points over the design space.
5. Finite element model updating

Finite element model updating is an approach to improve the correlation of finite element model and the actual structure by correcting the invalid assumptions of the model to an acceptable level of accuracy. In the structural dynamics, the structural response are often eigen-solutions related to such as natural frequencies and mode shapes. In this research, natural frequencies are employed as objective response. Therefore, the optimised objective function is formulated in terms of the residuals between analytical and measured natural frequencies and can be expressed as

\[ J = \sum_{i=1}^{n} W_i \left( \frac{\lambda_{i}^{\text{exp}}}{\lambda_{i}^{\text{fe}}} - 1 \right)^2 \]  

(5)

where, \( \lambda_{i}^{\text{exp}} \) is the \( i \)-th experimental eigenvalue and \( \lambda_{i}^{\text{fe}} \) is the \( i \)-th predicted eigenvalue from the finite element model and \( n \) is the number of eigenvalues involved in the updating procedure.

6. Results and discussions

A finite element model of laser stitch welded structure is considered to demonstrate the procedure of Design of Experiments (DOE)s based finite element model updating. The structure of 110 mm length with containing 20 laser stitch welds is assuming having nominal material properties with the starting values are stated in table 1.

| No | Parameter                          | Initial FE |
|----|-----------------------------------|------------|
| 1  | E, Hat Plate (GPa)                | 200.00     |
| 2  | E, Flat Plate (GPa)               | 200.00     |
| 3  | E, HAZ Hat Plate (GPa)            | 200.00     |
| 4  | E, HAZ Flat Plate (GPa)           | 200.00     |
| 5  | E, Weld (GPa)                     | 200.00     |

Finite element model of the structure was analysed by using modal analysis to identify the prediction dynamic behaviour which is natural frequencies. The first 6 natural frequencies were selected and been compared with experimental natural frequencies. Initially, the predicted natural frequencies were correlated with experimental counterpart by pairing the mode shapes. The correlations of the natural frequencies with corresponding differences are shown in table 2. The maximum and minimum errors that appeared in the natural frequencies are 15.11% and 1.37% respectively with total error recorded is 50.41%. After that, sensitivity based model updating method was conducted with the initial main goal is to reduce the total error of initial finite element model. In this study, Young’s modulus of the structure as shown in table 1 were selected as the updating parameters since it has significant effect to the experimental natural frequencies. The results of the sensitivity based model updating is shown in table 2. The total error recorded has been reduced from 50.41% to 36.11%. It can be seen that even sensitivity based model updating managed to reduce the initial error of finite element model, however, the results shows that there is still huge error in the updated model and thus, the model is not truly mimic the actual structure. Although sensitivity based model updating is one of the robust optimisation techniques, one of the reasons that contributed to this problem is the starting values of input parameters such as material properties of the structure is not near to the actual values [18]. This is because material properties of the initial FE model are based on nominal values. The values may not truly represent the actual material properties of the structure because there are lot of uncertainty in the structure. This uncertainty of the actual structure is further increased since the structure is assembled via laser stitch welding technique and the material properties may vary substantially with temperature and boundary condition [19]. Without considering the uncertainties, the updated results are not reliable enough to represent the physical structure due to the possibility for the finite element model to having ill-conditions due to the
objective gradient may trapped into local minima [20]. In addition, the results in table 2 shows that by using sensitivity based model updating without having reasonable starting material properties values will only contribute to the high computational time. This is due to the difficulties of the method to determine global optimum gradient and thus causing computationally intensive and also convergence difficulty [21]. Therefore, new procedure using design of experiment (DOE) methods to identify the reasonable starting values of material properties was introduced to address this issue.

Table 2. Comparison natural frequencies of initial FE model with sensitivity updated based FE model.

| Mode | Test (Hz) | Initial FE (Hz) | Error (%) | TradSensiti. Updated FE (Hz) | Error (%) |
|------|-----------|-----------------|-----------|-------------------------------|-----------|
| 1    | 521.25    | 514.11          | 1.37      | 524.36                        | 0.60      |
| 2    | 590.04    | 533.05          | 9.66      | 549.96                        | 6.79      |
| 3    | 596.88    | 561.07          | 6.00      | 571.81                        | 4.20      |
| 4    | 672.43    | 570.82          | 15.11     | 592.03                        | 11.96     |
| 5    | 681.01    | 613.39          | 9.93      | 633.05                        | 7.04      |
| 6    | 693.44    | 635.56          | 8.35      | 655.14                        | 5.52      |
| Total|           |                 |           | 50.41                         | 36.11     |

Table 3, table 4 and table 5 shows the result correlations of the experimental natural frequencies with the finite element models using DOE methods such as Central composite (CCD), D-optimal (D-Opt) and Latin hypercube sampling (LHS). The starting values of material properties for these models was identified by using those mentioned DOEs. From the tables, the total error recorded for the CCD based FE model, D-opt based FE model and LHS based FE model are 30.48%, 34.26% and 35.71% respectively. Initially, the results show that the correlations of all three FE based DOEs with experiment data are almost the same. However, the identification initial input values using different DOEs is vital since its goal is to sample the design space by particular arrangement of sampling points and distinguished by ability to obtain a minimum number of sampling points under bounded conditions. Therefore, the reliability of starting values of material properties can be defined further using FE model updating. Meanwhile, result in table 6 shows the starting values of material properties (Young’s modulus) using different DOEs.

Table 3. Comparison n natural frequencies of initial Central Composite Design (CCD) based FE model with updated CCD based FE model.

| Mode | Test (Hz) | CCD FE (Hz) | Error (%) | Updated CCD FE (Hz) | Error (%) |
|------|-----------|-------------|-----------|---------------------|-----------|
| 1    | 521.25    | 539.20      | 3.44      | 526.11              | 0.93      |
| 2    | 590.04    | 559.07      | 5.25      | 563.19              | 4.55      |
| 3    | 596.88    | 588.45      | 1.41      | 574.19              | 3.80      |
| 4    | 672.43    | 598.68      | 10.97     | 607.13              | 9.71      |
| 5    | 681.01    | 643.33      | 5.53      | 649.39              | 4.64      |
| 6    | 693.44    | 666.58      | 3.87      | 671.20              | 3.21      |
| Total|           |             |           | 30.48               | 26.84     |
Table 4. Comparison natural frequencies of initial D-Optimal (D-Opt) based FE model with updated D-Opt based FE model.

| Mode | Test (Hz) | D-Opt FE (Hz) | Error (%) | Updated D-Opt FE (Hz) | Error (%) |
|------|-----------|---------------|-----------|-----------------------|-----------|
| 1    | 521.25    | 527.63        | 1.22      | 527.327               | 1.17      |
| 2    | 590.04    | 552.83        | 6.31      | 568.316               | 3.68      |
| 3    | 596.88    | 575.83        | 3.53      | 575.231               | 3.63      |
| 4    | 672.43    | 593.12        | 11.79     | 614.399               | 8.63      |
| 5    | 681.01    | 636.84        | 6.49      | 655.943               | 3.68      |
| 6    | 693.44    | 659.31        | 4.92      | 677.575               | 2.29      |
| **Total** | **34.26** | **23.07** |            |                       |           |

Table 5. Comparison natural frequencies of initial Latin Hypercube Sampling (LHS) based FE model with updated LHS based FE model.

| Mode | Test (Hz) | LHS FE (Hz) | Error (%) | Updated LHS FE (Hz) | Error (%) |
|------|-----------|-------------|-----------|---------------------|-----------|
| 1    | 521.25    | 531.11      | 1.89      | 526.70               | 1.05      |
| 2    | 590.04    | 551.06      | 6.61      | 566.00               | 4.07      |
| 3    | 596.88    | 579.65      | 2.89      | 574.76               | 3.71      |
| 4    | 672.43    | 589.95      | 12.27     | 637.73               | 5.16      |
| 5    | 681.01    | 634.28      | 6.86      | 652.92               | 4.13      |
| 6    | 693.44    | 657.32      | 5.21      | 674.76               | 2.69      |
| **Total** | **35.72** | **19.81** |            |                       |           |

Table 6. Starting Young’s modulus value of CCD, D-Opt and LHS based FE model.

| No | Parameter               | CCD FE | D-Opt FE | LHS FE |
|----|-------------------------|--------|----------|--------|
| 1  | E, Hat Plate (GPa)      | 220.00 | 209.65   | 213.37 |
| 2  | E, Flat Plate (GPa)     | 220.00 | 218.85   | 214.07 |
| 3  | E, HAZ Hat Plate (GPa)  | 220.00 | 195.88   | 219.65 |
| 4  | E, HAZ Flat Plate (GPa) | 220.00 | 217.17   | 212.67 |
| 5  | E, Welds (GPa)          | 220.00 | 212.39   | 211.28 |

In this study, after successfully constructed new FE models using initial material properties values obtained from three different DOEs, the FE models then were undergoing an optimisation process, which is FE model updating in order to reduce its discrepancies with actual structure. Table 3, table 4 and table 5 shows the correlations of results between experimental natural frequencies and CCD based
updated FE, D-Opt based updated FE and LHS based updated FE with the total error recorded are 26.48%, 23.07% and 19.81% respectively. Meanwhile, table 7 shows the updated Young’s modulus value of sensitivity model updating, CCD, D-Opt and LHS based FE model. The results shows that LHS based updated FE model is the most accurate FE model to mimic the actual laser stitch welded structure because the FE model managed to reduce the total error and also individual errors significantly in comparison with sensitivity updated FE model, CCD based updated FE model and D-Opt based updated FE model. It can be seen in table 5, the maximum and minimum errors that appeared in the natural frequencies are 5.16% and 1.05% respectively.

### Table 7. Updated Young’s modulus value of sensitivity, CCD, D-Opt and LHS based FE model.

| No | Parameter               | Trad. Sensit. Updated FE | CCD Updated FE | D-Opt Updated FE | LHS Updated FE |
|----|-------------------------|---------------------------|----------------|------------------|----------------|
| 1  | E, Hat Plate (MPa)      | 207.48                    | 206.22         | 206.17           | 206.44         |
| 2  | E, Flat Plate (MPa)     | 220.00                    | 231.00         | 238.29           | 235.48         |
| 3  | E, HAZ Hat Plate (MPa)  | 180.00                    | 198.00         | 188.91           | 197.69         |
| 4  | E, HAZ Flat Plate (MPa) | 180.00                    | 198.00         | 197.16           | 191.41         |
| 5  | E, Weld (MPa)           | 220.00                    | 231.00         | 237.00           | 232.41         |

Results in table 8 reveal the comparison number of iterative minimisation and computational time between sensitivity, CCD, D-Opt and LHS based updated FE model. It can be seen that sensitivity based updating method required 49 iteration steps in order to complete objective function minimisation and consuming very high computational time, 1900 second. Meanwhile CCD based FE updating need 15 iteration steps with 280 second computational time. On the other hand, D-Opt and LHS based FE updating only required 3 iteration steps to minimising the errors with 45 second computational time. These results show the feasibility, reliability and time saving of DOEs based model updating particularly Latin hypercube sampling method in minimising the discrepancies of initial FE model (nominal material properties) using random sampling technique.

The results indicated that, better correlations between prediction and experimental natural frequencies can be achieved by considering reasonable starting values for input parameters. The results also show that statistical studies such as DOE method are essential to identified reasonable values of input parameters (material properties) for FE model of laser stitch welded structure.
Table 8. Comparison number of iterative minimisation and computational time of sensitivity, CCD, D-Optimal and Latin Hypercube based updated FE model.

| No | Method                        | Iterative Minimisation | Computation Time |
|----|-------------------------------|------------------------|------------------|
| 1  | Sensitivity Based FE Updating | 49 iterations          | 1900s            |
| 2  | CCD Based FE Updating         | 15 iterations          | 280s             |
| 3  | D-Optimal Based FE Updating   | 3 iterations           | 45s              |
| 4  | LHS Based FE Updating         | 3 iterations           | 45s              |

7. Conclusions
This paper presented an alternative finite element model updating procedure based on design of experiment methods using natural frequencies as response. DOE methods were used to estimate new starting values for input parameters of finite element model as to improve the accuracy, feasibility, and reliability of sensitivity based finite element model updating method. The DOE methods such as Central composite design (CCD), D-Optimal (D-Opt) and Latin hypercube sampling (LHS) has been employed in this study. The proposed procedure is illustrated on a complex jointed structure which is laser stitch welded structure since this structure contain a lot of uncertainties particularly on the material properties of subcomponents and weld joints. From the result, the DOEs managed to improve the initial finite element model by estimating new starting value for input parameters, the finite element model updating process becomes more efficient and converges fast compared with the sensitivity based model updating method particularly for Latin hypercube sampling. Therefore, the finite element model updating method can be easily implemented in practice rather than using nominal material properties that only causing high computational time and inaccuracy of the result.

This study has shown that a good understanding on uncertainties of actual structure and finite element model has play an important role in the success of the finite element updating method. A good approximation will lead to the accurate simulation prediction. A small number of updating parameters chosen in this work and an estimation of the starting values of input parameters by DOE methods may not been good enough to produce highly accurate predicted model. It is still a challenge to include large number of parameters in DOE methods in order to estimate other uncertain parameters because it can introduce more complex relation with experimental response (benchmark) and may consume much more computational time.

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