Vibration analysis of resistance spot welding joint for dissimilar plate structure (mild steel 1010 and stainless steel 304)

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Abstract: Resistance spot welding (RSW) is a proficient joining method commonly used for sheet metal joining and become one of the oldest spot welding processes use in industry especially in the automotive. RSW involves the application of heat and pressure without neglecting time taken when joining two or more metal sheets at a localized area which is claimed as the most efficient welding process in metal fabrication. The purpose of this project is to perform model updating of RSW plate structure between mild steel 1010 and stainless steel 304. In order to do the updating, normal mode finite element analysis (FEA) and experimental modal analysis (EMA) have been carried out. Result shows that the discrepancies of natural frequency between FEA and EMA are below than 10\%. Sensitivity model updating is evaluated in order to make sure which parameters are influences in this structural dynamic modification. Young’s modulus and density both materials are indicate significant parameters to do model updating. As a conclusion, after perform model updating, total average error of dissimilar RSW plate is improved significantly.

1. Introduction
Welding is the process of joining metals with the presence of heat, with or without the application of pressure and filler metal [1]. A typical automotive structure could contain thousands of spot weld joints that contribute significantly to the vehicle's structural stiffness and dynamic characteristics [2]. Spot weld falls under fusion welding process by applying method of melting the materials for joining purpose. RSW has excellent paybacks such as low cost, high speed and suitability for automation which makes it an attractive choice for auto-body assemblies, truck cabins, rail vehicles and home appliances [3]. Joining of dissimilar materials is of risky as the process necessitates a proper matches concerning the chemical, physical, and mechanical properties between the materials placed together [4]. In order to achieve a strong connection between mild steel and stainless steel, the right welding parameter should be selected [5]. Joining dissimilar materials has recently become very popular in industries because of the advantages associated with the weld joint [6]. The main target of combining materials are to drive for more optimal, lightweight and high performance structure in order to gain product performance needed besides it is widely employed for different applications requiring certain special combination of properties as well as to save cost [7] [8].
Modal analysis is the process of characterizing the dynamic properties of an elastic structure by identifying its modes of vibration. It is a kind of exact forecast of structural dynamic features such as the natural frequencies and damping ratios in order to vibration control and evaluating their performance in a dynamic situation is a substantial phase in the design of structures which means each mode has a specific natural frequency and damping factor which can be identified from practically any point on the structure [9]. EMA focuses on impact hammer which is a method of testing that allows users to calculate the natural frequencies (modes), damping ratio and mode shapes of the test structure. In reality, impact hammer test is a simple method to implement but difficult to obtain consistent results as the force applied while hammering cannot be fixed throughout the experiment. In additions, this technique requires little equipment and can provide shorter measurement times by applying impulse. The top frequently used numerical method is finite element (FE) method which is utilized to simulate the behavior of real systems. The purpose of numerical modeling can be categorized into three different main parts which are analysis, prediction and design [10]. FEA simulation is a computerized procedure for the analysis of structures.

Finite element model updating, as described before in this thesis, is a procedure to minimize the differences between analytical and experimental results. It appears that it is very difficult to discard the errors and inaccuracies in finite element model when the structure in study is a complex structure. Several methods of structural model updating have been proposed and the topic is still under active study in various areas. Most of these studies centred on approaches such as the optimal matrix updating [11] and sensitivity-based parameter estimation [12, 13]. Meanwhile, there are many other approaches of model updating procedure that are being researched by numerous scholars such as Bayesian model updating [14] stochastic [15] and perturbation method [16]. All these techniques have been extensively developed, applied, studied and commented by many researchers and notable figure in model updating field [13, 17, 18].

Approximation subject to the simple first-order Taylor’s series of expansion is used in model updating optimization in order to change the vector $\lambda$ of eigenvalues based on the vector $\theta$ of structure updating parameters as stated in Equation 1. below:

$$\lambda_{i+1} = \lambda_i + [S_i](\delta\theta)$$

Where $[S_i]$ is a sensitivity matrix of $i^{th}$ iteration, which signify the rate of change of the structural eigenvalues $\lambda_i$ with respect to changes in $\delta\theta$. The expression for the eigenvalue sensitivity $S_i$ can be stated as Equation 2.0 as follows:

$$S_i = \frac{\delta\lambda_i}{\delta\theta} = \phi_i^T \left[ \frac{\delta K}{\delta\theta} - \lambda_i \frac{\delta M}{\delta\theta} \right] \phi_i$$

The objective function, $J$, for the prediction error is defined as Equation specified style in document..1:

$$J = \sum_{i=1}^{n} W \left( \frac{\omega_{\hat{i}}}{\omega_i} - 1 \right)^2$$
where $\omega_e^2$ and $\omega_d^2$ are the experimental and finite element natural frequencies respectively and $W$ is the weighing factor for each mode.

In this paper, the main goal is to perform model updating based on sensitivity analysis of RSW dissimilar plate between two different types of materials; mild steel 1010 and stainless steel 304. This model updating is shown that modal properties can be improved significantly. Updating is completed when the error function minimized based on first five measured frequencies.

2. Modelling Plate Structure

2.1. Cutting materials

Mild steel and stainless steel are cut into specified dimension as depicted in Figure 1 by using shearing bench saw as shown in Figure 2 respectively below.

![Stainless steel 304 and Mild steel 1010](image1.jpg)

**Figure 1.** Stainless steel and mild steel

![Shearing bench saw](image2.jpg)

**Figure 2.** Shearing bench saw

2.2. Resistance Spot Welding Process

The history of welding initiate in the early twentieth century in which the localized heat source obtained from an electric arc that able to melts steel and coalesce two components together along a bond line to form a joint [19]. Resistance spot welding (RSW) is widely used for producing a typical BIW, that also being considered as dominant and important high speed process in automotive assembly which is normally made of thin metal sheets that are connected together by thousands of spot welds [20]. Welded structure strongly affected the global behavior for the whole structure and thus, it
is crucial to understand the dynamics characteristics of the welded joints which can be achieved via computational and experimental work [21]. In this paper, welding two dissimilar materials is need in which generally become more challenging than welding similar ones in term of differences in the chemical, physical and mechanical properties of the base metals even though the demands is accelerating [22, 23]. Set up parameter is a vital part to conduct welding process [5]. This prerequisite contributes to the quality and mechanical behavior of RSW in which might influenced the durability and crashworthiness of vehicle as it plays important role in joining parts in automotive [24]. Table 1 below shows the parameter set up for RSW in order to weld mild steel and stainless steel using RSW SSW-2020ATT machine as demonstrates in Figure 3.

| Parameter                | Value |
|--------------------------|-------|
| Current supplied         | 4 A   |
| Pressure applied         | 35 Psi|
| Holding time             | 5 s   |
| Diameter of electrode tips | 1 cm  |

The completion of RSW process formed a joined between dissimilar plate with 1cm in diameter for each spot as can be seen in Figure 4 below.

3. Finite Element Analysis
Finite element analysis is a very popular technique in structural dynamic analysis due to advances in numerical method and the availability of powerful computing facilities. The equation of motion can be showed dynamic properties of structure accompanying by easy geometric shape and standard physical characteristics. MSC Nastran Patran is a commercial finite element software package which having ability to model the specimen and utilize to generate its natural frequency and mode shapes using normal mode analysis (SOL103). The objective of numerical modeling can be classified into three different main parts which are analysis, prediction and design [25]. From analysis of dissimilar plate structure, modal parameters are gained and tabulated as in Table 2.

| Mode | Natural Frequency (Hz) | Mode Shapes |
|------|------------------------|-------------|
| 1    | 114.23                 | ![Mode 1](image1) |
| 2    | 115.48                 | ![Mode 2](image2) |
| 3    | 238.28                 | ![Mode 3](image3) |
| 4    | 245.76                 | ![Mode 4](image4) |
| 5    | 305.61                 | ![Mode 5](image5) |

4. Experimental Modal Analysis
Experimental modal analysis or modal testing has grown steadily in popularity for the past several decades. Modal testing is defined as the study of dynamics characteristic of a mechanical structure. Even though modal analysis can also be done analytically through computational simulation, experimental modal analysis has the advantage of having modal characteristic defined from actual measurements and not from assumptions. An important property of modes or the measured frequency response functions from a modal testing can be used to describe the structure’s dynamic properties.
The setup and the instrumentation used influence the experimental result in modal testing [26]. In order to gain accurate result of analysis, modal testing should be conducted in a free-free boundary condition. The experiment setup is illustrated in Figure 5.

From the experiments, natural frequencies and mode shapes of dissimilar plates were acquired and tabulated in Table 3.

**Table 3. Modal parameters using EMA**

| Mode | Natural frequencies (Hz) | Mode shape |
|------|--------------------------|------------|
| 1    | 119                      |            |
| 2    | 126                      |            |
| 3    | 214                      |            |
5. Model Updating

In model updating, there are two methods that can be implemented which is direct method and sensitivity method. In this paper, sensitivity method is chosen in which the most sensitive parameters will be selected for updating while less sensitive parameter is not taken into consideration for updating purpose. Eight parameters are having possibility to be updated undergo the sensitivity analysis using SOL200 in MSC Nastran software to select the suitable parameter to update. The sensitivities of the first five natural frequencies were tabulated in Table 4 and comparisons to be made in order to choose the most sensitive parameters.

Table 4. Sensitivity analysis for six parameters.

| Output Type | Young Modulus (E_{mild steel}) | Young Modulus (E_{stainless steel}) | Poisson Ratio (\nu_{mild steel}) | Poisson Ratio (\nu_{stainless steel}) | Density (\rho_{mild steel}) | Density (\rho_{stainless steel}) |
|-------------|--------------------------------|-------------------------------------|----------------------------------|--------------------------------------|-----------------------------|----------------------------------|
| NF 1        | 27.00                          | 31.23                               | -4.45                            | -5.82                                | -22.76                      | -35.65                          |
| NF 2        | 21.23                          | 37.64                               | -0.52                            | 1.42                                 | -25.80                      | -33.29                          |
| NF 3        | 64.03                          | 57.42                               | -0.10                            | -4.93                                | -61.42                      | -59.96                          |
| NF 4        | 50.76                          | 74.93                               | 5.26                             | 8.68                                 | -36.84                      | -89.61                          |
| NF 5        | 84.03                          | 71.80                               | -11.64                           | -6.72                                | -83.20                      | -72.37                          |

From all six parameters, it is clearly shown that poisson ratio, \( \nu \) is the less sensitive and will be not considered updating and optimization process. However, both dissimilar material of Young’s Modulus, \( E \) and density, \( \rho \) show high level of updating sensitivity. These two need to be chosen and therefore, there are four parameters that is going to be updated which is Young’s Modulus of mild steel, Young’s Modulus of stainless steel, density of mild steel and density of stainless steel. Updating is performed by minimizing the error function and executed on the basis of the first five modes of measured frequencies. The number of updating parameters is kept to be less than number of modes updated in order to avoid ill-conditioning problem arising during updating procedure [16]. Table 5 displays the error between FEA and EMA after updating.

Table 5. Percentage of error between FEA and EMA after updating

| Modes | Experiment (Hz) | Initial FEA (Hz) | Error (%) | Updated FEA (Hz) | Error |
|-------|-----------------|------------------|-----------|------------------|-------|
| 1     | 119             | 114.23           | 4.01      | 117.42           | 1.33  |
| 2     | 126             | 115.48           | 8.35      | 119.40           | 5.24  |
From the table 5, it can be concluded that after updating process, the natural frequency improved and total average error become decreased. It is proved that the density and Young’s Modulus which are considered as the sensitive parameter that significantly affect the modal properties of dissimilar plate structures. The changes of the initial and updated value of the updating parameters which consist of Young’s modulus and density of both dissimilar materials are shown in Table 6.

| Table 6. Updated value of parameters |
|-------------------------------------|
| Parameter                           | Initial Value | Updated Value | Deviation (%) |
| Young’s Modulus, $E_{\text{mild steel}}$ [GPa] | 210           | 194           | 7.62          |
| Young’s Modulus, $E_{\text{stainless steel}}$ [GPa] | 200           | 210           | 5.00          |
| Density, $\rho_{\text{mild steel}}$ (kg/m$^3$) | 7870          | 7634          | 3.00          |
| Density ($\rho_{\text{stainless steel}}$) (kg/m$^3$) | 8000          | 7840          | 2.00          |

6. Conclusion

In summary, this study has deals with two approaches to obtain modal parameters which are FEA and EMA. From the result, discrepancies are appears and hence, model updating was executed in order to improve the correlation between measured counterparts. Before proceed to model updating, sensitivity analysis had been done to make sure the most sensitive parameters will be chosen for model updating. Results show that Young modulus and thickness are the most sensitive parameters for updating. After perform model updating, total error of the natural frequencies for dissimilar plates is reduced. As conclusion, model updating could be applied in order to reduce the discrepancies between numerical and experimental data, thus improving the dynamic structure to have better correlation with the actual structure.

References

[1] Raja R, Rajkumar M. 2015 A review on trouble shooting, testing and safety precautions procedure for welding process.
[2] Husain NA, Ouyang H. 2011 Detection of damage in welded structure using experimental modal data. Journal of Physics: Conference Series;305(1):012120.
[3] Akkaş N, İlhan E, Varol F, Aslanlar S. 2016 Welding time effect on mechanical properties in resistance spot welding of s235jr (Cu) steel sheets used in railway vehicles. Acta Physica Polonica A;129(4):541-3.
[4] Montemor M. 2016 Corrosion issues in joining lightweight materials: A review of the latest achievements. Physical Sciences Reviews;1(2).
[5] Engelmann C, Meier D, Olowinsky A, Kielwasse M. Metal meets Composite-Hybrid Joining for Automotive Applications. LIM; 2015.
[6] Ishak M, Idris SRA. 2014 Study of resistance spot welding between aisi 301 stainless steel and AISI 1020 carbon steel dissimilar alloys. Journal of Mechanical Engineering and Sciences (JMES):6:793-806.
[7] Martinsen K, Hu SJ, Carlson BE. 2015 Joining of dissimilar materials. CIRP Annals - Manufacturing Technology;64(2):679-99.
[8] Meshram SD, Paradkar AG, Reddy GM, Pandey S. 2017 Friction stir welding: An alternative to fusion welding for better stress corrosion cracking resistance of maraging steel. Journal of Manufacturing Processes;25:94-103.

[9] Adel F, Shokrollahi S, Jamal-Omidi M, Ahmadian H. 2017 A model updating method for hybrid composite/aluminum bolted joints using modal test data. Journal of Sound and Vibration;396:172-85.

[10] Zahari SN, Zakaria AAR, Sani MSM. 2015 A review on model updating of joint structure for dynamic analysis purpose.

[11] Berman A, Nagy EJ. 1983 Improvement of a Large Analytical Model Using Test Data. AIAA Journal;21(8):1168-73.

[12] Bakir PG, Reynders E, De Roeck G. 2007 Sensitivity-based finite element model updating using constrained optimization with a trust region algorithm. Journal of Sound and Vibration;305(1):211-25.

[13] Mottershead JE, Link M, Friswell MI. 2011 The sensitivity method in finite element model updating: A tutorial. Mechanical Systems and Signal Processing;25(7):2275-96.

[14] Mtshembu L, Marwala T, Friswell MI, Adhikari S. 2011 Model selection in finite element model updating using the Bayesian evidence statistic. Mechanical Systems and Signal Processing;25(7):2399-412.

[15] Abu Husain N, Haddad Khodaparast H, Ouyang H. 2012 Parameter selection and stochastic model updating using perturbation methods with parameter weighting matrix assignment. Mechanical Systems and Signal Processing;32:135-52.

[16] Ouyang H, Mottershead JE; Haddad Khodaparast H, Abu Husain N. 2010 Application of the Perturbation Method With Parameter Weighting Matrix Assignments for Estimating Variability in a Set of Nominally Identical Welded Structures. (49194):95-104.

[17] Friswell MI, Mottershead JE, Ahmadian H. 2001 Finite–element model updating using experimental test data: parametrization and regularization. Philosophical Transactions of the Royal Society of London Series A: Mathematical, Physical and Engineering Sciences;359(1778):169-86.

[18] Mottershead JE, Friswell MI. 1993 Model Updating In Structural Dynamics: A Survey. Journal of Sound and Vibration;167(2):347-75.

[19] Moore P, Booth G. The Welding Engineer's Guide to Fracture and Fatigue. United Kingdom: Woodhead Publishing: 2015.

[20] Eisazadeh H, Hamedi M, Halvae A. 2010 New parametric study of nugget size in resistance spot welding process using finite element method. Materials & Design;31(1):149-57.

[21] Zahari SN, Sani MSM, Ishak M, editors. Finite element modelling and updating of friction stir welding (FSW) joint for vibration analysis. MATEC Web of Conferences; 2017: EDP Sciences.

[22] Wu W, Hu S, Shen J. 2015 Microstructure, mechanical properties and corrosion behavior of laser welded dissimilar joints between ferritic stainless steel and carbon steel. Materials & Design (1980-2015);65:855-61.

[23] Kimura M, Suzuki K, Kusaka M, Kaizu K. 2017 Effect of friction welding condition on joining phenomena and mechanical properties of friction welded joint between 6063 aluminium alloy and AISI 304 stainless steel. Journal of Manufacturing Processes;26:178-87.

[24] Marashi P, Pouranvari M, Amirabadollahian S, Abedi A, Goodarzi M. 2008 Microstructure and failure behavior of dissimilar resistance spot welds between low carbon galvanized and austenitic stainless steels. Materials Science and Engineering: A;480(1–2):175-80.

[25] Zahari SN, Zakaria AAR, Sani MSM, Zaman I. 2015 A review on model updating of joint structure for dynamic analysis purpose.

[26] Ewins D. 2003 Modal testing: theory, practice and application (mechanical engineering research studies: engineering dynamics series).