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Experimental Modal Analysis Procedure for a Laser Spot Welded Hat-Plate Structure

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Abstract. Measuring the dynamic behaviour of a structure made from light thin steel sheets becomes arduous as a result of the double impact, local modes and mass loading issues which lead to inaccurate results. In addition, the attachments of accelerometers, selection of suspension types and methods of excitation adopted to the measurement greatly affect the quality of the experimental results. The aim of this paper is to present detailed procedure for the experimental setup of a welded structure made from thin steel sheets. A hat shaped plate and flat plate connected together by several laser spot welds were used for the demonstration of the experimental modal analysis. The laser spot welded hat-plate structure was tested under free-free boundary conditions using impact testing with roving accelerometers and an LMS Test Lab. This work revealed that the proper procedures used for the experimental setup would help dynamicists enhance and improve the quality of the measured results of frequency response function and the results could be confidently used for the validation purposes and updating analytical models.

1. Introduction

The experimental modal analysis (EMA) has been used for decades by researchers [1-5] to measure the dynamic behaviour of physical test structures. The dynamic behaviour is characterised in terms of natural frequencies and mode shapes of the structures [6]. EMA has helped the researchers to understand experimentally the global behaviour of the structures. Nevertheless, the behaviour of the structures can also be determined using the finite element (FE) method introduced by [7]. The FE method which is one of the most powerful numerical methods requires relatively high-speed computers to solve the engineering problems without using the physical structure [8]. Although solving engineering problems

using the FE method, which is highly dependent on valid assumptions about model properties provided by the researchers, is faster than EMA, but the test results obtained from EMA are more reliable than those calculated from the finite element method. However, due to improper techniques of EMA procedure, the measured data is inaccurate and may not represent the real behaviour of the structure [9].

In the automotive industry, the assembled structures are made from thin steel sheets and connected with a thousand numbers of joints [10-11]. Complex structure with a large number of joints can exhibit a local behaviour that is difficult to accurately measure in the experimental modal analysis. Furthermore, EMA has the problems in deciding the measurement points, excitation point and boundary conditions. Hence, the right guideline on the experimental procedure is needed to make sure the measurement data is valid. Accurate EMA data is important to validate the prediction data analysed by finite element software. Numerous research work [12-17] have used EMA data to validate and improve their finite element model close to the measured one. For instance, [18-19] used experimental data to validate the reduce order finite element model of a jointed structure. EMA also used for damage detection on the structure as mentioned by [20-22]. However, no research work presents the guidelines for the experimental procedure for a welded structure made from thin steel sheets.

2. Experimental Set Up of Hat-Plate Structure

In this study, the experimental modal analysis was performed on the hat plate laser spot welded structure with a nominal thickness of 1.5 mm. The schematic diagram of the experimental modal analysis set-up is shown in Figure 1. The structure was discretized into several small squared segments. The purpose of the discretization was to have the appropriate number of the locations of measuring points. The determination of the number of the segments was carried out with the guidance from the results of modal parameters of the structure obtained from the finite element analysis. To simulate free boundary conditions, rubber bands and strings were used.
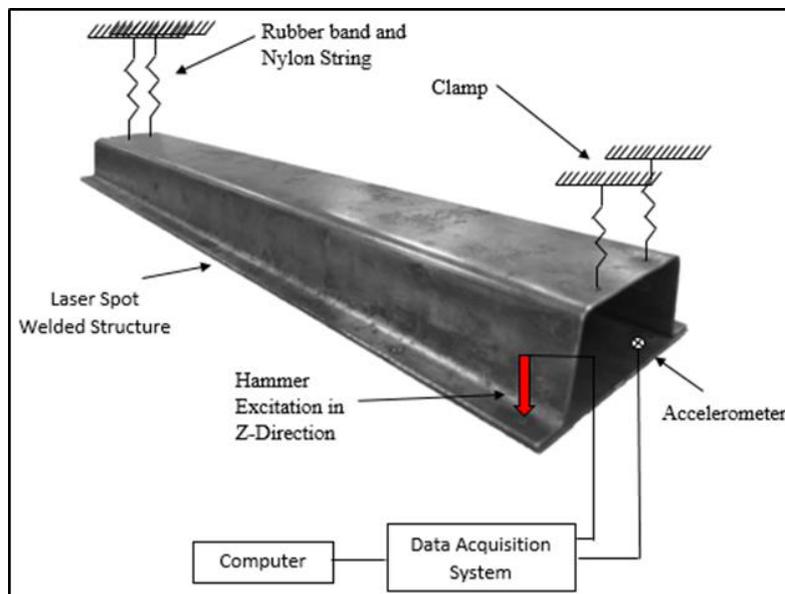

Figure 1: Experimental setup of laser spot welded hat-plate structure

Prior to performing the experimental work, several factors related to the experiments such as the number of accelerometers and measurement points and excitation methods should be considered. In this study, the initial prediction of the dynamic properties of the structure firstly performed to the test physical structure. Furthermore, the calculated natural frequencies and mode shapes of the structure were then used

for the selection of the excitation points and the locations of measurement points of the physical test structure. The frequency bandwidth of interest was within 0 to 900Hz.

In the experimental work, an impact hammer and roving accelerometers were used to measure the dynamic behaviour of the physical test structure. A total of three accelerometers was used with one was fixed at the excitation point and the other two were roved to all measurement points.

2.1 Measurement Points

The number and location of points to be used for the measurement of the dynamic behaviour of a structure must be carefully considered and selected. The total number of the measurement points should appropriately be calculated prior to carrying out tests. The smaller the number of measurement points used in the tests, the lower the quality of the mode shapes of the structure measured. Meanwhile, the larger the number of measurement points, the longer the time required for the measurement of the mode shapes. In this regard, the best way is to use the initial FE results for guidance. This is because FE results give an initial overview of the dynamic behaviour of the structure under study.

Furthermore, the distribution and the size of discretization of the measurement points must be equally spread throughout the structure. This will result in a suitable mesh for the mode visualization and also can prevent losing any modes of interest under study. The number of accelerometers used in the experimental measurement must be carefully considered. A large number of accelerometers will increase the amount of mass of the structure and will change the local stiffness of the structure especially for thin steel sheets structure. Therefore, [23] suggested making sure that the total mass of accelerometers must not exceed 10 per cent of the weight of the structure.

In this experiment, one fixed and two roving accelerometers were used in the measurement of the dynamic behaviour of the hat plate spot welded structure. The mass of one accelerometer used in the test was 1.5 grams while the total mass of the assembled structure was 1776 grams. Hence, the total mass of the accelerometers calculated clearly does not give any mass loading issues.

2.2 Selection of suspensions

To accurately generate the experimental frequency response function (FRF) required to fathom out the modal parameters which are the natural frequencies and mode shapes of a structure. The structure must be tested under free-free boundary conditions. In this work, the test on the hat-plate laser spot welded structure was conducted by suspending the structure via four rubber bands and nylon strings as shown in Figure 1. The main reason the test was conducted in that particular set up is to remove the influence of boundary conditions from the test. This is because it is very difficult to incorporate experimental boundary conditions into analytical models. The difficulties have given impetus to researchers to investigate the dynamic behaviour of structures under free-free boundary conditions. The effects of the using of support conditions for free boundary conditions to ensure the accuracy of the measured results were thoroughly discussed [24]–[26].

Free-free boundary conditions do not mean that the structure under tests was completely not being supported by something, but it was sufficient to demonstrate that the structure can move freely within a certain period of time while impact testing was being performed. In addition, the values of rigid body modes measured must be 0 Hz or at least less than 1 Hz. However, the rigid body modes that were much lower than the first elastic mode have an insignificant effect on the accuracy of the measured results. In this regard, the rule of thumb that can be applied and has been proposed by [27], the highest value of rigid body modes must be less than 10 per cent of the first frequency of elastic mode.

In order to simulate a structure in free-free boundary conditions, the structure can be suspended from very soft elastic cords, springs with rubber bands or placed on a very soft cushion. Meanwhile, the selection of suspensions is based on the weight of the structure. In this experiment, four strings and rubber bands were used to simulate a free-free configuration. The selection of the rubber bands was made based on the weight of the laser spot welded hat-plate structure so that the structure can move freely when a force excitation is given. The method of suspending the hat-plate structure is shown in Figure 2.

Figure 2: The structure is suspended using rubber bands and strings

2.3 Methods of excitation

Excitation methods can be categorised by using shakers or impact testing. In the spectral testing method, a shaker is connected to the structure and the shaker provides the necessary excitation force which is based on the specified input voltage. There are three different types of signal inputs produced by shakers such as sinusoidal, random and periodic. There are two main types of shakers that are commonly used by researchers. They are electromagnetic and electro-hydraulic shakers. For the electromagnetic shaker, the force is generated by an alternating current that drives a magnetic coil. The limit of the frequency of the shaker depends on the size of the shaker. On the hydraulic shaker, the force is generated through the use of hydraulics, which provides much higher force levels.

It is worth noting that applying a force excitation through the use of a shaker system is regarded as not particularly suitable for a lightweight structure. This is because the stinger and load cell by which the shaker is attached to the structure will cause mass loading issues. In addition, the way of the shaker being attached to the structure should be properly and carefully handled, especially in the direction of the measurement being carried out. This is to prevent the structure from being damaged. Another disturbing issue, using shaker systems in tests is that the way of the shaker being supported. The main body of the shaker must be isolated from the structure to prevent any reaction forces from being transmitted through the base of the shaker back to the structure. Lastly, the limitation of using shaker systems is the difficulty in adjusting the angle of shaker perpendicular to the face of the structure.

As a result of the limitations of shaker systems, [28] developed a new method of an excitation technique which is called impact testing. Impact testing which offers economical ways in terms of time and cost has become the most popular modal testing method in the structural dynamics community. An impact hammer with a load cell attached to its head used to apply the impulse and to measure the input force. The selection of the size of an impact hammer is dependent on the size of the structure under tests. If the size of the structure is small, then the size of the hammer should be small as well and vice versa.

One of the major setbacks of impact testing is that the difficulty of controlling the input force of the hammer. The force level excitation varies from node to node and therefore, to overcome the varying levels the structure should be excited at least ten times for each of the predefined measured nodes. Then, the average data obtained from the ten excitations is calculated. Another issue in impact testing is to make sure the excitation energy will cover all the measured nodes and frequency of interest during the experiment process. The excitation energy depends on the stiffness of the contacting surface of the structure. If the energy does not cover all the frequency of interest, the tip of the hammer is not suitable for that structure [23].

There are three types of hammer tips which are steel, plastic and rubber that are commonly used in modal testing. The harder the tip, the shorter the frequency content. In this experiment, the hammer tip used was a plastic type, and it can cover the frequency of interest of this study which is from 0 to 900 Hz. The schematic diagram of the modal testing set up using an impact hammer is shown in Figure 3.
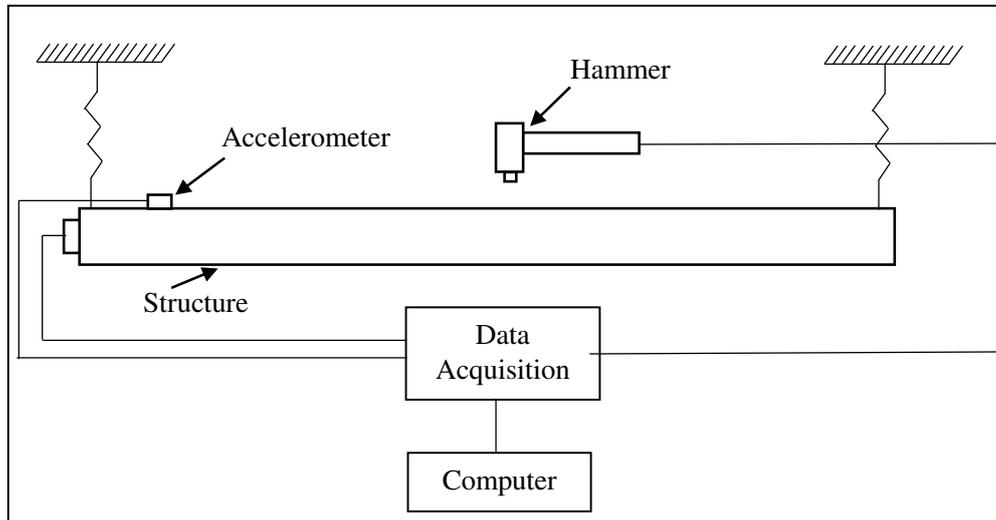

Figure 3: Schematic diagram of hammer excitation test set up

2.4 Attachment of accelerometers

Moreover, the location of the accelerometers attached to the structure is another factor that must be considered. The location cannot be far out from the nodes to minimize the error and missing modes. [29] introduced a new method for accelerometer placement using Generic Algorithm (GA) method. The method can estimate the target mode response with higher accuracy. Besides, the initial prediction from finite element model also can be used to decide the measuring point in the experimental modal analysis. All modes in the frequency range need to investigate the best accelerometers location that covers all mode shapes.

Accelerometers are attached to the structure by using adhesive, stud or magnetic mount at the measured nodes. Petroleum wax is commonly used to mount the accelerometers because it offers quick measurement of vibration. The amount of petroleum wax used to mount the accelerometers also needs to be considered. The excessive amount of wax will affect the accuracy of the measured value and cause mass loading issue. Hence, the usage of wax just enough to attach the accelerometers to the structure.

2.5 Frequency response function (FRF) analysis

Frequency response function (FRF) describes the relationship between excitation input forces and accelerometer output data in the function of frequency [30]–[32]. The dynamic behaviour (frequency, damping and mode shape) of the structure is obtained from a set of FRF measurement. Firstly, the response measured in the experimental modal analysis is in the time domain. Fast Fourier Transform (FFT) is used to transform the measured time domain to the frequency domain. The equation below [33] shows the formula used to calculate the frequencies before plotting in the graph:

$$H(\omega) = \sum_{r=1}^{n} \frac{\emptyset_i \emptyset_j / m}{\sqrt{\left(\omega_\eta^2 - \omega^2\right)^2 + \left(2\xi\omega\omega_\eta\right)^2}} \tag{1}$$

Where: ω = Frequency, ω_η = Natural frequency, $\emptyset$ = Mode shape, ξ = Damping and m = Mass

3. Results and Discussion

It is important to study the natural frequencies and mode shapes of engineering structures to help engineers to understand and design better structures. The well-accepted method of investigating the dynamic behaviour of the structures is the experimental modal analysis (EMA). However, there are no detailed guidelines, particularly on how to measure the dynamic behaviour of a welded structure made from thin steel sheets via the experimental modal analysis. On that account, the aim of this research was to present detailed guidance on how to accurately measure the dynamic behaviour of the structure using the experimental modal analysis.

Table 1 shows ten natural frequencies and corresponding model shapes of the hat-plate structure. The first mode is 503.832 Hz with the torsional mode shapes, and the last mode is 866.525 Hz. All modes have shown clearly deformation when the excitation frequency equal to the natural frequencies of the structure. The first three modes are shown the global bending and torsional modes while the higher modes tend to the complex in appearance and do not have common names. Luckily, the mode shapes do not have the local issues, and all modes have symmetrical movement.

Table 1: Experimental mode shapes and natural frequencies

Modes (I)	Shape (II)	Frequency Hz (III)
1		503.832
2		555.534
3		572.479
4		632.315
5		643.033
6		664.890
7		680.817

8		753.648
9		822.702
10		866.525

Figure 4 shows the frequency response function data of the hat-plate structure. The rigid body mode is lower and in the acceptable range which is 2.5 Hz. According to the rule of thumb, the rigid body modes must be less than 10 per cent of the first elastic mode. Hence, in this case, the rigid body mode was only 0.5 per cent from the first elastic mode. All the peaks in the frequency ranges illustrate that the structure is lightly damped. The sharp peak means that the structure has less than 5 per cent damping and can be negligible [34-35] in solving the equation of motion. The FRF also revealed that the experiment was carried out properly with less amount of noise in the FRF. Hence, this experimental data can be used as reference data in the model updating method.
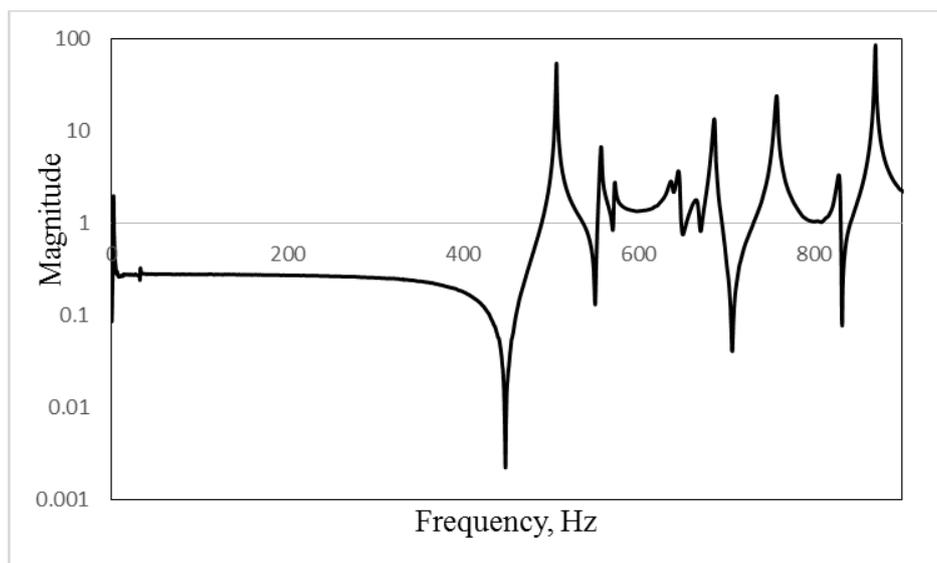

Figure 4: Frequency response function of the hat-plate structure

4. Conclusions

In this paper, the experimental procedure for a laser spot welded hat-plate structure made from thin steel sheets are presented. The five main topics about modal testing of the hat-plate structure which are measurement points, selection of suspensions, methods of excitation, attachments of accelerometers and frequency response function analysis have been thoroughly discussed. The experimental procedure has been successfully used to enhance and improve the quality of the measurement of the frequency response function of the hat-plate structure. The measured results then can be confidently used for validation purposes and also model updating of the finite element model of the hat-plate structure.

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