

Scanning Frequency Ranges of Harmonic Response for a Spot-Welded Copper-Aluminum Plate Using Finite Element Method

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ABSTRACT

In this paper, a finite element methodology is given in which finite element models of a three-weld Al-Cu plate is created with support and loading conditions emulating those seen in an optical lab. Harmonic response is sought for the models under the presumption that various defective welds are present. The numerical results are carefully examined to determine the guideline frequency range so the actual optical experiment can be carried out more efficiently.

INTRODUCTION

Optical techniques [1,2,3,4,5,6,7,8,9] have been popular for determining the quality of machine components subject to static and dynamic loading conditions. To determine defects in a spot-welded assembly, a non-destructive optical technique [7] is employed to obtain fringe patterns on the surface of the assembly subject to harmonic excitation. In order to capture all possible anomalies, a wide frequency range is selected. It is a lengthy process unless the frequency range is narrowed down to a target window in which the defective welds may potentially exist. In this paper we present a numerical approach that uses the frequency responses [10,11,12,13] of a finite element model of the welded assembly. In the finite element model, defective welds are assumed to exist and modeled as contact pairs [14]. In this study, the frequency response of a weld coupon

containing two plates bonded by three welds having different combination of defects is examined. The frequency ranges revealing the separation of the two plates at the defective welds are identified.

FINITE ELEMENT MODEL

Based on the actual test coupon seen in [Figure 1\(a\)](#), a solid model is created which consists of a 0.8 mm thickness copper plate and a 0.2 mm aluminum plate. As shown in [Figure 2](#), both plates are 45 × 40 mm in size. The nugget size is 5 × 4mm with a 0.1 mm indentation on the aluminum plate. There is no visible indentation on the copper plate. A 0.1 mm gap is assumed between the two plates. In the experimental procedure seen in the setup [Figure 1\(b\)](#), an oscillating hammer is placed below the middle weld of the copper plate as seen as a circle in [Figure 2](#). Note that the diameter of the circle is chosen to be 5 mm. For easy reference, the three welds are labeled as A, B, and C as seen in [Figure 2](#).

The mesh for the welded copper-aluminum plates is shown in [Figure 3](#) which mesh has 26,663 nodes and 12,809 quadratic elements. The finite element model is assumed to have a fixed support on the two vertical edges of the copper plate. The other two edges are free of any support. In this study, one or two welds are assumed defective. In the event of a perfect weld, the rectangular contact areas from both plates are given a perfect bonding condition so that the neighboring material points in the contact areas share the same displacement. On

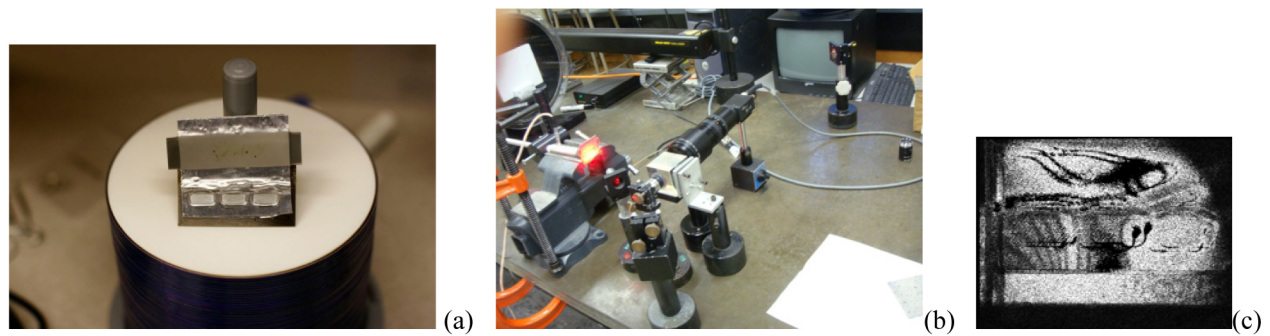


Figure 1. (a) A test coupon of the welded copper-aluminum plate, (b) apparatus setup, and (c) fringe pattern of an oscillated Al-Cu plate.

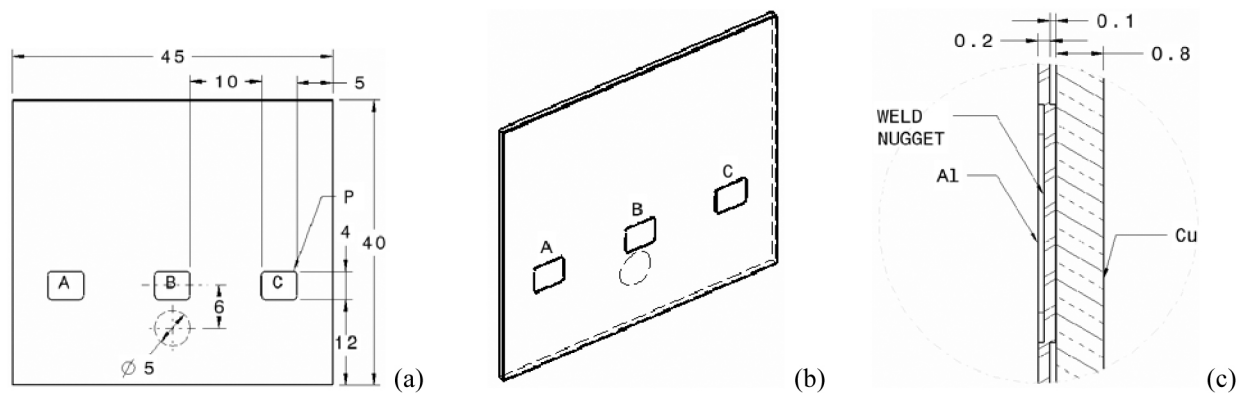


Figure 2. Solid model of the welded copper-aluminum plates.

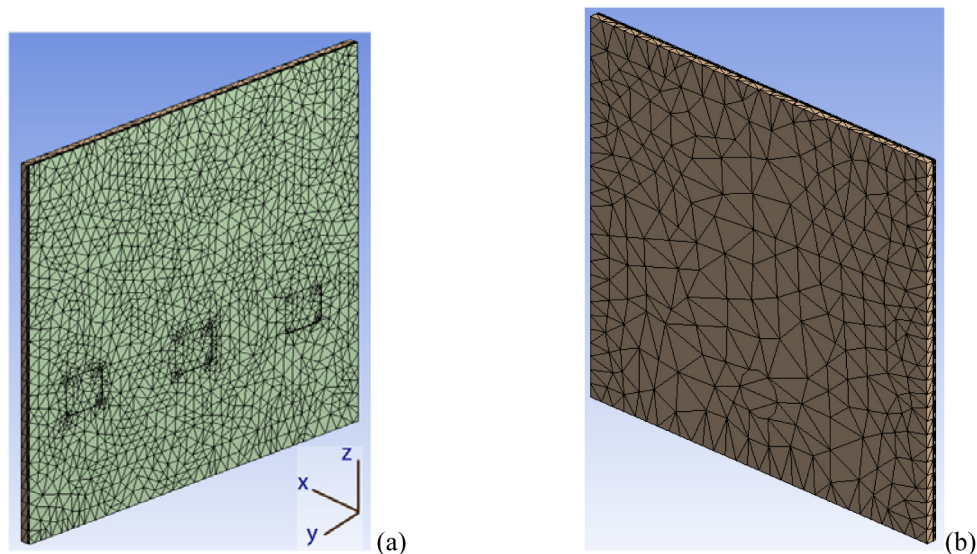


Figure 3. Finite element mesh for the welded copper-aluminum plates.

the contrary, for a defective weld a contact condition is defined between the two rectangular areas. Thus, a node from one plate cannot penetrate the other plate.

For the harmonic response, the pressure $p(t)$ exerted on the copper plate from the oscillating hammer follows the equation below,

Table 1. Material properties of aluminum and copper.

	Modulus of Elasticity, E (GPa)	Poisson's ratio, ν	Density, ρ (kg/m ³)
Aluminum	70	0.35	2,770
Copper	110	0.34	8,300

$$p(t) = P_0 e^{i\omega t}, \quad (1)$$

where the magnitude of the applied pressure is $P_0 = 10$ MPa, i is the imaginary number, ω is the input frequency, and t represents time. As in the experimental procedure, the frequency range used in the study is given below.

$$0 < \omega \leq 15 \text{ kHz}. \quad (2)$$

The material properties of aluminum and copper used in the current study are given below in [Table 1](#). Note that the damping effect is ignored in the current study.

MODAL ANALYSIS AND HARMONIC RESPONSE

Upon examination of the configuration, it is readily seen that there might be five different defective samples, which are listed in [Table 2](#). Case 5 represents a sample with three perfect welds. When a sample contains a failed weld, there is no bonding between the copper and aluminum plates within the rectangular area of the weld. In each of the cases, a modal analysis is performed first to determine the natural frequencies and mode shapes of the welded plates. Further, in the numerical computation of harmonic response the incremental frequency used to scan the entire frequency range is $\delta\omega = 10$ Hz. For each of the cases presented below, it took about 9 hours on a PC (Core 2 Quad, 4GB RAM) to complete and generated about 46 GB of data. In this paper, only results of Cases 1 and 3 are included.

Table 2. Five different cases of the welded coupon are considered in the harmonic response study. Legend: $\otimes$ signifies a perfect weld, while an equal sign “=” represents a failed weld.

Case	Weld		
	A	B	C
1	$\otimes$	$\otimes$	=
2	$\otimes$	=	$\otimes$
3	$\otimes$	=	=
4	=	$\otimes$	=
5	$\otimes$	$\otimes$	$\otimes$

CASE 1: A $\otimes$ B $\otimes$ C=

Modal Analysis

From the modal analysis, it is found the first natural frequency of the model is $\omega_1 = 229.27$ Hz, and $\omega_{66} = 15,226$ Hz is the first natural frequency exceeding the specified input frequency range seen in [Eqn. \(2\)](#). All 80 natural frequencies are given in the Excel file NatFreq_WC04.xlsx. The mode shapes for selected modes are given in [Figure 4](#) where the separation at weld C between the two plates is readily seen. A scaling factor is also employed to display the deformed shapes. As a result, penetration of the aluminum plate into the copper plate is visible. Penetration would have been invisible if the scaling factor of 1.0 is used.

Amplitude vs. Frequency

In the harmonic response study, one point at the upper right corner of the defective weld, marked as point P in [Figure 2\(a\)](#), is selected from each plate. The displacement-frequency plots are given below in [Figure 5](#), [Figure 6](#), [Figure 7](#), [Figure 8](#), [Figure 9](#). In the plots, the difference between the phase angles of the aluminum and copper plates is included. When calculating the frequency response, the amplitude A often exhibits the following form.

$$A = \frac{F_0}{\omega_n^2 - \omega^2}, \quad (3)$$

where, ω_n is a natural frequency and F_0 a constant. It is seen that the amplitude A is not always positive. However, in all the plots of amplitude vs. frequency, positive displacement is always used. When a negative value is calculated from [Eqn. \(3\)](#), its sign is reversed and a 180° (or π) phase angle is provided. Let ϕ_A and ϕ_C be the phase angles of points on the aluminum and copper plates, respectively. We define the difference in phase angles $\delta\phi$ as follows.

$$\delta\phi = \phi_A - \phi_C \quad (4)$$

In the following plots, the difference between the two phase angles $\delta\phi$ is also included.

Critical Frequency Ranges

Note that each spike in the above plots represents a resonant frequency. It is seen from further examining [Eqn. \(4\)](#) that two neighboring points from the welded plate are in phase when $\delta\phi = 0$. And, $\delta\phi = \pi$ when they are out of phase. As a result, the separation gap between the two points at P on the aluminum and copper plates reaches maximum when $\delta\phi = \pi$ at a given input frequency which is represented by a rectangular tooth in the plots above. To obtain the critical

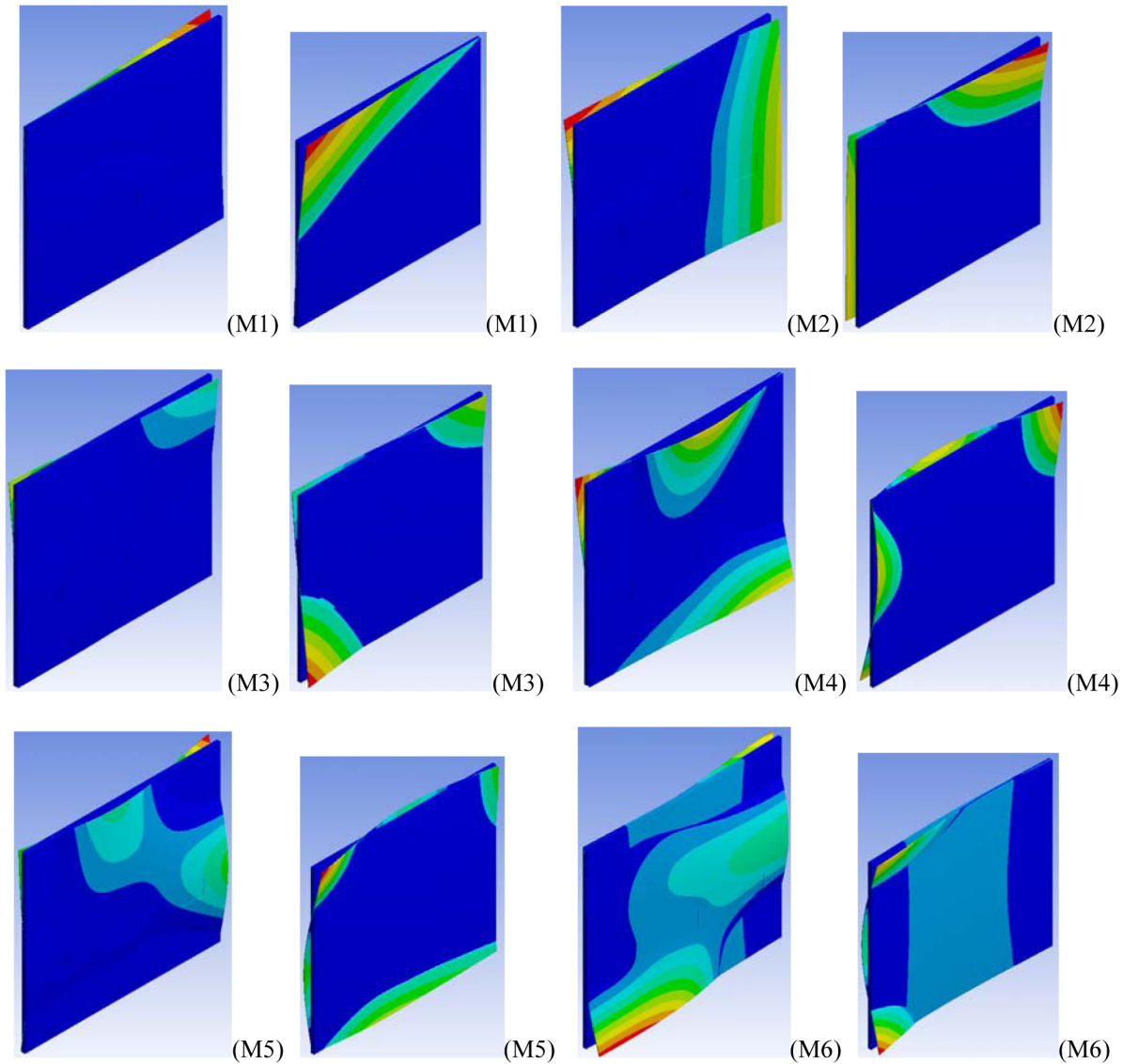


Figure 4. Mode shapes for the welded copper-aluminum plates where (Mn) represents n-th mode. Note that weld C is on the right side of the first image, and each mode is shown with two images from two viewing directions for clarity. Note that their corresponding natural frequencies are 229.27 Hz, 324.79 Hz, 451.99 Hz, 763.82 Hz, 1,016.7 Hz, and 1,078.5 Hz.

frequencies where the maximum separation between the two plates, we use the following guidelines:

- Input frequencies must be near a resonant frequency;
- A resonant spike must fall entirely within a squared tooth.

Therefore, upon examining the plots, the following natural frequencies are target for revealing anomalies in the welded specimen.

$$\begin{aligned} \omega_9 &= 1,592.3 \text{ Hz}, \omega_{17} = 3,223.32 \text{ Hz}, \\ \omega_{29} &= 6,382.2 \text{ Hz}, \omega_{30} = 6,498.2 \text{ Hz}, \end{aligned} \quad (5a)$$

$$\begin{aligned} \omega_{37} &= 7,794.5 \text{ Hz}, \omega_{44} = 9,857.1 \text{ Hz}, \\ \omega_{56} &= 12,449 \text{ Hz}, \omega_{62} = 14,377 \text{ Hz}. \end{aligned} \quad (5b)$$

Note that ω_{29} and ω_{30} are two neighboring natural frequencies and are only 100 Hz apart. Considering a 200 Hz of scanning frequency range, for the current case with defective weld C, the following targets are selected.

$$\begin{aligned} 1,495 \leq \omega \leq 1,695 \text{ Hz}, 3,125 \leq \omega \leq 3,325 \text{ Hz}, \\ 6,280 \leq \omega \leq 6,600 \text{ Hz}, \end{aligned} \quad (6a)$$

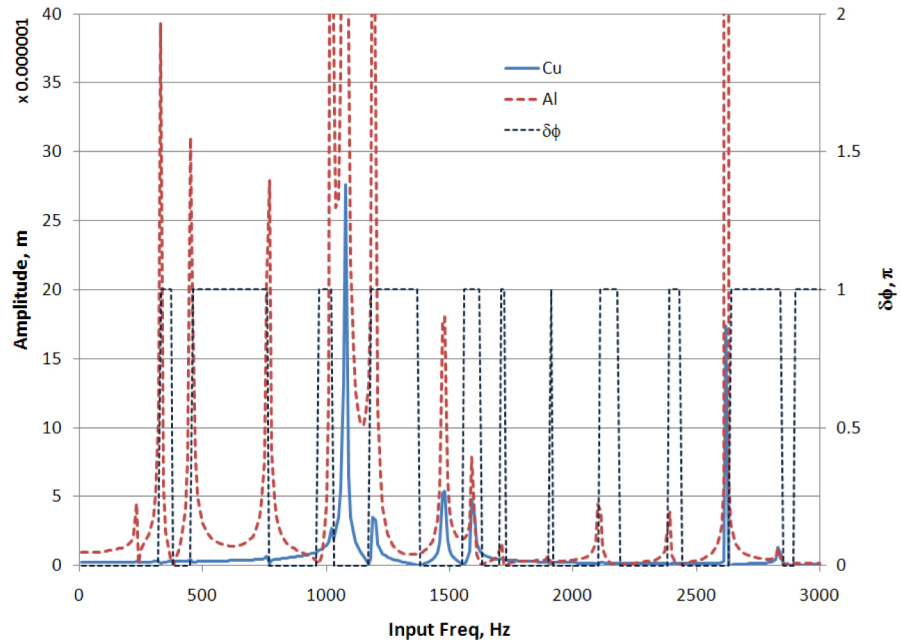


Figure 5. Harmonic response of point P from both Al and Cu plates - frequency range 0~3 kHz.

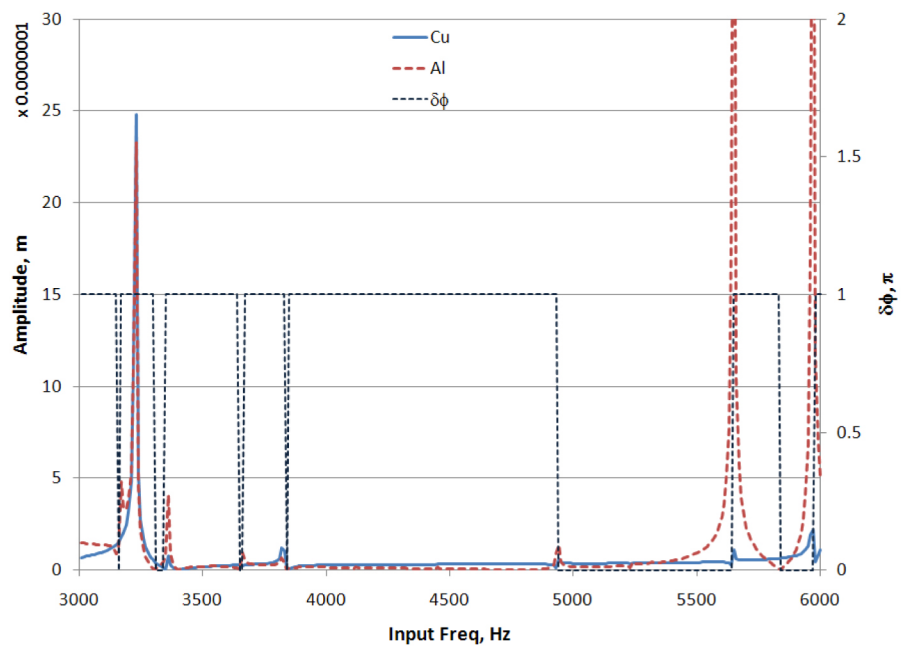


Figure 6. Harmonic response of point P from both Al and Cu plates - frequency range 3~6 kHz.