MULTI-MODE EXCITATION AND DATA REDUCTION FOR FATIGUE CRACK CHARACTERIZATION IN CONDUCTING PLATES

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ABSTRACT

Advances in the technique of fatigue crack characterization by resonant modal analysis have been achieved through a new excitation mechanism and data reduction of multiple resonance modes. A non-contacting electromagnetic device is used to apply a time varying Lorentz force to thin conducting sheets. The frequency and direction of the Lorentz force are such that resonance modes are generated in the test sample. By comparing the change in frequency between distinct resonant modes of a sample, detecting and sizing of fatigue cracks are achieved and frequency shifts caused by boundary condition changes can be discriminated against. Finite element modeling has been performed to verify experimental results.

INTRODUCTION

Resonant modal analysis has been shown to be a viable technique for fatigue crack characterization in thin plates [1,2]. Recent advances have improved the applicability of the technique through the use of a non-contact source as a means of inducing resonant vibrations in conducting sheets[3]. In this paper we will describe the operational principles of this source, and characterize the frequency dependence of the applied force. In addition, an improved data reduction technique designed to minimize the influence of boundary conditions will be described. Results are presented for the new non-contact source and data reduction method to characterize fatigue cracks in 1 mm thick aluminum alloy plates.

NONCONTACT DRIVER

From Faraday's Law of Induction,

$$\nabla \times \bar{E} = -\frac{d}{dt}\bar{B} \qquad (1).$$

If the electric field in (1) is produced in a conductor, eddy currents will flow according to ohm's law. For resistivity ρ, the induced current $\bar{J}$ is given by,

$$\nabla \times \bar{J} = -\frac{1}{\rho}\frac{d}{dt}\bar{B} \qquad (2).$$

In the presence of an external magnetic field $\bar{B}_0$, a force will be generated on the current given in (2). By considering the current as composed of a mesh of small circular loops, a magnetic dipole approximation can be used to compute the force on the circuit [4]. The force from an element $d\bar{A}$ of the mesh carrying current $\bar{J}$ can then be written as,

$$d\bar{F} = \bar{J}(\bar{n} \cdot \bar{\nabla})\bar{B}_0 d\bar{A} \qquad (3).$$

It is shown that (3) can be solved for the force $\bar{F}$ acting on a current loop as,

$$\bar{F} = \bar{J}\oint_c d\bar{s} \times \bar{B}_0 \qquad (4)$$

where the integral is taken around the closed curve formed by the circulating eddy current flow [4].

The device designed to apply the forcing function as given in (4) is depicted schematically in figure 1. A sinusoidal current was applied to the electromagnets in order to induce eddy current flow in the aluminum samples. Rare earth permanent magnets, situated at the poles of the electromagnet, are used to generate the static magnetic field. In the plane of the sample, a large portion of the magnetic field will flow parallel to the sample surface. The cross product of (4) therefore produces a force normal to the surface of the sample. Previous research has shown that flaws are most visible when the forcing function induces a torque across the centerline of the electromagnet [1]. The poles of the permanent magnets are therefore situated such that the force under each pole would be in opposite directions.
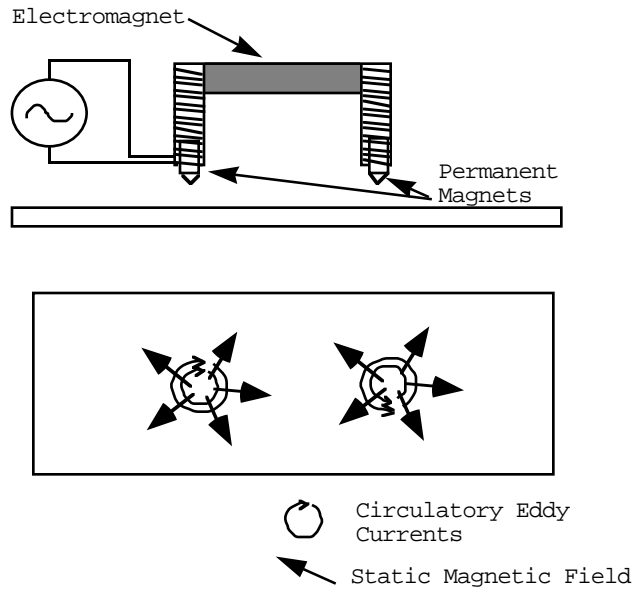
Fig. 1. Schematic diagram of device used to apply non-contact force to test samples.
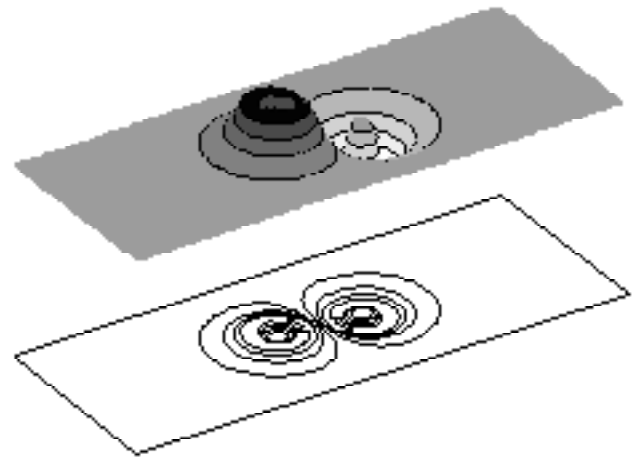

Fig. 2. Contour plot of force field generated by non-contact driver. Results obtained through FE modeling.
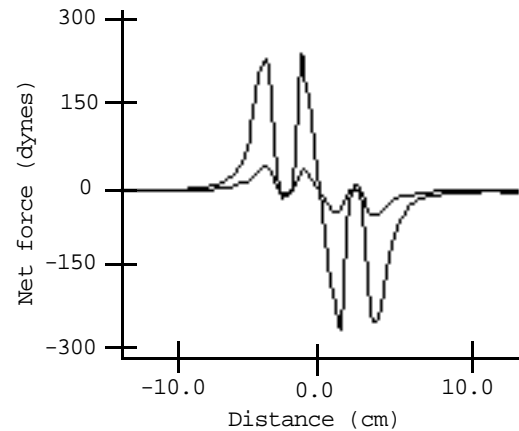

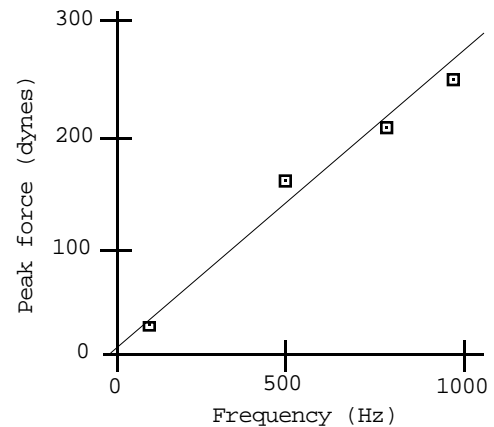Fig 3a. Cross section of force field for lorentz driver at 100 and 1000Hz.

Fig. 3b. Peak force generated at a point as a function of driving frequency.

To characterize the force field generated by the device described above a finite element model was constructed. Figure 2 displays the results obtained at an operating frequency of 500 Hz. The Force is seen to be largest in the area directly under the windings of the electromagnet, being opposite in magnitude at either pole. This is the area with the highest eddy current density. As the distance from the core is increased the field strength decreases as both the eddy current and magnetic field amplitudes decrease. Toward the center of each core the field strength rapidly diminishes to zero as the eddy current density in this region is zero.

The frequency dependence of the forcing device is shown in figure 3. The near linear response of the device as a function of frequency can be explained through an examination of the force field equation. The magnetic field in (4) is that due to the permanent magnets at the electromagnet poles and is static. The induced eddy current field, however, is frequency dependent. From Ohm's law,

$$ J = \frac{\varepsilon}{R} \qquad (5), $$

where J = current flow,
ε = induced electromotance,
and R = resistance around the loop.

The induced electromotance is given by,

$$\varepsilon = -\frac{dN}{dt} \qquad (6),$$

where N is the magnetic flux through the surface enclosed by the current loop. With sinusoidal excitation, the flux $N = N_0\sin\omega t$. Therefore, from (6), $\varepsilon = -N_0\omega\cos\omega t$ is linearly proportional to the frequency ω. For relatively low frequencies and thin plate samples, $\omega < 5$kHz and sample thickness of 1 mm., skin depth attenuation can be neglected so that the applied force will also vary linearly with frequency.

EXPERIMENTAL RESULTS

The non-contact driver described above has been used to study the characterization of fatigue cracks in thin metal plates through resonant modal analysis. Previous research has shown the applicability of the device to the generation of standing waves in samples clamped along three boundaries [3]. The present work focuses on reexamining the results from that study with the aim of reducing the boundary condition dependence of the technique, as well as extending the application of the non-contact driver to stiffer structures.

Figure 4 presents the vibrational response of an uncracked sample clamped along three boundaries. Each peak in the amplitude vs. frequency plot corresponds to a different resonant mode. The details of the experimental conditions can be found in [3]. Previous work has focused on monitoring a single resonance mode in order to determine the structural integrity of the test piece [1-3]. Using this approach, careful control must be exercised on the application of boundary conditions. By monitoring the normalized shift
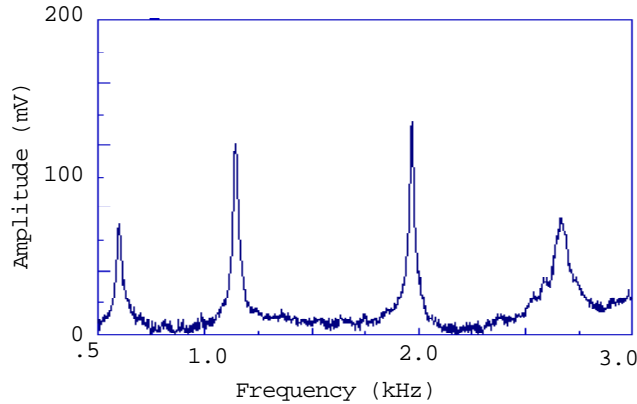
between distinct modes the effects of boundary conditions can be factored out. In this way changes in the clamping strength between samples can be ignored and finite element models need not have an identical match to the experimental boundary conditions.

It was found through finite element modeling that the fourth peak in figure 4 corresponds to a resonant mode which is nearly insensitive to fatigue crack growth perpendicular to the free edge. This peak was used to monitor the boundary conditions applied during a test. A crack length dependent parameter was constructed as the difference between the fourth and second resonance frequencies divided by the frequency of the second resonance peak. Figure 5 shows the results of this characterization scheme applied to several aluminum plate samples with fatigue cracks of varying lengths. The experimental values of the resonance modes were determined by fitting each peak to a Lorentzian distribution. The results are seen to correlate well with finite element predictions.

In order to test the applicability of the technique to stiffer structures 1 mm thick aluminum plates clamped along all four edges were tested. The details of sample preparation are given in [2]. The non-contact driver was found to perform as well as contacting methods for the generation of standing eigen-modes in these samples. The resonance frequencies, however, were found to be less sensitive to changes in the stiffness of the plates along the centerline, area of fatigue crack growth. The previous method of eigen-mode stimulation required the addition of permanent magnets to the sample surface. As the location of this extra mass was near the fatigue damaged area, changes in the stiffness in this region, caused by fatigue crack growth, were highlighted. The smaller resonance shifts of the

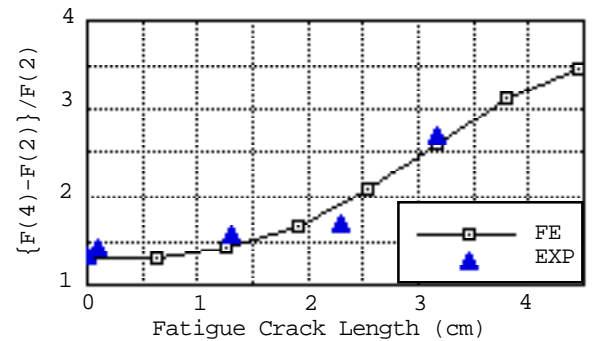Fig. 4. Vibrational response of unfatigued aluminum plate.

Fig. 5. Results of flaw characterization for edge cracked aluminum plate samples.

current experiment amplify the need to eliminate changes in the resonance frequencies caused by boundary condition variations.

Figure 6 displays the results of eigen-mode analysis performed on an unfatigued sample with a drilled center hole. The sample was clamped along all edges, giving a vibrational area of 25 x 10 cm^2. The two large peaks in the curve were determined by FE analysis to correspond to the frequencies of the second and fourth resonance modes respectively. Tests performed on fatigued samples showed a decrease in the frequency of both modes, with the frequency of the fourth mode experiencing a larger shift. The frequency difference between these two modes was used in an attempt to remove boundary condition dependence from the test results.

Figure 7 displays the test results for the center hole samples. The fatigue crack length plotted along the horizontal axis is the combined length of fatigue cracks on both sides on the center hole. The experimental results show a good correlation to finite element predictions. The scatter in the data, however, is seen to restrict characterization to relatively large fatigue cracks.

SUMMARY

The use of non-contact excitation as a means of generating standing eigen-modes allows for greater flexibility in the application of resonant modal analysis. The newly developed driver, able to stimulate standing waves as well as previous
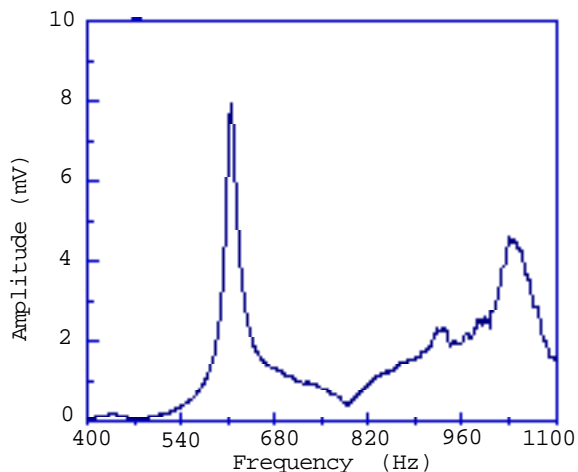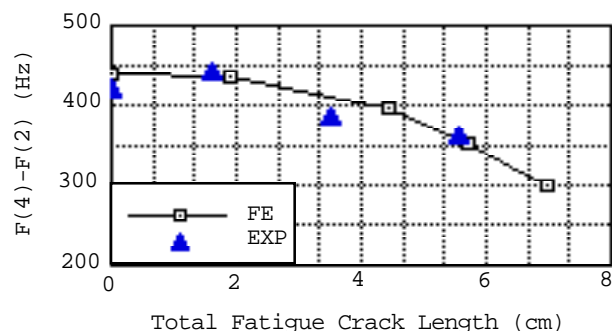
Fig. 7. Results of flaw characterization for center cracked aluminum plate samples.

methods [1-2], is portable and completely non-contacting. In this paper we have fully described the operating principle of the device and performed a detailed examination of the frequency dependence of the generated force.

Use was made of the non-contact driver to the characterization of fatigue cracks in both edge and center cracked samples. A new data reduction technique was developed in order to remove the boundary condition dependence of the characterization scheme. The results have shown a good correlation with finite element analysis for both sample sets. The center cracked samples, however, showed only a small frequency shift as a function of crack length for the current force field and area of investigation. Future research is aimed at customizing the generated force field in order to stimulate standing waves with resonance frequencies which are highly dependent on the structural integrity of a critical area. Boundary condition effects will be monitored with other, flaw independent resonance modes in order to maximize the detectability of a specific flaw type.

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Fig. 6. Vibrational response of unfatigued center hole sample. Clamped boundary conditions enforced on all edges.