EDDY CURRENT TESTING OF THICK ALUMINUM PLATES WITH HIDDEN CRACKS

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ABSTRACT. In this paper we present theoretical analysis which gives the possibility to determine optimum excitation frequencies in eddy current examination of thick aluminum plates. A computer controlled non-destructive testing system and a probe with a magnetoresistive sensor were utilized in laboratory tests. Experiments with specimens containing hidden cracks were carried out for a wide spectrum of frequencies. The optimum operating frequencies achieved from the experiments are in a very good agreement with those obtained by using theoretical analysis. Application of the optimum frequencies makes it possible to detect shallow cracks located on the reverse side of the specimens. Detection of a 15\% crack in a 10 mm thick plate made of aluminum and a 20\% crack in a 20 mm thick plate has been confirmed.

INTRODUCTION

Eddy current testing is one of the main techniques that are used for the non-destructive examination of metallic plates for defects such as hidden cracks and corrosion. The practice of eddy current testing consists of exciting an alternating current at a given frequency through a coil located near to the electrically conducting object being tested, and thus to induce eddy currents in the latter. As a result of the presence of defects, changes take place in the components of the associated magnetic field, which can be detected, e.g., as in our case, by a magnetoresistive (MR) sensor. Interpretation of magnetic field data in terms of flaw size, shape and position is dependent upon having a theoretical understanding of how the defects affect the induced current and hence perturb the associated magnetic field. The induced eddy currents are not uniformly distributed throughout the material. The skin effect causes the currents to be concentrated near the surface adjacent to the excitation coil. The effect increases with increasing excitation frequency. Generally speaking, the eddy current probes are more useful for surface testing, and for subsurface testing, lower frequencies are necessary, and in consequence this leads to multi-frequency measurements.

In this paper we present theoretical analysis which gives the possibility to determine optimum excitation frequencies in eddy current examination of thick aluminum plates. A computer controlled non-destructive testing system and a probe with a MR sensor were utilized in laboratory tests. Experiments with specimens containing hidden cracks were carried out for a wide spectrum of frequencies. The optimum frequencies achieved from the experiments are in a very good agreement with those obtained by using theoretical analysis.
EDDY-CURRENT PROBE AND MEASUREMENT SYSTEM

Figure 1a shows a cross section of the probe considered in this paper [1]. The probe includes an exciting coil (1) wound around a hollow cylindrical ferrite core (2), and supplied with an alternating current. The MR sensor (3) is placed inside the core directly over a surface of the tested conducting plate (4) having a defect (5). Such a location of the MR sensor protects the sensor from the working magnetic field and results in higher sensitivity to small changes in the magnetic field caused by surface and subsurface defects. The whole is covered with an electromagnetic aluminum screen (6). The exciting coil is separated from the electromagnetic screen by an insulating sheath (7). Lead-in wires (8) are brought out through a hole in the electromagnetic screen. Simple construction of the probe enables its miniaturization, thereby enhancing the spatial resolution of measurements.

Figure 1b presents a block diagram of the measurement system. The system was constructed at the Chair of Theoretical Electrotechnics & Computer Science, Technical University of Szczecin, Poland. Function synthesizer (Agilent 3120A) supply the excitation coil. The MR sensor is energized by a DC voltage from a power supply. The output of the MR sensor is connected with an instrumentation amplifier (CA-251F4 manufactured by NF). The amplified signal is converted into digital form by an A/D converter (DA4020, manufactured by Computer Boards). The computer further precedes the resulting discrete signal. In order to remove the interference of noises and to extract the amplitude of the required frequency components, the FFT algorithm is utilized. The resulting signals are used to create spectrograms. The spectrogram is a two-dimensional display of the relative amplitude of the output signal frequency components versus the sensor position [2]. The probe is scanned over a surface of the specimen in x and y directions by using an x, y scanner coupled with a personal computer. Computer programs are used to set the scan area and velocity of the probe and to collect data.

FIGURE 1. Measuring system: a) cross section of the probe (not in scale), b) block diagram of the measurement system
OPTIMUM EXCITATION FREQUENCIES

In eddy-current nondestructive testing, time varying magnetic fields are produced by excitation coils located close to a conducting specimen being tested. Induced eddy currents have the advantage of penetrating into subsurface regions and therefore being sensitive to their condition. The presence of flaws can be determined by monitoring the change in magnetic field over a surface of the specimen. However, the penetration of an ac magnetic field into the specimen is approximately exponentially attenuated with a characteristic decay distance given by the well-known formula for skin depth:

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$  \hspace{1cm} (1)

where $\sigma$ is the conductivity, $\omega = 2\pi f$ is the angular frequency, and $\mu$ is the magnetic permeability. It is obvious that in order to detect deep flaws, low excitation frequencies are required to achieve a sufficient penetration depth. Thus, one would feel intuitively that by performing surface magnetic field measurements at many excitation frequencies it could be possible to acquire wide-bandwidth information that can quantitatively characterize the whole specimen. High frequency measurements would respond to the regions near the surface, whereas low frequency measurements would respond to the regions at greater depth.

Consider a circular excitation coil of radius $r_0$, carrying a current $\sqrt{2I \sin \omega t}$, a height $z_0$ above, and coplanar to a defect free plate of conductivity $\sigma$, permeability $\mu_0$, and of thickness $d$ (Fig. 2; $r_0$ and $z_0$ are the mean values for the “real” exciter). A cylindrical polar coordinate system $(r, \phi, z)$ is adopted, with the axis of the coil along the $z$-axis and the $z = 0$ plane at the upper side of the plate. This model has already been considered by Dodd and Deeds [3]. In our paper we will use the model to find the optimum excitation frequency under which the inspection should be carried out to detect a flaw at an arbitrary point $P(r_1, z_1)$ inside the plate. Adapting the result of Dodd and Deeds to the present case, we obtain the following formula for the induced eddy current density vector:

$$\mathbf{J}(r, z) = -j \omega \sigma \mu_0 I_0 \int_0^\infty \alpha \exp(-\alpha z_0) J_1(\alpha r_0) J_1(\alpha r) \times$$
$$\left(\frac{(\alpha + \alpha_1) \exp[\alpha_1(2d + z)] + (\alpha_1 - \alpha) \exp(-\alpha_1 z)}{(\alpha + \alpha_1)^2 \exp(2\alpha_1 d) - (\alpha_1 - \alpha)^2}\right) d\alpha \cdot \mathbf{1}_e \hspace{1cm} (2)$$

where $J_1(\alpha r_0)$ is the Bessel function of the first kind and order one, the parameter $\alpha$ is the separation constant and $\alpha_1^2 = \alpha^2 + j \omega \mu_0 \sigma$. Let us consider the eddy current density vector at the point $P(r_1, z_1)$ inside the plate. Since $J_1(r_1, z_1)$ = 0 for $f = 0$ and $f = \infty$, therefore, somewhere between 0 and $\infty$ there is an appropriate frequency $f_{\text{opt}}$ such that the value of $|\mathbf{J}(r_1, z_1)|$ reaches its maximum for the given values of $r_0$, $z_0$, and $d$. This frequency is optimal for detecting a possible flaw at the point $P$ in case of the flawed plate. The optimum frequency can be found numerically. Consider first a lower side of the plate. The current density vector in the plane $z = -d$ at the bottom of the plate is given by

$$\mathbf{J}(r, -d) = -2 j \omega \sigma \mu_0 I_0 \int_0^\infty \frac{\alpha \exp[\alpha_1 d - \alpha z_0] J_1(\alpha r_0) J_1(\alpha r)}{(\alpha + \alpha_1)^2 \exp(2\alpha_1 d) - (\alpha_1 - \alpha)^2} \, d\alpha \cdot \mathbf{1}_e \hspace{1cm} (3)$$

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For the excitation coil with radius $r_0 = 10$ mm, placed at height $z_0 = 8$ mm above the plate, having 200 turns and supplied by an alternating current of rms value equal to 60 mA, the module of the eddy current density vector at the bottom of the 20 mm thick plate made of aluminum (conductivity $\sigma = 35$ MS/m) depends on the excitation frequency $f$ and the distance from the axis $z$ as in Fig. 3. The module of the eddy current density vector reaches its global maximum for $f_{opt} = 68$ Hz and $r = 16$ mm, and the conclusion is that under such a frequency the inspection of the bottom of the plate should be carried out. The optimum frequency $f_{opt}$ corresponds to the optimum skin depth $\delta_{opt} = \frac{1}{\sqrt{\pi f_{opt} \mu \sigma}}$, and we have found that $\delta_{opt}$ is an approximate linear function of the aluminum plate thickness $d$ (Fig. 4).
Multi-frequency eddy current method gives the possibility to detect flaws in the whole interior of a conducting plate without the need to change the testing parameters. One can find the frequency band necessary to reconstruct the interior of the plate by using (2). For given values of \( r_0, z_0, r, d \) and \( 0 \geq z \geq -d \) we look for \( f \) for which the module of the current density vector reaches its maximum at the chosen value of \( z \). The result is shown in Fig. 5.

**FIGURE 4.** Optimum skin depth for the inspection of the bottom of the plate as a function of plate thickness

**FIGURE 5.** Optimum frequencies to detect flaws in the whole interior of the aluminum plate (the frequency band: 132-298 Hz), \( d = 10 \) mm, \( r_0 = 10 \) mm, \( z_0 = 8 \) mm, \( r = 15 \) mm
RESULTS OF EXPERIMENTS

Simultaneously with the theoretical analysis the measurements were carried out. The computer controlled ECT system shown in Fig. 6 was utilized (the block diagram of the system is shown in Fig. 1b). Figure 6 shows also a photo of the eddy current probe (compare with Fig. 1a). Aluminum specimens used in the experiment are presented in Fig. 7. Thickness of the specimens was equal to 10 mm and 20 mm. The first (of thickness 10 mm) and second (of thickness 20 mm) set of specimens contained flaws having relative depth: 15%, 30%, 60% and 20%, 40%, relatively. Width of all the flaws was equal to 0.5 mm.

The experiments were done with outer flaws (OF). It means that the flaw and the probe were on the opposite sides of the specimen. The probe was moved perpendicularly to the flaws in steps of 0.5 mm. The lift-off was measured to be 0.5 mm. We used a multi-frequency excitation signal consisting of 20 sinusoidal components having frequencies from 60 Hz to 600 Hz in case of the 10 mm thick specimens and from 20 Hz to 120 Hz in case of the 20 mm thick specimens. Results of the measurements in the form of spectrograms and signal plots are shown in Figs. 8–11. It can be observed that the shallowest flaws (15% and 20%) can be easily detected.
FIGURE 8. Spectrograms: plots of the signal module as a function of frequency and the sensor position (aluminum specimen, thickness 10 mm, outer flaws having width of 0.5 mm).

FIGURE 9. Plot of the signal module as a function the sensor position (measured for the optimal frequency) and frequency characteristics obtained for the flaw having different depth (aluminum specimen, thickness 10 mm, outer flaws having width of 0.5 mm).

FIGURE 10. Spectrograms: plots of the signal module as a function of frequency and the sensor position (aluminum specimen, thickness 20 mm, outer flaws having width of 0.5 mm)

FIGURE 11. Plot of the signal module as a function the sensor position (measured for the optimal frequency) and frequency characteristics obtained for the flaw having different depth (aluminum specimen, thickness 10 mm, outer flaws having width of 0.5 mm).
**FIGURE 12.** Comparison of the curve representing maximal module of the calculated eddy current density at the bottom of the plate and the frequency characteristic obtained as a result of measurements (aluminum specimen, thickness 20 mm, outer flaw having width of 0.5 mm and relative depth of 20%). All plots normalized to maximal values.

Figure 12 shows the dependence on frequency of the maximal module of the eddy current density vector at the bottom of the plate obtained from equation (2) and the measured output signal caused by the outer flaw having depth of 20% in case of the 20 mm thick aluminum plate. Both the curves are normalized to the maximal values. As apparently seen in Fig. 12, there is a strong coincidence between results of theoretical analysis and measurements.

**CONCLUSIONS**

Compared to traditional eddy current methods, multi-frequency eddy-current technique offers a considerable advantage. This is the ability to detect flaws in the whole interior of a conducting body without the need to change the probe. Experiments with specimens containing hidden cracks were carried out for a wide spectrum of frequencies. The optimum operating frequencies achieved from the experiments are in a very good agreement with those obtained by using theoretical analysis.

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