USE OF A CHIRP WAVEFORM IN PULSED EDDY CURRENT CRACK DETECTION

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INTRODUCTION

When an electrical conductor containing a surface-breaking crack is subjected to a short pulse of electromagnetic radiation, the reflected field contains transient features related to the depth of the crack. This has been demonstrated in both theoretical calculations [1] and in experiments [2,3] on shallow (0.13 mm to 1.3 mm) slots in a low conductivity titanium alloy. Specifically, these results show that the peak crack signal is delayed in time by an amount proportional to the square of the crack depth, and that the signal decay times also increase with increasing depth.

Implementation of the pulsed eddy current method for crack depth measurement is, however, made difficult by the very short rise and decay times typical of crack depths and materials of interest. As shown in earlier work [1], pulse times of the order of tens of nanoseconds are required to separate the flaw signal from the background response associated with direct coupling of the source and receiver coils. To achieve adequate signal intensity with such short pulse widths, peak power requirements are large, thus complicating the design of an appropriate eddy current probe.

The work reported here is concerned with the use of a chirp waveform, coupled with autocorrelation analysis of the return signal, to synthesize a short, high intensity pulsed measurement. In principle, the advantage offered by the chirp approach over the direct pulsed eddy current method is that the pulse energy is distributed over a much longer time interval, thus reducing peak power requirements. The specific question addressed in this study is whether one can synthesize a pulse short enough for crack depth measurement within the constraints imposed by limited bandwidth and a chirp repetition rate adequate for convenient signal averaging.

THEORY

Our study is based on the two-dimensional crack model shown in Figure 1. To simplify the mathematics, we assume that the incident pulse is spatially uniform and produces a time-dependent magnetic field $H_0(t)$, with direction perpendicular to the plane of the figure, on the crack and conductor surfaces. The first step in the calculation is the determination of the field on the crack face.

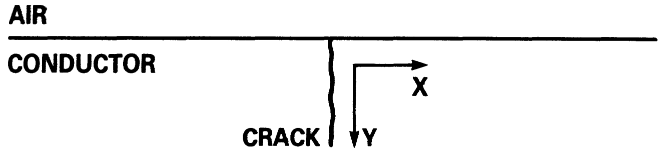

Fig. 1. Two-dimensional model of a crack. A spatially uniform, time-dependent field exists on the surface of the conductor and crack.

Rather than work directly with time-dependent fields, we choose instead to solve this problem first in the frequency domain by taking Fourier transforms with respect to time. If $h_o(\omega)$ is the transform of $H_o(t)$, then the transform of the field in the conductor can be written

$$h(x,y,\omega) = h_o(\omega)\ [e^{iqy} + \psi(x,y,\omega)] \tag{1}$$

with $q = (1 + i)/\partial$, where ∂ is the skin depth. The first term in the bracket is proportional to the unperturbed field at depth y, and the second term is proportional to the perturbation caused by the flaw.

The procedure for calculating $\psi(x,y,\omega)$ is similar to that reported earlier [1] and need not be described in detail. Briefly, we start with the scalar Helmholtz equation for ψ and transform to the following integral equation by means of Green's theorem:

$$1 - e^{iqy} = \int_o^d K(y,y') \left(\frac{\partial\psi(x,y',\omega)}{\partial x}\right)_{x=0} dy' \tag{2}$$

where d is the crack depth,

$$K(y,y') = i[H_o^{(1)}[(q|y - y'|] - H_o^{(1)}\ [q(y + y')]] \tag{3}$$

and $H_o^{(1)}$ is the zero order Hankel function. To solve for the x derivative of ψ, we first note that this quantity is proportional to the current density on the crack surface and is therefore singular at the crack tip. With this in mind we make the substitution $y/d = 1 - \gamma^2$ and solve instead for the nonsingular function

$$\gamma \frac{\partial\psi}{\partial x} = \sqrt{1 - y/d}\ \frac{\partial\psi}{\partial x}\ . \tag{4}$$

To obtain a numerical solution we use a 48-point Gaussian quadrature approximation to the integral in (2) and solve the resulting system of algebraic equations by matrix inversion.

Based on the development presented earlier [1], we next make use of the reciprocity theorem [4] to obtain the following expression for the transform of the flaw signal per unit crack length:

$$\Delta V(\omega) = h_o(\omega)G(\omega) \tag{5}$$

where the transform of the impulse response function is

$$G(\omega) = \frac{2}{\sigma} \int_0^d e^{iqy} \left(\frac{\partial \psi(x,y,\omega)}{\partial x} \right)_{x=0} dy \qquad (6)$$

Plots of the real part of $G(\omega)$ are presented in Figure 2; labels on the curves are crack depths in units of 0.001 inch (0.025 mm).

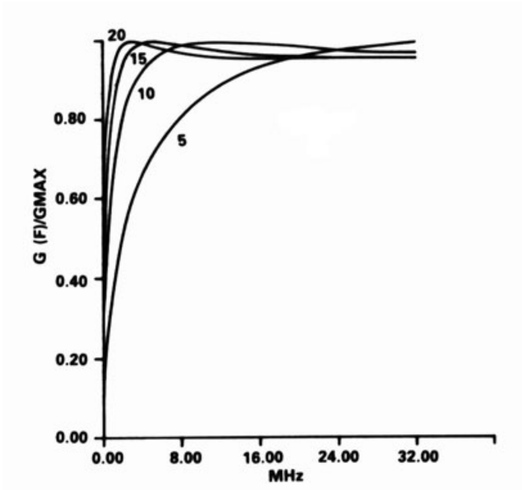

Fig. 2. Real parts of the Fourier transforms of impulse response functions for the geometry shown in Figure 1. Labels on the curves are crack depths in units of 0.001 inch (0.025 mm).

CHIRP/AUTOCORRELATION CALCULATIONS

Figure 2 shows that accurate determination of the time-dependent impulse response functions requires a bandwidth of more than 20 MHz. There is, however, a significant dependence on crack depth at much lower frequencies, which suggests that conventional probes with lower bandwidth might be useful for crack depth measurement by a pulsed eddy current method. The calculations described in this section were undertaken to explore this possibility using the chirp/autocorrelation approach.

To illustrate the principle, let us first consider a damped chirp waveform given by

$$H_o(t) = \begin{cases} \cos^2 \frac{\pi}{2} \frac{t}{T} \sin \omega_m \frac{t^2}{T} & 0 \leq t \leq T \\ 0 & \text{otherwise} \end{cases} \qquad (7)$$

This is a pulse of duration T with angular frequencies from zero to ω_m. Figure 3a is a plot of this function with T = 10 μsec and a maximum frequency of 4 MHz.

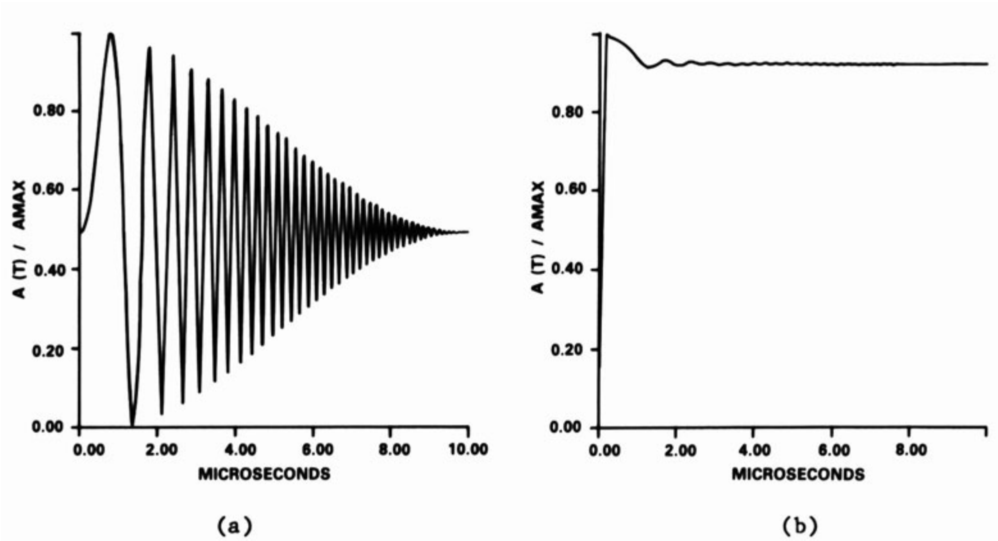

Fig. 3. A chirp waveform (a) and its autocorrelation function (b). Autocorrelation of a 10 μsec chirp with 4 MHz bandwidth synthesizes a short, time-domain pulse.

The autocorrelation function of $H_o(t)$ can be written in terms of $H_o(t)$ or its Fourier transform $h_o(\omega)$ as follows:

$$A(t) = \int_{-\infty}^{\infty} H_o(t')H_o(t + t')dt'$$

$$= \frac{1}{2\pi} \int_{-\infty}^{\infty} |h_o(\omega)|^2 e^{-i\omega t} d\omega \tag{8}$$

Figure 3b is the autocorrelation of the chirp plotted in Figure 3a, and shows how the autocorrelation operation synthesizes a short, time-domain pulse. The motivation for the present study is to see whether depth information can be obtained by a similar operation on the flaw response function given by (5).

Figures 4a and 4b are autocorrelation functions obtained by using $\Delta V(\omega)$ in place of $h_o(\omega)$ in (8), with the transform of (7) used for $h_o(\omega)$ in (5). The pulse duration T is 20 μsec in both cases; the bandwidth is 8 MHz in Figure 4a and 4 MHz in Figure 4b.

From Figure 4 we see two effects of limited bandwidth on the chirp/autocorrelation signal. As the bandwidth is decreased, peak arrival times for flaws of different depths tend to merge and shift to later times. Also, as bandwidth is decreased, differences in decay times become less pronounced. Both of these effects tend to make depth measurement based on temporal response more difficult to achieve with a small bandwidth chirp. On the other hand, a bandwidth of 8 MHz is not unreasonable, and, based on the results shown in Figure 4, should suffice for crack depth estimation. Further support for the idea is provided by experimental results reported elsewhere [3], which show that crack depth information can be derived from low-to-moderate bandwidth data.

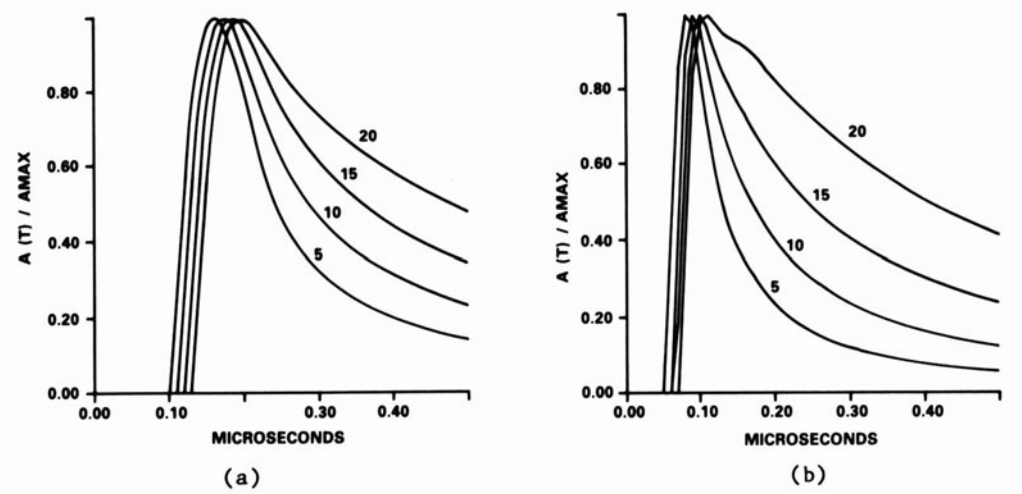

Fig. 4. Autocorrelation functions of the flaw response to chirp waveforms of 20 sec duration. The bandwidth is 8 MHz in (a) and 4 MHz in (b). Labels on the curves are crack depths in units of 0.001 inch (0.025 mm).

CONCLUSIONS

Calculations of crack response to a chirp waveform indicate that crack depth can be estimated from the autocorrelation of the flaw signal. For crack depths of 0.13 mm or greater in low conductivity materials, a bandwidth of about 8 MHz should be adequate. Although only one chirp duration was considered in the calculations, this chirp length (20 μsec) appears to be adequate from the standpoint of depth resolution. The 20 μsec chirp is also long enough to significantly reduce the peak power that would be needed to achieve comparable depth resolution by the direct pulsed eddy current method. Finally, the 20 μsec chirp is short enough to allow several repetitive pulses for signal averaging purposes while operating in a scanning mode. The chirp/autocorrelation synthesis of a pulsed eddy current experiment, with chirp bandwidth of about 8 MHz and duration of about 20 μsec, therefore appears to be a practical approach to the estimation of crack depth.

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