ELECTROMAGNETIC METHODS OF NONDESTRUCTIVE EVALUATION

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I. Introduction

The general objective of this program remains that of furthering the development of nondestructive evaluation, particularly in relation to its use as a means of quantitatively characterizing performance related properties of structural materials. The principal two areas of emphasis during this reporting period have been low frequency eddy current testing methods for nonferromagnetic metals and microwave testing of dielectric layers on conducting substrates using surface electromagnetic waves.
11. Summary of Progress

A. Microwave Testing

The investigation of the use of surface electromagnetic waves to measure the thickness and dielectric constant of a dielectric layer supported by a planar conductive substrate has been completed. The theoretical results show that the thickness and the dielectric constant can be measured independently by exciting a surface electromagnetic wave along the layer and the subsequent measurements of its propagation characteristics. The results of this theory have been tested by an experimental investigation of surface waves traveling along 1-2 cm thicknesses of layers of dielectric materials at a frequency of 10 GHz. The resulting predictions of thickness and dielectric constant are found to be quite accurate when applied to samples of known physical properties. The measurement of thinner layers may be accomplished by simply increasing the frequency of operation.

Some addition complexity of the actual experimental apparatus will result, but the same theory will still be valid. Technical details of both the theoretical work and the experimental set-up including a comparison of theory and experiment is included as Appendix A. A more detailed paper is presently under preparation and will be submitted to a suitable journal for publication.

B. Eddy Current Testing

The excitation of eddy currents in materials to detect flaws is well developed in practice. The theoretical solutions, however, of even the most basic geometries, which even remotely resemble practical testing situations, have not been attempted until recently. The numerical solutions of Dodd and Deeds [Journal of Applied Physics, Vol. 30, pp. 2823-2838, 1968] and the analytical work by Zaman, Gardner and Long for both cylindrical
planar geometries are the first real attempts to attack the basic eddy current problem on a theoretical level. The results of these studies have application in many practical cases where eddy current methods have been used for years.

The case of a single-turn loop surrounding an imperfectly conducting cylinder has been solved for a slightly restrictive set of physical parameters. The change in complex impedance of the coil was calculated as a function of the geometry of the problem (radii of the coil and core) and of the material properties of the core (conductivity).

In a similar fashion the impedance of a loop parallel to and near an infinitely large planar conductor was calculated. This change in complex impedance was found as a function of the size of the coil, the lift-off distance and the conductivity of the material. Again these results bear direct application for practical testing situations employing planar geometries.

The results of these previous investigations may also be used to calculate the change in impedance due to a flaw in the conducting material. A detailed derivation is given in Appendix B. A first approximation using only the fields in the unflawed sample has been developed for the usual case of a single coil eddy current system.

\[ \Delta z = \frac{\sigma}{l^2} \int_{V_F} \hat{\mathbf{E}} \cdot \hat{\mathbf{E}}_0 \, dv \]

This formula can then be applied to a small point flaw. Further development to degenerate types of flaws (thin discs, needle shapes, etc.) is also planned. The ultimate goal would be the prediction of the response of an ellipsoidal anomaly.
III. Publications and Presentations


IV. Scientific Personnel

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Appendix A

Nondestructive Evaluation of Dielectric Layers on Conductive Substrates by Microwave Surface Electromagnetic Waves
NONDESTRUCTIVE EVALUATION OF DIELECTRIC LAYERS ON CONDUCTIVE 
SUBSTRATES BY MICROWAVE SURFACE ELECTROMAGNETIC WAVES

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Abstract
The thickness and permittivity (or dielectric constant) of dielectric layers on electrically conductive substrates can be determined by suitable techniques using surface electromagnetic waves. The approach used here is to measure the cutoff frequency of the TM \( \text{SEW} \) mode and, in effect, the propagation constant of the TM \( \text{SEW} \) mode as a function of frequency. The theory of the method and some preliminary results obtained using \( \text{SEW} \) supported by a layer of polyethylene on an aluminum substrate are presented. We point to higher frequencies the method can be extended to thin protective coatings on metals, e.g., ceramic coatings on jet engine and coal utilization components.

INTRODUCTION
The idea of using surface electromagnetic waves (SEW) to measure the thickness and dielectric constant (or complex permittivity) of a layer of dielectric material on an electrically conductive substrate is well known. It has received considerable attention in relation to opto-electronic devices in which thin layers of optically transparent materials on conductive or semiconducting substrates are used as optical waveguides.\(^{(1,2)}\) The possibility of adapting the technique for nondestructive evaluation of other types of coatings was raised by Bell and co-workers.\(^{(1)}\) However, the idea does not appear to have been pursued to the point of practical application.

There are currently several potential applications of the method. Several in particular are noteworthy. One is the case of protective coatings on components of jet engines, coal combustion chambers, magnetohydrodynamic generators, and the like.\(^{(4)}\) Another is the case of polymeric coatings for environmental protection. There is also the case of surfaces of metals prepared for adhesive bonding, where the strength attained by the bond is known to be sensitive to the condition of the adherent surfaces.

This paper describes some preliminary work exploring some of the possibilities and practical problems associated with the SEW method. It is not aimed at a specific application. The work involves the use of microwaves in the 8-12 GHz range (free space wavelengths around 3 cm). "Coatings" are simulated by relatively thick (\( \approx 1.5 \) cm) slabs of a readily available plastic (polyethylene) placed on a large sheet of aluminum. For application to thin coatings, the techniques would have to be "scaled down" by one or two orders of magnitude. Fortunately there are no fundamental obstacles to this. Thus far only transverse magnetic (TM) waves have been used; the possibility of using transverse electric (TE) waves and combined TM and TE waves remains open.
The persian relation is found:

\[(\varepsilon t)\tan(\varepsilon t) = \varepsilon_0 x_0^t\]  

Equation (5) implicitly defines the propagation constant, \(\beta\), as a function of \(k_0\), \(t\) and \(\varepsilon\). This transcendental equation cannot be solved exactly in closed form. If Equation (5) is rewritten in the form

\[x \tan x = \varepsilon\left((c-1)(x_0 t)^2-x^2\right)^{1/2}\]  

where

\[x = \varepsilon t\]

it becomes clear that the solutions of the equation correspond to the intersection of the (circular) curve

\[y = \varepsilon\left((c-1)(x_0 t)^2-x^2\right)^{1/2}\]

with the curve

\[y = x \tan x\]

Multiple solutions to the equation occur, a new branch occurring as \(x\) increases by a multiple of \(\pi\). For \(x = n\pi\), the right hand side of Equation (6) must vanish, i.e.,

\[k_n = \frac{n\pi}{t(c-1)^{1/2}}, \quad n = 0, 1, \ldots \]  

The values of \(k_n\) given by Equation (7) correspond respectively to cutoff frequencies

\[\omega_n = \frac{nc}{t(c-1)^{1/2}}\]  

where \(c = \left(\varepsilon_0 \mu_0\right)^{-1/2}\) is the speed of light in vacuum. The fields corresponding to the solution of Equation (6) for \(n\pi < x < (n+1)\pi\) are described as the TM\(_n\) SEW modes. The cutoff frequency for the TM\(_0\) mode is, of course, zero: the TM\(_0\) mode can be excited for any frequency. The higher order modes can be excited only for frequencies exceeding their respective cutoff frequencies.

We note that a determination of the cutoff frequency of any mode except TM\(_0\) determines the quantity \(t(c-1)^{1/2}\).

If the left and right hand sides of Equation (6) are expanded as a power series in \(x\) about the
value \( x = n \), an approximate solution is obtained which may be written in the form

\[
\left( \frac{\alpha}{\kappa^2} \right)^2 = 1 + \left( \frac{\alpha-1}{\kappa} \right)^2 \left( k_0^2 k_n^2 \right)^2
\]  

Equation (9) is valid for \( k_0 \leq k_n \).

Equation (9) may be written

\[
\left( \frac{k_n}{k_0} \right)^2 = \left( \frac{\alpha-1}{\kappa} \right)^2 \left( k_0^2 k_n^2 \right)^2
\]  

Thus if the propagation constant \( \beta \) is determined as a function of the wave number \( k_0 \) (for fixed values of \( s \) and \( t \)), for values of \( k_0 \) greater than, but near \( k_n \), the quantity \( (\alpha-1)\kappa/\kappa \) may be determined as the slope of a graph of \( \left( \left( \alpha/\kappa \right)^2 - 1 \right)^{1/2} \) versus \( k_n \); the graph will intersect the \( k_n \)-axis at the value \( k_n \), which, in turn, determines the quantity \( \left( \alpha-1 \right)^{1/2} \). Writing

\[
\alpha = \left( \frac{\alpha-1}{\kappa} \right)^2
\]  

we have

\[
\cos \theta = \frac{\beta \kappa}{k_0} \left( \frac{\alpha-1}{\kappa} \right)^2 \left( k_0^2 k_n^2 \right)^2
\]  

and

\[
\sin \theta = \frac{\beta \kappa}{k_0} \left( \frac{\alpha-1}{\kappa} \right)^2 \left( k_0^2 k_n^2 \right)^2
\]  

Thus \( \cos \theta \) and \( \sin \theta \) are determined as functions of the experimentally measurable parameters \( s \) and \( k_n \).

PRISM METHOD OF LAUNCHING AND RECEIVING SEW

One practical means of launching a SEW is Otto's prism method,\(^5\) illustrated in Figure 2. If the angle of incidence \( \theta \) is such that the internal angle of incidence \( \theta \) exceeds the critical angle for the prism-air interface, then the \( s \)-component of the (now complex) propagation vector for the field below the prism is pure imaginary. By varying the angle of incidence \( \theta \) (and consequently the internal angle of incidence \( \theta \), the ratio \( \beta/\kappa_0 \) can (for appropriate values of \( k_0 \)) be made to assume the value

\[
\frac{\beta}{\kappa_0} \sin \theta = \frac{\beta}{\kappa_0} = \left( \frac{\alpha-1}{\kappa} \right)^2 \left( k_0^2 k_n^2 \right)^{1/2}
\]  

Figure 2. Prism Coupling Arrangement for Launching and Receiving Surface Electromagnetic Waves

necessary for a SEW on the substrate. At this condition, a SEW will propagate. Thus the condition for launching a TM\( \_n \) surface wave may be written

\[
\frac{\beta}{\kappa_0} \sin \theta = \frac{\beta}{\kappa_0} \left( \frac{\alpha-1}{\kappa} \right)^2 \left( k_0^2 k_n^2 \right)^{1/2}
\]  

where \( \epsilon_r \) is the relative permittivity of the prism material.

If the wave inside the prism, and incident on the prism-air interface, were an ideal plane wave, there would be a sharply defined internal angle of incidence \( \theta \), at which a TM\( \_n \) SEW could be launched. In practice the incident wave comprises plane waves with a range of propagation directions distributed about a central ray. Hence as \( \theta \) is varied, the amplitude of the launched TM\( \_n \) wave varies and is maximum for the theoretical value of \( \theta \). By measuring the value of \( \theta \) at which the amplitude of the TM\( \_n \) SEW is maximum, as a function of \( k_0 \) (or, equivalently, the frequency of the incident radiation), \( \beta/\kappa_0 \) is determined as a function of \( k_0 \), and Equations (10), (12) and (13) may be applied to determine \( \epsilon_r \) and \( \kappa_0 \).

EXPERIMENTAL METHOD

A block diagram of the experimental arrangement
timimum gap for the best-coupling is h = \lambda/2, where \lambda is the free-space wavelength of the microwaves.

An aluminum sheet (alloy #6061) of size 8" x 8" is used as the conductive substrate. Several polypropylene sheets of the same size but different thicknesses are used as the dielectric coating material. The polypropylene sheets are laved on the aluminum sheet and clamped in order to minimize air space between the polypropylene and the aluminum sheet.

There are two basic parameters we have to measure, namely the frequency and the incident angle in the air. Before making quantitative measurements we have to scan several times to determine the angular range within which the TM₀ and TM₁ modes propagate with maximum amplitude.

In the actual measurement, as the external angle \phi is increased, we have to adjust the position of the prism slightly in order to keep the central ray of the incident beam near the edge of the prism for most efficient coupling. Then the coupling angle can be obtained by scanning the incident beam from \phi = 0° to \phi = 80° and measuring the angle at which the most energy is coupled into the surface mode. The microwave frequency is obtained from the frequency meter.

![Figure 4. Surface Wave Intensity Versus External Angle of Incidence](image-url)
RESULTS

Figure 4 is a representative graph of the detected signal amplitude as a function of the external angle of incidence. The large peak corresponds to the TM₁ mode; the smaller second peak corresponds to the TM₂ mode. Table 1 shows an example of measurements obtained from a specimen of thickness t = 1.50 cm and the dielectric constant of the polypropylene layer ε = 2.25. There are two modes (TM₁ and TM₂) which can be propagated on this structure. The data in Table 1 is the result of the TM₁ mode, because only the higher mode is useful to determine the dielectric constant and thickness of the laser. The table basically contains the frequency f and the incident angle in the air, θ, the other data is simply determined from f and θ. The free-space wave number is k₀ = 2πf/λ, where c is the velocity of light in free space. The incident angle in the prism, θ₁, is obtained from the incident angle in the air, θ. There are two cases: i) for θ = 7π/4 then θ₁ = π/4 - sin⁻¹[(sin(7π/4))/n₀]; ii) if θ = 7π/4 then θ₁ = π/4 + sin⁻¹[(sin(7π/4))/n₁], where n₁ is the refractive index of the prism (n₁ < ε). The most important parameter we must know is the ratio c/ε₀. According to the theory of launching SEW by the prism coupling technique, the incident angle in the prism is determined by the equation c/ε₀ = k₀n₁ sin θ₁; therefore if we know n₁ = ε₀ = k₀c can be obtained from the equation c/ε₀ = k₀n₁ sin θ₁. k₀ in turn determines the quantity [(c/ε₀)²-1]¹/².

The approximate dispersion relation for any TMₙ mode of SEW near cutoff is given by Equation (9). From equation (10) we can see that if we plot [(c/ε₀)²-1]¹/² versus k₀, a straight line will result, and the slope s will be equal to (c-1)/ε₀; the intercept will be equal to the cutoff wave number k₁. A representative graph corresponding to the data in Table 1 is shown in Figure 5. For this particular case, the slope s = 8.39 × 10⁻³ m⁻¹ and k₁ = 186.7 m⁻¹.

After s and k₁ are determined, ε and t are obtained by means of Equations (12) and (13).

For the example, we have t = 2.16 and ε = 2.25 determined by the standard waveguide method, and t = 1.50 cm measured with a pair of calipers.

Table 1. Representative Data for TM₁ SEW on 1.5 Inch Polypropylene Layer on Aluminum Substrate

<table>
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<tr>
<th>Material Type</th>
<th>Thickness (cm)</th>
<th>Dielectric Constant</th>
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<tbody>
<tr>
<td>Aluminum</td>
<td>1.50</td>
<td>2.25</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1.50</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Figure 5. Function of Surface Wave Propagation Constant Versus Wave Number of Exciting Radiation

CONCLUSION

The possibility of measuring the thickness and dielectric constant of a dielectric layer on a conductive substrate by measuring the propagation constant of a TM SEW using the prism launching method has been demonstrated in a regime appropriate to the 8-12 GHz frequency range. To handle thinner dielectric layers it
will be necessary to employ much higher frequencies.

A number of important points remain to be investigated, including: (1) the effects of pronounced variations in the thickness of the dielectric layer; (2) the effects of pronounced variations in the dielectric constant of the dielectric layer; and (3) the effects of imperfections in the surface of the conductive substrate.

In order to rationally optimize the experimental arrangement it will be necessary to develop a detailed mathematical model of the prism SEW launching arrangement.

Finally, it would be worthwhile to investigate alternative launching arrangements including gratings (or similar periodic structures) and special horns; and to investigate the possibilities of using transverse electric (TE) modes as well as both TM and TE modes.

ACKNOWLEDGEMENT

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REFERENCES


Appendix B

Change in Impedance Due to a Flaw
in a Conducting Body
Change in Impedance Due to a Flaw in a Conducting Body

Consider a two-port network comprising (1) a transmitter T; a receiver R; and (3) a conductive body B containing a void of volume $V_F$ as shown in Figure 1. Consider the multiply connected region bounded by (1) the surface $S_F$ of the void; (2) the closed surface $S_T$ partially surrounding the transmitter and a portion of which coincides with a standard reference plane cutting the field-guiding structure; (3) a similar surface $S_R$ for the receiver; and (4) a boundary at infinity. Let $(\vec{E}_0, \vec{H}_0)$ denote the (time-harmonic) fields that would exist if the void in B were not present, with a current $I_R$ impressed at the reference plane of the receiver, with the transmitter open-circuited ($I_T=0$). Let $(\vec{E}, \vec{H})$ denote the (time-harmonic) fields actually existing with the void present, a current $I_T$ impressed at the reference plane of the transmitter, and the receiver open-circuited ($I_R=0$). Within the bounded volume, $(E_0, H_0)$ and $(\vec{E}, \vec{H})$ satisfy the same set of equations, i.e.

$$\nabla \times \vec{E} = -j\omega \mu_0 \vec{H} \quad \nabla \times \vec{H} = j\omega \epsilon(\vec{r}) \vec{E}$$

By the Lorentz reciprocity theorem, we have

$$\int_S [\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0] \cdot d\vec{S} = 0$$

where $d\vec{S}$ is an element of surface which is taken to be directed into the bounded volume. The surface $S$ is the union of surfaces,

$$S = S_F \cup S_T \cup S_R \cup S_F$$
We assume: (1) the tangential components of the electric field intensity vanish over \( S_T \) and \( S_R \) except over the respective reference planes (the transmitter and receiver are shielded); (2) the fields satisfy the radiation condition, so that the integral over \( S \) vanishes. Hence we have

\[
\int_{S_T \cup S_R} \left[ \mathbf{E}_0 \times \mathbf{H} - \mathbf{E} \times \mathbf{H}_0 \right] \cdot \hat{d}S = 0
\]

We assume the transmitter and receiver field guides to operate in their respective dominant modes for which currents and voltages are so defined that we have

\[
\int_{S_T} \left( \mathbf{E}_0 \times \mathbf{H} - \mathbf{E} \times \mathbf{H}_0 \right) \cdot \hat{d}S = I_T^0 V_T - I_T V_T
\]

\[
\int_{S_R} \left( \mathbf{E}_0 \times \mathbf{H} - \mathbf{E} \times \mathbf{H}_0 \right) \cdot \hat{d}S = I_R^0 V_R - I_R V_R
\]

By the assumptions made, \( I_T^0 = 0 \) (transmitter open-circuited for fields \((\mathbf{E}_0, \mathbf{H}_0)\)), and \( I_R = 0 \) (receiver open-circuited for fields \((\mathbf{E}, \mathbf{H})\)). Hence we have

\[
-I_T V_T^0 + I_R V_R + \int_{S_F} \left( \mathbf{E}_0 \times \mathbf{H} - \mathbf{E} \times \mathbf{H}_0 \right) \cdot \hat{d}S = 0
\]

Now, \( V_T^0 = z_{12}^0 I_R \), where \( z_{12}^0 \) is the transfer impedance between transmitter and receiver (no void); and

\( V_R = z_{12} I_T \), where \( z_{12} \) is the transfer impedance (with void).

Hence, we have
\[ \int_{I_{0}}^{t_{1}} (z_{12} - z_{12,0}) = -\int_{S_F} (E_0 \times H - \tilde{H} \times \tilde{H}) \cdot d\hat{S} \]

or,

\[ \Delta z_{12} = z_{12} - z_{12,0} = -\int_{I_{0}}^{t_{1}} \int_{S_F} (E_0 \times H - \tilde{H} \times \tilde{H}) \cdot d\hat{S} \]

\[ = -\int_{I_{0}}^{t_{1}} \int_{S_F} \nabla \cdot \left[ E_0 \times H - \tilde{H} \times \tilde{H} \right] dv \]

(Since the tangential components of fields are continuous across \( S_F \))

\[ \Delta z_{12} = -\int_{I_{0}}^{t_{1}} \int_{V_F} \left[ \tilde{H} \cdot (\nabla \times \tilde{E}) - \tilde{E} \cdot (\nabla \times H) + \tilde{H} \cdot \tilde{E} \cdot (\nabla \times \tilde{H}) \right] dv \]

\[ = -\int_{I_{0}}^{t_{1}} \int_{V_F} \left[ \tilde{H} \cdot (-j\omega \mu_H \tilde{E}) - \tilde{E} \cdot (j\omega \varepsilon_0 \tilde{E}) - \tilde{E} \cdot \tilde{H} + \tilde{E} \cdot (j\omega \varepsilon_0 \tilde{E}) \right] dv \]

\[ = +\int_{I_{0}}^{t_{1}} \int_{V_F} \tilde{E} \cdot \tilde{E} dv \]

\[ \therefore \Delta z_{12} = \int_{I_{0}}^{t_{1}} \int_{V_F} \hat{E} \cdot \hat{E} dv \]

\[ \therefore \Delta z_{12} = \frac{\omega}{I_{0}} \int_{V_F} \hat{E} \cdot \hat{E} dv \]

now,

\[ \tau_0 = \frac{j\omega}{\omega} \]

\[ \therefore \Delta z_{12} = \frac{\omega}{I_{0}} \int_{V_F} \hat{E} \cdot \hat{E} dv \]
An abstract of quantitative nondestructive eddy current testing techniques on nonferromagnetic structural metals has been continued. In addition an investigation of electromagnetic surface wave propagation in a dielectric layer on a conducting substrate was completed.