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ELECTROMAGNETIC METHODS OF NONDESTRUCTIVE EVALUATION

Report for

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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

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[IEEE Transactions on Instrumentation and Measurements, March 1981] and planar [Journal of Nondestructive Evaluation, 1981] 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.

$$\Delta z = \frac{\sigma}{I^2} \int_{V_F} \vec{E}_0 \cdot \vec{E}_0 dv$$

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

S. A. Long, C. G. Gardner, and A. Zaman, "Impedance of a Loop with a Cylindrical Conducting Core", accepted for publication in IEEE Transactions on Instrumentation and Measurements, March 1981 issue.

A. J. M. Zaman, S. A. Long, and C. G. Gardner, "The Impedance of a Single-Turn Coil Near a Conducting Half-Space", accepted for publication in Journal of Nondestructive Evaluation.

S. A. Long, A. J. M. Zaman, and C. G. Gardner, "Impedance of a Loop Near a Conducting Half-Space", paper presented at the DARPA/AF Symposium on Quantitative Nondestructive Evaluation, LaJolla, CA, July 1980.

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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 measurements using surface electromagnetic waves. The approach used here is to measure the cutoff frequency of the TM_1 SEW mode and, in effect, the propagation constant of the TM_1 SEW mode as a function of frequency. The theory of the method and some preliminary results obtained using 8-12GHz SEW supported by a layer of polypropylene on an aluminum substrate are presented. By going 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 material on conductive or semiconductive 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 coworkers.[3] 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 (~1.5 cm) slabs of a readily available plastic (polypropylene) 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.
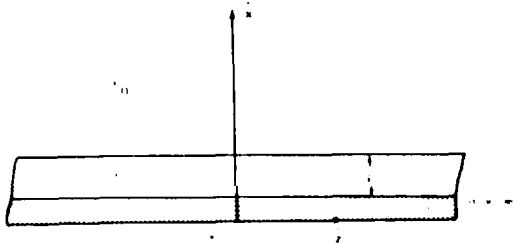
Figure 1. Dielectric Layer on Metal Substrate

THEORY

Referring to Figure 1, the illustrated unbounded planar structure can be shown from Maxwell's equations to support TM plane waves propagating in the z-direction (with surfaces of constant phase perpendicular to the z-direction) for which the z-component of the amplitude of the electric field is given by the relations:

$$E_z(x) = \begin{cases} E_0 \sin \kappa x & 0 \le x \le \ell \\ E_0(\sin \kappa \ell)e^{-\kappa_0(x-\ell)} & \ell < x \end{cases} \quad (1)$$

where

$$\kappa_0 = (\beta^2 - k_0^2)^{1/2} \quad (2)$$

$$\kappa = (\epsilon k_0^2 - \beta^2)^{1/2} \quad (3)$$

β is the propagation constant, and $k_0^2 = \omega^2 \mu_0 \epsilon_0$. ε is the permittivity of the dielectric layer of thickness ℓ. Conditions for such a surface wave exist when the relation

$$k_0 < \beta < \epsilon^{1/2} k_0 \quad (4)$$

is satisfied. For this case, both κ and κ_0 are real, positive quantities.

The remaining components of the electric field intensity, as well as the y-component of the magnetic field intensity follow from Maxwell's equations (the x-component and z-component vanish). When the requisite boundary conditions on the fields are imposed, the following dispersion relation is found:

$$(\kappa \ell)\tan(\kappa \ell) = \epsilon \kappa_0 \ell \quad (5)$$

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

$$x \tan x = \epsilon[(\epsilon-1)(k_0\ell)^2 - x^2]^{1/2} \quad (6)$$

where

$$x = \kappa \ell$$

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

$$y = \epsilon[(\epsilon-1)(k_0\ell)^2 - x^2]^{1/2}$$

with the curve

$$y = x \tan x .$$

Multiple solutions to the equation occur, a new branch occurring as x increases by a multiple of π. For x = nπ, the right hand side of Equation (6) must vanish, ie.,

$$k_n = \frac{n\pi}{\ell(\epsilon-1)^{1/2}}, \quad n = 0,1,\ldots \quad (7)$$

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

$$\omega_n = \frac{n\pi c}{\ell(\epsilon-1)^{1/2}} \quad (8)$$

where $c = (\mu_0 \epsilon_0)^{-1/2}$ is the speed of light in vacuo. The fields corresponding to the solution of Equation (6) for nπ<x<(n+1)π 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 $\ell(\epsilon-1)^{1/2}$.

If the left and right hand sides of Equation (6) are expanded as a power series in x about the

value $x = n\pi$, an approximate solution is obtained which may be written in the form

$$(\frac{\beta}{k_0})^2 = 1 + [(\frac{\epsilon-1}{\epsilon})\ell]^2(k_0-k_n)^2 \qquad (9)$$

Equation (9) is valid for

$$k_0 \gtrsim k_n .$$

Equation (9) may be written

$$[(\frac{\beta}{k_0})^2-1]^{1/2} = [(\frac{\epsilon-1}{\epsilon})\ell](k_0-k_n) \qquad (10)$$

Thus if the propagation constant β is determined as a function of the wave number k_0 (for fixed values of ϵ and ℓ), for values of k_0 greater than, but near k_n, the quantity $(\epsilon-1)\ell/\epsilon$ may be determined as the slope of a graph of $[(\beta/k_0)^2 -1]^{1/2}$ versus k_0; the graph will intersect the k_0-axis at the value k_n, which, in turn, determines the quantity $\ell(\epsilon-1)^{1/2}$. Writing

$$s = (\frac{\epsilon-1}{\epsilon})\ell \qquad (11)$$

we have

$$\epsilon = \frac{1+[1-4(\frac{sk_n}{n\pi})^2]^{1/2}}{2(\frac{sk_n}{n\pi})^2} \qquad (12)$$

and

$$\ell = (\frac{\epsilon}{\epsilon-1})s \qquad (13)$$

Thus ϵ and ℓ 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 ϕ is such that the internal angle of incidence θ exceeds the critical angle for the prism-air interface, then the x-component of the (now complex) propagation vector for the field below the prism is pure imaginary. By varying the angle of incidence ϕ (and consequently the internal angle of incidence θ), the ratio β/k_0 can (for appropriate values of k_0) be made to assume the value
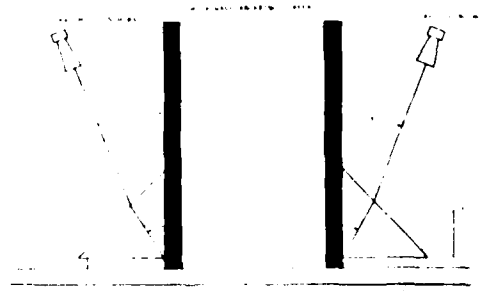

Figure 2. Prism Coupling Arrangement for Launching and Receiving Surface Electromagnetic Waves

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

$$\epsilon_p^{1/2}\sin\theta = \frac{\beta}{k_0} = \{1+(\frac{\epsilon-1}{\epsilon}\ell)^2(k_0-k_n)^2\}^{1/2} \qquad (14)$$

where ϵ_p 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 θ, 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 θ is varied, the amplitude of the launched TM_n wave varies and is maximum for the theoretical value of θ. By measuring the value of θ 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), β/k_0 is determined as a function of k_0, and Equations (10), (12) and (13) may be applied to determine ϵ and ℓ.

EXPERIMENTAL METHOD

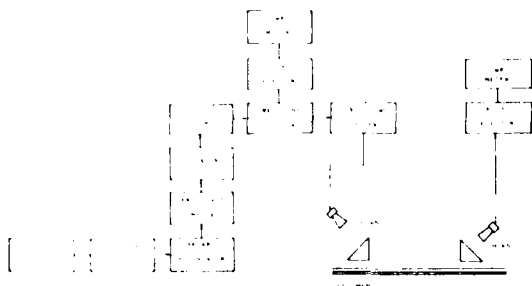A block diagram of the experimental arrangement

Figure 3. Block Diagram of Experimental Arrangement

is shown in Figure 3. A sweep oscillator which has a frequency range from 8.0 GHz to 12.4 GHz is used as the microwave source. For launching a surface electromagnetic wave, the prism coupling technique has been used. The $45°$ prisms were made of paraffin wax having a measured permittivity $\epsilon_p = 2.22$; the base size of the prisms is 20 cm $\times$ 20 cm. In order to minimize direct pick-up of any radiation other than SEW modes, two microwave absorbing screens were placed behind (or ahead of) the prisms. A gap of 4 cm was left between the microwave absorber and the specimen on which SEW propagated. Each microwave horn has an aperture 8 cm $\times$ 8 cm. In order to get a far-field pattern we have to set the distance between the transmission horn and prism $r = 2D^2/\lambda$, where D is the dimension of the aperture. For our case, r has to be greater than 45 cm. A divided circular quadrant (not shown in the figure) with a radius of 80 cm was built and the transmission horn mounted on it. For the receiving horn a similar scanning device with smaller radius (r = 50 cm) is used. The transmission and receiving horns can be independently scanned through $90°$.

For coupling the wave in the prism into the SEW, there must be an air gap between the prism and the dielectric layer. Experiment shows the op-

timum gap for the best-coupling is h = $\lambda/2$, where λ is the free-space wavelength of the microwaves.

An aluminum sheet (alloy #6061) of size 8'×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 layed on the aluminum sheet and clamped in order to minimize air space between the polypropylene and the aluminimum 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 TM_0 and TM_1 modes propagate with maximum amplitude.

In the actual measurement, as the external angle ϕ 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.
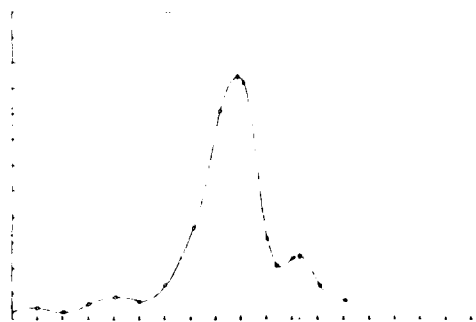

Figure 4. Surface Wave Intensity Versus External Angle of Incidence

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 TM_1 mode; the smaller second peak corresponds to the TM_0 mode. Table 1 shows an example of measurements obtained from a specimen of thickness $\ell = 1.50$ cm and the dielectric constant of the polypropylene layer $\varepsilon = 2.25$. There are two modes (TM_1 and TM_0) which can be propagated on this structure. The data in Table 1 is the result of the TM_1 mode, because only the higher mode is useful to determine the dielectric constant and thickness of the layer. The table basically contains the frequency f and the incident angle in the air, ϕ; the other data is simply determined from f and ϕ. The free-space wave number is $k_0 = 2\pi f/c$, where c is the velocity of light in free space. The incident angle in the prism, θ, is obtained from the incident angle in the air, ϕ. There are two cases: i) For $\phi < \pi/4$ then $\theta = \pi/4 - \sin^{-1}(\sin(\pi/4-\phi)/n_p)$; ii) If $\phi > \pi/4$ then $\theta = \pi/4 + \sin^{-1}(\sin(\phi-\pi/4)/n_p)$, where n_p is the refraction index of the prisms ($n_p = \sqrt{\varepsilon_p}$). The most important parameter we must know is the ratio ε/k_0. According to the theory of launching SEW by the prism coupling technique, the incident angle in the prism is determined by the equation $\varepsilon = k_0 n_p \sin\theta$; therefore if we know θ and n_p, ε/k_0 can be obtained from the equation $\varepsilon/k_0 = n_p \sin\theta$. ε/k_0 in turn determines the quantity $[(\varepsilon/k_0)^2-1]^{1/2}$.

The approximate dispersion relation for any TM_n mode of SEW near cutoff is given by Equation (9). From Equation (10) we can see that if we plot $[(\varepsilon/k_0)^2-1]^{1/2}$ versus k_0, a straight line will result, and the slope s will be equal to $(\varepsilon-1)/\varepsilon\ell$; the intercept will be equal to the cutoff wave number k_1. A representative graph corresponding to the data in Table 1 is shown in Figure 5. For this particular case, the slope $s = 8.39 \times 10^{-3}$m and $k_1 = 186.7$ m^{-1}. After s and k_1 are determined, ε and ℓ are ob-

tained by means of Equations (12) and (13). For the example, we have $\varepsilon = 2.16$ and $\ell = 1.56$ cm. These may be compared with the value $\varepsilon = 2.25$ determined by the standard waveguide method, and $\ell = 1.50$ cm measured with a pair of calipers.

Table 1. Representative Data for TM_1 SEW on 1.5 Inch Polypropylene Layer on Aluminum Substrate

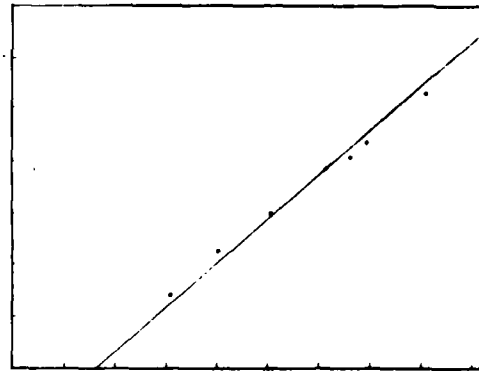**Figure 5.** Function of Surface Wave Propagation Constant Versus Wave Number of Exciting Radiation

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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2. Chung, P. S., Multi-Wavelength Determination of Single-Mode Optical Waveguide Parameters, Optica Acta, Vol. 23, No. 8, pp. 651-663 (1976).

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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 <u>would</u> exist if the void in B were <u>not</u> 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, $(\vec{E}_0, \vec{H}_0)$ and $(\vec{E}, \vec{H})$ satisfy the same set of equations, i.e.

$$\nabla \times \vec{E} = -j\omega\mu_0\vec{H} \; ; \qquad \nabla \times \vec{H} = j\omega\varepsilon(\vec{r})\vec{E}$$

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 <u>into</u> the bounded volume. The surface S is the union of surfaces,

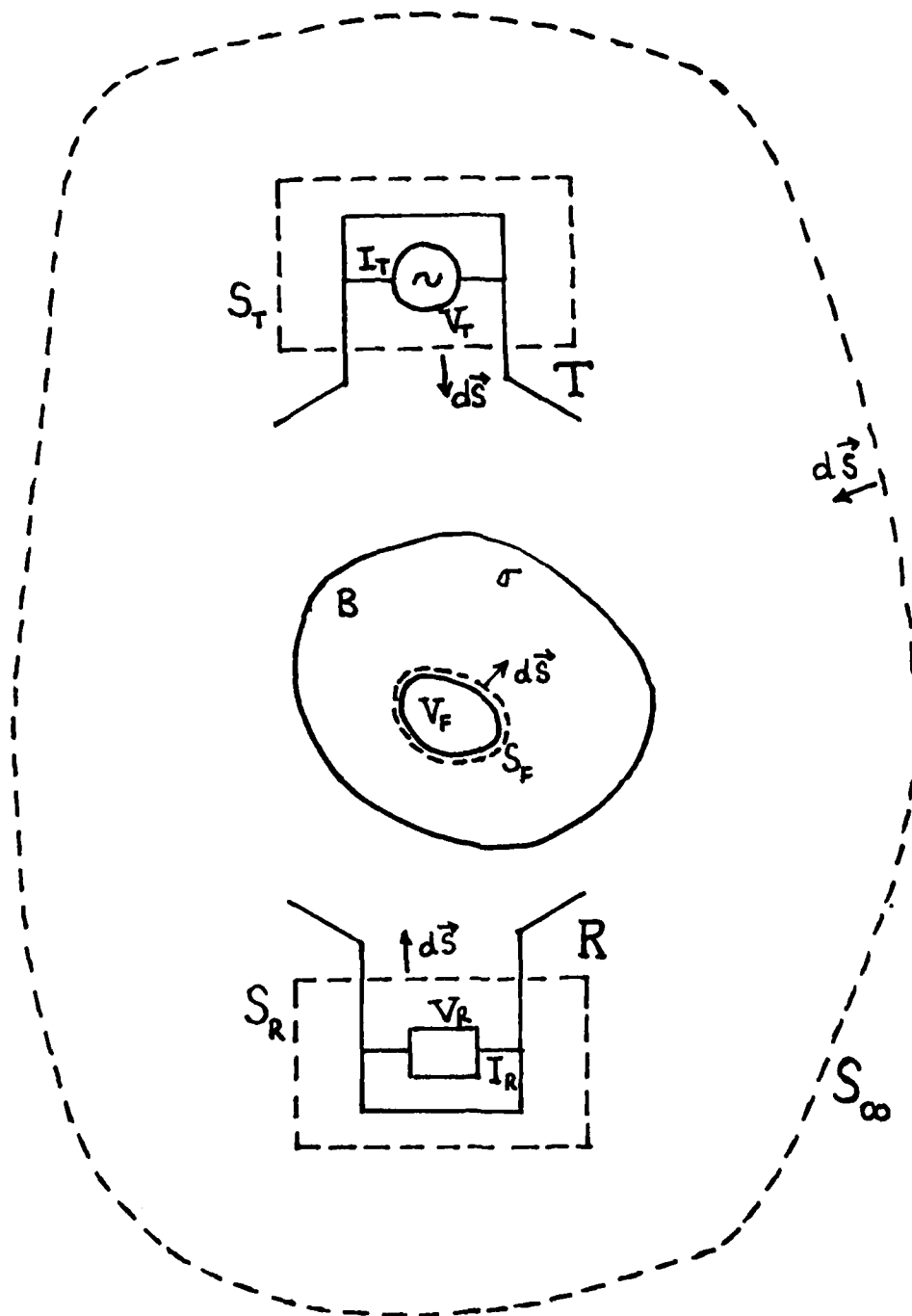$$S = S_\infty \; US_T \; US_R \; US_F$$

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Fig. 1

We assume: (1) the tangential components of the electric field intensity vanish over S_T and S_R <u>except</u> 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

$$\int_{S_T \cup S_R \cup S_F} [\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0] \cdot d\vec{S} = 0$$

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

$$\int_{S_T} (\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0) \cdot d\vec{S} = I_{T_0} V_T - I_T V_{T_0}$$

$$\int_{S_R} (\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0) \cdot d\vec{S} = I_{R_0} V_R - I_R V_{R_0}$$

By the assumptions made, $I_{T_0} = 0$ (transmitter open-circuited for fields $(\vec{E}_0, \vec{H}_0)$), and $I_R = 0$ (receiver open-circuited for fields $(\vec{E}, \vec{H})$). Hence we have

$$-I_T V_{T_0} + I_{R_0} V_R + \int_{S_F} (\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0) \cdot d\vec{S} = 0$$

Now, $V_{T_0} = z_{12_0} I_{R_0}$, 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

$$I_{R_0} I_T (z_{12} - z_{12_0}) = - \int_{S_F} (\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0) \cdot d\vec{S}$$

or,

$$\Delta z_{12} \overset{\Delta}{=} z_{12} - z_{12_0} = - \frac{1}{I_{R_0} I_T} \int_{S_F} (\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0) \cdot d\vec{S}$$

$$= - \frac{1}{I_{R_0} I_T} \int_{V_F} \nabla \cdot [\vec{E}_0 \times \vec{H} - \vec{E} \times \vec{H}_0] dv$$

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

$$\Delta z_{12} = - \frac{1}{I_{R_0} I_T} \int_{V_F} [\vec{H} \cdot (\nabla \times \vec{E}_0) - \vec{E}_0 \cdot (\nabla \times \vec{H}) - \vec{H}_0 \cdot (\nabla \times \vec{E}) + \vec{E} \cdot (\nabla \times \vec{H}_0)] dv$$

$$= - \frac{1}{I_{R_0} I_T} \int_{V_F} [\vec{H} \cdot (-j\omega\mu_0 \vec{H}_0) - \vec{E}_0 \cdot (j\omega\epsilon_0 \vec{E}) - \vec{H}_0 \cdot (-j\omega\mu_0 \vec{H}) + \vec{E} \cdot (j\omega\epsilon_0 \vec{E}_0)] dv$$

$$= + \frac{j\omega(\epsilon - \epsilon_0)}{I_{R_0} I_T} \int_{V_F} \vec{E}_0 \cdot \vec{E} \, dv$$

now, $\quad \epsilon = \epsilon_0 - j\sigma/\omega$

$$\therefore \quad \Delta z_{12} = \frac{\sigma}{I_{R_0} I_T} \int_{V_F} \vec{E}_0 \cdot \vec{E} \, dv$$

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study 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.

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