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CONTRACT TECHNICAL NOTE

ELECTROMAGNETIC WAVE REFLECTION FROM A METAL-BACKED NON-UNIFORM PLASMA LAYER FOR NON-NORMAL INCIDENCE

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HYPERVELOCITY RANGE RESEARCH PROGRAM
A PART OF PROJECT "DEFENDER"

GM DEFENSE RESEARCH LABORATORIES

SANTA BARBARA, CALIFORNIA

AEROSPACE OPERATIONS DEPARTMENT

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Henry M. Musal, Jr.

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INTRODUCTION

The purpose of this note is to document a technique for the calculation of the reflection coefficients for a plane transverse electromagnetic wave incident non-normally on a non-uniform plasma layer with a metal-backing wall. It is assumed that the plasma properties (plasma frequency and electron collision frequency) vary spatially only in the direction normal to the metal wall. The plasma layer is treated as a spatially non-uniform lossy dielectric material. The situation in which the incident electromagnetic wave is normally incident has been extensively treated in the literature*. For non-normal incidence, it is most convenient to consider an arbitrarily polarized incident electromagnetic wave to be composed of TE(transverse electric) and TM (transverse magnetic) modes. The reflection coefficient for each of these different modes is then found separately. This approach greatly simplifies the analysis.

* See, for example, Zivanovic[1].

THEORY

The geometry of the situation is shown in Figure 1. In the free-space region the incident electromagnetic wave propagates toward the plasma boundary at the angle θ_i to the normal, and the reflected electromagnetic wave propagates away from the plasma boundary also at the angle θ_i to the normal. These waves are both either TE or TM modes, that is, either the electric or the magnetic field is directed in the y-direction. Correspondingly, in the non-uniform plasma region the electric or magnetic field has only a y-direction component. These two different field configurations lead to two different reflection coefficients, which are most expeditiously found by two different approaches.

TE Mode Reflection Coefficient

The incident electromagnetic wave, for the TE mode, is given by

$$\vec{E}_i = \vec{1}_y \, E_i \, e^{-j k_v (x \sin\theta_i + z \cos\theta_i)} \tag{1}$$

$$\vec{H}_i = (-\vec{1}_x \cos\theta_i + \vec{1}_z \sin\theta_i) \left(\frac{\epsilon_v}{\mu_v}\right)^{1/2} E_i \, e^{-j k_v (x \sin\theta_i + z \cos\theta_i)} \tag{2}$$

where the time variation factor $\exp(j\omega t)$ has been suppressed, $\vec{E}_i$

and $\vec{H}_i$ are the electric and magnetic field intensities, $\vec{1}_x$, $\vec{1}_y$ and $\vec{1}_z$ are the x, y and z unit vectors, E_i is the complex amplitude of the incident wave, k_v is $2\pi/\lambda_v$ where λ_v is the wavelength of the incident wave in the free-space region, θ_i is the angle of incidence, and ϵ_v and μ_v are the free-space capacitivity and inductivity.

The reflected electromagnetic wave is given by

$$\vec{E}_r = \vec{1}_y E_r e^{-jk_v(x \sin\theta_i - z \cos\theta_i)} \tag{3}$$

$$\vec{H}_r = (\vec{1}_x \cos\theta_i + \vec{1}_z \sin\theta_i) \left(\frac{\epsilon_v}{\mu_v}\right)^{1/2} E_r e^{-jk_v(x \sin\theta_i - z \cos\theta_i)} \tag{4}$$

where the time variation factor $\exp(j\omega t)$ has been suppressed, $\vec{E}_r$ and $\vec{H}_r$ are the electric and magnetic field intensities, and E_r is the complex amplitude of the reflected wave. The TE mode reflection coefficient R_{TE} is given by

$$R_{TE} \equiv \frac{E_r}{E_i} \tag{5}$$

In the non-uniform plasma layer Maxwell's equations, with the time dependence $\exp(j\omega t)$, are

$$\nabla \times \vec{E} = -j\omega\mu_v \vec{H} \tag{6}$$

$$\nabla \times \vec{H} = j\omega \epsilon_v \epsilon \vec{E} \tag{7}$$

$$\nabla \cdot \epsilon \vec{E} = 0 \tag{8}$$

$$\nabla \cdot \vec{H} = 0 \tag{9}$$

where ϵ is the effective dielectric constant of the plasma, which varies spatially in the z-direction, and ω is the angular frequency of the time variation of the fields. The effective dielectric constant of the plasma ϵ is taken to be

$$\epsilon = 1 - \frac{\Omega_p^2}{1 - j\Omega_c} \tag{10}$$

where Ω_p and Ω_c are the normalized plasma and electron collision frequencies, respectively. In general, both Ω_p and Ω_c may be functions of position in the z-direction. The wave equation for $\vec{E}$ is found to be

$$\nabla^2 \vec{E} + k_v^2 \epsilon \vec{E} + \nabla \left[\frac{1}{\epsilon} (\nabla \epsilon) \cdot \vec{E} \right] = 0 \tag{11}$$

where the relationship $k_v^2 = \omega^2 \mu_v \epsilon_v$ has been used to simplify the result.

For the TE mode, $\vec{E}$ has only a y-direction component, and $\nabla\epsilon$ has only a z-direction component, hence the vector wave equation can be reduced to a single scalar partial differential equation for the y-direction component of the electric field intensity E_y (which is the total electric field in the plasma layer). This equation is

$$\partial_x^2 E_y + \partial_z^2 E_y + k_v^2 \epsilon E_y = 0 \tag{12}$$

Recognizing[2] that all fields must vary periodically in the x-direction according to the factor $\exp(-jk_v x \sin\theta_i)$, this partial differential equation can be reduced to the ordinary differential equation

$$\frac{d^2 u}{d\varsigma^2} + k_v^2 (\epsilon - \sin^2\theta_i) u = 0 \tag{13}$$

where

$$E_y = A u e^{-jk_v x \sin\theta_i} \tag{14}$$

and where the independent variable z has been transformed to a new independent variable ς, (where $\varsigma = h - z$), which is measured outward from the metal wall as shown in Figure 1. The associated magnetic field intensity in the plasma layer is

$$\vec{H} = \frac{A}{-j\omega\mu_v}\left[\vec{1}_x \frac{du}{d\xi} + \vec{1}_z(-jk_v \sin\theta_i)u\right] e^{-jk_v x \sin\theta_i} \tag{15}$$

which has both x- and z-direction components.

The appropriate boundary conditions are zero tangential electric field at the metal wall, and continuous tangential components of electric and magnetic fields at the interface between the free-space region and the plasma layer. These boundary conditions lead to the constraints

$$u\Big|_{\xi=0} = 0 \tag{16}$$

$$E_i + E_r = A u_h \tag{17}$$

$$\cos\theta_i E_i - \cos\theta_i E_r = -j\frac{A}{k_v} u_h' \tag{18}$$

where u_h and u_h' are the values of u and $du/d\xi$ at $\xi = h$. These equations can be solved to give the TE mode reflection coefficient R_{TE} in the form

$$R_{TE} = \frac{u_h \cos\theta_i + j\dfrac{u_h'}{k_v}}{u_h \cos\theta_i - j\dfrac{u_h'}{k_v}} \tag{19}$$

where u satisfies equation (13) with the initial condition given in equation (16).

TM Mode Reflection Coefficient

The incident electromagnetic wave, for the TM mode, is given by

$$\vec{H}_i = \vec{1}_y H_i e^{-jk_v(x \sin\theta_i + z \cos\theta_i)} \tag{20}$$

$$\vec{E}_i = (\vec{1}_x \cos\theta_i - \vec{1}_z \sin\theta_i) \left(\frac{\mu_v}{\epsilon_v}\right)^{1/2} H_i e^{-jk_v(x \sin\theta_i + z \cos\theta_i)} \tag{21}$$

where the time variation factor $\exp(j\omega t)$ has been suppressed and H_i is the complex amplitude of the incident wave. The reflected electromagnetic wave is given by

$$\vec{H}_r = \vec{1}_y H_r e^{-jk_v(x \sin\theta_i - z \cos\theta_i)} \tag{22}$$

$$\vec{E}_r = -(\vec{1}_x \cos\theta_i + \vec{1}_z \sin\theta_i) \left(\frac{\mu_v}{\epsilon_v}\right)^{1/2} H_r e^{-jk_v(x \sin\theta_i - z \cos\theta_i)} \tag{23}$$

where the time variation factor $\exp(j\omega t)$ has been suppressed and H_r is the complex amplitude of the reflected wave. The TM mode reflection coefficient R_{TM} is given by

$$R_{TM} \equiv \frac{H_r}{H_i} \tag{24}$$

In the non-uniform plasma layer, the wave equation for $\vec{H}$ is found to be

$$\nabla^2 \vec{H} + k_v^2 \epsilon \vec{H} + \frac{1}{\epsilon} (\nabla\epsilon) \times (\nabla \times \vec{H}) = 0 \tag{25}$$

For the TM mode, $\vec{H}$ has only a y-direction component, and $\nabla\epsilon$ has only a z-direction component, hence the vector wave equation can be reduced to a single scalar partial differential equation for the y-direction component of the magnetic field intensity H_y (which is the total magnetic field in the plasma layer). This equation is

$$\partial_x^2 H_y + \partial_z^2 H_y + k_v^2 \epsilon H_y - \frac{1}{\epsilon} \frac{d\epsilon}{dz} \partial_z H_y = 0 \tag{26}$$

Again, since all fields must vary periodically in the x-direction according to the factor $\exp(-jk_v x \sin\theta_i)$, this partial differential equation can be reduced to the ordinary differential equation

$$\frac{d^2 v}{d\varsigma^2} + k_v^2(\epsilon - \sin^2\theta_i)v - \frac{1}{\epsilon}\frac{d\epsilon}{d\varsigma}\frac{dv}{d\varsigma} = 0 \qquad (27)$$

where

$$H_y = Bv\,e^{-jk_v x \sin\theta_i} \qquad (28)$$

and where the independent variable z has been transformed to a new independent variable ς, (where ς = h-z), which is measured outward from the metal wall as shown in Figure 1. The associated electric field intensity in the plasma layer is

$$\vec{E} = \frac{B}{j\omega\epsilon_v\epsilon}\left[+\vec{1}_x\frac{dv}{d\varsigma} + \vec{1}_z(-jk_v\sin\theta_i)v\right] e^{-jk_v x \sin\theta_i} \qquad (29)$$

which has both x and z-direction components.

Application of the boundary conditions leads to the constraints

$$\left.\frac{dv}{d\xi}\right|_{\xi=0} = 0 \tag{30}$$

$$H_i + H_r = B\, v_h \tag{31}$$

$$\cos\theta_i\, H_i - \cos\theta_i\, H_r = -j\frac{B}{\epsilon_h k_v}\, v_h' \tag{32}$$

where v_h, v_h' and ϵ_h are the values of v, $dv/d\xi$ and ϵ at $\xi = h$. These equations can be solved to give the TM mode reflection coefficient R_{TM} in the form

$$R_{TM} = \frac{v_h \cos\theta_i + j\dfrac{v_h'}{\epsilon_h k_v}}{v_h \cos\theta_i - j\dfrac{v_h'}{\epsilon_h k_v}} \tag{33}$$

where v satisfies equation (27) with the initial condition given in equation (30).

RESULTS

This note shows that both the TE and TM mode electromagnetic wave reflection coefficients for oblique incidence on a metal-backed plasma layer, which is spatially non-uniform in the direction normal to the layer, can be found when the functional variation of the plasma properties is known. This is done by solution of a pair of ordinary second-order linear differential equations, with given initial conditions at the metal wall, over the interval defined by the thickness of the plasma layer. The differential equations are exact, hence the accuracy of the results depends only on the accuracy of the numerical solution of these equations.

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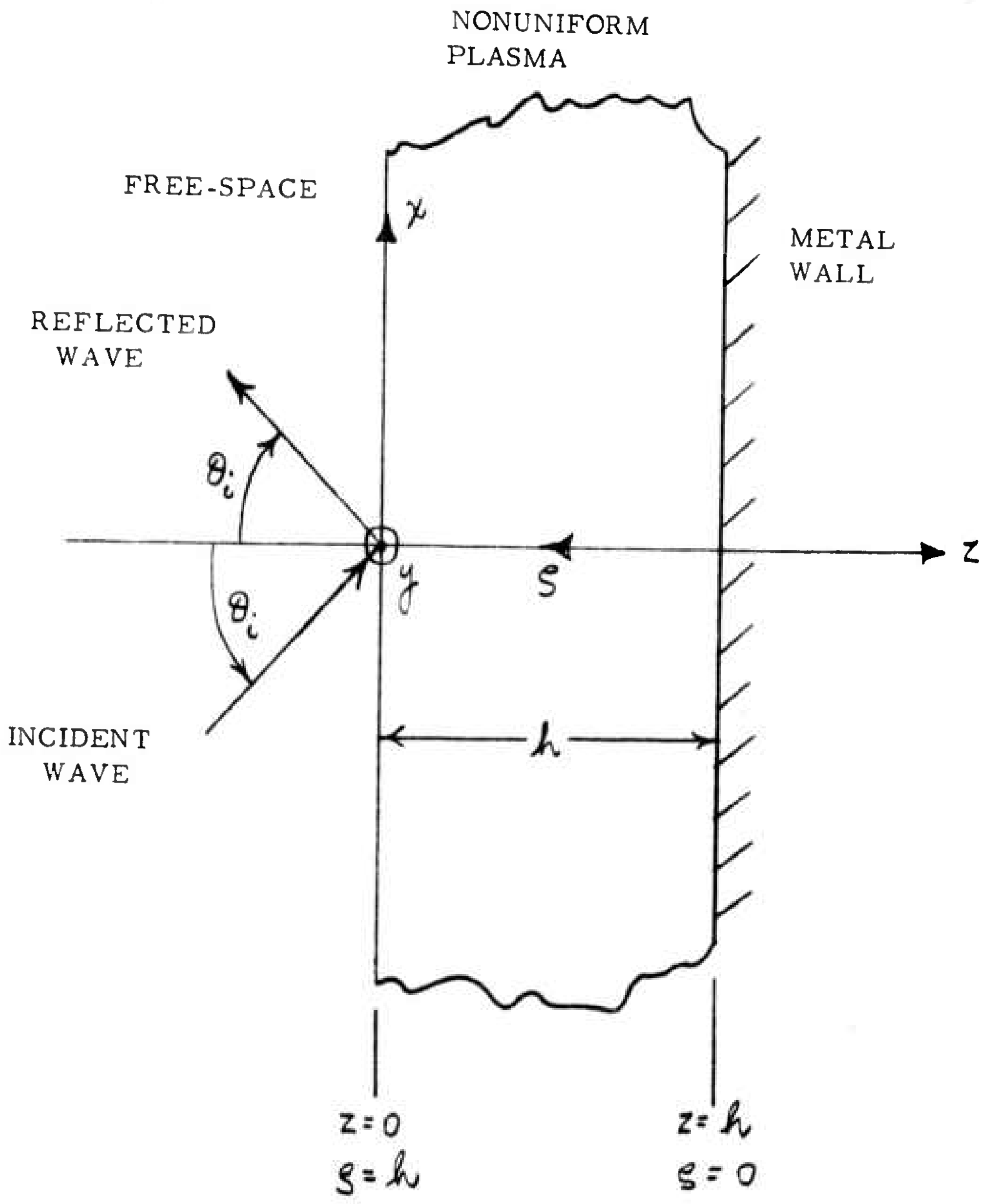

Figure 1 Geometry of the Electromagnetic Wave-Nonuniform Plasma Layer Reflection Problem

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