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THE REACTANCE OF A SYMMETRICAL PAIR OF STRIPS IN RECTANGULAR WAVEGUIDE

by
L. Lewin

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for
Air Force Cambridge Research Laboratories
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Project 4600 Task 460004
23 April 1963

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POLYTECHNIC INSTITUTE OF BROOKLYN
MICROWAVE RESEARCH INSTITUTE

ELECTROPHYSICS DEPARTMENT

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L. Lewin

Polytechnic Institute of Brooklyn
Microwave Research Institute
55 Johnson Street
Brooklyn 1, New York

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L. Lewin
Professor

Approved:

H. J. Carlin
Head, Electrophysics Department

Prepared for

Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

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ABSTRACT

An integral equation is found for the currents on a pair of symmetrical inductive strips in a rectangular waveguide, and is solved by known techniques to the quasi-static approximation. The integrals involved in the formula for the reactance presented to the waveguide are expressed in terms of elliptic integrals, and by a comparison of the result with the known result for a single inductive strip, the mutual inductance between a pair of strips in a waveguide is deduced.

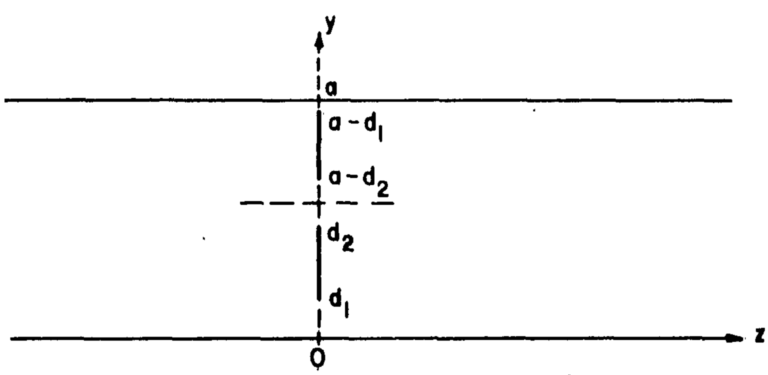
The Reactance of a Symmetrical Pair of Strips in Rectangular Waveguide

by L. Lewin

Introduction

Well-known formulae exist for the reactance produced by a single metal strip across a waveguide of rectangular cross-section. Similar formulae exist for the reactance of a diaphragm or insert from the guide walls. In the capacitive case one can be derived from the other by the method of images, and the same method will also produce a configuration consisting of a strip and diaphragm (equivalent to a pair of slits) or of two symmetrically placed strips. The method of images cannot be extended to the inductive case, and the particular arrangement of strip and diaphragm (or pair of slits) has been solved[1] using a singular integral equation approach. The present paper solves the companion problem of the reactance of a symmetrically placed pair of strips.

Geometrical Arrangement and Notation



The figure shows a waveguide of width a containing in the aperture plane $z = 0$ two strips, the first occupying the range $y = d_1$ to d_2 and the other symmetrically disposed. We refer all quantities to a time vector $\exp(j\omega t)$ and consider a wave of unit amplitude in the dominant mode incident from the left. It is polarized in the x-direction (perpendicular

[1] Lewin, L., "On the Resolution of a Class of Waveguide Discontinuity Problems by the Use of Singular Integral Equations", PGMTT, July 1961, p. 326.

to the plane of the paper) and since no distortion of the plane of polarization is involved in this problem all electric fields will be x-directed and we will concern ourselves only with this component.

The Field in the Guide

The incident field is

$$\sin(\pi y/a)\exp(-jk'z) \tag{1}$$

where $k' = 2\pi/\lambda_g$ and λ_g is the guide wavelength. This field sets up currents on the strips, which re-radiate back into the guide. If the current set up between the limits $y = \eta$ and $\eta + d\eta$ is written $I(\eta)d\eta$ then the field it produces is

$$dE = -j120\,k\,G(y,\eta)I(\eta)d(\pi\eta/a) \tag{2}$$

where the Green's function is given by

$$G(y,\eta) = \sum_{1}^{\infty} \sin(n\pi y/a)\sin(n\pi\eta/a)\exp(-\Gamma_n|z|)/\Gamma_n \quad . \tag{3}$$

Here, $k = 2\pi/\lambda$ where λ is the free-space wavelength, and the coefficients Γ_n are given by

$$\begin{aligned} \Gamma_n &= \left(n^2\pi^2/a^2 - k^2\right)^{\frac{1}{2}} \sim n\pi/a \qquad \text{for large } n \\ \Gamma_1 &= jk' \quad . \end{aligned} \tag{4}$$

The total field is obtained by integrating this from d_1 to d_2 and from $a - d_2$ to $a - d_1$. In the latter part we change variable from η to $a - \eta$, making use of the symmetry property to simplify the integral to a single range with the Green's function summed over odd order modes only. We make the following changes of variable

$$\begin{aligned} -j120\,k\,I(\eta) &= f(\pi\eta/a) \\ \pi y/a &= \theta \\ \pi\eta/a &= \phi \quad . \end{aligned} \tag{5}$$

Then the field radiated from the strip currents becomes, in the aperture plane,

$$E = 2\sum_{1}^{\infty}{}' \int f(\phi)\sin(n\theta)\sin(n\phi)d\phi/\Gamma_n \quad . \tag{6}$$

The prime indicates that the summation is over the odd integers only, whilst the integration is over a strip from $\pi d_1/a$ to $\pi d_2/a$. If to this field be added the incident field, the total must be zero over the strip. Hence we have the following integral equation for $f(\phi)$

$$0 = \sin\theta + 2\sum_{1}^{\infty}{}' \int f(\phi)\sin(n\theta)\sin(n\phi)\,d\phi/\Gamma_n \quad , \qquad \text{range of } \theta \text{ and } \phi \text{ over the strip.} \tag{7}$$

This equation can be re-written in a slightly different form, using the fact that the reflection coefficient R is the first term in (6), and the normalized reactance X is connected to R by the relation

$$-jX = \frac{1}{2}(1+R)/R \quad . \tag{8}$$

Thus,

$$(X\lambda_g/a)\sin\theta \int f(\phi)\sin(\phi)\,d\phi = \sum_{3}^{\infty}{}' \int f(\phi)\sin(n\theta)\sin(n\phi)\,d\phi\,(\pi/a\Gamma_n) \quad . \tag{9}$$

The Quasi-Static Solution

The quasi-static form is obtained by writing $\Gamma_n = n\pi/a$, $n > 1$, in (9). By the method shown in reference 1 a finite number of correction terms could be added without affecting the method. However, we shall be content here to examine the quasi-static solution only. We add and subtract the first term of the series on the right, summing it through the formula

$$\sum_{1}^{\infty}{}' \frac{\sin(n\theta)\sin(n\phi)}{n} = \frac{1}{4}\log\left|\frac{\sin\theta + \sin\phi}{\sin\theta - \sin\phi}\right| \quad . \tag{10}$$

We also make the change of notation

$$(1 + X\lambda_g/a) = W \tag{11}$$

so that (9) becomes

$$W\sin\theta \int f(\phi)\sin(\phi)\,d\phi = \frac{1}{4}\int f(\phi)\log\left|\frac{\sin\theta + \sin\phi}{\sin\theta - \sin\phi}\right|\,d\phi \quad . \tag{12}$$

In order to solve this equation for $f(\phi)$ we need to make a change of variable which transforms the range from $(\pi d_1/a)$, $(\pi d_2/a)$ to 0, π. This transformation, due to Schwinger, involves cosines; but since (12) involves sines it cannot be used directly. A differentiation is required, but since any constant contained in, or implied (via a Fourier series) in (12) goes out on differentiation, it must be expected that a return to (12) will be necessary later to fully determine the characteristics of the solution. (This is in contrast to the diaphragm problems, which can be solved in a straightforward manner from their original equations).

Differentiating (12) gives, after cancelling a factor cos θ

$$W\int f(\phi)\sin(\phi)\,d\phi = -\int \frac{f(\phi)\sin(\phi)\,d\phi}{\cos 2\phi - \cos 2\theta} \quad . \tag{13}$$

Make the substitution

$$\begin{aligned} \cos 2\phi &= \alpha + \beta x \\ \cos 2\theta &= \alpha + \beta y \end{aligned} \tag{14}$$

where x and y are new integration variables (confusion here with the coordinate variables will not arise), and α and β are chosen so that the range $\pi d_1/a$ to $\pi d_2/a$ of ϕ corresponds to 1 to -1 of x. Hence

$$\alpha + \beta = \cos(2\pi d_1/a), \quad \text{and} \quad \alpha - \beta = \cos(2\pi d_2/a) \quad . \tag{15}$$

Denoting the constant (with respect to θ) on the left of (13) by C, we get

$$C = -\frac{1}{4}\int_{-1}^{1} \sec(\phi)\, f(\phi)\, dx/(x-y) \tag{16}$$

with solution[1]

$$f(\phi) = (4C/\pi)\cos(\phi)\,(\gamma+x)(1-x^2)^{-\frac{1}{2}} \quad , \tag{17}$$

where γ is an undetermined constant. Inserting this in the expression on the left of (13) for C, we get the simple relation

$$W = -1/\beta\gamma \tag{18}$$

so that it remains only to determine γ to obtain W, and hence X from (11). Returning to (12) we find, putting $x = \cos\chi$, a new integration variable,

$$-4\pi\sin\theta = \int_0^{\pi} \frac{\beta(\gamma+\cos\chi)\,d\chi}{\left(\frac{1-\alpha-\beta\cos\chi}{2}\right)^{\frac{1}{2}}} \log\left|\frac{\sin\theta + \left(\frac{1-\alpha-\beta\cos\chi}{2}\right)^{\frac{1}{2}}}{\sin\theta - \left(\frac{1-\alpha-\beta\cos\chi}{2}\right)^{\frac{1}{2}}}\right| \tag{19}$$

and this equation, using any convenient value of θ, determines γ. A suitable value is $(\pi d_2/a)$, the largest it assumes in its range. From (15) we get

$$\sin\theta = \left(\frac{1-\alpha+\beta}{2}\right)^{\frac{1}{2}} \tag{20}$$

to be inserted into (19).

Evaluation of the Integrals

We make the substitution

$$Z = \left(\frac{1-\alpha-\beta\cos\chi}{1-\alpha+\beta}\right)^{\frac{1}{2}} \leq 1 \qquad (21)$$

and consider the expression

$$I(s) = \frac{1}{\pi}\int_0^{\pi}\frac{d\chi}{Z}\log\left|\frac{1+sZ}{1-sZ}\right| \quad . \qquad (22)$$

Then we require $I(s{=}1) = \int_0^1 I'(s)\,ds$, since $I(0) = 0$. Hence

$$I = \frac{2}{\pi}\int_0^{\pi}\int_0^1\frac{d\chi\,ds}{1-s^2Z^2} \qquad (23)$$

a form in which the χ integration can be readily carried out:

$$I = 2\int_0^1\frac{ds}{\left(1-s^2\right)^{\frac{1}{2}}\left(1-k^2s^2\right)^{\frac{1}{2}}} = 2K(k) \quad , \qquad (24)$$

where the modulus k of the elliptic function is given by

$$k = \left(\frac{1-\alpha-\beta}{1-\alpha+\beta}\right)^{\frac{1}{2}} = \frac{\sin(\pi d_1/a)}{\sin(\pi d_2/a)} \qquad (25)$$

from (15).

In a similar manner define

$$J(s) = \frac{1}{\pi}\int_0^{\pi}Z\,d\chi\,\log\left|\frac{1+sZ}{1-sZ}\right|$$

$$J(s{=}1) = \frac{2}{\pi}\int_0^{\pi}\int_0^1 d\chi\,ds\left[-1+1/(1-s^2Z^2)\right]s^{-2}$$

$$= 2\int_0^1\left[-\frac{1}{s^2} + \frac{1}{s^2\left(1-s^2\right)^{\frac{1}{2}}\left(1-k^2s^2\right)^{\frac{1}{2}}}\right]ds$$

$$= K(k) - E(k) + 1 \qquad \text{(see reference 2).} \qquad (26)$$

[2] Lewin, L., "Advanced Theory of Waveguides", Iliffe and Sons, 1951, p. 59.

Since $\beta(\gamma + \cos\chi)$ in (19) is equal to $(\beta\gamma + 1 - \alpha) - (1 - \alpha + \beta)Z^2$, the integration of (19) can now be expressed in terms of (24) and (26), and the final expression for the normalized reactance is

$$X = \frac{a}{\lambda_g}\left[-1 + \frac{K}{2E\sin^2(\pi d_2/a) - K\sin\left[\frac{\pi}{a}(d_2 + d_1)\right]\sin\left[\frac{\pi}{a}(d_2 - d_1)\right]}\right] \qquad (27)$$

$$\text{mod. } \sin(\pi d_1/a)/\sin(\pi d_2/a) \quad .$$

This is very similar in form to reference 1, Eq. (41), for the double aperture case, allowing for the different notation and complementary modulus. However, it does not seem possible to deduce one from the other; Babinet's principle does not appear to be applicable since the plane of polarization is not rotated.

It is readily confirmed that (27) reduces to the usual form for $d_2 = a/2$, a symmetrically placed single strip, and for $d_1 = 0$, a symmetrical inductive diaphragm.

From a comparison of equation (27), representing the reactance of a pair of strips, with equation (3.106) of reference (2), representing the reactance of a single unsymmetrical strip, an expression can be found representing the mutual reactance of a pair of strips symmetrically placed in a waveguide. In the limit of very small strip width the mutual reactance x_{12} to be added to the reactance of each strip is given by

$$x_{12} = \frac{a}{\lambda_g}\left\{-1 + \frac{1}{2}\operatorname{cosec}^2(\pi d/a)\log\sec(\pi d/a)\right\} \qquad (28)$$

where d is the displacement of a strip from the side wall. This formula is not valid when d is of the order of the strip width.

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Morningside Heights, New York, N.Y.
Attn: Dr. Schlesinger

University of Southern California, Engineering Center
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Los Angeles 7, California
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Attn: Dr. T. Pavlasek

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Electrical Engineering

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Institute of Cooperative Research
3400 Walnut Street, Philadelphia, Pa.
Attn: Department of Electrical Engineering

Polytechnic Institute of Brooklyn
Microwave Research Institute
55 Johnson Street, Brooklyn, New York
Attn: Dr. Arthur A. Oliner

Polytechnic Institute of Brooklyn
Microwave Research Institute
55 Johnson Street
Brooklyn, New York
Attn: Mr. A.E. Laemmel

The Pennsylvania State University
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Ferris Hall
W. Cumberland Avenue
Knoxville 16, Tennessee

The University of Texas
Electrical Engineering Research Lab.
P.O. Box 8026, University Station
Austin 12, Texas
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