MODAL ANALYSIS OF A COAXIAL TRAVELLING-WAVE SLOT ARRAY WITH INTERIOR PROBES

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ABSTRACT

A modal analysis, accounting for interior, slot, and exterior regions of a slotted coaxial waveguide, is modified to include interior conducting probes, which perturb the incident TEM field that excites the modal analysis.

INTRODUCTION

The travelling-wave antenna represents an elegant solution to the problem of exciting the elements of a linear array, and among such antennas the waveguide slot array benefits from low loss, a high degree of control of excitation, strength, and ease of manufacture. It has therefore been studied and used extensively [1, 2]. Slot arrays on coaxial cylindrical waveguides are commonly used for UHF and VHF broadcasting, for which the footprint is typically wide in azimuth, narrow in elevation, and somewhat depressed from the horizon [3]. The coaxial design allows a robust construction suitable for harsh environments found at many elevated broadcast locations. Due to the dominant TEM propagation inside the waveguide, slots spaced along the guide just under a wavelength apart will produce a beam at the desired elevation. These slots may be axial, circumferential, or tilted. Axial slots, which generate a horizontally polarised field, have only a small effect on the TEM guided wave. To achieve excitation in this case, the slots may be slightly tilted or a metal probe that protrudes into the waveguide may be placed near each slot to disturb the interior field. Fig. 1 shows an array of axial slots on a coaxial cylindrical waveguide and an interior probe beside a slot aperture.

Significant issues in designing such antennas are the degree of mutual coupling between slots, via either the exterior or the interior region of the coaxial waveguide, and the relationship between a probe's geometry and the excitation of the slot adjacent to it. The length and symmetry of the antenna suggest that a modal analysis would be an efficient solution, if it were not for the probes that break the symmetry of the interior region of the waveguide. In this paper we describe a technique for overcoming this problem that allows analysis of an array where the slots are arbitrarily located on the cylinder surface. We achieve a unified solution to the interior and exterior regions, including the effects of mutual coupling and quantifying the effect of the probes.

THE EXTERIOR REGION

Mutual coupling between apertures in a cylindrical surface has been dealt with previously in the context of conformal arrays [4, 5] and we adopt the same approach. Exterior fields are represented by outgoing cylindrical waves and slot apertures by magnetic surface currents. Enforcing boundary conditions leads to a general field solution that may be written as a dyadic relationship between the surface magnetic fields at different positions on the cylinder. Assuming TE_{10} modes in the slot apertures, the mutual admittance between two slots is derived by integration over the apertures, and the resulting infinite series and spectral integral may be evaluated numerically. The assumption of TE_{10} modes is a reasonable one for narrow slots. If greater accuracy is desired, the formulation may be extended in a straight-forward manner to include higher-order modes in the slots.

Cylindrical slot arrays used for UHF and VHF broadcasting have a small radius, typically 0.25 wavelengths, and in this circumstance the series converges rapidly. An acceleration technique due to Duncan [6] is used to transform the series whenever possible. However, when two slots are closely spaced along the cylinder the transformed series does not converge, and the original one is used. An asymptotic solution for large radii has been developed and its accuracy proven by comparison with other solutions in the literature [4]. We have found that this solution has acceptable accuracy for cylinder radii as small as 0.25 wavelengths. Slots that are widely spaced along the cylinder are joined by a geodesic curve with a large radius of curvature, and the asymptotic solution may sometimes offer an advantage in speed for such cases.

THE INTERIOR REGION

Fields in the interior region of the coaxial waveguide may be separated into TE and TM components. By enforcing the boundary condition on the surface of the inner conductor, assumed to be perfectly conducting, we obtain a field representation similar in form to that used for the exterior region. The slots that join the interior and exterior regions must also be considered. We consider these to be short lengths of rectangular waveguide, with length equal to the thickness of the outer coaxial conductor, and we assume that standard rectangular modes propagate in both directions. Although the curvature of the outer conductor will perturb these modes, this effect will be small when the slots are narrow and the conductor is thin in comparison to its radius. Again, our implementation is restricted to TE_{10} modes inside the slots.

Enforcing electric-field boundary conditions on the inner surface of the outer conductor, we obtain expressions for the interior field in terms of unknown amplitudes of the out-going and in-going slot modes. Enforcing magnetic-field boundary conditions on the interior slot apertures, we find that the coefficients of the unknown amplitudes may be interpreted as interior mutual admittances. They may be evaluated numerically using similar techniques to those for the exterior case. Finally, including the influence of the exterior mutual admittances yields a system of linear equations that may be solved to obtain the amplitudes of the slot modes, given a suitable excitation. Once the aperture fields produced by the slot modes are known, we may calculate the radiation pattern.

This formulation is similar in many respects to others in the literature that use circumferential slots [7, 8]. We determine the excitation by considering the probes.

INCLUDING INTERIOR PROBES

The input to the antenna is the fundamental TEM mode supported by the coaxial waveguide. Since the TEM mode has only an azimuthal component of the magnetic field, the electric current induced on the inner surface of the outer conductor is in the axial direction, and is not interrupted by the axial slots. Thus, no fields from the waveguide get coupled into these slots. If, for mechanical simplicity, the slots are to remain axial, an axial component of the magnetic field is needed in the interior region of the waveguide. The probes achieve this purpose. With the fundamental TEM mode incident, the presence of the probes will generate higher-order TE and TM modes, resulting in an axial component of the magnetic field in the interior region. The amplitudes of these higher order modes as well as those of the surface currents induced on the probes are determined by imposing the boundary condition that the tangential electric field is zero on the surface of each of the probes.

To obtain an expression for the axial magnetic field in the interior region, we initially disregard the presence of the slots, and assume the probes to be located inside a regular coaxial waveguide. The probes are assumed to be flat metal strips that may have an arbitrary tilt with respect to the radial direction. A square-root basis function for the induced surface current on the probe surfaces allows the boundary conditions to be satisfied with sufficient accuracy. A linear system of equations may be solved to obtain the unknown current amplitudes from the incident TEM amplitude, after which the axial magnetic fields beside the interior slot apertures may be calculated to provide the excitation term required in the previous section. We have found that the reaction of the slot fields on the probe currents is negligible, so we are justified in disregarding the presence of the slots when calculating these currents.

CONCLUSION

We have formulated and implemented a modal analysis for slot arrays on coaxial cylindrical waveguides, frequently used for UHF and VHF broadcast applications. The analysis includes the interior, exterior, and slot regions of the antenna, and incorporates the effects of both interior and exterior mutual coupling between slots. Slots are permitted to have an adjacent probe that protrudes into the waveguide, providing excitation of otherwise non-radiating axial slots. The behaviour of the interior field in the region of the probes gives an insightful view of the operation of the antenna, as illustrated in Fig. 2. We find the calculated radiation pattern for a typical broadcast antenna, shown in Fig. 3, to be consistent with the catalogue pattern for this design, which was obtained by experiment.

REFERENCES

[1] R S Elliott, “An improved design procedure for small arrays of shunt slots,” *IEEE Trans. Antennas Propagat.*, vol. 31, no. 1, pp. 48-53, January 1983.

[2] A J Sangster and A H I McCormick, “Theoretical design/synthesis of slotted waveguide arrays,” *IEE Proc. Pt. H*, vol. 136, no. 1, pp. 39-46, February 1989.

[3] D Casciola, G L Miers, and R A Surette, “UHF antenna choices,” IEEE *Transactions on Broadcasting*, vol. 45, no. 1, pp. 93-105, March 1999.

[4] T S Bird, “Comparison of asymptotic solutions for the surface field excited by a magnetic dipole on a cylinder,” *IEEE Trans. Antennas Propagat.*, vol. 32, no. 11, pp. 1237-1244, November 1984.

[5] T S Bird, “Accurate asymptotic solution for the surface field due to apertures in a conducting cylinder,” *IEEE Trans. Antennas Propagat.*, vol. 33, no. 10, pp. 1108-1117, October 1985 (with corrections in vol. 36, no. 8, p. 1195, August 1988).

[6] R H Duncan, “Theory of the infinite cylindrical antenna including the feed point singularity in antenna current,” *J. Res. Nat. Bur. Std.*, vol. 66D, pp. 181-188, 1962.

[7] C-W Lee and S H Son, “Radiation characteristics of dielectric-coated coaxial waveguide periodic slot with finite and zero thickness,” *IEEE Trans. Antennas Propagat.*, vol. 47, no. 1, pp. 16-25, January 1999.

[8] J K Park and H J Eom, “Radiation from multiple circumferential slots on a conducting circular cylinder,” *IEEE Trans. Antennas Propagat.*, vol. 47, no. 2, pp. 287-292, February 1999.

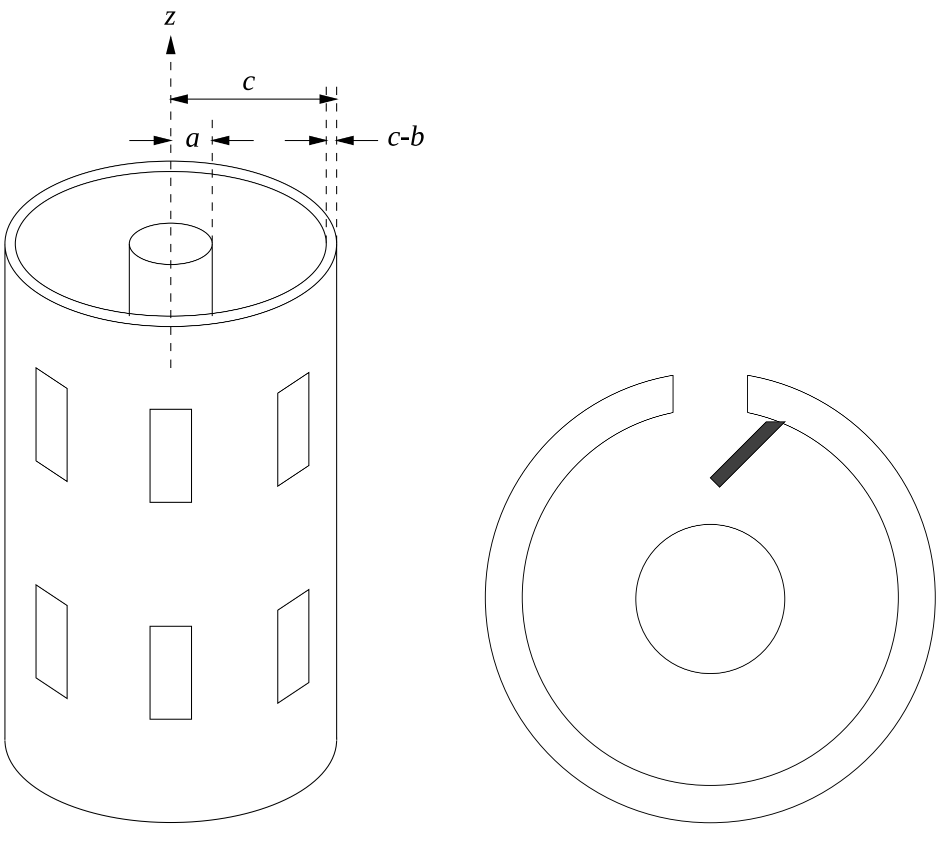

Fig. 1. A coaxial cylindrical waveguide, with interior radii a and b, supporting an array of axial slots cut into the outer conductor, which has thickness $c - b$. On the right is a cross-section of the cylinder showing an interior conducting probe beside a slot aperture.

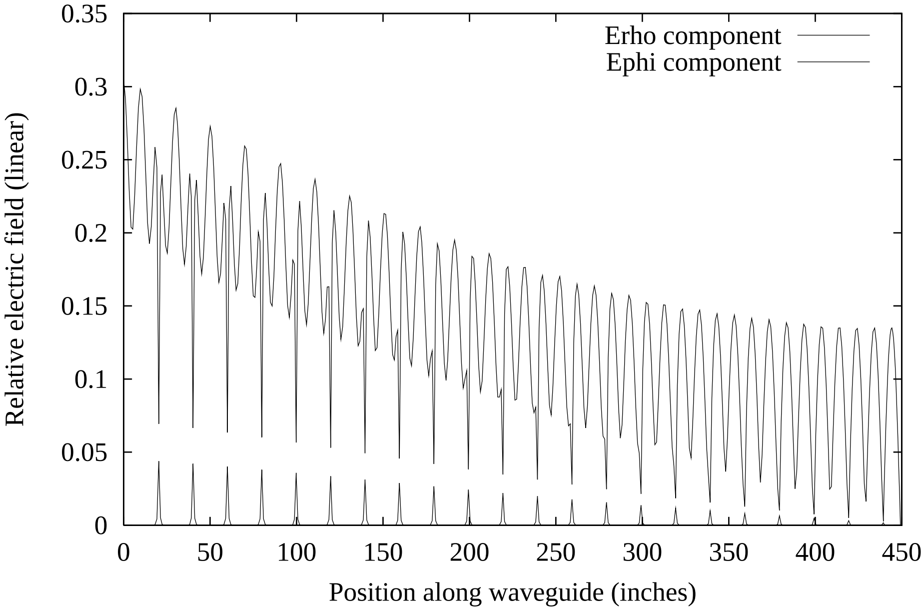

Fig. 2. Calculated interior fields for an example array of axial slots on a coaxial cylindrical waveguide. The radial field component E_{rho} is graphed along a line that intersects the probes beside one column of apertures, showing the decaying standing wave in the waveguide. The standing wave is interrupted by sharp nulls at each probe, as demanded by the boundary condition on the conducting probes. High-order modes generated in satisfying this condition contain an azimuthal field component E_{phi}, also graphed here along a line through the aperture centres. This component excites radiating aperture fields.

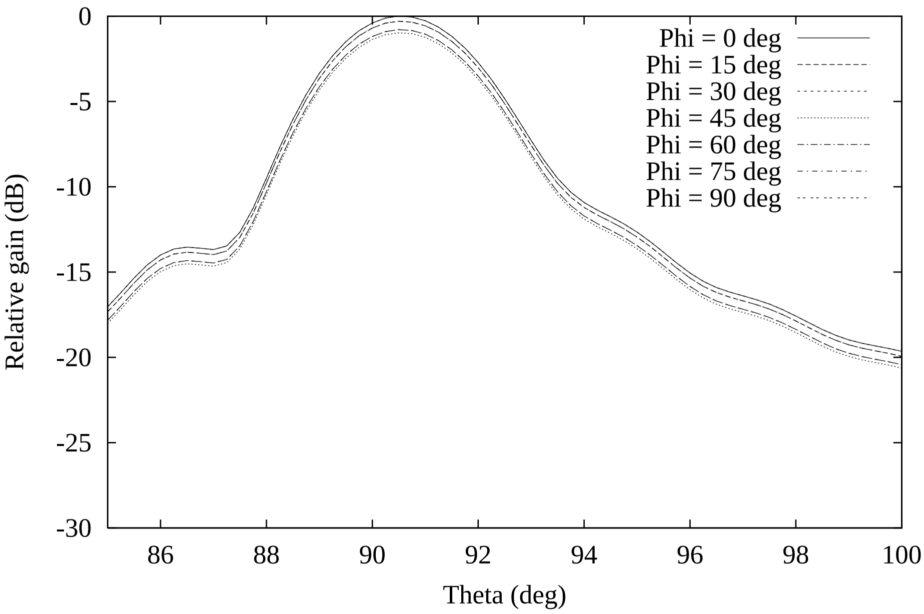

Fig. 3. Calculated radiation pattern cuts in the elevation direction for the same example array. The array comprises four columns of 22 slots on a cylinder of radius 0.25 wavelengths, and the pattern is almost isotropic in azimuth (phi).