Some Experiences in using NEC2 to Simulate Radiation from Slots on Cylinders

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ABSTRACT

A numerical method based on use of the NEC2 code has been used to study radiation from a slot in the surface of a conducting cylinder and the results used in a comparison with the eigenfunction series solution. The two cases of an axial and circumferential slot have been taken as representative between them of the more general case of an inclined slot. In the case of a circumferential slot, truncation of the cylinder to finite length has been found in all cases to lead to numerical and analytic results which are in poor agreement and this has been accounted for with an argument based on the geometrical theory of diffraction. However this alone is not enough to explain what is observed with axial slots where, for small cylinders, agreement of the two approaches is good but fails for larger cylinders. It is postulated that this is due to excitation of waveguide modes on the inside of the larger cylinders and the result confirmed by closing the ends of the cylinder in the NEC2 model with a system of radial wires, when agreement is again restored.

1. INTRODUCTION

Analytical studies of radiation from slots in infinite conducting cylinders have been made by a number of authors[1], [2], [3], [4], [5]. However, when as must necessarily be the case in practice, the cylinder in which the slot is cut is of finite length, to find the radiation pattern, resort has to be made to either numerical methods or some approximate technique of which, for a sufficiently large cylinder, the geometric theory of diffraction might be an example.

This paper presents some experiences with a numerical means of determining the radiation pattern of a narrow slot cut in the (assumed infinitesimally thin) wall of a hollow, perfectly conducting, finite, circular cylinder. The application which we have in mind is personal satellite wireless mobile communications and our interest will be with narrow slots, the length of which are no more than comparable with the half wavelength (resonant or near resonant slots).

The paper is arranged as follows. Section 2 reproduces the eigenfunction expansion of the electric field radiated by an arbitrarily oriented slot cut in an infinite cylinder. Next the radiation pattern of a slot cut in an otherwise similar finite cylinder is generated using the NEC2 package and compared with the eigenfunction solution and in the following section there is a discussion of the notable points of difference and the reasons for them. The paper concludes with a summary of its findings.

2. AN ARBITRARILY ORIENTED SLOT ON AN INFINITE CYLINDER

When the cylinder is of infinite length, an analytical solution for radiation from an arbitrarily oriented slot is possible in terms of cylindrical wave functions and has been known for a considerable time [4]. Figure 1 shows a coordinate system in terms of which it is convenient to write down the eigenfunction series expansion. The centre of the slot lies in the XOZ coordinate plane with OX passing through its centre, which is at $(a,0,0)$, a being the radius of the cylinder. The slot is excited by a voltage V applied across it.

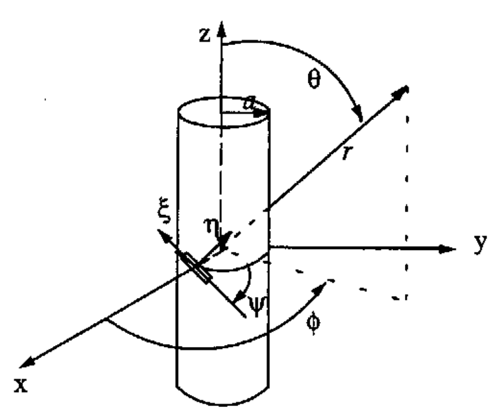


Figure 1 Geometrical parameters

With respect to local coordinates (η, ξ) drawn along the centrelines of the slot, it is assumed that its electric field distribution is oriented parallel to the η direction, in which it is also uniform, while in ξ it is sinusoidal. For this configuration, the series solutions for the two spherical components of the radiation field are

$$E_\theta = \frac{-V_0 \cos\psi e^{-jkr}}{2\pi^2 r \sin\theta} \sum_{n=-\infty}^{\infty} \frac{j^{n+1} e^{-jn\phi} I_n P_n}{H_n^{(2)}(ka \sin\theta)} \quad (1)$$

$$E_\phi = \frac{V_0 e^{-jkr}}{2\pi^2 r} \sum_{n=-\infty}^{\infty} \frac{j^n e^{-jn\phi} I_n P_n}{H_n^{(2)\prime}(ka \sin\theta)} \times \left[-\sin\psi + \frac{n \cos\psi \cos\theta}{ka \sin^2\theta} \right] \quad (2)$$

where

$$I_n = \frac{\frac{2\pi a}{l} \cos\frac{K_n l}{2a}}{\left(\frac{\pi a}{l}\right)^2 - K_n^2}$$

$$P_n = \frac{\sin\left(\frac{(ka\cos\psi\cos\theta - n\sin\psi)w}{2a}\right)}{\left(\frac{(ka\cos\psi\cos\theta - n\sin\psi)w}{2a}\right)}$$

$$K_n = ka \sin\psi \cos\theta + n\cos\psi$$

ψ is the inclination angle, l is the slot length, w is the slot width and k is the free space wavenumber.

Getting to the essentials of the problem is best facilitated by considering the two special cases $\psi = 0$ and $\psi = 90$, when the slot is respectively circumferential and axial. Calculations for the radiation pattern in the $\theta = 90$ plane (the XOY plane) for these two cases are shown in Figures 2, 3 and 4.

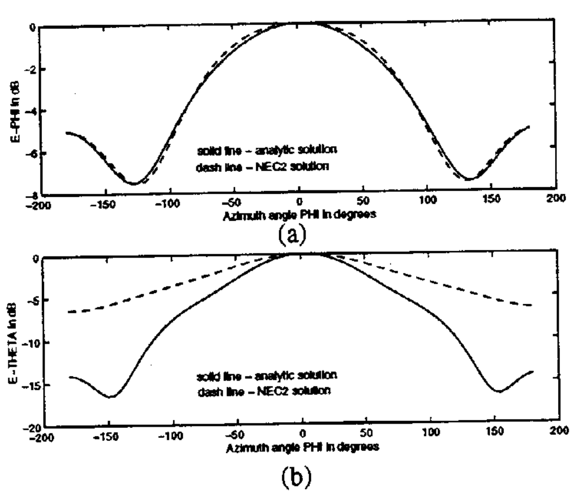


Figure 2. Comparison of normalised far–field pattern in the θ=90° plane obtained using an analytic solution and NEC2 for f=2GHz, ka=0.8, w=0.05λ, L=λ and (a) an axial with l=0.5λ and (b) a circumferential slot with 0.3λ.

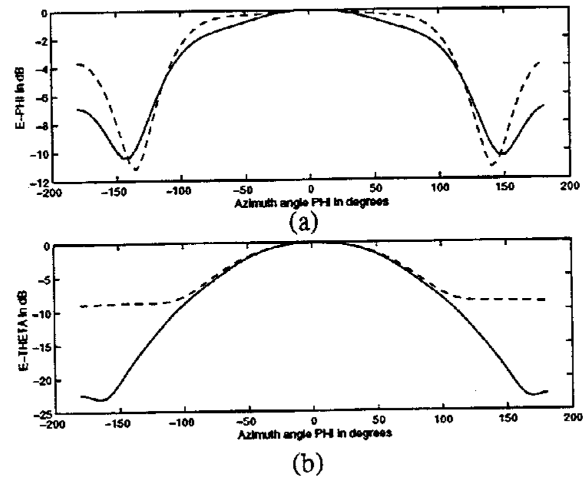


Figure 3. Comparison of normalised far–field pattern in the θ=90° plane obtained using an analytic solution and NEC2 for f=2GHz, ka=1.5, w=0.05λ, L=λ and (a) an axial with l=0.5λ and (b) a circumferential slot with l=0.3λ.

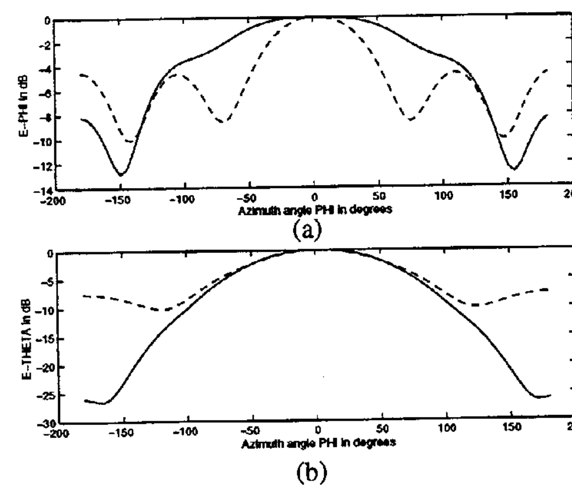


Figure 4. Comparison of normalised far–field pattern in the θ=90° plane obtained using an analytic solution and NEC2 for f=2GHz, ka=2, w=0.05λ, L=λ and l=0.5λ for (a) an axial and (b) a circumferential slot respectively.

3. NUMERICAL SOLUTION OF THE FINITE CYLINDER

The NEC2 package has been used to solve the same problems for a finite cylinder. NEC2 uses a wire grid approximation for the cylinder which, when cut and unfolded into a developed view, is the simple rectangular mesh shown in Figure 5. In modelling the axial slot, the spacing between the vertical wires is chosen to be the desired slot width. The same is done for the horizontal wires in the case of the circumferential slot.

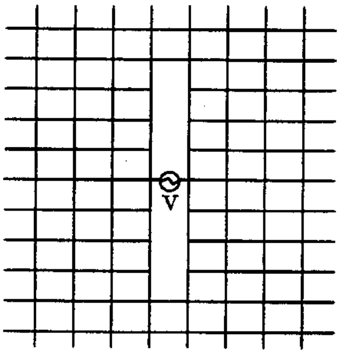


Figure 5. NEC2 Wire Grid Model

Three different cylinder sizes were considered for each slot orientation. These were $ka = 0.8$, 1.5 and 2.0. In each case the cylinder length was chosen as one wavelength. Figures 2, 3 and 4 superimpose the normalised (for each pattern, to its own maximum) NEC–derived and analytic solutions. The choice to compare normalised patterns was made as it renders differences between the two most easily apparent. However, it is to be remarked that where there is strong agreement, as in Figures 2a and 3a for example, at maximum, there is less than 0.5 dB displacement between the two absolute patterns. Not surprisingly, where the correlation is poor, as in Figures 2b and 3b, differences between maxima of up to 3 dB are in evidence. It is interesting to compare the normalised patterns to seek reasons for observed discrepancies.

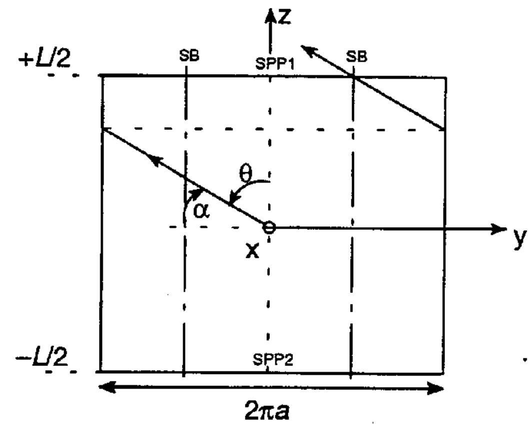
4. DISCUSSION

The geometric theory of diffraction [6] provides a good paradigm in which to look for the answers. Especially for the $ka = 0.8$ case, the cylinders which we have chosen would lie at the lower end of the range for which this theory can be expected to give accurate answers but, at least for the purposes of qualitative reasoning, that is not of great account.

In addition to direct radiation from the slot, on the surface of the cylinder it will also give rise to a family of creeping waves which will travel over helical paths (straight lines on a developed view), shedding tangential rays as they progress. Thus, for example, contributions to the radiation in the XOZ plane will emanate from the shadow boundaries formed by the lines of intersection of the plane YOZ with the cylinder.

When the cylinder is of finite length, these helical paths will eventually intersect with its open ends, when two things will occur.

One is that creeping rays which would have reached the far field point by being shed from parts of the cylinder now removed by truncation can no longer do so. So far as radiation in XOZ is concerned, looking at the developed view of the cylinder shown in Figure 6, we see that creeping waves which reach the shadow boundary by making the minimum transit of three quarters of a turn around the cylinder – and these, rather than the more frequently encircling creeping waves which will also be present, are those which make the major contribution to the radiation field – can only be present in $90-\alpha < \theta < 90+\alpha$, where $\alpha = \operatorname{atan}\left(\frac{L}{(3\pi a)}\right)$, the neighbourhood of the XOY plane. More of these creeping waves will be included by using a longer cylinder.



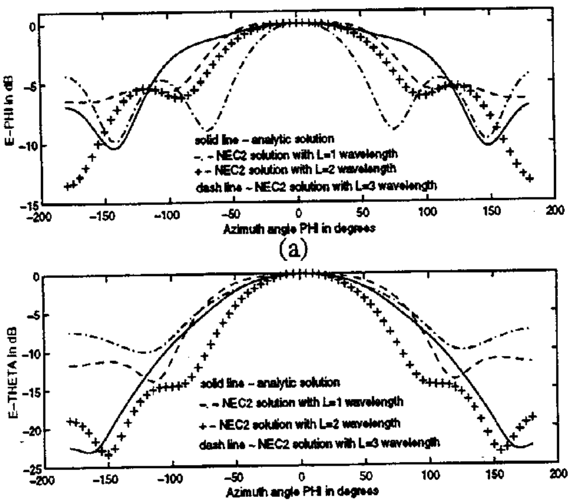
notes: SB refers to shadow boundary
SPP1 and SPP2 are the stationary phase points

Figure 6. Developed view of the slotted cylinder

The other effect is that there will be an edge diffraction contribution from the open ends of the cylinder, the dominant part of which will come from certain stationary phase points which can be located by use of Fermat's principle [6]. For radiation into the positive XOZ half plane ($\phi = 0°$) these will be the points of intersection of that half plane with the ends of the cylinder, immediately above and below the slot. For other values of ϕ in $\theta = 90°$, the stationary phase points will move circumferentially around the top and bottom edges of the cylinder in sympathy with ϕ (but through an angle which depends on the length of the cylinder and which is always less than ϕ).

The degree to which these perturbations can be expected to bring about significant deviation from the infinite cylinder result will vary markedly in the case of an axial as against a circumferential slot. The reason for this is not hard to see. In both cases the slot will behave like a magnetic dipole lain on the surface of the cylinder and the source pattern of a dipole is maximum transverse to its axis and zero along its length. In the case of an axial slot, this means that not only are the stationary phase points weakly illuminated, the more so for longer cylinders and indeed not at all for $\phi = 0°$, but the part of the family of creeping waves which is truncated off, being launched at angles closer to the dipole axis, is also weaker. With the circumferential slot, exactly the opposite is true.

Figure 7 shows the effect of increasing cylinder length for the case of $ka = 2.0$. In the light of the above it is no mystery that there is poor agreement between the eigenfunction series and the NEC2 solution in the case of a circumferential slot.



(b)

Figure 7. Comparison of normalised far–field pattern in the θ=90° plane obtained using an analytic solution and NEC2 for f=2GHz, ka=2, w=0.05λ, l=0.5λ and L=1λ, 2λ and 3λ for (a) an axial and (b) a circumferential slot.

The problem, however, is still not entirely solved for the axial slot. It is only with the smallest diameter cylinders that good agreement is obtained. As the cylinder becomes larger, there must be an expectation that both the slot directly and edge diffraction at the ends will excite propagating waveguide modes inside it. Power coupled into these modes will be conveyed without attenuation to the open ends of the cylinder, from where it will be radiated to interfere with the fields produced by the various mechanisms already identified. When this has the possibility of happening can be determined by looking at the cutoffs of the modes in cylindrical waveguide [7].

The TE11 mode has the lowest cutoff at $k_c a = 1.841$ and there is no other mode, TE or TM, which has a cutoff below $k_c a = 2.405$. In the case of the $ka = 0.8$ cylinder, we are therefore well away from any possibility of a waveguide mode being present to upset the agreement between the eigenfunction and NEC2 solutions. The opposite, of course, is true with $ka = 2.0$ and is held to explain the disagreement. The $ka = 1.5$ case is more interesting. Taken at face value, the evidence is that the cylinder is below waveguide cutoff, when there should be no problem. However, it is close enough to cutoff that, with a relatively short cylinder, evanescent fields will still reach the open ends of the cylinder, probably in sufficient strength to account for some of the minor discrepancies seen in Figure 3a.

A way of testing these conclusions is to repeat the NEC2 solution with a closed ended cylinder, modelled in this case by a system of radial wires across each end. This will leave nearly everything else in the problem intact (save that diffraction at the ends is now from a right angle wedge rather than a half plane) while eliminating any contribution from waveguide modes. Figure 8a makes the point; directly any possibility of a waveguide contribution is removed, agreement in the axial case between the eigenfunction and NEC2 solutions is much improved.

None of this, of course, is to say that, in the case of the circumferential slot, waveguide modes will not exist or also have the possibility of contributing to discrepancies between the eigenfunction and numerical solutions, but it is to say that in this instance, complete salvation is not to be had simply by their removal. As Figure 8b shows, while the situation is ameliorated, large discrepancies remain.

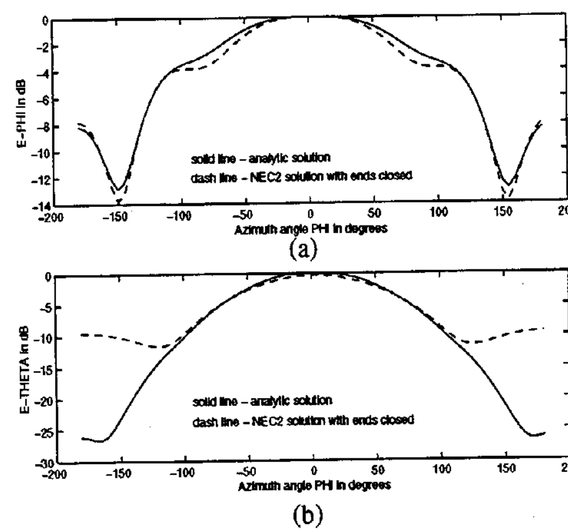


Figure 8. Comparison of normalised far–field pattern in the θ=90° plane obtained using an analytic solution and NEC2 for f=2GHz, ka=2, w=0.05λ, l=0.5λ and L=1λ for (a) an axial and (b) a circumferential slot.

5. CONCLUSION

A wire grid model based on the NEC2 code has been developed with which to simulate radiation from near resonant slots cut in the surface of a finite length conducting cylinder and the results compared with those obtained from an associated analytic solution which assumes an infinitely long cylinder. Discrepancies between the two have been explained using an argument based on the geometrical theory of diffraction which lends credibility to the numerical solution and confirms its usefulness for the study of radiation from arbitrarily oriented slots, which are believed to have potential application in the area of personal mobile satellite wireless communications.

An interesting intervention in the final result from waveguide modes propagating within the cylinder but not intended to be part of the model has also been observed. This serves to emphasise a need constantly to be on guard to ensure that a model is chosen which simulates only the problem of interest and nothing more. This observation may also make some contribution to comment which has appeared in NEC user–group e–mail discussions (NEC–LIST) on the apparent inability of NEC2 based solutions to match those obtained analytically for larger diameter cylinders.

6. ACKNOWLEDGMENT

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