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SCATTERING OF AN ELECTROMAGNETIC PULSE BY RECTANGULAR APERTURES IN SHIELDED ENCLOSURES

by

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ABSTRACT

The problem of scattering of EMP by apertures is investigated both from an experimental and analytical approach. The specific geometry selected is that of a rectangular aperture in a structure which is large compared to the dimensions of the aperture. The incident EMP is normal to the plane of the aperture with its electric field vector polarized perpendicular to the length of the aperture. Measurements of the scattered field inside the structure were made at many points for various sizes of apertures ranging from 1 m to 2.4 m in length and 1.5 mm to 15 cm in width. Computations of the scattered field were based on the theory of scattering of the field by a rectangular aperture in an infinite plane. Comparison of theory and experiment shows good agreement for the geometries considered.

scattering, apertures, rectangular apertures

I. INTRODUCTION

In recent years a major effort has been made to perform vulnerability and hardening analyses on military systems with respect to an incident electromagnetic pulse (EMP). One of the problems which must be considered as part of such an analysis is the penetration of EMP through apertures in shielded enclosures. An understanding of this problem is required to permit an analysis of coupling of the electromagnetic fields with system components within these enclosures.

Exact solutions to the problem of scattering by apertures are restricted to a few cases where the aperture is located in an infinite planar conducting surface and is of a simple geometric shape. Often, when a formal solution is known, mathematical approximations must be used which restrict the solution to specific ranges of frequencies. For example, when the dimensions of the aperture are large compared to the wave-length of the incident electromagnetic wave, the well known Kirchoff approximation greatly simplifies the solution. For the other extreme (dimensions small compared to the wavelength) the Rayleigh approximation is applicable.

The frequency content of the EMP considered here is in the range of 1 to 100 MHz. For most types of aperture problems encountered, this range of frequencies is too low for the Kirchoff approximation. Except for very small apertures, the Rayleigh approximation is also inadequate. Since these approximations do not apply for the case of scattering of EMP by apertures, one must consider the solutions for specific geometries of the aperture.

An exact theoretical analysis of diffraction of a scalar plane wave by a circular aperture in an infinite plane screen has been presented by Bowkamp[1]. Levine and Schwinger[2] formulated a variational attack to the problem of scalar diffraction through a plane screen and applied the method to the case of a circular aperture. A comparison to the exact calculation for this case showed that the variational calculation gives good results over the entire frequency range.

Previous work done on the penetration of EMP through apertures included the investigation of the problem for specific geometries[3,4,5,6,7,8,9]. The case examined in the present study is that of diffraction by a rectangular aperture in a structure. Suzuki[10] applied the variational method for a rectangular aperture in an infinite plane to compute the transmission coefficient. He also derived an approximate expression for the transmission coefficient for a long and narrow slot and was able to show excellent agreement with calculations using the variational method. The experimental methods and theoretical analysis described here will show how Suzuki's analysis can be applied to estimate the EMP within a structure resulting from penetrations through rectangular apertures.

II. EXPERIMENTAL APPROACH

Since a general solution for the fields inside a shielded enclosure with apertures does not exist, some simplifying assumptions must be made to permit the design of a meaningful experiment. We will consider the problem of a large shielded structure with a single rectangular aperture at the center of one of the faces of the structure. Our basic assumption will be that for structures large compared to the size of the aperture, the electromagnetic field at any point inside will be approximately the same as that resulting from an aperture in an infinite plane, modified by reflections of this field from the walls of the structure. We can test the extent of the validity of this assumption by comparing experimental measurements of the field at several points to calculations based on this assumption.

III. EXPERIMENTAL METHOD

The incident and scattered transient electromagnetic fields were measured using a field measurement box described by Vance[11]. This field measurement box is basically a shielded box 1 m on each side with the field sensors located on three faces of the box. The instrumentation consisting of a 454 Tektronix oscilloscope with the associated C-40 camera and P6047 voltage probe, battery and inverter is contained inside the box. The electric field sensors are capacitive top loaded short dipole antennas with response as measured by a voltage probe.

If the field measurement box is close to a conducting surface, the electromagnetic field will be distorted. To minimize this effect and for the reasons discussed in Part II, the dimensions of the structure used in the experiment were made much larger than those of the field measurement box. To reduce the effect of reflections of the scattered EMP by the inside walls of the structure, the side and top walls were oriented at an angle of 45° with respect to the plane of the incident wave. With this construction and with the field measurement box nearest to the slot, the reflected part of the field arrived at the measurement point much later than the initial part of the transmitted pulse. Because of the 1/R dependence of the scattered field, the amplitude of this late time portion of the waveshape was negligible compared to that of the initial part. Figure 1 shows the details of the structure and aperture configuration.

The orientation of the slot was chosen to produce maximum scattering of the incident EMP. From Babinet's principle, this requires that the slot be oriented so that the electric field vector of the incident pulse be perpendicular to the length of the slot. As will be described shortly, the incident EMP for this test had the electric field vector horizontally polarized and required a vertical slot for a maximum response.

The EMP for this test was generated by the Biconic simulator located at the Woodbridge Research Facility of Harry Diamond Laboratories. The simulator is basically a large dipole radiating antenna oriented parallel to ground. The far field from this antenna is polarized with the electric field vector parallel to the antenna. The net field at any point is given by the vector sum of the field from the antenna and of the ground reflection. At points far from the antenna, the earth behaves nearly as a perfect reflector for the EMP. The net field waveshape at these points is a very narrow pulse with a width and amplitude related to the time delay between the incident and reflected electromagnetic fields.

The test site was approximately 1600 feet from the radiating antenna, satisfying the far field condition. Measurements of the net horizontal electric field component of the EMP were made at several heights above the ground plane. These points were chosen to include the area over which the slots were to be positioned. The structure shown in Figure 1 was oriented facing the radiating antenna. The framework for the structure was made of 14 foot sections of 2" x 2" lumber. The front face of the structure was covered with aluminum window screen and the area around the slot was made of 30 gauge (15 mil.) aluminum sheet metal, which could be adjusted to construct a range of slot dimensions. The side, top and rear faces of the structure were covered with a light-weight, wire-mesh fence material.

Measurements of the transient electromagnetic field at points inside the structure were made for several different slot sizes. A summary of the various slot dimensions and positions of the field measurement box is shown in Table I. In all cases the slots were centered on the front face of the structure at 7 feet above ground.

TABLE I

Slot Dimensions and Locations of Test Points

SLOT DIMENSIONS		TEST POINT LOCATIONS	
LENGTH (m)	WIDTH (cm)	PERPENDICULAR DISTANCE FROM PLANE OF SLOT (m)	HEIGHT ABOVE GROUND PLANE (ft)
1	10	1	2, 3, 5, 7, 9, 11
1.5	5, 10, 15	1	2, 3, 5, 7, 9, 11
2	10		2, 3, 5, 7, 9, 11
2.4	10	1	2, 3, 5, 7, 9, 11
2.4	0.15, 10	2	2, 3, 5, 7, 9, 11

All measurements were made in a vertical plane passing through the slot perpendicular to the front face of the structure. It will be shown in the following section that for the geometry considered, the electric field component parallel to both the plane of the slot and the ground plane is the dominant component hence this was the only component measured.

IV. ANALYTICAL METHOD

Consider the case of an infinite plane conducting screen of infinitesimal thickness, containing a rectangular aperture of area A. Figure 2 shows a rectangular coordinate system with the origin at the center of the aperture and the screen in the x-y plane. If a plane wave is incident on the aperture in the half-space z<o, Suzuki[11] shows that the field components can be written in terms of Hertzian vectors Π^* of the magnetic type. For the case of the slot oriented as shown in Figure 2, the solutions for the electric field components are as follows:

$$E_x = jk\eta_o \frac{\partial \Pi_y^*}{\partial z}$$

$$E_y = 0 \qquad (1)$$

$$E_z = -jk\eta_o \frac{\partial \Pi_y^*}{\partial z}$$

where

$$\Pi_y^* = -\frac{1}{2\pi jk\eta_o} \int_A \mathcal{E}(\xi,\zeta) \frac{e^{-jkr}}{r} \, d\xi d\zeta \qquad (2)$$

$$k = \frac{\omega}{c}$$

$$\eta_o = \frac{E}{H} \quad \text{(Wave Impedance of Free Space)}$$

and $\mathcal{E}(\xi,\zeta)$ is the amplitude distribution for the electric field across the aperture. The variables ξ,ζ are the coordinates of a point on the aperture, and r is the distance between this point and a field point (x,y,z).

$$r = \left[(x-\xi)^2 + (y-\zeta)^2 + (z)^2 \right]^{1/2}$$

Suzuki derived an expression for $\mathcal{E}(\xi\ \zeta)$ for the case of a long and narrow aperture, and evaluated the integral $\int_A \mathcal{E}(\xi,\zeta)\, d\xi d\zeta$. We can use his results to compute the electric field components in Equation (1). Using the dipole approximation and the fact that we are usually interested in points so that r is much greater than the slot width, the fields are:

$$E_x = -\frac{jk}{2\pi}\frac{e^{-jkr}}{r}\left(1-\frac{1}{jkr}\right)\left(\frac{z}{r}\right)\int_A \mathcal{E}(x,y)\, dxdy \tag{3}$$

$$E_z = \frac{jk}{2\pi}\frac{e^{-jkr}}{r}\left(1-\frac{1}{jkr}\right)\left(\frac{x}{r}\right)\int_A \mathcal{E}(x,y)\, dxdy \tag{4}$$

We see that the field in the y-z plane is basically given by Equation (3). Using this equation we can compute the ratio of the fields at different heights above ground. At the resonant frequency the ratio of the amplitudes is given by:

$$\frac{(E_x)_1}{(E_x)_o} = \left(\frac{r_o}{r_1}\right)^2 \frac{\left[1 + \left(\frac{b}{\pi}\right)^2\left(\frac{1}{r_1}2 + \frac{1}{r_o}2\right) + \left(\frac{b}{\pi}\right)^4\left(\frac{1}{r_1 r_o}\right)^2\right]^{1/2}}{1 + \left(\frac{b}{\pi r_o}\right)^2} \tag{5}$$

where

$(E_x)_o$ = E_x behind center of slot at a distance r_o (x=y=0)

$(E_x)_1$ = E_x behind the slot at a distance r_1 (x=0,y≠0)

The solution for the scattered field, Equation (3) is stated as a single frequency solution. The usual Fourier transform techniques must be applied to compute the scattering of an incident EMP.

V. RESULTS

The photographs of the measured data were digitized using an INVAC digitizer. The digitizer was used in a free run mode, requiring the operator to trace over the response curve, while the digitizer records the x-y coordinates at a preset rate. By tracing over the waveshape up to ten times and averaging the resultant traces, the accuracy of the digitization was held to within 2% of the maximum time-amplitude deflections.

Figure 3(a,b) shows the waveshape of the horizontal electric field component of the incident pulse at 3 and 11 feet above the ground plane. The apertures were centered at 7 feet above ground, and Figure 3(c) shows the incident field at that height. For comparison, Figure 3(d) shows the field inside the structure at the same height, 1 m behind the front face, when there were no slots on this face. Comparing peak amplitudes for the two cases shows that the enclosure attenuates the incident field by approximately 75 db. This amount of attenuation proved to be sufficient to produce a large signal to noise ratio for even the smallest aperture considered here.

Computations of the electric field component at each test point were made using the methods described in Section IV. An approximation made for these computations was to assume the incident EMP to be constant in waveshape over the entire length of the slot, with the waveshape shown in Figure 3(c). Some typical results of the computations along with the measured responses are shown in Figures 4 and 5.

The results shown are grouped according to the type of parameter varied. Figure 4 shows the variation of the response of a 10 cm wide slot for lengths of 1 m and 2.4 m. Figure 5 shows the variation with distance from the slot, while Figures 4 and 5 can be used to compare the variation with slot widths for a length of 2.4 m.

Except for a scale factor, the measured waveshape was nearly constant for a given slot size at all test points. The ratios of the peak amplitudes at the different heights to the peak amplitude at 7 feet above ground are plotted in Figure 6 for four different slot sizes. The computed ratios using Equation (5) are shown in the same figure for comparison.

VI. CONCLUSIONS AND RECOMMENDATIONS

One of the most interesting results of this study is that a surprisingly large fraction of the incident field can be transmitted for very narrow apertures. (Compare for example the amplitudes of the incident and scattered field for a slot having a width of 1.5 mm.) An erroneous engineering approximation often made for the rectangular slot problem is that the field strength across the slot is directly proportional to the width of the slot.[12] This assumption would lead to completely incorrect results if it were applied to the analysis of the data in this experiment.

The dipole approximation for the scattered field is not very good for the case of the near field of a long slot. This may explain the differences in amplitude between the experimental data and computed field for that case. (See Figures 5 and 6(c,d).) For the most part there was good agreement between theory and experiment. In view of this, we have justified our basic assumption that the scattered fields from an aperture in a large structure can be related to the fields scattered by the aperture in an infinite plane.

There are many improvements which can be made both in the experimental and analytical approach to the study of the scattering problem. On the experimental side, some of the improvements are the following: (1) Use of a smaller field measurement device to permit a more localized measurement. This could be accomplished by the design of a smaller field measurement box and the use of a flexible, dielectric waveguide for the transmission of the signal to the data acquisition device. (2) Improvement in the accuracy of the measurements by the employment of better statistics for the data at each test point. To do this would require a repetitive EMP pulse and use of a spectrum analyzer for the data acquisition.

Improvements in the analysis can be made in several ways: (1) Take into account the variation of the incident field along the aperture; (2) Include higher multipole terms in the evaluation of the scattered field; (3) Consider the problem of modes of propagation, similar to those in waveguides, being established within structures whose dimensions are comparable to the wavelength of the aperture field.

It would be interesting to continue this study by measuring the scattered fields by apertures smaller than those considered so far. This would require the construction of a better shielded enclosure to reduce the signal-to-noise ratio. For very short slots, the variational technique in the analysis would have to be developed.

VII. ACKNOWLEDGEMENT

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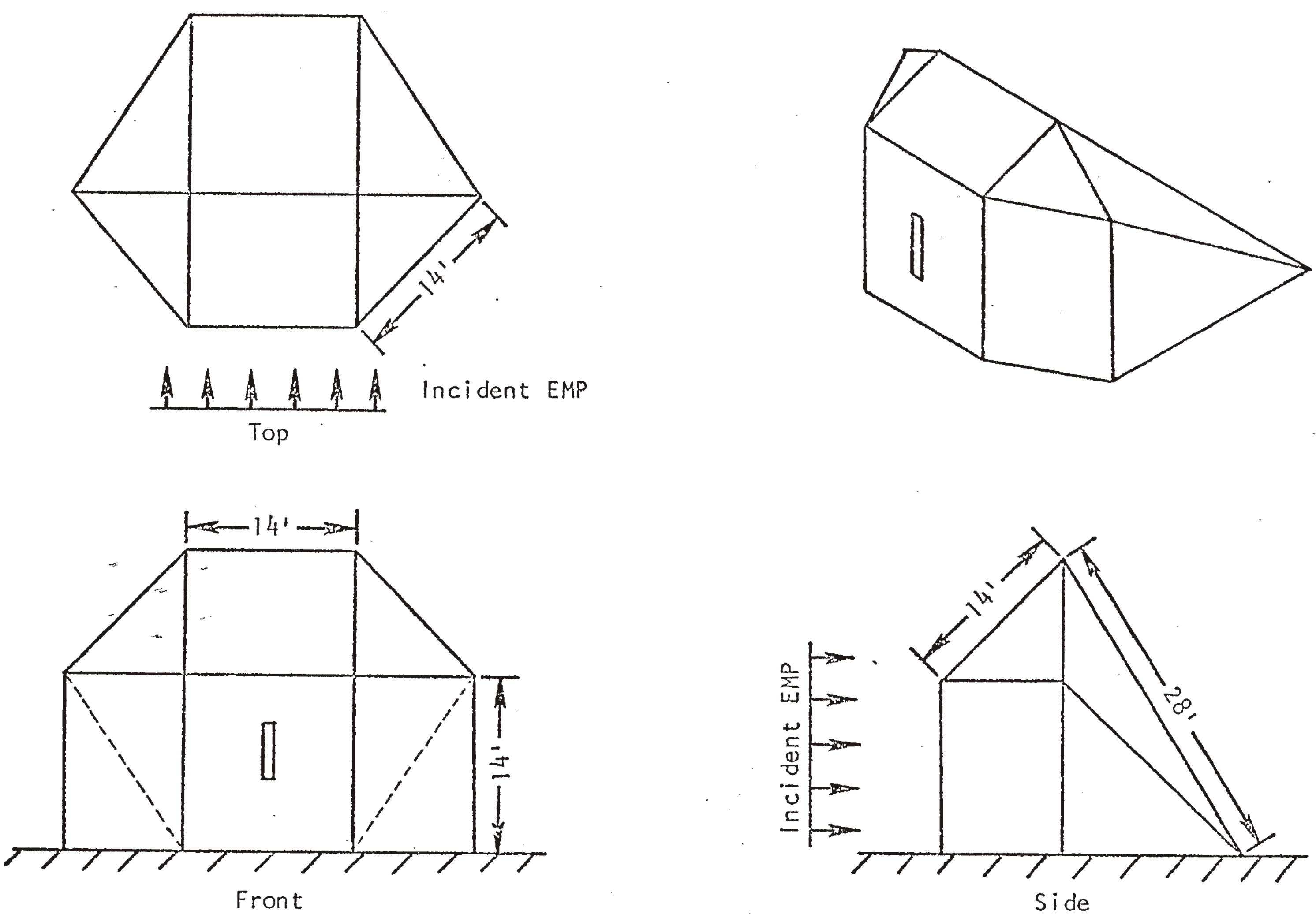

Figure 1. Geometry for the Structure and Aperture Configuration

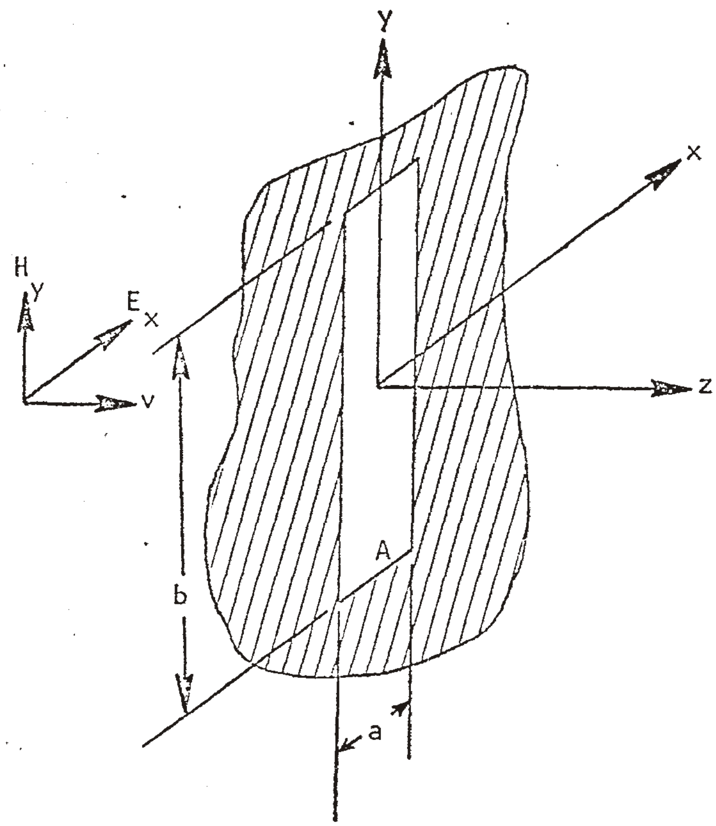

Figure 2. Coordinate System for the Scattering Problem

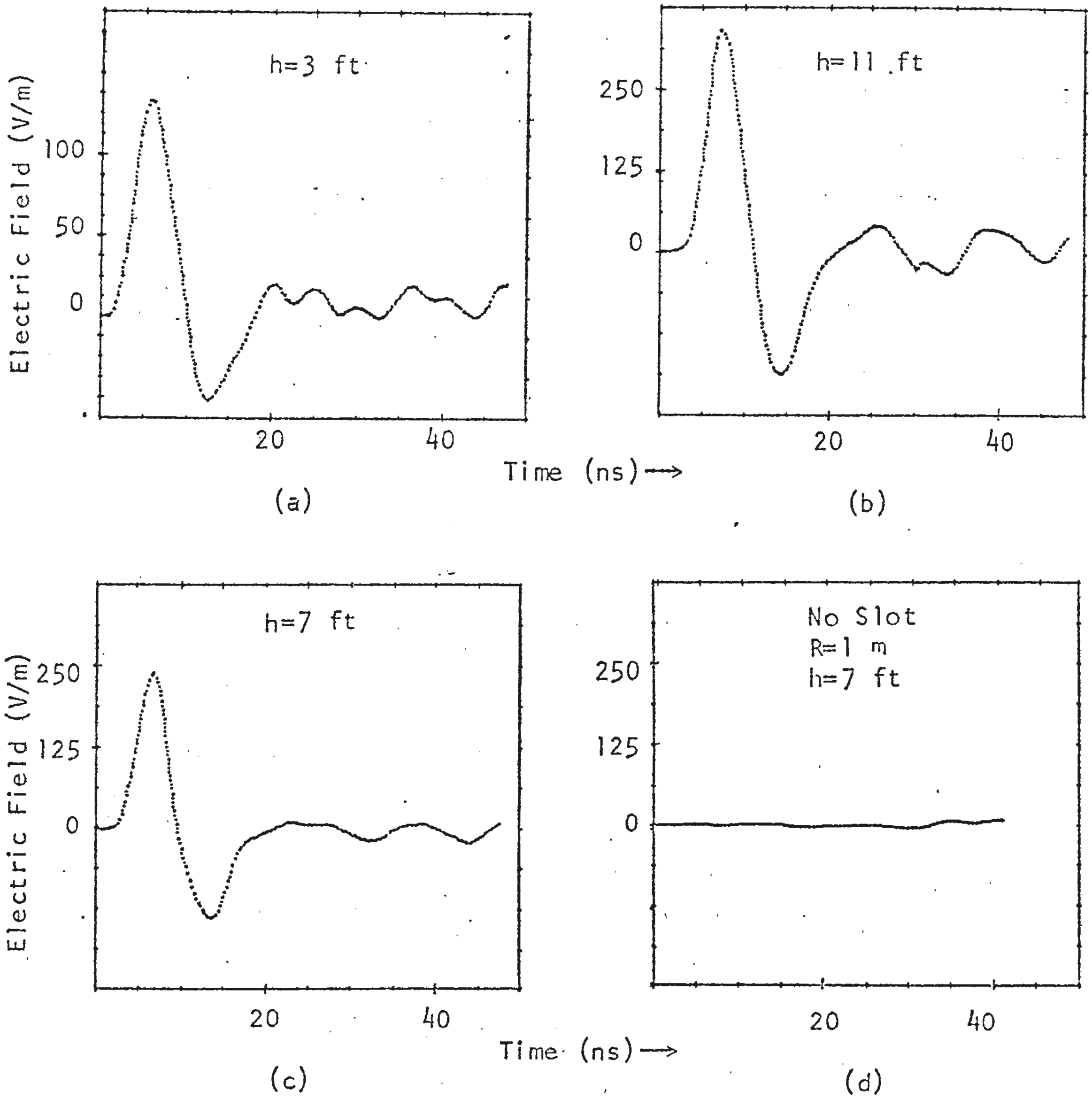

Figure 3. Incident EMP at Different Heights, h (a)-(c), and Field Inside the Enclosure without Slots (d)

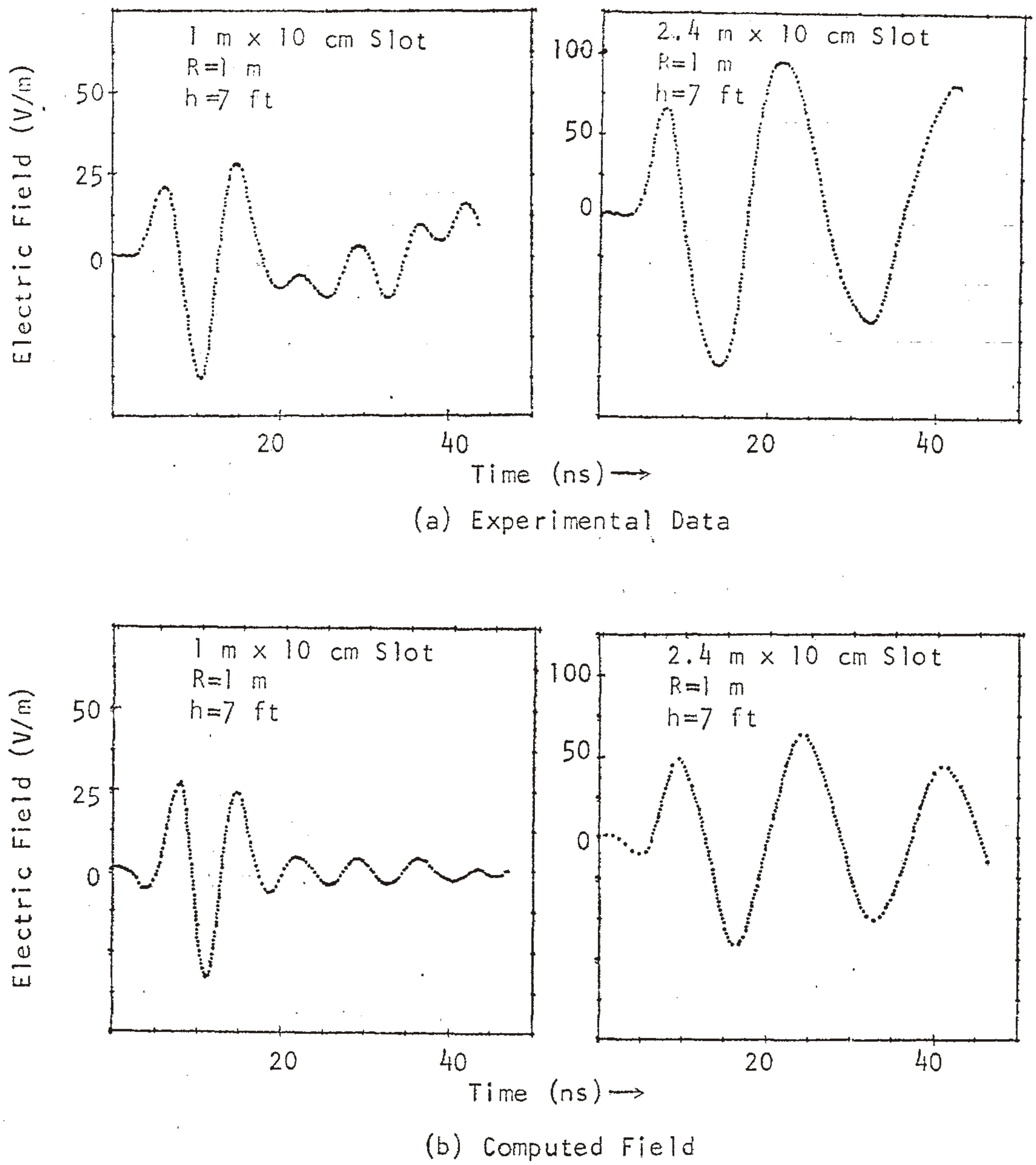

Figure 4. Scattered EMP by Slots of Different Lengths

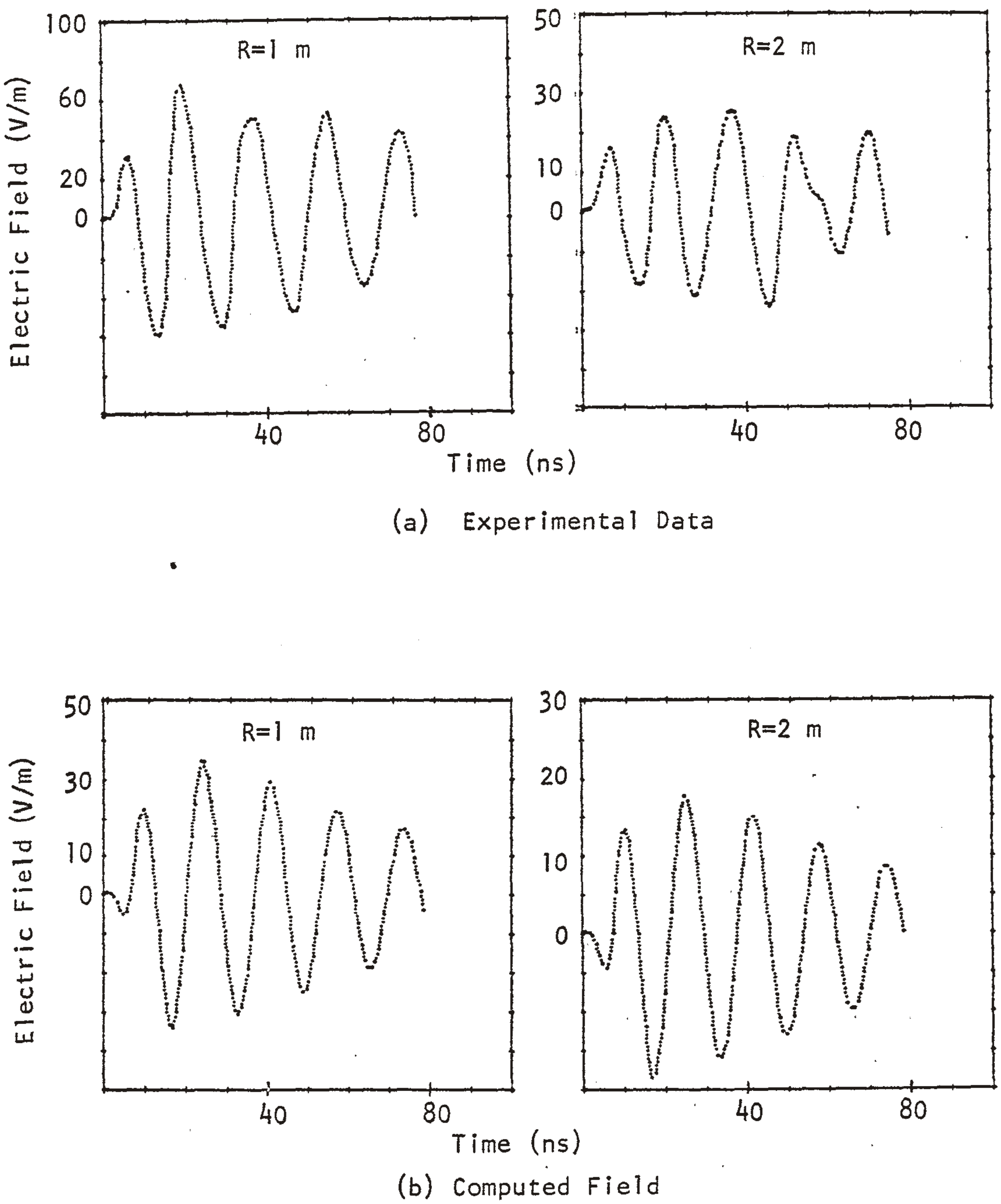

Figure 5. Scattered EMP by a 2.4 m x .15 cm Slot at Different Distances, R, From the Slot

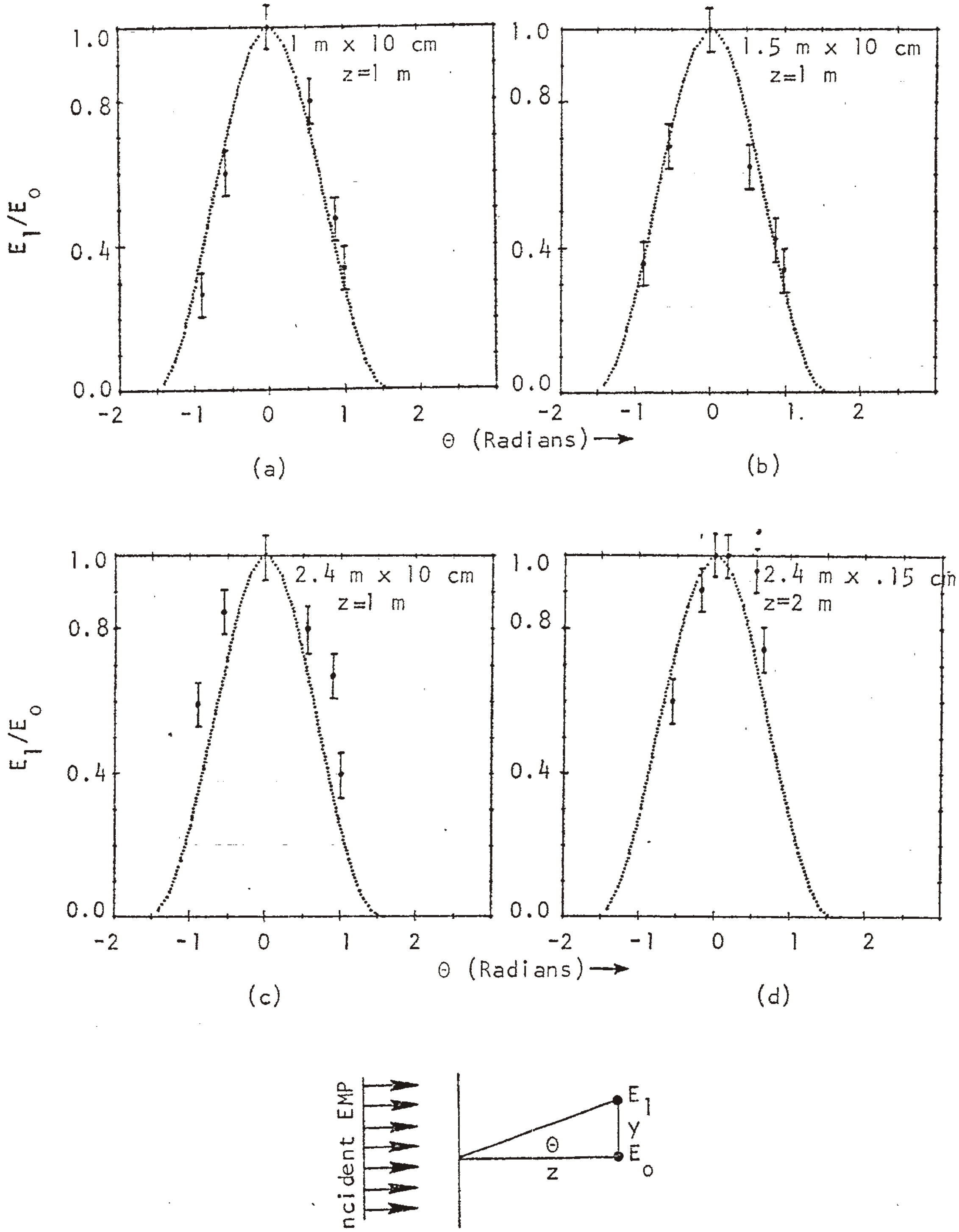

Figure 6. Angular Distribution of the Maximum Electric Field Amplitude