Responses of Electric-Field Probes Near a Cylindrical Model of the Human Body

DEVENDRA MISRA, MEMBER, IEEE, AND KUN-MU CHEN, FELLOW, IEEE

Abstract —**A theoretical and experimental study on the response of an E-field probe near a cylindrical model of the human body has been conducted. The body is simulated with a long cylindrical dielectric shell filled with saline water, and a single E-field probe oriented in various directions, or an orthogonal probe is located near its surface. The model with the probe is illuminated by a TE or TM plane EM wave. The response of the probe was found to be strongly dependent on the probe location with respect to the direction of the incident EM wave, the probe separation from the model surface, the probe orientation, and the polarization of the incident EM wave. The effect due to the dielectric shell on the probe response, with and without the presence of saline water, was carefully investigated. In all cases, the agreement between theory and experiment was found to be very good.**

I. Introduction

An ELECTRIC-FIELD probe is often carried by a person on his body surface for sensing the intensity of the electromagnetic fields he is exposed to. It is, therefore, worthwhile to study the responses of these probes in the proximity of the human body. The study was conducted theoretically as well as experimentally, and useful results are reported in this paper. For an analytical treatment of the problem, the human body is modeled as two concentric cylinders of infinite length, illuminated by a linearly polarized plane EM wave. The responses of single as well as orthogonally connected E-field probes near the body are determined after solving the boundary value problem. These results were verified experimentally using a cylindrical dielectric shell filled with saline water and the frequencies of 2 GHz, 2.45 GHz, and 3 GHz. In order to see the effect of a thin dielectric shell on the response of the probe, the experimental results were also compared with the theoretical results ignoring the presence of the container (considering the saline water column only), and the effect of the shell was found to be insignificant. However, the experimentally recorded responses of the probe near the empty shell were found to be affected greatly by the shell. This somewhat confusing phenomenon can be explained when the experimental results are compared with the corresponding theoretical results. Only selected results are given in this paper for brevity, and more results are available elsewhere [1]. It is noted that, to our best knowledge, no work on this subject has been reported.

Manuscript received May 13, 1984; revised January 14, 1985. This research was supported in part by the National Science Foundation under Grant ECS-8001772-01.

The authors are with the Department of Electrical Engineering and Systems Science, Michigan State University, East Lansing, MI 48824.

II. Theoretical Background

In order to determine the response of a probe near the cylindrical model, the total electric field at the probe location is required. It can be determined by solving the boundary value problem assuming a TM or TE polarized incident wave [2]. For a TM wave incidence as shown in Fig. 1, the total electric field at a point (r, ϕ) outside the cylinder is found, assuming $(\partial/\partial z) \rightarrow 0$ and the electric-field components along the radial and azimuthal directions E_r and E_ϕ, respectively, are zero as follows:

$$\vec{E}(r,\phi) = \hat{z}E_{0z}\exp(-jk_0 r\cos\phi) + \hat{z}\sum_{n=0}^{\infty} d_n H_n^{(2)}(k_0 r)\cos(n\phi) \quad (1)$$

where E_{0z} represents the amplitude of the incident field and k_0 is the wavenumber of free space. $\hat{z}$ is the unit vector along the axis of the cylinder. The constant d_n is found to be

$$d_n = E_{0z}\epsilon_n j^{-n}\frac{J_n(k_0 r_2)}{H_2^{(2)}(k_0 r_2)}\left[\frac{\dfrac{J_n'(k_0 r_2)}{J_n(k_0 r_2)} - A_n}{A_n - \dfrac{H_n^{(2)\prime}(k_0 r_2)}{H_n^{(2)}(k_0 r_2)}}\right] \quad (2)$$

$$A_n \triangleq \frac{k_2}{k_0}\left[\frac{H_2^{(2)\prime}(k_2 r_2) - X_n H_n^{(1)\prime}(k_2 r_2)}{H_n^{(2)}(k_2 r_2) - X_n H_n^{(1)}(k_2 r_2)}\right] \quad (3)$$

and

$$X_n \triangleq \frac{H_n^{(2)}(k_2 r_1)}{H_n^{(1)}(k_2 r_1)}\left\{\frac{\dfrac{J_n'(k_1 r_1)}{J_n(k_1 r_1)} - \dfrac{k_2}{k_1}\dfrac{H_n^{(2)\prime}(k_2 r_1)}{H_n^{(2)}(k_2 r_1)}}{\dfrac{J_n'(k_1 r_1)}{J_n(k_1 r_1)} - \dfrac{k_2}{k_1}\dfrac{H_n^{(1)\prime}(k_2 r_1)}{H_n^{(1)}(k_2 r_1)}}\right\} \quad (4)$$

where ϵ_n is the Neumann number in (2), and k_1 and k_2 represent complex wavenumbers of the saline water and the dielectric shell, respectively. The usual notations for Bessel and Hankel functions are employed in (1)–(4).

Now, consider a small cylindrical receiving antenna (probe) located at a distance of R $(R > r_2)$ from the axis of the cylinder and aligned along the z-axis as shown in Fig. 1. We use the induced EMF method [3] to determine the response of the probe. The boundary condition which must

0018-9480/85/0600-0447$01.00 ©1985 IEEE

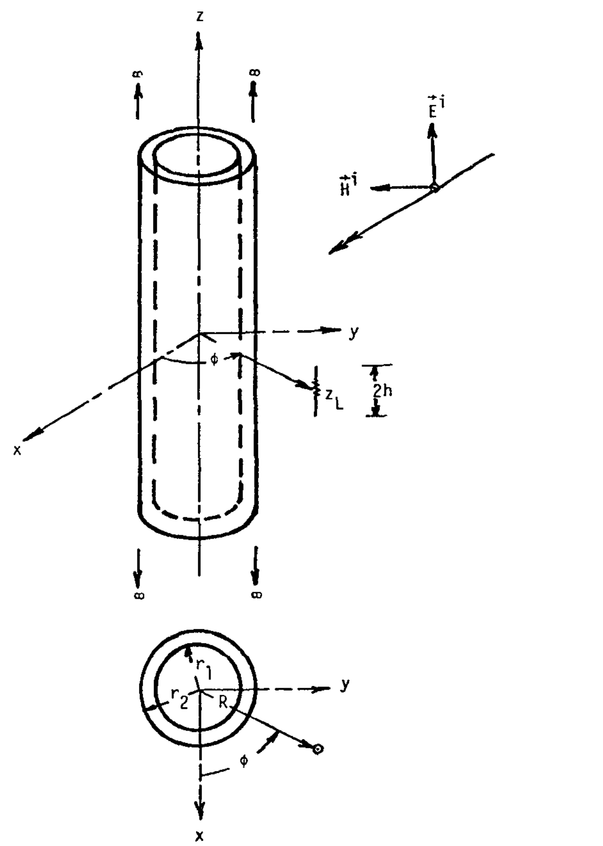


Fig. 1. A TM-polarized plane wave illuminates a vertical receiving probe located near a long sheathed conducting cylinder.

be satisfied by the electrical field at the antenna surface is

$$\hat{z}\cdot\vec{E}_p = V_0\delta(z) = Z_L I_0 \delta(z) \tag{5}$$

where V_0 is the voltage across the probe load impedance Z_L due to the current I_0 at $z=0$ on the probe (the central terminals of the probe), and

$$\vec{E}_p = \vec{E} + \vec{E}_{\text{self}} + \vec{E}_{\text{image}} \tag{6}$$

where $\vec{E}$ is given by (1), $\vec{E}_{\text{self}}$ is the electric field maintained by the induced current on the receiving probe, and $\vec{E}_{\text{image}}$ is the electric field maintained by its image created by the presence of the cylindrical body. Here, the effect of the probe–body coupling is included via image theory, and the strength of the image is approximated by weighting it with an appropriate reflection coefficient [4].

We assume $I_0 f(t)$ is the induced current over the antenna, where $f(t)$ is the current distribution function with $f(0)$ equal to unity, as usual, and defining

$$V_{\text{eq}} = \int_{-h}^{h} f(t)\hat{z}\cdot\vec{E}\,dt \tag{7}$$

$$Z_{\text{in}} = -\frac{1}{I_0}\int_{-h}^{h} f(z)\hat{z}\cdot\vec{E}_{\text{self}}\,dz \tag{8}$$

and

$$z_m = -\frac{1}{\Gamma_z I_0}\int_{-h}^{h} f(z)\hat{z}\cdot\vec{E}_{\text{image}}\,dz \tag{9}$$

the boundary condition (5) gives

$$I_0 = \frac{V_{\text{eq}}}{Z_L + Z_{\text{in}} + \Gamma_z Z_m} \tag{10}$$

where Z_{in} is the input impedance of the receiving probe antenna, Z_m is the mutual impedance of it and its image assuming the perfectly conducting body with a flat surface, and Γ_z is an appropriate reflection coefficient weighting function [4]. However, as shown in the following paragraph, in practice, $|Z_L + Z_{\text{in}}| \gg |\Gamma_z Z_m|$; therefore, the effect of the probe–body coupling is ignored throughout in the theoretical calculations.

Z_{in} is very large for a small probe. For example, if the total length $2h$ of the probe is 1.3 cm, input impedance Z_{in} is found to be about $2 - j1137\ \Omega$ at 2.45 GHz [5]. A zero-bias diode is generally connected across the terminals of the probe antenna and the highly resistive leads are used to connect the terminals of the probe to the input terminals of an amplifier and the recorder [8]. Thus, the load impedance of the probe Z_L consists of the diode impedance in parallel with the characteristic impedance of the high resistive leads. The value of Z_L is usually designed to be higher than the input impedance of the probe antenna Z_{in}. More information is available in [11]. If two of these probes are placed in parallel 2.54 cm (arbitrary) apart, which represent the probe and its image, the mutual impedance Z_m can be computed [6] as $2.06 - j2.07\ \Omega$. Since $|\Gamma_z| \leq 1$, $|Z_L + Z_{\text{in}}| \gg |\Gamma_z Z_m|$ for all practical purposes. Therefore, (10) may be approximated as

$$I_0 \simeq V_{\text{eq}}/(Z_L + Z_{\text{in}}). \tag{11}$$

Assuming a triangular distribution of current over the probe [12], V_{eq} in (7) can be evaluated easily.

It is noted that a TM-polarized field will be coupled to an axially aligned probe only, while a TE-polarized field will be coupled to a radially and an azimuthally aligned probe, but not to an axially aligned probe.

When the cylindrical body is exposed to a TE-polarized EM wave, the electric field will be coupled to both, azimuthally as well as radially aligned probes. This boundary value problem can be solved using the geometry and the coordinate system as depicted in Fig. 2. This time the magnetic-field components H_r and H_ϕ and the electric-field component E_z are zero. The partial derivative with respect to z is also zero. Thus, the electric-field components $E_r(r,\phi)$ and $E_\phi(r,\phi)$ can be determined easily.

As before, the load current I_0^ϕ for an azimuthally aligned probe as shown in Fig. 2(a), can be determined via the induced EMF method [3] and the image theory to account for the probe–body coupling [4]. It is found to be

$$I_0^\phi = \frac{V_{\text{eq}}^{\text{TE},\phi}}{Z_L + Z_{\text{in}} + \Gamma_\phi Z_{m\phi}} \tag{12}$$

whereas $V_{\text{eq}}^{\text{TE},\phi}$ for the small probe is found after assuming

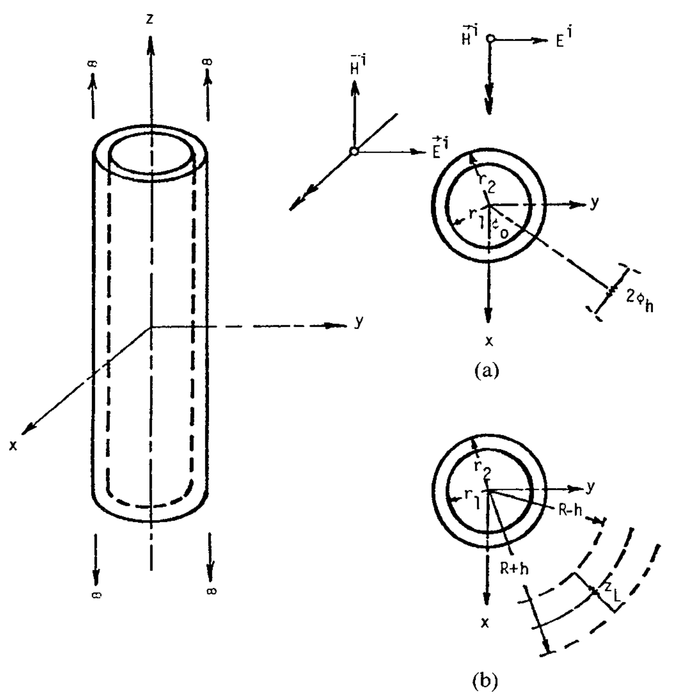


Fig. 2. A TE-polarized plane wave illuminates a horizontal receiving probe located near a long sheathed conducting cylinder. (a) The probe is oriented azimuthally and (b) the probe is oriented radially.

the triangular distribution of current over it as

$$V_{\mathrm{eq}}^{\mathrm{TE},\phi} \approx \frac{\zeta_0 H_{0z}\phi_h R}{2}\left[\cos\left(\phi_0 - \frac{\phi_h}{4}\right)\right.$$
$$\cdot \exp\left\{-jk_0 R\cos\left(\phi_0 - \frac{\phi_h}{2}\right)\right\}$$
$$\left.+\cos\left(\phi_0 + \frac{\phi_h}{4}\right)\exp\left\{-jk_0 R\cos\left(\phi_0 + \frac{\phi_h}{2}\right)\right\}\right]$$
$$+ j\zeta_0 e_0 \phi_h R H_0^{(2)\prime}(k_0 R) + \frac{j2\zeta_0 R}{\phi_h}$$
$$\cdot \sum_{n=1}^{\infty} \frac{e_n}{n^2}\{1-\cos(n\phi_h)\}\cos(n\phi_0) H_n^{(2)\prime}(k_0 R) \tag{13}$$

where

$$\zeta_0 = \sqrt{\mu_0/\epsilon_0} = \text{intrinsic impedance of free space}$$

$$e_n = \epsilon_n H_{0z}^{j^{-n}} \frac{J_n(k_0 r_2)}{H_n^{(2)}(k_0 r_2)} \left\{ \frac{\dfrac{J_n'(k_0 r_2)}{J_n(k_0 r_2)} - B_n}{B_n - \dfrac{H_n^{(2)\prime}(k_0 r_2)}{H_n^{(2)}(k_0 r_2)}} \right\} \tag{14}$$

$$B_n = \frac{k_0}{k_2}\left[\frac{H_n^{(2)\prime}(k_2 r_2) - C_n H_n^{(1)\prime}(k_2 r_2)}{H_n^{(2)}(k_2 r_2) - C_n H_n^{(1)}(k_2 r_2)}\right] \tag{15}$$

and

$$C_n = \frac{H_n^{(2)}(k_2 r_1)}{H_n^{(1)}(k_2 r_1)} \left\{ \frac{\dfrac{J_n'(k_1 r_1)}{J_n(k_1 r_1)} - \dfrac{k_1}{k_2}\dfrac{H_n^{(2)\prime}(k_2 r_1)}{H_n^{(2)}(k_2 r_1)}}{\dfrac{J_n'(k_1 r_1)}{J_n(k_1 r_1)} - \dfrac{k_1}{k_2}\dfrac{H_n^{(1)\prime}(k_2 r_1)}{H_n^{(1)}(k_2 r_1)}} \right\}. \tag{16}$$

ϵ_n is the Neumann number, and the usual notations of Bessel functions and their derivatives are employed.

Also, still for all practical purposes, $|Z_L + Z_{\mathrm{in}}| \gg |\Gamma_\phi Z_m|$ in (12), i.e., the contribution from the probe–body coupling term is relatively small and, hence, can be neglected.

Following a similar procedure, the load current I_0^r in the radially aligned probe shown in Fig. 2(b) can be found as

$$I_0^r = \frac{V_{\mathrm{eq}}^{\mathrm{TE},r}}{Z_L + Z_{\mathrm{in}} + \Gamma_r Z_{mr}} \tag{17}$$

where $V_{\mathrm{eq}}^{\mathrm{TE},r}$ is evaluated after assuming a triangular distribution function of current over the short dipole. It can be found as

$$V_{\mathrm{eq}}^{\mathrm{TE},r} \approx \frac{4\zeta_0}{hk_0^2} H_{0z}\tan\phi\sec\phi\sin^2\left(\frac{k_0 h\cos\phi}{2}\right)$$
$$\cdot\exp(-jk_0 R\cos\phi) + \frac{j\zeta_0}{hk_0}\sum_{n=1}^{\infty} ne_n\sin(n\phi)$$
$$\cdot\left[(h-R)H_n^{(2)}\left\{k_0\left(R-\frac{h}{2}\right)\right\}\cdot\ln\left(\frac{R}{R-h}\right)\right.$$
$$\left.+(h+R)H_n^{(2)}\left\{k_0\left(R+\frac{h}{2}\right)\right\}\ln\left(\frac{R+h}{2}\right)\right]$$
$$+\frac{j\zeta_0}{k_0}\sum_{n=1}^{\infty} ne_n\sin(n\phi)\left[H_n^{(2)}\left\{k_0\left(R-\frac{h}{2}\right)\right\}\right.$$
$$\left.-H_n^{(2)}\left\{k_0\left(R+\frac{h}{2}\right)\right\}\right] \tag{18}$$

where ζ_0 and e_n are as defined earlier.

It may be noted that the probe is collinear with its image this time [7]. However, it can be demonstrated that the effect of the probe–body coupling is still relatively very small [1] and, hence, the term $\Gamma_r Z_{mr}$ in (17) can be neglected for all practical purposes. Further, when $k_1 = k_2$ and $r_1 = r_2$, the boundary value solution reduces to the well-known results of scattering by the cylinder of complex permittivity.

Responses of the axial, azimuthal, and radial probes are proportional to the magnitude square of the probe currents given by (11), (12), and (17), respectively. The response of an orthogonally connected probe system can be determined by summing up the individual responses.

III. Results and Comparison

For experimental studies, a plexiglass cylindrical shell (inner and outer radii 0.146 m and 0.1524 m, respectively, and 0.83 m high) filled with saline water was illuminated

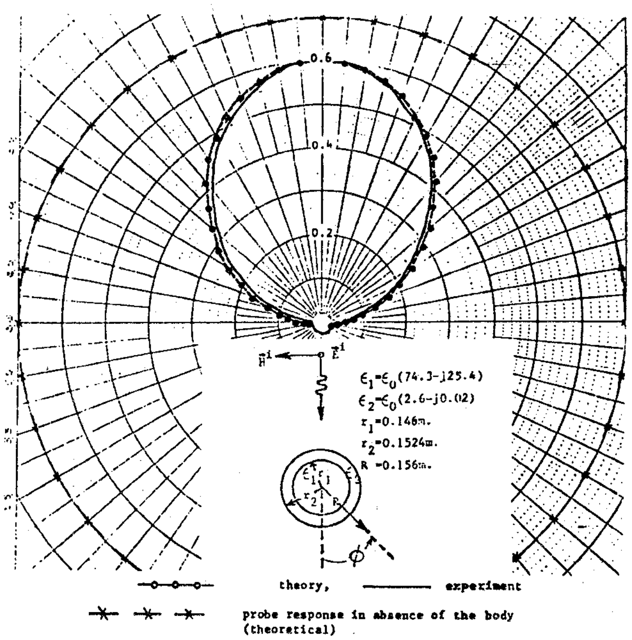


Fig. 3. Response of an axially aligned E-probe near a sheathed conducting cylinder illuminated by a TM-polarized plane wave at 2.45 GHz.

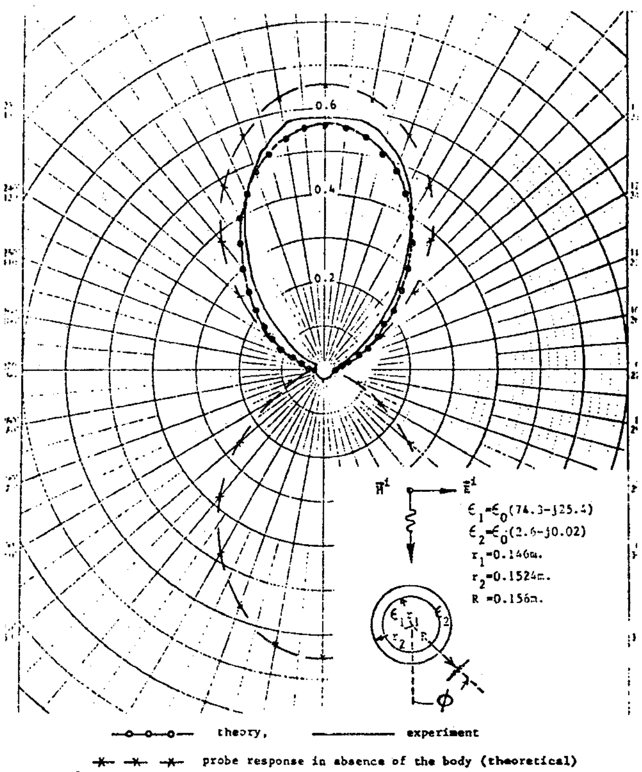


Fig. 4. Response of an azimuthally aligned E-probe near a sheathed conducting cylinder illuminated by a TE-polarized plane wave at 2.45 GHz.

by plane EM waves of various frequencies and polarizations using a GR-type 1360-B signal generator and a pyramidal horn antenna. A suitable short E-field probe [8] was fixed on the surface of the shell about midway from its ends. The output of this probe, available through a pair of resistive leads, was connected to an antenna pattern recorder. Thus, the probe antenna, which was about 1.3 cm long, was about 40 cm away (always over 2λ) from the ends of the cylinder. Its orientation was adjusted according to the polarization of the incident wave. Also, the transmitting horn antenna was located at a suitable distance to ensure uniform plane-wave illumination of the cylinder in an anechoic chamber. The polarization of the incident field was changed by rotating the horn antenna by 90° about its axis. The shell was filled up with saline water (salt/water $=1/75$ by weight) to simulate the human body [9]. With this arrangement, the end effect of the finite cylinder used in the experiment was found to be insignificant, and a good agreement was obtained between the experimental results and the theoretical results which were based on the geometry of an infinite cylinder. The experiments were conducted at three different frequencies, viz., 2 GHz, 2.45 GHz, and 3 GHz [1]. However, only a few results are presented here for brevity.

Fig. 3 shows the measured and theoretical responses of an axially aligned probe as a function of its location in terms of azimuthal angle ϕ, when a TM-polarized plane wave of 2.45 GHz is incident on the sheathed conducting cylinder from the $\phi=180°$ direction. In this case, the probe response shows a maximum on the front side (i.e., $\phi=180°$) and a very small output on the backside (i.e., $\phi=0°$). This type of probe response is understandable via shadow region formation behind a conducting body illuminated by EM waves. As seen in Fig. 3, the agreement between experiment and theory is very good. It is noted that the theoretical results shown in Fig. 3 were calculated by taking into account the existence of the dielectric shell. These theoretical results were not altered significantly when the existence of the shell was ignored. This implies that the dielectric shell has a negligible effect on the EM wave scattering and the probe response when it is filled with saline water. Also included in Fig. 3 is the probe response at the same location but in free space after the sheathed conducting cylinder was removed. This free-space probe response has a circular pattern with a magnitude a little larger than the maximum of the probe response in the presence of the simulated body. This comparison of the magnitudes of the probe responses does not have significant meaning because of the probe response in the presence of the simulated body can be varied greatly when the spacing between the probe and the body is changed, due to the standing wave pattern of the EM wave created by the body surface.

When a TE-polarized plane wave illuminates the sheathed conducting cylinder, both the azimuthally as well as the radially aligned probes respond. Fig. 4 shows the response of an azimuthally aligned probe as a function of ϕ when a TE-polarized plane wave of 2.45 GHz illuminates the sheathed conducting cylinder from the direction of $\phi=180°$. The probe response shows a maximum on the front side ($\phi=180°$) and a very small output on the backside ($\phi=0°$). In Fig. 4, the measured probe response agrees quite well with the corresponding theoretical probe response. It is noted that the theoretical results were very close for the cases of with and without taking into account the presence of the dielectric shell. The other pattern in Fig. 4 represents the probe response in free space or in the

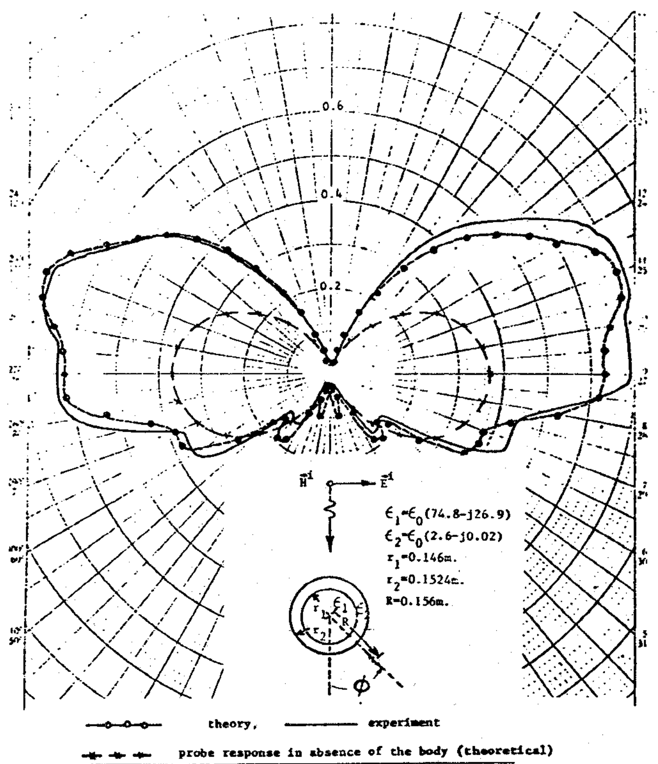


Fig. 5. Response of a radially aligned E-probe near a sheathed conducting cylinder illuminated by a TE-polarized plane wave at 2.00 GHz.

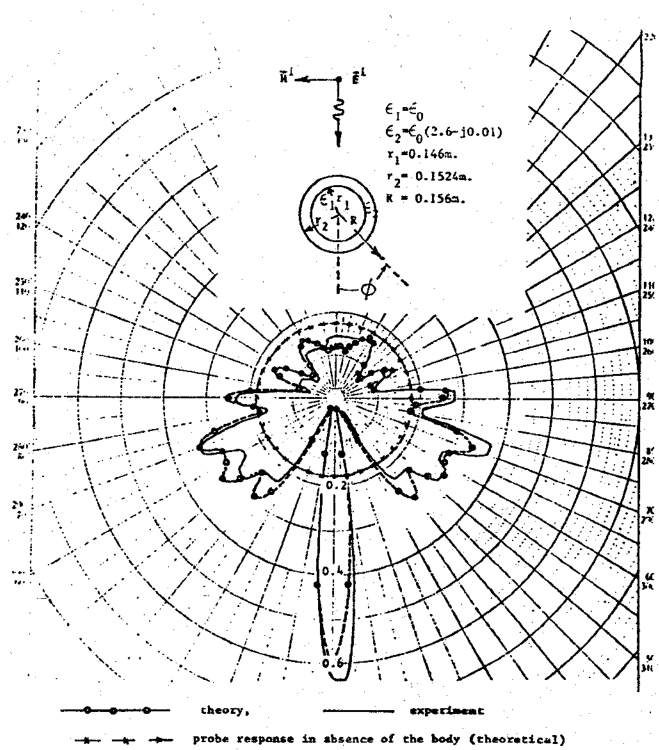


Fig. 6. Response of an axially aligned E-probe near a cylindrical dielectric shell illuminated by a TM-polarized plane wave at 3.00 GHz.

absence of the sheathed conducting cylinder. This free-space probe response has a maximum at the directions of $\phi = 0°$ and 180°, because the probe is parallel to the incident electric field for these cases, and it has a null at the directions of $\phi = 90°$ and 270°, because the probe is perpendicular to the incident electric field for these cases.

Fig. 5 depicts the measured and theoretical responses of a radially aligned probe for a TE-polarized plane-wave illumination with a frequency of 2 GHz. The probe response shows a maximum on the right and left sides (i.e., at $\phi = 110°$ and $\phi = 250°$) and a negligible value on the front and back sides ($\phi = 180°$ and $\phi = 0°$) of the sheathed conducting cylinder. The computed results in which the presence of the dielectric shell is included compare well with the experimental results as shown in Fig. 5. Again, when the presence of the shell is ignored in the calculations, the theoretical results still compare fairly closely with these experimental results in all cases. The free-space probe response has a similar pattern as other patterns in Fig. 5 with the exception of smaller magnitude. This phenomenon is due to the fact that the induced electric field on the conducting body surface at the direction of $\phi = 90°$ and 270° is higher than the incident electric field, commonly known as the electric-field enhancement [13].

From previous results, it is learned that the theoretical results on the probe response are not significantly affected by the presence of the shell and, at the same time, the theoretical probe response matches very well with the measured probe response. This implies that the shell in the presence of filled saline water does not scatter the EM wave significantly. To explore this implication more carefully, experiments were performed with the empty dielectric shell. Fig. 6 shows one of these experimental results. In this figure, the response of an axially aligned E-field probe near the empty shell is shown, when it is illuminated by a TM-polarized plane wave of 3 GHz. The measured response pattern shows a large peak in the back side ($\phi = 0°$) and some minor peaks in other directions. This result is completely different from the one we would expect if the presence of the shell can be ignored; the probe response would have a circular pattern then. Obviously, the empty shell, in the absence of filled saline water, scatters the EM wave significantly. To assure this contention, the corresponding theoretical probe response, with the probe located on the surface of the empty shell, was calculated and it was found to be in good agreement with the measured probe response. As mentioned earlier, the effect of the probe image is ignored in all the calculations. These results indicate that the empty dielectric shell in free space scatters the incident EM wave significantly, but when the shell is filled with a medium of high-dielectric constant, the effect of the shell can then be ignored.

The theory considered for the responses of different E-field probes in the preceding section matches very well with the experimental results. Hence, the response of a system of three orthogonally aligned probes, which is an usual sensor for the electromagnetic radiation, can be predicted easily by combining the responses of the three individual, viz., axial, azimuthal, and radial, probes. Fig. 7 illustrates the response of such a sensor near a cylindrical model with electrical parameters equivalent to those of the biological body [10]. The incident wave is assumed to be at 2.45 GHz and its polarization angle varies from 0° to 30°, 60°, and 90°. It may be noted that the response of the sensor is about the same on the front side for all four

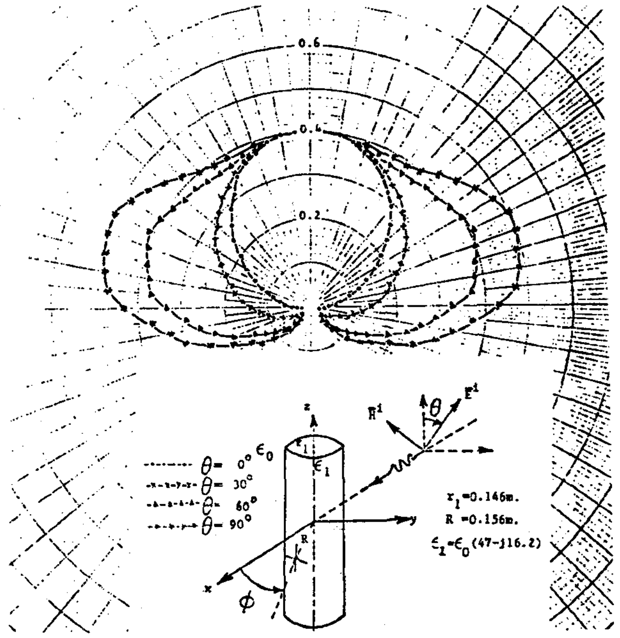


Fig. 7. Response of an orthogonally connected E-probe system near a biological body illuminated by plane wave of different polarization angles θ at 2.45 GHz.

polarization angles; it increases on the sides with an increase in the polarization angle of the incident field. The large shadow region on the back side is always there.

IV. Conclusions

The response of E-field probes in the proximity of the human body is studied in this paper. The probe response is found to be not only the function of the location of the probe on the body, but also the separation of the probe from the body surface. The polarization angle and the direction of the incident field also affect the response to a large extent. The probe response may be very small or a null if the incident field is from the back side. Also, it may indicate a lower level than the actual incident field because of the destructive interference with the reflected waves.

We also reconfirmed a phenomenon known to researchers in the bioelectromagnetic area: an empty dielectric container perturbs an impressed EM field significantly. However, when it is filled with biological media or bodies, the effect of the container becomes negligible. Physically, this phenomenon can be explained as follows. When an empty dielectric container ($\epsilon = 2 \sim 5\epsilon_0$) is located in the free space ($\epsilon = \epsilon_0$), the incident EM wave is significantly scattered or perturbed by the container. However, if the container is filled with a biological medium (with a high permittivity, $\epsilon = 40 \sim 70\epsilon_0$, and a finite conductivity), the existence of the container (with a lower permittivity and a nearly zero conductivity) becomes insignificant because the biological medium scatters the EM wave much more than the container does. In this study, we have proved this phenomenon both theoretically and experimentally.

References

[1] D. K. Misra, "Scattering of electromagnetic waves by human body and its applications," Ph.D. dissertation, Michigan State University, East Lansing, 1984.

[2] R. F. Harrington, *Time Harmonic Electromagnetic Fields*. New York: McGraw-Hill, 1961, pp. 198–201.

[3] E. C. Jordan and K. G. Balmain, *Electromagnetic Waves and Radiating Systems*. Englewood Cliffs, NJ: Prentice-Hall, 1968, p. 535.

[4] E. K. Miller *et al.*, "Analysis of wire antenna in the presence of a conducting half space. Part II. The horizontal antenna in free space," *Can. J. Phys.*, vol. 50, pp. 2614–2627, 1972.

[5] R. W. P. King, *The Theory of Linear Antennas*. Cambridge, MA: Harvard University Press, 1956, pp. 191–192.

[6] R. S. Elliot, *Antenna Theory and Design*. Englewood Cliffs, NJ: Prentice-Hall, 1981, pp. 332–333.

[7] E. K. Miller *et al.*, "Analysis of wire antenna in the presence of a conducting half space. Part I. The vertical antenna in free space," *Can. J. Phys.*, vol. 50, pp. 879–888, 1972.

[8] K. M. Chen, S. Rukspollmuang, and D. P. Nyquist, "Measurement of induced electric fields in a phantom model of man," *Radio Sci.*, vol. 177, no. 5, pp. 49S–59S, Sept.–Oct. 1982.

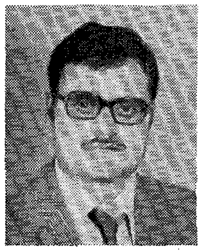
[9] J. A. Saxton and J. A. Lane, "Electrical properties of sea water," *Wireless Engineer*, vol. 29, pp. 269–275, Oct. 1952.

[10] C. C. Johnson and A. W. Guy, "Nonionizing electromagnetic wave effects in biological materials and systems," *Proc. IEEE*, vol. 60, pp. 692–718, June 1972.

[11] H. I. Bassen and G. S. Smith, "Electric field probes—A review," *IEEE Trans. Antennas Propagat.*, vol. AP-31, no. 5, pp. 710–718, Sept. 1983.

[12] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*. New York: Wiley, 1981, p. 80.

[13] W. R. Smythe, *Static and Dynamic Electricity*. New York: McGraw-Hill, 1968, p. 65.



Devendra Misra (M'74) was born in Unnao (U.P.), India, in 1949. He received the Ph.D. degree in electrical engineering from Michigan State University in 1984.

Since March 1984, he has been working as a Research Associate in Electrical Engineering at Michigan State University. During 1973–80, he held research and teaching faculty positions in India. He worked as a Teaching and Research Assistant during his studies at Michigan State University. His current interests include microwave/millimeter-wave circuits and antennas.

Kun-Mu Chen (SM'64–F'76) was born in Taipei, Taiwan, China, on February 3, 1933. He received the B.S.E.E. degree from the National Taiwan University, Taipei, Taiwan, in 1955, and the M.S. and Ph.D. degrees in applied physics from Harvard University, Cambridge, MA, in 1958 and 1960, respectively.

While at Harvard University, he held the C.T. Loo and the Gordon McKay Fellowships. From 1956 to 1957, he was a Teaching Assistant at the National Taiwan University, and from 1959 to 1960, he was a Research Assistant and Teaching Fellow at Harvard University. From 1960 to 1964, he was associated with the Radiation Laboratory, University of Michigan, Ann Arbor, where he was engaged in studies of electromagnetic theory and plasma. In 1962, while on leave from the University of Michigan, he was a Visiting Professor of Electronics at Chao-Tung University, Taiwan. Since 1964, he has been with Michigan State University, East Lansing, first as Associate Professor of Electrical Engineering, and since 1967, as Professor of Electrical Engineering. From 1968 to 1973, he was the Director of the Electrical Engineering program of the Department of Electrical Engineering and Systems Science. He has published numerous papers on electromagnetic radiation and scattering, plasmas, and the interaction of electromagnetic radiation with biological systems.

Dr. Chen is a fellow of the American Association for the Advancement of Science, a member of U.S. Commissions A, B, and C of the International Scientific Radio Union, Sigma Xi, Phi Kappa Phi, and Tau Beta Pi. He is the recipient of Distinguished Faculty Award from Michigan State University in 1976. He is also the recipient of Achievement Award in Science and Engineering from the Taiwanese American Foundation in 1984.