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RECEPTION AND TRANSMISSION
OF
TRANSIENT ELECTROMAGNETIC FIELDS

by

H J Schmitt
Harvard University

SEPTEMBER 1963

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SANDIA CORPORATION MONOGRAPH

RECEPTION AND TRANSMISSION
OF
TRANSIENT ELECTROMAGNETIC FIELDS

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by

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ABSTRACT

The receiving and transmitting properties of small linear antennas, conical antennas, and loops for transient electromagnetic fields have been investigated experimentally. Short electrical dipoles loaded by a capacitance represented by a cathode follower can be used successfully for the measurement of transient fields with rise times of less than 1 nano-second, if the first antenna resonance is suppressed by a series resistor at the base of the antenna. The currents induced on nonresonant structures by transient electromagnetic fields are investigated and their application to a direct measurement of the time sequence of the electromagnetic field is discussed. Signals with a simple and known time dependence such as a unidirectional pulse can be radiated into space if the reflection of current waves at discontinuities of the antenna structure is avoided. In a manner similar to that useful for the absorption of continuous waves in media with a stratified conductivity, it is shown that reflections at discontinuities can be avoided by dipoles with tapered resistive loading.

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RECEPTION AND TRANSMISSION OF TRANSIENT ELECTROMAGNETIC FIELDS

Introduction

The transient response of antennas has recently found increasing attention.¹⁻⁶ Such interest arises partly from a desire to transmit and receive signals with increased frequency bandwidth with a minimum distortion in the antenna system.^{7,8} This includes the observation of pulsed signals or frequency-modulated signals necessary for target discrimination through radar. Even wider frequency spectra are encountered in nonperiodic electromagnetic disturbances such as lightning or sudden bursts of ionization due to natural or artificial excitation. A faithful reproduction of the time sequence of the electromagnetic disturbance in turn may allow the determination of the nature of the physical processes involved in the phenomena.

For continuous periodic waves the electromagnetic field in space is related to the induced current or voltage in a transmission line connected to the antenna by a complex steady-state transfer function which depends on the geometry of the antenna. The undistorted reproduction of the electromagnetic disturbance requires that the steady-state transfer function be a constant as a function of frequency for the antenna system between the highest and the lowest significant frequency components in the spectrum of the disturbance, or the highest and the lowest frequencies which can be resolved in the display system.

The transfer functions of conventional antennas, such as dipoles and loops, are not normally frequency independent. In order to obtain an instantaneous frequency-independent response, corrective networks including passive and active elements must be inserted between the antenna and the oscilloscopic display system. If instantaneous display is not significant, a different approach is possible, in which the transient electromagnetic disturbance is recorded by a conventional dispersive antenna and the true signal subsequently reconstructed by operating on the measured signal with the inverse transfer function. Such inversion may be accomplished on machine computers if the transfer functions are accurately known.

Only the instantaneous display of transient phenomena is considered in this report. The highest frequency which can be resolved on oscilloscopes is 1000 Mc/sec, corresponding to rise times of electric or magnetic fields of approximately 0.4 nanosecond. Hence, interest centers on receiving systems which are essentially flat in frequency response from dc (or some low frequency) to about 1000 Mc/sec. Several simple antenna configurations of practical importance are investigated with respect to their receiving characteristics in free space. The related problem of transmission of short electromagnetic disturbances is also investigated experimentally for the purpose of an eventual calibration of receiving elements. A further application is discussed that involves the investigation of scattering and diffraction of short unidirectional pulses by various objects.

Antennas for the Observation of Transient Signals

It is reasonable to assume that antennas for which the steady-state transfer function is a simple and known function of frequency in a significant frequency range are most easily adapted to the reception of transient electromagnetic disturbances. Simple steady-state transfer functions are obtained for antennas that are either sufficiently small in linear dimensions compared to the smallest wavelength in free space (corresponding to the highest significant frequency in the transient spectrum) or antennas that are sufficiently large compared to the longest significant wavelength in the transient spectrum. If, for example, unidirectional pulses with rise times of the order of 0.5×10^{-9} sec and durations of 60×10^{-9} sec are to be investigated, the linear dimension h of the receiving system is limited by $h \ll 30$ cm or, for large antennas, at least one linear dimension must be $h \gg 18$ m and, moreover, no dimension should be comparable to wavelengths within the frequency range from approximately 8 Mc/sec to 1000 Mc/sec to avoid resonances in the antenna system. For the duration of the transient signal such an antenna appears as an infinitely long antenna. Within this time interval, no resonances can occur and a reasonably accurate replica of the original signal may be achieved if the steady-state transfer function of the infinitely large or long antenna is independent of frequency, or if corrective networks are used to compensate the frequency dependence of this transfer function. For the large antenna other difficulties arise since the theoretical receiving and transmitting characteristics of antennas large compared to the wavelength are not very accurately known, except for thin dipoles⁹ and biconical antennas.¹⁰ Experimentally the investigation of the transient reception by such large antennas requires locally plane-wave fields over comparable dimensions with an accurately known time dependence. At the present time, facilities with the necessary physical size are not available.* The investigation therefore centers on electrically small antennas and includes only one particular type of a large receiving device which could be investigated in the limited space available.

Small Antennas for the Observation of Transient Phenomena

As a specific example of an antenna with a simple and known transfer function, consider the electrically short dipole. If the dipole antenna of half-length h and radius a , used as a receiver, is placed at the origin of the coordinate system (Figure 1) inclined with respect to the direction of the electric field vector $E = \hat{y}E_0$ of a linearly polarized wave by angles θ and ψ , the induced open-circuit voltage V_{oc} at the terminals of the antenna is by definition of the effective half-length h_e ,¹¹

$$V_{oc} = +2h_e\left(\theta, \psi, \frac{a}{h}\right)E_0 e^{j\omega t} \cos \psi. \quad (1)$$

By application of Thévenin's theorem, the voltage V_L across a load impedance Z_L becomes

$$V_L = \frac{V_{oc} Z_L}{Z_{in} + Z_L} = + \frac{Z_L}{Z_{in} + Z_L} 2h_e\left(\theta, \psi, \frac{a}{h}\right)E_0 e^{j\omega t} \cos \psi, \quad (2)$$

* A large ground screen is presently under construction.

Figure 1. Geometrical configuration of the receiving antenna

where Z_{in} is the input impedance of the antenna. For an electrically short and thin dipole a good approximation for broadside incidence, $\theta = 90^\circ$, $\psi = 0^\circ$, is

$$h_e\left(90^\circ, 0^\circ, \frac{a}{h}\right) \sim \frac{h}{2} \quad (3)$$

and $Z_{in} = \frac{1}{j\omega C_A}$, where C_A is the static capacitance between the two parts of the dipole. Within the limits of this approximation the voltage across the load is

$$V_L = + \frac{Z_L h}{\frac{1}{j\omega C_A} + Z_L} E_o e^{j\omega t} \quad (4)$$

It is immediately apparent that for a capacitive load impedance the steady-state transfer function is independent of frequency:

$$V_L = \frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C_A} + \frac{1}{j\omega C}} h E_o e^{j\omega t} = \frac{h}{1 + \frac{C}{C_A}} E_o e^{j\omega t} \quad (5)$$

To a very good approximation such a capacitive load is represented by the input terminals of a cathode follower. The output impedance of the cathode follower can be matched to the characteristic impedance of a transmission line. Hence, the undistorted signal would be transformed into a voltage across the conductors of the transmission line.

The steady-state transfer function of physical dipoles that are base loaded by a capacitor of $3 \mu\mu f$, $\Omega = 2 \ln \frac{h}{a} = 10$, is plotted as a function of $\beta h = \frac{\omega h}{c_o}$ ($\beta = 2\pi/\lambda_o$, $c_o = 1/\sqrt{\epsilon_o \mu_o} = 3 \times 10^8$ m/sec) in Figure 2. Values of the effective length and input impedance are those obtained from the second-order King-Middleton theory.⁹ It is seen that the transfer function is substantially constant only for extremely short dipoles with $\beta h \leq 0.5$, i. e., for an upper frequency limit of 1000 Mc/sec, about $h \leq 2.5$ cm.

Figure 2. Steady-state transfer function for center-loaded receiving dipole. Numerical values for input impedance and effective length are second-order approximations; $\Omega = 10$, $h = 5$ cm, center load $R + j\omega C$, $C = 3 \mu\text{f}$.

Furthermore, the transfer function for a capacitively base-loaded half dipole rises rapidly up to frequencies in the vicinity of the first dipole resonance at $h \sim \frac{\lambda_0}{4}$. If the decrease in gain of the display system beyond the nominal cut-off frequency f_c is only slight, the over-all transfer function of the antenna system and the display system will continue rising beyond f_c until it ultimately drops off beyond the antenna resonance. The major contribution in this case arises from components in the vicinity of resonance and consequently leads to ringing at the resonant frequency of the antenna, even for short antennas. This has been clearly observed experimentally for incident fields with step-function and pulse-shaped dependence.

Physically the transient ringing can be understood by considering the motion of charges induced on the antenna by the applied field.¹ It results from the successive reflections of waves of charge accumulation at the center of the dipole and at the antenna tips. The reflection of these charge waves can be suppressed at the center of the dipole by connecting an appropriate load impedance at this point. It has previously been found that for antennas with a radius of about 1 millimeter a practical value for the suppression of transient ringing is a resistance of $R \sim 600$ ohms.¹ This corresponds approximately to the resistive part of the input impedance of the infinitely long dipole antenna with $a = 0.5$ mm for a frequency of roughly 1000 Mc/sec.⁴ Hence, it may be expected that a resistive load in series with the input capacitance of the cathode follower leads to a smoother behavior of the steady-state transfer function for short dipoles. This is shown graphically in Figure 2. Among the various assumed values of the series resistor it is found that $R/2 \sim 250$ ohms achieves a maximally flat response curve for thin monopoles ($\Omega = 10$).

It should be noted that for a purely resistive load, and under the assumption $R \ll 1/\omega C_A$, which holds for sufficiently low frequencies, the response of short dipoles

$$V_L = \frac{+hR}{R + \frac{1}{j\omega C_A}} E_0 e^{j\omega t} \cos \psi \sim +j\omega C_A R h E_0 e^{j\omega t} \cos \psi \quad (6)$$

corresponds to the time-differentiated incident electric field.

As a second specific example, a small loop antenna of area f is considered. Subject to the condition that the circumference is small compared to the wavelength, the current $I = I_0 e^{j\omega t}$ induced in the conducting loop is constant and related to the incident magnetic field by

$$(R + j\omega L)I = -\frac{\partial}{\partial t} \int B_n df \sim -j\omega B_n f, \quad (7)$$

where L is the self inductance of the loop and R the lumped or distributed total resistance in the loop circuit. The component of the magnetic field normal to the surface of the loop is denoted by B_n . Let the loop be oriented with its surface perpendicular to the magnetic field of a plane wave. The voltage across the load resistor R is

$$V_L = IR = \frac{R}{R + j\omega L} (-j\omega B_n f) = \frac{R}{R + j\omega L} \left(-j\omega \frac{E_0 f}{c_0} \right). \quad (8)$$

The steady-state transfer function in this approximation is independent of frequency if R is negligible compared to ωL . This is difficult to achieve because for loops small compared to λ the reactance ωL is a small number.

Loops have the advantage that no cathode follower with its inherent limitations is needed since the induced voltage is maintained across a very low impedance. However, as $R \rightarrow 0$ also $V_L \rightarrow 0$ and no useful response is obtained. Also, transient ringing due to circulating current waves may arise and no simple means to suppress them has been found without adversely affecting the behavior of the transfer function at low frequencies.

It should be noted that for a resistive load $R \gg \omega L$ as is the case if a transmission line of characteristic resistance $R_c \sim 50$ ohms is connected directly to a small loop, the response is

$$V_L \sim -j\omega \frac{E_o}{c_o} \dot{r} \quad (9)$$

This is again proportional to the time derivative of the incident wave.

It is interesting to compare the receiving response to the response of the same elements when used as transmitting antennas. For the linear dipole the radiated transverse component of the electric field in the far zone is

$$E_{\theta}^{\text{rad}} = j \frac{I \sqrt{\frac{\mu_o}{\epsilon_o}}}{2\pi r} e^{-j\beta r} F\left(\theta, \beta h, \frac{a}{h}\right), \quad (10)$$

where I is the current at the center of the dipole and $F\left(\theta, \beta h, \frac{a}{h}\right)$ is the field factor.¹² With the reciprocity relation

$$F\left(\theta, \beta h, \frac{a}{h}\right) = \beta h_e \left(\theta, \beta h, \frac{a}{h}\right) \quad (11)$$

and the substitution of the open-circuit generator voltage V_{oc} and the equivalent generator impedance Z_g , the radiation field of an electrically short dipole can be written as

$$E_{\theta}^{\text{rad}} = \frac{j\omega h V_{oc}}{\frac{1}{j\omega C_A} + Z_g} \frac{e^{-j\beta r}}{4\pi c_o r} \quad (12)$$

If the antenna is driven from a transmission line, in general, $Z_g \ll 1/\omega C_A$ and the field response corresponds to the second derivative of the driving voltage in time. In particular, this holds also if the equivalent generator impedance is capacitive $Z_g = 1/j\omega C_g$. This situation represents a special case of the following general theorem: the time derivative of the current response of an element when used to receive an incident electromagnetic field of arbitrary time dependence is proportional to the field response of the element when used as a transmitter provided the exciting voltage has the same time dependence as the incident electric field in the receiving case. Equal load and generator impedances are assumed in the derivation.¹

For a small loop antenna the transverse electric field in the far zone is¹³

$$E_{\phi}^{\text{rad}} = \frac{Z_o I \omega^2}{4\pi r c_o^2} f \sin \theta e^{-j\beta r} r \quad \left(Z_o = \sqrt{\frac{\mu_o}{\epsilon_o}} \right) \quad (13)$$

In terms of the driving voltage supplied by a generator of equivalent impedance Z_g

$$E_{\phi}^{\text{rad}} = \frac{Z_o f}{4\pi r c_o^2} V_{oc} \frac{\omega^2}{Z_g + j\omega L} \sin \theta e^{-j\beta r} \quad (14)$$

If the small loop is driven by a transmission line, in general, $Z_g = R \gg \omega L$ and the field response corresponds to the second derivative of the time dependence of the driving voltage. If, on the other hand, $Z_g \ll \omega L$, the field response is proportional to the first time derivative of the applied voltage. The reciprocity relation between receiving characteristics and transmission characteristics is satisfied.

A variety of modified examples of small antennas, including biconical and resistive antennas as well as resistively tapered antennas, is discussed in connection with the evaluation of measurements.

Large Antennas for the Observation of Transient Phenomena

Small antennas that are essentially high-impedance devices, such as linear dipoles or biconical antennas, are useful for the observation of rapid transient phenomena only in conjunction with a cathode follower. This limits the available output voltage to a fraction of a volt, independent of the strength of the electromagnetic signal. Since available amplifiers have frequency limits of about 300 Mc/sec (~ 3 -nanosecond rise time), oscillographic resolution of phenomena of 1-nanosecond duration or less requires sampling techniques. This in turn presupposes repetitive phenomena.

For the instantaneous display of nonrecurring rapid electromagnetic transient phenomena, voltages across the load of the order of 20 volts are required for sufficient deflection in the CRT without need of preamplification. For this application it is essential that the receiving antenna have an impedance which is sufficiently low to allow direct connection to a transmission line. Moreover, to avoid dispersion, the equivalent impedance must be independent of the frequency for frequencies within the transient spectrum. In principle, this can be achieved by using large wide-angle biconical antennas¹⁴ or Beverage-type antennas. This approach is not pursued further here since it could not be readily subjected to experimental test.

A different approach suggests the investigation of structures that are essentially nonresonant. Specifically, let σ be the volume conductivity of a thin conducting foil of thickness δ , small compared to the skin depth at all significant frequencies. Let the foil be infinitely extended in the transverse dimensions with its normal oriented parallel to the z -axis (Figure 3). If a plane electromagnetic disturbance with an arbitrary time dependence travels along the z -axis, a current is induced in the

Figure 3. Plane-wave transmission through a resistive foil

resistive foil. From the continuity conditions of electric and magnetic fields it follows

$$H_y^{(1)}(z=0) = (1-R) H_y^i \quad (15)$$

$$H_y^{(2)}(z=\delta) = T H_y^i,$$

where $H_y^{(1),(2)}$ denote the tangential magnetic fields, respectively, on the front and rear surfaces of the resistive foil, R and $T = 1 + R$ the reflection coefficient and the transmission coefficient for the freely suspended foil, and H_y^i the magnetic field of the incident disturbance. The induced surface current $\vec{K} = \hat{x} K_x$ has the same time dependence as the electric or magnetic field. Specifically,

$$K_x = \frac{2Z_o}{2R_s + Z_o} H_y^i = \frac{2}{Z_o + 2R_s} E_x^i; \quad R_s = \frac{1}{\sigma\delta}. \quad (16)$$

The potential difference between two points on the resistive foil separated by a distance d along the x -axis is

$$V_{oc} = R_s \cdot K_x \cdot d \quad (17)$$

and the equivalent generator impedance per unit width is $Z_g = R_s \cdot d$ ohms/m. If two electrodes of

width b (measured transverse to the current flow) are attached to the foil, to a good approximation

$$Z_g = \frac{R_s \cdot d}{b} \quad (18)$$

and, subject to the condition that the current is not seriously perturbed, the voltage across the load Z_L becomes

$$V_L = \frac{Z_L Z_g}{Z_L + Z_g} b \cdot K_x \quad (19)$$

The sensitivity of this receiving device is shown graphically in Figure 4 as a function of the surface resistance of the foil. In practice, the conducting foil can be made by depositing graphite on insulating cloth or a plastic, or it may consist of small lumped resistors arranged in a mesh if the grid constant is sufficiently small compared to the shortest significant wavelength.* In principle, the transverse dimensions of a foil should be larger than the distance traveled by light in the largest time period to be observed in order to avoid effects from the termination of the foil, hence for pulses with 60-nanosecond duration approximately 18 m in radius. The minimum dimensions may indeed be smaller due to the attenuation of contributions from the edges before reaching the connecting transmission line. These limits have not been clearly established, but excellent results have been obtained experimentally with much smaller foils for nonplanar field distributions.

This approach may be extended to tubular cylinders made from conducting foils of comparable thickness and surface resistance. It is shown in the appendix that the induced electric field tangent to

Figure 4. Relative potential difference on conducting foil for plane-wave incidence

* The value of the mesh resistor is the same as the surface resistance desired.

an infinitely long tubular cylinder of radius b when excited by a periodic plane wave linearly polarized in the axial direction and normally incident on the cylinder is given by

$$E^{\text{tang}}(r = b) = E^i \frac{R_s/Z_0}{\frac{R_s}{Z_0} - jk_0 b \ln \frac{2}{\gamma k_0 b}}, \quad (20)$$

where $\gamma = 0.5772$. The assumption $k_0 b \ll 1$ has been used. The open-circuit voltage between two points or circular lines spaced a distance d along the axis is $V_{oc} = E^{\text{tang}} d$. Subject to the restriction

$$\frac{R_s}{Z_0} \gg k_0 b \ln \frac{2}{\gamma k_0 b},$$

the open-circuit voltage is independent of frequency and the equivalent generator impedance is purely resistive.

It is interesting to note that the current on a perfectly conducting cylinder of radius a and infinite length is not frequency independent. From the rigorous formula applicable for equal orientation of the cylinder and axial polarization¹⁵ for small $k_0 a$, the following result is obtained:

$$K_z = \frac{E^i}{-jZ_0 k_0 a \ln \frac{2}{\gamma k_0 a}}. \quad (21)$$

To the limit of this approximation the current decreases monotonically with increasing frequency. Also, for a thin solid cylinder of finite conductivity, the current is frequency dependent.

Experimental System

In view of the difficulty of setting up in a laboratory space a transient radiation field with simple and known time dependence such as a unidirectional pulse of variable duration, the response of receiving elements to transient electromagnetic fields was investigated by means of the local field of TEM waves guided along an open transmission line. The experimental system is sketched in Figure 5. The transmission line consists of a single wire of radius $a = 0.15$ cm supported by a number of foamed polystyrene blocks at a height $b = 1$ cm above a metal ground screen. For all significant frequencies the field distribution corresponds to the static field that surrounds the equivalent Lecher system. It is also sketched in Figure 5. Note that the electric field is essentially normal, the magnetic field essentially tangent to the ground screen, for distance of 10 cm, 20 cm, and 30 cm to a height of 5 cm, 10 cm, and 15 cm, respectively. Within these limitations the local field may be considered a good approximation of a plane linearly polarized electromagnetic wave.

The dimensions of the ground screen are 12 feet x 4 feet and the length of the transmission line is 10 feet. It is terminated in its characteristic resistance $R_c = 60 \ln(2b/a) \approx 210$ ohms (for the image line).

Figure 5. Experimental system for observation of the transient response of antennas

The termination is not entirely perfect due to the inductive leads to the resistor and gives rise to a small reflection, which can be observed in the photographic displays to arrive several nanoseconds after the direct signal.

Unidirectional pulses with a short rise time and variable duration are obtained from a Mercury switch pulser that has a repetition rate of approximately 700 pps. They are led through a section of RG58U cable to a short vertical extension of the transmission line that is used as the feeder. Note that the cable must be sufficiently long so that no secondary reflections are observed during the time interval of interest. At a distance of 4 feet from the driven end of the image line, a series of holes has been cut into the ground screen at various distances from the transmission line to position the antenna under test.

For the measurement of transient reception by small antennas a cathode follower was constructed with a rise-time capability of approximately 0.5 nanosecond and an output impedance of 50 ohms. The circuit diagram is shown in Figure 6. The geometric dimensions are kept to a minimum. The grid connector of the tube (RCA 955) extends through a threaded jacket of 1-cm length directly through the ground screen for attachment of the antenna. All terminals of the tube are blocked for rf by small ceramic capacitors to avoid internal resonances as far as possible. The attenuation of the cathode follower is approximately 10 db, the input capacitance under operational condition was measured to be 3 μmf. The input is shunted by 2.2 megohms, which leads to a time constant of $\tau = RC \sim 6.6 \times 10^{-6}$ sec.

Hence, pulses with a duration of less than $1\ \mu\text{sec}$ are accurately reproduced, even if obtained from high-impedance devices. For longer pulses a gradual differentiation results. Some measurements were also carried out with a commercial cathode-follower probe (Tektronix P6025 CF). For a comparable rise time, it showed smaller spurious ringing. The output signal of the probe is led directly to the input of a sampling oscilloscope (Tektronix 611). The time base of the scope is

Figure 6. Cathode-follower circuit; rise time $\leq 1\ \text{nsec}$

triggered from the end of the pulse-forming cable of the pulse generator, connected to the trigger input through a resistor of 5 kilo-ohms and a series capacitor of $20\ \mu\text{f}$. This preserved the rise of the leading edge of the pulse. The pulse obtained from the pulse generator, the same pulse observed on the transmission line by means of a passive probe (Tektronix P6026, frequency limit 800 Mc/sec) and by either of the cathode followers, connected directly to the transmission line is shown in Figure 7. The distortion due to the junction between transmission line and feeding cable is seen to be negligible. In Figure 7 as well as all subsequent oscilloscope traces the time scale is from right to left.

In order to investigate the transmission characteristics of antennas, the single-wire transmission line was removed and the inner conductor of the coaxial-line output of the pulse generator was extended directly to the terminal of the driven antenna. The receiving system remained essentially unchanged.

Figure 7. System response for step-function input; $1\ \text{nsec/div}$

- (a) direct observation
- (b) step-on transmission line, passive probe
- (c) step-on transmission line, Tektronix cathode follower
- (d) step-on transmission line, laboratory built cathode follower

Experimental Results and Discussion

The response of short linear antennas to electromagnetic fields with a step-function time dependence was measured first as a function of the half length h of the dipoles. The results are reproduced in Figure 8 for a spacing of 10 cm from the transmission line. As outlined before, the transient ringing due to the dipole resonances is clearly seen to be superimposed on the steady-state response. For the shortest dipole used, $h = 1$ cm, the ringing is not sufficiently resolved and partially lost by noise. As the dipole length increases, the period of the oscillations increases proportionally. For a longer dipole, $h = 50$ cm, the first resonance frequency f_r is about 150 Mc/sec, the next resonance near 450 Mc/sec and further resonances at $(2n + 1)f_r$, ($n = 1, 2, \dots$). Hence, the contributions from at least the first three resonances are contained in the response which shows characteristic ringing with a saddle-type appearance. The responses for dipoles with lengths of $h = 20$ cm and $h = 50$ cm are quantitatively incorrect since the field deviates markedly from a plane wave. The effect of a nonplanar field is shown in Figure 9 where the steady-state amplitude of the response to an input signal in the form of a step function is shown plotted against the dipole length. According to Equation (5), the response should vary in a manner proportional to h^m where $m > 1$ due to the increase in antenna length and antenna capacitance. It is seen that for the chosen distance (10 cm) away from the transmission line, for $h \geq 10$ cm, the amplitude rises much more slowly than calculated for an antenna in a plane-wave field. The secondary response, arriving with a delay of about 13 nanoseconds, arises from the residual reflection at the termination of the transmission line. A slight ringing with approximately a 1.5-nanosecond period is also due to internal resonances in the cathode follower and is superimposed on the antenna ringing. This distortion becomes less pronounced for longer antennas since the loading of the input of the cathode follower by a smaller equivalent generator impedance of the antenna tends to reduce the spurious resonances.

Figure 8. Response of linear monopoles above a ground screen to step-function field. Base loaded by cathode follower, $C = 3 \mu\text{f}$, time scale 2 nsec/div

(a) $h = 50$ cm,	50 mv/div	(d) $h = 5$ cm,	10 mv/div
(b) $h = 20$ cm,	50 mv/div	(e) $h = 1.9$ cm,	2 mv/div
(c) $h = 10$ cm,	20 mv/div	(f) $h = 1$ cm,	0.6 mv/div

Figure 9. Steady-state output voltage of base-loaded monopole as a function of antenna length; distance from transmission line is 10 cm

The effect of a damping series resistor placed at the base of the antenna is demonstrated in Figure 10A for a constant length ($h = 5$ cm). In accordance with theory, the transient ringing is increasingly suppressed for larger values of the resistance. The optimum value is close to 200 ohms for which a maximally flat steady-state transfer function was also calculated for antennas with $\Omega = 10$. The effect of the radius of the antenna is not very critical. The optimum resistance tends to be smaller for fatter antennas. For resistances beyond 500 ohms, the rise time of the pulse response is substantially increased corresponding to a drop of the transfer function at higher frequencies. For nearly optimal loading, the response is shown on an enlarged time scale (10^{-9} sec/div in Figures 10f and 10g) taken with the laboratory built cathode follower and the commercial probe. The residual ringing is entirely due to the cathode followers. The same response for a longer antenna where the internal ringing is reduced is shown in Figure 10B (dipole half length $h = 13$ cm). If the antenna is placed further from the transmission line, the response remains unchanged for the shorter antennas except in amplitude.

A similar result is obtained if the damping resistor is distributed over the length of the antenna rather than lumped at the base. Measurements are reproduced in Figure 11 for antennas consisting of

(a)

(f)

(b)

(g)

(c)

(d)

(e)

Figure 10A. Response of linear monopoles above a ground screen to step-function field. Base loaded by cathode follower, $C = 3 \mu\text{mf}$ in series with resistor R , $h = 5 \text{ cm}$.

- (a) $R = 0$, 2 nsec/div, 10 mv/div
- (b) $R = 100 \text{ ohms}$, 2 nsec/div, 10 mv/div
- (c) $R = 200 \text{ ohms}$, 2 nsec/div, 5 mv/div
- (d) $R = 500 \text{ ohms}$, 2 nsec/div, 5 mv/div
- (e) $R = 2000 \text{ ohms}$, 2 nsec/div, 5 mv/div
- (f) $R = 380 \text{ ohms}$, 1 nsec/div, 8 mv/div
- (g) $R = 380 \text{ ohms}$, 1 nsec/div, 8 mv/div
(Tektronix cathode follower)

Figure 10B. Same as Figure 10A; $R = 300 \text{ ohms}$, $h = 13 \text{ cm}$, Tektronix cathode follower, time scale 1 nsec/div and 2 nsec/div, 20 mv/div

Figure 11. Response of resistively tapered monopoles above a ground screen to step-function field. Base loaded by cathode follower, $C = 3 \mu\text{f}$, $h = 6.5 \text{ cm}$, 2 nsec/div , 10 mv/div .

- (a) $R = 0$
- (b) 25 - 50 - 100 - 200 - 400 ohms
(1/2-watt resistors)
- (c) 50 - 100 - 200 - 400 - 800 ohms
(1/2-watt resistors)
- (d) 100 - 200 - 400 - 800 - 1600 ohms
(1/2-watt resistors)
- (e) 200 - 400 - 800 - 1600 - 3200 ohms
(1/2-watt resistors)

four 1/2-watt carbon resistors soldered in series with resistance values staggered from low values near the base to high values near the tip. The half length of the antenna in this case is 6.5 cm, and the response is compared to a conducting wire of equal length. Note that for optimum response the value of the resistor at the base is lower than the optimum value found for an antenna with a single lumped resistor at the base.

If a short dipole antenna is loaded by a resistive element rather than by a high-impedance cathode follower, the response consists of a single sharp spike corresponding to the time derivative of the applied step-function signal (Figure 12). For long dipoles resistively loaded at the base, the response will in general show ringing resulting from multiple reflections at the dipole ends. For a dipole of infinite length, multiple reflections cannot occur in a finite time interval, and the response consists of a sharp rise followed by a gradual decrease of the voltage across the load (Figure 13). For this case, the measured response is quantitatively incorrect due to the nonplanar field. It shows, however, that with an increasing load resistance a more faithful reproduction of the transient field is approached. The noise level, increasing with load resistance, is due to the reception of radio stations.

The behavior of small antennas with high input impedance in the significant frequency range is essentially similar and relatively little affected by the detailed geometry of the antenna. The response of a short half dipole ($h = 1.2 \text{ cm}$) with capacitive end loading in the form of a circular metallic disk with a radius of 1 cm, oriented parallel to the ground screen is shown in Figure 14. The resonance ringing can again be eliminated by a damping resistor at the base in series with the input of the cathode follower. The sensitivity of this "capacitive" probe is equal to the sensitivity of a half dipole with $h = 5 \text{ cm}$.

Figure 12. Response of linear monopole above a ground screen to step-function field. Base loaded by transmission line, $R_c = 50$ ohms, 1 nsec/div.

- (a) $h = 1$ cm
- (b) $h = 2$ cm
- (c) $h = 10$ cm

Figure 13. Response of semi-infinite monopole above a ground screen to step-function field; 2 nsec/div, 50 mv/div, base load:

- (a) 50 ohms
- (b) 200 ohms
- (c) 560 ohms
- (d) 10,000 ohms

Figure 14. Response of capacitively top-loaded monopole above a ground screen to step-function field; time scale 1 nsec/div, base load:

- (a) cathode follower
- (b) cathode follower + 180 ohms in series
- (c) cathode follower + 820 ohms in series

The response of a half biconical antenna with a flare angle that was varied from 0.05 radian to 0.73 radian and a half-length of $h = 10$ cm is shown in Figure 15. In this case the distance to the transmission line is 30 cm so that reasonable homogeneity of the incident field can be assumed. With increasing flare angle, the transient ringing which is superimposed on the step response is seen to die out more rapidly and the period of the ringing frequency is lengthened according to the longer optical path along the hemispherical top of the cone. The two antennas with smallest flare angles were made of solid stock, the cones with larger flare angles were folded from brass sheet and the top soldered to the cone. Also, wooden cones with conducting silver paint were tested with substantially similar results. As for the dipole, the transient ringing can be suppressed by means of a base resistor. For the antennas with flare angles of 0.1 radian and 0.4 radian, the response with a 220-ohm series load is shown in Figure 16. The rise time for the narrower cone is seen to be slightly superior. For the wider cone a shorter rise time would be obtained with a lower damping resistance. This indicates that the optimum load resistance tends to decrease slightly with increasing flare angle of the antenna.

The sensitivity of probes to transient signals can be raised by increasing the effective capacitance between the antenna and the ground screen. This is shown in the case of the biconical structure. As a similar example, the antenna may be surrounded by a dielectric with a relative dielectric constant $\epsilon_r > 1$. The response of an antenna immersed in a dielectric cone of polystyrene, $\epsilon_r = 2.5$, with a flare angle of 0.1 radian is shown in Figure 17. The cone is mounted to resemble a conventional biconical antenna. It is noteworthy that in the absence of a damping resistor the transient ringing is very pronounced and sustained for longer times than for the simple metallic wire. This is in part explained in terms of trapped waves traveling along the antenna

Figure 15. Response of conical monopole above a ground screen to step-function field; $h = 10$ cm, 2 nsec/div, cathode-follower base load:

- (a) linear dipole
- (b) 0.05 radian
- (c) 0.1 radian
- (d) 0.27 radian
- (e) 0.4 radian
- (f) 0.73 radian

Figure 16. Response of conical monopole above a ground screen to step-function field. Base loaded by cathode follower in series with resistor $R = 220$ ohms, 2 nsec/div, $h = 10$ cm

- (a) 0.1 radian
- (b) 0.4 radian

Figure 17. Response of monopole covered with dielectric cone of 0.1 radian to step-function field; 2 nsec/div, $h = 10$ cm, base load:

- (a) cathode follower
- (b) cathode follower + 200 ohms in series

with reduced loss in the form of reradiation. Also, the period of transient ringing is lengthened due to a reduced phase velocity in the dielectric medium. In a different configuration the capacitance of a linear antenna is increased if a number of transverse wire sections are attached to the main antenna, their spacing and their length increasing toward the tip of the antenna (log-periodic antenna). The response is reproduced in Figure 18 for various load conditions. The classification of this type of antenna as "broadbanded" is meaningless if the antenna dimensions are small compared to the shortest wavelength contained in the signal spectrum.

The response of small wire loops is frequency independent only in the limiting case of negligible load resistance. A series of measurements using circular half-loops to measure an electromagnetic signal with a pulse-shaped time dependence (20-nanosecond pulse duration) is shown in Figure 19. The terminal of the loop is connected directly to a coaxial transmission line and the desired resistance adjusted by shunting small lumped resistors. For both sizes of loops the differentiation of the pulse shape is clearly visible. As predicted by theory the true pulse shape is best approximated with a load that has the lowest resistance (2 ohms). Also, the reproduction of low frequencies, as illustrated by the flatness of the top of the pulse, is superior for larger loops owing to the larger value of the self-inductance. It is also clearly evident, however, that a significant transient ringing is superimposed on the response. Similar to the ringing for dipole antennas, the transient response in loops is due to circulating currents along the wire. The transient ringing is partly clouded in the exposures with long time base. It is shown in more detail in Figure 19B and can be seen to exceed the desired signal in amplitude. If the current response for slowly varying signals is to be preserved, no simple scheme to suppress the loop resonances has been found. A resistive loading, which can be used successfully for linear antennas, immediately leads to a differentiation of the pulse top. If the loop is made even smaller, i. e., $\phi < 3$ cm, the load resistance would have to be reduced too, and the useful amplitude would become too small. In addition, pick-up between the junction and the transmission line may become the overwhelming contribution. In a different approach the inductance of the loop may be increased, for example,

(a)

(b)

(c)

(d)

Figure 18. Response of log-periodic antenna above a ground screen to step-function field; $h = 10$ cm, 2 nsec/div, base load:

- (a) resistor 50 ohms
- (b) cathode follower, $C = 3 \mu\mu f$
- (c) cathode follower, $C = 3 \mu\mu f$ in series with resistor 200 ohms
- (d) cathode follower, $C = 3 \mu\mu f$ in series with resistor 300 ohms

(a)

(b)

(c)

(d)

(e)

(f)

Figure 19A. Response of half-loop above a ground screen to step-function field; 5 nsec/div, magnetic field parallel to loop normal

- (a) diameter 6 cm, load 10 ohms
- (b) diameter 6 cm, load 3.3 ohms
- (c) diameter 6 cm, load 2 ohms
- (d) diameter 3 cm, load 10 ohms
- (e) diameter 3 cm, load 3.3 ohms
- (f) diameter 3 cm, load 2 ohms

Figure 19B. Same as Figure 19A with diameter 6 cm, load 2 ohms, 1 nsec/div

by introducing a ferrite core. Preliminary measurements showed a slight improvement of pulse shape for a given loop diameter and load resistance. The permeability of the ferrite core is significantly larger than the permeability of free space for frequencies below about 100 Mc/sec. Hence, the impedance of the loop is increased for those frequencies, and stays more nearly constant as a function of frequency. The introduction of dispersive cores may warrant further investigation.

Clearly, small loops with different geometric shapes (such as rectangular loops) will have a behavior similar to that of circular structures.

In order to test the feasibility of measuring the currents induced in a thin conducting foil of large transverse dimensions, a section of conducting cloth ("Uscon," U. S. Rubber, 4 feet wide, 3 feet high) with an average surface resistance of 800 ohms/square was suspended from a wooden frame normal to the ground screen. Electrical contact to the transmission-line wire and to the image plane was achieved by painting the edges with conducting silver solution. A section of 50-ohm coaxial transmission line, connected directly to the oscilloscope, was led through the ground screen about 1 cm behind the conducting foil. The inner conductor of this cable was extended to a height of 2 cm and brought into electrical contact at the rear face of the foil. The response obtained for three different distances of the pick-up point away from the transmission line is shown in Figure 20. The response is perfect for a small distance of 10 cm and for a 20-cm distance from the line. Some degrading is visible for the largest distance used, 30 cm from the line. It should be noted that this point is also only 30 cm away from the edge of the foil and the edge of the ground screen, where reflections may arise. The degrading also may be due to strong inhomogeneities of the foil, the surface resistance varying between 400 and 1000 ohms/square. No differentiation in pulse amplitude occurs for longer pulses.

The theoretically equivalent structure of a long, hollow, lossy cylinder could not be tested appropriately because of the amplitude distribution of the exciting field. For the inhomogeneous field surrounding the image line, a rapid rise followed by a slow drop in signal level was observed for a step-function signal. The drop-off is believed to be caused by the decrease with height above the ground screen in the axial component of the electric field.

(a)

(b)

(c)

Figure 20. Voltage across terminals on conductive foil for normally incident step-function field; $R_s \sim 800$ ohms, inner conductor RG58U cable connected at a height of 2 cm above a ground screen, 1 nsec/div, distance from transmission line

(a) 10 cm, 50 mv/div

(b) 20 cm, 20 mv/div

(c) 30 cm, 10 mv/div

Either the measurement of current induced in a conducting foil or a small dipole antenna with base resistor in conjunction with a cathode follower allows accurate measurement of the transient electromagnetic field set up by a driven antenna. For convenience, and in order to eliminate spurious ringing in the electronic devices, the signal radiated from antennas driven by unidirectional signals with step-function time dependence was measured with the passive resistive-foil system. Space limitations allowed only a 4-foot distance between driven antenna and point of observation so that only the results for small antennas are representative for far-zone field responses.

For linear antennas, the far-zone field response due to a step-function excitation was computed previously for various generator resistances.¹ Due to multiple reflections of current waves on the antenna, the theoretical response depends critically on the generator impedance. Experimental results are recorded in Figure 21. For the shortest antenna, $h = 9$ cm, the effect of the first resonance in the transfer function at about $f_r \sim 820$ Mc/sec is overwhelming. Higher resonances do not contribute as their frequency lies well beyond the resolution of the oscilloscope. When the antenna length is increased to $h = 20$ cm, the contribution of frequency components near the next resonance at $3f_r \leq 1125$ Mc/sec is also resolved. The observed response may be compared directly with the computed result, Figure 3 in Reference 1, where a cut-off near $3f_r$ was used in the graphical integration of the Fourier-decomposed response. The equivalent generator impedance for the experimental result is 100 ohms, while in the computed curve $R_g = 0$ has been assumed resulting in a longer transient ringing. As the dipole length is further increased, the time between reflections from the antenna tips becomes longer and the response, including the contributions from an increasing number of resonances, approaches a sequence of alternating pulses damped out slowly in time.

Figure 21. Radiation field of linear monopole above a ground screen excited by step-function voltage; $R_g = 50$ ohms, 1 nsec/div

(a) $h = 9$ cm

(b) $h = 20$ cm

(c) $h = 40$ cm

For a number of applications the transmission of simple transient waves is of interest. This requires the suppression of the long persisting transient ringing of the antenna. To a limited degree this can be achieved by introducing a resistor at the base of the antenna. The value is to be chosen so as to absorb as completely as possible the transient wave reflected at the antenna tip and returning to the base of the dipole. Its value is in general of the same order of magnitude as the optimum base load for a receiving antenna,* hence for $\Omega = 10$ approximately 300 ohms in each branch of the dipole.

* It is different due to the assumption that the transmitting antenna is driven by a transmission line with an ohmic resistance, while for the receiving antenna the cathode follower represents a capacitive termination.

The measured transmitting response of a dipole ($h = 10$ cm) and for two biconical antennas is shown in Figure 22. The shape of the response for the dipole agrees precisely with the calculated result (Reference 1, Figure 5). It represents the radiation associated with a charge concentration traveling first toward the antenna tip (positive peak) and after reflection traveling back toward the base (negative peak) where it is neutralized completely. If the dipole is sufficiently short, the radiated field corresponds precisely to the input signal differentiated twice with respect to time. Note that for a biconical antenna the optimum resistance is higher than for a straight dipole; it increases with increasing flare angle.

Clearly, if a single unidirectional pulse is to be transmitted, the reflection of the wave traveling along the conductor toward the tip must be made negligible. Similar to the gradual absorption of electromagnetic waves in media with stratified conductivity this may be approximated by providing the dipole with a tapered axial resistivity. In the simplest form, the antenna is made of a string of small lumped carbon resistors with resistance values increasing in some form of stratification toward the antenna tip. Some characteristics of such an antenna may be inferred from its similarity to a transmission line. In particular, it is necessary for the antenna to have a certain minimum length since the length of the resistive taper must be comparable to a quarter wavelength if it is to be effective. Hence, for an antenna of finite length the suppression of the negative peak is never quite complete. There are always frequency components below some "cut-off" frequency which are reflected. If the resistive taper extends over the entire length of the antenna, the negative peak should be smoothed out with increasing antenna length. This is clearly shown to be the case in the experimentally observed transient radiation field of a dipole with a linear taper of resistivity and a half-length $h = 40$ cm (Figure 23). The slight residual negative response is likely to be further reduced for longer antennas. Due to spacial limitations this was not pursued further.

Figure 23. Radiation field of a resistively tapered monopole above a ground screen excited by step-function voltage; 1 nsec/div, $h = 40$ cm, 30 resistors (1/2-watt) from 10 ohms to 300 ohms in steps of 10 ohms

Figure 22. Radiation field of short base-loaded antennas above a ground screen excited by step-function voltage; 1 nsec/div, $h = 10$ cm

- (a) linear monopole, $R_g = 270$ ohms
- (b) conical monopole, 0.26 radian, $R_g = 380$ ohms
- (c) conical monopole, 0.73 radian, $R_g = 610$ ohms

The suppression of the reflection from the tip of the antenna is also confirmed by direct observation of the reflection of transient signals from the input terminals in a manner reported in Reference 4. Experimental results for linear antennas driven by a 50-ohm coaxial cable are shown in Figure 24. Each picture represents a superposition of exposures of the reflected response obtained with an open-circuit termination of the coaxial line and a termination in the antenna under test. For the unloaded linear metallic antenna an initial reflection occurs directly at the input terminal. Part of the transient signal travels along the antenna wire and, after reflection at the antenna tip, re-emerges into the coaxial transmission line. This is shown by the delayed subsequent rise resulting in voltages in the transmission line exceeding those for a perfect reflection at an open end. The following drop in the reflection response (Figure 24 (a)) results from multiple reflections. If a base load is introduced (Figure 24 (b)), the reflected current wave is attenuated. It is also noted that no multiple reflections arise. Finally, for a tapered resistive antenna no reflection from the antenna tip is observable for sufficiently high values of resistance per unit length. The total signal reflected from the antenna shows a gradual and continuous rise ultimately approaching the value for an open circuit, since the antenna impedance in the steady state is infinite for direct current.

The transmitting response of a loop antenna is more complex and depends also on the orientation of the loop with respect to the direction of observation. Results for a circular loop driven by a coaxial line with a signal consisting of a step-function time dependence are shown in Figure 25. As for the dipole antenna, ringing occurs; it may be interpreted in detail by consideration of the traveling wave of charge accumulation and appropriately taking into account the delay due to the varying optical distance between the charge wave front and the point of observation. A theoretical investigation of the transient response of a driven loop has not yet been reported. For the symmetrical position, if the plane of the loop is directed toward the point of observation, the amplitude of the response decreases with decreasing size of the loop and the time sequence of the response approaches the third time derivative of the input signal. If the circular loop is series loaded by a resistor at the point opposite the driven terminal, the reflection at this point may be nearly eliminated, similar to the termination of a Lecher system in its characteristic resistance. The transient response in this case is determined by a single current wave traveling along the loop first upward and subsequently downward, to be ultimately absorbed in the resistor. The transmitting response resembles that of a base-loaded dipole and is reproduced in Figure 26. Also, for a symmetric position of the loop, the resulting positive and negative peaks are symmetric.

Figure 24. Reflection of a voltage wave with step-function time dependence from open-circuit termination of transmission line and from transmission line terminated by antenna above a ground screen; 1 nsec/div, $h \sim 40$ cm

- (a) unloaded metallic linear antenna ($a \sim 1$ mm)
- (b) base loaded metallic linear antenna ($a \sim 1$ mm), $R = 300$ ohms
- (c) resistively tapered antenna, as in Figure 23.

Figure 25. Radiation field of half-loop above a ground screen excited by step-function voltage; 1 nsec/div, $R_g = 50$ ohms, $a = 1$ mm; I: $\phi = 30$ cm, II: $\phi = 10$ cm, III: $\phi = 5$ cm

- (a) loop normal toward observer
- (b) driven end toward observer
- (c) driven end away from observer

If the driven end is nearer to the observer, the additional delay increases the time separation between the oppositely directed peaks. If the driven end is away from the observer, the time spacing is decreased.

Applications

The frequency-independent response of short base-loaded dipoles to transient electromagnetic fields and the possibility of setting up electromagnetic fields with pulse-shaped time dependence using a resistively tapered antenna allows a study of the reflection, scattering and transmission of such signals by simple or complex obstacles. In the experimental set-up, the size of the available ground screen was relatively small and diffraction from the edges resulted in interferences at the point of observation early after passage of the direct radiated signal. With a distance of about 3 feet between the transmitting antenna and the receiving probe, the response as a function of time for a step-function driving signal is shown in Figure 27. The direct pulse is seen to be followed with some delay by more

Figure 26. Radiation field of circular half-loop above a ground screen excited by step-function voltage; 1 nsec/div, $\phi = 15$ cm, $R_g = 50$ ohms, end load $R = 220$ ohms

(a), (b), and (c) same as in Figure 25

(a)

(b)

(c)

Figure 27. Scattering of short video pulses.

Transmitting antenna: resistively tapered monopole, $h = 40$ cm; receiving antenna: short base-loaded dipole; 1 nsec/div

- (a) scattering from edges of ground screen
- (b) reflection from metallic reflector 8" behind receiving antenna
- (c) backscattering from metallic circular cylinder ($\phi = 5$ ") 8" behind receiving antenna

(a)

(b)

Figure 28. Scattering of step-function field from linear parasitic antenna above a ground screen. Shown is step-function response in the absence of parasitic antenna and superimposed effect of resonance scatterer; $h = 11$ cm, distance 30 cm, 2 nsec/div, measured in near zone of transmission line field

- (a) unloaded parasite
- (b) parasite base loaded with $R = 50$ ohms

or less random oscillations due to scattering from the edges of the screen and the surrounding walls. If a metallic reflector is placed 8 inches behind the probe (Figure 27 (b)), the reflected pulse with inverted amplitude has a delay of approximately 1.4 nanoseconds, clearly separated from the direct pulse. A long circular cylinder ($\phi = 5$ inches) placed behind the probe also leads to a back-scattered pulse with reversed and much-reduced amplitude (Figure 27 (c)). More detailed investigations have also been made on the time behavior of the diffracted field in the shadow zone of cylinders.

If the scattering element is resonant in nature, the scattered field will show the characteristic ringing associated with one or more resonances. A particular situation involves the scattering from a linear dipole which may also be considered as the response of the probe in the presence of a parasitic element. To avoid the effect of the edges of the ground screen, an experiment was carried out with the near field surrounding the open transmission line. Both the probe and the parasitic scatterer were placed at a transverse distance of 20 cm from the transmission line, displaced axially by approximately 30 cm. The transmission line was driven by a step-function signal. Figure 28 shows superimposed the response of the probe with and without the parasitic element (half-length 11 cm). In the absence of the parasitic element the step function is well reproduced, disturbed only slightly by spurious responses in the cathode follower. The small dip in the amplitude at later times is due to reflections from the imperfect termination of the transmission line. The presence of the parasitic element produces a superimposed ringing response due to current waves induced in the parasite and reversed in direction

(a)

(b)

(c)

Figure 29. Response of base-loaded monopole in a radome to step-function field above a ground screen; 2 nsec/div

- (a) response without radome
- (b) response inside radome (1/4" plexiglass walls)
- (c) response inside radome as in (b) with conducting layer (salt water)

after reflection at the tips of the antenna. It is seen that even a small resistive loading (50 ohms) at the base of the parasitic monopole reduces the ringing significantly. Similar measurements with reactive loading of scatterers are of interest in the practical problems associated with the reduction of back-scattering from cylindrical objects over a wide frequency range.

In practice it is often desirable to place the receiving element in a radome. The presence of thin dielectric walls does not visibly affect the transient response of the field probe, as is inferred from Figure 29. The short loaded dipole was surrounded by an enclosure of 1/4-inch plexiglass, $\epsilon_r = 2.56$, at an average distance of about 4 inches. If the surfaces of the radome are covered with a conducting layer (salt water), the response quickly degenerates (Figure 29 (c)). Here tissue paper saturated with 0.5 molar KCl solution corresponding approximately to sea water was placed on the outside of the radome. Essentially the low-frequency components are cut out and the pulse top shows a characteristic drop in voltage level. The dispersion of short video pulses in conducting media has been investigated more thoroughly in a recent paper.¹⁶

The transient field probe can be used to investigate other repetitive transient disturbances. As a simple example, the field radiated by a short spark, maintained between the contacts of a conventional relay placed above the ground screen, has been observed (Figure 30). Since the detailed nature of the electromagnetic transient process depends on many parameters including the geometry of the relay, no discussion is attempted here. The response resembles that of a small transmitting loop, as would be expected in view of the current path in the relay when this is closed suddenly by the spark. It is noteworthy that the rise time is equal to or less than 0.5 nanosecond, the limit of the cathode follower and the oscilloscope.

Figure 30. Electromagnetic transient disturbance radiated by simple relay, measured with base-loaded monopole above a ground screen; 1 nsec/div

Conclusion

The experimental observation of transient electromagnetic fields with complex frequency spectra and arbitrary time dependence is made difficult by the transient oscillations occurring in the antenna system and the generally reduced sensitivity at low frequencies. Where repetitive transient fields are to be measured accurately, a sampling system can be used with inherent sensitivities of about 1 mv for useful deflections on the cathode-ray tube. Hence, cathode followers can be inserted into the circuit. Short electric dipoles, biconical antennas, and other essentially high-impedance antennas can be used successfully for the observation of transients if terminated by a cathode follower and the transient ringing is suppressed by a damping resistor at the base. Rise times of less than 1 nanosecond are obtained for such receiving systems.

For the observation of nonrepetitive transient fields it is either necessary to amplify the output of the cathode follower which will limit the resolution to about 3 nanoseconds (i.e., Tektronix oscilloscope 585), or to use receiving devices with low input impedance, where the signal can be led directly to a transmission line and subsequently to the deflection plates of an oscilloscope. The currents and potential differences induced by the transient field in an essentially nonresonant device such as a plane conducting foil can be used for this purpose.

The observed transmission of transient electromagnetic signals from simple radiating structures is in excellent agreement with calculated results. For the purpose of radiating signals with a simple time dependence, such as a video pulse, the reflection of charge waves from discontinuities on the antenna can be avoided by using resistive tapers. The theory of such structures forms a difficult problem which has not been treated yet.

Due to space limitations, antennas that are large compared to the longest wavelength in the significant part of the spectrum could not be investigated. For practical purposes, such as the observation of electromagnetic phenomena associated with nuclear explosions, these may offer advantages.¹⁷ The question of antenna arrays operated with broadband signals is also of increasing importance in establishing scanning limits in phased arrays.

The investigation of scattering and diffraction of short pulsed signals by complex objects has implications for target discrimination in radar. Experiments again require a larger free-space environment.

APPENDIX

The linearly polarized plane wave incident on the cylinder may be expanded in terms of cylinder functions

$$E_z^{\text{inc}} = E_o e^{-j\omega t} \sum_{m=0}^{\infty} \epsilon_m j^m J_m(k_o r) \cos m\phi$$

$$\epsilon_m = 1 \quad \text{for } m = 0$$

$$\epsilon_m = 2 \quad \text{for } m \neq 0$$

For small radii of the tubular cylinder of inner radius a and outer radius $b = a + \delta$, no azimuthal dependence exists, hence only terms with $m = 0$ need be considered. In the exterior, the scattered field is

$$E_x^{\text{sc}} = e^{-j\omega t} S_o H_o^{(1)}(k_o r) \quad r \geq b.$$

In the interior of the conducting layer,

$$E_z^{(1)} = e^{-j\omega t} \left[A_o H_o^{(1)}(k_i r) + B_o H_o^{(2)}(k_i r) \right] \quad a \leq r \leq b$$

and in the interior of the tube,

$$E_z^{(2)} = C_o J_o(k_o r) e^{-j\omega t}.$$

The tangential magnetic field is given in terms of the electric field

$$H_\phi = -\frac{1}{j\omega\mu} \frac{\partial E_z}{\partial r}.$$

The propagation constant inside the conducting material is denoted as k_i . If $R_s = 1/\sigma\delta$ is finite and $\delta \ll b$, it holds that $k_i b \gg 1$, $k_i a \gg 1$, and the Hankel functions may be replaced by their asymptotic expressions for large arguments. The boundary conditions for the tangential field components at the surface $r = a$ and $r = b$ yield in this case ($k_i b \gg 1$, $k_o b \ll 1$)

$$E_o - jS_o \frac{2}{\pi} \ln \frac{2}{\gamma k_o b} = A_o \frac{e^{jk_i b}}{\sqrt{\frac{\pi}{2} k_i b}} j^{-\frac{1}{2}} + \frac{B_o e^{-jk_i b}}{\sqrt{\frac{\pi}{2} k_i b}} j^{\frac{1}{2}} \quad (A1)$$

$$\frac{A_o e^{jk_i a} j^{-\frac{1}{2}} + B_o e^{-jk_i a} j^{\frac{1}{2}}}{\sqrt{\frac{\pi}{2} k_i a}} \sim C_o \quad (A2)$$

$$A_o e^{jk_i a} j^{-\frac{3}{2}} + B_o e^{-jk_i a} j^{\frac{3}{2}} \sim 0 \quad (A3)$$

$$\frac{k_o}{j\omega\mu} E_o \frac{k_o b}{2} + \frac{S_o k_o}{j\omega\mu} \left(\frac{-j2}{\pi k_o b} \right) = \frac{k_i}{-j\omega\mu} \left[-A_o \frac{e^{jk_i b}}{\sqrt{\frac{\pi}{2} k_i b}} j^{-\frac{3}{2}} - B_o \frac{e^{-jk_i b}}{\sqrt{\frac{\pi}{2} k_i b}} j^{\frac{3}{2}} \right] \quad (A4)$$

The amplitude B_o is substituted in terms of A_o from Equation (A3). Equation (A1) is divided by Equation (A2) and the exponential function

$$e^{-2jk_i(l-a)} = e^{-2jk_i\delta}$$

is expanded for small values of $k_i\delta$. For the amplitude of the scattered wave, the following result is obtained:

$$S_o = \frac{\pi}{2} \frac{E_o}{j \ln \frac{2}{\gamma k_o b} - \frac{R_s}{Z_o} \frac{1}{k_o b}}$$

This reduces to the result for the thin metallic cylinder of radius b if $R_s = 0$. No scattering results if $R_s \rightarrow \infty$. The total electric field strength on the outside of the cylinder is

$$E^{\tan}(r=b) = E_o + S_o \left(-j \frac{2}{\pi} \ln \frac{2}{\gamma k_o b} \right) = \frac{E_o \frac{R_s}{Z_o}}{\frac{R_s}{Z_o} - j k_o b \ln \frac{2}{\gamma k_o b}}$$

For $k_o b = 0.1$, the value of the frequency-dependent term in the denominator is 0.241. It decreases rapidly in significance with decreasing values of $k_o b$.

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