Interaction Notes

Note 200

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Electromagnetic Dimensional Scale Modeling

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ABSTRACT

Analytical techniques are available to estimate the induced and scattering energies in certain simple structures. For more complicated structures, such techniques are either difficult to perform or cannot result in answers that are sufficiently accurate. Thus, complete systems are tested in simulated EM fields. In the case of very large systems, even full-scale testing cannot be performed because simulators cannot completely illuminate the system with EM energy.

Electromagnetic dimensional (or geometric) scale modeling is an accepted technique that has been used by antenna designers to solve complicated electromagnetic problems in analog form. This technique can be applied to transient EM problems by scaling the rise and fall times of the transient EM environment.

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1 APPLICATION TO EMP HARDNESS TESTING

With geometric scale modeling, it is possible to define the response of very large and complex systems to an EM transient prior to actual testing. This ability is of particular importance if a premium is placed on test facilities or equipment availability. The results of scale modeling tests can lead to better placement of sensors or can define the effects of test instrumentation on the actual test results. They can also be used to determine the worst-case and best-case orientations and simulator field distortions caused by the system being tested. These effects are important in defining the threat relatability of the actual system tests. EM scale modeling can assist the analyst in estimating the responses of complex systems and provide insight into the electromagnetic behavior of the system. Scale modeling is also very useful for defining waveforms for testing by direct injection.

EM dimensional scale modeling is most useful when macroscopic modeling is used to determine the overall response characteristics of the system as illustrated in Figure 1. Macroscopic modeling can be used to determine the surface currents on the exterior surfaces of the system, current on conducting penetrations into the system, and the electric and magnetic fields external to the system. The conducting surfaces of the system including the effects of ground and ground conductivity can be modeled. Microscopic weaknesses in the system such as cracks or imperfections in shields, or in effectiveness of gasket materials on hatches cannot be evaluated using dimensional scale modeling. Dimensional scale modeling is most useful when the scaling is chosen so that the measured EM coupled energies result from first-order effects on the model.

2 GEOMETRICAL SCALING

A full-scale system can be described by spatial coordinates x, y, z, time coordinate t, and electric and magnetic field vectors $E(x, y, z, t)$ and $H(x, y, z, t)$. The corresponding quantities in the model system are primed. There are scale factors that relate the full-scale to the model system quantities such that:[1]

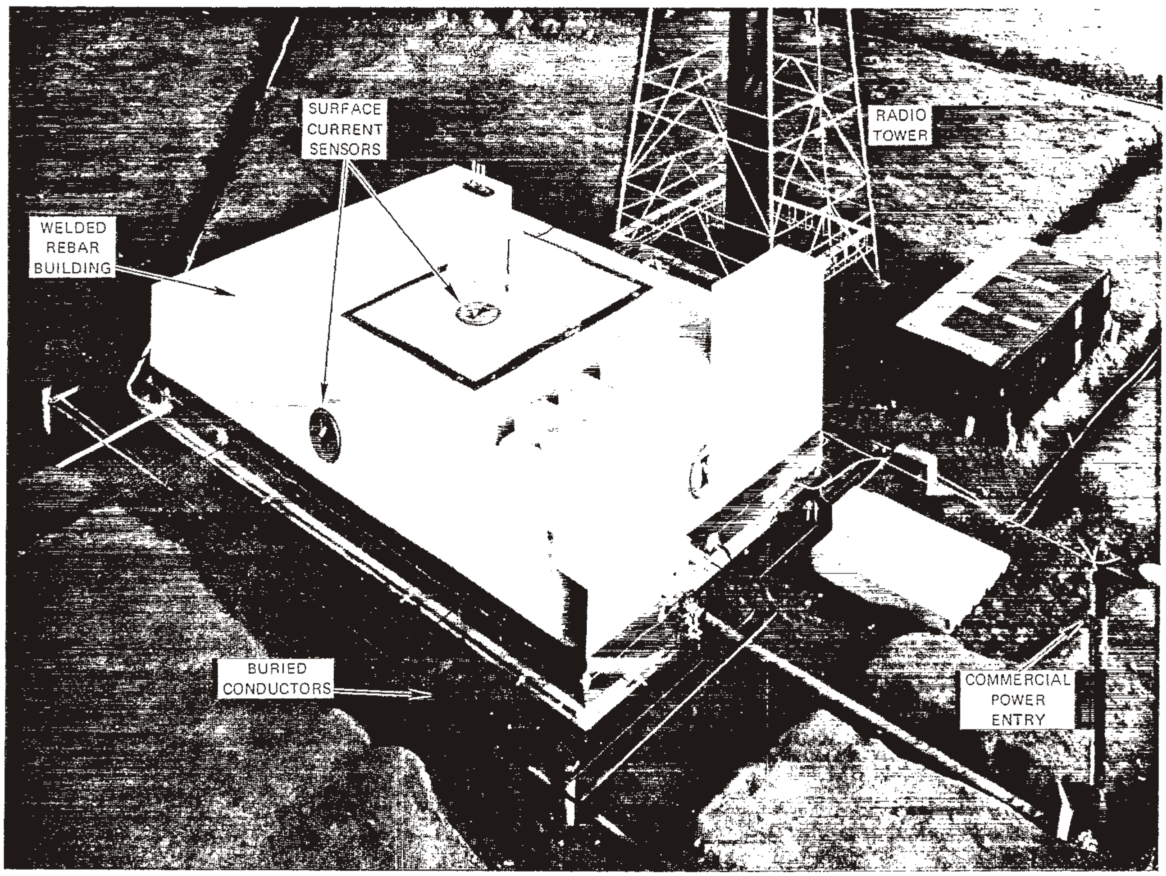

FIGURE 1 1/40 DIMENSIONAL SCALE MODEL

$$
\begin{aligned}
x &= px' \\
y &= py' \\
z &= pz' \\
t &= \gamma t' \\
E(x, y, z, t) &= \alpha E'(x', y', z', t') \\
H(x, y, z, t) &= \beta H'(x', y', z', t')
\end{aligned}
\tag{1}
$$

where p is the mechanical scale factor, γ is the time scale factor, α is the electric intensity scale factor, and β is the magnetic scale factor.

Relationships between the scale factors (p, γ, α, β) may be found that ensure that the model is an accurate simulation of the full-scale system. This step is accomplished by equating Maxwell's equations in the full-scale system to a set of equations derived from Maxwell's equations in the model system, which are transformed to full-scale quantities by the appropriate scale factors.

When the scale factors p, γ, α, and β are definitely known quantities, the model is an absolute model defined by the scaling equations. If p, γ, and the ratio α/β are known, then the model is a geometrical model.

In practice, there are certain restrictions on the choice of scale factors because of the limited ranges of variation of permittivity ϵ, conductivity σ, and permeability μ that are available in the media that can be used for models. Generally, air in the full-scale system is modeled by air in the model system so that:

$$\epsilon(x, y, z) = \epsilon'(x', y', z') \tag{2}$$

and:

$$\mu(x, y, z) = \mu'(x', y', z') \,. \tag{3}$$

Thus, for air, the scaling equations can only be satisfied when $\alpha = \beta$ and $p = \gamma$ giving:

$$\frac{p\alpha}{\gamma\beta} = 1 \tag{4}$$

These conditions require the relationship between conductivities to be

$$p\sigma(x, y, z) = \sigma'(x', y', z') . \tag{5}$$

Thus, it is apparent that, for a model restricted to using air as the scaled air medium, there are only two scale factors (p and α or β), which can be arbitrarily chosen. For a geometrical model, only p needs to be chosen since the ratio α/β needs only to be unity. The ratio α/β is the ratio of wave impedances in the full-scale and model EM media. Since air is used for both systems, the ratio is unity.

The requirements to be satisfied in constructing a geometrical model are:

$$\begin{aligned} x' &= x/p & \epsilon' &= \epsilon \\ y' &= y/p & \sigma' &= p\sigma \\ z' &= z/p & \mu' &= \mu . \\ t' &= t/p \end{aligned} \tag{6}$$

The requirement for conductivity is not necessarily satisfied by using air in the model to simulate air in the full-scale system since air has a small conductivity that varies with frequency. For frequencies of interest in EMP problems, however, air at sea level can be assumed to be a perfect insulator and its conductivity can be ignored. Similar assumptions can be made for scaling highly conductive materials. The loss in good conductors such as most metals is generally negligible (compared with other losses) so that scaling of conductivity is not usually required for such conductors. Scaling of conductivity is necessary, however, for poor conductors such as the soil.

The parameter p, which determines the scale of the model, is chosen to yield a model of reasonable size. The relationships between the full-scale system characteristics and the model quantities that can be obtained directly from model measurements are:

electric field	$E' = E$
magnetic field	$B' = B$
current	$I' = I/p$

length	$\ell' = \ell/p$
time	$t' = t/p$
frequency	$f' = pf$
wavelength	$\lambda' = \lambda/p$
phase velocity	$v' = v$
propagation constant	$k' = pk$
resistance	$R' = R$
reactance	$X' = X$
impedance	$Z' = Z$
capacitance	$C' = C/p$
inductance	$L' = L/p$

3 DIMENSIONAL SCALE MODELING TECHNIQUES

EM scale modeling of systems to determine their responses to transient EM fields is generally limited in the choice of the scaling parameter p by available transient energy sources. When these sources are in the form of switch discharged capacitors, they can achieve transient rise times of the order of 10^{-10} seconds through the use of mercury-wetted, reed type relays with contacts under gas pressure in a coaxial geometry as illustrated in Figure 2. The capacitor is charged through the charging resistor and discharged through the coaxial geometry, which is formed by the switch and switch housing. The capacitor in Figure 2 can be replaced with coaxial cable to form square output waveforms and the entire system can be designed to operate at the coaxial cable impedance. Energy sources of the type illustrated in Figure 2 can be constructed to produce output voltages from 1 to 4 kV. They can be easily converted to repetitive pulses at ac power frequencies, and being single-ended, can drive any scaled field simulator that has a single-ended input (for example, a monopole or parallel-plate transmission line). By utilizing a balun, a long dipole can be used to radiate EM energy at any incidence angle or polarization.

The system for receiving and recording scale model measurement waveforms consists of sensors, a sampling oscilloscope operated in the triggered mode,[2] and an X-Y recorder to display the data. Sampling oscilloscopes can easily have rise time capabilities

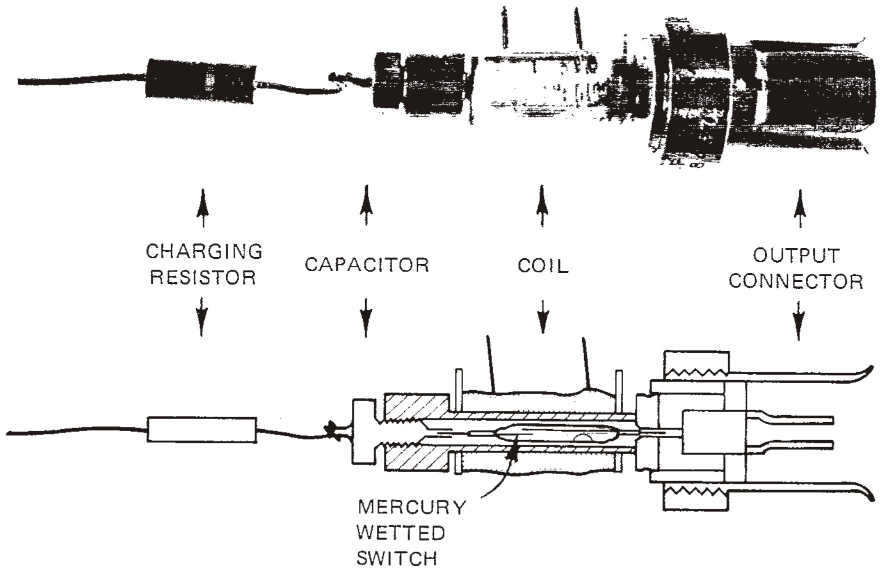

FIGURE 2 SCALE-MODELING TRANSIENT ENERGY SOURCE

of 3×10^{-11} seconds. To trigger operation from a repetitive energy source, however, it is necessary to use a delay line in the signal channel to compensate for sweep delays in the oscilloscope. This delay line tends to limit the signal channel rise time to no better than 10^{-10} seconds.

Measurements that can be made on models are the electric and magnetic fields and the currents on conductors and conducting surfaces. Small capacitive probe antennas utilizing anodize as a dielectric such as that illustrated in Figure 3, can be used to sense the electric field that is normal to a conducting surface. Such a sensor can have sufficient capacitance to drive a coaxial cable with a low frequency limit that is adequate for observing transient pulse widths of 20 ns. The rise time response can be less than 10^{-11} seconds. Commercially available probes for measuring current J or magnetic field B with a small slot antenna, as illustrated in Figure 4, are limited in their response to about 3×10^{-10} second rise time so that the capability to measure current is the limiting factor in setting the scaling factor p if the electromagnetic transient rise time is to be observed. Special small loops can be constructed to improve the current and magnetic field measurement rise time; however, they generally have decreased sensitivity, which limits their application in scale model measurements.

EM scale modeling of a system entails a scaled construction of the conductive and EM features of that system. The various parts of the system are duplicated in miniature. However, only those features that define the EM characteristics need be properly scaled in the scale model. Generally, only those features that can have a first-order effect on the interaction of the system with the incident wave must be reproduced in the scale model. Features that have little effect such as internal conductors and small apertures, do not need to be reproduced; however, if they can be easily scaled, they may improve the utility of the model. EM scale modeling thus is used to study the gross features of the system that control the total system response. Secondary energy coupling effects that occur within the system are usually not readily amenable to scaling. If these secondary features are to be investigated using a scale model, they must be modeled to a scale where only first-order effect phenomena are investigated.

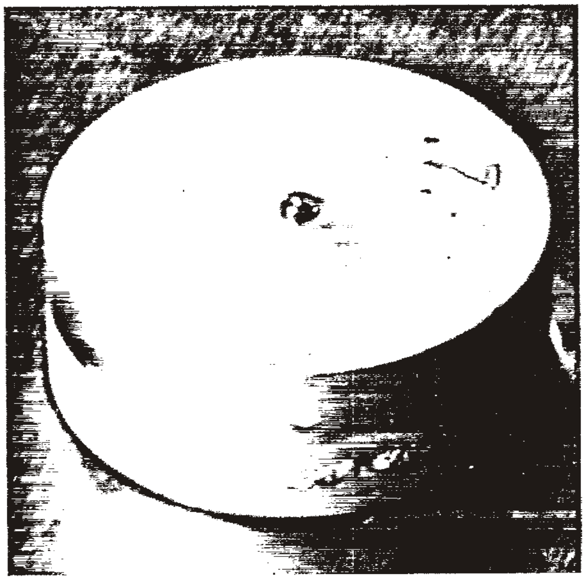

FIGURE 3 SCALE-MODELING ELECTRIC FIELD SENSOR

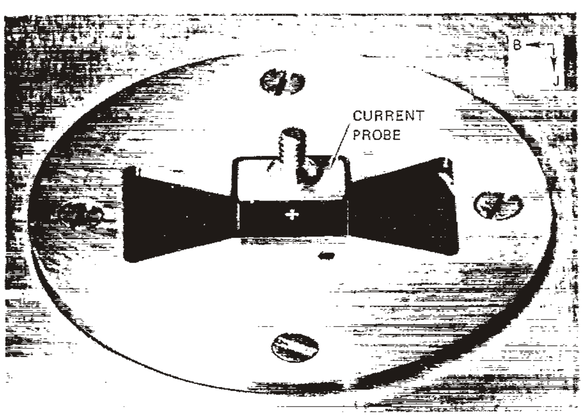

FIGURE 4 SCALE-MODELING MAGNETIC FIELD SENSOR

In the construction of EM scale models, EM planes of symmetry can sometimes be utilized to reduce the model size and to provide shielding for the instrumentation. Generally, symmetry planes can only be utilized when modeling simulators and very special systems such as missiles or aircraft. The conductive materials used in scale models are commonly copper sheet and wire, tubing, and mesh. Earth is modeled by adding salt to real earth to increase conductivity. Dielectric materials are generally modeled with plastics or wood.

The scale factor selected for modeling an EM response (or coupling) problem depends on the purpose of the modeling test. If the response caused by a 10^{-8} to 10^{-9} second transient rise time is to be investigated, then a scale factor p of less than 50 will be required if the scale model measurements are to observe this rise time. For large systems, it is desirable to use larger scale factors. Fortunately, such factors can be used because the rise time response of systems is approximately the excitation rise time convolved with the time corresponding to the dimensions of the system that are parallel to the incident field polarization.[3] When using scale factors that give a faster response than the measurement system response rise time, the data should be checked to verify that the rise time is not limited by the measurement system.

When scale modeling transient EM coupling, it is possible to scale the EMP transient waveform and thus obtain response data that can be directly interpreted for the transient response of the full-scale system or for direct injection waveforms. In scale modeling EM field simulators or an entire system to determine the response of the components of the system, it is often convenient to use a short (or impulse-like) transient so that clear times and system responses can be separated. Figure 5 shows an example of this approach for a modeled monopole. Both the clear time and the multiple reflections on the monopole are directly observed and can be interpreted in travel times on the scaled model.

For observing the natural response of a system, it is preferable to use a long square wave with low frequency energies so that the system's natural resonances can be observed. Figure 6 shows the response of a system to a short (impulse-like) transient and its response to a long, square-wave transient. The square-wave response is the integral of the impulse response and provides a direct measurement of the late-time (low-frequency) response characteristics that are not easy to observe from the impulse response. With careful interpretation, almost any transient that excites the scaled system can be used to determine the response characteristics of that system.

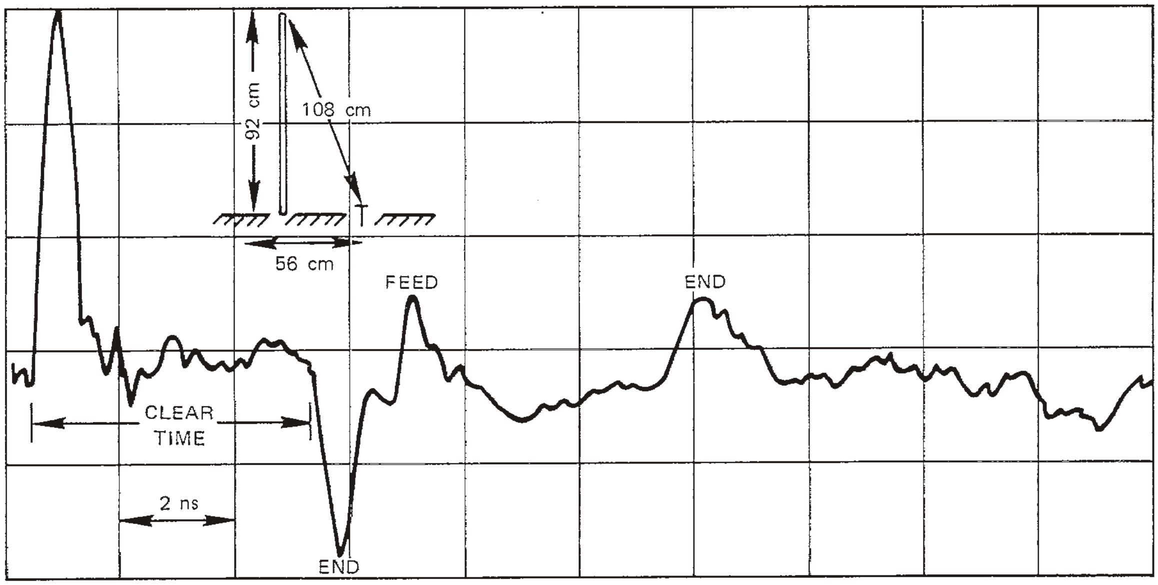

FIGURE 5 SCALE MODEL MEASUREMENT OF MONOPOLE REFLECTIONS

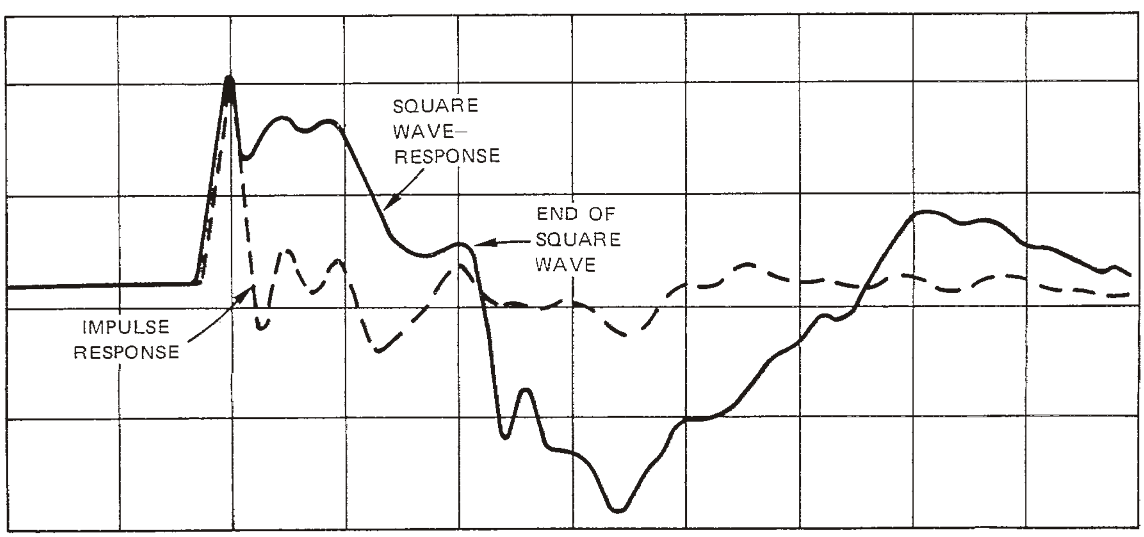

FIGURE 6 SYSTEM IMPULSE AND SQUARE WAVE RESPONSE

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