On the Wide-Band CW Illumination of Large-Scale Systems—Part II: The Rhombic Illuminator

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Abstract—The Phillips Laboratory has recently designed and constructed a continuous wave illuminator for studying the responses of large-scale systems subject to vertically or horizontally polarized electromagnetic stresses incident from the horizontal. The illuminator is developed by a nonuniform two-wire transmission line oriented over the system under test. When the wires are driven from a common mode voltage with respect to the ground a vertically polarized electric field is generated and when the wires are driven from equal but opposite voltages a horizontally polarized electric field is developed. The structure is called the rhombic illuminator since the wire configuration is very similar to the rhombic antenna. In order to illustrate the use of the illuminator, data are presented for the illumination field and for the response of an illuminated aircraft recorded at the Phillips Laboratory.

Index Terms—Continuous wave, fiber optics.

I. INTRODUCTION

THERE are a number of sources for intense electromagnetic illumination including lightning, high-power radars, RF broadcast transmitters, nuclear weapon detonation, wireless power transmission, etc. In some cases, the results have been tragic. The Blackhawk helicopter downings and the accident aboard the U.S. aircraft carrier Forrester during the Vietnam War are examples [1], [2]. Determining the effects on large-scale systems from high-power illumination is not a simple procedure. Nonlinear and irreversible processes must be expected. Reproducing these effects and identifying the coupling mechanisms under threat exposures may be very difficult and prohibitive in terms of the cost and the time required. It has been shown in a companion paper that these problems can be overcome through low-level continuous wave (CW) illumination supplemented by high-level direct drive applications [3].

By exposing a system to low-level CW illumination, it is possible to determine transfer functions relating particular responses within a system to the illuminating field strength. In addition it is possible to identify electromagnetic coupling paths and to establish the relative importance of the various coupling mechanisms for large-scale systems. Supplementing these results with high-level direct drive applications will allow the exercise and study of nonlinear effects. Low-level CW studies can be performed with relatively few personnel,

relatively little hazard to personnel, and a relatively small investment in equipment and facilities when compared to full-scale studies using high-level or threat exposures.

The expected effects resulting from illumination with a narrow-band high-power source can be obtained by the appropriate scaling of the low-level responses. For responses where nonlinear processes are expected, it may be necessary to implement direct drive excitations at levels determined by the scaled low-level responses. When the illumination is from a wide-band or ultrawide-band source, the response of the system can be determined via Fourier frequency superposition utilizing Fourier transform applications. Computed responses can be used to establish the appropriate pulse excitation to be emulated in the direct-drive applications. These topics are addressed in detail in a companion paper [3].

Generally, intense electromagnetic stresses, whether deliberate or inadvertent, may come from a variety of directions as well as exhibit differing polarizations. Consequently, the low-level CW illuminator/simulator may have a variety of polarization and incident angle requirements. An illuminator described in a companion paper can be used to simulate overhead illumination providing essentially horizontal polarization for the incident fields [3]. In this paper, a rhombic nonuniform transmission line configuration is presented. It is called a rhombic illuminator since the configuration resembles the rhombic antenna. The rhombic transmission line configuration can provide horizontal propagation with a vertical electric field and a horizontal magnetic field or it can provide a vertical magnetic field with a horizontal electric field. The system is illuminated by launching a quasi TEM mode and absorbing it in a resistive termination. By using the freedom of orientation of the system under test a veritable infinity of illumination scenarios are available where the illumination field is nearly uniform over the target. The frequency range of the illumination extends from dc to a few gigahertz.

In order to illustrate the use of the rhombic illuminator to study the electromagnetic response of large scale systems, the instrumentation and data analysis used at the large electromagnetic system-level illuminator (LESLI) research facility at the Phillips Laboratory are described. Measurement data for an F-16 aircraft testbed are presented and discussed.

II. RHOMBIC ILLUMINATOR

The rhombic illuminator is a two-wire transmission line configuration oriented over the ground, as shown in Fig. 1. The source is located at one end and a resistive termination is

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Fig. 1. An illustration of the rhombic illuminator driven from a common mode source.

Fig. 2. Field maps of the incident field (not including ground reflections) for the rhombic illuminator driven from a common mode source and from a differential source.

located at the opposite end with a resistance selected to abate the reflection as much as possible. A common mode drive, as shown in Fig. 1, produces a vertically polarized electric field and a horizontal magnetic field in the region below the wires.

Correspondingly a differential mode drive produces a horizontal electric field and a vertical magnetic field as shown in Fig. 2. For the differential mode drive, the two wires are driven from equal but opposite voltages with respect to the ground. In both cases a quasi TEM wave is launched by the source at one end and is absorbed by a resistive termination matched to the transmission line characteristic impedance at the other end of the structure.

The characteristic transmission line impedance of the rhombic transmission line varies from the input to the termination. According to Zuffada and Engheta [4], the characteristic impedance at a given cross section is for common mode drive (each wire driven from the same voltage)

$$Z_{CC}(x) = \frac{\eta_0}{4\pi} \left[\ln \frac{1 + \sqrt{1 + [a/h(x)]^2} - a/h(x)}{1 - \sqrt{1 + [a/h(x)]^2} + a/h(x)} + \frac{1}{2} \ln \left\{ 1 + \left[\frac{2h(x)}{w(x)} \right]^2 \right\} \right] \quad (1)$$

and for a differential mode drive (wires driven from equal but opposite voltages)

$$Z_{CD}(x) = \frac{\eta_0}{\pi} \left[\ln \frac{1 + \sqrt{1 + [2a/w(x)]^2} - 2a/w(x)}{1 - \sqrt{1 + [2a/w(x)]^2} + 2a/w(x)} - \frac{1}{2} \ln \left\{ 1 + \left[\frac{w(x)}{2h(x)} \right]^2 \right\} \right] \quad (2)$$

It is easily shown that

$$\frac{h(x)}{w(x)} = \frac{h_A}{w_A} \quad (3)$$

for the rhombic wire configuration where w_A and h_A are the wire separation and height, respectively, at the apex of the configuration as shown in Fig. 1. Note that both expressions for the characteristic impedances contain two logarithm terms—one that is position dependent and the other position independent. Accordingly, the characteristic impedances should vary slowly over the length of the structure.

A goal in the simulation of system illumination is the production of uniform illumination. For the transmission line illuminator, a quasi-TEM wave is generated. Ground plane losses affect both the propagated field strength and the orientation of the field vectors. The differential mode drive provides illumination that is reflected from the ground plane where the reflected field components reduce the total field by opposing the incident field components near the ground. However, ground reflections for the common mode drive produces field components that add to the incident field. Consequently, the total field of the differential mode drive is significantly smaller than the total field of the common mode drive for a given driving voltage [4]–[7]. According to Zuffada and Engheta [4], optimum uniformity occurs when

$$w_A = \frac{2h_A}{\sqrt{3}} \quad (4)$$

for the common-mode excitation and when

$$w_A = h_A \quad (5)$$

for the differential mode excitation.

An illustration of the rhombic illuminator that is used at the Phillips Laboratory LESLI facility is shown in Fig. 3. Configuration dimensions are provided in Table I. As seen in the figure, the ground plane parameters vary over the length of the transmission line. In the launch region, there is a highly conducting plate resting on the concrete base. After a saw-tooth transition region that is used to reduce reflections from the end of the launch section, the ground plane is a bare concrete pad with steel rebar where the system under test is located. After the bare concrete region the ground plane is arid New Mexico desert soil.

The launched signal initially propagates across a conducting plate onto the concrete pad and, finally, over a soil region to the termination. The lossy ground absorbs power out of the wave front and tilts the wave front forward. The result of this action is the reduction of the normal component of the electric field near the ground. As the propagation continues across the ground plane, the reduction of the normal component of the electric field extends to greater heights above the ground. For the configuration shown in Fig. 3, both measurements and calculations show that the normal component of the electric field at the height of the typical aircraft fuselage under illumination is very near the value that would occur if the ground were perfectly conducting [5]–[7]. The electric field uniformity over the working volume of the rhombic illuminator is addressed in some detail by Donohoe *et al.* [6].

TABLE I
DIMENSIONS OF THE RHOMBIC ILLUMINATOR LOCATED AT THE PHILLIPS LABORATORY LESLI FACILITY

	Common Mode	Differential Mode
Overall Length (x_T)	207 meters	207 meters
Maximum Wire Height (h_A) at $x_A = 107$ m	26 meters	26 meters
Maximum Wire Separation (w_A)	32.3 meters	52 meters
Wire Radius (a)	0.0032 meters	0.0032 meters
Max. Transmission Line Impedance [$Z_{CC}(x_A)$, $Z_{CD}(x_A)$]	331 Ohms	1122 Ohms
Transmission Line Impedance at the Input [$Z_{CC}(0)$, $Z_{CD}(0)$]	116 Ohms	282 Ohms

Fig. 3. The rhombic illuminator that is used at the Phillips Laboratory LESLI facility.

A corresponding study of the wave impedance variation over the working volume is reserved for future study.

The characteristic impedance of the rhombic transmission line varies over the length of the line with a maximum value at the highest point of the configuration, i.e., at $x = x_A$. For the parameters shown in Table I, the maximum value of the common mode characteristic impedance is $Z_{CC}(x_A) = 331\Omega$. At the driving point of the configuration, a simple feed fixture is used to allow the two-wire balanced configuration to be driven from a coaxial transmission line through a type N connector. The wire height and separation at the feed fixture are 1" and 1.75", respectively. For these dimensions, (1) yields $Z_{CC}(0) = 116\Omega$, which introduces a significant impedance mismatch that may affect the output of the linear amplifier driving the structure.

Driving the rhombic structure in a differential mode configuration from a 50- Ω source requires coping with a greater impedance mismatch than occurs for the common mode drive. Considering the same wire separation and height yields $Z_{CD}(0) = 282\Omega$, which indicates that impedance transforming balun is needed for this configuration. A suitable wide-band 4:1 impedance-transforming air core balun has been designed and is currently in use [3].

If the termination resistance matches the characteristic impedance at the termination, then reflections would be minimized and the input impedance to the rhombic configuration

should be relatively constant over the operating range. At low frequencies where the length of the transmission line is a small fraction of a wavelength, the input impedance is essentially the termination resistance. As the frequency is increased the input impedance will approach the characteristic impedance of the input region. When the frequency is further increased to the point that transmission line considerations are no longer valid (multimoding occurs), i.e., at frequencies $f \geq c/2h_A$ where c is the speed of light, there may be significant reflections from the apex region. This will affect the field uniformity as well as the input impedance to the rhombic line. However, at those frequencies, ground losses, wire losses, and radiation losses provide sufficient attenuation that the apex reflection does not present a significant problem [6].

III. DATA COLLECTION AND PROCESSING

The response to an electromagnetic stress can be expressed conveniently as a transfer function that relates a measured current, voltage or an internal field strength in terms of the incident field. Using this result it is possible to determine the response for any illumination intensity, or using Fourier transform theory, it is possible to determine the response to pulsed illumination [3]. Automatic network analyzers are particularly suited to obtaining transfer functions.

As an illustration of the instrumentation appropriate for making transfer function measurements with the rhombic transmission line illuminator, the system used at the Phillips Laboratory LESLI facility is presented. In order to make accurate transfer function measurements an automatic network analyzer is used to drive the rhombic transmission line, as shown in Fig. 4. Here, an HP 8753C network analyzer is used to drive the rhombic configuration through a 100-W wide-band amplifier. The amplifier compensates for the reduction in incident field strength from the expanding wave front and the inherent ohmic losses. For multiple measurements a second analyzer is located in a screen box either inside the system under illumination or at a safe distance away. Fiber-optic data links are used to connect and synchronize the network analyzers, as well as to provide the connection to the computer controlling the instrumentation.

Included in Fig. 4 are provisions for three sensors, a high-frequency current/voltage probe and two magnetic field sen-

Fig. 4. The schematic of the instrumentation for measurements in the rhombic transmission line illuminator located in the LESLI facility of the Phillips Laboratory, Kirtland AFB, NM.

sors are shown. One magnetic field sensor is located in the launch section of the rhombic transmission line illuminator. Its response is directly proportional to the time derivative to the magnetic field incident on the sensor and is simply related to the field incident on the system under test. A field-mapping exercise can quantitate that relationship as well as determine the variation of the illuminating field over the system under test. Consequently internal measurements can be recorded by the other two sensors and used to obtain the transfer functions relating the internal responses to the illumination field. This process is discussed in detail in a companion paper [3].

The frequency range of interest to the Phillips Laboratory extends from 100 kHz to 1 GHz. Consequently, the sensors, data links, and recording devices have a compatible frequency ranges. The network analyzers are computer controlled and measurements are performed via frequency sweeps with logarithmic spacing in the samples. Since the measurements are performed in the field, the Federal Communications Commission (FCC) would not allow measurement data to be collected in the communication frequency bands.

IV. SAMPLE RESULTS

A measurement of the horizontal component of the magnetic field that is developed in the working volume of the rhombic illuminator at the Phillips Laboratory LESLI facility is shown in Fig. 5 for a common mode drive. These data were obtained for the frequency range 100 MHz to 1 GHz

and at a point identified as the center of the region when the test object—an F-16 aircraft—would be located. The instrumentation was capable of measurements at much lower frequencies. The height of the test point above the ground plane was selected to coincide with the mid line of the fuselage and the orientation of the sensor (EG&G MGL-6 B-dot sensor [8]) was adjusted to respond to the principle component of the magnetic field. The structure performed as a transmission line for frequencies up to about 500 MHz. Above this frequency multimoding and diffraction effects begin to affect the field measurements. In spite of these phenomena, the magnetic field that is developed is relatively uniform with frequency. Multiple measurements demonstrate that some noise perturbations of the data are present. The readily apparent straight line segments in the swept frequency data are the result of linear interpolation across the frequency bands assigned for communication.

Internal field measurements are possible with the instrumentation setup shown in Fig. 4. The F-16 aircraft used for these measurements was a test bed and not an operational aircraft. It was intended for studying the interaction processes and providing an estimate of responses. In Fig. 6 data are provided for the magnetic field inside the cockpit. Nose-on illumination was used to obtain the data in Fig. 6 in the following figures. In order to obtain a transfer function for the response, the ratio of the data sets in Fig. 6 must be evaluated. Results for the transfer function are shown in Fig. 7. Magnetic field data are

Fig. 5. Incident horizontal magnetic field component recorded in the LESLI rhombic illuminator driven from a common mode source. The measurement point is 3 m above the concrete pad in the working volume.

Fig. 6. The magnetic field recorded inside the cockpit of the F-16 test-bed aircraft overlaid with the incident magnetic field measurement (the upper data curve).

presented here since magnetic field sensors are less sensitive to the environment than electric field sensors [8]. Consequently the internal measurement of the magnetic field is much easier to perform and provides more accurate results. Note that the magnetic field strengths at the measurement point inside the

cockpit are, in general, less than the incident field strength, even at resonant frequencies.

Generally, voltage measurements are difficult and inaccurate at high frequencies. This is the result capacitive coupling of the measurement apparatus and the impedance loading from the

Fig. 7. The ratio of the cockpit magnetic field to the incident magnetic field.

Fig. 8. Current induced on a cable shield inside the cockpit region of the F-16.

sensor attachment. Repeat measurements were used to verify the data obtained. For the attempted voltage measurements, no consistent data were obtained.

Current measurements are much easier to perform and to provide accurate results. Current measurements obtained for the shield of a shielded cable bundle are provided in Fig. 8. Repeated measurements indicate that the signal-to-

noise ratio for these data is about 10 dB. Noise sources include instrumentation system noise primarily from the fiber optics (F/O) link, ambient electromagnetic noise, and noise from the amplifier/network analyzer instrumentation. The current sensor used for these measurements was a BMM high-frequency current probe developed by EG&G [8]. In order to achieve microwave frequency performance, the sensor design gave up

Fig. 9. The transfer admittance for the cable shield current data in Fig. 8.

sensitivity. Some ferrite core current probes can be operated at frequencies near 1 GHz and provide significantly more sensitivity. The appropriate transfer admittance that ratios the induced shield current to the incident field can be obtained by evaluating the ratio of the current data in Fig. 8 to the incident field data in Fig. 5.

The transfer admittance results are shown in Fig. 9. For an illuminating discussion of the transfer admittance concept and aircraft testing see Joffe and Gavan [9], [10].

Data are presented only for the common mode drive. Similar results have been obtained for the differential mode drive as well. However, the determination of the incident field for the differential mode illumination is more difficult. For this operating configuration the reference sensor is located in the launch region directly below one of the transmission line wires and the incident magnetic field is measured directly below one of the wires nearest the location of the system under test. A measurement of the incident magnetic field is recorded by placing a magnetic ground plane sensor on a large metal plate resting on the concrete pad and recording the component of the magnetic field perpendicular to the transmission line wire. The magnetic field recorded from the sensor is two times the incident magnetic field according to image theory. This result is used with two-wire transmission line theory and analytical geometry to obtain the field components incident on the system under test. Consequently, the quantitative relationship between the reference sensor and the field components illuminating the system under test is readily determined.

V. CONCLUSIONS

The evaluation of the response of a large-scale system to intense electromagnetic illumination can be accomplished

by using low-level illumination and appropriately scaling the response to the threat level. An illuminator capable of fully illuminating a large-scale system is the rhombic transmission line, which can produce two polarization exposures, vertical electric field/horizontal magnetic field, or a vertical magnetic field/horizontal electric field. A sample of the data collected at the rhombic illuminator that is located at the Phillips Laboratory LESLI facility at the Kirtland AFB, NM, is presented to illustrate the nature of the data and how it is analyzed.

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