

A New Sensor Structure for the Measurement of an Electromagnetic Pulse

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Abstract—Harry Diamond Laboratories (HDL), Woodbridge, VA, currently uses groundplane version electric- and magnetic-field sensors to measure the electric and magnetic fields produced during a simulated high-altitude electromagnetic pulse (HEMP). These sensors are also used for the measurement of such pulsed fields in the vicinity of metallic enclosures. A new sensor structure has been developed to measure the electric and magnetic fields accurately.

The authors have recently fabricated and mounted a hollow metallic cylinder behind the sensor's 0.218-m (8 1/2 in) ground plane to house a fiber-optic transmitter, amplifiers, and other equipment necessary for data collection. The presence of this metallic cylinder increases ("enhances") the amplitude of a signal when measured with this new sensor structure geometry ("sensor/cylinder"). The electric- and magnetic-field enhancements caused by the presence of this metallic cylinder were measured in both the frequency and time domains. The enhancement was also calculated numerically using a three-dimensional finite-difference code. To eliminate unwanted field coupling to the sensor's coaxial signal cable, the output of the sensor is transmitted through fiber-optic cables to remotely located recording equipment.

In the frequency domain, the enhancements for both the electric and magnetic field were determined using a large transverse electromagnetic (TEM) cell. In the time domain, the enhancements were determined by comparing simulated HEMP fields measured with this sensor/cylinder to those measured with miniature electric- and magnetic-field sensors.

The degree of enhancement of this sensor/cylinder will vary as a function of distance when the sensor/cylinder is placed next to a conducting object, such as a metallic shelter. These enhancements were also determined using miniature electric- and magnetic-field sensors.

I. INTRODUCTION

HARRY DIAMOND Laboratories (HDL) Woodbridge, VA, currently uses groundplane version electric- and magnetic-field sensors when measuring the electric and magnetic fields produced during a simulated high-altitude electromagnetic pulse (HEMP). These sensors are mounted on a 0.218-m circular (8 1/2 in) aluminum plate that provides both a finite groundplane and a mounting surface for the sensors. Previously, these sensors had been mounted on a 1-m³ aluminum box whenever electromagnetic fields were recorded during HEMP simulation. The 1-m³ box was needed to shield and contain the recording equipment, such as oscilloscopes and cameras, necessary for data collection.

With the advent of fiber optics, the 1-m³ box was no longer required and could be replaced by a much smaller

and more convenient enclosure. The new enclosure chosen was an aluminum cylinder approximately 0.254 m (10 in) long with a diameter of 0.167 m (6 1/2 in). This size was chosen to allow the electric- and magnetic-field sensors to be mounted on the metallic cylinder without serious sensor modification and also to house the transmitter portion of the fiber-optic data link, small signal amplifiers, power supply, and coaxial cables associated with the collection of field data.

With this metallic cylinder so close to the sensor, it was necessary to examine and characterize the effect of the cylinder on the measurement of electromagnetic fields, so that its effect could then be removed.

This paper documents the various techniques used to characterize the field perturbation caused by the presence of the metallic cylinder. It will be shown later that the presence of this cylinder increased the amplitude of the measured electromagnetic fields by a constant value for the measured frequency range of 500 kHz to 100 MHz. This perturbation will be referred to as an enhancement. First, the field enhancement caused by the metallic cylinder over frequency was measured using TEM cells with a continuous wave (CW) source; second, the enhancement was measured in the time domain by comparing electric and magnetic fields measured with a sensor mounted on the metallic cylinder to those measured with miniature sensors mounted directly to a fiber-optic transmitter; and third, the enhancement was calculated numerically using a three-dimensional finite-difference code.

The authors were also concerned with the effects that a nearby conducting plane (specifically, a metallic shelter) would have on the field enhancement of the sensor/cylinder. This effect was investigated along with errors associated with inaccurate positioning of the sensor/cylinder.

II. THE METALLIC CYLINDER

The metallic cylinder was designed specifically to house the transmitter portion of the fiber-optic link, amplifiers, power supply, cables, and other equipment associated with data collection. Its compact size also allows greater sensor positional flexibility than the previously used 1-m³ box when measuring electromagnetic fields.

Fig. 1 shows the metallic cylinder with an electric-field sensor attached on one end. The electric-field sensor shown in Fig. 1 is protected with a 1/8-in-thick fiberglass

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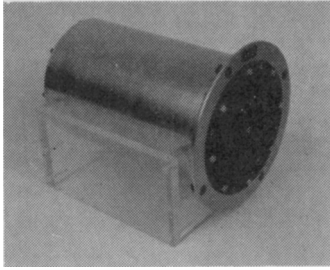


Fig. 1. Metallic cylinder with electric-field sensor attached.

sheet. The sensor is a top-loaded monopole above a 8 1/2-in circular aluminum groundplane. The cylinder is exactly 0.263 m (10 1/4 in) long with a diameter of 0.163 m (6 3/8 in). The front end of this cylinder is left open so that an electric- or magnetic-field sensor can be mounted to it. These sensors can be connected to the fiber-optic transmitter through short coaxial cables. The cylinder also houses a small dc to dc converter, which is used to power the preamplifiers in each electric-field sensor and small signal amplifiers if required. The dc to dc converters were designed so that they would receive all their power directly from the fiber-optic transmitter battery pack.

III. DETERMINING THE ENHANCEMENT CAUSED BY THE METALLIC CYLINDER

A. Cylinder Response in Frequency Domain

To compute the enhancement caused by the metallic cylinder as a function of frequency, a field sensor was mounted on the cylinder and this sensor/cylinder was placed inside large TEM cells. The sensor/cylinder was placed midway between the center conductor and the groundplane of the TEM cell by means of a dielectric stand. The TEM cells used for this test are located at the National Bureau of Standards in Boulder, CO; these cells provided a constant amplitude field within ± 1 dB over the frequencies of interest. The electric and magnetic fields measured by the sensors were transmitted to remotely placed recording equipment through fiber-optic cables. The field enhancements caused by the cylinder were computed by comparing the electric and magnetic fields measured with a sensor mounted on the metallic cylinder to those fields computed at the sensor location without the presence of the sensor/cylinder. Errors associated with these measurements were less than ± 1 dB. The equations used to compute the field enhancement caused by the metallic cylinder are as follows:

$$EF^E(f) = \frac{E^{\text{cyl}}(f)}{E^{\text{TEM}} \times T_1(f)} \quad (1)$$

$$EF^H(f) = \frac{H^{\text{cyl}}(f)}{H^{\text{TEM}} \times T_2(f)} \quad (2)$$

$$H^{\text{TEM}} = \frac{E^{\text{TEM}}}{120\pi} \quad (3)$$

$$E^{\text{TEM}} = \frac{v}{b} \quad (4)$$

where $EF^E(f)$, $EF^H(f)$ is the enhancement caused by the cylinder for the electric and magnetic field, respectively; $E^{\text{cyl}}(f)$, $H^{\text{cyl}}(f)$ are the respective electric and magnetic fields measured by a sensor mounted on the metallic cylinder; E^{TEM} , H^{TEM} are the respective electric and magnetic fields computed at the center of the TEM cell between the septum and the bottom of the cell without the presence of the cylinder, $T_1(f)$, $T_2(f)$ are the respective transfer functions (ratio of applied field strength to sensor output voltage) of the electric- and magnetic-field sensors that were measured by HDL using a TEM cell [1], v is the applied input voltage to the TEM cell for a given frequency, and b is the separation distance between the septum and the bottom of the TEM cell.

The TEM cell size was 6 (l) by 3 (w) by 3 (h) m, with the separation between the septum and the bottom of the cell being 1.5 m. The cell provides planewave electromagnetic fields inside the cell, and maintains a TEM mode from dc to approximately 40 MHz. A smaller TEM cell was used to cover the frequency range up to 100 MHz. The smaller cell size was 2.4 (l) by 1.2 (w) by 1.2 (h) m, with the distance between the septum and the bottom of the cell being 0.6 m. There was an appreciable interaction between the smaller cell and the metallic cylinder because of the size of the cylinder relative to the smaller cell. The effect was adjusted by using the enhancement measured in the large cell at the overlapping frequencies between the larger and smaller cell.¹ For magnetic fields, there are two possible sensor/cylinder orientations for each field component measured. For this reason, the magnetic fields were measured for two angles of electric-field polarization (Ψ), one with the sensor/cylinder axis parallel to the incident electric field ($\Psi = 0$ degrees) and the other with the sensor/cylinder axis normal to the electric field ($\Psi = 90$ degrees). For electric fields, there is only one possible sensor/cylinder orientation for each component; this orientation is with the sensor/cylinder parallel to the electric field. For electric fields, the average enhancement caused by the cylinder was measured to be approximately 2.24 with the polarization angle of $\Psi = 0$ degrees. For magnetic fields, the average enhancement was approximately 1.35 for $\Psi = 0$ degrees and 1.26 for $\Psi = 90$ degrees. Figs. 2 and 3 show the enhancement caused by the metallic cylinder as a function of frequency. As can be seen by these plots, the frequency response of the sensor/cylinder is essentially flat; varying no more than ± 1 dB from the selected average value with a standard deviation of 0.3 dB for electric fields and 0.5 dB for magnetic fields over the frequencies measured.

B. Cylinder Response in the Time Domain

To compute the enhancement caused by the metallic cylinder in the time domain, a series of tests were performed using the Army Electromagnetic Pulse Simulator Operations (AESOP) in Woodbridge, VA. AESOP is a

¹M. Crawford (National Bureau of Standards, Boulder CO) recommended this technique during a conversation on 3/19/86 during the TEM cell measurements.

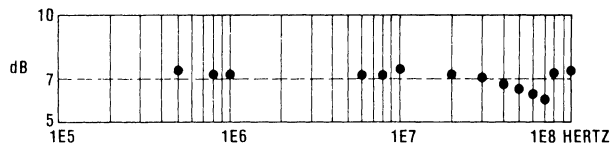


Fig. 2. Electric-field enhancement ($EF^E(f)$) caused by the metallic cylinder.

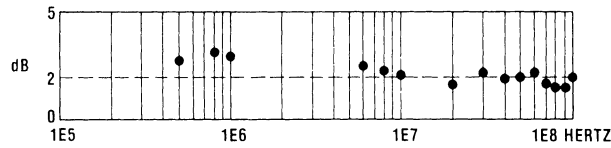


Fig. 3. Magnetic-field enhancement ($EF^H(f)$) caused by the metallic cylinder.

full threat-level fixed-site HEMP simulator. Using basically a 7-MV pulse generator and 300-m horizontal biconic radiating antenna, AESOP can produce a radiated free field from 20 to 50 kV/m at 50 m from the pulser.

To measure the electric- and magnetic-field enhancement caused by the metallic cylinder in the time domain, the authors had to first design and construct miniature electric- and magnetic-field sensors that would attach directly to the front end of the fiber-optic transmitter (0.083 (w) by 0.103 (h) by 0.147 (l) m). Second, the miniature sensors mounted on the transmitter were placed inside a TEM cell (2 (l) by 0.67 (h) by 1 (w) m) and the transfer functions of the miniature sensors mounted on the transmitter were measured.

We have already determined through frequency-domain analysis that the enhancement caused by the metallic cylinder is reasonably flat (with a standard deviation of 0.3 dB for electric fields and 0.5 dB for magnetic fields) over the measured frequency range; also, there was no appreciable change in waveshape between the fields measured with the miniature sensor mounted on a fiber-optic transmitter and those fields measured using the sensor/cylinder. It was, therefore, concluded that simply comparing the peak amplitudes of the fields measured with the miniature sensor mounted on the transmitter and those fields measured using the sensor/cylinder was sufficient to characterize the enhancement caused by the cylinder in time domain.

To compute the magnetic-field enhancement caused by the metallic cylinder, the radial component of the magnetic field from AESOP was measured with the small magnetic-field sensor mounted on a fiber-optic transmitter. The miniature sensor mounted on the transmitter was then replaced with the sensor/cylinder to measure the same field component. The ratio of the peak amplitude measured by the sensor/cylinder to that measured by the miniature sensor mounted on the transmitter represents the magnetic-field enhancement caused by the metallic cylinder. This value was 1.25 with the metallic cylinder both normal and parallel to the electric field.

To compute the electric-field enhancement caused by the metallic cylinder, the horizontal electric field from

TABLE I
AVERAGE ELECTRIC AND MAGNETIC-FIELD ENHANCEMENT CAUSED BY THE METALLIC CYLINDER

Field	Pulse	Analytical*	cw
Electric	2.00	2.27	2.24
Magnetic	1.25	1.28	1.26

(*Computer modeled using 3-D finite-difference code by EMA, Inc., Denver, CO [3].)

AESOP was measured with a miniature electric-field sensor mounted on a fiber-optic transmitter. The miniature sensor mounted on the transmitter was then replaced with the sensor/cylinder to measure the same horizontal electric-field component. The ratio of the peak amplitude of these two waveforms represents the electric-field enhancement caused by the cylinder; this value was 2.00. The sensor/cylinder was parallel to the electric field. A summary of the derived field enhancements can be found in Table I [2].

C. Enhancement Caused by the Cylinder When Next to a Conducting Plane

When the metallic cylinder is placed next to a conducting plane, such as a large metallic enclosure, the enhancement of the electric and magnetic field will change. This change is dependent on both the distance from the conducting surface and from the sensor/cylinder orientation. At the time of this investigation, the authors were concerned with the cylinder enhancement when the sensor/cylinder was placed 0.305 m (12 in) from an Army S280C shelter. The sensor/cylinder was used to measure the shielding effectiveness (insertion loss) of the S280C shelter. An S280C shelter is a double-skinned aluminum enclosure approximately 2.3 by 2.3 by 3.7 m in size.

D. Enhancement Caused by the Metallic Cylinder When Placed 0.305 m (12 in) from an Exterior Shelter Wall

To measure the electric- and magnetic-field enhancements caused by the cylinder when placed 0.305 m from the shelter, the authors again used the miniature electric- and magnetic-field sensors, as mentioned earlier, that would attach directly to the front end of the fiber-optic transmitter.

Measurement Approach: To measure the enhancement caused by the cylinder when placed 0.305 m from the shelter, the miniature sensor mounted on a transmitter was placed 0.305 m from the rear of the shelter and electric and magnetic fields were recorded. The miniature sensor mounted on the fiber-optic transmitter was then replaced by the sensor/cylinder, and the electric and magnetic fields were again recorded. The ratio of the peak amplitudes of the fields measured with the sensor mounted on the transmitter to those measured with the sensor/cylinder was 1.86 for electric fields and 1.17 for magnetic fields. These values represent the electric- and magnetic-field enhancement caused by the cylinder at this location.

The basic assumption made when using the miniature

sensor mounted on the transmitter was that the interactions between the miniature sensor mounted on a transmitter and the shelter could be neglected. This assumption is justified since the longest dimension of the miniature sensor mounted on the transmitter is approximately 0.05λ at 100 MHz, the highest frequency of interest, where λ is the wavelength. Also, the volume of the miniature sensor mounted on a transmitter is only 5.2×10^{-5} times that of the shelter. Again, peak amplitudes were used to determine the enhancement caused by the cylinder in the time domain since there was no appreciable change in waveshape between the fields measured with the miniature sensor mounted on the transmitter and those measured using the sensor/cylinder.

F. Enhancement Caused by the Metallic Cylinder When Placed 0.305 m (12 in) from an Interior Shelter Wall

Measurement Approach: The electric- and magnetic-field enhancements when the sensor/cylinder was placed inside the shelter were derived using the same procedures as were used for the external enhancements. When the miniature electric-field sensor mounted on a transmitter response was compared to the sensor/cylinder measured response, the electric-field enhancement caused by the metallic cylinder placed 0.305 m from the internal shelter wall was 1.89. When the miniature magnetic-field sensor mounted on the transmitter response was compared to the field response measured with the sensor/cylinder, the magnetic-field enhancement caused by the metallic cylinder placed 0.305 m from an interior shelter wall was 1.4.

F. Estimation of Field Variation as a Function of Sensor/Cylinder Positioning

To determine if a measured signal is selective to sensor/cylinder positioning next to a conducting plane, electric and magnetic fields were measured as a function of sensor/cylinder distance from an S280C shelter. The effects of misaligning the sensor/cylinder were also studied.

Peak amplitude variation caused by a sensor/cylinder positioning error was first examined by measuring magnetic fields while varying the angle of the sensor/cylinder axis with respect to the shelter wall. The plane containing the magnetic-field sensor was held fixed so that the sensor was still measuring the same magnetic-field component. With the sensor/cylinder angle varied up to 30 degrees from a vertical position (sensor/cylinder parallel to the shelter wall and perpendicular to the electric-field polarization), the peak amplitude varied less than 0.6 percent. The peak amplitude variation was 1.6 percent when the sensor/cylinder angle was varied up to 30 degrees from a horizontal position (sensor/cylinder perpendicular to the shelter wall and parallel to the electric-field polarization). During these measurements, there were no appreciable changes in pulse waveshape.

Variations of the peak magnetic field were also measured as a function of distance between the shelter wall and the sensor/cylinder. With the axis of the sensor/cyl-

inder parallel to the shelter, peak amplitudes varied approximately 7 percent when the sensor/cylinder distance was varied from 0.127 to 0.305 m (5 to 12 in). With the sensor/cylinder axis perpendicular to the shelter wall, and the distance varied from 0.064 to 0.305 m (2.5 to 12 in), peak amplitudes varied approximately 8 percent. There was no appreciable change in waveshape during these measurements.

The sensor/cylinder axis can either be perpendicular or parallel to the shelter when a desired magnetic-field component is measured. However, electric-field sensors do not have these two degrees of freedom. The axis of the sensor/cylinder must always be parallel with the desired field component. The amplitude of the electric field varied approximately 61 percent, (without appreciable change in waveshape) when the sensor/cylinder distance was varied from 0.019 to 0.254 m (3/4 to 10 in). It should be noted that a small positioning error leads to a large variation in peak amplitude of the electric field when the sensor/cylinder is placed very close (less than 0.152 m) to the shelter. The peak amplitude of the electric field varied less than 10 percent when the sensor/cylinder was varied from 0.152 to 0.254 m.

Some significant results, determined through these tests, as the measurements taken with the sensor/cylinder 0.305 m from the shelter have shown, is that there is at least a 6.2-percent increase in the measured peak magnetic field with the sensor/cylinder perpendicular to the shelter wall, as compared to measurements taken with the sensor/cylinder parallel to the shelter wall. For this reason, all magnetic fields were measured with the sensor/cylinder axis placed parallel with the shelter wall to minimize the enhancement caused by the cylinder.

To summarize, when the sensor/cylinder axis is normal to a shelter wall and the electric-field polarization is parallel to the sensor/cylinder axis, appreciable field enhancements will occur for magnetic fields. When the axis of the sensor/cylinder is oriented parallel to the shelter wall and the electric field is polarized perpendicular to the sensor/cylinder, field enhancement is minimized. These results were also confirmed by EMA Inc. [3].

IV. CONCLUSIONS

A field sensor, when mounted to the metallic cylinder as described in this paper, is a very convenient, and more importantly, an optimum technique to record electromagnetic fields. It has been shown that the presence of this metallic cylinder causes a field enhancement that is linear over the frequency range measured. This enhancement varies by no more than ± 1 dB from the average value with a standard deviation of approximately 0.3 dB for electric fields and 0.5 dB for magnetic fields.

Through three independent analysis methods, the field enhancement caused by the presence of the metallic cylinder has been investigated. The enhancements caused by the metallic cylinder were determined to be 2.24 for electric fields and 1.26 for magnetic fields in free field (i.e., without the presence of the shelter). Of the three testing

methods discussed, these values were chosen to represent the enhancement caused by the cylinder because of the controlled environment and accuracy to which fields were recorded during testing. Table I shows the enhancements derived for the three aforementioned methods.

Testing has shown that improperly aligning the sensor/cylinder during the measurement of a magnetic field has a minimal effect on the measured signal. A sensor/cylinder misalignment of 30 degrees will only introduce perturbations of less than 2 percent. The sensor/cylinder, on the other hand, is sensitive to position as a function of distance from the shelter wall, because the enhancement caused by the cylinder changes as a function of distance. This effect can be minimized by defining sensor location to be at least 0.152 m (6 in) from the shelter. For the

measurements recorded by HDL, 0.305 m (12 in) has proven to be a convenient distance to choose because of the minimal effect on measured fields due to positional error and the similarity of this distance with other accepted means of shelter testing (i.e., MIL-STD-285).

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