SMALL ANTENNAS—AN OVERVIEW

This article discusses state-of-the art technology and ongoing research and new developments in small antennas and data transmission links which have been designed to provide EMI measurements that would not be possible, or would be severely restricted with the use of standard antennas. It is intended that the treatment provided herein be somewhat superficial, so that an in-depth knowledge of antenna theory is not necessary to digest its content. Accordingly, the article is addressed to the professional who must deal with all engineering phases of a product, and must make sound engineering judgments based on enough information to be cognizant of the engineering problems associated with these phases.

Electromagnetic field measurements have traditionally been made with standard relatively large antennas that have been fabricated without critical attention to minimization of the sensing element or means of transmitting the received data so as not to perturb the measured field. This is not to imply that these factors were considered trivial in designing antennas. Rather, the intended use of the antennas did not justify the expense of attempting to miniaturize and provide non-perturbing data links, and in any case, the technology did not exist which could provide the means to accomplish these desirable designs.

In recent years, new technology has emerged which has placed a higher demand on the antenna design engineer to miniaturize. The factors causing this have been higher frequencies to be measured, smaller electronic units with smaller voltages and currents, and recent trends by federal agencies to consider susceptibility of individual equipment, rather than only addressing EMI emissions from intentional or inadvertent transmitting units (74).

The higher frequencies require smaller antennas due to their shorter wavelengths, the smaller electronic units require accesibility of antennas, smaller voltages and currents require close-in measurements near critical components, and the susceptibility trend will require that hardening techniques be designed into equipment that may receive undesired signals. These hardening techniques require that the electromagnetic fields be known within the equipment, whether these fields are internally or externally generated.

The types of equipment that are in need of design engineering that incorporate EMI analysis and prototype measurements are innumerable. They can range from the automobile electronic ignition and radar braking systems, to home computer games and television sets, to elaborate industrial computers and medical diagnostic equipment. All share the common potential of susceptibility to EMI, which if not thoroughly considered, can result in significant changes to production equipment. These changes may only become evident after the equipment is placed into use by the customer, and does not perform as expected due to EMI problems.

Antennas to be Considered

There are many definitions of antennas in terms of "long," "short," "small," "fat," "thin," "linear," ad infinitum, with mathematical expressions for determining the fields of these antennas which may or may not be calculable. The fields are also dependent on near zone and far zone conditions and relative sizes of transmitting and receiving antennas, ground planes, and reflecting or absorbing materials. Even an elementary treatment of the various complications in antenna parameters is far beyond the scope of this article, and is deferred to the numerous published references on antenna theory. This overview therefore consists of a cursory examination of "small" antennas that have been proven in tests, and are much less than a wavelength in their largest dimension measured from the input terminals. It will also consist of a look at ongoing and future research into antennas that provide a reasonable degree of confidence in providing accurate field measurements. Another antenna, the CAVITENNA, is discussed in the Susceptibility Sources section of this issue of ITEM.

Electromagnetic Fields of Interest

There are many different types of electromagnetic field measurements, depending on the type of sensor used. These include E-Field, H-Field, power density, current density, energy, potential, flux density, time derivative functions of these units, etc. For most EMC applications, the field parameters of interest are the E-Field (V/m) and the H-Field (A/m). Both must be measured to define the electromagnetic field in near field conditions. When far-zone conditions apply, either can be calculated from measuring the other by using the free space intrinsic impedance relationship $E = ZH$. The near zone presents complex conditions and both the E-Field and H-field must be measured to quantify the electromagnetic field. Knowledge of the E-Field and H-Field will allow the conversion into other units if the permitivity, conductivity, and permeability of the medium are known, and are uniform. Sensors have been fabricated to display these units and others directly; however, most are used in special applications, such as nuclear Electromagnetic Pulse (EMP), and geophysical measurements. For these reasons, the antennas considered in this paper will be restricted to E-Field and H-Field antennas, or sensors, which can be considered special forms of antennas.

Basic Theory of Small Sensors

The basic geometry of the passive E-Field sensor is that of a capacitive dipole as shown in Figure 1.

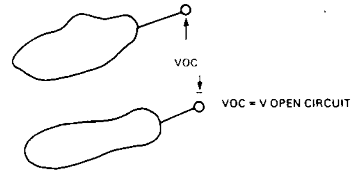

Figure 1. Basic Geometry of Passive E-Field Sensor

The Norton and Thevenin equivalent circuits are illustrated in Figure 2.

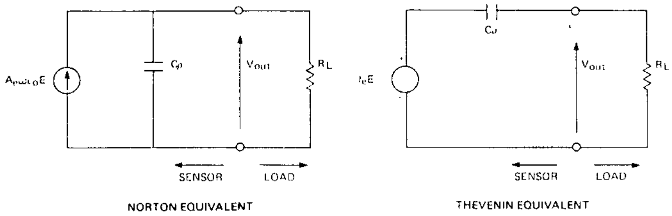

Figure 2. Norton and Thevenin Equivalent Circuits for Passive E-Field Sensors

The parameters of the passive electric field sensor are:

A_e = effective area
l_e = effective length
L_p = sensor inductance
μ_o = permeability of free space

From the equivalent circuits

$$A_e = \frac{C_p l_e}{\varepsilon_o} \qquad \text{Equation 1}$$

and the sensor output voltage is

$$\text{Vout} = \frac{\varepsilon_o E A_e R_L}{C_p\left(R_L + \frac{1}{j\omega C_p}\right)} \qquad \text{Equation 2}$$

$$\text{if } R_L >> \frac{1}{\omega C_p}$$

$$\text{then Vout} = \frac{\varepsilon_o A_e E}{C_p} \qquad (2)$$

Equation (2) is the desired output, and is satisfied by the appropriate choice of R_L at the frequency of interest. A shunt capacitance may be needed to "swamp" the actual probe capacitance and offset stray capacitive effects. In this case, C_P in Equation (2) is replaced by the value of the shunt capacitance, provided it is much larger than C_P.

The basic geometry of the passive H-Field sensor is that of an inductive loop shown in Figure 3.

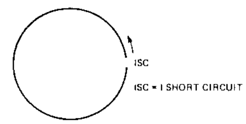

Figure 3. Basic Geometry of Passive H-Field Sensor

The Norton and Thevenin equivalent circuits are illustrated in Figure 4.

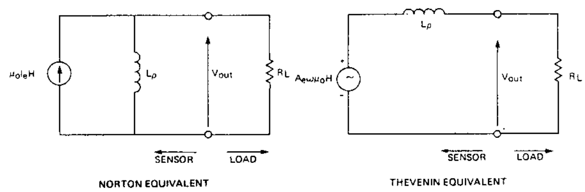

Figure 4. Norton and Thevenin Equivalent Circiuts for Passive H-Field Sensors

The parameters of the passive magnetic field sensor are:

A_e = effective area
l_e = effective length
C_p = sensor capacitance
ε_o = permittivity of free space

From the equivalent circuits:

$$A_e = \frac{l_e L_p}{\mu_o} \qquad \text{Equation 3}$$

and the sensor output voltage is

$$\text{Vout} = \frac{j\omega\mu_o A_e H R_L}{j\omega L_p + R_L} \qquad \text{Equation 4}$$

$$\text{if } R_L << \omega L_p \qquad \text{Equation 5}$$

$$\text{Vout} = \frac{\mu_o A_e H R_L}{L_p}$$

As with the electric field sensor, Equation (5) is the desired output for the H-Field sensor, and appropriate loading must be used to obtain this output. These relationships govern the response of small passive receiving antennas. There are, perhaps, as many shapes that can be constructed using these basic equations as there are "standard"antenna shapes and configurations. However, as the shapes become more complicated, the mathematical treatments of their performance can become extremely difficult, if not impossible, to handle. A number of sensors with relatively simple geometrics have been fabricated and tested with good results. Sketches of some of these senors are shown in Figure 5 with a typical functional block diagram of the sensor unit, data link and receiver.

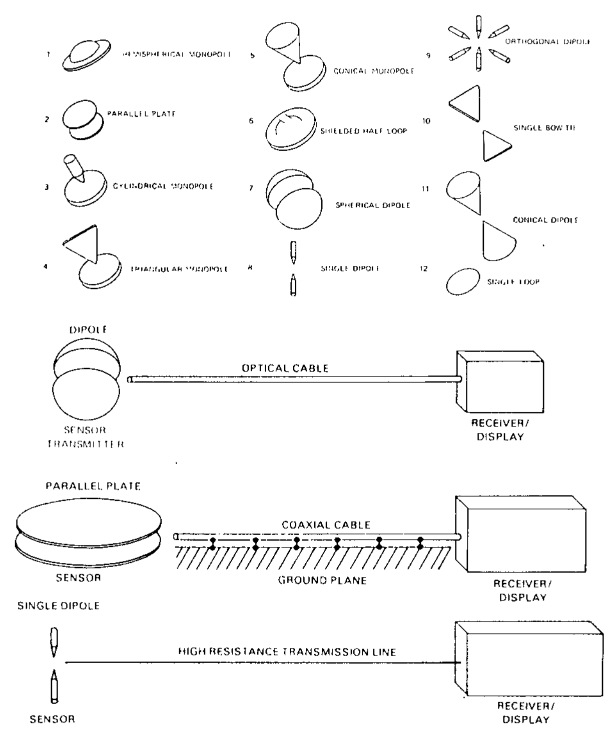

Figure 5. Existing Sensors — Block Diagram of Sensor Unit, Data Link and Receiver

Sensors 1 through 5 of Figure 5 are E-Field "surface"sensors. These measure the component of the E-Field normal to the surface over which the sensor is placed. Sensor 6 is an H-Field "surface" sensor. It measures the tangential magnetic field at the surface over which the sensor is placed. Sensors 7 through 11 are E-Field "free field" sensors, and sensor 12 is an H-Field "free field" sensor. A brief explanation of each sensor is provided, with the numbers corresponding to those in Figure 5.

1. Hemispherical Monopole over a ground plane. Its parameters are essentially the same as that of the spherical dipole with the exception that one of the hemispheres is replaced by the finite ground plane to obtain field measurements at a surface.
2. Parallel Plate (MF - VHF, approximately 1 MHz - 200 MHz) surface field sensor measures the normal component of the E-Field to the surface over which it is positioned. It is used in the lower frequency application where a cylindrical monopole would be too long to be of practical use.
3. Cylindrical Monopole (MF - UHF, approximately 10b MHz - 1 GHz) surface field sensor measures the normal component of the E-Field to the surface over which the sensor is positioned. The data transmission is coaxial cable, should be under the ground plane, or as close to it as possible, to avoid perturbing the measured field.
4. Triangular Monopole (UHF - SHF, approximately 1 GHz - 18 GHz) surface field sensor is a higher frequency version of the cylindrical monopole.
5. Conical Monopole (same as number 4.).
6. Shielded Half-Loop (VHF - UHF, approximately 200 MHz - 1 GHz) surface field sensor, measures magnetic fields tangential to the surface over which the sensor is placed. The gap reduces undesired E-Field response.
7. Spherical Dipole (ELF - MF, DC to approximately 1 MHz) free field sensor allows placement of an electronic circuit within its volume which processes the measured data into a frequency modulated signal, which is transmitted via fiber optic link. The spherical shape allows relatively easy analysis of the sensor and the fiber optic cable isolates the sensor.
8. Single Dipole (MF - UHF, approximately 100 kHz - 2 GHz) free field sensor measures the free field at relatively high frequencies. Isolation and data transmission are accomplished via high resistance transmission lines.
9. Orthogonal Dipole parameters are essentially the same as for the single dipole, with the exception that three dipoles are mounted orthogonally to provide isotropicity.
10. Single Bow-Tie (UHF - SHF, approximately 1 GHz - 18 GHz) free field sensor is a higher frequency version of the single dipole.
11. Conical Dipole (same as number 10).
12. Single Loop (MF - VHF, approximately 1 MHz - 200 MHz) free field sensor measures the magnetic free field. Isolation and data transmission are accomplished via high resistance transmission lines.

Inherent Problems of Small Sensors

The sensors of today's technology are not immune to problems. Some of these problems are:

1. Transmission data. There are three basic means to transmit the data from the sensor to the receiver; high resistance carbon impregnated plastic lines, coaxial cable, and fiber optic links. Limitations are described below.
   a) High resistance transmission lines—work only above 100 kHz, are subject to changes with vibration, and require that the measured signal be rectified in the sensor.
   b) Coaxial cables—must be oriented parallel to the measured field or mounted on a ground plane.
   c) Fiber optics—require an optical transmitter at the sensor location.
2. Fabrication difficulty—Not all probes of this type lend themselves to ease of fabrication—small changes in tolerance can lead to erroneous readings.
3. Isotropicity—difficult to achieve, and must be accomplished by physically changing the orientation of the sensor, with the exception of sensor 9.
4. Sensitivity—decreases with size.
5. Unwanted E-Field response in magnetic sensors and unwanted H-Field response in electric sensors.

Although these problems are inherent in passive sensors of this type, attention to good engineering design and practice has alleviated many of these problems in sensors currently in use. Proper grounding of coaxial cables, orientation of cables, shielding, use of gaps in magnetic sensors, fiber optic data links, careful machining of parts, and the use of highly stable components have all been employed to provide a high degree of accuracy in field measurements. This accuracy, however, does approach a limit, and researchers are constantly striving for improvement in these types of sensors and the development of new sensor concepts.

New Sensor Concepts

Researchers have continued to explore new concepts in sensor technology. Examples of these concepts are glass substrate, cryogenic, Hall effect, resonant scatterers, and others. These sensors are in various stages of development in government and private research programs and are not further discussed in this paper, since most have rather specialized applications.

Although these sensors may have their rightful place in EMC, one concept has recently emerged that appears to provide a completely new method of EM measurement that may have almost unlimited application. This concept employs a jacketed fiber optic cable as a sensing element with extremely high sensitivity for electric and magnetic fields. The fiber sensor works by magnetostrictive of electrostrictive jacketing of the light-carrying cable. When the cable is appropriately jacketed, the electric or magnetic field causes an elongation of the cable, which changes the phase of the light transmitted through the fiber. This phase change is then converted by the use of an interferometer into the electric or magnetic field strength, as appropriate. A conceptual diagram of a fiber optic sensing system is shown in Figure 6.

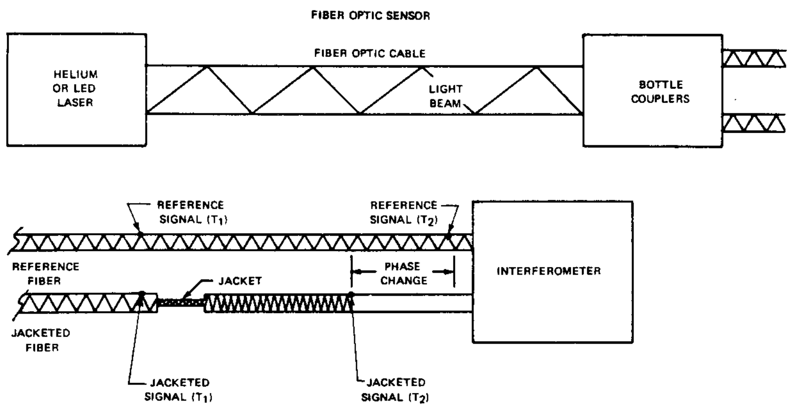

Figure 6. Conceptual Diagram of Fiber Optic Sensing System

A beam of light is transmitted through a single mode fiber optic cable, which is split into a reference fiber and a jacketed fiber by bottle couplers. The resultant two light beams are identical in phase. When the jacketed fiber is stressed by a magnetic or electric field, an elongation of the optical fiber results. This causes a phase change in this fiber. The phase of the reference signal is compared with that of the signal in the jacketed cable in an interferometer and the phase differential is converted into the appropriate field strength units.

The upper theoretical frequency limit of the fiber optic sensor is thought to be about 500 kHz. This limit is primarily based on the physical ability of the jacketing material to respond at a fast rate. Considering the enormous strides made in other fiber optic technology, it seems reasonable to believe that ongoing research will provide non-perturbing fiber optic sensors for the entire frequency spectrum. The sensitivity of the fiber optic sensor already betters that of conventional passive sensors by several orders of magnitude.

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