Testing for Radiated Emission by Electronic Devices

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ABSTRACT

Methods and testing facilities are described. Advantages and disadvantages are discussed for the gigahertz transverse electromagnetic (GTEM) cell, mode stirred chamber (MSC), semi-anechoic chambers (SAC), and open-area test site (OATS). An example is presented illustrating the use of the AMP MSC to assist a customer in reducing radiated emission from a computer product.

INTRODUCTION

The main purpose of testing electronic devices for emission of electromagnetic radiation is to ascertain compliance with regulations and standards. Manufacturers of electronic related products are required to comply with mandated levels of emissions in order to sell legally their products. The Federal Communications Commission (FCC) regulates emission levels and test techniques in the U.S. The European Community (EC), comprising twelve countries, has issued a set of European Norms (EN) that regulate product emission/immunity levels and test techniques. Both FCC and EN regulatory documents presume the use of an open-area test site (OATS) for measurements. Alternate testing facilities are acceptable provided data taken at such can be correlated with data taken at an OATS.

Achieving product compliance with mandated emission levels is usually a sequential process. A typical product compliance cycle involves:

1. A precompliance scan is used to identify frequencies at which radiated emission is potentially noncompliant. This is carried out at a precompliance test facility to minimize the test time required at the final compliance test facility, to minimize error margin, to reduce overall cost, and gain the benefits of its convenience. Data obtained at a precompliance test facility will have a margin of error that has been determined either quantitatively or qualitatively. For instance, a 10-dB error margin would imply that any emission within 10 dB of the limit needs to be scanned at the compliance facility. If emission outages are encountered, corrective action is undertaken and testing is repeated. A precompliance test will often include radiated immunity testing to determine if the upset threshold of the device under test (DUT) is above mandated levels. Immunity testing is required by the EC, but not by the FCC.
2. In a compliance test, emissions at the marginal frequencies of the product will usually be scanned. Appropriate bandwidth and detector functions are selected depending on which agency's approval is required. The focus of the compliance test facility is on radiated emissions. Immunity testing is often done at other facilities. Testing at the compliance facility is done to achieve low error margins and to adhere to regulatory procedures. Both the FCC and EC require that the maximum radiated emissions be measured and that the emission be maximized by cable orientation changes. These cable orientation changes are variables which pose difficulties no matter which technique or facility is used.

TECHNIQUES FOR MEASURING RADIATED EMISSIONS [1-6]

There are four widely accepted techniques for performing radiated emission measurements, each of which will be discussed. In addition, the ability of the technique to be modified for immunity testing will be examined.

Open-Area Test Site (OATS)

An OATS is situated on flat terrain, free from obstructions (buildings, fences, etc.). It has a ground screen which acts as a standardized reflective surface, a turntable, and a measurement mast. The OATS is exposed to the local electromagnetic ambient environment; many are exposed to the weather. Products are placed on the turntable and measurements are made at a distance specified by the appropriate agency (3 m, 10 m, or 30 m). The height of the receiving antenna is adjusted by the mast which varies the antenna height within a range of one to four meters. Maximum emissions are recorded as the turntable is rotated, the mast height varied and the DUT cable orientation is changed.

A recognized problem with OATSs is the variability of results depending on the facility used. One study compared 17 certified OATSs and found wide variation due primarily to worn or broken connectors and cables, antenna factors, and poor ground planes. Variations of 20 to 30 dB in emission amplitude were reported for identical test setups measured at different OATSs. Other factors that can affect emission readings, which were not varied in the cited study, are radome effects in all-weather facilities, turntable effects, and termination of the ground screen. All these issues led to the release of ANSI C63.4-1992 which specifies site attenuation requirements to be met by the test site.

A key feature of ANSI C63.4-1992 is that an OATS must meet a specified performance level referred to as normalized site attenuation (NSA). The theoretical NSA is the electric field insertion loss between a transmitting and a receiving antenna accounting for ground reflection, antenna height variation, and free-space loss. If dipole antennas are used with a 3-meter separation, mutual impedance terms are added to account for lower frequency near-field effects between the antennas. The shape of the theoretical NSA curve carries the frequency-dependent term $-20 \log_{10} f$, which comes from the Friis Transmission equation:

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4 \cdot \pi \cdot R}\right)^2 \cdot G_{0t} \cdot G_{0r},$$

where

P_r = received power, P_t = transmitted power, λ = wavelength, R = distance between transmitting and receiving antennas, G_{0t} = gain of the transmitting antenna, and G_{0r} = gain of the receiving antenna.

Since the radiated power is proportional to the square of the field strength, the received electric field is proportional to the wavelength λ or inversely proportional to the frequency f according to $-20 \log_{10} f$.

By specifying the measurement technique and values for error margin and NSA, regulatory agencies are achieving better site to site correlation. Broken or worn cables and connectors, wrong antenna factors, and ground plane effects will lead to an NSA which does not meet the requirements of ANSI C63.4-1992. For an OATS, the measured NSA must correlate to within 4 dB of the theoretical NSA value at a single point, usually the center of the turntable.

As a compliance test facility, the OATS is the standard to which other facilities are compared. However, an OATS is not designed for precompliance test activities and consequently has major drawbacks if used for this purpose. One of them is that for precompliance testing ready access to an engineering laboratory with diagnostic tools is highly desirable. Such are usually not available at an OATS. Furthermore, iterative testing at an OATS is time consuming, a high electromagnetic ambient is present, and the device to be tested is exposed to the weather. Radiated immunity testing is another aspect of precompliance testing which an OATS is not very well suited simply because FCC regulations prohibit the outdoor broadband transmitted power required for such testing. All these circumstances make OATSs not very attractive as precompliance test facilities.

Semi-Anechoic Chamber (SAC)

SACs are indoor radiated emission test facilities. Using sheet steel bonded to a plywood core, an electromagnetically quiet enclosure can be constructed. Ventilation ports, power access, and personnel access are each carefully addressed so that the plane wave shielding effectiveness can be 100 dB over the frequency range of interest. To dampen the quality factor, Q, and simulate an OATS, carbon filled polyurethane cones or ferrite tiles are mounted on the ceiling and walls. The exterior dimensions of such a chamber can vary from 10 x 10 x 10 ft to 80 x 24 x 12 ft–or even more.

The FCC and EC have alternate site provisions for radiated emission measurements at other then an OATS. ANSI C63.4-1992 recognizes SACs as an alternate site, provided they meet the volumetric NSA requirements. Radiated emission data taken in SACS which meet this requirement can be submitted to the regulatory agency and are recognized as having a direct correlation to radiated emission data gathered at an OATS. If the SAC does not meet the volumetric NSA requirement, radiated emission data can vary more than acceptable to the regulatory agency.

Unlike an OATS, which must meet the NSA requirements at a single point, the SAC must meet the NSA over the volume occupied by the (DUT). The better the ability of the anechoic material to dampen the Q-factor of the chamber or to absorb RF radiation, the closer actual NSA matches the theoretical NSA.

Carbon-filled polyurethane cones perform well when the length of each cone is at least one quarter wavelength. At 30 MHz this requires approximately 8-ft-long cones. Cone shape and doping levels can optimize performance. The dielectric loss mechanism in the carbon filler is due to the frequency-dependent, complex permittivity.

A complimenting technology for RF absorption is the use of ferrite tiles. They are approximately 1/4 inch thick and 4 inches square. The loss mechanism of ferrite tiles is due to their frequency-dependant complex permeability. The tiles are usually applied in combination with carbon-filled polyurethane cones; above 100 MHz even small cones of that material are effective RF absorbers. Typically, the ferrite tiles are first attached to the chamber wall and the carbon filled polyurethane cones are then attached to the tiles. The combination of tiles and cones gives wide bandwidth performance without the need for very long cones. Thus, the size of the chamber can be reduced.

Using a geometric ray-tracing algorithm the NSA can be predicted. Required input data are the chamber size and the RF absorber material return loss as a function of frequency and incident angle. A manufacturer of SACS has generated NSA graphs for two different chambers. These graphs compare ideal and predicted NSA for vertical and horizontal polarizations. Only the frequency range of 30 MHz to 200 MHz has been computed since this range is the SAC design challenge. Predictions were made for both a large (80 x 48 x 25 ft) 10-m compliance facility and a smaller (24ft x 14ft x 12ft) precompliance facility. Results for the 10-m compliance facility show a maximum departure of only 2 dB from the theoretical NSA. The precompliance chamber achieves a ±4-dB variation at frequencies above 80 MHz. Below this frequency departure from the theoretical value can be as much as 16 dB. To correlate precompliance radiated emission data from a DUT with data taken at an OATS requires statistical averaging. This averaging of many products is required only at frequencies where the measured NSA deviates from the theoretical NSA by more that 4 dB. A first-order approximation is that the deviation between theoretical and measured NSA is the margin of error.

For immunity testing acceptable to regulatory agencies, field uniformity may have a maximum amplitude variation of ±3 dB over the product volume. As with the NSA, this requirement is most difficult to meet at lower frequencies (30 MHz to 100 MHz) and may require ferrite tiles or 8-ft cones. A common technique to achieve better field uniformity is to add cones or tiles on the floor when this testing is performed since a ground plane is not required for immunity testing. For military product testing, the only technique allowed by MIL-STD-462D is with a SAC. The SAC must have absorber material above, behind, and alongside the DUT, as well as behind the measurement antenna. The specified absorption characteristics are easily met with 2-ft carbon-filled polyurethane cones.

A major advantage of a SAC is the ability to vary the DUT cable configuration to find the maximum emission. The dominant radiation source of many products are the cables, which requires the ability to orient them for maximum emission. The major disadvantages of a SAC are its size and the initial cost.

Gigahertz Transverse Electromagnetic (GTEM) Cell

The GTEM cell has emerged as the most recent emission/immunity test facility. It is a hybrid between an anechoic chamber and a TEM cell; it has many advantages over OATSs and SACs. The GTEM cell is a rectangular-flared coaxial structure. One of its ends, the cell apex, is equipped with a connector for interfacing to standard coaxial cables. The other end is a wide bandwidth termination made of resistors and RF absorbing cones. The wide bandwidth of operation is denoted by "gigahertz." As with SACs, the size varies with the application. For desktop equipment testing a GTEM cell would be 25 ft long with a cross section of 11 ft by 13 ft at the flared end.

The fundamental theory behind GTEM measurements is that any radiating structure, for instance, a DUT, can be accurately modeled as a sum of electric and magnetic dipole moments. This theory is actually applied twice: first, when the total radiated power from the DUT is measured and, second, when predicting the radiated emission of the DUT that will be measured at an OATS. The GTEM is described analytically as a parallel plate waveguide where the dominant (lowest) frequency of propagation mode is TEM.

Two key assumptions are made in the theoretical development:

1. All dipole moments are assumed to be in phase. Unintentional radiators are not designed to act as highly directive antennae or behave with complicated phase differentiation in their radiation patterns.
2. OATS measurements are made in the far field that allows the DUT to be modeled as a resonant dipole. Near-field predictions are possible but would require twelve measurements.

The DUT can be thought of as a system of electric and magnetic dipoles with its integral behavior being the result of a superposition of the effects of the individual dipoles. Using this model, the DUT is characterized by a set of twelve independent parameters, because each of the two resulting dipoles will have in general three spatial components with each component comprising a real and an imaginary part. Thus to determine all values for the resulting electric and magnetic dipoles, in principle twelve independent measurements are required to find the twelve unknown parameters. Introducing two reasonable assumptions simplifies the problem considerably and reduces the number of parameters to three. First, assuming that all dipole moments are in phase reduces the number of unknowns and consequently the number of equations to six. The problem can be reduced further to three unknowns and three equations by assuming TEM power only at the cell apex and by taking advantage of symmetry considerations.

It has been shown that if the three apex voltages correspond to three orthogonal rotations of the DUT, the vector sum of these voltages measured in three independent directions is equal to the sum of the dipole moments for this geometry under the assumptions stated above. Three orthogonal rotations are required to couple the dipoles to the cavity and excite the TEM mode. The total radiated power emitted by the DUT can be determined from the propagation constant and the sum of the dipole moments.

As stated above, the analysis assumes that the GTEM is a parallel plate waveguide and that the dominant propagation mode is TEM. For this structure the higher order modes TE_n and TM_n will propagate, but are weakly coupled and the broadband match provided by the termination suppresses the formation of higher order modes. Thus, essentially the total power radiated from the DUT in the TEM mode is measured.

To predict OATS performance of the DUT, it is assumed that the total radiated power, as calculated from the apex voltages, is present at the terminals of a fictitious resonant dipole. The predicted radiation pattern from the resonant dipole accounts for ground plane effects and the effect of scanning in height with the receiving antenna. The calculated peak amplitude is recorded and compared to the radiated emission limit line.

The GTEM radiated emission test procedure is as follows:

1. Strap the product to a platform.
2. With the product operating, measure the terminal voltage from the GTEM cell.
3. Repeat the above test with the product orthogonally rotated.
4. Repeat the above test in the third orthogonal rotation.

The GTEM correlation algorithm performs the following computations:

1. Calculates the vector sum of the three measured voltages. The three voltages being the result of the DUT orthogonal rotations.
2. Computes the total radiated power emitted by the DUT as determined from the summation of the three voltages and the TEM mode equations for the GTEM.
3. Computes the current excitation of an equivalent Hertzian dipole when excited with the power calculated in step 2.
4. Places the hypothetical Hertzian dipole at a specified height over a perfect ground plane.
5. Computes the horizontally and vertically polarized field strength at appropriate height intervals over the total operator selected correlation algorithm height within the range of one to four meters.
6. Selects the maximum values of the horizontally or vertically polarized field strengths over the height selected.
7. Presents the maximum value for comparison to the chosen EMC limit.

The test data generated from this technique can achieve very good correlation to data taken at an OATS. As of December 2, 1993, the FCC will accept data taken in a GTEM as equivalent to OATS provided that

1. Data equivalence achieved by comparison of results between OATS and GTEM is established. Emissions are to be measured using both GTEM and OATS methods for the specific product type as a test case. If correlation is established, the GTEM results will suffice in the future.
2. If the DUT has any cabling, the cabling must be set up identically to the test case for which equivalence was established.

The GTEM cell can be an excellent tool for radiated immunity testing. Its advantage is the generation of a uniform TEM wave over an appreciable volume and high field strength per unit input power. This feature and the GTEM's ability to measure radiated emissions make it attractive as a precompliance facility.

The major drawback of the GTEM is in measuring cable emissions. Orthogonal rotations of a cable are not very practical and this is required for the theory to predict the total radiated power from the DUT. In practice, the cables are orientated to generate the highest apex voltage. Products which have test setups or cabling dimensions larger than about 1.5 meters cannot be accurately tested in a GTEM.

Mode Stirred Chamber (MSC)

The MSC, like the SAC, can be constructed of sheet steel laminated to a plywood core. The laminated panels are assembled to form a chamber. Attention to doors, air flow, and wiring is similar to those for a SAC. The MSC does not have any RF absorbing material on the walls, instead, the interior surface is highly reflective. A motorized paddle wheel or vane is located inside the chamber and provides mode stirring action.

Unlike the GTEM, which primarily supports TEM propagation, the MSC is designed as a resonant cavity. At five times the first rectangular cavity resonant frequency, the mode spacing in frequency space is very dense. This results in the loss of antenna directivity in the MSC. Stated another way, the field density within the chamber is nearly constant over the interior volume. This feature is usually stated as the gain of any antenna in a MSC being unity. The antenna factor or ratio of electric field to terminal voltage of a receiving antenna does not become unity in a MSC.

The MSC as a precompliance tool can be used effectively as a device for measuring radiated immunity. It is possible to generate a calibration curve relating free space power density to average power density in the MSC. System response to MSC average power density is similar to free space power density within about 5 dB at any given frequency. The MSC can also be used to measure differences in radiated emission by a DUT when changes to the DUT are made. The property of unity gain results in repeatable measurements since the effects of cable movement are minimized.

Figure 1 shows an example of how radiated emission measurements made in a MSC have aided in product improvement. A computing product, after having failed radiated emission tests at an OATS, was characterized in the AMP MSC. The baseline radiated emission data, representing the original product, are shown in Figure l(a). The product was modified and retested. Figure l(b) shows measurement for the modified product. Subsequently, the modified product was retested at an OATS. It was found that the radiated emissions were reduced by approximately the same amount as had been measured in the MSC.

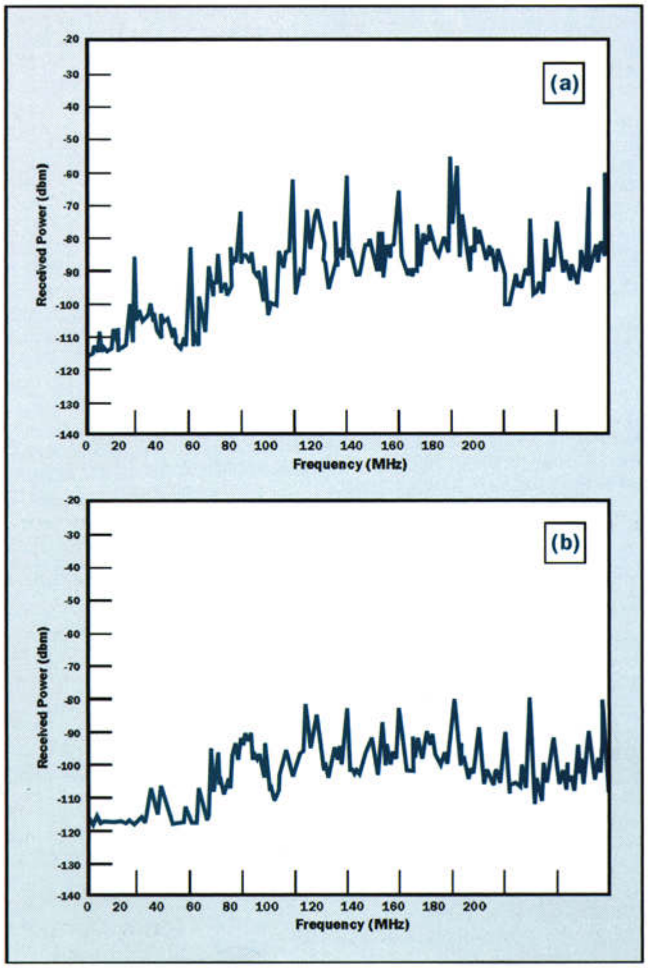

Figure 1. Illustration of radiated emission measurements in a MSC. (a) original emission of a computing product; (b) emission after product modification.

Total radiated power from a DUT can be measured with the MSC. The MSC differs from the GTEM in that energy carried by non-TEM modes is also measured and included in the total MSC-radiated power measurement. However, the high Q-factor caused by the reflective walls of the MSC artificially enhances the field strength at resonant frequencies. The result is a radiated power measurement that is different from the total radiated power that would be generated by the same DUT at an OATS.

SUMMARY

The gigahertz transverse electromagnetic (GTEM) cell is ideal for radiated immunity and emissions testing provided the DUT has no or minimal cabling. Emission measurements made in a GTEM cell are accepted by regulatory agencies. The mode stirred chamber (MSC) is good for statistical averaging of data for improvement/degradation comparisons and for radiation immunity testing. Emission measurements made in a MSC are not accepted by regulatory agencies. Semi-anechoic chambers (SAC) are usually large and expensive but provide the greatest degree of flexibility for immunity and emission testing. If military products are of interest, the SAC is the only facility recognized by MIL-STD-462D for radiated emission compliance. Emission measurements made in a SAC are accepted by regulatory agencies. The open-area test site (OATS), if properly constructed and periodically calibrated, provides precise measurements but suffers from exposure to local electromagnetic ambients. Emission measurements made at an OATS are accepted by regulatory agencies.

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