This paper compares measurement results obtained using a 2.7 m x 3.1 m x 4.6 m reverberation chamber and a 4.9 m x 6.7 m x 8.5 m anechoic chamber to determine the EM susceptibility of equipment under test (EUT). The frequency range was 200 MHz - 18 GHz. The "correlation factor" between the two techniques appears to be directly proportional to the gain of the EUT. Four sample EUTs included in this study were: one centimeter dipole probe, a ridged horn antenna, a small rectangular TEM transmission cell with an aperture and a modified 7.0 cm (2.75") diameter folded fin aircraft rocket.

1.0 Introduction

The use of mode tuned/stirred reverberation chambers for performing electromagnetic compatibility (EMC) measurements appears to have considerable potential. Such a chamber is capable of providing a very efficient conversion of source power to high-intensity fields for performing radiated immunity testing of large size equipment and whole systems. However, test results obtained using reverberation chambers have been questioned in the past because of the lack of a clear correlation with other more conventional measurement techniques. This report describes efforts to obtain a "correlation factor" between results of measurements made in a reverberation chamber and in an anechoic chamber. This was done first for reference standard EUTs and then for an EUT more typical of an operational equipment. Tests were performed using a 2.7 m x 3.1 m x 4.6 m reverberation chamber and a 4.9 m x 6.7 m x 8.5 m anechoic chamber located at the National Bureau of Standards (NBS), Boulder, Colorado.

A number of preliminary tests were performed to determine the operational parameters of the NBS reverberation chamber, and to evaluate the interactions between EUT, the chamber, and the rf sources used in performing these measurements. Some of these tests and their results were presented previously [1]. Additional results, especially related to comparing and understanding the relationship between reverberation chamber and anechoic chamber EM susceptibility measurements are given in this paper. These include a study of the complex wave impedance and the scattering effect of the EUT upon determination of the test field inside a reverberation chamber. Four sample EUTs were included in this study. They are: 1) a one centimeter dipole probe antenna (200 MHz to 18 GHz), 2) a ridged horn antenna (800 MHz to 10 GHz), 3) a 3.0 cm x 5.0 cm x 11.4 cm rectangular coaxial transmission line (TEM) cell with a 1.4 cm diameter circular aperture (200 MHz - 4000 MHz), and 4) a modified 7.0 cm (2.75") diameter folded fin aircraft rocket, (FFAR) (200 MHz - 12.0 GHz). The "correlation factor" between the two techniques/facilities (reverberation and anechoic chamber) is shown to be the EUT's far field gain.
available for both the mode-tuned and the mode-stirred approaches [2].

The field strength in the chamber can be determined in two ways. The first is to measure the power received, $P_r$, by the reference antennas, and then determine the "equivalent" power density, $P_d$, in the enclosure from the following equation:

$$ P_d = \frac{4\pi P_r}{\lambda^2} \tag{1} $$

where $\lambda$ is the wavelength. The validity of equation (1) derives from the assumption that the field distribution at each point in the antenna aperture plane is a composite of randomly polarized plane waves; and hence, the average response for the antenna over an solid angle then approaches a value as if the antenna had a gain of unity. The "equivalent" electric field, $E_A$, is found using the expression:

$$ E_A = \sqrt{\bar{n} P_d} = \frac{4\pi}{\lambda} \sqrt{30 P_r} \tag{2} $$

where $\bar{n}$ is the statistically averaged wave impedance in the chamber. This averaged wave impedance is assumed to be approximately equal to 120+ ohms. This implies that equation (2) is valid only for determining the average values of $E_A$. Obviously, the wave impedance inside the reverberation chamber will have large variations as a function of tuner orientation and chamber location. To test the validity of equation (2), independent measurements were made of the maximum, average, and minimum magnetic and electric fields in the chamber. These measurements were made using a one centimeter diameter loop probe and a one centimeter long dipole probe. The probes were rotated through three orthogonal orientations aligned with the chamber axes located at the center of the test zone. The magnitude of the total magnetic and total electric field were then determined as the square root of the sum of the squared values of each of the three components for each the magnetic and electric fields. The corresponding ratios of the electric-field and magnetic-field amplitudes for a data base of 200 positions of the tuner were then used to determine an "equivalent" wave impedance. The results are shown in figure 2. Four curves are given. Three curves show the maximum, average and minimum wave impedance determined as a function of frequency. The fourth curve shows the wave impedance calculated when the electric-field was a maximum. Note that even though the wave impedance varies widely as expected with frequency, the average wave impedance at frequencies above 200 MHz (the lower frequency limit recommended for our chamber) is approximately 120+ ohms. The fourth curve was included because, as will be discussed later in this paper, the convenient parameter for comparing reverberation chamber with anechoic chamber obtained EUT susceptibility data is the EUT's peak response. This, typically corresponds to a maximum electric field in the reverberation chamber. Note that the wave impedance corresponding with the maximum E-field typically is greater than 120ω ohms and was found to be as large as 1600 ohms in the frequency range (200-500) MHz. This can contribute to an error in determining $E_A$ maximum, using equation (2), as large as 2 dB.

The second method, used to determine the field strength in the reverberation chamber, is to measure the electric-field using an electrically small dipole probe that has been previously calibrated in a standard uniform field. This is the same dipole probe, referred to above, that was used to determine the chamber's wave impedance. The assumption made in using the probe, is that since it is electrically small, the fields measured in the reverberation chamber over the aperture of the dipole will be uniform (i.e., "equivalent" to the standard uniform field used in the probe's calibration); and hence the probes response will give an accurate measurement of the "equivalent" field strength in the chamber. Results of the measurements comparing the electric-field strength generated in the chamber based upon 1) reference antenna received power measurement, and 2) the calibrated probe measurements are shown in figure 3. The maximum and average electric-field strengths shown were adjusted to one watt net input power. The agreement shown is typical of the random variations in the data used to determine the field in a reverberation chamber. Note however, the systematic offset difference is less than 2 dB. This result also strengthens the validity of equation (2).

Another important observation from figure 3 is the approximate 8 dB difference in signal amplitude between the maximum and average field strengths. This can be explained simply in terms of the structure of the cavity modes in the chamber [3]. For a cavity of dimensions, $a$, $b$, and $d$, the modes $\phi_{mnp}$, in all three dimensions can be represented as:

$$ \phi_{mnp}(x,y,z) \propto \sin \frac{m\alpha}{a} \sin \frac{n\beta}{b} \sin \frac{p\gamma}{d} \tag{3} $$

where $\alpha$, $\beta$, and $\gamma$ correspond to the three orthogonal axes of the chamber and $m$, $n$, and $p$ are the associated mode numbers.

Antennas typically respond to a specific field component, or in the reverberation chamber case, to the composite field impinging upon the antenna's aperture. However, measured power is related to 

$$ \phi_{mnp}^2(x,y,z). $$

The peak value of $\phi_{mnp}^2(x,y,z)$ occurs when each component is a maximum or

$$ \text{Peak} \left( \phi_{mnp}^2(x,y,z) \right) \leq 1. \tag{4} $$

The average value of $\phi_{mnp}^2(x,y,z)$ is given by

$$ \text{Ave} \left( \phi_{mnp}^2(x,y,z) \right) \geq \frac{1}{\text{abd}} \int_{V} \phi_{mnp}^2(x,y,z) \, dx \, dy \, dz = \frac{1}{8} \tag{5} $$

The ratio of $\text{Peak}(\phi_{mnp}^2(x,y,z)) / \text{Ave}(\phi_{mnp}^2(x,y,z))$ in the limit then is 8 which corresponds to 9 dB (i.e., this is the theoretical maximum difference that can exist between the peak response and average response of an antenna or EUT measured in a reverberation chamber). In practice, the mode mixing is not 100 percent efficient to achieve a perfect average; hence one obtains a peak offset in all three dimensions. Hence the average difference of 7 to 8 dB shown in figure 3 is expected.

2.2 Anechoic Chamber

A block diagram of the NBS Anechoic Chamber EMC measurement system is shown in figure 4. The test field is established inside the chamber by means of rf sources connected to a standard gain transmitting antenna. This "standard field" is computed from [4]
where $P_{\text{net}}$ is the net power in watts delivered to the transmitting antenna, $G$ is the effective gain for the transmitting antenna, and $D$ is the separation distance in meters. Equation (6) assumes far field conditions for a field point on axis of the transmitting antenna so that $G$ is the maximum power gain.

The net power, $P_{\text{net}}$, is determined using calibrated power meters and bi-directional couplers from the expression

$$P_{\text{net}} = P_{\text{inc}} CR_f - P_{\text{ref}} CR_R.$$  

(7)

Where $P_{\text{inc}}$ is the forward incident power and $P_{\text{ref}}$ is the reverse (reflected power) measured on the sidearm of the coupler, and $CR_f$ and $CR_R$ are the forward and reverse coupling ratios for the coupler referenced to its output port.

The transmitting antennas used are open ended waveguides (200 to 500 MHz) and standard gain horns (500 MHz to 18 GHz).

Comparisons of the response or susceptibility characteristics of EUT (or antennas) obtained using an anechoic chamber and a reverberation chamber are typically made in terms of peak values. The reason for this is obvious when one considers the difficulty in obtaining a true average response for an EUT from anechoic chamber data. Even determining the EUT's peak response in an anechoic chamber (depending of course upon how well behaved the EUT pattern characteristic is) can require considerable measurements involving complete pattern measurements.

In the past, questions have been raised particularly regarding the validity of the peak reverberation chamber results. However, the relationship between peak and average measurements in the reverberation chamber exhibited in figure 3 and equations (4) and (5) will enable one to extract one set of data (e.g., average) from the other (e.g., peak) quite accurately (within ± 2 dB). Note that, for average data, the average wave impedance in the reverberation chamber was approximately the same as in the anechoic chamber.

3.0 Some Recent Measurement Results

3.1 Effects of Scattering from Metal Objects Placed Inside A Reverberation Chamber

Two test objects were selected to simulate an EUT placed in the chamber to evaluate their scattering effect upon the field distribution inside the chamber. The first object was a solid welded aluminum box 30 cm x 50 cm x 60 cm in size. The second was an electronic equipment rack 56 cm x 67 cm x 114.3 cm in size. Tests were first made to determine the E-field uniformity or distribution in the empty chamber as a function of spatial position and frequency. Seven NBS isotropic probes, designed to operate at frequencies up to 2 GHz, were placed inside the enclosure in a grid evenly spaced 1 meter apart along the center line in length and width, an 1/2 meter apart in height. This field outlines center line cuts through two-thirds of the chamber's volume. The maximum and average values for each E-field component (vertical, longitudinal, and transverse) and their vector sum were determined for all seven probes for 200 tuner positions (one complete rotation at 1.8° increments). Each of the two test objects was then placed inside the enclosure at the center of the chamber. The E-field measurements were then repeated using the remaining 6 probes (one probe located at the center of the test zone was removed to accommodate the test objects). These results were compared with the empty chamber E-field distribution measurements. Little or no difference was noted in the statistical sense (both average and maximum measured amplitudes). From a practical standpoint, it is therefore concluded that the presence of metallic objects (or scattering from EUT) in the chamber has negligible effect on the statistical E-field distribution in the chamber and hence upon the test environment.

3.2 Comparison in the Received Power of a Rigid Horn Measured in the NBS Reverberation and Anechoic Chambers

A comparison of the output response data obtained for the 1.0 cm dipole using the NBS reverberation chamber and the NBS anechoic chamber are given in figure 5. Note that the probe output response in the anechoic chamber is greater, in general, by about 2.5 dB than its output in the reverberation chamber. This data suggests that the correlation between the results may be related to the EUT's gain characteristics in the two chambers (i.e., the gain of the dipole probe is approximately 2.5 dB). Determination of a far-field gain for a complex receptor (for example the EUT described in section 3.4) is extremely difficult. Therefore, a simple, well defined broadband receiving antenna, a ridged horn, was used as an EUT to repeat similar tests performed using the 1 cm dipole. The horn is designed to operate in the frequency range 800 MHz - 10 GHz. For these measurements, in the anechoic chamber, the peak response (peak received power) of the horn occurs when the horn is bore-site aligned and polarization matched with the source antenna. These measurement results were then compared with the horn's peak received power in the reverberation chamber with the same level, 10 mW/cm², exposure field. The results are shown in figure 6a. Note that the horn's response is greater in the anechoic chamber than in the reverberation chamber. To see if this difference corresponds to the difference in the gain characteristics of the horn in the anechoic chamber, as compared to that in the reverberation chamber, the horn was calibrated to determine its far-field gain in the frequency range 800 MHz - 10 GHz. These results are shown in figure 6b. Again, note the general agreement between the difference in the horns' response measured in the two facilities and the horns planar field gain.

3.3 Measurement of rf Coupling Through Apertures in TEM Lines

Measurements were made using the reverberation and anechoic chambers to evaluate the rf coupling through apertures cut into a series of TEM cells or transmission lines. Three TEM cells and two circular coaxial lines were used. Similar models (EUTs) have been used for evaluating shielding effectiveness of connector assemblies [5]. The results obtained for one of the TEM cells, (shown in the photograph of figure 7) are given in figure 8. The dimensions for this particular cell are 3.0 cm x 6.0 cm x 14.4 cm with a 1.4 cm diameter aperture centered in the top of the outer conductor. The theoretically predicted peak coupling for a uniform field exposure is also shown on figure 8 [6]. Note that the theoretical peak values...
are approximately equal to the measured values in the anechoic chamber. Again, the anechoic chamber peak data are generally higher than the peak reverberation chamber data. At frequencies below 1 GHz, significant signal couples into the EUT other than those specified aperture thus influencing the results. Also, note that the average reverberation chamber data is approximately 7-8 dB lower than the peak data, similar again to both the 1 cm dipole and ridged horn results.

3.4 Comparison of the Measurements of the EM Susceptibility of a Modified 7.0 cm Folding Fin Aircraft Rocket (FFAR)

A 7.0 cm FFAR was modified with a thermocouple element to simulate and replace the rocket's electro-explosive device (EED). This was done to allow measurement of the rf current coupling into the EED's bridge wire circuit when the rocket is exposed to an rf field. The rocket was also modified with a 1.27 cm plastic spacer at the base of its fin (on the tail section) to increase the rf coupling to the bridge wire circuit. This lessened the requirements for high rf power to generate fields sufficient to perform these measurements. This modification was justified, realizing the purpose of this study was to compare susceptibility results obtained for the rocket in different environments and not to simply evaluate an EUT's susceptibility to EMI. Photographs showing the rocket placement inside the NBS reverberation chamber and the NBS anechoic chamber are shown in figures 9 and 10 respectively. Measurement results of the rocket's thermocouple peak output current resulting from rf coupling as a function of frequency are shown in figures 11 a and 11 b. These data were obtained using exposure fields normalized to 10 mW/cm² in each of the chambers. The anechoic chamber data were obtained by rotating the rocket in azimuth in a planar far-field using both vertical and horizontal polarizations. The rocket was rolled a few degrees around its axis before each azimuth cut. Sufficient roll angles were used to determine the peak response. Examples of pattern data obtained in the anechoic chamber at three selected frequencies are shown in figure 12. A total of 719 patterns were obtained in the anechoic chamber from which the peak response at each frequency was determined. These data were then used to plot curve A of figure 11a. Note that curve A (anechoic chamber data) indicated greater response or more susceptibility, except at one frequency (1800 MHz), than curve B (reverberation chamber peak response). Again, the proposed explanation for this is the difference in the gain characteristics of the rocket's response in the anechoic chamber for example see figure 12) as compared with its gain characteristics in the reverberation chamber. The rocket gain is lost in the reverberation chamber.

Figure 11 b shows the difference between curve A and B for figure 11a. Figure 13 compares the peak results of measurements made of the rocket's response in a large reverberation chamber (3.35 m x 5.79 m x 7.01 m) at the Naval Surface Weapons Center (NSWC), Dahlgren, Virginia and in the NBS reverberation chamber. In general the agreement is within measurement tolerances except at 200 MHz. This frequency approaches the lower limit for using the reverberation chamber and is also where the rocket is most susceptible.

4.0 Conclusions/Summary

In conclusion, three significant statements appear to be justified by this study:

1) The directional characteristics of an antenna or EUT placed inside a reverberation chamber are lost and the equivalent gain approaches unity.

2) The response of an antenna or EUT measured inside a reverberation chamber is less than when measured inside an anechoic chamber (open space) in proportion to its gain. Hence, it appears that the EUT's gain is the desired "correlation factor." This implies that susceptibility criteria determined for an EUT using a reverberation chamber must include an additional factor proportional to the EUT's estimated maximum gain as a function of frequency.

3) The response of EUT to an electromagnetic field after it has penetrated the EUT's shield, appears to be equivalent in both reverberation and anechoic chambers.

In summary, the following observations are offered. Significant advantages do exist, for using a reverberation chamber for EMC measurements. These include:

1) Electrical isolation from or to the external environment;
2) Accessibility (indoor test facility);
3) The ability to generate high level fields efficiently. For example, 1 watt net input power into the NBS reverberation chamber results in electric fields of approximately 70 V/m. This is approximately 1/10 the input power required to generate the same level field in the NBS anechoic chamber, assuming far-field separation distances;
4) Large test areas, for example almost 2/3 of the volume inside a reverberation chamber can be used excluding an area approximately 1/2 meter spacing to the walls;
5) Broad frequency coverage (in the NBS chamber from 200 MHz to at least 18 GHz);
6) Testing is cost effective. This is especially true in comparison to anechoic chamber testing. Significant savings are realized in two major ways. First the facility installation and measurement system procurement cost for a reverberation chamber are significantly less than for an anechoic chamber. Second, the time required to perform a complete EMC analyses of an EUT should be much less using a reverberation chamber. Again, from our experience in evaluating the 7.0 cm FFAR, it required approximately 1/10 the test time to obtain the reverberation chamber test results as compared to the anechoic chamber results shown on figure 11a;
7) The reverberation chamber has potential use for both rocketed susceptibility and emission testing with minor instrumentation changes; and
8) No physical rotation of the EUT is required, since the field in the reverberation chamber is rotated around the EUT.

These advantages may well outweigh the disadvantages implied in the first two conclusions given above, at least for some applications. The obvious trade off is one of measurement uncertainty one can tolerate in determining the EMC/EMI characteristics of specific EUT and the inherent measurement uncertainties associated with determining the amplitude of the test fields inside the reverberation chamber.

5.0 Acknowledgement

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6.0 References


Figure 4. Block diagram of NBS anechoic chamber EMC/EMI measurement system. Side view of chamber. The outside width is 6.7 m.

Figure 5. Comparison of 1 cm dipole probe's peak response to EM field established inside NBS reverberation and anechoic chambers. Output normalized to E-field exposure of 37 dB V/m.

Figure 6a. Antenna output versus frequency.

Figure 6b. Difference in output response of ridged horn measured in NBS reverberation and anechoic chambers compared to calibrated gain of horn.

Figure 6. Comparison of ridged horn's peak response to EM field established inside NBS reverberation and anechoic chambers. Output from horn normalized to exposure power density of 10 mW/cm².
Figure 7. Photograph of 3.0 cm x 6.0 cm x 11.4 cm rectangular TEM cell with 1.4 cm diameter aperture.

Figure 8. Comparison of power coupled to one port of 3.0 cm x 6.0 cm x 11.4 cm TEM cell with 1.4 cm diameter aperture placed inside NBS reverberation chamber and NBS anechoic chamber. Opposite port of cell terminated into 50 ohms. Exposure field normalized to 37 dB V/m peak.

Figure 9. Photograph of modified 7.0 cm Folding Fin Aircraft Rocket inside NBS reverberation chamber.

Figure 10. Photograph of modified 7.0 cm Folding Fin Aircraft Rocket inside NBS anechoic chamber.
Figure 11a. Thermocouple output vs frequency.

Figure 11b. Difference in thermocouple output measured in NBS reverberation chamber and NBS anechoic chamber.

Figure 11. Comparison of 7.0 cm modified FFAR thermocouple response to EM field established inside NBS reverberation chamber and NBS anechoic chamber. Data normalized to exposure power density of 10 mW/cm².

Figure 12a. 700 MHz, Hor. Polar., Roll = 330°.

Figure 12b. 1800 MHz, Hor. Polar., Roll = 0°.

Figure 12c. 3800 MHz, Hor. Polar., Roll = 0°.

Figure 12d. 3800 MHz, Vert. Polar., Roll = 0°.

Figure 12. Examples of azimuth rotation patterns of 7.0 cm modified FFAR thermocouple response taken in NBS anechoic chamber.
Figure 13. Comparison of 7.0 cm modified FFAR thermocouple response to EM field established inside NBS and NSWC reverberation chambers. Data normalized to exposure power density of 10 mW/cm².