An Introduction to Reverberation Chambers for Radiated Emission/ Immunity Testing

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The interest in reverberation chambers for radiated emission and immunity testing has grown significantly over the past few years. This is because reverberation chambers provide a cost-effective, robust, all-aspect-angle, reproducible test environment with high field-to-input power ratios.

Introduction

The recent increased requirements for immunity testing along with the continued requirements for emissions testing has generated a demand for additional radiated test capabilities. Manufacturing organizations as well as commercial test houses are seeking lower cost facilities as well as more cost-effective testing. Costs for reverberation chambers can be substantially lower than other test techniques and should be considered as an option for new facilities. Since a variety of conductive materials, including steel, aluminum, and galvanized sheets or wire meshes can be welded or bolted together, low-cost conversion of the large inventory of existing screen rooms or shielded enclosures is also an attractive option. The high field-to-input power ratios may also significantly lower amplifier costs associated with high field requirements. For the same level of test result uncertainty, reverberation chambers offer the possibility of significant savings in test time. Further, if the equipment-under-test (EUT) normally operates in a cavity, a reverberation chamber provides the most representative simulation of the operational electromagnetic environment (EME) and avoids the intrinsic overtest of an equally robust anechoic chamber test.

In the past, several factors contributed to the relatively limited utilization of reverberation chambers. One factor was the lack of acceptance of reverberation chambers in commercial and military standards. Currently, several standards permit the use of reverberation chambers as an alternative test procedure. In addition, several immunity standards permitting reverberation chamber use for testing commercial electronics, vehicles, and medical equipment are under consideration or in development.

A second factor was the intrinsic statistical nature of a reverberation chamber test. The statistical nature must be included in chamber calibration and field monitoring, test planning, and results analysis. This article discusses the statistical nature of the concept, some typical characterization measurements, and the advantages and disadvantages of reverberation chambers.

Statistical Nature of Reverberation Chamber Testing

Most EMC testers are aware of the large spatial variability possible (> 30 dB) when testing at a fixed frequency in a typical shielded enclosure. Small changes in the test setup can result in significantly different conclusions about EUT emission or immunity levels. To experienced testers, it should be apparent that a single measurement in a cavity has little value. However, by application of statistical techniques, the uncertainty in field characteristics, and hence EUT performance characteristics, can be reduced to acceptable uncertainty levels.

Theory predicts that a properly operated reverberation chamber provides a test EME which is statistically isotropic and homogeneous within an acceptable uncertainty and confidence level over a large working volume.[1,2,3] Isotropic implies that at a given location the statistics of the EME are the same in any direction. Homogeneous implies all spatial loca-

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tions at a sufficient distance from metal surfaces are statistically equivalent.

This test EME is obtained by sufficient sampling of independent, complex (non-regular) cavity boundary conditions. Boundary condition changes are commonly obtained with one or more rotatable metal tuners. Theory now exists which predicts the relationship between sampling requirements and EME uncertainty and confidence limits.[4]

Typically, there is a lowest usable frequency (LUF) for which the desired statistical properties can be achieved. The LUF depends on the cavity dimensions, quality factor, and tuner effectiveness. For many reverberation chambers, the LUF is on the order of 200 MHz. For a cavity with dimensions comparable to those of a typical 10-m anechoic chamber, the LUF could be on the order of 80 MHz. An extensive experimental database supports the theory of reverberation chamber operation above the LUF.[5,6,7] Operation of a cavity below the LUF requires special procedures and data interpretation and will not be discussed here.

A cavity has a modal structure defined by its boundary conditions. The modal structure is deterministic and derivable (at least in principle) from Maxwell's equations. If the boundary condition is changed, a different but still deterministic field structure will exist. If the cavity boundary conditions are complex and could be changed a sufficiently large number of times by some mechanism, the EME for the ensemble would exhibit the desired statistical characteristics.

The inclusion of a rotatable (continuous or stepped operation) tuner(s) in the cavity operationally permits an approach to obtaining the desired statistical characteristics. The tuner in a reverberation chamber serves two purposes. The first is to achieve the desired complexity in the cavity boundary conditions. A perfectly regular rectangular cavity (without a tuner present), as well as several other regular shapes, do not yield the desired complexity. However, with an electrically large and electrically complex tuner in the cavity, the desired boundary condition complexity is operationally achievable. The second purpose of the tuner is to simulate a sufficiently large collection of cavities with complex boundary conditions. To the extent that the tuner or other items in the cavity provide variable and complex boundary conditions, the cavity EME will approach the desired statistical characteristics over the working volume.

It should be noted that reverberation chamber operations can be described either by the electric field or by the electric field squared. P. Corona and his colleagues at the Instituto Universitario Navale, Naples, Italy pioneered the use of the electric field description, and since 1976 have published many papers on reverberation chamber characteristics.[8] Historically, the electric field squared has been used at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) and will be the approach discussed here.

It is beyond the scope of this article to cover the statistical theory of reverberation chambers in detail. Suffice it to say that it can be shown that the statistical variation of the electric field squared (or received power) measured by a probe or monitor antenna at a fixed location and frequency in a properly operated reverberation chamber should be described by a chi-squared distribution with two degrees of freedom. A chi-squared distribution is completely characterized by one parameter, its mean. Without any loss of generality, the mean normalized cumulative distribution function (CDF) is the most convenient way to compare measured data to theory. The CDF can be displayed in a linear or logarithmic format. The logarithmic format is common since most instrumentation collects data in a logarithmic format. Figure 1 shows the mean normalized CDF for a chi-squared distribution with two degrees of freedom in a logarithmic format. This curve provides the theoretically predicted distribution against which measured data can be compared.

For immunity testing we must be able to quantify the variability of the maximum EME (the tail of the distribution in Figure 1) for reverberation chamber testing to be viable. In fact, a theoretical distribution for the maximum can be derived using the extreme value theory for ordered statistics.

Again, it is convenient to consider the CDF of the distribution of the maximum. Figure 2 shows the CDF of the maximum (referenced to the mean) for several values of N. The CDF permits a trade-off between N, the number of independent samples (independent boundary conditions or independent tuner positions), and the acceptable uncertainty for a given confidence level. Consider the 68% confidence limits shown by the horizontal lines in Figure 2. This level is compatible with the procedures for determining overall uncertainty in test results. The measurement uncertainty procedures currently under development require determination of the 1 σ uncertainty for each source of error before combining them as the square root of the sum of the individual σ^2. For N = 20, the

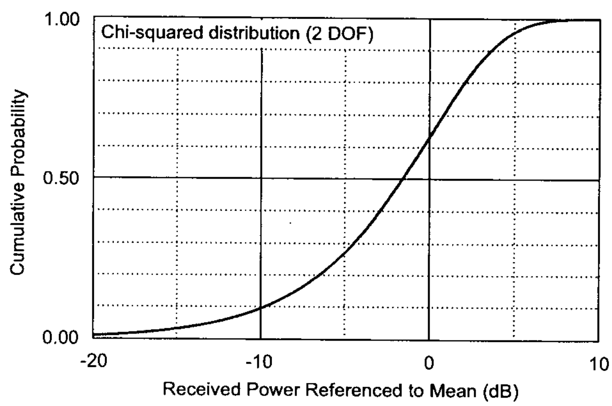

Figure 1. *Cumulative Distribution Function for a Chi-squared Distribution with Two Degrees of Freedom.*

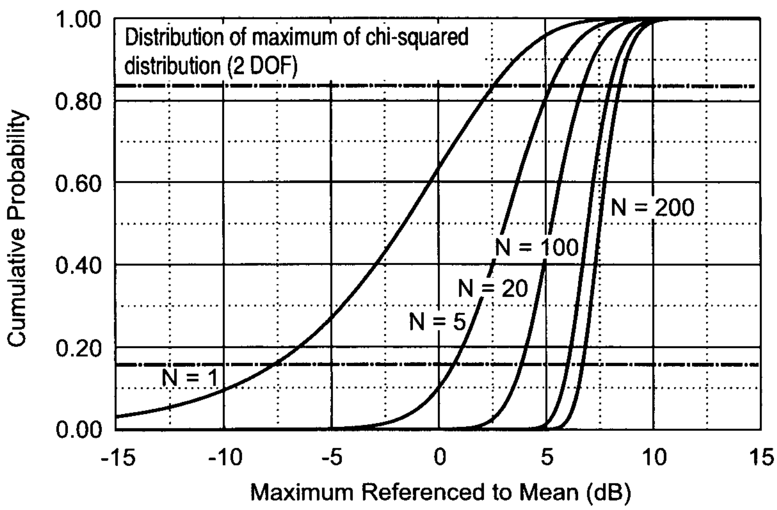

Figure 2. *Cumulative Distribution Function for the Maximum for Several Values of N Independent Samples.*

uncertainty in the maximum (referenced to the mean) for 68% confidence limits is 1.5 dB. If a smaller uncertainty is required with the same confidence, we would increase the number of independent samples. For example, for N = 100, the uncertainty in the maximum (referenced to the mean) would be 1 dB. Thus, the distribution for the maximum not only quantifies the theoretical uncertainty in the most important test parameter, it also provides a procedure for optimizing the test time for the acceptable uncertainty and confidence limits.

An important issue for any EMC test technique is how the field at the EUT is determined. For reverberation chambers we again make use of the intrinsic properties of isotropy and homogeneity. Since the field is homogeneous, a measurement at any location in the working volume should represent the field at any other location in the working volume. Thus an antenna/probe at a location remote from the EUT can be used to monitor/set the test EME. We can be even more specific. Theory predicts that measurement of the *mean* of a *specific* component (e.g., the x component) at a *specific* location defines the *maximum* of *all* components at *all* locations in the working volume within a *quantifiable* uncertainty! This is a very robust prediction. How well measured data conforms to theory will be demonstrated later.

The final observation is that all reverberation chambers are statistically equivalent. This has two important aspects. The first pertains to the impact of variations in the EUT test configuration. Test results in a properly operated reverberation chamber should be insensitive (within some uncertainty) to variations in the EUT configuration. This insensitivity has obvious benefits.

The second aspect of statistical equivalence pertains to testing in different reverberation chambers. The statistical characteristics of the EME in properly operated reverberation chambers are independent of cavity construction and volume. This implies that EUT test results from all properly operated reverberation chambers should be the same within some uncertainty. This aspect of statistical equivalence also has obvious benefits.

This section has identified the requirements for proper operation of a reverberation chamber. They are a cavity with complex boundary conditions which are changed a sufficient number of times and operation above some minimum frequency.

The section has also discussed the statistical characteristics of the EME in a properly operated reverberation chamber. The characteristics include isotropy and homogeneity over a large working volume, and statistical equivalence. The section also indicated that theory predicts the fields at an EUT can be determined from a remote measurement by a monitor antenna/probe.

Typical Reverberation Chamber Characterization Measurements

The most basic reverberation chamber characterization measurement involves sampling the received power at a specific location at a fixed frequency for multiple tuner positions. These data can be obtained from a tuner sweep (stepped or continuous) over one revolution. This has been termed a stirring ratio measurement in some references. Figure 3 shows a typical tuner sweep measurement in the NSWCDD reverberation chamber. The data reflect the effect of boundary condition (e.g., tuner position) changes on the chamber modal structure. The mean of the trace will vary linearly with input power and chamber losses (quality factor). The structure of the trace will vary with the transmit and monitor antenna locations, orientations, and polarizations, and with the configuration of all metallic items (EUT, cables, support equipment) within the chamber. Normalizing the Figure 3 data by its mean and sorting the data from the minimum received power to the maximum received power yields an experimental CDF which can be compared to the theoretical curve in Figure 1.

Figure 4 shows the maximum and minimum departure from theory for the CDFs derived from measurements at twelve reverberation chambers worldwide and includes the data from

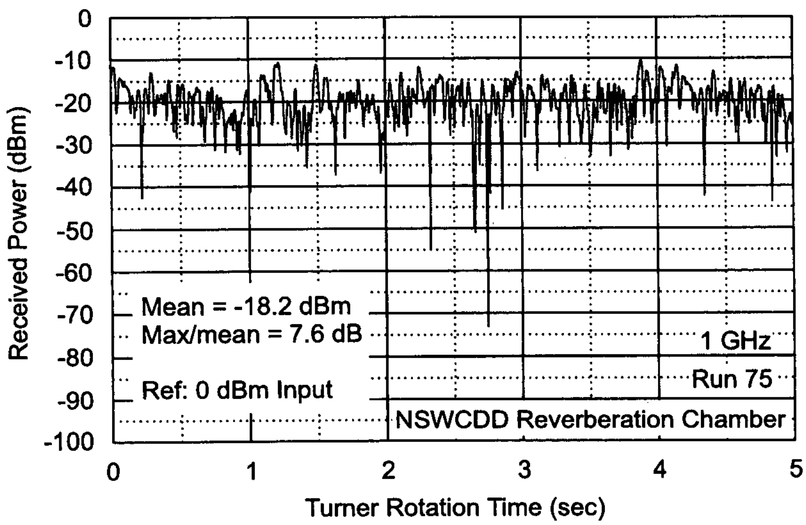

Figure 3. *Tuner Sweep Data at 1 GHz in the NSWCDD Reverberation Chamber.*

Figure 3. In some cases, multiple measurements (up to 11) from a single reverberation chamber are included in Figure 4. The chambers vary in volume by a factor of more than 50 and are constructed of a variety of materials including bare steel, primed and painted steel, aluminum, and galvanized sheets. The data for each chamber were acquired at 1 GHz using the instrumentation and standard procedures of each organization. Figure 4 shows the degree of statistical equivalence that can be expected for the EME in operational reverberation chambers

Finally, multiple tuner sweep data (similar to that shown in Figure 3) can be used to evaluate how well the field at an EUT location can be determined from data at a remote monitor location. The National Institute of Standards and Technology (NIST) collected tuner sweep data using ten, 3-axis probes.[9] The minimum probe spacing was 0.5 m and the maximum spacing was 7 m. Data were collected for many frequencies from 80 MHz to 18 GHz. The 1 GHz data were analyzed and the results are shown in Figure 5. Markers show the measured means for the x, y, and z components of probe #1. These data are an indication of the isotropy at the location of probe #1. Also shown is the mean of the means of the three components for all ten probes. The 95% confidence limits for the mean of all components of all probes indicate the uncertainty in the isotropy and homogeneity of the fields over the sampled region.

Markers also show the measured maximum value of the three components of all ten probes. The maximum value of any component of any probe can be compared to the theoretically predicted value based on the mean of any component of any probe — in this case the x component of probe #1. The theoretically predicted maximum and the 95% confidence limits are shown in Figure 5. These were derived from a curve similar to those shown in Figure 2 for 225 independent samples. The number of independent samples was derived from correlation coefficient calculations using the data from tuner sweep measurements. These data indicate the viability of predicting the test field at the EUT based on the measured mean of a single component at a remote location for a properly operated reverberation chamber.

The maximum data have a standard deviation of less than 2 dB. These data reflect the expected statistical variability in the maximum as well as the measurement uncertainty between the ten 3-axis probes and the homogeneity of the chamber. These data are an indication of the uncertainty in the isotropy and homogeneity of the test field achievable throughout the working volume of a reverberation chamber.

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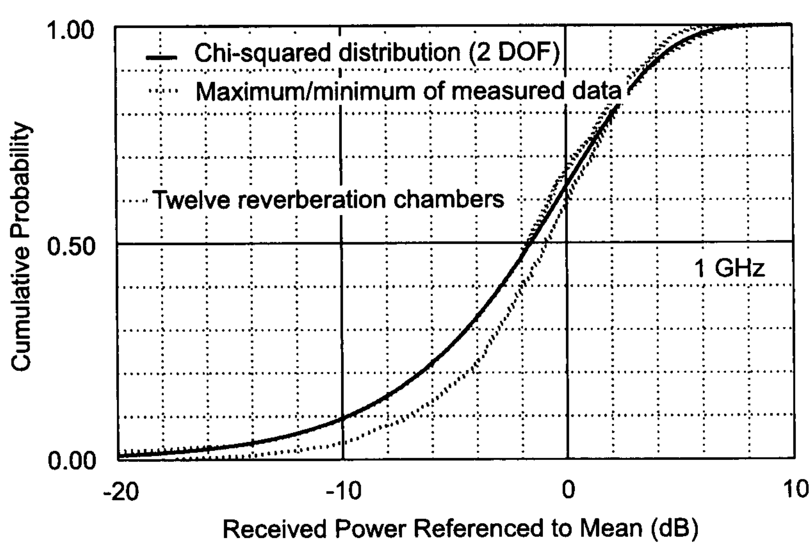

Figure 4. *Cumulative Distribution of Tuner Sweep Data for 12 Reverberation Chambers.*

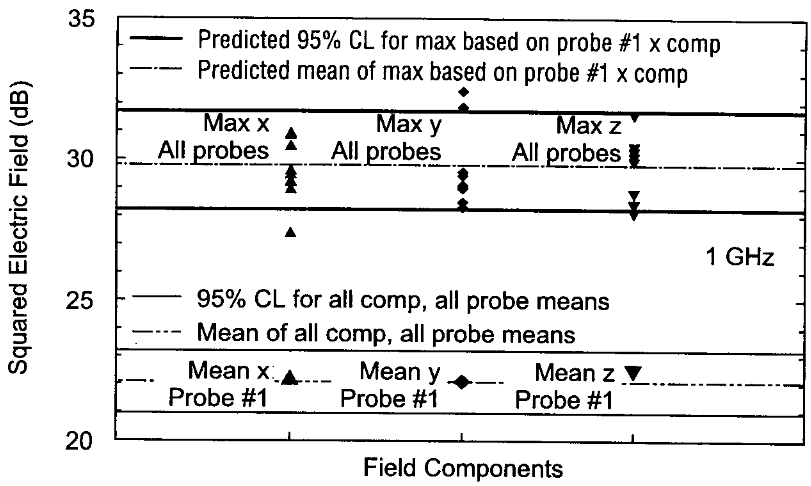

Figure 5. *Maximum and Mean Data of the Electric Field Squared Obtained from 10 Three-Axis Probes in a Reverberation Chamber.*

Advantages and Disadvantages

ADVANTAGES

A reverberation chamber is the best simulation of the electromagnetic environment for an EUT which operates in a cavity such as a computer room or medical facility or inside a motor vehicle or aircraft.

An emission or immunity test in a properly operated reverberation chamber is a robust, all-aspect-angle test. Throughout the working volume the fields are isotropic and homogeneous within some uncertainty. All properly operated reverberation chambers are statistically equivalent. This implies that test results will be insensitive to the details of EUT configuration, and therefore, test repeatability should be high. Statistical equivalence also implies that testing in different facilities should have good reproducibility.

Reverberation chambers have a high field to input power ratio. In a reverberation chamber the working volume to total volume ratio is high. Reverberation chamber facility costs are relatively low.

DISADVANTAGES

The statistical nature of the test must be understood and included in planning, procedures, and data analysis and interpretation. Reverberation chambers are currently accepted in only a few standards. Utilization of reverberation chambers for emissions testing will require acceptance of total radiated power as a pass/fail criterion.

There is a lowest usable frequency defined by the cavity dimensions, tuner effectiveness, and cavity quality factor.

Directivity and polarization effects are not measurable. The high quality factor in reverberation chambers may impose constraints on pulse testing. Depending on test conditions, correlation of test results to other test techniques may be difficult or impractical.

Summary

Reverberation chambers have advantages and disadvantages and are not an electromagnetic test panacea.

Reverberation chamber testing is a statistical process. The theory for operation above the lowest usable frequency is well established and supported by an extensive data base.

Reverberation chambers provide an ambient isolated and cost effective emission and immunity test capability.

Community acceptance of reverberation chambers is growing.

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