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Studio di metodologie innovative di prova e di integrazione tra prove di tipo e metodo analitico per le qualifiche ambientali, meccaniche, sismiche ed elettromagnetiche di componenti e sistemi per le centrali nucleari

Parte II: camera riverberante per prove EMC

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PARTE II: CAMERA RIVERBERANTE PER PROVE EMC

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Rapporto sullo studio di metodologie innovative di prova e di integrazione tra prove di tipo e metodo analitico per le qualifiche ambientali, meccaniche, sismiche ed elettromagnetiche di componenti e sistemi per le centrali nucleari.

Part II: Reverberation chambers for EMC tests

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Executive Summary of the Document

This report deals with a general description of Reverberation Chambers for EMC use.

The first part presents an overview of the Reverberation Chamber functioning principles and preliminary calculations of some important parameters of the empty chamber such as the first resonant frequencies and the estimated Q factor. This basic but crucial analysis serves as an essential starting point for understanding basic operating processes.

The second part concerns operating procedures and details necessary for the calibration and characterization of the ENEA reverberation chamber according to the international standard IEC 61000-4-21.

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List of Abbreviations

EM	**Electromagnetic**
EMC	**Electromagnetic compatibility**
EUT	**Equipment Under Test**
RC	**Reverberation chamber**
OATS	**Open Area Test Site**
AC	**Anechoic Chamber**
TEM	**Transverse Electromagnetic**
TX	**Transmitting (antenna)**
RX	**Receiving (antenna)**
LUF	**Lowest Usable Frequency**
SR	**Stirring Ratio**
Q	**Quality Factor**
IL	**Insertion Loss**
ACF	**Antenna Calibration Factor**
CCF	**Chamber Calibration Factor**
CLF	**Chamber Loading Factor**
T	**Chamber time constant**

1. Reverberation Chamber Principles

An electromagnetic reverberation chamber is an electrically large, highly conductive closed cavity or chamber used to perform EM measurements (both emissions and immunity) on electronic equipment. Any facility that fits this description can be considered a reverberation chamber (also called a mode-stirred chamber).

A rotating paddle or other means of altering the geometry of the room is almost always used in a reverberation chamber for “mode-stirring” or “mode-tuning”. Sometimes a frequency-modulated source is used to achieve “electronic mode-stirring”.

A closed cavity has many propagating modes which form 3-dimensional standing wave patterns with a large number of resonant modes. This gives rise to regions where the field is small and other locations where it is large. Typical variations are of the order of 40 dB, making the perceived test field very strongly dependent on the exact location inside the cavity. At sufficiently high frequencies, the coupling between an equipment and an antenna varies rapidly with position and frequency. When a large number of modes are present (as in a reverberation chamber) the field pattern becomes highly detailed (although regular), but there are still large and rapid variations in field values with position and frequency. The mode stirrer or tuner alters the boundary conditions, thus moving the position of the maxima and minima of the field magnitude.

The shape of a reverberation chamber is by and large unimportant – very different shapes have shown to perform equally well. Instead, the volume of the chamber is the key factor for satisfactory performance. When choosing a rectangular room as a basis for building a reverberation chamber, ideally the dimensions should not be simple multiples or rational fractions of each other – this gives the largest number of modes with different resonance frequencies, and in principle improves the room performance, particularly at lower frequencies.

Modelling the operation of a reverberation chamber is of interest because it allows the rapid comparison of different scenarios, and the determination of much greater information about the field structure than is easily possible with measurements. However modelling electrically large, high-Q structures, such as reverberation chambers, is not a trivial exercise. For this sort of model, full wave numerical electromagnetic modelling methods are suitable; Ray tracing methods have also been used and are suitable for modelling the high frequency behavior of reverberation chambers.

2. Reverberation Chamber Theory

Modes within an Ideal Cavity

In order to define the distribution of modes inside an ideal cavity it is necessary to start from the general idea of a resonator. In general, a resonator can be obtained by short-circuiting a rectangular waveguide and this operation must be done at two sufficiently separated ends. When at a given frequency the geometrical dimensions of a resonator reach a specific lengths, an EM field inside the resonator forms a standing wave pattern.

By using Maxwell's equations it is possible to mathematically describe the field distribution inside a cavity:

$$
\begin{aligned}
\overline{\nabla} \times \overline{E} &= -j\omega\mu\overline{H} \\
\overline{\nabla} \times \overline{H} &= j\omega\varepsilon\overline{E} + \bar{j} \\
\overline{\nabla} \cdot \overline{E} &= 0 \\
\overline{\nabla} \times \overline{H} &= 0
\end{aligned}
$$

where $\overline{E}$ and $\overline{H}$ are the electric and the magnetic field strength, $\bar{j}$ is the electric current density, ε denotes the dielectric permittivity and μ is the magnetic permeability. By applying the property of vector identity to the first two Maxwell's equations

$$\overline{\nabla} \times \left(\overline{\nabla} \times \overline{X}\right) = \overline{\nabla}\left(\overline{\nabla} \cdot \overline{X}\right) - \Delta\overline{X}$$

it is possible to derive the electrical and magnetic wave equations. These equations can be used to describe the fields inside a cavity:

$$
\begin{aligned}
\Delta\overline{E} &= \frac{1}{c^2}\frac{\partial^2\overline{E}}{\partial t^2} \\
\Delta\overline{H} &= \frac{1}{c^2}\frac{\partial^2\overline{H}}{\partial t^2}
\end{aligned}
$$

where c is the propagation speed of the EM waves within the resonator and c_0 is the speed of the EM waves in the vacuum:

$$c = \frac{c_0}{\sqrt{\varepsilon_r \mu_r}}$$

The electrical and magnetic wave equations can be solved by using the boundary conditions that are derived for the tangential components of the electric and magnetic fields:

$$\overline{\nabla} \times \overline{E} = \overline{n}_{12} \times \left(\overline{E}_2 - \overline{E}_1\right) = \overline{0}$$

$$\overline{E}_{\tan 2} - \overline{E}_{\tan 1} = \overline{0}$$

and:

$$\overline{\nabla} \times \overline{H} = \overline{n}_{12} \times \left(\overline{H}_2 - \overline{H}_1\right) = \overline{0} \xrightarrow{for} k < \infty$$
$$\overline{\nabla} \times \overline{H} = \overline{n}_{12} \times \left(\overline{H}_2 - \overline{H}_1\right) = \overline{j}_s \xrightarrow{for} k \to \infty$$

$$\overline{H}_{\tan 2} - \overline{H}_{\tan 1} = \overline{0} \xrightarrow{for} k < \infty$$
$$\overline{H}_{\tan 2} - \overline{H}_{\tan 1} = \overline{j}_s \xrightarrow{for} k \to \infty$$

where n_{12} is a normal vector that points from region 1 into region 2 and $\overline{j}_s$ is the surface current density.

It is also possible to derive the boundary conditions for the normal components of the electric field:

$$\overline{\nabla} \cdot \overline{D} = \overline{n}_{12}\left(\overline{D}_2 - \overline{D}_1\right) = \eta$$
$$D_{nor2} - D_{nor1} = \eta$$

and the magnetic field:

$$\overline{\nabla} \cdot \overline{B} = \overline{n}_{12}\left(\overline{B}_2 - \overline{B}_1\right) = 0$$
$$B_{nor2} - B_{nor1} = 0$$

where η is the surface charge. Two of the equations of the boundary conditions in the case of an ideal cavity, can be approximated in this way:

$$\left.\overline{E}_{\tan}\right|_{\partial V} = \overline{0}$$
$$\left.\overline{H}_{nor}\right|_{\partial V} = 0$$

These last two equations are valid on the PEC wall surface ∂V of the cavity for the normal component of the magnetic field and for the tangential component of the electric field. Applying these concepts to the rectangular geometry of an ideal cavity resonator the obtained results are:

$$x = 0 \quad \vee \quad x = w \quad \rightarrow \quad E_y = 0, E_z = 0, H_x = 0$$

$$y = 0 \quad \vee \quad y = l \quad \rightarrow \quad E_x = 0, E_z = 0, H_y = 0$$

$$z = 0 \quad \vee \quad z = h \quad \rightarrow \quad E_x = 0, E_y = 0, H_z = 0$$

By means of the first and the third equation, the electrical and magnetic wave equations derived before can be fulfilled by certain EM field standing wave patterns inside the cavity, those are called as the cavity modes. The cavity modes are divided in two main parts, the first category is called transverse electric(TE) and it represents the modes which have a zero electric field component along the z-direction (E_z=0) while the second category is the transverse magnetic (TM) and it indicates the modes which do not have a magnetic field along the z-direction (H_z=0).
In the case of the field components of TM_{mnp} modes in an ideal rectangular cavity resonator:

$$\begin{aligned}
E_x(x,y,z) &= -\frac{1}{k_{mn}^2}\left(\frac{m\pi}{w}\right)\left(\frac{p\pi}{l}\right)\cdot E_0 \cos\left(\frac{m\pi}{w}x\right)\sin\left(\frac{n\pi}{h}y\right)\sin\left(\frac{p\pi}{l}z\right) \\
E_y(x,y,z) &= -\frac{1}{k_{mn}^2}\left(\frac{n\pi}{h}\right)\left(\frac{p\pi}{l}\right)\cdot E_0 \sin\left(\frac{m\pi}{w}x\right)\cos\left(\frac{n\pi}{h}y\right)\sin\left(\frac{p\pi}{l}z\right) \\
E_z(x,y,z) &= E_0 \sin\left(\frac{m\pi}{w}x\right)\sin\left(\frac{n\pi}{h}y\right)\cos\left(\frac{p\pi}{l}z\right) \\
H_x(x,y,z) &= \frac{j\omega\varepsilon}{k_{mn}^2}\left(\frac{n\pi}{h}\right)\cdot E_0 \sin\left(\frac{m\pi}{w}x\right)\cos\left(\frac{n\pi}{h}y\right)\cos\left(\frac{p\pi}{l}z\right) \\
H_y(x,y,z) &= -\frac{j\omega\varepsilon}{k_{mn}^2}\left(\frac{m\pi}{w}\right)\cdot E_0 \cos\left(\frac{m\pi}{w}x\right)\sin\left(\frac{n\pi}{h}y\right)\cos\left(\frac{p\pi}{l}z\right) \\
H_z(x,y,z) &= 0
\end{aligned}$$

The indices *m, n* and *p* are integer numbers (where *m,n*=1,2,3,…. and *p*=0,1,2,….). Such indices are used to indicate the number of half wavelengths in the three direction x, y and z. The factor *w* is the width, *h* is the height and *l* is the length of cavity.

The same conclusions can be also derived for the TE_{mnp} modes:

$$
\begin{aligned}
&E_x(x,y,z) = \frac{j\omega\mu}{k_{mn}^2}\left(\frac{n\pi}{h}\right)\cdot H_0 \cos\left(\frac{m\pi}{w}x\right)\sin\left(\frac{n\pi}{h}y\right)\sin\left(\frac{p\pi}{l}z\right)\\
&E_y(x,y,z) = -\frac{j\omega\mu}{k_{mn}^2}\left(\frac{m\pi}{w}\right)\cdot H_0 \sin\left(\frac{m\pi}{w}x\right)\cos\left(\frac{n\pi}{h}y\right)\sin\left(\frac{p\pi}{l}z\right)\\
&E_z(x,y,z) = 0\\
&H_x(x,y,z) = -\frac{1}{k_{mn}^2}\left(\frac{m\pi}{w}\right)\left(\frac{p\pi}{l}\right)\cdot H_0 \sin\left(\frac{m\pi}{w}x\right)\cos\left(\frac{n\pi}{h}y\right)\cos\left(\frac{p\pi}{l}z\right)\\
&H_y(x,y,z) = -\frac{1}{k_{mn}^2}\left(\frac{n\pi}{h}\right)\left(\frac{p\pi}{l}\right)\cdot H_0 \cos\left(\frac{m\pi}{w}x\right)\sin\left(\frac{n\pi}{h}y\right)\cos\left(\frac{p\pi}{l}z\right)\\
&H_z(x,y,z) = H_0 \cos\left(\frac{m\pi}{w}x\right)\cos\left(\frac{n\pi}{h}y\right)\sin\left(\frac{p\pi}{l}z\right)
\end{aligned}
$$

In this second case *m* and *n* are equal to 0,1,2,3… while *p* is equal to 0,1,2,….

Both for the TE and the TM case the constant K_{mn} is equal to:

$$
k_{mn}^2 = \left(\frac{m\pi}{w}\right)^2 + \left(\frac{n\pi}{h}\right)^2 \rightarrow k_{mn} = \sqrt{\left(\frac{m\pi}{w}\right)^2 + \left(\frac{n\pi}{h}\right)^2}
$$

It is also necessary to define the angular frequency ω:

$$
\frac{\omega}{c} = k_{mnp} = \sqrt{\left(\frac{m\pi}{w}\right)^2 + \left(\frac{n\pi}{h}\right)^2 + \left(\frac{p\pi}{l}\right)^2}
$$

In a cavity in which the walls are PEC and there are no losses due to dissipative elements present inside the cavity, it is possible to define the formula used to evaluate the cut-off frequencies for any individual modes:

$$
f_{mnp} = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{w}\right)^2 + \left(\frac{n\pi}{h}\right)^2 + \left(\frac{p\pi}{l}\right)^2}
$$

It is not impossible to have modes having the same cut-off frequency, and this is true for all TE_{mnp} and TM_{mnp} cavity modes with *m*>=1, *n*>=1 and *p*>=1. These modes with the same cut-off frequency are called degenerate modes.

By applying these theoretical concepts to a real case like the ENEA shielded room, it is possible to find the modal structure of this chamber for the TE and TM case. In the graph of Fig. 1, the asterisks and the lines are used to identify the presence of a mode. The line representation is used only for modes that are sufficiently separated from the others.

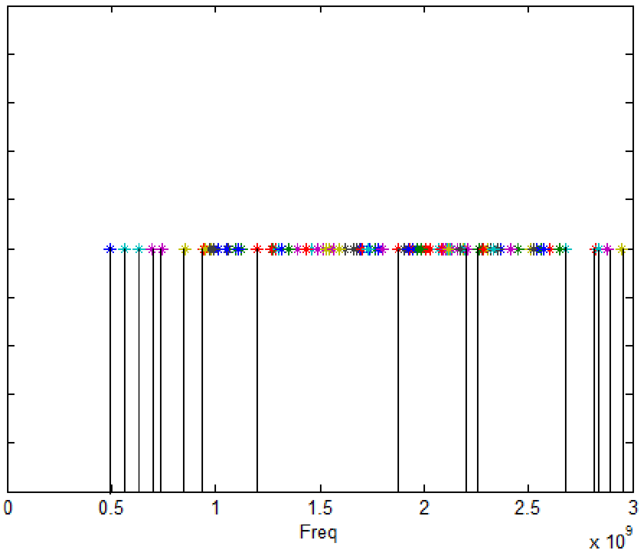

Fig.1:Theoretical modal structure for the chamber under study (ENEA shielded room dimensions: h=3.04 m, w=3.62 m, l=5.24 m). The first 100 modes are represented.

It is possible to see more in details the modal structure for the first modes, as illustrated in Fig. 2. It is possible to note that no degenerate modes are present, since the *h* and *w* dimensions of the ENEA chamber have different values.

In practice, a reverberation chamber is not an ideal cavity but it is dominated by losses in the walls. As a consequence, if the condition of $k >> \omega\varepsilon$ is valid, the shape of the field distribution inside the cavity is not modified but the magnitude of the field is reduced. By considering a *k* value that is smaller than the ideal value (infinite), the field distribution is a scaled version of the one obtained for *k* that goes to infinite.

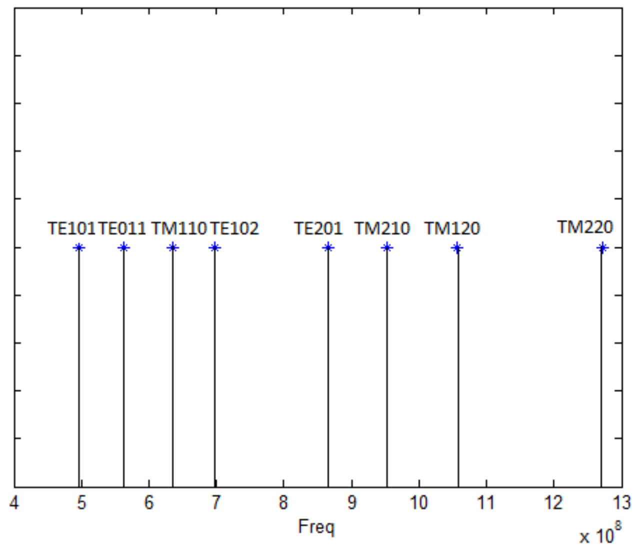

Fig 2: Theoretical modal structure for the first eight modes of the ENEA shielded room.

Lowest Usable Frequency

The frequency at which a RC is able to satisfy the basic operational requirements is called the *lowest usable frequency* (*LUF*). Different definitions apply, e.g. the LUF is the value of frequency from which at least 1.5 modes/MHz are present, or for which there are 60-100 modes inside an ideal cavity of the dimensions of the RC.

The LUF can also be found by knowing the cutoff frequency f_c of the fundamental mode of an ideal cavity with the same sizes of the RC. The frequency f_{LUF} is equal to 3 f_c.

These first two definitions are qualitative and they give a general idea on how well a RC of a certain dimension will work.

Number of Cavity Modes

Starting from the assumption of an empty RC without any stirrer device, it is possible to evaluate the cumulated number of modes, the mode density and also the “modal gap”. Those values are used to find from which value of f_{LUF} the chamber fulfills the fundamental RC requirements.

An expression can be used to find an approximation of the cumulated number of modes that are above cutoff for a specific value of frequency f:

$$N(f) \cong \frac{8\pi}{3} \cdot lwh \cdot \left(\frac{f}{c_0}\right)^3 - (l + w + h)\frac{f}{c_0} + \frac{1}{2}$$

In order to satisfy the LUF condition, the value of *N(f)* must be between 60 and 100 modes.
The mode density represents the number of modes per frequency interval; it can be found by applying the formula below

$$\frac{\partial N}{\partial f} \cong 8\pi \cdot lwh \cdot \frac{f^2}{c_0^{\ 3}} - (l + w + h)\frac{1}{c_0}$$

At least 1.5 modes/MHz above cutoff are required to have a sufficient statistical field uniformity and isotropy inside a RC.
Another important factor that it is interesting to know is the cutoff frequency of any individual mode into an ideal rectangular cavity:

$$f^i_{(m,n,p)} = \frac{c_0}{2}\sqrt{\left(\frac{m}{l}\right)^2 + \left(\frac{n}{w}\right)^2 + \left(\frac{p}{h}\right)^2}$$

The factors *m,n,p* are integers values that are positive or equal to zero, but only one of these factors can be equal to zero at the same time. It is necessary to arrange in an ascending order all the values of cutoff frequencies and after that operation it is possible to change the index *i* with a new consecutive index *i'*. By doing this operation the obtained result is:

$$f^{i'+1}_{(m,n,p)} \geq f^{i'}_{(m,n,p)'} \qquad \forall i'$$

The set *(m,n,p)'* is different from *(m,n,p)* and it represents a different mode. By subtracting the previous value from the successive one, the "modal" gap between consecutive modes is evaluated:

$$\Delta f^{\,i'+1;i'} = f^{i'+1}_{(m,n,p)} - f^{i'}_{(m,n,p)'}$$

The obtained value is really important to compare different RCs and to understand the quality of chamber; the rule is: the smaller the value of the "modal gap" the higher the quality of the RC is.

It is possible to apply the concepts that are described in this section to a real chamber, in this particular case the chamber used for the evaluation is a RC that has been built starting from a ENEA shielded room. The internal dimensions of the shielded room are:

$$Height = h = 3{,}04m$$
$$Width = w = 3{,}62m$$
$$Depth = l = 5{,}24m$$

In order to find the lowest usable frequency, the cumulated number of modes is set equal to 100 (condition that is explained in the section concerning the LUF), and then the equivalent value of frequency is found by solving:

$$100 \cong \frac{8\pi}{3} \cdot lwh \cdot \left(\frac{f_{LUF}}{c_0}\right)^3 - (l + w + h)\frac{f_{LUF}}{c_0} + \frac{1}{2}$$

$$f_{LUF} = 1{,}813 \cdot 10^8 \, Hz$$

To check if obtained frequency fulfills also the other conditions for the LUF, the mode density must have at least a value of 1.5 modes/MHz above cutoff:

$$\frac{\partial N}{\partial f} \cong 8\pi \cdot 5{,}24 \cdot 3{,}62 \cdot 3{,}04 \cdot \frac{\left(1{,}813 \cdot 10^8\right)^2}{\left(3 \cdot 10^8\right)^3} - (5{,}24 + 3{,}62 + 3{,}04)\frac{1}{3 \cdot 10^8} = 1{,}725 \, \mathrm{mod}/\, MHz$$

Another interesting point is to find the values of cutoff frequency for some individual modes:

$$f_{(1,1,0)} = \frac{3 \cdot 10^8}{2}\sqrt{\left(\frac{1}{5{,}24}\right)^2 + \left(\frac{1}{3{,}62}\right)^2} = 5{,}036 \cdot 10^7 \, Hz = 50{,}36 MHz$$

$$f_{(0,1,1)} = \frac{3 \cdot 10^8}{2}\sqrt{\left(\frac{1}{3{,}62}\right)^2 + \left(\frac{1}{3{,}04}\right)^2} = 6{,}443 \cdot 10^7 \, Hz = 64{,}43 MHz$$

$$f_{(1,0,1)} = \frac{3 \cdot 10^8}{2}\sqrt{\left(\frac{1}{5{,}24}\right)^2 + \left(\frac{1}{3{,}04}\right)^2} = 5{,}704 \cdot 10^7 \, Hz = 57{,}04 MHz$$

$$f_{(1,1,1)} = \frac{3 \cdot 10^8}{2}\sqrt{\left(\frac{1}{5{,}24}\right)^2\left(\frac{1}{3{,}62}\right)^2 + \left(\frac{1}{3{,}04}\right)^2} = 7{,}050 \cdot 10^7 \, Hz = 70{,}50 MHz$$

It is also possible to find the theoretical curve that indicates the number *N* of modes above cutoff for the ENEA shielded room (illustrated in Fig. 3).

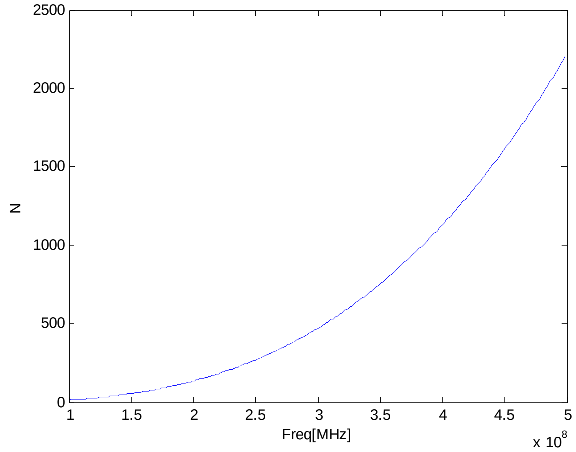

Fig 3: Theoretical number of modes *N* above cutoff in the ENEA shielded room.

By applying the formula used to find the value of the mode density, it is possible to sketch the graph representing the ideal curve of the mode density for the ENEA shielded room (Fig. 4).

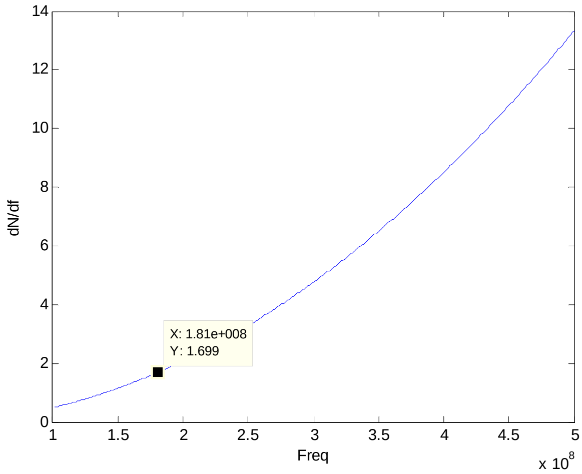

Fig 4: Theoretical mode density for the ENEA shielded room.

<u>Stirring Ratio</u>

In order to evaluate the efficiency of the stirrer inside a RC, the stirring ratio (*SR*) is defined; also, SR can be defined as the parameter used to understand how much the field is modified by a rotating stirrer. It is necessary to evaluate and to store all values of the received power of an antenna inside the cavity for different positions of the stirrer device. The transmitted power is not modified for all rotational stirrer angles. When all the measures are completed, by looking at the archived data only the maximum and the minimum values of received power are used to compute the SR:

$$SR = \max_{\varphi_j=\varphi_1\ldots\varphi_n} P_{Rx}(x_0, y_0, z_0) - \min_{\varphi_j=\varphi_1\ldots\varphi_n} P_{Rx}(x_0, y_0, z_0)$$

In this method the stirrer is not rotating continuously but it rotates with discrete stirrer steps (this method is called mode-tuned). The case of a continuous stirrer rotation is called mode-stirring, and for this case a sort of "time averaging" is required.

Another possible definition for the stirring ratio is the next one:

$$SR = \frac{\max_{\varphi_j=\varphi_1\ldots\varphi_n} \left|E(x_0, y_0, z_0)\right|}{\min_{\varphi_j=\varphi_1\ldots\varphi_n} \left|E(x_0, y_0, z_0)\right|}$$

In this case the SR is evaluates by the ratio between the maximum and the minimum value of the electric field strength at a fixed point over one revolution of the stirrer.

Usually the stirrer ratio is indicated in dB, the lower acceptable limit for the SR being 20 dB. If the SR is high, it indicates that the stirrer is really efficient.

Quality Factor

The quality factor Q is used to give an idea of the ability of a RC to store energy. If the value of Q is high, it indicates that the chamber is efficient and it has low losses. In order to find the chamber Q, usually a TX and a RX antenna are positioned inside the chamber and the values of transmitted power P_{TX} and of received power P_{RX} are measured. In this way it is possible to compute the expression below for different angles of the stirrer:

$$Q = \frac{16\pi^2 V}{\lambda^3} \frac{P_{RX}}{P_{TX}}$$

There are different conditions that are able to modify the quality factor of a RC, for example:

- Loading introduced by the cables, probes and tripods of the antennas that are inside the chamber
- Loading due to the presence of the EUT
- Presence of apertures, doors and any other particular constructions
- Intrinsic chamber properties like the conductivity of the wall material

It is also possible to find a formula for Q starting from theoretical considerations: the quality factor is based on the time averaged stored energy W_S and on W_d , which is the energy dissipated in one period within a resonator.

W_S is defined as:

$$W_s = \frac{1}{2}\iiint_V \overline{D}\cdot\overline{E}dv = \frac{1}{2}\varepsilon\iiint_V \left|\overline{E}\right|^2 dv$$

The expression of Q is:

$$Q = 2\pi\frac{W_s}{W_d} = \frac{\omega W_s}{W_d}$$

By inserting the formula of W_s in Q, and taking into account that the dissipated power is equal to the net input power P_{in}:

$$Q = \frac{\omega\varepsilon}{2P_{in}}\iiint_V \left|\overline{E}\right|^2 dv$$

To evaluate Q in a practical case, it is necessary to know all the losses of the chamber as the wall losses, aperture due to doors and contacts between the panels of the wall, losses due to the antennas and to the EUT. The previous formula includes all these losses.
Another possible easier formula that takes into account only for ohmic losses of the walls can be derived:

$$Q = \frac{3V}{2\mu_r\delta_s A}\frac{1}{\left[1+\frac{3\lambda}{16}\left(\frac{1}{w}+\frac{1}{l}+\frac{1}{h}\right)\right]} \qquad \delta_s = \frac{1}{\sqrt{\pi\mu f k}}$$

where V indicates the chamber volume while A is the inner RC surface.
In the IEC 61000-4-12 standard for typical values of l, w, h and for wavelengths lower than one meter, an approximation for Q is given by:

$$Q \cong \frac{3V}{2\mu_r\delta_s A}$$

The two last expressions are often used, but the quality factor obtained by the direct measurements in practical cases is smaller by a factor 10…500, and this is due to the presence of loss mechanisms and of the Joule heating of the walls.

By means of the formula that approximates the quality factor taking into account the ohmic losses, it is possible to sketch the graph of the quality factor in the case of the ENEA shielded room (Fig. 5). The red curve shows how the *Q* factor is modified by having a small reduction of magnetic permeability while the green one represents the *Q* factor for a higher value of magnetic permeability.

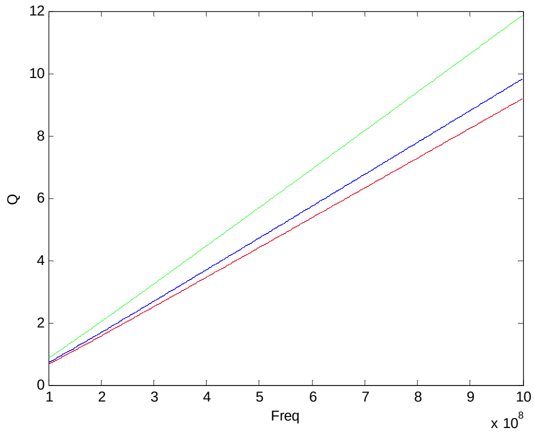

Fig 5: Theoretical Quality factor for the ENEA shielded room.

3. Field Statistics in a Reverberation Chamber

There are two types of approach that are used to describe theoretically an ideal EM environment within an RC. One assumes that an RC can be studied as an EM cavity characterized by a quasi-stationary fields structures corresponding to the cavity resonant modes; unfortunately if the shape of the cavity is too complex, the structures of the resonant fields shall be very difficult to solve analytically.

The second approach is to consider the plane wave integral representation for fields based on the angular plane wave spectrum. By using this concept it is possible to represent the angular spectrum of a limited portion of the working volume in a probabilistic way based on simple correlation assumption.

It is possible to determine the probabilistic model for EM fields if the considered volume is far from walls and stirrers. It is also important to say that this model is limited to high excitation frequency because, only in this case, the random properties of the plane wave spectrum are assured. In any case, both the approaches lead the same field probabilistic description.

Ergodicity

The Ergodicity property can be described by considering an RC excited by the EM field in three different cases.

The first case is when the stirrer is not moving and only a single frequency EM field is excited; according to this assumption, it is possible to consider a set S_n of n values that represent the EM quantity measured in different locations inside the working volume.

In the second case the stirrer is still fixed and only one location is used to compute the measurement; this time a set F_n of n values is defined to contain the EM quantity measured at different excitation frequencies.

In the third case only a single frequency EM field is excited inside the RC but the stirrer is not fixed. A set R_n is used to represent the EM quantity measured in a fixed location but for different positions of the stirrer.

Now considering the property of Ergodicity it is possible to note that the sets S_n, F_n and R_n have the same statistical properties when measurement samples are independent. In conclusion, when a spatial shift, a frequency shift or a stirrer rotation are considered, the EM quantities are characterized by the same probabilistic distribution.

Probabilistic Distributions

The starting point of the probabilistic model is that the real and imaginary parts of the three rectangular component of the electric and magnetic field are independent from each other and they have a Normal (Gaussian) distribution.
It is possible to collect in the following Table I the distributions for electric and magnetic fields amplitude and square amplitude.

Table I

EM quantity X	Distribution	Probability density function f(x)	Mean value	Variance
$\mathrm{Re}\{E_{x,y,z}\}$ $\mathrm{Im}\{E_{x,y,z}\}$	Normal (Gaussian)	$\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{x^2}{2\sigma^2}\right]$	0	σ^2
$\lvert E_{x,y,z}\rvert$	χ_2 (Rayleigh*)	$\frac{x}{\sigma^2}\exp\left[-\frac{x^2}{2\sigma^2}\right]$	$\sqrt{\frac{\pi}{2}}\sigma$	$\sigma^2\left(2-\frac{\pi}{2}\right)$
$\lvert E_{x,y,z}\rvert^2$	$\chi_2^{\ 2}$ (Exponential)	$\frac{1}{2\sigma^2}\exp\left[-\frac{x^2}{2\sigma^2}\right]$	$2\sigma^2$	$4\sigma^4$

Magnetic field quantities have the same distribution of the electric ones; the power and the current received by an antenna have the same distributions of the square amplitude and of the amplitude, respectively, as shown in Table I (second and third row).
It is important to note that statistical models of Table I are obtained for samples constituted of independent measurements.

Correlation Function

For single frequency continuous wave fields that are mechanically stirred, the above probabilistic description characterizes the fields in a given spatial point during the stirrer rotation. In order to give a complete probabilistic description, it is also important to know something about spatial correlation of the EM fields.

The spatial correlation functions for fields and energy density are found starting from the integral plane wave representation.

Statistical Uncertainty and Estimator Accuracy

It is important to know the statistical behavior of the EM fields inside the chamber to be able to evaluate the uncertainty of a test done in an RC. Often in the RC measurements it is interesting to evaluate the interval in which a certain percentage *p* of the values from a standard Gaussian distribution are contained. This operation can be done by solving:

$$p = F(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt$$

The so called maximum likelihood estimator (MLE) can be used as an estimator of the EM-field. In fact, the MLE estimator is always asymptotically unbiased, and its accuracy can be easily evaluated. Asymptotically unbiased means that its mean is the true value for large amounts of data.

In order to evaluate the amount of data required to get a certain estimator accuracy, the following formula applies:

$$\widetilde{d} = \frac{1+\frac{k}{\sqrt{bN}}}{1-\frac{k}{\sqrt{bN}}}$$

and in dB notation:

$$\widetilde{d} = 10\log_{10}\frac{1+\frac{k}{\sqrt{bN}}}{1-\frac{k}{\sqrt{bN}}}$$

where b is the number of dimensions of the field data to be estimated, k is used to determine the confidence level (ex. k=±1.96σ for p=0.95) and finally N is the number of statistically independent stirrer positions that are required. If b=1, it means that the field probe is sensitive to a single component of the field.

The formula used to evaluate N is:

$$N = \frac{k^2}{b}\left(\frac{10^{\frac{\tilde{d}}{10}}+1}{10^{\frac{\tilde{d}}{10}}-1}\right)^2$$

The lowest achievable uncertainty $\pm\tilde{d}$ is dependent on N, so it is essential to make sure that an RC in combination with a stirrer are able to provide at least N independent distributions. It is necessary to evaluate the correlation coefficient for the chosen step angle of the stirrer assuming that uncorrelated stirrer position yield independent samples. It is really important to check if a stirrer is not capable to provide a required number N of uncorrelated field distribution over a complete rotation; at low frequency it is more difficult to satisfy the requirements.

4. Operating Procedure for the ENEA Reverberation Chamber Calibration

The aim of a calibration is to check if the generated fields, defined under certain limits, have the same magnitude for all polarizations and for a given number of tuner steps. One procedure is the so called *empty chamber calibration* and it consists in the comparison between the peak fields measured by the E-probes with respect to the mean received power of the reference antenna. In order to perform the calibration it is necessary to use isotropic probes. The mean data of the antenna is evaluated for eight different places inside the chamber in order to increase the accuracy (Fig. 6).

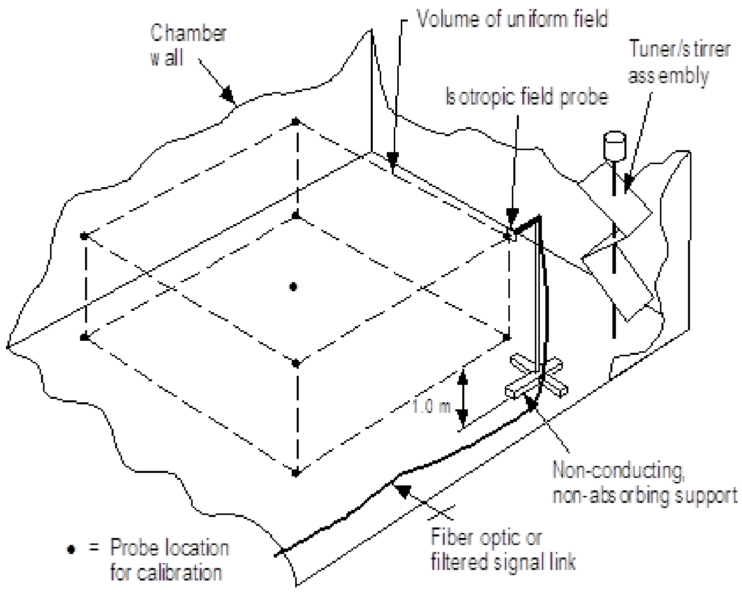

Fig 6: The test volume and calibration locations in a RC.

The calibration procedure should be performed only once in the life of the chamber or only in the cases of relevant modifications.

Measurement System

The measurement system has to be able to generate the proper power inside the chamber and acquire information on the electric field, the power being transmitted and reflected by the transmitting antenna, the power received by the receiving antenna and the stirrer angular position.
Typically, the following list of test equipment is recommended for the measurement system:

- *Screened room* ENEA RC internal dimensions: 3.04 m x 3.62 m x 5.24 m (height). Volume: 57.66 m3. One main access door of 1.20 m x 2.44 m; and a secondary one of 0.92 m x 2.14 m.
- *TX/RX antennas* The antennas must be efficient in the frequency range of utilization of chamber. Typically log-periodic, horn and/or short dipoles antennas are used.

  The antennas must be mounted to reduce the influence on the field distribution within the cavity:

  - All cables feeding the antennas must be low-loss ones, and routed as close as possible to the cavity walls.
  - The tripods holding the antennas must be entirely made in low-epsilon plastic or wood, thus avoiding unwanted loading and distortion of the EM field.
- *Signal generator* Must cover the frequency band of interest.
- *Power Amplifier(s)* Must cover the frequency band of interest and have a low harmonic distortion.
- *Spectrum analyzer* Necessary to measure and record the received power.
- *Directional Couplers* The (bi-)directional couplers are used to measure the forward and reflected power at the transmitting antenna terminals. They must cover the operating frequency range.
- *Power Meter and Probe Heads* The power meter is used to measure the forward and reflected power provided by the bidirectional couplers. The two channels must be completely independent from each other and be able to measure power simultaneously, thus the net power delivered to the RC can be calculated from these measurements.

- *Field Probe* The field probe is utilized to measure the three components of the electric field and is helpful only during calibration of the RC. For actual EMC measurements, a field probe is not necessarily needed, but still recommended [1].
- *Electromagnetic Absorbers* A sufficient amount of absorbers (efficient at the desired frequency band) is needed in order to perform the loading verification of the chamber, which is a crucial validation parameter.
- *Attenuator, cables and adaptors* Since high reflections are often present in reverberation chambers, attenuators are needed to protect sensitive equipment like, i.e. the amplifier(s) and the spectrum analyzer. All coaxial cables must be low-loss.
- Data acquisition and interfacing All active devices of the RC equipment setup (signal generator, power meter, field probe, spectrum analyzer, and stirrer drive controller) might be able to be remote controlled from a computer. Data acquisition programs must also be included. The programs should be especially adapted to the requirements of measurements used for performance assessment and calibration: they must allow to define a cubic test grid for the field probe system by setting 8 different spatial positions within the RC, the frequency range of interest (that can be split into different frequency bands, in case a change of the amplifiers and/or the antennas must be performed), the desired rotational stirrer steps, dwell time for the stirrer, and all the settings of the spectrum analyzer. The acquired measurement data must saved into a convenient format. To facilitate data handling, it is advised that results are post processed after measurements.

If the calibration and characterization of the ENEA RC is intended to be performed using mode-tuning techniques (under static conditions), then any time the stirrer is moved, the measurement has to be paused to allow any mechanical oscillations to die out. The general measurement procedure is represented as a flow diagram in Fig. 7.

Stirrer Efficiency

In order to correctly apply the international standard IEC 61000-4-21 [1], the assessment of the stirrer efficiency should be known. This is performed by means of the autocorrelation coefficient.

Stirrer performance data must be obtained by measuring the received power at several (typically 450) evenly spaced intervals over one stirrer rotation and for different frequency points (typically 15) logarithmically spaced in the frequency band of interest (typically from 1 up to 10 times the first resonance).

The aim of this procedure is that by knowing the first order autocorrelation for each frequency, the number of stirrer intervals required by the standard in the different frequency bands can be ensured to be correct. In other words, calibration according to the international standard IEC 61000-4-21 requires a minimum of independent field samples for every frequency band (e.g. 50 stirrer steps from the start frequency to three times the start frequency. It should be noted that the start frequency is not the LUF, it is just an approximate starting frequency point given in [1]). To assure that the stirrer is able to provide such a number of independent field samples, the first order autocorrelation has to be measured.

Using the same measured data, some data ratios as the stirring ratio and the power deviation to the mean can be further computed. They serve as important, empirically-based performance indicators.

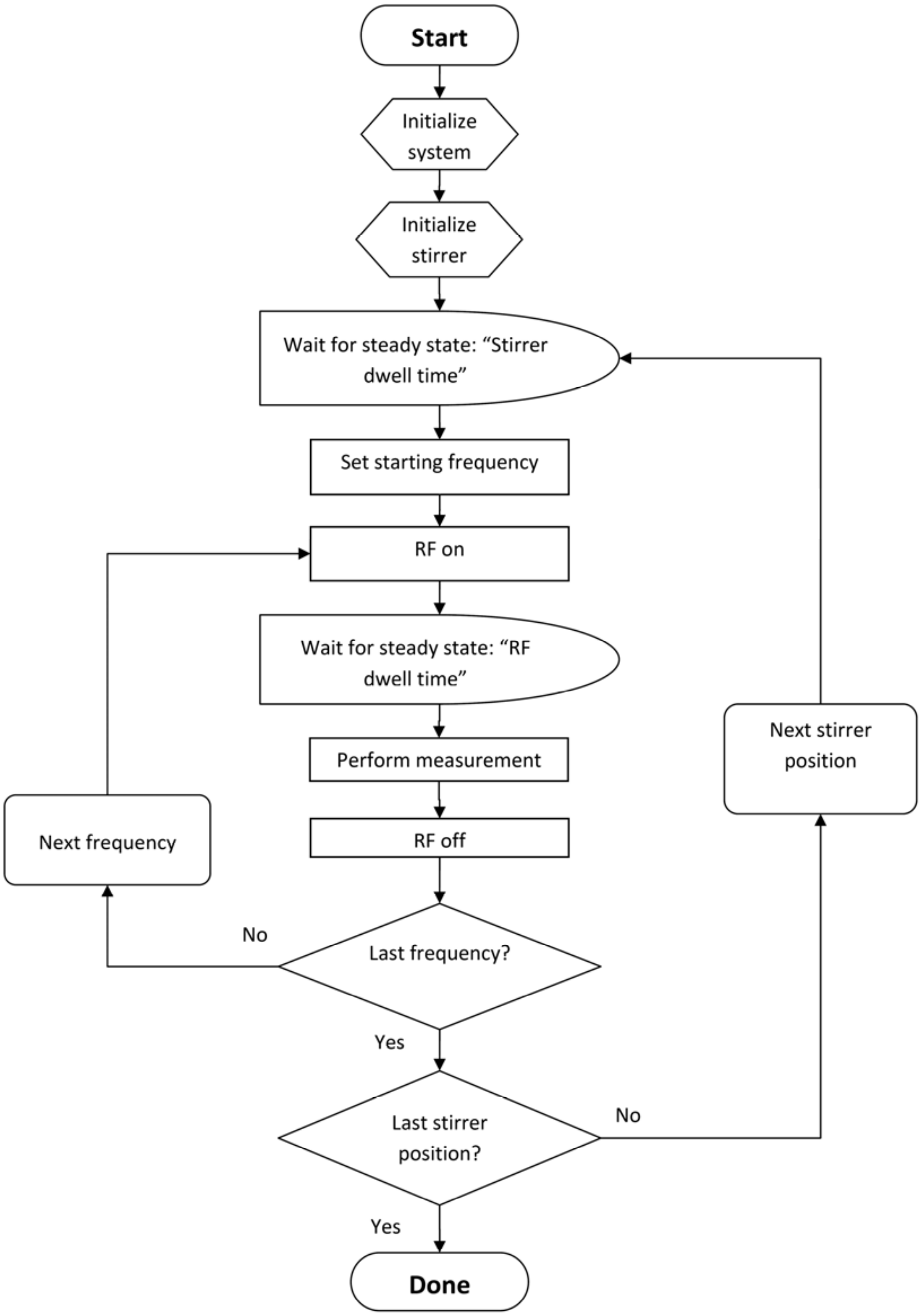

Fig 7: Measurement flow diagram.

Review of IEC 61000-4-21

The lowest useable frequency from which a RC can be used is mainly determined by the size and shape of the chamber and the effectiveness of the stirrer [2, 3, 4]. A procedure for calibrating a RC (thus, knowing its LUF) is described in [1].

> *Calibration.* The procedure of determining the LUF and characterizing important factors (such as e.g. the maximum tolerable loading of the chamber, the insertion loss, etc.) is known as the "calibration process"[1] [1]. The calibration procedure should be performed only once in the life of the chamber or only in the cases of relevant modifications.
>
> For the calibration, the fields must be recorded at eight positions within the working volume (these positions must be the corner points of the working volume). The working volume must keep a minimum distance of λ_{LUF} /4 away from RC walls, stirrers, antennas, and any other electromagnetically relevant objects. Field uniformity must be tested at 45 logarithmically spaced frequencies over the first decade, after only 20 frequencies per decade are required. The number of stirrer positions goes from a total of 50 for the lower frequencies to a total of 12 for the higher frequencies.
>
> The step-by-step procedure is clearly detailed in Annex B, section 1.1 in the IEC 61000-4-21 standard [1].
>
> The maximum of each single-axis electric field component occurring during one full rotation of the stirrer $(\phi_j = \phi_1 \ldots \phi_N)$ is determined and then normalized to the mean net input power P_i
>
> $$\tilde{E}_{\xi,i} = \frac{\max\limits_{\phi_j=\phi_1\ldots\phi_N} |E_\xi(\mathbf{r}_i)|_{\phi_j}}{\sqrt{P_i}},$$
>
> where $\xi = x, y, z$ or *total*, j is the stirrer position and i is the spatial position $i = 1 \ldots 8$. It should be pointed out that E_{total} refers to all data together, not to the total vectorial field strength [1].

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[1] In the second edition of the IEC standard, which is by the moment of writing this operating procedure under review, the word "validation" will replace that of calibration, for being more suitable and appropriate. Nevertheless in the following we will adopt the terminology as well as the nomenclature and symbol of the first edition of [1].

Subsequently, the standard deviation (deviation between the eight positions in space) is calculated for the field components and also for all the data together (i.e. a total of 24 field values consisting of eight positions for each of E_x, E_y, and E_z).

In order to compute the individual (*x, y* and *z* components) and the combined (*total*) standard deviations, using 1, the three arithmetic per-axis average values

$$\left\langle \tilde{E}_\xi \right\rangle = \frac{1}{8}\sum_{i=1}^{8} \tilde{E}_{\xi,i}$$

and the combined arithmetic average

$$\left\langle \tilde{E}_{total} \right\rangle = \frac{1}{24}\sum_{\xi=\{x,y,z\}}\sum_{i=1}^{8} \tilde{E}_{\xi,i}$$

are calculated. Finally, the individual per-axis standard deviations

$$\sigma_\xi = \sqrt{\frac{\sum_{i=1}^{8} \tilde{E}_i - \left\langle \tilde{E}_\xi \right\rangle}{8-1}}$$

as well as the combined standard deviation

$$\sigma_{total} = \sqrt{\frac{\sum_{\xi=\{x,y,z\}}\sum_{i=1}^{8} \tilde{E}_{\xi,i} - \left\langle \tilde{E}_{xyz} \right\rangle}{24-1}}$$

can be derived.

For convenience, the standard deviation is expressed in terms of dB relative to the mean:

$$\sigma_\xi = 20\log_{10}\frac{\sigma_\xi + \left\langle \tilde{E}_\xi \right\rangle}{\left\langle \tilde{E}_\xi \right\rangle}.$$

The IEC 61000-4-21 standard requires also the determination of some other parameters, such as the antenna calibration factor, the insertion loss, etc. They are calculated using the power received by the reference antenna. These factors characterize the chamber for further measurements, and can be easily calculated following the equations in [1], annex B.

The calibration detailed in this section needs only to be performed after the construction of the chamber, and after major modifications, i.e. changing the stirrer is considered to be a major modification if the change results in changes in stirrer efficiency, or changing the antennas. However, it is a good practice to perform a calibration of the chamber yearly.

Field Uniformity

For acceptable mode-stirring, the four standard deviations in dB relative to the mean, plotted against frequency should lay below a tolerance level defined in [1], which is:

$$\sigma_\xi \le \begin{cases} 4 \text{ dB} & 80 \text{ MHz} \le f \le 100 \text{ MHz} \\ -\frac{f(\text{MHz})}{300} + \frac{13}{3} \text{ dB} & 100 \text{ MHz} < f \le 400 \text{ MHz} \\ 3 \text{ dB} & 400 \text{ MHz} < f \end{cases} .$$

The IEC standard also states that three frequencies per octave may exceed the limits above by no more than 1 dB.

Caveats for Calibration

Applying the requirements and using the procedures introduced in section 5 a statistical description of RCs can be performed by means of a field uniformity measurement. However, some precautions need to be taken when performing such measurements and has been reported in [5]. Specifically they refer to the number of frequency points and the harmonic distortion produced by the amplifiers. Even though all the requirements are met, uneducated application of the standard may give results that are not satisfactory.

Maximum Chamber Loading Verification

One important part of the calibration process described in [1] is the maximum chamber loading verification. Recall that poor reverberation conditions can be found in a good performing chamber if the Q-factor is lowered up to an unacceptable level. Since an EUT can potentially load the chamber when inserted for performing measurements, the idea of the maximum chamber loading verification process is to measure up to what point the chamber can be loaded without degrading too much its performance. As a result of this once-in-a-lifetime process, RC users are able to identify if a particular EUT will load the chamber up to an unacceptable level or not, by performing a quick calibration before each measurement [1]. This is done by the systematical insertion of absorbers inside the chamber and the measurement of the field uniformity. By a trial-and-error approach, one should find the amount of absorber necessary to degrade the chamber up to an unacceptable level.

5.References

[1] CISPR/A and IEC SC 77B: IEC 61000-4-21 - Electromagnetic Compatibility (EMC) - Part 4-21: Testing and Measurement Techniques - Reverberation Chamber Test Methods, International Electrotechnical Commission (IEC) International standard, August 2003.

[2] C. Bruns: “Three-dimensional simulation and experimental verification of a reverberation chamber”, PhD Dissertation, Swiss Federal Institute of Technology, Zurich, Switzerland, 2005.

[3] J. Clegg, A. C. Marvin, J. F. Dawson, S. J. Porter: “Optimization of Stirrer Design in a Reverberation Chamber”, IEEE Transactions on Electromagnetic Compatibility, vol. 47, no. 4, pp. 824-832, November 2005.

[4] O. Lunden, L. Jansson, M. Backstrom: “Measurements of Stirrer Efficiency in Mode-stirred Reverberation Chambers”, FOA Technical Report: FOA-R-99-01139-612-SE, Linkoping, Sweden, May 1999.

[5] R. Serra, M. Bozzetti, F. G. Canavero: “Misleading Issues that Came Up when Calibrating the Alenia Aeronautica Reverberation Chamber,” International Conference on Electromagnetics in Advanced Applications, pp. 913-916, Torino, Italy, September 2009.

[6] D. Hill: *Electromagnetic Fields in Cavities: Deterministic and Statistical Theories*, Piscataway, IEEE Press, 2009.