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Sammanfattning

Elektronisk utrustning testas avseende dess tålighet mot strålad störning. Denna test bör vara snabb, noggrann och repeterbar. Om en sådan test utförs i en modväxlande kammare behöver endast medeleffekten mottagen i en referensantenn mätas.

Nyckelord:

Elektromagnetisk förenlighet, Elektromagnetisk statistik, Elektromagnetisk sårbarhet, Modväxlande kammare, Provning avseende tålighet mot strålad störning

Summary

In performing a radiated susceptibility test of electronic equipment it is important that it can be done in an accurate and repeatable manner. When performing the test in a reverberation chamber, only the average received power in a reference antenna has to be measured. Different test values, e.g., the maximum rectangular component of the electric field or the maximum total resultant of the electric field, can be calculated outgoing from the average received power. The accuracy of such procedure is higher than the accuracy of a direct measurement of the electric fields.

Keywords:

Electromagnetic compatibility, Electromagnetic statistics, Electromagnetic vulnerability, Radiated susceptibility test, Reverberation Chamber

Contents

Chapter 1

Introduction

Electronic equipment can be disturbed or even destroyed by strong electromagnetic fields. Hence, there is a need for testing the susceptibility of electronic equipment. A radiated susceptibility test (RST) is often performed in an anechoic chamber (AC) or at an open area test site (OATS). Fig. 1.1 shows one example of an RST at an OATS. A powerful source, in this case the Swedish microwave test facility (MTF) is here used to irradiate the equipment under test (EUT). The principle is simple; the MTF generates a plane electromagnetic wave illuminating the EUT. The strength of the plane wave is measured, and it can be concluded whether the EUT can withstand a certain threat or not.

However, most of the electromagnetic energy generated by the MTF does not hit the EUT. Despite using a highly directive antenna to direct the energy on to the EUT, most of the electromagnetic energy is just irradiated out into space. Also, if the EUT is well shielded electromagnetically, most of the electromagnetic energy hitting the EUT is not absorbed in the EUT but reflected out into space.

Here, the reverberation chamber (RC) has a substantial advantage. An RC is a room with walls, ceiling, and floor completely in metal, see Fig. 1.2. The EUT is placed inside the RC and electromagnetic energy is pumped into the RC through an antenna. The energy pumped into the RC is not lost out into space, but reflected at the walls back into the chamber. Hence, the electromagnetic energy is reused. The total electromagnetic energy inside the chamber will not reach infinity; it is limited by the conductivity in the walls which is not infinite, imperfections in the walls, and by energy absorbed by antennas and the EUT. In practice it is often the limited conductivity of the walls which (at the higher frequencies) is the main absorber of electromagnetic energy . Still, the reuse of electromagnetic energy implies that when the RC is used, substantially smaller electromagnetic sources can be used to generate the same stress onto the EUT versus the case when the AC/OATS is used. Fig. 1.3 shows an example of the 250 W sources used to generate electromagnetic energy for the RC. Those are to be compared to the size of the MTF in Fig. 1.1.

Independent of which test facility is used it is important to quantify the strength of the stress imposed upon the EUT. In the case when an AC or an OATS is used most

Figure 1.1: A typical radiated susceptibility test (RST) at an open area test site (OATS). The Swedish microwave test facility (MTF), on the left side of the picture, generates a strong electromagnetic plane wave which hit the equipment under test (EUT), on the right side of the picture. It is concluded whether the EUT can withstand a certain test level or not.

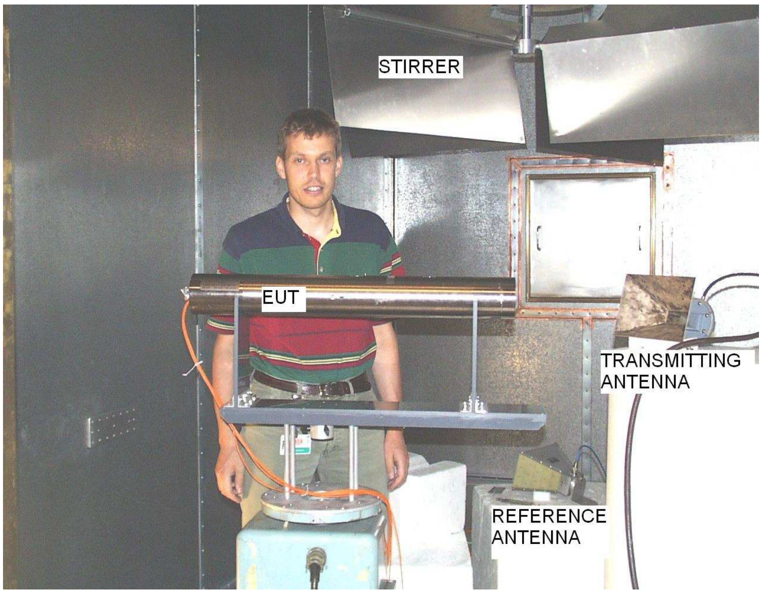

Figure 1.2: A typical radiated susceptibility test (RST) in a reverberation chamber (RC). Electromagnetic power is pumped into the reverberation chamber through a transmitting antenna. Thereby the equipment under test (EUT) is stressed. The strength of the stress is measured by a reference antenna and/or a reference field probe. It is concluded whether the EUT can withstand a certain test level or not.

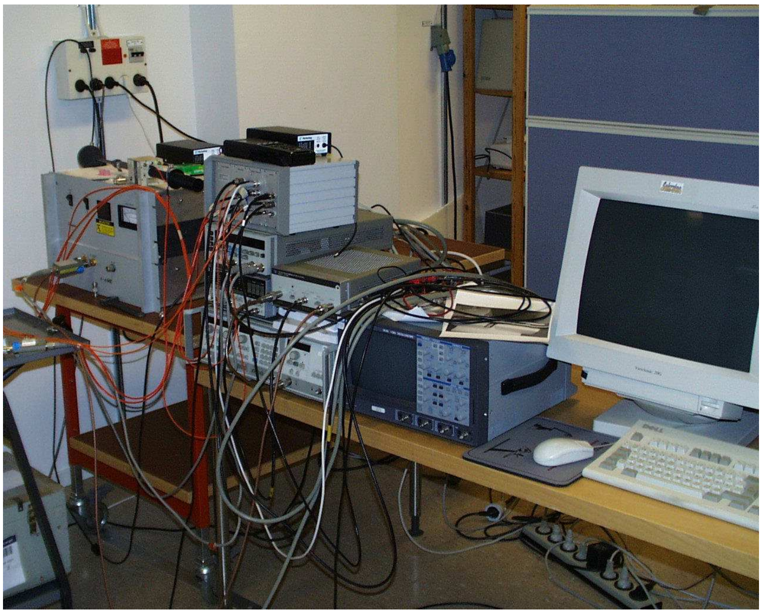

Figure 1.3: Equipment necessary to generate the electromagnetic energy which is pumped into the reverberation chamber (RC). The size of this equipment is substantially smaller than the microwave test facility (MTF) in Fig. 1.1.

often the EUT is stressed by a plane electromagnetic wave. It is generally accepted by the community, and also reflected in many standards, to use the strength of the electric field as the measure of the stress imposed upon the EUT. When people in the community begin to use the RC, not too surprisingly they measure the electric field in the RC and take it as a measure of the strength imposed upon the EUT. However, in difference to the AC/OATS, there is not a plane electromagnetic wave inside the RC. Inside the RC, a standing electromagnetic wave pattern is built up and the electric field has components in all three orthogonal directions[1]. A debate starts, still ongoing, whether the electric field in one dimension, a rectangular component of the electric field, is the best measure of the stress imposed upon the EUT, or if the resultant of the electric field, often called the total electric field, is the best measure. Still some other people argue for using the power received in an antenna as the best measure of the true stress.

However, the true stress on the EUT is of course the same, independent of which quantity we use to quantify it in. By the analogy with a car crash, the effect of the car crash is the same, independent if we quantify it by the speed of the car when it crashes or if we quantify it by the impulse onto the car. In this paper we show how we can chose to measure one quantity and from it easily calculate the other quantities.

[1]It can be shown, only outgoing from Maxwell's equations, that the electric field for a monochromatic wave at one point is elliptically polarised and hence the electric field is directed within a plane. However, if the field is not strictly monochromatic and/or we include a little bit more than strictly one point, the electric field is three dimensional.

We thereby make the choice of test quantity just a matter of convenience. A test house can easily specify all the test quantities in a protocol.

In the presentations below many distribution functions are given. They are given for completeness, but we hope that the reader will manage to focus on the practical aspects and look up the distribution functions when they are to be implemented.

Chapter 2

Test quantities

2.1 Strength of Our Test Facility

Looking upon Fig. 1.2 one could simply conclude that the amount of electromagnetic power which we pump into the RC is a measure of the stress we put onto the EUT. Though true, such a definition of the stress has one major drawback; The strength of the stress onto the EUT will depend on the magnitude of the electromagnetic power losses in the walls, antennas, the EUT, and other objects inside the RC. A better measure of the strength of the stress, is the electromagnetic energy (W) inside the RC, because that measure includes the effect of all the losses. Still, if the chamber is large, the energy density is lower and hence also the stress onto the EUT is lower compared to a small chamber. To take that into account a better quantity to use is the electromagnetic energy density[1],

$$w \triangleq \frac{W}{V} \; . \tag{2.1}$$

The statistics of the electromagnetic fields close to the walls are different from those away from the walls. The general electromagnetic theory for the RC is developed for a working volume of the RC which excludes the volume too close to the walls[2]. As a consequence the more exact definition of V is the working volume of the RC, and W the total electromagnetic energy inside the working volume.

There is still another factor to take into account; we have a standing wave inside the RC and as a consequence the energy density is not homogenously distributed within the working volume of the RC, but varies from point to point inside the working volume. Hence the stress on the EUT depends on where (inside the working volume) we position the EUT. To straighten things out, we introduce two concepts, the strength of our test facility and the strength of the stress we put onto the EUT. The average energy density defined in (2.1) is a complete measure of the strength of

[1] The sign $\triangleq$ denote *defined as*.

[2] For a more exact definition of the working volume, see e.g. [1].

our test facility. The actual strength of the stress which we put onto the EUT will depend on where we put the EUT, and we will soon comeback to that.

In practice, the average energy density w can be measured by a reference antenna. The actual power received by the reference antenna depends on the position of the reference antenna inside the working volume, but it can be seen as a random variable P which is exponentially distributed [2–4]. It follows from (21) and (42) in [2] or (47) and (66) [3], that the expected value of the received power in the reference antenna is[3],

$$\mathbb{E}\{P\} = c\frac{\lambda^2}{8\pi}w \ , \tag{2.2}$$

where c is the speed of light and λ is the wavelength of the electromagnetic field. It follows from (2.2) that $\mathbb{E}\{P\}$ can just as well as w be used as measure of the strength of our test facility. Which one of the two quantities to use is just a matter of convenience; We choose to use $\mathbb{E}\{P\}$. However, we can never measure an expected value; we have to approximate the expected value with the average value,

$$\langle P \rangle = \frac{1}{\mathbb{N}} \sum_{n=1}^{\mathbb{N}} P_n \ . \tag{2.3}$$

By approximating $\mathbb{E}\{P\}$ by $\langle P \rangle$ we introduce an error. That error is however decreased by increasing the number of independent measurements ($\mathbb{N}$) of the received power (P_n). To get independent measurements of the received power, the reference antenna can be moved around in the working volume, but in practise the same affect is more easily achieved by changing the boundary conditions in the RC by rotating the stirrer in Fig. 1.2 to $\mathbb{N}$ different positions.

2.2 Strength of the Stress We Put Onto the EUT

Measuring $\{P_n\}_{n=1}^{\mathbb{N}}$ are the only measurements we have to do. Thereby we have measured the strength of our test facility as good as we can. The actual stress onto the EUT is random. The stress, whatever quantity or measure used is a random variable. However, we can define distribution functions for the stress random variables, and the only test facility parameter we have to put in is $\langle P \rangle$. That we show below.

2.2.1 Rectangular component of the electric field as stress

Let us assume that we think that a rectangular component of the electric field (E_r) is the best measure of the stress onto the EUT. The probability distribution function (pdf) of E_r is [2, (55)], [3, (75)],

[3] We assume that the reference antenna is completely impedance matched and lossless. If that is not the case, it can easily be compensated for.

$$f_{E_r}(e_r) = \frac{e_r}{\sigma^2} e^{-\frac{e_r^2}{2\sigma^2}} = 2\frac{e_r}{E_c^2} e^{-\frac{e_r^2}{E_c^2}} \ , \tag{2.4}$$

where σ and

$$E_c = \sqrt{2}\sigma \ , \tag{2.5}$$

are two constants[4]. The cumulative distribution function (cdf) of E_r is,

$$F_{E_r}(e_r) \equiv \int_0^{E_r} f_{E_r}(x)\mathrm{d}x = 1 - e^{-\frac{e_r^2}{2\sigma^2}} = 1 - e^{-\frac{e_r^2}{E_c^2}} \ . \tag{2.6}$$

The expected value of E_r is,

$$\mathbb{E}\left\{E_r\right\} = \sqrt{\frac{\pi}{2}}\sigma = \frac{\sqrt{\pi}}{2}E_c \ , \tag{2.7}$$

and we define the normalised E_r,

$$R \triangleq \frac{E_r}{E_c} = \frac{E_r}{\frac{2}{\sqrt{\pi}}\mathbb{E}\left\{E_r\right\}} \ , \tag{2.8}$$

with the pdf,

$$f_R(r) = 2re^{-r^2} \ , \tag{2.9}$$

and the cdf,

$$F_R(r) = 1 - e^{-r^2} \ . \tag{2.10}$$

When performing a radiated susceptibility test (RST) with $\mathbb{N}$ different stirrer positions, the distribution functions are valid for all the $\mathbb{N}$ different stirrer positions. Most often one is interested in the maximum value which is reached, and we therefore define,

[4]It might seem superfluous to define both E_c and σ. However, σ is close related to the underlying assumptions in the basic theory; The quadrature components of the rectangular component of the electric field are both normally distributed with expected value 0 and standard deviation σ. On the other hand E_c fulfils the basic relation $\mathbb{E}\left\{E_r^2\right\} = E_c^2$. However, we can treat both σ and E_c just as basically the same constant and it will turn out that it will disappear in the calculations.

$$G(\mathbb{N}) \triangleq \max\{R_n\}_{n=1}^{\mathbb{N}} \; . \tag{2.11}$$

Assuming that all $\{R_n\}_{n=1}^{\mathbb{N}}$ are independent we get the cdf for G,

$$\begin{aligned} F_G(g) &\equiv \mathbb{P}(G \le g) = \mathbb{P}(\text{All } R_n \le g) \\ &= (1 - e^{-g^2})^{\mathbb{N}} \; , \end{aligned} \tag{2.12}$$

and the pdf for G,

$$f_G(g) \equiv \frac{\mathrm{d}F_G(g)}{\mathrm{d}g} = 2\mathbb{N} g e^{-g^2}(1 - e^{-g^2})^{\mathbb{N}-1} \; . \tag{2.13}$$

We stated above that the measurement of $\langle P \rangle$ is the only measurement we have to do, but at the same time we implicitly stated that we have to find some relation between the maximum value of the rectangular component of the electric field and $\langle P \rangle$. To do so we first define,

$$Q \triangleq \frac{\langle P \rangle}{\mathbb{E}\{P\}} \; . \tag{2.14}$$

The pdf of Q is [4, (52)],

$$f_Q(q) = \gamma(q, \mathbb{N}, \frac{1}{\mathbb{N}}) = \frac{\mathbb{N}^{\mathbb{N}}}{(\mathbb{N}-1)!} q^{\mathbb{N}-1} e^{-\mathbb{N} q} \; , \tag{2.15}$$

where we have introduced the gamma probability distribution function γ. The cdf of Q is,

$$F_Q(q) = \Gamma(q, \mathbb{N}, \frac{1}{\mathbb{N}}) = \frac{\mathbb{N}^{\mathbb{N}}}{(\mathbb{N}-1)!} \int_0^q y^{\mathbb{N}-1} e^{-\mathbb{N} y} \mathrm{d}y \; , \tag{2.16}$$

where we have introduced the gamma cumulative distribution function Γ. Both γ and Γ are functions which are implemented in many numerical mathematical tools. For reasons which soon will be clear, we define,

$$O \triangleq \sqrt{Q}. \tag{2.17}$$

The cdf of O is

$$F_O(o) \equiv \mathbb{P}(O \le o) = \mathbb{P}(Q \le o^2) = \Gamma(o^2, \mathbb{N}, \frac{1}{\mathbb{N}}) \; . \tag{2.18}$$

The pdf of O is

$$f_O(o) = 2o\gamma(o^2, \mathbb{N}, \frac{1}{\mathbb{N}}) \ . \tag{2.19}$$

We now define one of the major random variables,

$$M \triangleq \frac{G}{O}. \tag{2.20}$$

The pdf of M is [5, p. 96]

$$f_M(m) = \int_0^\infty o f_G(om) f_O(o) \mathrm{d}o \tag{2.21}$$

and the cdf of M is [5, p. 96]

$$F_M(m) = \int_0^\infty F_G(om) f_O(o) \mathrm{d}o \ . \tag{2.22}$$

To show the usefulness of the random variable M we substitute (2.8), (2.11), (2.14) and (2.17) into (2.20),

$$M = \frac{\sqrt{\mathbb{E}\{P\}}}{E_c} \frac{E_{r,max}}{\sqrt{\langle P \rangle}} \ , \tag{2.23}$$

where we also have introduced the abbreviation,

$$E_{r,max} \triangleq \max\{E_{r,n}\}_{n=1}^{\mathbb{N}} \ . \tag{2.24}$$

By substituting (A.1), (A.2) and (2.5) into (2.23) we get[5],

$$M = \sqrt{\frac{\lambda^2}{8\pi} \frac{3}{Z_0}} \frac{E_{r,max}}{\sqrt{\langle P \rangle}} \ , \tag{2.25}$$

or rewritten,

[5] Z_0 is the free space wave impedance.

$$E_{r,max} = \sqrt{\frac{8\pi}{\lambda^2}\frac{Z_0}{3}} M \sqrt{\langle P \rangle} \ . \tag{2.26}$$

Equation (2.26) is what we promised at the beginning of this chapter. It gives a relation between the test facility strength parameter $\langle P \rangle$ and the stress on to the EUT which we in this section have defined as $E_{r,max}$. The relation is basically the random variable M, which distribution functions we have derived above[6].

2.2.2 Total electric field as stress

In this subsection we assume that the total electric field (E_t) is the best measure of the stress onto the EUT. We do derivations similar with section 2.2.1. We start with the pdf, [2, (57)] or [3, (81)], and cdf for E_t,

$$f_{E_t}(e_t) = \frac{e_t^5}{E_c^6} e^{-\frac{e_t^2}{E_c^2}} \ , \tag{2.27}$$

$$F_{E_t}(e_t) = 1 - e^{-\frac{e_t^2}{E_c^2}} \left(1 + \frac{e_t^2}{E_c^2} + \frac{e_t^4}{2E_c^4} \right) \ . \tag{2.28}$$

We introduce the normalised E_t,

$$\mathbb{T} \triangleq \frac{E_t}{E_c} \ , \tag{2.29}$$

with pdf and cdf,

$$f_{\mathbb{T}}(t) = t^5 e^{-t^2} \ , \tag{2.30}$$

$$F_{\mathbb{T}}(t) = 1 - e^{-t^2} \left(1 + t^2 + \frac{t^4}{2} \right) \ , \tag{2.31}$$

and the maximum value,

$$H(\mathbb{N}) \triangleq \max\{\mathbb{T}_n\}_{n=1}^{\mathbb{N}} \ , \tag{2.32}$$

with pdf and cdf,

[6] One can also see the reason why we introduced the square root in (2.17); otherwise the relation between $E_{r,max}$ and $\langle P \rangle$ would have included the parameter E_c, which is a measure of the strength of the test facility.

$$f_H(h) = \mathbb{N}h^5 e^{-h^2}\left[1 - e^{-h^2}\left(1 + h^2 + \frac{h^4}{2}\right)\right]^{\mathbb{N}-1} , \tag{2.33}$$

$$F_H(h) = \left[1 - e^{-h^2}\left(1 + h^2 + \frac{h^4}{2}\right)\right]^{\mathbb{N}} . \tag{2.34}$$

We define,

$$N \triangleq \frac{H}{O} , \tag{2.35}$$

with pdf and cdf,

$$f_N(n) = \int_0^\infty o f_H(on) f_O(o) \mathrm{d}o , \tag{2.36}$$

$$F_N(n) = \int_0^\infty F_H(on) f_O(o) \mathrm{d}o , \tag{2.37}$$

and in complete similarity with (2.25) and (2.26) we get,

$$N = \sqrt{\frac{\lambda^2}{8\pi}\frac{3}{Z_0}}\frac{E_{t,max}}{\sqrt{\langle P \rangle}} , \tag{2.38}$$

$$E_{t,max} = \sqrt{\frac{8\pi}{\lambda^2}\frac{Z_0}{3}} N\sqrt{\langle P \rangle} , \tag{2.39}$$

where

$$E_{t,max} \triangleq \max\{E_{t,n}\}_{n=1}^{\mathbb{N}} . \tag{2.40}$$

Please, note the similarity between (2.26) and (2.39). The only difference is the two different random variables M and N, respectively.

2.2.3 Power as stress

The theory for using power as the measure of the stress has already been derived in [4]. Here we will only give the results. The pdf and cdf for the power received in lossless impedance matched antenna is[7],

[7]The right hand side of equation (2.41),(2.42),(2.45),(2.46),(2.48), (2.49),(2.51),(2.52) and (2.53) are only given to show the close relation between the random variables in this section and the random variables in section 2.2.1.

$$f_P(p) = \frac{1}{\mathbb{E}\{P\}} e^{-\frac{p}{\mathbb{E}\{P\}}} = \frac{\sqrt{\frac{E_c^2}{\mathbb{E}\{P\}}}}{2\sqrt{p}} f_{E_R}\left(\sqrt{\frac{E_c^2}{\mathbb{E}\{P\}} p}\right) , \tag{2.41}$$

$$F_P(p) = 1 - e^{-\frac{p}{\mathbb{E}\{P\}}} = F_{E_R}\left(\sqrt{\frac{E_c^2}{\mathbb{E}\{P\}} p}\right) , \tag{2.42}$$

where [2, (42) and (48)] or [3, (66) and (72)],

$$\mathbb{E}\{P\} = \frac{\lambda^2}{4\pi} \frac{3\sigma^2}{Z_0} = \frac{\lambda^2}{8\pi} \frac{3E_c^2}{Z_0} . \tag{2.43}$$

We introduce the normalised power,

$$X \triangleq \frac{P}{\mathbb{E}\{P\}} , \tag{2.44}$$

with pdf and cdf,

$$f_X(x) = e^{-x} = \frac{1}{2\sqrt{x}} f_R(\sqrt{x}) , \tag{2.45}$$

$$F_X(x) = 1 - e^{-x} = F_R(\sqrt{x}) , \tag{2.46}$$

and the maximum value,

$$Z(\mathbb{N}) \triangleq \max\{X_n\}_{n=1}^{\mathbb{N}} , \tag{2.47}$$

with pdf and cdf,

$$f_Z(z) = \mathbb{N}\left(1 - e^{-z}\right)^{\mathbb{N}-1} e^{-z} = \frac{1}{2\sqrt{z}} f_G(\sqrt{z}), \tag{2.48}$$

$$F_Z(z) = \left(1 - e^{-z}\right)^{\mathbb{N}} = F_G(\sqrt{z}) . \tag{2.49}$$

We define,

$$T \triangleq \frac{Z}{Q} , \tag{2.50}$$

with pdf and cdf,

$$f_T(t) = \int_0^\infty q f_Z(qt) f_Q(q) \mathrm{d}q = \frac{1}{2\sqrt{t}} f_M(\sqrt{t}) \ , \tag{2.51}$$

$$F_T(t) = \int_0^\infty F_Z(qt) f_Q(q) \mathrm{d}q = F_M(\sqrt{t}) \ , \tag{2.52}$$

and in similarity with (2.26) we get,

$$P_{max} = T \langle P \rangle = M^2 \langle P \rangle \ , \tag{2.53}$$

where

$$P_{max} \triangleq \max\{P_n\}_{n=1}^{\mathbb{N}} \ . \tag{2.54}$$

It follows from (2.53) that,

$$T = M^2 \ . \tag{2.55}$$

That simple relation is no coincidence; it reflects that an antenna reacts on a rectangular component of the electric field.

Chapter 3

Test Values

Equations (2.26),(2.39) and (2.53) give us three measures of the stress onto the EUT. All three depend on the strength of our test facility via the average received power in the test facility ($\langle P \rangle$). However, there is no exact value of the measures, because the expressions include the random variables M, N and T, respectively. That is a fundamental property of performing a radiated susceptibility test (RST) in the RC; there is uncertainty about the true stress onto the EUT. That is an inherent property of the RC as test facility and not a measurement error in normal sense. One could be mislead to think that by actually measuring the quantities on the left hand side of (2.26), (2.39) and (2.53), the uncertainty should be smaller. *Nothing could be more wrong.* Though true that the quantities in (2.26),(2.39) and (2.53) certainly can be measured with a high accuracy, much higher than the uncertainty in M, N and T, it is irrelevant. The key point is that the EUT and measurement antenna and/or probe will always face different stresses. That is an inherent property of using the RC as a test facility, the actual stress is a random variable. The best thing we can do is to measure the strength of our test facility. That we do by measuring the average received power in the test facility ($\langle P \rangle$). The actual stress onto the EUT is just one random sample of many possible outcomes.

With that taken into consideration, how do we show our test results in a practical manner? We probably want to say that we have tested our EUT up to a certain level, and that level we want to be a number, not a random variable. One way to do that is to introduce confidence bounds. Let us define the bound m_α so that with α probability, the random variable M is larger than m_α,

$$F_M(m_\alpha) = 1 - \alpha \ . \tag{3.1}$$

Often m_α is called the *alpha* percentile. By introducing the inverse function F_M^{-1} we get,

$$m_\alpha = F_M^{-1}(1-\alpha)\ , \tag{3.2}$$
$$n_\alpha = F_N^{-1}(1-\alpha)\ , \tag{3.3}$$
$$t_\alpha = F_T^{-1}(1-\alpha)\ , \tag{3.4}$$

where we also introduced the similar bounds for the N and T random variables. By using the bounds in (3.2), (3.3) and (3.4) in (2.26),(2.39) and (2.53), respectively, we can easily introduce the test values,

$$E_{r,maxT} = \sqrt{\frac{8\pi}{\lambda^2}\frac{Z_0}{3}} m_\alpha \sqrt{\langle P \rangle}\ . \tag{3.5}$$
$$E_{t,maxT} = \sqrt{\frac{8\pi}{\lambda^2}\frac{Z_0}{3}} n_\alpha \sqrt{\langle P \rangle}\ , \tag{3.6}$$
$$P_{maxT} = t_\alpha \langle P \rangle\ . \tag{3.7}$$

The three test values above are typical values to be specified in a protocol. The choice of α depends on the actual test being performed, but is also a matter of convenience. To get a high confidence that the true stress onto the test object is higher than the one specified in the test protocol the 95% percentile may be used. On the other hand, if one is afraid of overtesting, the 5% percentile may be used. If one wants a typical value, the 50% percentile may be used. In Fig. 3.1, the 95%, 50% and 5% percentiles are shown as function of the number of independent stirrer positions, for the M, N and T random variables. The values for some specific numbers of independent stirrer positions are given in in table 3.1. For the reader who understands the dB concept it should not be hard to understand outgoing from (2.55) that the percentiles for the M and T are identical in a dB-scale.

Percentiles						
$\mathbb{N}$	M			N		
	$m_{95\%}$ (dB)	$m_{50\%}$ (dB)	$m_{5\%}$ (dB)	$n_{95\%}$ (dB)	$n_{50\%}$ (dB)	$n_{5\%}$ (dB)
1	-11.7	1.05	13.8	-1.29	6.90	18.7
2	-5.45	2.73	10.9	1.70	7.47	14.8
4	-1.53	4.10	9.75	3.93	8.12	13.0
12	2.36	5.80	9.35	6.45	9.09	12.0
35	4.75	7.06	9.58	8.13	9.90	11.9
100	6.38	8.05	10.0	9.30	10.6	12.1

Table 3.1: The 95%, 50% and 5% percentiles for the M and N random variables given at some specific number of independent stirrer positions ($\mathbb{N}$). The percentiles for the random variables M and T, are identical in a dB-scale.

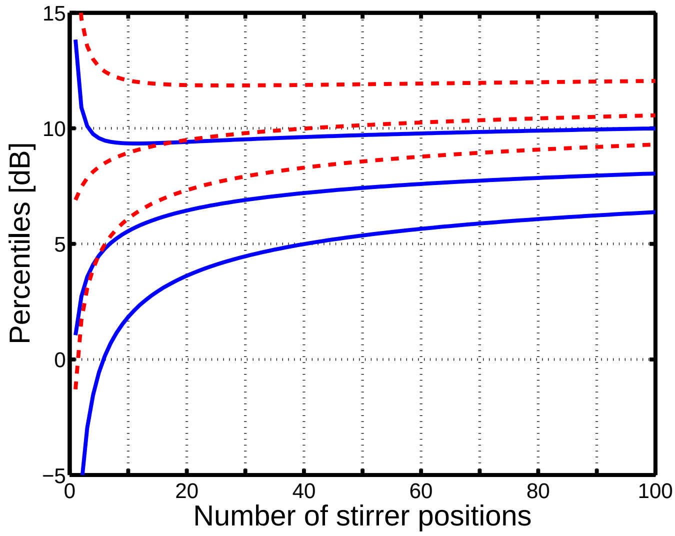

Figure 3.1: The 95%, 50% and 5% percentiles as function of the number of stirrer positions for the M, N and T random variables. The blue solid lines show the percentiles for M, and the red dashed lines show the percentiles for N. (The 95% percentiles are the lower curves and the 5% percentiles are the upper curves.) The percentiles for M and T are identical in a dB-scale.

Chapter 4

Measurements

To test the validity of the theory presented in chapter 2 we have performed measurements. The measurements were performed in our large RC, with dimensions $5.10 \text{ m} \times 2.46 \text{ m} \times 2.93 \text{ m}$. Electromagnetic power was pumped into the chamber and inside the RC, the electric field was measured with a Holaday HI-6005 probe and the received power with a waveline 299 horn antenna. The field probe has been positioned at 9 different positions inside the RC (the eight corners and one in the middle). For every position the electric field and the received power was measured for 200 different stirrer positions at 15 equidistant positioned frequencies in the interval 2.6 GHz to 4.0 GHz[1]. However, we have excluded the frequencies 3.2 GHz − 3.6 GHz from the results. The reason being that the field probe is not accurate in that frequency interval. Actually, the field probe has to be calibrated. At the higher frequencies (GHz) internal resonances occur in the measurement probe, and the probe need to be accurately calibrated with small frequency intervals. That has not been done with our probe, and hence we are forced to exclude the frequency interval.

Good agrement between measurement results and theory has already been reported for the T-distribution in [4], and in Figs. 4.1 and 4.2 good agreement between measurement results and theory can be seen also for the M- and N- distributions.

[1]All values are independet.

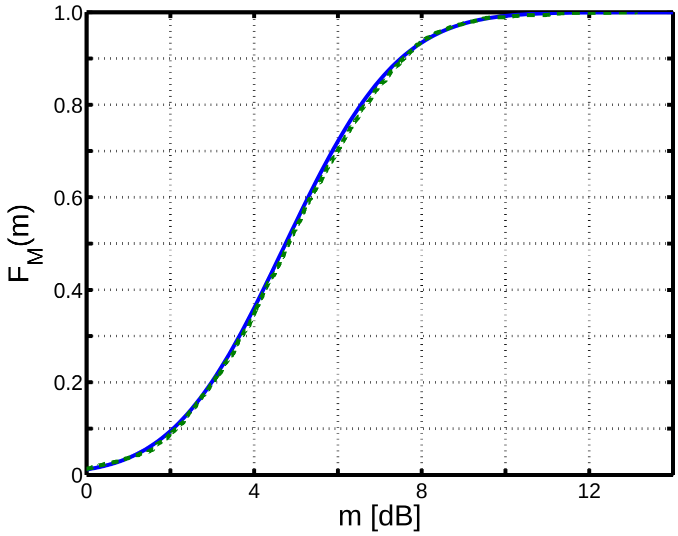

Figure 4.1: The graph shows the cumulative distribution function for the random variable M with 20 independent stirrer positions. The blue solid curve is the theoretical curve given by (2.22) and the green dashed curve are measurement results. The agreement is very good, but please read the postscript chapter.

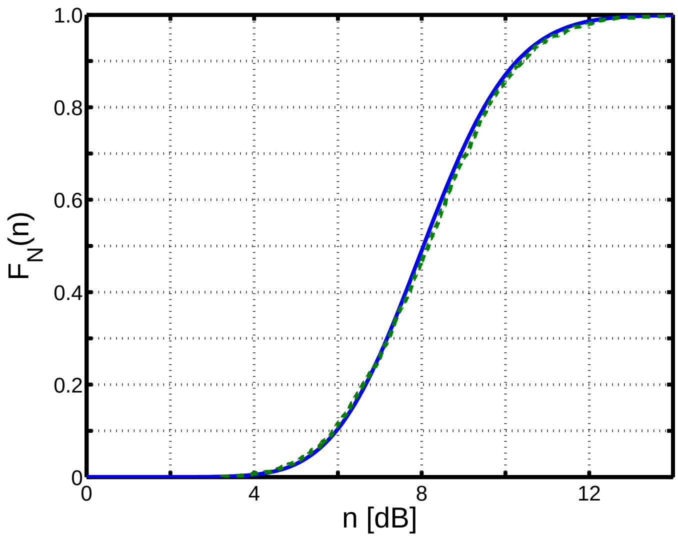

Figure 4.2: The graph shows the cumulative distribution function for the random variable N with 20 independent stirrer positions. The blue solid curve is the theoretical curve given by (2.37) and the green dashed curve are measurement results. The agreement is very good, but please read the postscript chapter.

Chapter 5

Postscript

The Figs. 4.1 and 4.2 show good agreement between measurement results and theory for the M- and N- distributions, but the figures are fakes. In both figures all measurement values are divided by the factor $\sqrt{\pi/2}$. We have checked both the theory and the measurements several times and we cannot find any error. We have compared the theory and the measurements for other number of independent stirrer positions. Again good agreement is reached when all measurement values are divided by the factor $\sqrt{\pi/2}$. It is very clear that the discrepancy factor is $\sqrt{\pi/2}$, e.g., a division by the factor $\sqrt{3/2}$ gives a substantial less good agreement. We think that the theory is correct and hence we have decided to submit this work to the community to comment on. Correspondence is welcome

Chapter 6

Summary

A radiated susceptibility test (RST) in a reverberation chamber (RC) can easily be performed by placing the EUT and a reference antenna inside the RC. The EUT is stressed for $\mathbb{N}$ stirrer positions and the average value of the power received in the reference antenna is monitored. The different test values to which we stress our EUT, and to specify in a measurement protocol, are easily calculated with the (3.5), (3.6) and (3.7).

Appendix A

Two equations

In this appendix we list two useful equations. These are (42) in [2] or (66) in [3],

$$\mathbb{E}\left\{P\right\} = \frac{E_0^2}{Z_0}\frac{\lambda^2}{8\pi}, \tag{A.1}$$

and (48) in [2] or (72) in [3],

$$E_0^2 = 6\sigma^2. \tag{A.2}$$

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Biography

 Magnus Höijer received the Ph.D. degree in photonics and the M.Sc. degree in engineering physics, both from the Royal Institute of Technology, Stockholm, Sweden, EU, in 1998 and 1992, respectively.

Dr. Höijer is currently a senior scientist at the Swedish Defence Research Agency, Linköping, Sweden. In 1999-2001 he worked at Ericsson Saab Avionics, Linköping. The work included numerical descriptions of the Reverberation Chamber, and electromagnetic coupling to critical electronic equipment in aircrafts. In 1991 and 1992 he worked at Seiko Instruments, Chiba, Japan and Siemens Halbleiter, Munich, Bavaria, Germany, EU, respectively, investigating the ESD-endurance of transistors and constructing DRAM. His current research interests include polarisation and directivity dependencies in Radiated Susceptibility Testing, electromagnetic coupling to electronics and not at least the Reverberation Chamber.

Dr. Höijer is a member of the International Electrotechnical Commission (IEC) working group on Reverberation Chamber and member of the Swedish International Scientific Radio Union (URSI) Commission E. He is the Swedish PoC for the EU FP 7 projects HIRF-SE and CATHERINE.


Olof Lundén received the electrical engineering degree from Stockholms stads tekniska aftonskola, Sweden in 1970. Since 1961, he has been with the Swedish Defence Research Agency, FOI. He is a metrology expert. His current research interests include measurement systems integration and evaluation, e.g., reverberation chambers, high-power microwave (HPM) test facilities and antennas. Mr. Lundén is the Chairman of the Swedish International Scientific Radio Union (URSI) Commission A, Electromagnetic Metrology, and a member of the Swedish International Electrotechnical Commission (IEC) Technical Committee TC85.