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Preface

The idea for this book was conceived as the result of a meeting on this fascinating topic. We did not feel like the most legitimate people to discuss this question; some aspects of it could be detailed in a very learned way by many of our colleagues who are experts in this domain. We have here a unique opportunity to praise the many engineers and researchers who efficiently contribute in France, in Europe and in the entire world to enriching the knowledge and know-how on reverberation chambers.

This book has greatly benefited from the contributions of Daniël De Zutter, Professor at Ghent University (Belgium), and Alain Reineix, CNRS (French National Center for Scientific Research) Research Director at the Xlim laboratory. They had the significant responsibility of carefully proofreading the manuscript. Their remarks have helped us to shed light on and clarified numerous questions that arose during reading, for the benefit of all readers. We thank them deeply for their help.

We would also like to thank M. Paolo Corona, Professor at Parthenope University of Naples (Italy), for honoring us by writing the foreword of this book and for providing some unknown testimonies of the history of reverberation chambers.

Foreword

The authors of this book have done me the honor of entrusting me with this foreword, and above all of mentioning my activities in the field of the mode-stirred chambers at the Academic Naval Institute of Naples (currently Parthenope University of Naples). Somehow, I have on this matter the benefit of age, which allows me to give some little-known indications about a period of time when there were very few people studying reverberation chambers. It is particularly pleasant to see that nowadays this subject finds a place in numerous sessions, during conferences and other international meetings.

As is so often the case, activity comes from a very specific and almost always anecdotal motivation. This was the case for reverberation chambers. At the beginning of the 1970s, microwaves started to spread in Italy and there were some worries about them. In 1974-1975, we were consulted about the methods of measuring electromagnetic radiation. At this time, we were working on the extraction principle of the signals drowned out by noise, as well as on the possibility of using this technique in the field of electromagnetic waves. The idea to make electromagnetic radiation become incoherent via agitation of the walls or, more easily, with the rotation of the metal surfaces was then almost natural.

At the same time, in the United States, we were studying the inefficiency of the MIL-STD norms, for the evaluation of shielding effectiveness. The method used a compact resonant cavity, where it was possible to make the tuning frequency vary, thanks to the use of metal inserts, diving more or less strongly in the cavity. The technique consisting of using the same method, in order to no longer obtain the resonance but to carry out an average evaluation on several positions of these metal inserts, was also natural. The idea then was to no longer use a cavity, but a shielded chamber instead. The team was formed of McDonnel Douglas (Saint-Louis), the US Navy Dahlgren Laboratory, and Boulder NBS (currently NIST).

The first article with an international impact (1976) brought American and English researchers to visit us in Naples, and at a meeting of information exchange (1977) at Litton, Minneapolis, officiated by D. Robertson (GeorgiaTech). We confronted the two points of view, that differ on the mode stirring question, whether it was done step-by-step or continuously. This debate is still relevant nowadays, because mode stirring requires a specific sampling of the measurements. I will not dwell on this question as it is well discussed in this book. Let us thus come back to the development of the first works on this subject.

In 1979, I installed the first mode-stirred chamber at NBS/NIST, by modifying an old shielded chamber. But we should not forget that some chambers were already in operation in the United States at McDonnel, US Navy Dahlgren, Litton and in some other places. The basic principles were all already determined, but we had to convince the experts of the strong potential of this method. At the beginning of the 1980s, NBS/NIST made a big effort and M. Crawford developed a systematic experimental activity, covering a wide range of frequencies. The results of these experiments were published in the *Technical Notes* of NBS, and nowadays mark the transit from a pioneer activity to a real emergence of the subject. The first already considered statistic formulations will improve, the practical use will spread, and the international standards will take it into account. At the same time, the subject was being developed in Europe. After the pioneer work done in Italy, we could find the study of reverberation chambers in France, the United Kingdom, the Netherlands and then in Germany. Continuing this description would certainly be beyond the scope of this foreword, because this book by B. Démoulin and P. Besnier does not limit itself to the study of the current state of the matter, but also presents the main episodes of its development.

In any case, we can find two lines of study: electromagnetic field statistics, often limited to an analysis evaluation without support of physical modeling, and the practical use, above all in reference to the international standards. Despite the fact that it is an activity that started more than 30 years ago, we find very few things about it in the literature. We can find chapters in the general texts of electromagnetism and of electromagnetic compatibility, and, to my knowledge, only one book recently and exclusively devoted to the subject, but its remains quite abstract. Evidently, we can try to summarize a quite voluminous bibliography. However, this is a difficult exercise, especially because of the progressive nature of the research results accumulated over time. This book by B. Démoulin and P. Besnier is the perfect aid to help us, being very complete from the theoretical point of view, as well as from the practical point of view. Above all, it aims at extracting from the numerous bibliographical entries, the essential principles necessary for the use of reverberation chambers. The measurement methods resulting from reverberation chambers are indeed simple in principle, and the use of reverberation chambers is not difficult. This book manages to convince us of that fact, without however forgetting to give the reader the basic operating principles and the restrictions of use. The authors did not yield to the temptation of exploiting their scientific activity in the field, although it is ample and of a high level. They position themselves with readers who have a basic knowledge in electromagnetism, in order to give complete knowledge of what underlies the functioning of reverberation chambers. Consequently, readers are progressively brought to the level of the state of the art: this is a very difficult exercise that the authors have achieved perfectly, thanks to their knowledge and their activity in the domain.

I have mostly talked about the use of the book, and not its qualities. There are good reasons for that fact. First, this book is perfect and complete, but I particularly appreciated it from the point of view of the mission it has taken upon itself. This book satisfies the need for a single reference, at a homogeneous level, that could be used by anybody who does not have the chance to follow the development of the exploitation method of mode stirred chambers. This will encourage more frequent use of this test system and the development of new applications, a subject that the book will also discusses. We have to be grateful to the authors for wanting to write a book that aids understanding and better situates the subject in the literature, without flaunting their knowledge or the originality of their activity, which is spread throughout the book. This is a sacrifice for the researcher, especially if we consider that the research groups of Lille and Rennes have given and still give the important contribution of burning issues to the theoretical and experimental exploitation of mode stirred chambers.

Professor Paolo CORONA
Parthenope University of Naples
July 2011

Introduction

Before introducing the motivation and the content of this book, we will carry out a brief retrospective of the advent of reverberation chambers in electromagnetism.

The first experiments recounting the confinement of electromagnetic waves in a reverberation chamber probably date back to 1976. We will find the details of these experiments in a publication by P. Corona from the Naval Academic Institute of Naples (Italy). The objective of these precursory works was above all the measurement of the radio source emissions. It was then demonstrated that the wave confinement led to a direct evaluation of the total power radiated by the object. At this moment there are two competing theories: one considers that the electromagnetic power in the chamber is mainly governed by the resonance mechanisms and the second considers the emission as the radiation of the blackbody, imported from the statistic thermodynamics [COR 76a, COR 76b, COR 02].

Together with the research led and carried out by P. Corona, reverberation chambers were already being developed in the United States. Around 1980, we may mention the building of a chamber at the National Institute of Standard and Technologies (formerly called the National Bureau of Standards), where the theory of the stirred modes was founded, borrowed from the statistical analyses. We find this approach in many publications, notably written by M. Crawford, G. Koepke, T. Lehman. The physical-statistical analysis was then continued by works published 20 years later by D.A. Hill, J. Ladbury, L. Arnaut, L. Jansson, M. Bäkström and by many other scientists working on and increasingly discussing this subject [ARN 02, CRA 74, CRA 86, HIL 94, JAN 99, LEH 91, LEH 97].

Reverberation chambers have been designed in this context and devoted to the measurements of the electromagnetic compatibility. Indeed, as of this time, the demand turns first to the measurements of the attenuation of the connectors and cable shields. The concerned frequencies are then extended from hundreds of MHz to tens of GHz. Knowing that the reduction of the wavelength comes with a decrease in the antenna size, it was decided to favor the confinement techniques in the reverberant environment. We could add the advantage of producing oversized cavities compared to the wavelength to these primary properties. We thus managed to generate fields of random amplitude, amplitudes coordinated by a mode stirring. Contrary to measurements in free space, the method gave, to the objects under test, insensitivity to the criteria of directivity and wave polarization. These factors, combined with the emergence of high amplitude fields, stimulated by resonances, will immediately extend the reverberation chambers to immunity and susceptibility tests [WAR 96].

At the same time and with the efforts of M. Hatfield of the Naval Surface Warfare Center in the United States, test methods using a reverberation chamber enter the international standards with texts currently recognized by the International Electrotechnical Commission (IEC) and the aeronautics standardization [HAT 00].

Nowadays, the use of reverberation chambers, in France as well as in other European countries, intensifies with the need for the tests, but also in order to extend their scope in a very significant scientific research effort. In France, we can count several chambers distributed in some universities and other installations devoted to military activities, the automobile industry and aeronautics, without forgetting their interest for the study of the expected biological effects of radio waves. The use of reverberation chambers also concerns applications other than electromagnetic compatibility, since they simulate the propagation environments generating multiple reflections and, because of that fact, are very disruptive for modern telecommunication techniques [LIE 04].

To this day, there are many articles produced by the scientific community on the subject of reverberation chamber, and thus this book does not have the objective being added as a contribution to these high level works. The authors preferred a conventional physical approach, hoping it will help engineers, technicians or beginner students to understand the basics.

The eight chapters of this book, by a gradual description, bring the reader from the analysis of the mode stirring and the properties of field distribution, to the applications illustrated by measurement examples found in various installations.

The book is made up of three topics that we will briefly summarize.

Chapters 1, 2, 3 and 4 discuss the physics of the chamber’s operation. From the analysis of other test means, we can show that a test in reverberation chamber integrates measurement errors. We will try to quantize their amplitude and stationary behavior. Resorting to the 1D model will facilitate an understanding of the generation of eigenmodes, whose identity will then be specified for a rectangular chamber. The concepts of the modal cells and of the plane wave spectrum will be used to introduce the principle of mode stirring, and then indirectly (Chapter 3) the link that we can establish between the disordered distribution of the fields and the estimate of the error margins of their average amplitudes. This part will largely use the results and demonstrations from the articles published by D.A. Hill [HIL 94]. The statistical tests concluding Chapter 3 will supply the tools able to confront the experiment on idealized field or power distributions stated by the probability density function of Rayleigh distribution or exponential distribution, respectively. Chapter 4 is mainly devoted to the characterization of the chambers, tackling the evaluation of the mode stirring procedures, as well as a few demonstrations relative to the application of statistical theories, in preparation for the calibration of the field's amplitude.

Chapters 5, 6 and 7 discuss the questions of the chambers' use. Their aim is not to do a detailed description of the standard documents. On the contrary, the authors wanted to extract from the official methodology the protocols forming the strongest links with the physical and theoretical analyses undertaken in the previous chapters. These in-depth explanations of the phenomena will be followed by results of experiments carried out on electronic equipments or on components tested in several reverberation chambers installed in France. This is how we will find, in Chapter 5, immunity and susceptibility tests performed on electronic on-board car equipment. Chapter 6, devoted to the emission measurements, will be illustrated by an experiment coming from a radiation constituted of spectrum lines spreading on more than 1 GHz. The analysis will insist on the confrontation of measurements done on chambers of different volumes. Chapter 7 exclusively turned on the shield effectiveness, discusses the problem of the evaluation of the attenuations brought by shielded cables or connectors, by shielded enclosures, and then by materials offering a certain opacity to the radio waves. This chapter will be illustrated by results of experiments successively practiced on a coaxial test tube, comprising a small aperture on a shielded box, with a slit and on a polymer conductor material, deposited against a plane substratum in fiberglass.

To conclude this book, Chapter 8 begins the link with some recent research works accomplished on the reverberation chamber. This part is not exhaustive and the authors propose a discussion on the physical limits of some approaches described in the previous chapters. It is obvious that for purely didactic reasons, the phenomena have often been reduced to ideal situations. Such is the case for field distribution, whose reality is found between the purely periodic model of the standing waves and the perfect disorder established on the hypothesis of the maximal entropy. We will find in this last chapter the results of the measurements, proving that a reverberation chamber does not rigorously follow the model of the disordered field, notably when we get close to the minimal frequency of use of the chamber. This analysis will lead to the probability density function of Weibull. In this part of the book, the subject of the capture of statistically independent field or power data, will also be taken and improved by the search for a correlation estimator more appropriate to the context of the reverberation chamber.

In the presentation of the text, the authors have deliberately repeated formulas that they judge important, or in other cases, some demonstrations. We notably find this process at the end of Chapter 3, where we have the calculations leading to the determination of the radiated power by an object tested in reverberation chamber. This reasoning will partially be repeated, and then detailed in Chapter 6, which is entirely devoted to the emission measurements. We think that this practice limits the constant returns to the zones anterior to the text and that it facilitates in the same time the merger of the different chapters.

Knowing that the reverberation chambers are still prone to in-depth studies, the authors have replaced the conventional conclusions of Chapter 8 with open discussions on questions mainly related to the physical functioning.

To complete the main text, five appendices detail physical concepts or auxiliary calculations. Moreover, after each chapter, the reader will find bibliographical references.

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Chapter 1

Position of the Reverberation Chambers in Common Electromagnetic Tests

1.1. Introduction

In addition to the conduction tests, the common immunity or emission tests required in electromagnetic compatibility involve the production of electric fields of an amplitude higher than 1 V/m, or on the contrary the measurement of low fields, whose amplitude can be close to 100 µV/m.

The use of the electromagnetic plane wave concept offers experimenters the means to qualify most of the devices as tests recommended by international standards or conceived for specific applications. The plane wave is based on a theoretical ideal stating that no experiment can rigorously reproduce. Paradoxically, we will see in this first chapter and the subsequent stages of the book, that it is the confrontation of the plane wave concept that allows us quite frequently to appreciate the reproducibility criteria of a test.

The estimate of the error margins is thus the major concern during the design of new test methods or during the improvement of the existing test methods.

These reasons have thus encouraged us to write the first section of this chapter about the theoretical concepts of plane waves. Although generally confused with the ray propagation adopted in geometrical optics methods, the plane wave has significantly different physical properties. The particularity of the plane wave is above all due to the polarization plane perpendicular to the propagation direction of the wave. Another property is added to this first property, stipulating that the orthogonal electric field $\vec{E}$ and magnetic field $\vec{H}$ vectors carried by the wave, remain invariant for an observer moving in the polarization plane. Moreover, thanks to the resolution of Maxwell's equations in a vacuum, one shows that the ratio of the amplitudes of $\vec{E}$ and $\vec{H}$ corresponds to the square root of the ratio of the absolute magnetic permeability μ_0 and the absolute electric permittivity ε_0. This is the impedance of the plane wave, approximately taking the real value of 377 Ω.

The following section will be concerned with the examination of the physical behavior of objects submitted to tests done in a TEM cell and in an anechoic shielded chamber. With the help of an object reduced to a small magnetic loop, several sources of uncertainties will be identified. They result from the imperfections of the instruments and from the environment of the object under test. The open discussion on the contribution of these uncertainties will lead to the physical principle of mode-stirred reverberation chambers. Contrary to the methods previously described, reverberation chambers directly introduce, from their functioning principle, uncertainties which may be characterized by statistical analysis. These properties will be implemented in the calibration protocols, which will guarantee the reproducibility of the tests carried out in chambers of various volumes and constitution.

1.2. Electromagnetic fields and plane waves

In accordance with the predictions of the J.C. Maxwell equations, established at the end of the 19th Century, the electromagnetic waves are recounted by a propagation phenomenon in the space linking an electric field vector $\vec{E}$ and a magnetic field vector $\vec{H}$. In the current system of standardized units, electric and magnetic field are respectively expressed in *V/m* and *A/m*. The most known effects generated by the fields are expressed in terms of currents or voltages induction, appearing in the electric circuits exposed to the waves and that we generally call electromagnetic interferences. Implementing an electromagnetic test will thus consist of the measurement of the field amplitude and of the effects consecutive to the induction phenomena that they produce.

The most elementary representation of an electromagnetic wave is made up of the *plane wave*, whose properties are close to the ray propagation in optics. Most of the tests designed to evaluate the behavior of electronic equipment exposed to fields animated by sinusoidal amplitude variations are also based on the notion of plane waves. The formalism of plane waves also concerns the undesirable electromagnetic fields emitted by this equipment, while these are operated in usual conditions.

In the context of electromagnetic compatibility, the analysis of the behavior of electronic equipment subjected to an electromagnetic field will concern *immunity* or *susceptibility* tests.

The immunity is the aptitude of a device to operate without fault, when it is exposed to electromagnetic interference, whose physical characteristics have been specified beforehand by a measurement protocol. Susceptibility tests are designed to determine the parameters of the interference causing faulty functioning of this same device.

The emission measurement relates to the evaluation of the electromagnetic fields or to the interference level that electronic equipment can produce in its close environment during use. To carry out an emission measurement thus consists of determining the fields' amplitude observed on the electromagnetic spectrum, generated by this equipment and at a distance specified by an appropriate protocol [HAR 61].

1.2.1. *Definition and properties of plane waves*

Let us consider the geometrical Cartesian graph *oxyz* shown in Figure 1.1.

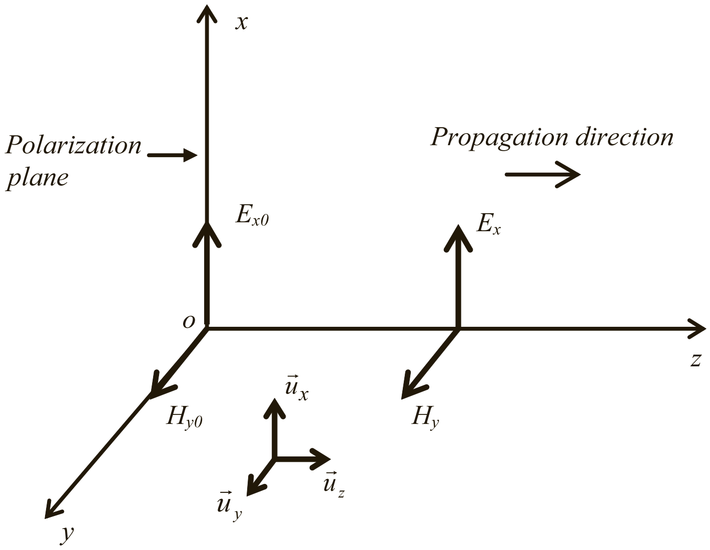

Figure 1.1. *Cartesian geometrical references of a plane wave*

The plane wave is made up of vector functions $\vec{e}(z,t)$ and $\vec{h}(z,t)$ dependent on the space variable *z* and on the time variable *t*. Knowing that this wave will then be animated by sinusoidal amplitude variations with the time variable, their representation in the diagram of Figure 1.1 can be reduced to the maximal, root mean square (rms) or complex amplitudes alone, designated by an upper-case syntax.

With the previous assumptions, we associate with the plane wave two amplitude vectors of electric $\vec{E}$ and magnetic $\vec{H}$ orthogonal fields. The plane containing the vectors $\vec{E}$ and $\vec{H}$ is called the *polarization plane*. The plane wave is such that the amplitude and direction of the vectors $\vec{E}$ and $\vec{H}$ remain invariant in the polarization plane; *the propagation direction* of the wave is perpendicular to the polarization plane.

For the example illustrated in Figure 1.1, the polarization plane is merged with the *oxy* graph, and the propagation direction is contained on the *oz* axis perpendicular to the previous graph. When the propagation has the same direction as the *oz* axis, it is a forward wave and when the propagation is in the opposite direction, it is a backward wave. The use of unit vectors (at the bottom of Figure 1.1) leads to $\vec{E}$ and $\vec{H}$, expressed under the forms:

$$\vec{E} = E_x \vec{u}_x \qquad \vec{H} = H_y \vec{u}_y \tag{1.1}$$

1.2.1.1. *Waves equations*

From the development of Maxwell equations, we manage to link $\vec{e}$ and $\vec{h}$ to the variables *z* and *t* by the following waves equations:

$$\frac{\partial^2 \vec{e}}{\partial z^2} - \frac{1}{v_0^2}\frac{\partial^2 \vec{e}}{\partial t^2} = 0 \qquad \frac{\partial^2 \vec{h}}{\partial z^2} - \frac{1}{v_0^2}\frac{\partial^2 \vec{h}}{\partial t^2} = 0 \tag{1.2}$$

The v_0 parameter represents the propagation speed in the considered environment; if the wave propagates in a vacuum, v_0 is the speed of light in vacuum so-called celerity *c*. An expression close to *c* can be established with the help of the absolute magnetic permeability of the vacuum μ_0 and of the electric permittivity ε_0, i.e.:

$$v_0 = c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \tag{1.3}$$