Anechoic and Reverberation Chambers

Theory, Design, and Measurements

Qian Xu and Yi Huang

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To our families

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About the Authors

Dr. Qian Xu received the BEng and MEng degrees from the Department of Electronics and Information, Northwestern Polytechnical University, Xi'an, China, in 2007 and 2010 respectively, and received the PhD degree in electrical engineering at the University of Liverpool (UoL), UK, in 2016. He is now an Associate Professor at the College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, China. He worked as a Radio Frequency (RF) engineer in Nanjing, China in 2011, an Application Engineer in CST (Computer Simulation Technology) Company, Shanghai, China in 2012, and a Research Assistant at UoL in 2016.

His work at the UoL was sponsored by Rainford EMC Systems Ltd. (now part of Microwave Vision Group) and Centre for Global Eco-Innovation. He finished his PhD in three years and has authored/co-authored more than 70 papers. Three of his papers received the Best Student Paper Award (third prize, first author) at LAPC (Loughborough Antenna & Propagation Conference) 2014, Best Non-Student Paper Award (first prize, coauthor) at LAPC 2015 and Best Non-Student Paper Award (third prize, coauthor) at LAPC 2016 respectively. He is a reviewer of Institute of Electrical and Electronics Engineers (IEEE) Transactions on Electromagnetic Compatibility (EMC) and IEEE Antennas and Wireless Propagation Letters. He developed new reverberation chamber and anechoic chamber measurement control systems at UoL. He also proposed a series of new measurement methods in reverberation chambers and quantified the stirring efficiency by using the total scattering cross section. He has developed a new software package for the Rainford EMC Systems which accelerates the anechoic chamber design greatly.

Prof. Yi Huang received his BSc in Physics (Wuhan, China), MSc (Eng) in Microwave Engineering (Nanjing, China) and DPhil in Communications from the University of Oxford, United Kingdom, in 1994. He has been conducting research in the areas of radio communications, applied electromagnetics, radar, and antennas since 1986. He has been interested in reverberation chamber theory and applications since 1991. His experience includes three years spent with NRIET (China) as a Radar Engineer and various periods with the Universities of Birmingham, Oxford, and Essex as a member of research staff. He worked as a Research Fellow at British Telecom Labs in 1994 and then joined the Department of Electrical Engineering & Electronics, University of Liverpool (UoL), UK, as a Lecturer in 1995, where he is now the Chair in Wireless Engineering, the Head of High Frequency Engineering Group, and the Deputy Head of the Department.

Dr. Huang has published over 300 refereed research papers in international journals and conference proceedings and is the principal author of the popular book *Antennas: From Theory to Practice* (John Wiley & Sons, 2008). He has received many research grants from research councils, government agencies, charity, EU, and industry; acted as a consultant to various companies; served on a number of national and international technical committees (such as the UK Location & Timing KTN, IET, EPSRC, and European ACE); and has been an Editor, Associate Editor or Guest Editor of four international journals. He has been a keynote/invited speaker and organiser of many conferences and workshops (e.g. IEEE iWAT, WiCom, LAPC, UCMMT, and Oxford International Engineering Programmes). He is at present the Editor-in-Chief of *Wireless Engineering and Technology*, an Associate Editor of *IEEE Antennas and Wireless Propagation Letters,* the Rep for the UK and Ireland to European Association of Antennas and Propagation (EurAAP), a Senior Member of IEEE, and a Fellow of IET.

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Acronyms

AAC	average absorption coefficient
AC	anechoic chamber
ACF	auto-correlation function
ACS	absorption cross section
AF	antenna factor
AR	axial ratio
ASCII	American Standard Code for Information Interchange
AUT	antenna under test
AVF	antenna validation factor
BEM	boundary element method
BER	bit error rate
BFS	breadth-first search
BSE	base station emulator
CAD	computer-aided design
CDF	cumulative distribution function
CEM	computational electromagnetics
CISPR	International Special Committee on Radio Interference (Comité International Spécial des Perturbations Radioélectriques)
CLF	chamber loading factor
CLT	central limit theorem
COM	component object model
CPU	central processing unit
CV	coefficient of variance
CVF	chamber validation factor
DG	diversity gain
DoF	degrees of freedom
DUT	device under test
EM	electromagnetic
EMC	electromagnetic compatibility
EUT	equipment under test
FACET	fast anechoic chamber evaluation tool
FD	frequency domain
FDFD	frequency domain finite-difference
FDTD	finite-difference time domain
FEM	finite element method
FFT	fast Fourier transform
FIT	finite integration technique
FITD	finite integration time domain

FMM	fast multipole method
FT	Fourier transform
FU	field uniformity
GA	genetic algorithm
GEV	generalised extreme value
GO	geometric optics
GPU	graphics processing unit
GTEM	gigahertz transverse electromagnetic
GUI	graphical user interface
IE	integral equation
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFFT	inverse fast Fourier transform
IFT	inverse Fourier transform
i.i.d.	independent and identically distributed
IP	intellectual property
LoS	line-of-sight
LPDA	log-periodic dipole array
LUF	lowest usable frequency
MIMO	multiple-input multiple-output
MLE	maximum likelihood estimation
MLFMM	multilevel fast multipole method
MoM	moment method or method of moment
NLoS	none-line-of-sight
NPL	National Physical Laboratory
NSA	normalised site attenuation
NUAA	Nanjing University of Aeronautics and Astronautics
OOP	object-oriented programming
OTA	over-the-air
OUT	object under test
PBC	periodic boundary condition
PC	personal computer
PDF	probability density function
PEC	perfect electric conductor
PILA	planar inverted-L antenna
PMC	perfect magnetic conductor
PML	perfectly matched layer
PO	physical optics
PVC	polyvinyl chloride
P2A	point-to-area
P2L	point-to-line
P2P	point-to-point
RAM	radio absorbing material
RC	reverberation chamber
RCS	radar cross section
RF	radio frequency
RIMP	rich isotropic multipath environment

Rx	receiving
SA	site attenuation
SBR	shooting bouncing ray
SE	shielding effectiveness
SF	spreading factor
SNR	signal-to-noise ratio
SR	stirring ratio
SSH	scalar spherical harmonics
STD	standard deviation
STL	stereolithography
SVSWR	site voltage-standing-wave ratio
TCS	transmission cross section
TD	time domain
TE	transverse electric
TEM	transverse electromagnetic
TG	time gating
TIS	total isotropic sensitivity
TLM	transmission line matrix
TM	transverse magnetic
TRP	total radiated power
TSCS	total scattering cross section
Tx	transmitting
UoL	University of Liverpool
UK	United Kingdom
USRP	universal software radio peripheral
VNA	vector network analyser
VSH	vector spherical harmonics
WV	working volume

1

Introduction

1.1 Background

Anechoic chambers (ACs) and reverberation chambers (RCs) are two very different types of indoor measurement facilities and have been widely used in acoustics as well as in electromagnetics. It is interesting to note that these chambers share similar phenomena, physical quantities, and mathematical expressions in some ways. This book is about ACs and RCs in electromagnetics. Inside an AC, electromagnetic (EM) waves are absorbed by the absorbing materials at the boundary, while inside an RC, EM waves are reflected by the conducting reflector at the boundary. Over the years, these two different chambers have found some common or complimentary applications in antennas, electromagnetic compatibility (EMC), and radio communication measurements. Each has its advantages and disadvantages. Thus, it makes a perfect sense to bring these two different chambers into one book. They are like two sides of one coin: one is based on deterministic theory and the other is based on statistical theory; people working on RCs can be inspired by those working on ACs, and vice versa. Dual quantities can also be found in absorbing and scattering phenomena. This book is aimed at providing a clear and systematic approach to their design, measurement, and applications. Some latest developments are also included. In this chapter, we present an overview of both chambers while more details are provided in later chapters.

1.1.1 Anechoic Chambers

An ideal AC is a room designed to emulate free space – no radio waves are reflected from the walls, ceiling, and floor. The reason for using an AC is well-known: an ideal free space is required for EM measurement in an indoor environment that is not affected by the weather and interference outside the chamber, thus repeatable results can be obtained. A typical AC is given in Figure 1.1a and a typical measurement scenario with an aircraft is shown in Figure 1.1b.

In practice, because no ACs can absorb EM waves perfectly and reflections always exist, the performance of an AC needs to be characterised to show how close it is to the ideal free space. Thus, how to design an AC effectively and efficiently becomes an important issue. A problem is how to optimise the performance of such a chamber for a given chamber size using the least amount of radio absorbing materials (RAMs) to minimise the cost and maximise the test volume (i.e. the equipment under the test area). The cost of the RAM depends on its size and type. How to choose the RAMs and arrange them properly is another key problem. Currently, the design of the chamber depends on the designer's experience and sometimes a trial-and-error approach or a large safe margin has to be adopted. Intuitively, a large space with high-performance absorbing materials leads to a good AC, but to quantify the chamber performance a well-defined and accurate mathematical model needs to be created. Thus, a scientific and objective way to find the best solution is required. An analytical solution is

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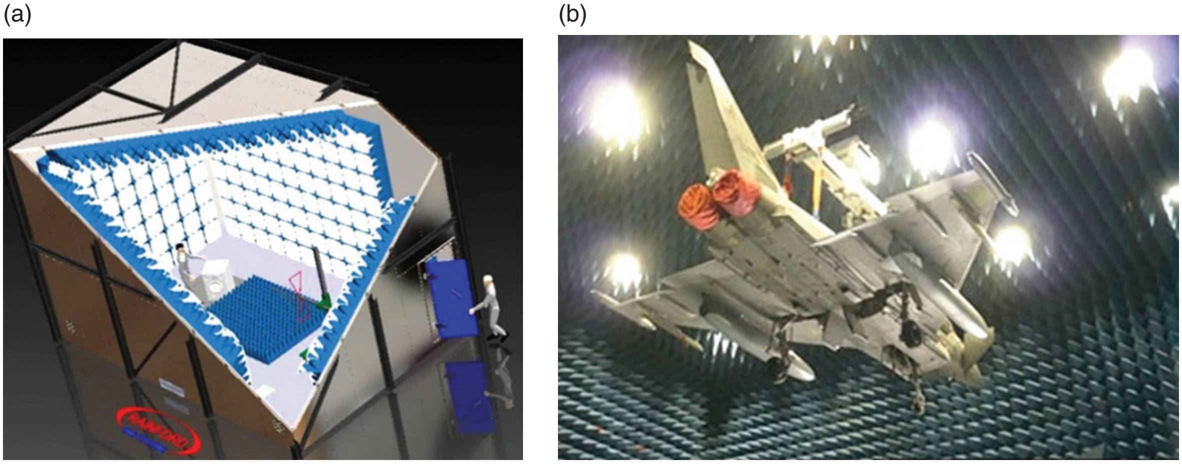


Figure 1.1 Anechoic chamber: (a) 3D model with a cutting plane and (b) measurement with an aircraft inside an AC (pictures from Rainford EMC Systems, Microwave Vision Group).

almost impossible for such a complex system, which offers an opportunity to bring computational electromagnetics (CEMs) and real engineering problems together.

If an efficient computer-aided design (CAD) tool was available to predict the performance of an AC, the designer could design the chamber better, faster, and more accurately with the help of computers, not just relying on experience.

The figures of merit used to characterise the chamber performance in practice are site attenuation (SA) for a full AC (all walls are covered with RAMs) and normalised site attenuation (NSA) for a semi-AC (no RAMs on the floor), field uniformity (FU), and site voltage-standing-wave ratio (SVSWR) [1, 2]. The procedures to measure these figures of merit and acceptable limits are given in relevant standards [1, 2].

It is well-known that the performance of ACs is closely related to the reflectivity of RAMs and how to arrange them [3, 4]. The first patented absorber was used to improve the front-to-back ratio of an antenna in 1936 [5]. During World War II (1939–1945), −20 dB (near normal incident angles) in the frequency range of about 2–15 GHz was obtained as the well-known Jauman absorber [6]. During the war years, Neher [7] demonstrated that the reflection from a long pyramidal shaped structure was much smaller than the reflection from a panel of the same absorber. This demonstrated the important role of geometry in the reflection reduction of RAMs. The first commercially available absorber started in 1953. In the early 1950s, 'dark-rooms' were built at a number of government and commercial organisations [8–10]; at that time, a typical level of reflected signal at S band was about 20 dB below the level of the direct signal. In the late 1950s, a new generation of broadband absorbers was able to produce a reflection coefficient of about −40 dB for near-normal incident angles. In the 1960s, by using ferrite underlayers, the thickness of the absorber was reduced greatly at low frequencies and the tapered chamber was developed, which showed a better performance than the rectangular chamber [10, 11]. The normal reflection coefficient at high frequencies achieved −60 dB. Nowadays, by combing the ferrite tiles and the pyramid absorbers, the reflection coefficient can achieve −25 dB at 30 MHz and −51 dB at 18 GHz (http://www.mvg-world.com/en/system/files/fiche_uh_absorbers_hypyr-loss_en_bd_oct_25th.pdf). More details will be discussed in the following chapters.

Three basic types of AC are used in practice, as shown in Figure 1.2: the rectangular chamber (Figure 1.2a), the tapered chamber (Figure 1.2b), and the compact chamber (Figure 1.2c). Test regions are marked with a circle, waves propagate along the lines ideally and absorbers are plotted as small triangles. In practice, because of the reflection and scattering of the RAMs, and because extraneous signals exist, the field in the test region is not uniform. The tapered chamber normally can provide a better FU than the rectangular chamber at lower frequencies, but the SA of a tapered chamber does not follow the Friis free-space transmission formula because of the multiple reflections from the tapered walls [3]. This should be noted for some special measurements such as using the three-antenna method to measure the gain of antennas. A compact chamber can be used to illuminate a large object with plane wave at higher frequencies because the object under test needs to be placed at the far-field region. When the frequency is high, the far-field condition cannot be satisfied without the use of a reflector. A parabolic reflector is normally used to generate a plane wave at higher frequencies, as shown in Figure 1.2c.

How to obtain an optimised AC has been investigated for many years. A well-known book was written by L. H. Hemming in 2002 [3] that provided an overview of this topic, including RAM characteristics, ACs of different shapes, and measurements in ACs. Geometric optics (GO) was mentioned as a general method to analyse the AC, but the calculation was done by hand and how to implement it using a computer was not given. In a recent book [12], B. K. Chuang reviewed the GO method for AC design in one chapter. Although CEMs have evolved over the years, compared with other CEM methods the GO method is still the most robust and efficient in AC analysis. The most attractive advantage is that no detailed information of the material properties (permittivity, conductivity, and permeability) needs to be known; only the reflection coefficient is enough to describe the RAMs. The simulation time is also short with an acceptable error.

In this book we present a systematic solution for AC design, from theory to measurement. The solution proposed in this book is meant to be general and useful for all types of ACs, that is, not limited to specific shapes; it is also possible to use this solution to explore new chamber shapes with special requirements.

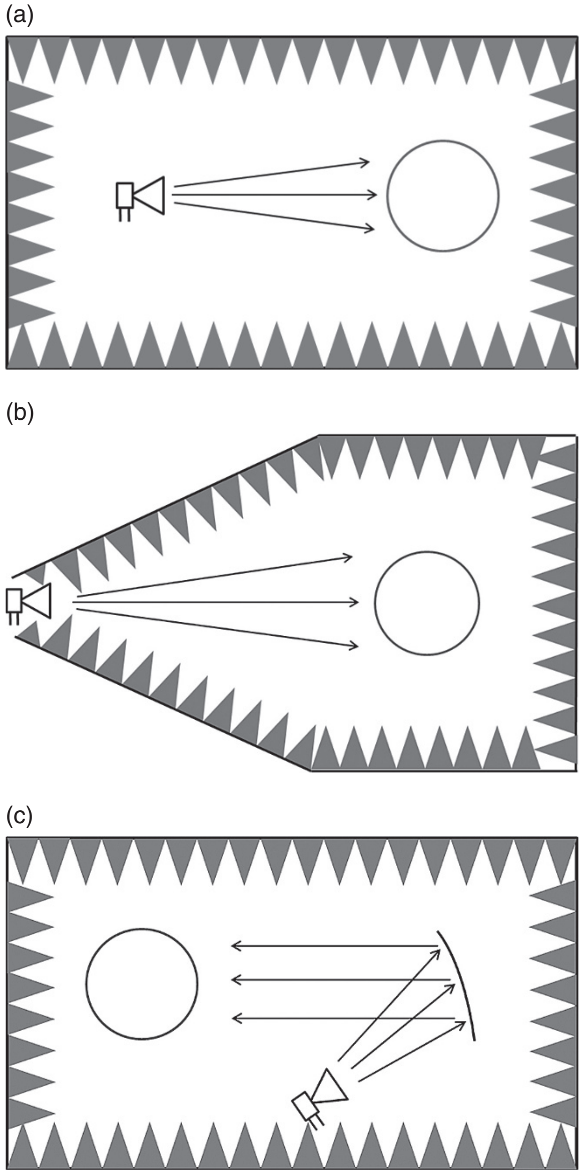
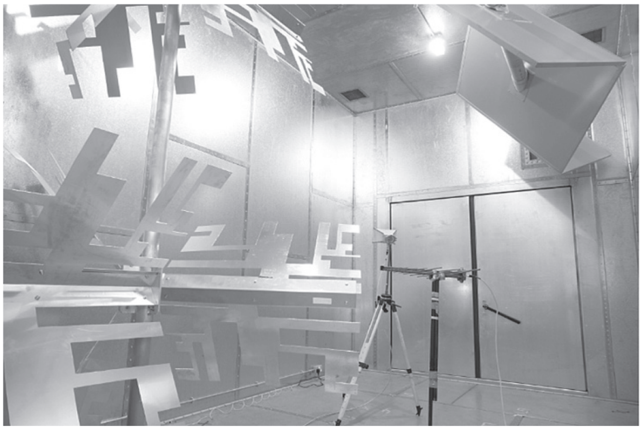


Figure 1.2 Three types of ACs: (a) rectangular chamber, (b) tapered chamber, and (c) compact chamber.

1.1.2 Reverberation Chambers

Unlike an AC, an RC is an electrically large conducting-screened room with electrically large stirrers used to stir the field inside the chamber (https://en.wikipedia.org/wiki/Electromagnetic_reverberation_chamber). The RC is also known in the literature as a reverberating chamber, a reverb, a mode-stirred chamber or a mode-tuned chamber. In this book the term 'reverberation chamber' is used as it is now widely used and accepted. The EM field inside the chamber is expected to be statistically uniform and isotropic. Two RCs are shown in Figure 1.3. In Figure 1.3a, two stirrers at the corner of the RC are used while in Figure 1.3b, one stirrer is employed near the middle of the RC.

(a)



(b)

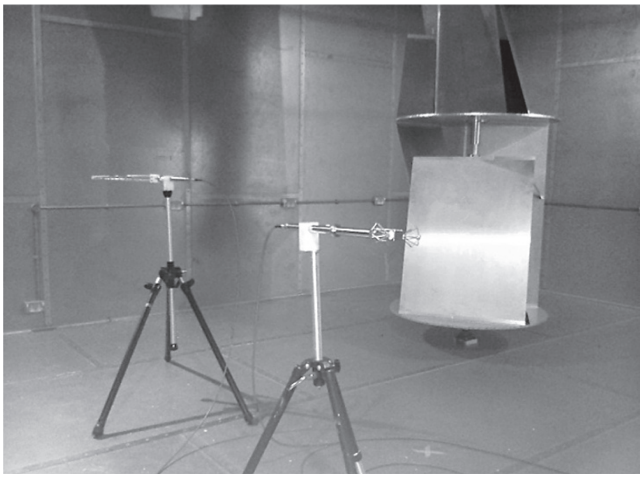


Figure 1.3 Reverberation chambers: (a) RC at the University of Liverpool, UK, width 3.6 m, length 5.8 m, height 4 m, and (b) RC at the National Physical Laboratory, UK, width 5.8 m, length 6.5 m, height 3.5 m.

The first RC was probably proposed by H. A. Mendes in 1968 for EMC measurements [13] and was then adopted by American military standard MIL-STD-1377. An international standard on using an RC for EMC testing was published in 2003 and revised in 2011 [14]. Over the years, many researchers have worked on it and made significant advancements: P. Corona improved our understanding of RCs for EMC measurements [15] and D. A. Hill proposed a plane-wave integral representation of fields in the RC [16]. Like the Friis transmission equation in free space, Hill's equation reveals the transmission law in a multipath environment [16]. Systematic theory has been found to describe the fields in an ideal RC [16, 17]. It should also be noted that, when the RC is not working in the over-mode condition (i.e. not electrically large), the statistical behaviour deviates from the expected distribution functions. Thus, there is a blurred region from deterministic behaviour to statistical behaviour [17]. In practical engineering, we try to avoid working in this region as an RC of different shapes may have different behaviour, and it would be difficult to have a general theory to fit the measurement results in this region. At a lower frequency (i.e. the chambers are electrically small cavities), deterministic theory can be used, at a higher frequency (i.e. the chambers are electrically large cavities) Hill's theory can be applied.

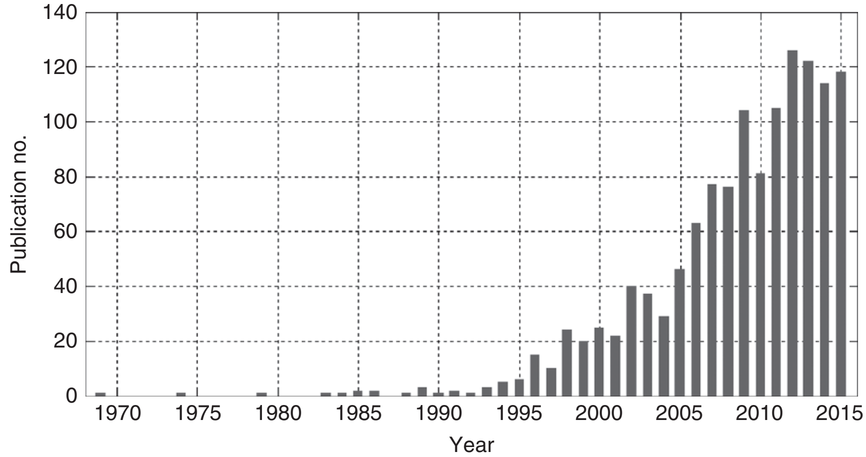


Figure 1.4 Number of publications per year (data from IEEE Xplore, key word: reverberation chamber).

The number of RC papers published over the past 45 years is shown in Figure 1.4. The numbers are from IEEE database. It is interesting to see that the number increased significantly in the 2000s, but the initial study on RCs is from 1968! The reason seems to be that the RC is no longer a specialised facility for EMC tests; it has gradually become a test facility for antenna measurement, bio-electromagnetics, material measurement, radio channel emulation, etc.

Like an AC, there are also many useful parameters to characterise an RC, such as K-factor, independent sample, correlation coefficient, FU, stirrer efficiency, enhanced backscatter constant, total scattering cross section, etc. Currently there is no unique parameter to summarise all these effects, and the relationships between some of them are still ambiguous. Because of the complexity of the statistical electromagnetics, there are still things we do not know and the application of the RC is expanding thanks to the researchers on this topic all over the world.

The stirring technique is a lasting topic in RC research. It is well known that to achieve a statistical EM field in a cavity, some kind of stirring mechanism needs to be involved to stir the field inside. From the integral expression of the electric field (integrate source with Green's function), to stir the electric field we can change the boundary conditions or change the source. The boundary conditions can be changed by (i) altering the internal structure, for example using asymmetric stirrers [14], helical stirring [18] or a carrousel stirrer [19–21], and (ii) changing the boundary structure, for example by a wall vibrating boundary [22–25], an oscillating stirrer [26], a sliding wall [27] or reactively loaded antennas [28]. If the source is changed, one can change the position or orientation of the source [29–31] or use multiple source excitations [32]. Frequency stir is an effective and efficient method: by mixing the results from different frequencies separated by more than the coherent bandwidth [33, 34], a similar effect can be obtained. It should be noted that not all stirring methods are applicable to all applications. For example, if the Q factor of an RC needs to be kept constant (Q factors can also be treated as random variables [35]) during the stirring process, the sliding wall method may not be suitable as it changes the volume of the RC when stirring; if a device under test has a very narrow frequency band response, frequency stir should be very carefully applied, as frequency stir normally presumes other factors unchanged in the stirring bandwidth. If it is wider than the working bandwidth of the device, the response could be smoothed out.

Unlike ACs, the performance of an RC is not sensitive to the shape of the cavity when it is electrically large, as the mode number is not sensitive to the shape but the volume of the cavity. Rectangular shape is the most popular as it is easy to build, but this does not mean that it is the best shape from an electrical point of view. Other shapes of RC are also possible, such as triangular [36] and non-parallel walls [37, 38], which could provide better performance in some cases. However, considering the fact that one can add scatterers or panels into a rectangular RC to change its internal shape, and it is not easy to extend a special shape (e.g. triangular shape) into a rectangular shape after the RC is built, rectangular shape is still the favourite choice for its reconfigurability and generality.

In the RC part of this book we present fundamental theory, typical measurements, and design principles of RCs. We have tried to minimise the mathematical derivations and make the book easy to use in practice. The book not only includes knowledge that is already known, but also presents information that is relatively new.

1.1.3 Relationship between Anechoic Chambers and Reverberation Chambers

There have been some discussions on the relations between ACs and RCs. People get inspiration on RCs from ACs and vice versa. The RC can be considered as an opposite environment to the AC. The two types of chamber can be related and compared as follows.

1) *Different philosophies behind the two chambers*. The RC takes advantage of multipath waves while the AC tries to eliminate them.
2) *The AC is a deterministic environment while the RC is a statistical environment*. Correspondingly, the AC can be used to verify conclusions from CEMs, and the RC can be used to verify results from statistical electromagnetics. There can be statistical variables in deterministic theory, and there are deterministic quantities in statistical theory. For both chambers, we find uncertainties in certainties and find certainties in uncertainties.
3) From the communication channel point of view, the AC can be considered as an ideal Gaussian channel, while the RC can be considered as a Rayleigh channel or Rician channel. This is very useful when one wants to emulate the channel for a communication system to measure the bit error rate (BER), total isotropic sensitivity (TIS), channel capacity, etc.
4) Some physical quantities are very difficult to measure in one kind of chamber, but are easy to measure in another kind of chamber. An AC is very good for measurements with directional variables such as radiation pattern, antenna gain, and scattering cross section, while an RC is good at measurements with assembled variables such as antenna radiation efficiency, TIS, total radiated power, average absorption cross section, and shielding effectiveness.
5) Dual physical quantities exist in absorbing and scattering phenomenon. In the RC, the vector superposition of the random scattered field of many stirrer positions tends to be zero, as if it is absorbed. This provides insight in the RC design: if a stirrer leads a better random scattered field than another it means the performance of the stirrer is better. This is discussed in detail in the book.

1.2 Organisation of this Book

The AC has been used in the radio frequency (RF) and microwave industry for many years. However, design guidelines are mostly based on the experience accumulated over the years. There is one book related to AC design, published a few years ago [4], but the CEM algorithms have been developed greatly in the last 10 years or so. The industry has also moved on; different companies need to share information without disclosing sensitive data. This book provides the latest systematic solutions for AC design using state-of-the-art CEM algorithms. By using CAD, chamber designers can now optimise the chamber (structure, absorber layout, antenna positions) to maximise the performance while minimise the cost. This book will provide guidelines on this and show real design examples verified by measurements.

As a very different chamber, the RC has been used in EMC measurements and tests for a long time, but recent advances show that RCs can be used in many other applications and could be even better than ACs in some applications. There are a couple of books relating to RCs [16, 17] but the emphasis of these books is on EM theory and EMC measurement protocols. In recent years many new applications of RCs have been developed [39, 40]. This book covers a series of the latest measurement methods in RCs. New understandings of RCs from the time domain are also included, providing new points of view which cannot be seen from only the frequency domain.

This book covers the most recent advances in AC and RC designs and measurements. It will be interesting to show that these two types of chambers are closely related, the design of the RC can be inspired by the design of the AC, and there exist dual quantities between random scattering and absorption. The book is organised as follows:

Chapter 2. *Theory for Anechoic Chamber Design*. This chapter details the theory for AC design without considering how to realise it. Basic knowledge on absorbing materials is given. CEM algorithms are reviewed and discussed. Two forms of GO methods are introduced and it is shown that one is easier to use than the other in software realisation.

Chapter 3. *Computer-aided Anechoic Chamber Design*. This chapter focuses on how to realise the hybrid geometric optics–finite element method (GO-FEM) in AC design. Details on algorithm implementation are presented. It is shown how an AC design problem can be solved by using a CEM model step by step. This chapter mixes computer graphics and electromagnetics. Acceleration strategies are also given, and the reader could benefit from the use of computer graphics and graphics processing unit (GPU) computing.

Chapter 4. *Anechoic Chamber Design Examples and Verifications*. This chapter explains the figure of merits of AC performance: NSA, SVSWR, and FU. Procedures on how to measure the figures of merit are given and physical understandings are also addressed. Practical design examples are given together with simulation and measurement results.

Chapter 5. *Fundamentals of the Reverberation Chamber*. This chapter introduces the basic theory of RCs, and definitions of figures of merit, such as lowest usable frequency (LUF), working volume (WV), FU, and stirrer efficiency, are explained. Discussions on the CAD of RCs are also given. Unlike AC design, currently there is no mature software tool for RC design, but the design process can be aided by using a computer.

Chapter 6. *The Design of a Reverberation Chamber*. This chapter focuses on the design guidelines and time domain behaviour of the chamber; it is shown that some difficulties in the frequency domain measurement can be resolved from the time domain measurement. The stirrer efficiency is defined by using the total scattering cross section of stirrers. The theoretical limit of the performance of stirrers (which is a longstanding problem) can be obtained from the time domain information. The time domain understanding can also be applied to the RC design.

Chapter 7. *Applications in the Reverberation Chamber*. This chapter summarises a range of measurements inside an RC, including radiated immunity, radiated emission, antenna measurement (*S* parameters, efficiency, diversity gain, and radiation pattern), material measurement, shielding effectiveness measurement, channel emulation, and volume measurement. Theories, measurement procedures, and data processing are also explained.

Chapter 8. *Measurement Uncertainty in the Reverberation Chamber*. RC measurement data are usually analysed from a statistical point of view, this chapter investigates the measurement uncertainty in the RC. This chapter is authored by Xiaoming Chen, Yuxin Ren, and Zhihua Zhang.

Chapter 9. *Inter-Comparison Between Antenna Radiation Efficiency Measurements Performed in an Anechoic Chamber and in a Reverberation Chamber*. To have an in-depth understanding of both ACs and RCs, this chapter compares measurements of antenna efficiency in ACs and RCs at the National Physical Laboratory in the UK. This chapter is authored by Tian-Hong Loh and Wanquan Qi.

Chapter 10. *Discussion on Future Applications*. This chapter predicts possible future applications and highlights some unsolved problems which could serve as a good starting point for researchers.

Appendices. In the appendices, some relevant detailed information is provided which includes code snippets, reference values, report template, and frequently used statistics.

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