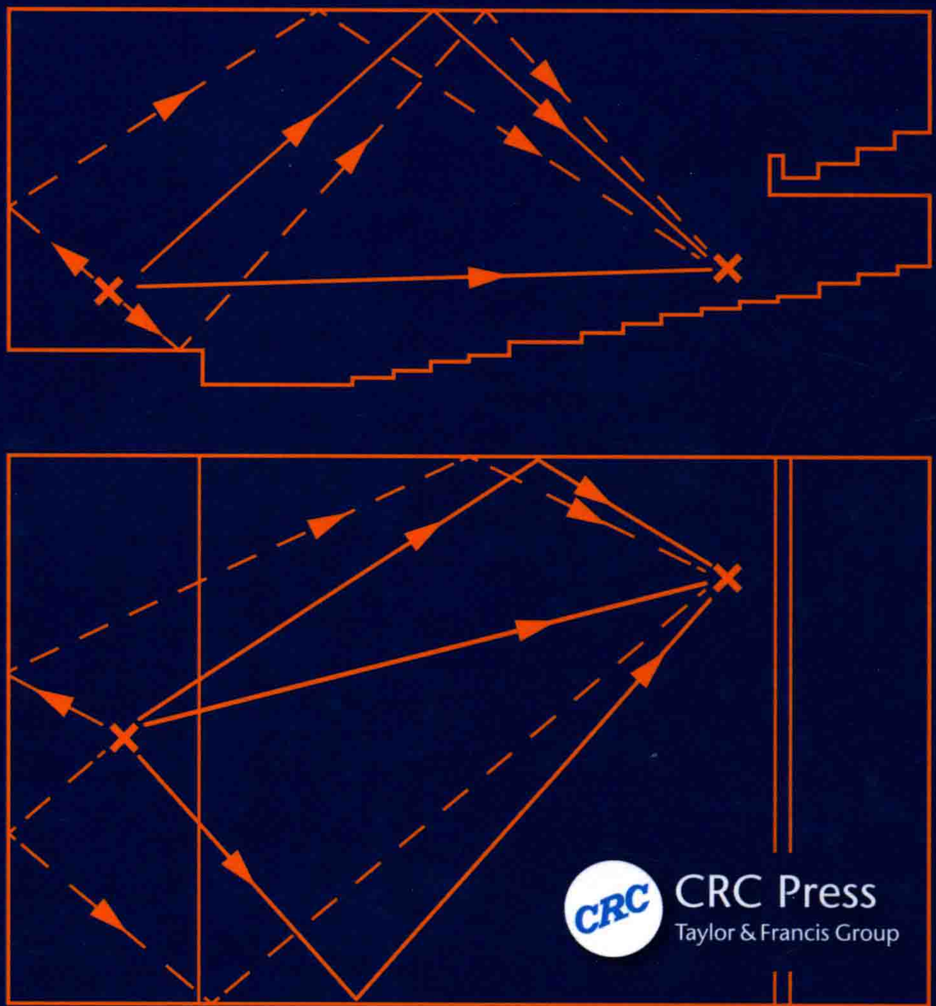
Sixth Edition

Room Acoustics

Heinrich Kuttruff



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List of symbols

LATIN CAPITAL LETTERS

A	constant, equivalent absorption area, absorption cross-section
B	constant, frequency bandwidth, irradiation density
C	constant, clarity index, circumference
$\mathbf{C}$	correlation matrix
D	diameter, thickness, definition, diffusion constant
$\mathbf{D}$	diagonal matrix (in Section 7.8)
E	energy
F	force, arbitrary function
G	strength factor
$G(\omega)$, $G(f)$	transfer function, arbitrary function
H	transfer function, distribution of damping constants
IACC	interaural cross correlation
$J_n(z)$	Bessel function of order n
K_n	normalization constant
$K(\mathbf{r},\mathbf{r}')$	kernel (of integral equation)
$\mathbf{K}$	stiffness matrix (in Section 3.5)
L	length, sound pressure level
LEF	lateral energy fraction
M	mass
$\mathbf{M}$	mass matrix (in Section 3.5)
M'	specific mass (= mass per unit area)
N	integer
P	power, probability
PL	sound power level
Q	volume velocity, quality factor
Q_s	scattering cross-section
R	reflection factor, distance, radius of curvature, resistance
R_r	radiation resistance
S	area
$S(\omega)$, $S(f)$	spectral density or spectral function
SPL	sound pressure level
T	period of an oscillation, transmission factor, reverberation or decay time
V	volume
$W(\omega)$, $W(f)$	power spectrum
$W(\mathbf{r},\mathbf{r}')$	propagator (in Section 10.5)
$\mathbf{W}$	transformation matrix (in Section 7.8)

Y	admittance, wall admittance
Z	impedance, wall impedance
Z_r	radiation impedance

LATIN LOWER CASE LETTERS

a	radius, constant
$a(t)$	weighting function
b	thickness, constant
$b(t)$	weighting function
c	sound velocity
d	thickness, distance
$e(t)$	envelope
f	frequency
$f(\mathbf{r},\mathbf{v},t)$	distribution function of particles
g	directivity or gain
$g(t)$	impulse response
h	height, width
$h(t)$	decaying sound pressure
i	imaginary unit (= $\sqrt{-1}$)
$j(\mathbf{r},t,\mathbf{u})$	energy flux density
k	angular wavenumber
l	integer, length
m	integer, attenuation constant, modulation transfer function
$m(\Omega)$	modulation transfer function
n	integer, normal direction
n_s	density of scatterers
p	sound pressure
q	amplifier gain, volume velocity per unit volume
r	radius, distance, resistance
r_c	critical distance or diffuse-field distance
r_s	flow resistance
$r(t)$	reflection response
s	scattering coefficient
$s(t)$	time function of a signal
t	time or duration
t_s	centre time (centre of gravity)
$\mathbf{u}$	unit vector
$\mathbf{v}$	velocity, particle velocity
$v(\mathbf{r})$	test function (in Section 3.5)
w	energy density
x,y,z	Cartesian coordinates

GREEK CAPITAL LETTERS

$\Gamma(\vartheta,\varphi)$	directional factor
Δ	difference, Laplacian operator
θ	angle, temperature in degrees centigrade

Λ_n	shape function (in Section 3.5)
Ξ	specific flow resistance
Ψ	correlation coefficient
Ω	solid angle

GREEK LOWER CASE LETTERS

α	angle, absorption coefficient
β	angle, specific admittance
β'	phase constant
γ	angle
γ'	attenuation constant
γ^2	relative variance of path length distribution
δ	decay constant, difference
$\delta(t)$	Dirac or delta function
ε	angle
ζ	specific impedance
η	imaginary part of the specific impedance
ϑ	angle
κ	adiabatic or isentropic exponent
$\kappa(r,r')$	symmetric kernel
λ	wavelength
ξ	real part of the specific impedance
ρ	density, reflection coefficient (= $1 - \alpha$)
ρ_n	radius of nth Fresnel zone
σ	porosity, standard deviation
τ	transit time or delay time
φ	angle, phase angle
χ	phase angle of reflection factor
ψ	phase angle
ω	angular frequency

Preface

This book is intended to present the fundamentals of room acoustics in a systematic and scientifically correct way and to give an overview of the present state-of-the-art techniques in room acoustics. I hope that it will contribute to a better understanding of the factors responsible for what is commonly called good or poor 'acoustics of a room'.

One aspect of room acoustics concerns the physical laws of the generation, the propagation and absorption of sound in an enclosure. These laws are most effectively formulated in the language of mathematics. Therefore, to understand this book in its entirety, the reader should have a reasonable mathematical background and some elementary knowledge of wave propagation. (Certain derivations may be omitted without detriment by readers with more limited mathematical training.) However, the image conveyed by a purely physical description of sound propagation would be incomplete, if not useless, without regarding the physiological and psychological factors involved in the human perception of sound since it is the person attending a concert or a lecture who is the ultimate consumer of acoustics.

More than four decades have passed since the publication of the first edition of this book, and in the meantime many important insights and improvements in the techniques of room acoustical measurements and simulation have been introduced. The preceding editions of this book have tried to take regard of these progresses and thus in a way reflect this development which was mainly made possible by the rapid progress in digital techniques. This holds too for the present edition into which several matters of practical or fundamental interest have been included. One of them being the reflection of a spherical wave from a plane, locally reacting boundary – in room acoustics a rather fundamental process. Another new section presents an elementary explanation of the finite element method. In both cases, the theoretical fundamental has been laid long ago, but only the progresses in modern computer techniques have turned these methods into practical tools. A newly inserted component is, by the way, a section on 'Virtual Reality', the acoustical component of which is auralization.

To stay within the scope of this book, I have refrained from describing examples of completed rooms, apart from very few exceptions. As far as concert halls or opera theatres are concerned, the interested reader is referred to L.L. Beranek's famous collection 'Concert and Opera Halls',[1] which presents technical data, drawings and photos of as many as 67 halls along with many interesting observations made by musicians, criticsand experts in acoustics and other areas.

The literature on room acoustical subjects is so extensive that I have made no attempt to provide an exhaustive list of references. References have only been given in those cases where the work has been directly mentioned in the text, or in order to satisfy the possible demands for more detailed information.

Heinrich Kuttruff
Aachen, Germany
July 2016

REFERENCE

1. Beranek LL. *Concert and Opera Halls: How They Sound*. Woodbury, NY: Acoustical Society of America, 1996.

Acknowledgments

Despite many changes and amendments, this edition is still based on the competent and sensitive English translation of the original text provided by late Professor Peter Lord of the University of Salford. Furthermore, I am indebted to several readers of this book for various helpful suggestions. I also express my gratitude for the support he received from the Institute of Technical Acoustics of Aachen University, in particular, from Professor Michael Vorländer, Dr. Gottfried Behler, Professor Anselm Goertz and several other persons. I also thank the publisher for the pleasant and successful cooperation. Last but not least, I thank my wife most sincerely for her patience in the face of numerous evenings and weekends I had devoted to this work.

Introduction

We all know that a concert hall, theatre, lecture room or a church may have good or poor 'acoustics'. As far as speech in these rooms is concerned, it is relatively simple to make some sort of judgement on their quality by rating the ease with which the spoken word is understood. However, judging the acoustics of a concert hall or an opera house is generally more difficult, since it requires considerable experience, the opportunity for comparisons and a critical ear. Even so, the inexperienced cannot fail to learn about the acoustical reputation of a certain concert hall should they so desire, for instance, by listening to the comments of others or by reading the critical reviews of concerts in the press.

An everyday experience (although most people are not consciously aware of it) is that living rooms, offices, restaurants and all kinds of rooms for work can be acoustically satisfactory or unsatisfactory. Even rooms which are generally considered insignificant or spaces such as staircases, factories, passenger concourses in railway stations and airports may exhibit different acoustical properties; they may be especially noisy or exceptionally quiet, or they may differ in the ease with which announcements over the public address system can be understood. That is to say, even these spaces have 'acoustics', which may be satisfactory or less than satisfactory.

Despite the fact that people are subconsciously aware of the acoustics to which they are daily subjected, there are only a few who can explain what they really mean by 'good or poor acoustics' and who understand factors which influence or give rise to certain acoustical properties. Even fewer people know that the acoustics of a room is governed by principles which are amenable to scientific treatment. It is frequently thought that the acoustical design of a room is a matter of chance, and that good acoustics cannot be designed in a room with the same precision as a nuclear reactor or space vehicle is designed. This idea is supported by the fact that opinions on the acoustics of a certain room or hall frequently differ as widely as the opinions on the literary qualities of a new book or on the architectural design of a new building. Furthermore, it is well known that sensational failures in this field do occur from time to time. These and similar anomalies add even more weight to the general belief that the acoustics of a room is beyond the scope of calculation or prediction, at least with any reliability, and hence the study of room acoustics is an art rather than an exact science.

In order to shed more light on the nature of room acoustics, let us first compare it to a related field: the design and construction of musical instruments. This comparison is not as senseless as it may appear at first sight, since a concert hall too may be regarded as a large musical instrument, the shape and material of which determine to a considerable extent what the listener will hear. Musical instruments – string instruments for instance – are, as is well known, not designed or built by scientifically trained acousticians but, fortunately, by people who have acquired the necessary experience through long and systematic practical training. Designing or building musical instruments is therefore not a technical or scientific discipline but a sort of craft or an 'art' in the classical meaning of this word.

Nevertheless, there is no doubt that the way in which a musical instrument functions, that is, the mechanism of sound generation, the determining of the pitch of the tones generated and their timbre through certain resonances, as well as their radiation into the surrounding air, is all purely physical processes and can therefore be understood rationally, at least in principle. Similarly, there is no mystery in the choice of materials; their mechanical and acoustical properties can be defined by measurements to any required degree of accuracy. (How well these properties can be reproduced is another problem.) Thus, there is nothing intangible nor is there any magic in the construction of a musical instrument: many particular problems which are still unsolved will be understood in the near future. Then, one will doubtless be in a position to design a musical instrument according to scientific methods, that is, not only to predict its timbre but also to give, with scientific accuracy, details for its construction, all of which are necessary to obtain prescribed or desired acoustical qualities.

Room acoustics is different from musical instrument acoustics in that the end product is usually more costly by orders of magnitude. Furthermore, rooms are produced in much smaller numbers and have by no means geometrical shapes which remain unmodified through the centuries. On the contrary, every architect, by the very nature of his profession, strives to create something which is entirely new and original. The materials used are also subject to the rapid development of building technology. Therefore, it is impossible to collect in a purely empirical manner sufficient know-how from which reliable rules for the acoustical design of rooms or halls can be distilled. An acoustical consultant is confronted with quite a new situation with each task, each theatre, concert hall or lecture room to be designed, and it is of little value simply to transfer the experience of former cases to the new project if nothing is known about the conditions under which the transfer may be safely made.

This is in contrast to the making of a musical instrument where the use of unconventional materials as well as the application of new shapes is either firmly rejected as an offence against sacred traditions or dismissed as a whim. As a consequence, time has been sufficient to develop well-established empirical rules. And if their application happens to fail in one case or another, the faulty product is abandoned or withdrawn from service – which is not true for large rooms in an analogous situation.

For the above reasons, the acoustician has been compelled to study sound propagation in closed spaces with increasing thoroughness and to develop the knowledge in this field much further than in the case with musical instruments, even though the acoustical behaviour of a large hall is considerably more complex and involved. Thus, room acoustics has become a science during the past century and those who practise it on a purely empirical basis will fail sooner or later, like a bridge builder who waives calculations and relies on experience or empiricism.

On the other hand, the present level of reliable knowledge in room acoustics is not particularly advanced. Many important factors influencing the acoustical qualities of large rooms are understood only incompletely or even not at all. As will be explained below in more detail, this is due to the complexity of sound fields in closed spaces – or, as may be said equally well – to the large number of 'degrees of freedom' which we have to deal with. Another difficulty is that the acoustical quality of a room ultimately has to be proved by subjective judgements.

In order to gain more understanding about the sort of questions which can be answered eventually by scientific room acoustics, let us look over the procedures for designing the acoustics of a large room. If this room is to be newly built, some ideas will exist as to its intended use. It will have been established, for example, whether it is to be used for the showing of cine films, for sports events, for concerts or as an open-plan office. One of the first tasks of the consultant is to translate these ideas concerning the practical use into the language of objective sound field parameters and to fix values for them which he thinks will best meet the requirements. During this step, he has to keep in mind the limitations and peculiarities of our subjective listening abilities. (It does not make sense, for instance, to fix the duration of sound decay with an accuracy of 1% if no one can subjectively distinguish such small differences.) Ideally, the next step would be to determine the shape of the hall, to choose the materials to be used, to plan the arrangement of the audience, of the orchestra and of other sound sources, and to do all this in such a way that the sound field configuration will develop, which has previously been found to be the optimum for the intended purpose. In practice, however, the architect will have worked out already a preliminary design, certain features of which he considers imperative. In this case, the acoustical consultant has to examine the objective acoustical properties of the design by calculation, by geometric ray considerations, by model investigations or by computer simulation, and he will eventually have to submit proposals for suitable adjustments. As a general rule, there will have to be some compromise in order to obtain a reasonable result.

Frequently, the problem is refurbishment of an existing hall, either to remove architectural, acoustical or other technical defects or to adapt it to a new purpose which was not intended when the hall was originally planned. In this case, an acoustical diagnosis has to be made first on the basis of appropriate measurement. A reliable measuring technique which yields objective quantities, which are subjectively meaningful at the same time, is an indispensable tool of the acoustician. The subsequent therapeutic step is essentially the same as described above: the acoustical consultant has to propose measures which would result in the intended objective changes in the sound field and consequently in the subjective impressions of the listeners.

In any case, the acoustician is faced with a twofold problem: on the one hand, he has to find and apply the relations between the structural features of a room – such as shape, materials and so on – with the sound field which will occur in it, and on the other hand, he has to take into consideration as far as possible the interrelations between the objective and measurable sound field parameters and the specific subjective hearing impressions effected by them. Whereas the first problem lies completely in the realm of technical reasoning, it is the latter problem which makes room acoustics different from many other technical disciplines in that the success or failure of an acoustical design has finally to be decided by the collective judgement of all 'consumers', that is, by some sort of average, taken over by the comments of individuals with widely varying intellectual, educational and aesthetic backgrounds. The measurement of sound field parameters can replace to a certain extent systematic or sporadic questioning of listeners. But, in the final analysis, it is the average opinion of listeners which decides whether the acoustics of a room is favourable or poor. If the majority of the audience (or that part which is vocal) cannot understand what a speaker is saying, or thinks that the sound of an orchestra in a certain hall is too dry, too weak or indistinct, then even though the measured reverberation time is appropriate or the local or directional distribution of sound is uniform, the listener is always right; the hall does have acoustical deficiencies.

Therefore, acoustical measuring techniques can only be a substitute for the investigation of public opinion on the acoustical qualities of a room and it will serve its purpose better the closer the measured sound field parameters are related to subjective listening categories. Not only must the measuring techniques take into account the hearing response of the listeners but the acoustical theory too will only provide meaningful information if it takes regard of the consumer's particular listening abilities. It should be mentioned at this point that the sound field in a real room is so complicated that it is not open to exact mathematical treatment. The reason for this is the large number of components which make up the sound field in a closed space regardless of whether we describe it in terms of vibrational modes or, if we prefer, in terms of sound rays which have undergone one or more reflections from boundaries. Each of these components depends on the sound source, the shape of the room and on the materials from which it is made; accordingly, the exact computation of the sound field is usually quite involved. Supposing this procedure was possible with reasonable expenditure, the results would be so confusing that such a treatment would not provide a comprehensive survey and hence would not be of any practical use. For this reason, approximations and simplifications are inevitable; the totality of possible sound field data has to be reduced to averages or average functions which are more tractable and condensed to provide a clearer picture. Hence, we have to resort so frequently to statistical methods and models in room acoustics, whichever way we attempt to describe sound fields. The problem is to perform these reductions and simplifications once again in accordance with the properties of human hearing, that is, in such a way that the remaining average parameters correspond as closely as possible to particular subjective sensations.

From this it follows that essential progress in room acoustics depends to a large extent on the advances in psychological acoustics. As long as the physiological and psychological processes which are involved in hearing are not completely understood, the relevant relations between objective stimuli and subjective sensations must be investigated empirically – and should be taken into account when designing the acoustics of a room.

Many interesting relations of this kind have been detected and successfully investigated during the past few decades. But other questions which are no less important for room acoustics are unanswered so far, and much work remains to be carried out in this field.

It is, of course, the purpose of all efforts in room acoustics to avoid acoustical deficiencies and mistakes. It should be mentioned, on the other hand, that it is neither desirable nor possible to create the 'ideal acoustical environment' for concerts and theatres. It is a fact that the enjoyment when listening to music is a matter not only of the measurable sound waves hitting the ear but also of the listener's personal attitude and his individual taste, and these vary from one person to another. For this reason, there will always be varying shades of opinion concerning the acoustics of even the most marvellous concert hall. For the same reason, one can easily imagine a wide variety of concert halls with excellent, but nevertheless different, acoustics. It is this 'lack of uniformity' which is characteristic of the subject of room acoustics, and which is responsible for many of its difficulties, but it also accounts for the continuous power of attraction it exerts on many acousticians.

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