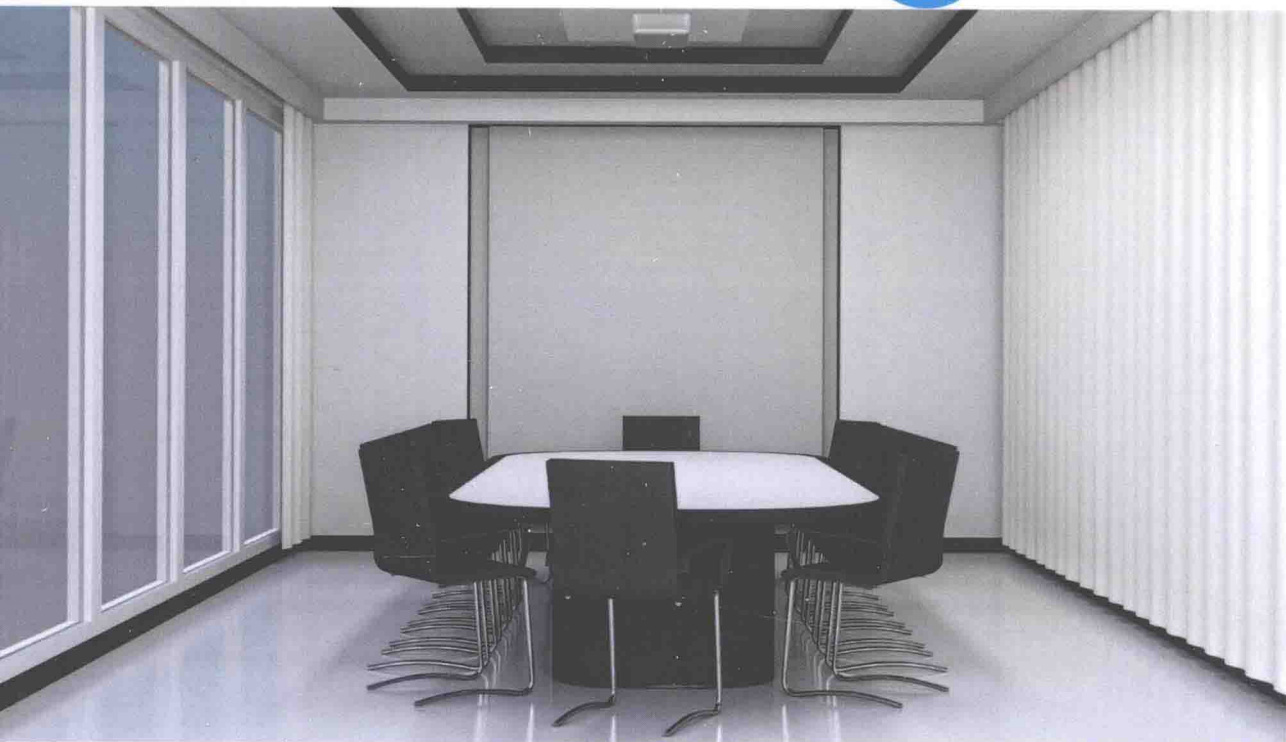


Building



Acoustics

Marc Asselineau

 CRC Press
Taylor & Francis Group

Building Acoustics

Marc Asselineau
Peutz & Associates



CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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Printed on acid-free paper
Version Date: 20150209

International Standard Book Number-13: 978-1-4665-8244-6 (Paperback)

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Foreword

When I met Marc Asselineau for the first time during the International Congress of Acoustics in Beijing in 1992, we quickly befriended each other because we were happy to find a bit of France at this event that was not heavily attended by Europeans at that time. These were the early years of a young PhD possessed with a passion for music who was destined to enjoy a long career in a large international engineering consulting company. Those were the times when computer models were appearing that could compute the acoustic performances of buildings and the acoustic quality of large spaces. Famous names in architectural acoustics, such as Lothar Cremer, Leo Beranek, and Robert Josse in France, had defined the basis of this discipline in the middle of the 20th century, but one had to wait until the 1980s to see the considerable development of architectural acoustics driven by a strong demand for comfort and quality in built spaces, and then made possible by the abundant choice of products, components, and processes, especially developed for building acoustics. Motivated by the requirements of the European single market and the development of ISO and CEN standards, laboratory test methods have been improved.

However, neither computer models nor standards or test codes nor test reports, as excellent as they may be, provide the one element that is indispensable to the acoustician, the architect, and the contractor to solve their problems, namely, practical experience. It is this particular element that this book presents, and that to my knowledge has no equal apart, partly, from a few courses given by experienced acousticians to a privileged few.

My experience as a consultant at the French Information and Documentation Centre on Noise (CIDB), who meets people experiencing difficulties with noise, shows that the first and perhaps the most difficult part is to try and properly analyze the problem of the client, who comes in the hope of being delivered a prescription (in the medical sense) for a “product” that takes not too much space and is preferably not expensive that will solve everything even before the actual cause can be identified. The distinctive quality of this book is that it tries to prompt the reader to analyze the various situations globally and shows through numerous real life examples the route to understanding and solving the problem. An apprenticeship in acoustics through examples is certainly easier than one gained by learning theory, and it is also more convincing to a number of professionals who work hands-on, such as architects and contractors. This does not prevent the curious minded or the specialist reader from digging deeper into the very complete literature listed at the end of each chapter.

The book can be read in two different ways:

1. The architect or engineer who looks to solve a specific problem can quickly find in the table of contents the chapter of interest and go to the required information without having to read all the preceding text.

2. The beginner in building acoustics can use this as a bedside book: it is easy to read, the style is pleasant and often funny, and the numerous examples of what should be done, and especially what should not be done, show that beside being a scientific discipline acoustics require a good deal of observation and a capacity for situation analysis.

A very novel chapter covers interactions between acoustics and other disciplines such as structural engineering and HVAC engineering that require compromises that are satisfactory to every one of them.

The acoustic quality of rooms is certainly the domain of acoustics that is the most difficult to resolve, as it inevitably reflects the knowledge of the designer, but also his or her response to schools of thought, aesthetical trends, and the opinions of musical critics. The acoustics of a large and prestigious hall represent somewhat personal work that will be either foremostly liked or disliked by the audience. In this respect, a merit of the book is that it illustrates various points of view through real projects, some of which have been undertaken by the author.

I have no doubt that this original book offers a precious service to anyone looking to enter the fascinating world of acoustics and to progress quickly without waiting for their own experience to accumulate.

Jacques Roland

Former Head of the Acoustic and Lighting Department of the French Scientific and Technical Building Centre (CSTB), former president of the European Standardization Technical Committee TC126 "Building Acoustics"

Preface

Many years ago an architect and friend of mine took the opportunity of the inauguration of his latest building to tease his architectural team and his engineers. In the course of this exercise he pointed out that the acoustician really could be a nuisance—he would complain there is too much noise in one place but not enough sound level at another; he would dream of uncoupled structures; and he might even dream of strange, ugly looking surface coverings in rooms. He eventually concluded that the acoustician probably is blind. Not to be outdone, the acoustician retorted that the architect has probably been deaf. Other specialists got their share as well from the structural engineer accused of constantly lightening the superstructure to the HVAC engineer suspected of reverting back to a medieval castle-like façade full of narrow slits. Once the laughter had settled we slowly realized that although we had been working together for quite a number of years, we just did not know much about the other's trade.

Back at the office, reflecting on the exchange I then remembered some questions by respectable university people knowledgeable in the field of physical acoustics, who clearly did not know much about noise reduction, let alone building with an acoustic intent. I also vividly remembered that whenever I was tasked with teaching the basics of noise control in industry, there were bound to be at least a couple of questions from the audience about concert hall acoustics and another about noise control at home!

This particular exchange eventually came to haunt me when I was invited to try and write a book. One of the first tasks was to try and see what others had previously written. There are quite a number of academics who have managed to write large theoretical books, so there was no need to try and fit too many formulas that practically nobody would bother to understand anyway (not only the mathematics but also their domain of validity). Although I have tried to give the basics that a beginner would expect to find, my thoughts have been directed toward colleagues and friends. I have also tried to give an overview of the acoustical challenges that a project may bring forward for several types of construction. I have also included a long list of incidents observed over more than a quarter of century of professional experience to illustrate the point and leave an impression on the reader.

Acknowledgments

This book would not have been possible without the encouragement of quite a few people. To start with I thank Mr. Tony Moore, Senior Editor, Taylor & Francis, for inviting me to write this book.

I acknowledge the support of those of my colleagues from Peutz who encouraged me, especially Mrs. A. Gaulupeau, who provided both technical advice and moral support! I also thank Peutz & Associates through MM J. Granneman (General Director of Peutz) and S. Mercier (Director of Peutz France) who authorized me to write this book during my free time and eventually publish it. I also thank Professor J.G. Migneron (Université Laval, Québec, Canada), who inducted me in the field of building and environmental acoustics, and Senior Engineer P. Heringa (Peutz, Nijmegen, Netherlands) who encouraged me throughout my career.

A special thank you to Mr. Q. Gaulupeau for his skill at the craft of enhancing my drawings.

Special thanks are due to those of my colleagues and directors, especially MM. R. Metkemeijer and K. Ogendoorn, who encouraged over the last 30 years with my involvement in acoustic congresses as they proved to be a permanent source of knowledge.

I would also like to thank several clients and partners as well as friends who pushed me to write; Dr. Chevret (INRS), Dr. Viollon (EDF), and Mrs. Seve (formerly with UGC cinemas).

Finally, I express my thanks to my family who encouraged me in this work.

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Introduction

In the antique world acoustics was considered to be the science of sciences, the one that could explain universal harmony.

Nowadays, it often suffers from an ostentatious separation between what is considered to be the academic world and what is considered to be real life. There are quite a few fields under the name *acoustics*, ranging from infrasound to ultrasound through the audible world, and dealing with different things from practical noise control in a building to sonar on ships to physiological damage to the hearing system.

This book is devoted to the field of building acoustics. Equations have been kept to a minimum, while literature references have been offered for the reader interested to push further his theoretical knowledge.

Experience shows that a good building usually is a project where everybody concerned has been able to make his point and the various issues have been discussed and understood by all interested parties. Acoustics often is part of a global problem that can only be solved by a complete design team fed the relevant data by the end user and accustomed to collaborative work.

Experience has, sometimes painfully, taught us that the first condition for a building project to succeed is for everybody on the design team and the end user team too to try and understand each other's needs. But in order to be able to communicate with the other members of the team, the acoustician prefers not to be obliged to explain again and again some rather basic (to him) principles. Similarly, the other team members love it when they are not reduced to explaining to a dumb acoustician why they so desperately need a lighter structure or a specific thermal insulation. The basic idea object of the exercise, as we currently see it, is not to try and produce one more building acoustics book whose reading is limited to specialists, but to try to provide a nonspecialist reader with keys for understanding each other's requirements.

More to the point, one can be appalled on a regular basis when discovering how rather simple mistakes have managed to reach construction stage or, even worse, commissioning stage (e.g., What about polystyrene as an absorptive material? Do not laugh, it has happened!). Hence, this book is readable by nonspecialists, if only to give them a rough idea of what the problems might be and what should be asked by all involved parties to clarify the matter (after all, this is the spirit of today's sustainable development projects, isn't it?). Examples are given to illustrate the various points of interest. Readers especially interested in the subject (e.g., a junior acoustical engineer, or an architect or engineer in another speciality) can then go on to a more specialized chapter and complete their learning through the relevant literature references.

While performance halls have, of course, found their place in this book, smaller but essential spaces (those whose bad acoustics can ruin your day) are discussed: open-plan offices and restaurants (yes, there are many similarities between them), production facilities, sport facilities, meeting rooms, and transport stations, just to name a few.

While the reader may not emerge as a fully fledged engineer after reading this book, he will come out knowing enough to express his needs to a specialized consultant and to avoid the worst acoustic mistakes should he be left to his own devices.

Acoustics

2.1 DEFINITION OF ACOUSTICS

Acoustics is defined as the science of sound. The word comes from the Greek *acoustikos*, meaning “for hearing.”

Hearing is not limited to the human species. It is crucial in the animal world, as it enables them to detect an incoming danger or help pinpoint prey. More to the point, speech is used by many species, especially humans, for communication.

In the antique world acoustics was sometimes considered the science of sciences. Nowadays, it features numerous widely branches ranging, for example, physical acoustics, building acoustics, underwater acoustics, etc. A quite comprehensive list can be found in [1, 2]. Basically, when dealing with acoustics, three entities are involved: a source, a propagation medium, and a receiver. The source converts energy into vibrations of the propagation medium; it can be, for example, a vibrating rod or a surface. The propagation medium can be solid (e.g., metal, wood), liquid (e.g., water), or gas (e.g., air).

2.2 BRIEF HISTORY

The reader interested in the history of acoustics can find more developed information in references [3–6]. Here is only a brief reminder of a few points of interest.

In the antique world acoustics was sometimes considered the science of sciences. Musical acoustics were studied by scientists and philosophers who dreamed to discover the secrets of world order. During his investigations of musical intervals, Pythagoras (6th century BC) discovered harmonics. Vitruvius wrote a treatise featuring considerations on theatres, including echoes and reverberation (20 BC); he also compared sound propagation to the circles in water. Aristotle explained wave motion as contractions and expansions of air bumping into the one next to it.

The knowledge of the Greeks was passed on to the Romans and the Arabs, with the latter developing during the Middle Ages. Later the Renaissance saw the development of architectural acoustics and musical acoustics again.

Kircher (1602–1680) worked on sound propagation. While he wrongly concluded that no propagation medium was necessary, he also worked in architectural acoustics regarding the focusing by vaulted ceilings and the amplification effect by the bell of brass instruments.

Mersenne (1588–1648) managed to measure the sound propagation speed in 1640 using an artillery gun; he found that attenuation was a function of the distance to the power 2. He also found that the resonance frequency of a string was inversely proportional to its length and proportional to the square root of its tension [7]. Using both a handheld gun (generating high-pitched sounds) and an artillery gun (generating low-pitched sounds)

Gassendi (1592–1655) experimentally proved that speed propagation was independent of frequency. Huygens (1629–1695) showed that sound is an undulatory phenomenon, and Newton developed a mathematical formulation of the propagation of sound with an expression of the sound speed. Sauveur (1653–1716) looked at the composition of sounds and distinguished between the fundamental and its harmonics, whose decomposition defines tone color. He also defined nodes (locations where there is no elongation) and antinodes (locations where the elongation is maximal), and used the term *acoustics* to cover the science of sound. Bernoulli (1700–1782) explained the coexistence of small oscillations too.

With the development of mathematics in the 18th century, serious work was undertaken regarding sound propagation. D'Alembert (1717–1783), Euler (1707–1783), and Lagrange (1736–1813) developed the formal wave propagation equations. And Fourier (1768–1831) proposed his harmonic analysis of sound. Later developments included sound propagation in liquids (Sturm and Colladon in 1827) and solids (Hassenfratz in 1794 and Biot in 1808), as well as membrane or plate vibrations that were experimentally demonstrated by Chladni and theoretically investigated by Germain (1815), Poisson, and Clebsch.

The 19th century saw a significant interest in the perception of sound. Ohm showed that the hearing mechanism could distinguish frequencies (1843), and Corti proposed a model of the inner ear in 1851. Fechner published his *Elements of Psychophysics* (1860), where the relationship between sensation and excitation was investigated. Helmholtz (1821–1894), who was both a physicist and a physiologist, published his physiological theory of music (1877). Physical acoustics were not forgotten as Lord Rayleigh (1842–1919) published his *Theory of Sound* (1877) and Kundt (1839–1894) worked on resonances and stationary waves in tubes.

The 20th century saw an increase of interest in computational matters. As soon as 1901, the Boston Symphony Hall was the first such facility to be designed (by none other than Sabine) using acoustic computations. With the availability of computational methods and new technology, a first attempt at active noise cancellation was made in 1934 by Olsen, and Cremer developed the theory of sound transmission through a wall (1942).

2.3 NOTIONS OF LEVELS

2.3.1 Characterizing Sound

Sound, as perceived by our ears, is made of periodic vibrations of air. It can last for a given duration of time. It can feature a specific pitch. It can be more or less intense. This means that to describe a sound, one must use three dimensions: time (in s), frequency (in Hz), and level (in dB).

The representation of level in dB versus frequency in Hz is known as the *spectrum*.

2.3.2 Sound Level

According to Weber's law, perception varies like the logarithm of excitation. This has led to a logarithmic expression of the sound level L_p , which is expressed as

$$L_p = 10 \log (p^2/p_0^2)$$

where p is the variation of acoustic pressure, and p_0 is the reference corresponding to the smallest perceptible acoustic pressure variation, with

$$p_0 = 2 \times 10^{-5} \text{ Pa}$$

2.3.3 Weightings

The human ear does not perceive all sounds in the same way, depending on their frequency and loudness. This has led to a frequency weighting system standardized over the years by the International Electrotechnical Commission (IEC) [8], based on the Fletcher and Munson equal loudness curves [10]. The A weighting was initially introduced for low-level sounds (up to 40 phons), with higher-level sounds being treated to other weighting curves designated as B, C, and D, the latter being especially devoted to aircraft sound level measurements. Nowadays, both the B and the D curves have disappeared [9], but the C curve, which better takes into account the low-frequency sound levels, is currently used in a few occupational noise regulations. More to the point, it has also found its way into some community noise regulations, for example, in Scandinavian countries [11], where it is used to help define limits for background noise.

Here are a few examples of A-weighted sound level values:

- 18 dB(A): Woodland area without wind (and without birds singing either!)
- 30 dB(A): Cinema projection room (empty)
- 45 dB(A): Workstation with the desktop computer's fan running
- 70 dB(A): Busy street
- 90 dB(A): Airport façade with a plane maneuvering at the pier
- 140 dB(A): 5 m from a jet engine

Now one has probably noted that due to the weighting curve shape, it is possible to achieve a given weighted value with rather different spectrum shapes. For example, a 100 dB(A) value can be achieved with a 100 dB pure tone at 1000 Hz, but also with 126 dB at 63 Hz. In order to avoid the presence of too sharp a tone or a frequency band in a spectrum, one usually specifies noise limits using simultaneously a global A-weighted sound level value and a frequency contour featuring higher levels in the lower-frequency range than in the higher-frequency range. One can either use the noise rating (NR) contour as defined by standard ISO 1996:1971 [12] or the noise criteria (NC) contour as defined by ANSI S12-2-2008 [13].

2.3.4 Addition

Addition of sound level contributions can be performed as a logarithmic addition. Let's add two contributions, L_{p1} and L_{p2} ; the resulting sound pressure level L_{ptot} will be

$$L_{ptot} = 10 \log ((10^{(L_{p1}/10)}) + (10^{(L_{p2}/10)}))$$

Should one find logarithms unmanageable, all is not lost: it is possible to use a simple table of additions (Table 2.1). Starting with the highest of the two sound level values to be added (which is noted X in Table 2.1), one looks up the difference to the value to be added. A couple of examples are given in Section 2.3.6.2.

By the way, one can derive an important consequence for noise control purposes: Adding a noise source whose contribution is no greater than the original sound level minus 15 dB will not affect the overall sound level value.

2.3.5 Equivalent Sound Levels and Statistical Sound Levels

How does one describe a temporally fluctuating noise? A simple way is to make reference to its energetic value and use the equivalent sound level, given the symbol L_{eq} , which represents a nonfluctuating signal containing as much acoustic energy as the signal under study over the period of time considered. Incidentally, the A-weighted value, which is widely used in surveys, is given the symbol L_{Aeq} .