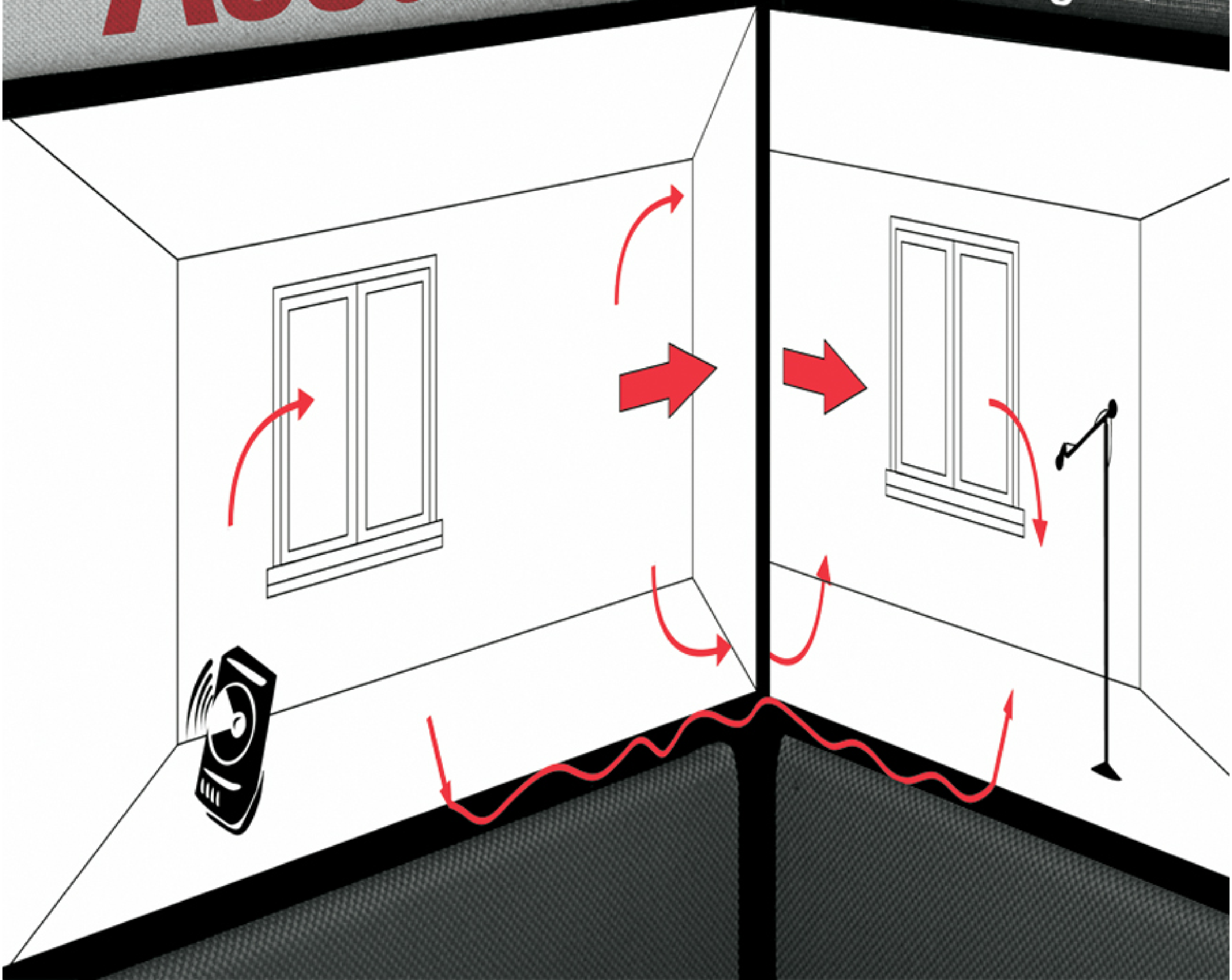
Building Acoustics

Tor Erik Vigran



Building Acoustics

Building or architectural acoustics is taken in this book to cover all aspects of sound and vibration in buildings. The book covers room acoustics but the main emphasis is on sound insulation and sound absorption and the basic aspects of noise and vibration problems connected to service equipment and external sources. Measuring techniques connected to these fields are also brought in. It is designed for advanced level engineering studies and is also valuable as a guide for practitioners and acoustic consultants who need to fulfil the demands of building regulations.

It gives emphasis to the acoustical performance of buildings as derived from the performance of the elements comprising various structures. Consequently, the physical aspects of sound transmission and absorption need to be understood, and the main focus is on the design of elements and structures to provide high sound insulation and high absorbing power. Examples are taken from all types of buildings. The book aims at giving an understanding of the physical principles involved and three chapters are therefore devoted to vibration phenomena and sound waves in fluids and solid media. Subjective aspects connected to sound and sound perception is sufficiently covered by other books; however, the chapter on room acoustics includes descriptions of measures that quantify the "acoustic quality" of rooms for speech and music.

Tor Erik Vigran is professor emeritus at the Norwegian University of Science and Technology, Head of the Acoustic Committee of Standards Norway, the Norwegian standardization organization, and member of several working groups within ISO/TC 43 and CEN/TC 126.

Building Acoustics

Tor Erik Vigran

Taylor & Francis
Taylor & Francis Group
LONDON AND NEW YORK

First published 2008 by Taylor & Francis
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

Simultaneously published in the USA and Canada
by Taylor & Francis
270 Madison Avenue, New York, NY 10016, USA

This edition published in the Taylor & Francis e-Library, 2008.

"To purchase your own copy of this or any of Taylor & Francis or Routledge's
collection of thousands of eBooks please go to www.eBookstore.tandf.co.uk."

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

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
Vigran, Tor Erik.
[Bygningsakustikk English]
Building acoustics / Tor Erik Vigran.
p. cm.
Includes bibliographical references and index.
1. Soundproofing. 2. Architectural acoustics. 3. Acoustical engineering. I. Title.
TH1725.V54 2008
729'.29–dc22
2007039258

ISBN 0-203-93131-9 Master e-book ISBN

ISBN13: 978-0-415-42853-8 (hbk)
ISBN13: 978-0-203-93131-8 (ebk)

ISBN10: 0-415-42853-X (hbk)
ISBN10: 0-203-93131-9 (ebk)

Contents

CHAPTER 4
Room acoustics

CHAPTER 5
Sound absorbers

field in the sound is a superposition of plane waves. As seen from the formula, the intensity at the boundaries differs only by the constant 4, different from the corresponding one in a plane progressive wave. Introducing this result into Equation (4.25) we get

$$W = \frac{\tilde{p}^2}{4\rho_0 c_0} \cdot A + \frac{V}{\rho_0 c_0^2} \cdot \frac{\mathrm{d}\left(\tilde{p}^2\right)}{\mathrm{d}t}. \tag{4.27}$$

Obviously, the pressure root-mean-square value here must be interpreted as a short-time averaged variable, i.e. the averaging must be performed over a time interval much less than the reverberation time. The general solution of this equation is given by

$$\tilde{p}^2 = \frac{4\rho_0 c_0}{A} \cdot W + K \cdot \mathrm{e}^{-\frac{Ac_0}{4V}t}. \tag{4.28}$$

The constant K is determined by the initial conditions. We shall look into two special cases, applying this solution.

4.5.1.1 The build-up of the sound field. Sound power determination

We now assume that the sound pressure is zero when the source is turned on, ($\tilde{p} = 0$ at $t = 0$), which gives

$$K = -\frac{4\rho_0 c_0}{A} \cdot V \quad \text{and}$$
$$\tilde{p}^2 = \frac{4\rho_0 c_0}{A} W \left(1 - \mathrm{e}^{-\frac{Ac_0}{4V}t}\right). \tag{4.29}$$

The sound will then build up arriving at a stationary value when the time t goes to infinity. The RMS-value of the sound pressure becomes

$$\tilde{p}^2_{t\to\infty} = \frac{4\rho_0 c_0}{A} W. \tag{4.30}$$

The equation then gives us the possibility of determining the sound power emitted by a source by way of measuring the mean square pressure in a room having a known total absorbing area. For laboratories this type of room is called a *reverberation room* and procedures for such measurements are found in international standards (see e.g. ISO 3741).

A couple of important points concerning such measurements must be mentioned. As pointed out above, one has to determine the time and space averaged value of the sound pressure squared. This is accomplished either by measurements using a microphone (or an array of microphones) at a number of fixed positions in the room or by a microphone moved through a fixed path in the room (line, circle etc.). One must, however, avoid positions near to the boundaries where the sound pressure is systematically higher than in the inner parts of the room. Waterhouse (1955) has shown that the sound pressure level at a wall, at an edge and at a corner, respectively, will be 3, 6 and 9 dB higher than the average level in the room. This is also easily demonstrated by direct measurements. Restricting the determination of the average sound pressure level to the inner part of a room, normally half a wavelength away from the boundaries, implies that we are “losing” a part of the sound energy. One therefore finds that the standards include a frequency-dependent correction term, the so-called *Waterhouse correction* to compensate for this effect and the power is then calculated from

$$W = \frac{\tilde{p}_\infty^2}{4\rho_0 c_0} A\left(1 + \frac{Sc_0}{8Vf}\right), \tag{4.31}$$

where S is the total surface area of the room. In addition, the standard ISO 3741 includes some minor corrections for the barometric pressure and temperature and furthermore, the absorption area A is substituted by the so-called *room constant R* where

$$R = \frac{A}{1 - \frac{A}{S}} = \frac{A}{1 - \bar{\alpha}}, \tag{4.32}$$

and where $\bar{\alpha}$ is the mean absorption factor of the room boundaries. Normally, the mean absorption factor is required to be small for laboratory reverberation rooms making this correction also small. However, in the high frequency range (above 8–10 kHz) this may not be the case, especially due to air absorption (see section 4.5.1.3).

4.5.1.2 Reverberation time

Turning off the sound source when the stationary condition is reached, i.e. setting $\tilde{p}^2(t) = \tilde{p}_\infty^2$ at time $t = 0$, and $W = 0$ for $t > 0$, we get

$$\tilde{p}^2(t) = \tilde{p}_\infty^2 \cdot \mathrm{e}^{-\frac{Ac_0}{4V}\cdot t}. \tag{4.33}$$

As the reverberation time T is defined by the time elapsed for the sound pressure level to decrease by 60 dB, or equivalent, that the sound energy density has decreased by a factor 10^{-6}, we write

$$\frac{\tilde{p}^2(T)}{\tilde{p}_\infty^2} = 10^{-6} = \mathrm{e}^{-\frac{Ac_0}{4V}\cdot T}, \tag{4.34}$$

which gives us the reverberation time, commonly denoted T_{60}, as

$$T_{60} = \ln\left(10^6\right) \cdot \frac{4V}{c_0 A} \approx \frac{55.26}{c_0} \cdot \frac{V}{A}. \tag{4.35}$$

This is the famous reverberation time formula by Sabine, which is the most commonly used in practice in spite of its simplicity and the assumptions lying behind its derivation. Obviously, it cannot be applied for rooms having a very high absorption area. Setting the absorption factor equal to 1.0 for all surfaces, we still get a finite reverberation time whereas it is obvious that we shall get no reverberation at all. Other formulae have been developed taking account of the fact that the reverberation is not a continuous process but involves a stepwise reduction of the wave energy when hitting the boundary surfaces. We shall not go into detail but just refer to a couple of these formulae. The first one is denoted *Eyring's formula* (see Eyring (1930)), which may be expressed as

$$T_{\mathrm{Ey}} = \frac{55.26}{c_0} \cdot \frac{V}{-S \cdot \ln(1-\bar{\alpha})}, \tag{4.36}$$

where $\bar{\alpha}$ as before is the average absorption factor of the room boundaries, i.e.

$$\bar{\alpha} = \frac{1}{S} \sum_i \alpha_i S_i. \tag{4.37}$$

The formula is obviously correct for the case of totally absorbing surfaces as we then get T_{Ey} equal to zero. For the case of $\bar{\alpha} \ll 1$, the formula will be identical to the one by Sabine.

Still another is the *Millington–Sette formula* (Millington (1932) and Sette (1933)), where one does not form the average of the absorption factors as above but is using the average of the so-called absorption exponents $\alpha' = -\ln(1-\alpha)$. This leads to

$$T_{\mathrm{MS}} = \frac{55.26}{c_0} \cdot \frac{V}{-\sum_i S_i \ln(1-\alpha_i)}. \tag{4.38}$$

One drawback of this formula is that the reverberation time will be zero if a certain subsurface has an absorption factor equal to 1.0. In practice, the absorption factors α_i have to be interpreted as an average factor for e.g. a whole wall. It is claimed (see e.g. Dance and Shield (2000)) that when modelling the sound field in rooms having strongly absorbing surfaces this formula gives a better fit to measurement data than the formulae of Sabine and Eyring.

Sabine's formula is however widely used, also by the standard measurement procedure for determining the absorption area and absorption factors of absorbers of all types (see ISO 354). By the determination of absorption factors one measures the reverberation time before and after introduction of the test specimen, here assumed to be a plane surface of area S_{t}, into the room. The absorption factor is then given by

$$\alpha_{\mathrm{Sa}} = \frac{55.26 \cdot V}{c_0 S_{\mathrm{t}}} \left(\frac{1}{T} - \frac{1}{T_0} \right). \tag{4.39}$$

T_0 and T are the reverberation times without and with the test specimen present, respectively. One thereby neglects the absorption of the room surface covered by the test specimen but this surface is assumed to be a hard surface, normally concrete, having negligible absorption. We shall return to this measurement procedure in the following chapter.

To conclude this section, we mention that various extensions of the simple reverberation time formulae have been proposed, in particular to cover situations where the absorption is strongly non-uniformly distributed in the room. A review of these formulae may be found in Ducourneau and Planeau (2003), who performed an experimental investigation in two different rooms comparing, altogether, seven different formulae. However, this number includes the three formulae presented above.

Here, we shall present just one example of the formulae particularly developed for covering the aspect of non-uniformity, a formula given by Arau-Puchades (1988). It applies strictly to rectangular rooms only and may be considered as a product sum of Eyring's formula defined for the room surfaces in the three main axis directions, *X*, *Y* and *Z*, each term weighted by the relative area in these directions. It may be expressed as

$$T_{\mathrm{AP}} = \left[q \cdot \frac{V}{-S\ln(1-\bar{\alpha}_X)} \right]^{\frac{S_X}{S}} \cdot \left[q \cdot \frac{V}{-S\ln(1-\bar{\alpha}_Y)} \right]^{\frac{S_Y}{S}} \cdot \left[q \cdot \frac{V}{-S\ln(1-\bar{\alpha}_Z)} \right]^{\frac{S_Z}{S}}, \quad (4.40)$$

where q is the factor $55.26/c_0$. Using this formula one may e.g. assign the area S_X to the ceiling and the floor having average absorption factor $\bar{\alpha}_X$, the two sets of sidewalls to the corresponding surface areas and absorption coefficients with indices *Y* and *Z*. It will appear that this formula will predict quite longer reverberation times than predicted by the simple Eyring's formula in case of low absorption on the largest surfaces of the room.

4.5.1.3 The influence of air absorption

In the derivation of the formulae above we assumed that all energy losses were taking place at the boundaries of the room. This is only partly correct as one in larger rooms and/or at high frequencies one may have a significant contribution to the absorption caused by energy dissipation mechanisms in the air itself. This is partly caused by thermal and viscous phenomena but for sound propagation through air by far the most important effect is due to *relaxation* phenomena. This is related to exchange of vibration energy between the sound wave and the oxygen and nitrogen molecules; the molecules extract energy from the passing wave but release the energy after some delay. This delayed process leads to hysteretic energy losses, an excess attenuation of the wave added to other energy losses.

The relaxation process is critically dependent on the presence of water molecules, which implies that the excess attenuation, also strongly dependent on frequency, is a function of relative humidity and temperature. Numerical expressions are available (see ISO 9613–1) to calculate the attenuation coefficient, which include both the "classic" thermal/viscous part besides the one due to relaxation. The standard gives data that are given the title atmospheric absorption, as attenuation coefficient α in decibels per metre. This is convenient due to the common use of such data in predicting outdoor sound propagation. For applications in room acoustics, we shall, however, make use of the *power attenuation coefficient* with the symbol m, at the same time reserving the symbol α for the absorption factor. The conversion between these quantities is, as shown earlier, simple as we find

$$\alpha = \text{Attenuation}\left(\text{dB/m}\right) = 10 \cdot \lg(\mathrm{e}) \cdot m \approx 4.343 \cdot m. \quad (4.41)$$

Examples on data are shown in Figure 4.8, where the power attenuation coefficient m is given as a function of relative humidity at 20° Celsius, the frequency being the parameter.

4.9 REFERENCES

ISO 9613–1: 1993, Acoustics – Attenuation of sound during propagation outdoors. Part 1: Calculation of the absorption of sound by the atmosphere.

ISO 3382: 1997, Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters. [Under revision to become ISO 3382 Acoustics – Measurement of room acoustic parameters. Part 1: Performance rooms; Part 2: Ordinary rooms.]

ISO 3741: 1999, Acoustics – Determination of sound power levels of noise sources using sound pressure – Precision methods for reverberation rooms.

ISO 354: 2003, Acoustics – Measurement of sound absorption in a reverberation room.

ISO 140–14: 2004, Acoustics – Measurement of sound insulation in buildings and of building elements. Part 14: Guidelines for special situations in the field.

ISO 16032: 2004, Acoustics – Measurement of sound pressure level from service equipment in buildings – Engineering method.

ISO/DIS 17497–1: 2002, Acoustics – Measurement of the sound scattering properties of surface. Part 1: Measurement of the random-incidence scattering coefficient in a reverberation room.

Abramowitz, M. and Stegun, I. A. (1970) *Handbook of mathematical functions*. Dover Publications Inc., New York.

Arau-Puchades, H. (1988) An improved reverberation formula. *Acustica*, 65, 163–180.

Cox, T. J., Avis, M. R. and Xiao, L. (2006) Maximum length sequences and Bessel diffusers using active technologies. *J. Sound and Vibration*, 289, 807–829.

Cox, T. J. and D'Antonio, P. (2004) *Acoustic absorbers and diffusers*. Spon Press, London and New York.

Cox, T. J. and Lam, Y. W. (1994) Prediction and evaluation of the scattering from quadratic residue diffusers. *J. Acoust. Soc. Am.*, 95, 297–305.

Dance, S. M. and Shield, B. M. (1997) The complete image-source method for the prediction of sound distribution in fitted non-diffuse spaces. *J. Sound and Vibration*, 201, 473–489.

Dance, S. M. and Shield, B. M. (2000) Modelling of sound fields in enclosed space with absorbent room surfaces. Part II. Absorptive panels. *Applied Acoustics*, 61, 373–384.

Davy, J. L., Dunn, I. P. and Dubout, P. (1979) The variance of decay rates in reverberation rooms. *Acustica*, 43, 12–25.

Ducourneau, J. and Planeau, V. (2003) The average absorption coefficient for enclosed spaces with non uniformly distributed absorption. *Applied Acoustics*, 64, 845–862.

Eyring, C. F. (1930) Reverberation time in "dead" rooms. *J. Acoust. Soc. Am.*, 1, 217–241.

Haas, H. (1951) Über den Einfluss eines Einfachechos auf die Hörsamkeit der Sprache. *Acustica*, 1, 49–58.

Heinz, R. (1993) Binaural room simulation based on an image source model with addition of statistical methods to include the diffuse sound scattering of walls and to predict the reverberant tail. *Applied Acoustics*, 38, 145–159.

Jovicic, S. (1971) Untersuchungen zur Vorausbestimmung des Schallpegels in Betriebgebäuden. Report No. 2151. Müller-BBN, Munich.

Jovicic, S. (1979) Anleitung zur Vorausbestimmung des Schallpegels in Betriebgebäuden. Report. Minister für Arbeit, Gesundheit und Soziales des Landes Nordrhein-Westfalen, Düsseldorf.