Springer Handbook of Acoustics

Springer Handbooks provide a concise compilation of approved key information on methods of research, general principles, and functional relationships in physical sciences and engineering. The world's leading experts in the fields of physics and engineering will be assigned by one or several renowned editors to write the chapters comprising each volume. The content is selected by these experts from Springer sources (books, journals, online content) and other systematic and approved recent publications of physical and technical information.

The volumes are designed to be useful as readable desk reference books to give a fast and comprehensive overview and easy retrieval of essential reliable key information, including tables, graphs, and bibliographies. References to extensive sources are provided.

Springer Handbook of Acoustics

Thomas D. Rossing (Ed.)

With CD-ROM, 962 Figures and 91 Tables

Springer

Editor:

Thomas D. Rossing
Stanford University
Center for Computer Research in Music and Acoustics
Stanford, CA 94305, USA

Editorial Board:

Manfred R. Schroeder, University of Göttingen, Germany
William M. Hartmann, Michigan State University, USA
Neville H. Fletcher, Australian National University, Australia
Floyd Dunn, University of Illinois, USA
D. Murray Campbell, The University of Edinburgh, UK

Library of Congress Control Number: 2006927050

ISBN: 978-0-387-30446-5 e-ISBN: 0-387-30425-0
Printed on acid free paper

© 2007, Springer Science+Business Media, LLC New York
All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC New York, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden. The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

The use of designations, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Product liability: The publisher cannot guarantee the accuracy of any information about dosage and application contained in this book. In every individual case the user must check such information by consulting the relevant literature.

Production and typesetting: LE-TeX GbR, Leipzig
Handbook Manager: Dr. W. Skolaut, Heidelberg
Typography and layout: schreiberVIS, Seeheim
Illustrations:
schreiberVIS, Seeheim & Hippmann GbR, Schwarzenbruck
Cover design: eStudio Calamar Steinen, Barcelona
Cover production: WMXDesign GmbH, Heidelberg
Printing and binding: Stürtz AG, Würzburg

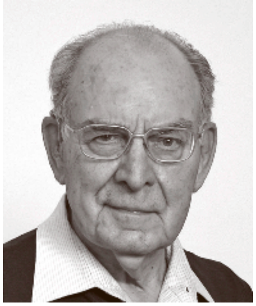
SPIN 11309031 100/3100/YL 5 4 3 2 1 0

Foreword

The present handbook covers a very wide field. Its 28 chapters range from the history of acoustics to sound propagation in the atmosphere; from nonlinear and underwater acoustics to thermoacoustics and concert hall acoustics. Also covered are musical acoustics, including computer and electronic music; speech and singing; animal (including whales) communication as well as bioacoustics in general, psychoacoustics and medical acoustics. In addition, there are chapters on structural acoustics, vibration and noise, including optical methods for their measurement; microphones, their calibration, and microphone and hydrophone arrays; acoustic holography; model analysis and much else needed by the professional engineer and scientist.

Among the authors we find many illustrious names: Yoichi Ando, Mack Breazeale, Babrina Dunmire, Neville Fletcher, Anders Gade, William Hartmann, William Kuperman, Werner Lauterborn, George Maling, Brian Moore, Allan Pierce, Thomas Rossing, Johan Sundberg, Eric Young, and many more. They hail from countries around the world: Australia, Canada, Denmark, France, Germany, Japan, Korea, Sweden, the United Kingdom, and the USA. There is no doubt that this handbook will fill many needs, nay be irreplaceable in the art of exercising today's many interdisciplinary tasks devolving on acoustics. No reader could wish for a wider and more expert coverage. I wish the present tome the wide acceptance and success it surely deserves.

Göttingen, March 2007 Manfred R. Schroeder



Prof. Dr. M. R. Schroeder
University Professor
Speach and Acoustics Laboratory
University of Göttingen,
Germany

Preface

Prof. em. T. D. Rossing

Northern Illinois University
Presently visiting Professor
of Music at Stanford University

"A handbook," according to the dictionary, "is a book capable of being conveniently carried as a ready reference." Springer has created the Springer Handbook series on important scientific and technical subjects, and we feel fortunate that they have included acoustics in this category.

Acoustics, the science of sound, is a rather broad subject to be covered in a single handbook. It embodies many different academic disciplines, such as physics, mechanical and electrical engineering, mathematics, speech and hearing sciences, music, and architecture. There are many technical areas in acoustics; the Acoustical Society of America, for example, includes 14 technical committees representing different areas of acoustics. It is impossible to cover all of these areas in a single handbook. We have tried to include as many as possible of the "hot" topics in this interdisciplinary field, including basic science and technological applications. We apologize to the reader whose favorite topics are not included.

We have grouped the 28 chapters in the book into eight parts: Propagation of Sound; Physical and Nonlinear Acoustics; Architectural Acoustics; Hearing and Signal Processing; Music, Speech, and Electroacoustics; Biological and Medical Acoustics; Structural Acoustics and Noise; and Engineering Acoustics. The chapters are of varying length. They also reflect the individual writing styles of the various authors, all of whom are authorities in their fields. Although an attempt was made to keep the mathematical level of the chapters as even as possible, readers will note that some chapters are more mathematical than others; this is unavoidable and in fact lends some degree of richness to the book.

We are indebted to many persons, especially Werner Skolaut, the manager of the Springer Handbooks, and to the editorial board, consisting of Neville Fletcher, Floyd Dunn, William Hartmann, and Murray Campbell, and for their advice. Each chapter was reviewed by two authoritative reviewers, and we are grateful to them for their services. But most of all we thank the authors, all of whom are busy people but devoted much time to carefully preparing their chapters.

Stanford, April 2007 Thomas D. Rossing

List of Authors

Iskander Akhatov
North Dakota State University
Center for Nanoscale Science and Engineering,
Department of Mechanical Engineering
111 Dolve Hall
Fargo, ND 58105-5285, USA
e-mail: *iskander.akhatov@ndsu.edu*

Yoichi Ando
3917-680 Takachiho
899-6603 Makizono, Kirishima, Japan
e-mail: *andoy@cameo.plala.or.jp*

Keith Attenborough
The University of Hull
Department of Engineering
Cottingham Road
Hull, HU6 7RX, UK
e-mail: *k.attenborough@hull.ac.uk*

Whitlow W. L. Au
Hawaii Institute of Marine Biology
P.O. Box 1106
Kailua, HI 96734, USA
e-mail: *wau@hawaii.edu*

Kirk W. Beach
University of Washington
Department of Surgery
Seattle, WA 98195, USA
e-mail: *kwbeach@u.washington.edu*

Mack A. Breazeale
University of Mississippi
National Center for Physical Acoustics
027 NCPA Bldg.
University, MS 38677, USA
e-mail: *breazeal@olemiss.edu*

Antoine Chaigne
Unité de Mécanique (UME)
Ecole Nationale Supérieure de Techniques
Avancées (ENSTA)
Chemin de la Hunière
91761 Palaiseau, France
e-mail: *antoine.chaigne@ensta.fr*

Perry R. Cook
Princeton University
Department of Computer Science
35 Olden Street
Princeton, NJ 08540, USA
e-mail: *prc@cs.princeton.edu*

James Cowan
Resource Systems Group Inc.
White River Junction, VT 85001, USA
e-mail: *jcowan@rsginc.com*

Mark F. Davis
Dolby Laboratories
100 Potrero Ave,
San Francisco, CA 94103, USA
e-mail: *mfd@dolby.com*

Barbrina Dunmire
University of Washington
Applied Physics Laboratory
1013 NE 40th Str.
Seattle, WA 98105, USA
e-mail: *mrbean@u.washington.edu*

Neville H. Fletcher
Australian National University
Research School of Physical Sciences and
Engineering
Canberra, ACT 0200, Australia
e-mail: *neville.fletcher@anu.edu.au*

Anders Christian Gade
Technical University of Denmark
Acoustic Technology, Oersted.DTU
Building 352
2800 Lyngby, Denmark
e-mail: *acg@oersted.dtu.dk*,
anders.gade@get2net.dk

Colin Gough
University of Birmingham
School of Physics and Astronomy
Birmingham, B15 2TT, UK
e-mail: *c.gough@bham.ac.uk*

William M. Hartmann
Michigan State University
1226 BPS Building
East Lansing, MI 48824, USA
e-mail: *hartmann@pa.msu.edu*

Finn Jacobsen
Ørsted DTU, Technical University of Denmark
Acoustic Technology
Ørsteds Plads, Building 352
2800 Lyngby, Denmark
e-mail: *fja@oersted.dtu.dk*

Yang-Hann Kim
Korea Advanced Institute of Science
and Technology (KAIST)
Department of Mechanical Engineering
Center for Noise and Vibration Control (NOVIC)
Acoustics and Vibration Laboratory
373-1 Kusong-dong, Yusong-gu
Daejeon, 305-701, Korea
e-mail: *yanghannkim@kaist.ac.kr*

William A. Kuperman
University of California at San Diego
Scripps Institution of Oceanography
9500 Gilman Drive
La Jolla, CA 92093-0701, USA
e-mail: *wkuperman@ucsd.edu*

Thomas Kurz
Universität Göttingen
Friedrich-Hund-Platz 1
37077 Göttingen, Germany
e-mail: *t.kurz@dpi.physik.uni-goettingen.de*

Marc O. Lammers
Hawaii Institute of Marine Biology
P.O. Box 1106
Kailua, HI 96734, USA
e-mail: *lammers@hawaii.edu*

Werner Lauterborn
Universität Göttingen
Drittes Physikalisches Institut
Friedrich-Hund-Platz 1
37077 Göttingen, Germany
e-mail:
w.lauterborn@dpi.physik.uni-goettingen.de

Björn Lindblom
Stockholm University
Department of Linguistics
10691 Stockholm, Sweden
e-mail: *lindblom@ling.su.se*,
blindblom@mail.utexas.edu

George C. Maling, Jr.
Institute of Noise Control Engineering of the USA
60 High Head Road
Harpswell, ME 04079, USA
e-mail: *maling@alum.mit.edu*

Michael McPherson
The University of Mississippi
Department of Physics and Astronomy
123 Lewis Hall
P. O. Box 1848
University, MS 38677, USA
e-mail: *mcph@phy.olemiss.edu*

Nils-Erik Molin
Luleå University of Technology
Experimental Mechanics
SE-971 87 Luleå, Sweden
e-mail: *nem@ltu.se*

Brian C. J. Moore
University of Cambridge
Department of Experimental Psychology
Downing Street
Cambridge, CB2 3EB, UK
e-mail: *bcjm@cam.ac.uk*

Alan D. Pierce
Boston University
College of Engineering
Boston, MA , USA
e-mail: *adp@bu.edu*

Thomas D. Rossing
Stanford University
Center for Computer Research in Music and
Acoustics (CCRMA)
Department of Music
Stanford, CA 94305, USA
e-mail: *rossing@ccrma.stanford.edu*

Philippe Roux
Université Joseph Fourier
Laboratoire de Geophysique Interne et Tectonophysique
38041 Grenoble, France
e-mail: *philippe.roux@obs.ujf-grenoble.fr*

Johan Sundberg
KTH–Royal Institute of Technology
Department of Speech, Music, and Hearing
SE-10044 Stockholm, Sweden
e-mail: *pjohan@speech.kth.se*

Gregory W. Swift
Los Alamos National Laboratory
Condensed Matter and Thermal Physics Group
Los Alamos, NM 87545, USA
e-mail: *swift@lanl.gov*

George S. K. Wong
Institute for National Measurement Standards (INMS)
National Research Council Canada (NRC)
1200 Montreal Road
Ottawa, ON K1A 0R6, Canada
e-mail: *George.Wong@nrc-cnrc.gc.ca*

Eric D. Young
Johns Hopkins University
Baltimore, MD 21205, USA
e-mail: *eyoung@jhu.edu*

Contents

1 Introduction to Acoustics

Part A Propagation of Sound

2 A Brief History of Acoustics

3 Basic Linear Acoustics

Part B Physical and Nonlinear Acoustics

Part C Architectural Acoustics

Part D Hearing and Signal Processing

Part E Music, Speech, Electroacoustics

Part F Biological and Medical Acoustics

Part G Structural Acoustics and Noise

Part H Engineering Acoustics

List of Abbreviations

A

ABR	auditory brainstem responses
AC	articulation class
ACF	autocorrelation function
ADC	analog-to-digital converter
ADCP	acoustic Doppler current profiler
ADP	ammonium dihydrogen phosphate
AM	amplitude modulated
AMD	air moving device
AN	auditory nerve
ANSI	American National Standards Institute
AR	assisted resonance
ASW	apparent source width
AUV	automated underwater vehicle

B

BB	bite block
BEM	boundary-element method
BER	bit error rate
BF	best frequency
BR	bass ratio

C

CAATI	computed angle-of-arrival transient imaging
CAC	ceiling attenuation class
CCD	charge-coupled device
CDF	cumulative distribution function
CMU	concrete masonry unit
CN	cochlear nucleus
CND	cumulative normal distribution
CSDM	cross-spectral-density matrix

D

DAC	digital-to-analog converter
DL	difference limen
DOF	degree of freedom
DRS	directed reflection sequence
DSL	deep scattering layer
DSP	digital speckle photography
DSP	digital signal processing
DSPI	digital speckle-pattern interferometry

E

EARP	equal-amplitude random-phase
EDT	early decay time
EDV	end diastolic velocity
EEG	electroencephalography
EOF	empirical orthogonal function
EOH	electro-optic holography
ERB	equivalent rectangular bandwidth
ESPI	electronic speckle-pattern interferometry

F

FCC	Federal Communications Commission
FEA	finite-element analysis
FEM	finite-element method
FERC	Federal Energy Regulatory Commission
FFP	fast field program
FFT	fast Fourier transform
FIR	finite impulse response
FM	frequency modulated
FMDL	frequency modulation detection limen
FOM	figure of merit
FRF	frequency response function
FSK	frequency shift keying

G

GA	genetic algorithm

H

HVAC	heating, ventilating and air conditioning

I

IACC	interaural cross-correlation coefficient
IACF	interaural cross-correlation function
IAD	interaural amplitude difference
ICAO	International Civil Aircraft Organization
IF	intermediate frequency
IFFT	inverse fast Fourier transform
IHC	inner hair cells
IIR	infinite impulse response
IM	intermodulation
IRF	impulse response function
ISI	intersymbol interference
ITD	interaural time difference
ITDG	initial time delay gap

J

JND	just noticeable difference

K

KDP	potassium dihydrogen phosphate

L

LDA	laser Doppler anemometry
LDV	laser Doppler vibrometry
LEF	lateral energy fraction
LEV	listener envelopment
LL	listening level
LOC	lateral olivocochlear system
LP	long-play vinyl record
LTAS	long-term-average spectra

M

MAA	minimum audible angle
MAF	minimum audible field
MAP	minimum audible pressure
MCR	multichannel reverberation
MDOF	multiple degree of freedom
MEG	magnetoencephalogram
MEMS	microelectromechanical system
MFDR	maximum flow declination rate
MFP	matched field processing
MIMO	multiple-input multiple-output
MLM	maximum-likelihood method
MLS	maximum length sequence
MOC	medial olivocochlear system
MRA	main response axis
MRI	magnetic resonance imaging
MTF	modulation transfer function
MTS	multichannel television sound
MV	minimum variance

N

NDT	nondestructive testing
NMI	National Metrology Institute
NRC	noise reduction coefficient

O

OAE	otoacoustic emission
ODS	operating deflexion shape
OHC	outer hair cells
OITC	outdoor–indoor transmission class
OR	or operation
OSHA	Occupational Safety and Health Administration

P

PC	phase conjugation
PCM	pulse code modulation
PD	probability of detection
PDF	probability density function
PE	parabolic equation
PFA	probability of false alarm
PIV	particle image velocimetry
PL	propagation loss
PLIF	planar laser-induced fluorescent
PM	phase modulation
PMF	probability mass function
PS	phase stepping
PS	peak systolic
PSD	power spectral density
PSK	phase shift keying
PTC	psychophysical tuning curve
PVDF	polyvinylidene fluoride
PZT	lead zirconate titanate

Q

QAM	quadrature amplitude modulation

R

RASTI	rapid speech transmission index
REL	resting expiratory level
RF	radio frequency
RIAA	Recording Industry Association of America
RMS	root-mean-square
ROC	receiving operating characteristic
RUS	resonant ultrasound spectroscopy

S

s.c.	supporting cells
S/N	signal-to-noise
SAA	sound absorption average
SAC	spatial audio coding
SAW	surface acoustic wave
SBSL	single-bubble sonoluminescence
SDOF	single degree of freedom
SE	signal excess
SEA	statistical energy analysis
SG	spiral ganglion
SI	speckle interferometry
SIL	speech interference level
SIL	sound intensity level
SISO	single-input single-output
SL	sensation level
SM	scala media
SNR	signal-to-noise ratio
SOC	superior olivary complex
SP	speckle photography
SPL	sound pressure level
SR	spontaneous discharge rate
ST	scala tympani

STC	sound transmission class
STI	speech transmission index
SV	scala vestibuli
SVR	slow vertex response

T

TDAC	time-domain alias cancellation
TDGF	time-domain Green's function
THD	total harmonic distortion
TL	transmission loss
TLC	total lung capacity
TMTF	temporal modulation transfer function
TNM	traffic noise model
TR	treble ratio
TR	time reversal
TTS	temporary threshold shift
TVG	time-varied gain

U

UMM	unit modal mass

V

VBR	variable bitrate
VC	vital capacity

W

WS	working standard

X

XOR	exclusive or

1. Introduction to Acoustics

This brief introduction may help to persuade the reader that acoustics covers a wide range of interesting topics. It is impossible to cover all these topics in a single handbook, but we have attempted to include a sampling of hot topics that represent current acoustical research, both fundamental and applied.

Acoustics is the science of sound. It deals with the production of sound, the propagation of sound from the source to the receiver, and the detection and perception of sound. The word *sound* is often used to describe two different things: an auditory sensation in the ear, and the disturbance in a medium that can cause this sensation. By making this distinction, the age-old question "If a tree falls in a forest and no one is there to hear it, does it make a sound?" can be answered.

1.1 Acoustics: The Science of Sound

Acoustics has become a broad interdisciplinary field encompassing the academic disciplines of physics, engineering, psychology, speech, audiology, music, architecture, physiology, neuroscience, and others. Among the branches of acoustics are architectural acoustics, physical acoustics, musical acoustics, psychoacoustics, electroacoustics, noise control, shock and vibration, underwater acoustics, speech, physiological acoustics, etc.

Sound can be produced by a number of different processes, which include the following.

Vibrating bodies: when a drumhead or a noisy machine vibrates, it displaces air and causes the local air pressure to fluctuate.

Changing airflow: when we speak or sing, our vocal folds open and close to let through puffs of air. In a siren, holes on a rapidly rotating plate alternately pass and block air, resulting in a loud sound.

Time-dependent heat sources: an electrical spark produces a crackle; an explosion produces a bang due to the expansion of air caused by rapid heating. Thunder results from rapid heating by a bolt of lightning.

Supersonic flow: shock waves result when a supersonic airplane or a speeding bullet forces air to flow faster than the speed of sound.

1.2 Sounds We Hear

The range of sound intensity and the range of frequency to which the human auditory system responds is quite remarkable. The intensity ratio between the sounds that bring pain to our ears and the weakest sounds we can hear is more than 10^{12}. The frequency ratio between the highest and lowest frequencies we can hear is nearly 10^3, or more than nine octaves (each octave representing a doubling of frequency). Human vision is also quite remarkable, but the frequency range does not begin to compare to that of human hearing. The frequency range of vision is a little less than one octave (about 4×10^{14}–7×10^{14} Hz). Within this one octave range we can identify more than 7 million colors. Given that the frequency range of the ear is nine times greater, one can imagine how many sound *colors* might be possible.

Humans and other animals use sound to communicate, and so it is not surprising that human hearing is most sensitive over the frequency range covered by human speech. This is no doubt a logical outcome of natural selection. This same match is found throughout much of the animal kingdom. Simple observations show that small animals generally use high frequencies for communication while large animals use low frequencies. In Chap. 19, it is shown that song frequency f scales with animal mass M roughly as $f \propto M^{-1/3}$.

The least amount of sound energy we can hear is of the order of 10^{-20} J (cf. sensitivity of the eye: about one quantum of light in the middle of the visible spectrum $\approx 4\times10^{-19}$ J). The upper limit of the sound pressure that can be generated is set approximately by atmospheric pressure. Such an ultimate sound wave would have a sound pressure level of about 191 dB. In practice, of course, nonlinear effects set in well below this level and limit the maximum pressure. A large-amplitude sound wave will change waveform and finally break into a shock, approaching a sawtooth waveform. Nonlinear effects are discussed in Chap. 8.

1.3 Sounds We Cannot Hear: Ultrasound and Infrasound

Sound waves below the frequency of human hearing are called *infrasound*, while sound waves with frequency above the range of human hearing are called *ultrasound*. These sounds have many interesting properties, and are being widely studied. Ultrasound is very important in medical and industrial imaging. It also forms the basis of a growing number of medical procedures, both diagnostic and therapeutic (see Chap. 21). Ultrasound has many applications in scientific research, especially in the study of solids and fluids (see Chap. 6).

Frequencies as high as 500 MHz have been generated, with a wavelength of about 0.6 μm in air. This is on the order of the wavelength of light and within an order of magnitude of the mean free path of air molecules. A gas ceases to behave like a continuum when the wavelength of sound becomes of the order of the mean free path, and this sets an upper limit on the frequency of sound that can propagate. In solids the assumption of continuum extends down to the intermolecular spacing of approximately 0.1 nm, with a limiting frequency of about 10^{12} Hz. The ultimate limit is actually reached when the wavelength is twice the spacing of the unit cell of a crystal, where the propagation of multiply scattered sound resembles the diffusion of heat [1.1].

Natural phenomena are prodigious generators of infrasound. When Krakatoa exploded, windows were shattered hundreds of miles away by the infrasonic wave. The ringing of both the Earth and the atmosphere continued for hours. The sudden shock wave of an explosion propels a complex infrasonic signal far beyond the shattered perimeter. Earthquakes generate intense infrasonic waves. The faster moving P (primary) waves arrive at distant locations tens of seconds before the destructive S (secondary) waves. (The P waves carry information; the S waves carry energy.) Certain animals and fish can sense these infrasonic precursors and react with fear and anxiety.

A growing amount of astronomical evidence indicates that primordial sound waves at exceedingly low frequency propagated in the universe during its first 380 000 years while it was a plasma of charged particles and thus opaque to electromagnetic radiation. Sound is therefore older than light.

1.4 Sounds We Would Rather Not Hear: Environmental Noise Control

Noise has been receiving increasing recognition as one of our critical environmental pollution problems. Like air and water pollution, noise pollution increases with population density; in our urban areas, it is a serious threat to our quality of life. Noise-induced hearing loss is a major health problem for millions of people employed in noisy environments. Besides actual hearing loss, humans are affected in many other ways by high levels of noise. Interference with speech, interruption of sleep, and other physiological and psychological effects of noise have been the subject of considerable study. Noise control is discussed in Chap. 23. The propagation of sound in air in Chap. 4, and building acoustics is the subject of Chap. 11.

Fortunately for the environment, even the noisiest machines convert only a small part of their total energy into sound. A jet aircraft, for example, may produce a kilowatt of acoustic power, but this is less than 0.02% of its mechanical output. Automobiles emit approximately 0.001% of their power as sound. Nevertheless, the shear number of machines operating in our society makes it crucial that we minimize their sound output and take measures to prevent the sound from propagating throughout our environment. Although reducing the emitted noise is best done at the source, it is possible, to some extent, to block the transmission of this noise from the source to the receiver. Reduction of classroom noise, which impedes learning in so many schools, is receiving increased attention from government officials as well as from acousticians [1.2].

1.5 Aesthetic Sound: Music

Music may be defined as an art form using sequences and clusters of sounds. Music is carried to the listener by sound waves. The science of musical sound is often called musical acoustics and is discussed in Chap. 15.

Musical acoustics deals with the production of sound by musical instruments, the transmission of music from the performer to the listener, and the perception and cognition of sound by the listener. Understanding the production of sound by musical instruments requires understanding how they vibrate and how they radiate sound. Transmission of sound from the performer to the listener involves a study of concert hall acoustics (covered in Chaps. 9 and 10) and the recording and reproduction of musical sound (covered in Chap. 15). Perception of musical sound is based on psychoacoustics, which is discussed in Chap. 13.

Electronic musical instruments have become increasingly important in contemporary music. Computers have made possible artificial musical intelligence, the synthesis of new musical sounds and the accurate and flexible re-creation of traditional musical sounds by artificial means. Not only do computers talk and sing and play music, they listen to us doing the same, and our interactions with computers are becoming more like our interactions with each other. Electronic and computer music is discussed in Chap. 17.

1.6 Sound of the Human Voice: Speech and Singing

It is difficult to overstate the importance of the human voice. Of all the members of the animal kingdom, we alone have the power of articulate speech. Speech is our chief means of communication. In addition, the human voice is our oldest musical instrument. Speech and singing, the closely related functions of the human voice, are discussed in a unified way in Chap. 16.

In the simplest model of speech production, the vocal folds act as the source and the vocal tract as a filter of the source sound. According to this model, the spectrum envelope of speech sound can be thought of as the product of two components:

Speech sound = source spectrum × filter function.

The nearly triangular waveform of the air flow from the glottis has a spectrum of harmonics that diminish in amplitude roughly as $1/n^2$ (i. e., at a rate of $-12\,\mathrm{dB/octave}$). The formants or resonances of the vocal tract create the various vowel sounds. The vocal tract can be shaped by movements of the tongue, the lips, and the soft palate to tune the formants and articulate the various speech sounds.

Sung vowels are fundamentally the same as spoken vowels, although singers do make vowel modifications in order to improve the musical tone, especially in their high range. In order to produce tones over a wide range of pitch, singers use muscular action in the larynx, which leads to different registers.

Much research has been directed at computer recognition and synthesis of speech. Goals of such research include voice-controlled word processors, voice control of computers and other machines, data entry by voice, etc.In general it is more difficult for a computer to understand language than to speak it.

1.7 How We Hear: Physiological and Psychological Acoustics

The human auditory system is complex in structure and remarkable in function. Not only does it respond to a wide range of stimuli, but it precisely identifies the pitch, timbre, and direction of a sound. Some of the hearing function is done in the organ we call the ear; some of it is done in the central nervous system as well.

Physiological acoustics, which is discussed in Chap. 12, focuses its attention mainly on the peripheral auditory system, especially the cochlea. The dynamic behavior of the cochlea is a subject of great interest. It is now known that the maximum response along the basilar membrane of the cochlea has a sharper peak in a living ear than in a dead one.

Resting on the basilar membrane is the delicate and complex organ of Corti, which contains several rows of hair cells to which are attached auditory nerve fibers. The inner hair cells are mainly responsible for transmitting signals to the auditory nerve fibers, while the more-numerous outer hair cells act as biological amplifiers. It is estimated that the outer hair cells add about 40 dB of amplification to very weak signals, so that hearing sensitivity decreases by a considerable amount when these delicate cells are destroyed by overexposure to noise.

Our knowledge of the cochlea has now progressed to a point where it is possible to construct and implant electronic devices in the cochlea that stimulate the auditory nerve. A cochlear implant is an electronic device that restores partial hearing in many deaf people [1.3]. It is surgically implanted in the inner ear and activated by a device worn outside the ear. An implant has four basic parts: a microphone, a speech processor and transmitter, a receiver inside the ear, and electrodes that transmit impulses to the auditory nerve and thence to the brain.

Psychoacoustics (psychological acoustics), the subject of Chap. 13, deals with the relationships between the physical characteristics of sounds and their perceptual attributes, such as loudness, pitch, and timbre.

The threshold of hearing depends upon frequency, the lowest being around 3–4 kHz, where the ear canal has a resonance, and rising considerably at low frequency. Temporal resolution, such as the ability to detect brief gaps between stimuli or to detect modulation of a sound, is a subject of considerable interest, as is the ability to localize the sound source. Sound localization depends upon detecting differences in arrival time and differences in intensity at our two ears, as well as spectral cues that help us to localize a source in the median plane.

Most sound that reaches our ears comes from several different sources. The extent to which we can perceive each source separately is sometimes called segregation. One important cue for perceptual separation of nearly simultaneous sounds is onset and offset disparity. Another is spectrum change with time. When we listen to rapid sequence of sounds, they may be grouped together (fusion) or they may be perceived as different streams (fission). It is difficult to judge the temporal order of sounds that are perceived in different streams.

1.8 Architectural Acoustics

To many lay people, an acoustician is a person who designs concert halls. That is an important part of architectural acoustics, to be sure, but this field incorporates much more. Architectural acousticians seek to understand and to optimize the sound environment in rooms and buildings of all types, including those used for work, residential living, education, and leisure. In fact, some of the earliest attempts to optimize sound transmission were practised in the design of ancient amphitheaters, and the acoustical design of outdoor spaces for concerts and drama still challenge architects.

In a room, most of the sound waves that reach the listener's ear have been reflected by one or more surfaces of the room or by objects in the room. In a typical room, sound waves undergo dozens of reflections before they become inaudible. It is not surprising, therefore, that the acoustical properties of rooms play an important role in determining the nature of the sound heard by a listener. Minimizing extraneous noise is an important part of the acoustical design of rooms and buildings of all kinds. Chapter 9 presents the principles of room acoustics and applies them to performance and assembly halls, including theaters and lecture halls, opera halls, concert halls, worship halls, and auditoria.

The subject of concert hall acoustics is almost certain to provoke a lively discussion by both performers and serious listeners. Musicians recognize the importance of the concert hall in communication between performer and listener. Opinions of new halls tend to polarize toward extremes of very good or very bad. In considering concert and opera halls, it is important to seek a common language for musicians and acousticians in order to understand how objective measurements relate to subjective qualities [1.4,5]. Chapter 10 discusses subjective preference theory and how it relates to concert hall design.

Two acoustical concerns in buildings are providing the occupants with privacy and with a quiet environment, which means dealing with noise sources within the building as well as noise transmitted from outside. The most common noise sources in buildings, other than the inhabitants, are related to heating, ventilating, and air conditioning (HVAC) systems, plumbing systems, and electrical systems. Quieting can best be done at the source, but transmission of noise throughout the building must also be prevented. The most common external noise sources that affect buildings are those associated with transportation, such as motor vehicles, trains, and airplanes. There is no substitute for massive walls, although doors and windows must receive attention as well. Building acoustics is discussed in Chap. 11.

1.9 Harnessing Sound: Physical and Engineering Acoustics

It is sometimes said that physicists study nature, engineers attempt to improve it. Physical acoustics and engineering acoustics are two very important areas of acoustics. Physical acousticians investigate a wide range of scientific phenomena, including the propagation of sound in solids, liquids, and gases, and the way sound interacts with the media through which it propagates. The study of ultrasound and infrasound are especially interesting. Physical acoustics is discussed in Chap. 6.

Acoustic techniques have been widely used to study the structural and thermodynamic properties of materials at very low temperatures. Studying the propagation of ultrasound in metals, dielectric crystals, amorphous solids, and magnetic materials has yielded valuable information about their elastic, structural and other properties. Especially interesting has been the propagation of sound in superfluid helium. Second sound, an unusual type of temperature wave, was discovered in 1944, and since that time so-called third sound, fourth sound, and fifth sound have been described [1.6].

Nonlinear effects in sound are an important part of physical acoustics. Nonlinear effects of interest include waveform distortion, shock-wave formation, interactions of sound with sound, acoustic streaming, cavitation, and acoustic levitation. Nonlinearity leads to distortion of the sinusoidal waveform of a sound wave so that it becomes nearly triangular as the shock wave forms. On the other hand, local disturbances, called *solitons*, retain their shape over large distances.

The study of the interaction of sound and light, called acoustooptics, is an interesting field in physical acoustics that has led to several practical devices. In an acoustooptic modulator, for example, sound waves form a sort of moving optical diffraction grating that diffracts and modulates a laser beam.

Sonoluminescence is the name given to a process by which intense sound waves can generate light. The light is emitted by bubbles in a liquid excited by sound. The observed spectra of emitted light seem to indicate temperatures hotter than the surface of the sun. Some experimental evidence indicates that nuclear fusion may take place in bubbles in deuterated acetone irradiated with intense ultrasound.

Topics of interest in engineering acoustics cover a wide range and include: transducers and arrays, underwater acoustic systems, acoustical instrumentation, audio engineering, acoustical holography and acoustical imaging, ultrasound, and infrasound. Several of these topics are covered in Chaps. 5, 18, 24, 25, 26, 27, and 28. Much effort has been directed into engineering increasingly small transducers to produce and detect sound. Microphones are being fabricated on silicon chips as parts of integrated circuits.

The interaction of sound and heat, called thermoacoustics, is an interesting field that applies principles of physical acoustics to engineering systems. The thermoacoustic effect is the conversion of sound energy to heat or visa versa. In thermoacoustic processes, acoustic power can pump heat from a region of low temperature to a region of higher temperature. This can be used to construct heat engines or refrigerators with no moving parts. Thermoacoustics is discussed in Chap. 7.

1.10 Medical Acoustics

Two uses of sound that physicians have employed for many years are *auscultation*, listening to the body with a stethoscope, and *percussion*, sound generation by the striking the chest or abdomen to assess transmission or resonance. The most exciting new developments in medical acoustics, however, involve the use of ultrasound, both diagnostic imaging and therapeutic applications.

There has been a steady improvement in the quality of diagnostic ultrasound imaging. Two important commercial developments have been the advent of real-time three-dimensional (3-D) imaging and the development of hand-held scanners. Surgeons can now carry out procedures without requiring optical access. Although measurements on isolated tissue samples show that acoustic attenuation and backscatter correlate with pathology, implementing algorithms to obtain this information on a clinical scanner is challenging at the present time.

The therapeutic use of ultrasound has blossomed in recent years. Shock-wave lithotripsy is the predominant surgical operation for the treatment of kidney stones. Shock waves also appear to be effective at helping heal broken bones. High-intensity focused ultrasound is used to heat tissue selectivity so that cells can be destroyed in a local region. Ultrasonic devices appear to hold promise for treating glaucoma, fighting cancer, and controlling internal bleeding. Advanced therapies, such as puncturing holes in the heart, promoting localized drug delivery, and even carrying out brain surgery through an intact skull appear to be feasible with ultrasound [1.7].

Other applications of medical ultrasound are included in Chap. 21.

1.11 Sounds of the Sea

Oceans cover more than 70% of the Earth's surface. Sound waves are widely used to explore the oceans, because they travel much better in sea water than light waves. Likewise, sound waves are used, by humans and dolphins alike, to communicate under water, because they travel much better than radio waves. Acoustical oceanography has many military, as well as commercial applications. Much of our understanding of underwater sound propagation is a result of research conducted during and following World War II. Underwater acoustics is discussed in Chap. 5.

The speed of sound in water, which is about 1500 m/s, increases with increasing static pressure by about 1 part per million per kilopascal, or about 1% per 1000 m of depth, assuming temperature remains constant. The variation with temperature is an increase of about 2% per °C temperature rise. Refraction of sound, due to these changes in speed, along with reflection at the surface and the bottom, lead to waveguides at various ocean depths. During World War II, a *deep channel* was discovered in which sound waves could travel distances in excess of 3000 km. This phenomenon gave rise to the deep channel or sound fixing and ranging (SOFAR) channel, which could be used to locate, by acoustic means, airmen downed at sea.

One of the most important applications of underwater acoustics is sound navigation and ranging (SONAR). The purpose of most sonar systems is to detect and localize a target, such as submarines, mines, fish, or surface ships. Other SONARs are designed to measure some quantity, such as the ocean depth or the speed of ocean currents.

An interesting phenomenon called cavitation occurs when sound waves of high intensity propagate through water. When the rarefaction tension phase of the sound wave is great enough, the medium ruptures and cavitation bubbles appear. Cavitation bubbles can be produced by the tips of high-speed propellers. Bubbles affect the speed of sound as well as its attenuation [1.7, 8].

References

1.1 U. Ingard: Acoustics. In: *Handbook of Physics*, 2nd edn., ed. by E.U. Condon, H. Odishaw (McGraw-Hill, New York 1967)

1.2 B. Seep, R. Glosemeyer, E. Hulce, M. Linn, P. Aytar, R. Coffeen: *Classroom Acoustics* (Acoustical Society of America, Melville 2000, 2003)

1.3 M.F. Dorman, B.S. Wilson: The design and function of cochlear implants, Am. Scientist **19**, 436–445 (2004)

1.4 L.L. Beranek: *Music, Acoustics and Architecture* (Wiley, New York 1962)

1.5 L. Beranek: *Concert Halls and Opera Houses*, 2nd edn. (Springer, Berlin, Heidelberg, New York 2004)

1.6 G. Williams: Low-temperature acoustics. In: *McGraw-Hill Encyclopedia of Physics*, 2nd edn., ed. by S. Parker (McGraw-Hill, New York 1993)

1.7 R.O. Cleveland: Biomedical ultrasound/bioresponse to vibration. In: *ASA at 75*, ed. by H.E. Bass, W.J. Cavanaugh (Acoustical Society of America, Melville 2004)

1.8 H. Medwin, C.S. Clay: *Fundamentals of Acoustical Oceanography* (Academic, Boston 1998)

Part A

Propagat

Part A Propagation of Sound

2 A Brief History of Acoustics
Thomas D. Rossing, Stanford, USA

3 Basic Linear Acoustics
Alan D. Pierce, Boston, USA

4 Sound Propagation in the Atmosphere
Keith Attenborough, Hull, UK

5 Underwater Acoustics
William A. Kuperman, La Jolla, USA
Philippe Roux, Grenoble, France

2. A Brief History of Acoustics

Although there are certainly some good historical treatments of acoustics in the literature, it still seems appropriate to begin a handbook of acoustics with a brief history of the subject. We begin by mentioning some important experiments that took place before the 19th century. Acoustics in the 19th century is characterized by describing the work of seven outstanding acousticians: Tyndall, von Helmholtz, Rayleigh, Stokes, Bell, Edison, and Koenig. Of course this sampling omits the mention of many other outstanding investigators.

To represent acoustics during the 20th century, we have selected eight areas of acoustics, again not trying to be all-inclusive. We select the eight areas represented by the first eight technical areas in the Acoustical Society of America. These are architectural acoustics, physical acoustics, engineering acoustics, structural acoustics, underwater acoustics, physiological and psychological acoustics, speech, and musical acoustics. We apologize to readers whose main interest is in another area of acoustics. It is, after all, a broad interdisciplinary field.

2.1 Acoustics in Ancient Times

Acoustics is the science of sound. Although sound waves are nearly as old as the universe, the scientific study of sound is generally considered to have its origin in ancient Greece. The word acoustics is derived from the Greek word *akouein*, to hear, although Sauveur appears to have been the first person to apply the term acoustics to the science of sound in 1701 [2.1].

Pythagoras, who established mathematics in Greek culture during the sixth century BC, studied vibrating strings and musical sounds. He apparently discovered that dividing the length of a vibrating string into simple ratios produced consonant musical intervals. According to legend, he also observed how the pitch of the string changed with tension and the tones generated by striking musical glasses, but these are probably just legends [2.2].

Although the Greeks were certainly aware of the importance of good acoustical design in their many fine theaters, the Roman architect Vitruvius was the first to write about it in his monumental *De Architectura*, which includes a remarkable understanding and analysis of theater acoustics: "We must choose a site in which the voice may fall smoothly, and not be returned by reflection so as to convey an indistinct meaning to the ear."

2.2 Early Experiments on Vibrating Strings, Membranes and Plates

Much of early acoustical investigations were closely tied to musical acoustics. Galileo reviewed the relationship of the pitch of a string to its vibrating length, and he related the number of vibrations per unit time to pitch. Joseph Sauveur made more-thorough studies of frequency in relation to pitch. The English mathematician Brook Taylor provided a dynamical solution for the frequency of a vibrating string based on the assumed curve for the shape of the string when vibrating in its fundamental mode. Daniel Bernoulli set up a partial differential equation for the vibrating string and obtained solutions which d'Alembert interpreted as waves traveling in both directions along the string [2.3].

The first solution of the problem of vibrating membranes was apparently the work of S. D. Poisson, and the circular membrane was handled by R. F. A. Clebsch. Vibrating plates are somewhat more complex than vibrating membranes. In 1787 *E. F. F. Chladni* described his method of using sand sprinkled on vibrating plates to show nodal lines [2.4]. He observed that the addition of one nodal circle raised the frequency of a circular plate by about the same amount as adding two nodal diameters, a relationship that Lord Rayleigh called Chladni's law. Sophie Germain wrote a fourth-order equation to describe plate vibrations, and thus won a prize provided by the French emperor Napoleon, although Kirchhoff later gave a more accurate treatment of the boundary conditions. *Rayleigh*, of course, treated both membranes and plates in his celebrated book *Theory of Sound* [2.5].

Chladni generated his vibration patterns by "strewing sand" on the plate, which then collected along the nodal lines. Later he noticed that fine shavings from the hair of his violin bow did not follow the sand to the nodes, but instead collected at the antinodes. *Savart* noted the same behavior for fine lycopodium powder [2.6]. Michael *Faraday* explained this as being due to acoustic streaming [2.7]. Mary *Waller* published several papers and a book on Chladni patterns, in which she noted that particle diameter should exceed 100 μm in order to collect at the nodes [2.8]. Chladni figures of some of the many vibrational modes of a circular plate are shown in Fig. 2.1.

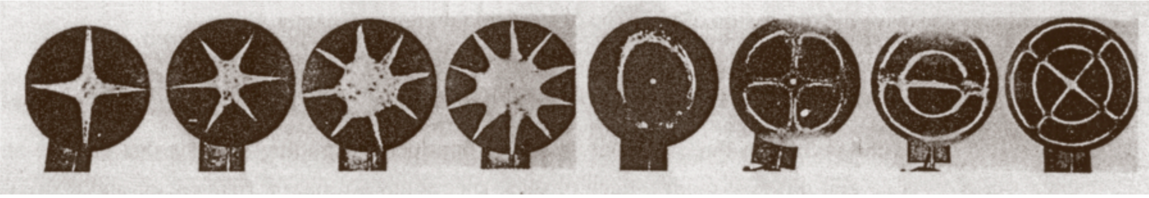


Fig. 2.1 Chladni patterns on a circular plate. The first four have two, three, four, and five nodal lines but no nodal circles; the second four have one or two nodal circles

2.3 Speed of Sound in Air

From earliest times, there was agreement that sound is propagated from one place to another by some activity of the air. Aristotle understood that there is actual motion of air, and apparently deduced that air is compressed. The Jesuit priest Athanasius Kircher was one of the first to observe the sound in a vacuum chamber, and since he could hear the bell he concluded that air was not necessary for the propagation of sound. Robert Boyle, however, repeated the experiment with a much improved pump and noted the much-observed decrease in sound intensity as the air is pumped out. We now know that sound propagates quite well in rarified air, and that the decrease in intensity at low pressure is mainly due to the impedance mismatch between the source and the medium as well as the impedance mismatch at the walls of the container.

As early as 1635, Gassendi measured the speed of sound using firearms and assuming that the light of the flash is transmitted instantaneously. His value came out to be 478 m/s. Gassendi noted that the speed of sound did not depend on the pitch of the sound, contrary to the view of Aristotle, who had taught that high notes are transmitted faster than low notes. In a more careful experiment, Mersenne determined the speed of sound to be 450 m/s [2.9]. In 1650, G. A. Borelli and V. Viviani of the Accademia del Cimento of Florence obtained a value of 350 m/s for the speed of sound [2.10]. Another Italian, G. L. Bianconi, showed that the speed of sound in air increases with temperature [2.11].

The first attempt to calculate the speed of sound through air was apparently made by Sir Isaac Newton. He assumed that, when a pulse is propagated through a fluid, the particles of the fluid move in simple harmonic motion, and that if this is true for one particle, it must be true for all adjacent ones. The result is that the speed of sound is equal to the square root of the ratio of the atmospheric pressure to the density of the air. This leads to values that are considerably less than those measured by Newton (at Trinity College in Cambridge) and others.

In 1816, Pierre Simon Laplace suggested that in Newton's and Lagrange's calculations an error had been made in using for the volume elasticity of the air the pressure itself, which is equivalent to assuming the elastic motions of the air particles take place at constant temperature. In view of the rapidity of the motions, it seemed more reasonable to assume that the compressions and rarefactions follow the adiabatic law. The adiabatic elasticity is greater than the isothermal elasticity by a factor γ, which is the ratio of the specific heat at constant pressure to that at constant volume. The speed of sound should thus be given by $c = (\gamma p/\rho)^{1/2}$, where p is the pressure and ρ is the density. This gives much better agreement with experimental values [2.3].

2.4 Speed of Sound in Liquids and Solids

The first serious attempt to measure the speed of sound in liquid was probably that of the Swiss physicist Daniel Colladon, who in 1826 conducted studies in Lake Geneva. In 1825, the Academy of Sciences in Paris had announced as the prize competition for 1826 the measurement of the compressibility of the principal liquids. Colladon measured the static compressibility of several liquids, and he decided to check the accuracy of his measurements by measuring the speed of sound, which depends on the compressibility. The compressibility of water computed from the speed of sound turned out to be very close to the statically measured values [2.12]. Oh yes, he won the prize from the Academy.

In 1808, the French physicist *J. B. Biot* measured the speed of sound in a 1000 m long iron water pipe in Paris by direct timing of the sound travel [2.13]. He compared the arrival times of the sound through the metal and through the air and determined that the speed is much greater in the metal. Chladni had earlier studied the speed of sound in solids by noting the pitch emanating from a struck solid bar, just as we do today. He deduced that the speed of sound in tin is about 7.5 times greater than in air, while in copper it was about 12 times greater. Biot's values for the speed in metals agreed well with Chladni's.

2.5 Determining Frequency

Much of the early research on sound was tied to musical sound. Vibrating strings, membranes, plates, and air columns were the bases of various musical instruments. Music emphasized the importance of ratios for the different tones. A string could be divided into halves or thirds or fourths to give harmonious pitches. It was also known that pitch is related to frequency. Marin Mersenne (1588–1648) was apparently the first to determine the frequency corresponding to a given pitch. By working with a long rope, he was able determine the frequency of a standing wave on the length, mass, and tension of the rope. He then used a short wire under tension and from his rope formula he was able to compute the frequency of oscillation [2.14]. The relationship between pitch and frequency was later improved by Joseph Sauveur, who counted beats between two low-pitched organ pipes differing in pitch by a semitone. Sauveur deduced that "the relation between sounds of low and high pitch is exemplified in the ratio of the numbers of vibrations which they both make in the same time." [2.1]. He recognized that two sounds differing a musical fifth have frequencies in the ratio of 3:2. We have already commented that Sauveur was the first to apply the term *acoustics* to the science of sound. "I have come then to the opinion that there is a science superior to music, and I call it *acoustics*; it has for its object sound in general, whereas music has for its objects sounds agreeable to the ear." [2.1]