

Formulas of Acoustics

F. P. Mechel (Ed.)

Formulas of Acoustics

Second Edition

With contributions by:

**M. L. Munjal, M. Vorländer, P. Költzsch, M. Ochmann, A. Cummings,
W. Maysenhölder, W. Arnold**

Prof. Dr. Fridolin P. Mechel
Landhausstraße 12
71120 Grafenau
Germany

Library of Congress Control Number: 2008922894

ISBN: 978-3-540-76832-6

This publication is available also as:

Electronic publication under ISBN 978-3-540-76833-3 and

Print and electronic bundle under ISBN 978-3-540-76834-0

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in other ways, and storage in data banks. Duplication of this publication or parts thereof is only permitted under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution under the German Copyright Law.

© Springer-Verlag Berlin Heidelberg New York 2008

The use of registered names, 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.

Springer is part of Springer Science+Business Media

springer.com

Editor: Dr. Christoph Baumann, Kerstin Kindler, Heidelberg, Germany

Development Editor: Lydia Mueller, Heidelberg, Germany

Typesetting and Production: le-tex publishing services oHG, Leipzig, Germany

Cover Design: Frido Steinen-Broo, Girona, Spain

Printed on acid-free paper

SPIN: 12190720 2109 — 5 4 3 2 1 0

Preface to the first edition, abbreviated

Modern acoustics is more and more based on computations, and computations are based on formulas. Such work needs previous and contemporary results. It consumes much time and effort to search needed formulas during the actual work. Therefore, fundamentals and results of acoustics that can be expressed as formulas will be collected in this book.

The formula collection is subdivided into fields of acoustics (Chapters). For some fields, in which this author is not expert enough, he invited co-authors to contribute. Most colleagues contacted for possible contributions were convinced of the project and agreed spontaneously.

The material within a field of acoustics is subdivided in Sections which deal with a defined task. Some overlap of Sections should be tolerated; but the subdivision into well-defined Sections will be helpful to the reader to find a particular topic of interest.

The present formula collection should not be considered a textbook in a condensed form. Derivations of a presented result will be described only as far as they are helpful in understanding the problem; the more interested reader is referred to the “source” of the result. Useful principles and computational procedures will also be included, even if they need more describing text. Symbols and quantities will be defined in the Section, and wherever useful a sketch will help to explain the object and the task.

One of the advantages of a formula collection is seen in uniform definitions, notations and symbols for quantities. A strict uniformity in the form of a central list of symbols used never works, according to this author’s observation. Therefore, only commonly used symbols (such as medium density, speed of sound, circular frequency, etc.) are collected in a central list of symbols (see Conventions); other symbols are defined in the relevant chapter.

Most Sections contain, below their title or in the text, a reference to the literature. It cannot be the task and intention of this book either to indicate time priorities of publications concerning a topic or to give a survey of the existing literature. The reference quoted is the source of more information, which the author has used.

Higher transcendental functions used in the formulas will be explained by reference to mathematical literature, if necessary. If functions are used with different definitions in the literature, the definition applied here will be presented.

The authors think that the book in its present form contains most of traditional and modern results of both fundamental and special character so that the book can be

helpful to researchers and engineers in the fields of physical acoustics, noise control, and room acoustics.

The manuscript was written in a camera ready form (in order to avoid proof reading). So printing errors are the responsibility of the editing author. He would be grateful for indications of such errors.

The author gratefully acknowledges the support given to the project by the co-authors and by the publisher.

Grafenau, October 2001

Preface to the second edition

The book was out of print in 2004. The need of reprint gave a first opportunity to apply some corrections to (rather harmless) misprints and to a few more serious formula errors (the positions of the errors are marked by a footnote ^{*)}). Some of the shown diagrams were generated by the computing program *Mathematica*[®]; this program unfortunately has lost its ability to write axes and plot labels so that they can be understood by receiving text programs. Therefore transcriptions to plot labels are enumerated near the diagrams, where necessary. This second edition is moderately enlarged by some additional topics in new Sections.

Grafenau, May 2008

Contents

Preface to the first edition, abbreviated	V
Preface to the second edition	VI
Contents	VII
Contributors	XIX
A Conventions	1
B General Linear Fluid Acoustics	5
<i>F.P. Mechel</i>	
B.1 Fundamental Differential Equations	5
B.2 Material Constants of Air	8
B.3 General Relation for Field Admittance and Intensity	11
B.4 Integral Relations	12
B.5 Green's Functions and Formalism	13
B.6 Orthogonality of Modes in a Duct with Locally Reacting Walls	19
B.7 Orthogonality of Modes in a Duct with Bulk Reacting Walls	20
B.8 Source Conditions	21
B.9 Sommerfeld's Condition	22
B.10 Principles of Superposition	22
B.11 Hamilton's Principle	25
B.12 Adjoint Wave Equation	26
B.13 Vector and Tensor Formulation of Fundamentals	26
B.14 Boundary Condition at a Moving Boundary	38
B.15 Boundary Conditions in Liquids and Solids	39
B.16 Corner Conditions	40
B.17 Surface Wave at Locally Reacting Plane	41
B.18 Surface Wave Along a Locally Reacting Cylinder	42
B.19 Periodic Structures, Admittance Grid	44
B.20 Plane Wall with Wide Grooves	48
B.21 Thin Grid on Half-Infinite Porous Layer	50
B.22 Grid of Finite Thickness with Narrow Slits on Half-Infinite Porous Layer	53
B.23 Grid of Finite Thickness with Wide Slits on Half-Infinite Porous Layer	56

C	Equivalent Networks	59
	<i>F.P. Mechel</i>	
C.1	Fundamentals of Equivalent Networks	59
C.2	Distributed Network Elements	65
C.3	Elements with Constrictions	71
C.4	Superposition of Multiple Sources in a Network	73
C.5	Chain Circuit	73
C.6	Partition Impedance of Orifices	74
D	Reflection of Sound	127
	<i>F.P. Mechel</i>	
D.1	Plane Wave Reflection at a Locally Reacting Plane	127
D.2	Plane Wave Reflection at an Infinitely Thick Porous Layer	129
D.3	Plane Wave Reflection at a Porous Layer of Finite Thickness	130
D.4	Plane Wave Reflection at a Multilayer Absorber	132
D.5	Diffuse Sound Reflection at a Locally Reacting Plane	133
D.6	Diffuse Sound Reflection at a Bulk Reacting Porous Layer	136
D.7	Sound Reflection and Scattering at Finite-Size Local Absorbers	136
D.8	Uneven, Local Absorber Surface	141
D.9	Scattering at the Border of an Absorbent Half-Plane	142
D.10	Absorbent Strip in a Hard Baffle Wall, with Far Field Distribution	144
D.11	Absorbent Strip in a Hard Baffle Wall, as a Variational Problem	146
D.12	Absorbent Strip in a Hard Baffle Wall, with Mathieu Functions	148
D.13	Absorption of Finite-Size Absorbers, as a Problem of Radiation	153
D.14	A Monopole Line Source Above an Infinite, Plane Absorber; Integration Method	154
D.15	A Monopole Line Source Above an Infinite, Plane Absorber; with Principle of Superposition	162
D.16	A Monopole Point Source Above a Bulk Reacting Plane, Exact Forms	165
D.17	A Monopole Point Source Above a Locally Reacting Plane, Exact Forms	167
D.18	A Monopole Point Source Above a Locally Reacting Plane, Exact Saddle Point Integration	170
D.19	A Monopole Point Source Above a Locally Reacting Plane, Approximations	173
D.20	A Monopole Point Source Above a Bulk Reacting Plane, Approximations	179
E	Scattering of Sound	185
	<i>F.P. Mechel</i>	
E.1	Plane Wave Scattering at Cylinders	185
E.2	Plane Wave Scattering at Cylinders and Spheres	188
E.3	Multiple Scattering at Cylinders and Spheres	198
E.4	Cylindrical Wave Scattering at Cylinders	199

E.5	Cylindrical or Plane Wave Scattering at a Corner Surrounded by a Cylinder	201
E.6	Plane Wave Scattering at a Hard Screen	208
E.7	Cylindrical or Plane Wave Scattering at a Screen with an Elliptical Cylinder Atop	209
E.8	Uniform Scattering at Screens and Dams	214
E.9	Scattering at a Flat Dam	223
E.10	Scattering at a Semicircular Absorbing Dam on Absorbing Ground	226
E.11	Scattering in Random Media, General	230
E.12	Function Tables for Monotype Scattering	238
E.13	Sound Attenuation in a Forest	242
E.14	Mixed Monotype Scattering in Random Media	244
E.15	Multiple Triple-Type Scattering in Random Media	248
E.16	Plane Wave Scattering at Elastic Cylindrical Shell	260
E.17	Plane Wave Backscattering by a Liquid Sphere	263
E.18	Spherical Wave Scattering at a Perfectly Absorbing Wedge	264
E.19	Impulsive Spherical Wave Scattering at a Hard Wedge	266
E.20	Spherical Wave Scattering at a Hard Screen	268
E.21	Spherical Wave Scattering at a Cone	270
E.22	Polar Mode Numbers at a Soft Cone	275
E.23	Polar Mode Numbers at a Hard Cone	279
E.24	Scattering at a Cone with Axial Sound Incidence	282
F	Radiation of Sound	287
	<i>F.P. Mechel</i>	
F.1	Definition of Radiation Impedance and End Corrections	287
F.2	Some Methods to Evaluate the Radiation Impedance	289
F.3	Spherical Radiators	291
F.4	Cylindrical Radiators	295
F.5	Piston Radiator on a Sphere	297
F.6	Strip-Shaped Radiator on Cylinder	299
F.7	Plane Piston Radiators	301
F.8	Uniform End Correction of Plane Piston Radiators	309
F.9	Narrow Strip-Shaped, Field-Excited Radiator	309
F.10	Wide Strip-Shaped, Field-Excited Radiator	311
F.11	Wide Rectangular, Field-Excited Radiator	313
F.12	End Corrections	316
F.13	Piston Radiating Into a Hard Tube	327
F.14	Oscillating Mass of a Fence in a Hard Tube	328
F.15	A Ring-Shaped Piston in a Baffle Wall	329
F.16	Measures of Radiation Directivity	330
F.17	Directivity of Radiator Arrays	330
F.18	Radiation of Finite Length Cylinder	335
F.19	Monopole and Multipole Radiators	337
F.20	Plane Radiator in a Baffle Wall	339

F.21	Ratio of Radiation and Excitation Efficiencies of Plates	344
F.22	Radiation of Plates with Special Excitations	344
G	Porous Absorbers	347
	<i>F.P. Mechel</i>	
G.1	Structure Parameters of Porous Materials	347
G.2	Theory of the Quasi-homogeneous Material	350
G.3	Rayleigh Model with Round Capillaries	352
G.4	Model with Flat Capillaries	354
G.5	Longitudinal Flow Resistivity in Parallel Fibres	356
G.6	Longitudinal Sound in Parallel Fibres	358
G.7	Transversal Flow Resistivity in Parallel Fibres	360
G.8	Transversal Sound in Parallel Fibres	370
G.9	Effective Wave Multiple Scattering in Transversal Fibre Bundle	381
G.10	Biot's Theory of Porous Absorbers	385
G.11	Empirical Relations for Characteristic Values of Fibre Absorbers	394
G.12	Characteristic Values from Theoretical Models Fitted to Experimental Data	399
H	Compound Absorbers	403
	<i>F.P. Mechel</i>	
H.1	Absorber of Flat Capillaries	404
H.2	Plate with Narrow Slits	407
H.3	Plate with Wide Slits	411
H.4	Dissipationless Slit Resonator	415
H.5	Resonance Frequencies and Radiation Loss of Slit Resonators	419
H.6	Slit Array with Viscous and Thermal Losses	420
H.7	Slit Resonator with Viscous and Thermal Losses	426
H.8	Free Plate with an Array of Circular Holes, with Losses	429
H.9	Array of Helmholtz Resonators with Circular Necks	435
H.10	Slit Resonator Array with Porous Layer in the Volume, Fields	437
H.11	Slit Resonator Array with Porous Layer in the Volume, Impedances	444
H.12	Slit Resonator Array with Porous Layer on Back Orifice	449
H.13	Slit Resonator Array with Porous Layer on Front Orifice	452
H.14	Array of Slit Resonators with Subdivided Neck Plate	456
H.15	Array of Slit Resonators with Subdivided Neck Plate and Floating Foil in the Gap	457
H.16	Array of Slit Resonators Covered with a Foil	462
H.17	Poro-elastic Foils	465
H.18	Foil Resonator	469
H.19	Ring Resonator	471
H.20	Wide-Angle Absorber, Scattered Far Field	474
H.21	Wide-Angle Absorber, Near Field and Absorption	480
H.22	Tight Panel Absorber, Rigorous Solution	485

H.23	Tight Panel Absorber, Approximations	493
H.24	Porous Panel Absorber, Rigorous Solution	496
I	Sound Transmission	503
	<i>F.P. Mechel</i>	
I.1	“Noise Barriers”	503
I.2	Sound Transmission through a Slit in a Wall	506
I.3	Sound Transmission through a Hole in a Wall	511
I.4	Hole Transmission with Equivalent Network	515
I.5	Sound Transmission through Lined Slits in a Wall	517
I.6	Chambered Joint	520
I.7	“Noise Sluice”	521
I.8	Sound Transmission Index sound transmission through plates through Plates, Some Fundamentals	525
I.9	Sound Transmission through a Simple Plate	532
I.10	Infinite Double-Shell Wall with Absorber Fill	538
I.11	Double-Shell Wall with Thin Air Gap	540
I.12	Plate with Absorber Layer Behind	541
I.13	Sandwich Panels	542
I.14	Finite-Size Plate	551
I.15	Single Plate across a Flat Duct	555
I.16	Single Plate in a Wall Niche	559
I.17	Strip-Shaped Wall in Infinite Baffle Wall	564
I.18	Finite-Size Plate with a Front Side Absorber Layer	567
I.19	Finite-Size Plate with a Back Side Absorber Layer	570
I.20	Finite-Size Double Wall with an Absorber Core	571
I.21	Plenum Modes	574
I.22	Sound Transmission through Suspended Ceilings	577
I.23	Office Fences	582
I.24	Office Fences, with Second Principle of Superposition	584
I.25	Infinite Plate Between Two Different Fluids	587
I.26	Sandwich Plate with an Elastic Core	589
I.27	Wall of Multiple Sheets with Air Interspaces	591
J	Duct Acoustics	595
	<i>F.P. Mechel</i>	
J.1	Flat Capillary with Isothermal Boundaries	595
J.2	Flat Capillary with Adiabatic Boundaries	598
J.3	Circular Capillary with Isothermal Boundary	598
J.4	Lined Ducts, General	601
J.5	Modes in Rectangular Ducts with Locally Reacting Lining	605
J.6	Least Attenuated Mode in Rectangular, Locally Lined Ducts	607
J.7	Sets of Mode Solutions in Rectangular, Locally Lined Ducts	613
J.8	Flat Duct with a Bulk Reacting Lining	619
J.9	Flat Duct with an Anisotropic, Bulk Reacting Lining	621
J.10	Mode Solutions in a Flat Duct with Bulk Reacting Lining	623

J.11	Flat Duct with Unsymmetrical, Locally Reacting Lining	625
J.12	Flat Duct with an Unsymmetrical, Bulk Reacting Lining	628
J.13	Round Duct with a Locally Reacting Lining	629
J.14	Admittance of Annular Absorbers Approximated with Flat Absorbers	643
J.15	Round Duct with a Bulk Reacting Lining	645
J.16	Annular Ducts	647
J.17	Duct with a Cross-Layered Lining	650
J.18	Single Step of Duct Height and/or Duct Lining	658
J.19	Sections and Cascades of Silencers, no Feedback	671
J.20	A Section with Feedback Between Sections Without Feedback	672
J.21	Concentrated Absorber in an Otherwise Homogeneous Lining	675
J.22	Wide Splitter-Type Silencer with Locally Reacting Splitters	680
J.23	Splitter-Type Silencer with Locally Reacting Splitters in a Hard Duct	683
J.24	Splitter Type Silencer with Simple Porous Layers as Bulk Reacting Splitters	688
J.25	Splitter-Type Silencer with Splitters of Porous Layers Covered with a Foil	692
J.26	Lined Duct Corners and Junctions	693
J.27	Sound Radiation from a Lined Duct Orifice	697
J.28	Conical Duct Transitions; Special Case: Hard Walls	702
J.29	Lined Conical Duct Transition, Evaluated with Stepping Duct Sections	705
J.30	Lined Conical Duct Transition, Evaluated with Stepping Admittance Sections	712
J.31	Mode Mixtures	715
J.32	Mode Excitation Coefficients	718
J.33	Cremer's Admittance	720
J.34	Cremer's Admittance with Parallel Resonators	725
J.35	Influence of Flow on Attenuation	731
J.36	Influence of Temperature on Attenuation	740
J.37	Stationary Flow Resistance of Splitter Silencers	741
J.38	Non-linearities by Amplitude and/or Flow	742
J.39	Flow-Induced Non-linearity of Perforated Sheets	748
J.40	Reciprocity at Duct Joints	750
J.41	Mode Sets in Flat Ducts with Unsymmetrical, Locally Reacting Lining	750
J.42	Mode Sets in Annular Ducts with Unsymmetrical, Locally Reacting Lining	754
J.43	Mode Sets in Annular Ducts via Mode Sets in Flat Ducts with Unsymmetrical Lining	762
J.44	Bent, Flat Ducts with Locally Reacting Lining	762
J.45	Lined Bow Duct Between Lined Straight Ducts	775
J.46	Zero-Order and First-Order Transmission Loss of Turning-Vane Splitter Silencers	781

J.47	Bent and Straight Ducts with Unsymmetrical Linings	785
J.48	Silencer with Rectangular Turning-Vane Splitters	787
K	Muffler Acoustics	793
	<i>M.L. Munjal, F.P. Mechel</i>	
K.1	Acoustic Power in a Flow Duct	793
K.2	Radiation from the Open End of a Flow Duct	795
K.3	Transfer Matrix Representation	796
K.4	Muffler Performance Parameters	796
K.5	Uniform Tube with Flow and Viscous Losses	798
K.6	Sudden Area Changes	799
K.7	Extended Inlet/Outlet	801
K.8	Conical Tube	803
K.9	Exponential Horn	804
K.10	Hose	804
K.11	Two-Duct Perforated Elements	806
K.12	Three-Duct Perforated Elements	814
K.13	Three-Duct Perforated Elements with Extended Perforations	820
K.14	Three-Pass (or Four-Duct) Perforated Elements	825
K.15	Catalytic Converter Elements	828
K.16	Helmholtz Resonator	830
K.17	In-Line Cavity	831
K.18	Bellows	831
K.19	Pod Silencer	832
K.20	Quincke Tube	833
K.21	Annular Airgap Lined Duct	834
K.22	Micro-Perforated Helmholtz Panel Parallel Baffle Muffler	836
K.23	Acoustically Lined Circular Duct	837
K.24	Parallel Baffle Muffler (Multipass Lined Duct)	839
L	Capsules and Cabins	843
	<i>F.P. Mechel</i>	
L.1	The Energetic Approximation for the Efficiency of Capsules	843
L.2	Absorbent Sound Source in a Capsule	847
L.3	Semicylindrical Source and Capsule	853
L.4	Hemispherical Source and Capsule	857
L.5	Cabins, Semicylindrical Model	861
L.6	Cabin with Plane Walls	865
L.7	Cabin with Rectangular Cross Section	869
M	Room Acoustics	873
	<i>M. Vorländer, F.P. Mechel</i>	
M.1	Eigenfunctions in Parallelepipeds	873
M.2	Density of Eigenfrequencies in Rooms	876
M.3	Geometrical Room Acoustics in Parallelepipeds	877
M.4	Statistical Room Acoustics	879
M.5	The Mirror Source Model	882

M.5.1	Foundation of Mirror Source Approximation	882
M.5.2	General Criteria for Mirror Sources	883
M.5.3	Field Angle of a Mirror Source	884
M.5.4	Multiple Covering of MS Positions	885
M.5.5	Convex Corners	886
M.5.6	Interrupt Criteria in the MS Method	887
M.5.7	Computational Parts of the MS Method	888
M.5.8	Inside Checks	888
M.5.9	What Is Needed in the Traditional MS Method?	889
M.5.10	The Object	890
M.5.11	A Concave Model Room, as an Example	891
M.5.12	The MS Method in Rooms with Convex Corners	896
M.5.13	A Model Room with Convex Corners	899
M.5.14	Other Grouping of Mirror Sources	903
M.5.15	Combination of Corner Fields to Obtain the Room Field	906
M.5.16	Collection of the MSs of a Wall Couple in a Corner Source	907
M.5.17	A Kind of Reciprocity in the MS Method	910
M.5.18	Limit Case of Parallel Walls	910
M.5.19	The Second Principle of Superposition (PSP)	913
M.5.20	The PSP for Unsymmetrical Absorption	920
M.5.21	A Global Application of the PSP	921
M.5.22	Reverberation Time with Results of the MS Method	922
M.5.23	A Room with Concave Edges as an Example	924
M.6	Ray-Tracing Models	935
M.7	Room Impulse Responses, Decay Curves and Reverberation Times	939
M.8	Other Room Acoustical Parameters	940
N	Flow Acoustics	945
	<i>P. Költzsch</i>	
N.1	Concepts and Notations in Fluid Mechanics, in Connection with the Field of Aeroacoustics	945
N.1.1	Types of Fluids	945
N.1.2	Properties of Fluids	945
N.1.3	Models of Fluid Flows	946
N.2	Some Tools in Fluid Mechanics and Aeroacoustics	949
N.2.1	Averaging	949
N.2.2	Decomposition (in General)	950
N.2.3	Decomposition of the Physical Quantities in the Basic Equations	951
N.2.4	Correlations	953
N.2.5	Scales	953
N.3	The Basic Equations of Fluid Motion	954
N.3.1	Continuity Equation, Momentum Equation, Energy Equation	954
N.3.2	Thermodynamic Relationships	955

N.3.3	Non-linear Perturbation Equations, non-linear Euler Equations	956
N.3.4	Formulation of Euler Equations to Use in Computational Aeroacoustics (CAA)	958
N.4	The Equations of Linear Acoustics	960
N.5	Inhomogeneous Wave Equation, Lighthill's Acoustic Analogy	963
N.5.1	Lighthill's Inhomogeneous Wave Equation	963
N.5.2	Solutions of Inhomogeneous Wave Equation	965
N.6	Acoustic Analogy with Source Terms Using Pressure	967
N.6.1	Lighthill's Representation of the Source Term with Use of Pressure	967
N.6.2	Pressure-Source theory (Ribner)	968
N.6.3	Pressure-Source Theory (Meecham)	969
N.7	Acoustic Analogy with Mean Flow Effects, in the Form of Convective Inhomogeneous Wave Equation	970
N.7.1	Phillips's Convective Inhomogeneous Wave Equation	970
N.7.2	Lilley's Convective Inhomogeneous Wave Equation	971
N.7.3	Lilley's Wave Equation with a New Lighthill Stress Tensor	972
N.7.4	Convected Wave Equation for the Dilatation (Legendre)	972
N.7.5	Goldstein's Third-Order Inhomogeneous Wave Equation	973
N.7.6	Goldstein-Howes Inhomogeneous Wave Equation	973
N.7.7	Ribner's Recent Reformulation of Lighthill's Source Term	974
N.7.8	Inhomogeneous Wave Equation Including Stream Function (Albring/Detsch)	975
N.8	Acoustic Analogy in Terms of Vorticity, Wave Operators for Enthalpy	976
N.8.1	Powell's Theory of Vortex Sound	976
N.8.2	Howe's Formulation of Acoustic Analogy Equation for Total Enthalpy	977
N.8.3	Möhring's Equation with Source Term Linearly Dependent on Vorticity Field	980
N.8.4	Convected Wave Operators for Total Enthalpy in Comparison	980
N.8.5	Doak's Theory of Aerodynamic Sound Including the Fluctuating Total Enthalpy as a Basic Generalised Acoustic Field for a Fluid	981
N.9	Acoustic Analogy with Effects of Solid Boundaries	984
N.9.1	Ffowcs Williams-Hawkings (FW-H) Inhomogeneous Wave Equation, FW-H Equation in Differential and Integral Form	984
N.9.2	Curle's Equation	988
N.10	Acoustic Analogy in Terms of Entropy, Heat Sources as Sound Sources, Sound Generation by Turbulent Two-Phase Flow	988
N.10.1	Acoustic Analogy in Terms of Entropy, Sound Generation by Fluctuating Heat Sources (Dowling, Howe)	988

N.10.2	Acoustic Analogy in Terms of Heat Release, Turbulent Density Fluctuations and Turbulent Velocity Fluctuations on Outer Flame Surface (Strahle)	991
N.10.3	Sound Power Radiated by a Turbulent Flame	991
N.10.4	Sound Generation by Turbulent Two-Phase Flow	992
N.11	Acoustics of Moving Sources	993
N.11.1	Sound Field of Moving Point Sources	994
N.11.2	Formulation of Equation of Sound Sources in Motion Based on Ffowcs Williams–Hawkings Equation	997
N.11.3	Moving Kirchhoff Surfaces	998
N.12	Aerodynamic Sound Sources in Practice	1000
N.12.1	Jet Noise	1000
N.12.2	Rotor Noise	1007
N.13	Power Law of the Aerodynamic Sound Sources	1012
O	Analytical and Numerical Methods in Acoustics	1019
	<i>M. Ochmann, F.P. Mechel</i>	
O.1	Computational Optimisation of Sound Absorbers	1019
O.2	Computing with Mixed Numeric-Symbolic Expressions, Illustrated with Silencer Cascades	1028
O.3	Five Standard Problems of Numerical Acoustics	1034
O.3.1	The Radiation Problem	1034
O.3.2	The Scattering Problem	1036
O.3.3	The Sound Field in Interior Spaces	1037
O.3.4	The Coupled Fluid–Elastic Structure Interaction Problem	1037
O.3.5	The Transmission Problem	1039
O.4	The Source Simulation Technique (SST)	1040
O.4.1	General Description of the Source Simulation Technique	1041
O.4.2	Spherical Wave Functions and Symmetry Relations	1042
O.4.3	Variants of the SST with Spherical Wave Functions	1044
O.4.4	Position of Sources and Their Optimal Choice	1053
O.4.5	Numerical Aspects	1054
O.4.6	A Numerical Example: Sound Scattering from a Non-Convex Cat’s-Eye Structure	1056
O.4.7	Concluding Remarks	1057
O.5	The Boundary Element Method (BEM)	1059
O.5.1	Boundary Integral Equations	1059
O.5.2	Discretization of the Boundary Integral Equation	1063
O.5.3	Solution of the Linear System of Equations	1064
O.5.4	Critical Frequencies and Other Singularities	1066
O.5.5	The Interior Problem: Sound Fields in Rooms and Half-Spaces	1070
O.5.6	The Scattering and the Transmission Problem	1072
O.6	The Finite Element Method (FEM)	1074
O.6.1	Introduction	1074

O.6.2	The Sound Field in Irregular Shaped Cavities with Rigid Walls	1075
O.6.3	Supplementary Aspects and Fluid-Structure Coupling	1078
O.7	The Cat's Eye Model	1081
O.7.1	Cat's Eye Model and General Fundamental Solutions*)	1082
O.7.2	Mode Orthogonality	1085
O.7.3	Remaining Boundary Conditions	1086
O.7.4	Mode Coupling Integrals	1088
O.7.5	Reduction of the System of Equations	1091
O.8	The Orange Model	1094
O.8.1	Elementary Solutions and Field Formulations	1094
O.8.2	Orthogonality of Modes	1095
O.8.3	Field Matching	1096
O.8.4	Mode Coupling Integrals and Mode Norms	1098
O.8.5	Reduction of the Systems of Equations	1098
O.8.6	Numerical Examples	1099
P	Variational Principles in Acoustics	1109
	<i>A. Cummings</i>	
P.1	Eigenfrequencies of a Rigid-Walled Cavity and Modal Cut-on Frequencies of a Uniform Flat-Oval Duct with Zero Mean Fluid Flow	1110
P.2	Sound Propagation in a Uniform Narrow Tube of Arbitrary Cross-Section with Zero Mean Fluid Flow	1112
P.3	Sound Propagation in a Uniform, Rigid-Walled, Duct of Arbitrary Cross-Section with a Bulk-Reacting Lining and no Mean Fluid Flow: Low Frequency Approximation	1117
P.4	Sound Propagation in a Uniform, Rigid-Walled, Rectangular Flow Duct Containing an Anisotropic Bulk-Reacting Wall Lining or Baffles	1118
P.5	Sound Propagation in a Uniform, Rigid-Walled, Flow Duct of Arbitrary Cross-Section, with an Inhomogeneous, Anisotropic Bulk Lining	1120
P.6	Sound Propagation in a Uniform Duct of Arbitrary Cross-Section with one or more Plane Flexible Walls, an Isotropic Bulk Lining and a Uniform Mean Gas Flow	1124
P.7	Sound Propagation in a Rectangular Section Duct with four Flexible Walls, an Anisotropic Bulk Lining and no Mean Gas Flow	1127
Q	Elasto-Acoustics	1133
	<i>W. Maysenhölder, F.P. Mechel</i>	
Q.1	Fundamental Equations of Motion	1133
Q.2	Anisotropy and Isotropy	1135
Q.3	Interface Conditions, Reflection and Refraction of Plane Waves	1139
Q.4	Material Damping	1140
Q.5	Energy	1143
Q.5.1	General Relations	1143

Q.5.2	Surface Intensity	1143
Q.5.3	Time-Harmonic Wavefields	1144
Q.5.4	Rayleigh's Principle	1144
Q.5.5	Energy Velocity and Group Velocity	1145
Q.6	Random Media	1145
Q.7	Periodic Media	1146
Q.8	Homogenisation	1148
Q.8.1	Bounds on Effective Moduli	1148
Q.8.2	Effective Moduli for Particular Structures	1149
Q.9	Plane Waves in Unbounded Homogeneous Media	1151
Q.9.1	Anisotropic Media	1151
Q.9.2	Isotropic Media	1153
Q.10	Waves in Bounded Media	1154
Q.10.1	Plate Waves	1154
Q.10.2	Rayleigh Waves	1159
Q.10.3	Waves in Thin Plates	1160
Q.10.4	Waves in Thin Beams	1163
Q.11	Moduli of Isotropic Materials and Related Quantities	1165
Q.12	Modes of Rectangular Plates	1170
Q.13	Partition Impedance of Plates	1174
Q.14	Partition Impedance of Shells	1176
Q.15	Density of Eigenfrequencies in Plates, Bars, Strings, Membranes	1178
Q.16	Foot Point Impedances of Forces	1179
Q.17	Transmission Loss at Steps, Joints, Corners	1184
Q.18	Cylindrical Shell	1186
Q.19	Similarity Relations for Spherical Shells	1190
Q.20	Sound Radiation From Plates	1191
R	Ultrasound Absorption in Solids	1197
	<i>W. Arnold</i>	
R.1	Generation of Ultrasound	1198
R.2	Ultrasonic attenuation	1199
R.3	Absorption and Dispersion in Solids Due to Dislocations	1204
R.4	Absorption Due to the Thermoelastic Effects, Phonon Scattering and Related Effects	1206
R.5	Interaction of Ultrasound with Electrons in Metals	1208
R.6	Wave Propagation in Piezoelectric Semiconducting Solids	1210
R.7	Absorption in Amorphous Solids and Glasses	1210
R.8	Relation of Ultrasonic Absorption to Internal Friction	1211
R.9	Gases and Liquids	1211
R.10	Kramers-Kronig Relation	1211
	Chapter Index	1215
	General Index	1251

Contributors

Prof. Dr. M. L. Munjal
Dept. Mechanical Engineering
Indian Institute of Science
Bangalore 560 012
India

Prof. Dr. M. Vorländer
Institut für Technische Akustik
RWTH Aachen
Templergraben 55
52056 Aachen
Germany

Prof. Dr. Peter Költzsch
Jägerstraße 17
01099 Dresden
Germany

Prof. Dr. M. Ochmann
Technische Fachhochschule Berlin
Luxemburger Straße 10
13353 Berlin
Germany

Prof. Dr. A. Cummings
Trenwith
Ludlow Road, Little Stretton, Church Stretton
Salop SY6 6RB
UK

Prof. Dr. W. Maysenhölder
Altenbergstraße 33
70180 Stuttgart
Germany

Prof. Dr. W. Arnold
Frauenhofer Institut für Prüfverfahren
Universität Saarbrücken, Gebäude 37
66123 Saarbrücken
Germany