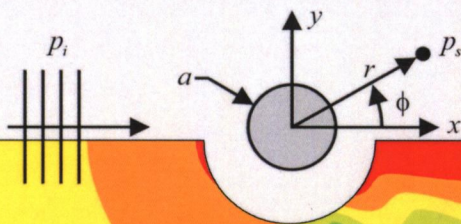


Acoustic Analyses Using **MATLAB[®]** and **ANSYS[®]**

Carl Q. Howard and Benjamin S. Cazzolato



CRC Press
Taylor & Francis Group

A SPON PRESS BOOK

Acoustical Engineering

"This book is a must for those wanting to explore and investigate the world of computational engineering acoustics. ...Its comprehensive instructional framework supports a conversational, down-to-earth narrative style."

—Andrew Peplow, *Noise and Vibration Specialist*,
Atlas Copco Rock Drills, Sweden

"These guys know their stuff!! ...I thoroughly recommend this book to anyone who is involved in acoustic modelling—it forms the perfect basis for acoustic coursework as well as being useful for research and industrial modelling of acoustic devices."


—Ian Bedwell, *Thales Australia, Underwater Systems, Technical Consultant*

This is the first book of its kind that describes the use of Ansys® finite element analysis (FEA) software, and MATLAB® engineering programming software to solve acoustic problems. It covers simple text book problems, such as determining the natural frequencies of a duct, to progressively more complex problems that can only be solved using FEA software, such as acoustic absorption and fluid-structure-interaction. It also presents benchmark cases that can be used as starting points for analysis. There are practical hints too for using ANSYS software. The material describes how to solve numerous problems theoretically, and how to obtain solutions from the theory using MATLAB engineering software, as well as analyzing the same problem using ANSYS Workbench and ANSYS Mechanical APDL.

The source code for MATLAB scripts and ANSYS models, which provide readers with valuable tools for doing their own validations are available for download at <http://www.mecheng.adelaide.edu.au/avc/software>. **Acoustic Analyses Using MATLAB® and ANSYS®** can be used as a textbook for graduate students in acoustics, vibration, and related areas in engineering; undergraduates in mechanical and electrical engineering; and as an authoritative reference for industry professionals.

Dr. Carl Howard is a lecturer at the University of Adelaide. He has been a consultant with Vipac Engineers and Scientists, Warley, and Colin Gordon and Associates, and also worked at United Technologies Research Center.

Dr. Ben Cazzolato is an associate professor at the University of Adelaide. He has over two decades' experience as an acoustic consultant and academic researcher.

 **CRC Press**
Taylor & Francis Group
an informa business
www.crcpress.com

K22321

ISBN 978-1-138-74748-7



9 781138 747487

Howard

Cazzolato

Acoustic Analysises Using MATLAB[®] and ANSYS[®]



Acoustic Analyses Using **MATLAB®** and **ANSYS®**

Carl Q. Howard and Benjamin S. Cazzolato



CRC Press

Taylor & Francis Group

Boca Raton London New York

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

A SPON PRESS BOOK

MATLAB® and Simulink® are trademarks of The MathWorks, Inc. and are used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB® and Simulink® software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB® and Simulink® software.

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

First issued in paperback 2017

© 2015 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

ISBN-13: 978-1-4822-2325-5 (hbk)
ISBN-13: 978-1-138-74748-7 (pbk)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Howard, Carl Q., 1970- author.
Acoustic analyses using Matlab and Ansys / Carl Q. Howard and Benjamin S. Cazzolato.
pages cm
Summary: "This book describes the use of Ansys finite element analysis software and MATLAB
Includes bibliographical references and index.
ISBN 978-1-4822-2325-5 (hardback)
1. Acoustical engineering--Mathematics. 2. Finite element method--Data processing. 3.
MATLAB. 4. ANSYS (Computer system) I. Cazzolato, Benjamin S., 1969- author. II. Title.

TA365.H69 2015
620.20285'53--dc23
2014015094

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Acoustic Analyses Using
MATLAB®
and ANSYS®

Foreword

Although ANSYS Mechanical has supported acoustic and vibroacoustic analyses for more than two decades, it was not until relatively recently that the demand for performing these simulations has grown appreciably. Over the past several years, noise considerations for rotating machinery, passenger comfort in vehicles, and acoustic performance of tablets and other ubiquitous electronic devices have taken a more dominant role in their respective design processes. These, of course, are but a few examples out of many applications where the engineer must now consider the acoustic response along with traditional structural and thermal simulations in evaluating product design.

Development of the acoustic capabilities in ANSYS Mechanical has been driven by customer feedback and requirements, and the fruit of these efforts have enabled analysts to solve challenging problems in ANSYS Workbench in a fraction of the time historically needed. That being said, however, for many engineers, acoustics may be a new field to them; conversely, acousticians may not be familiar with how certain concepts are implemented in a finite element software program.

This book provides an in-depth and practical guide on performing acoustic and vibroacoustic simulations using ANSYS Mechanical. For the engineer with limited background in acoustics, this text serves as an excellent companion to other books that cover acoustic fundamentals; the numerous examples provide many opportunities for the reader to relate finite element results with theory and learn best practices along the way. For the acoustician, the explanations focused on numerical methods as well as the comparisons with MATLAB results are illuminating, and the step-by-step instructions are invaluable for readers new to ANSYS Workbench.

It is a pleasure for me to write the introduction to this book, and I am certain it will have a wide appeal in both academic and industrial circles. Carl Howard and Ben Cazzolato have produced a well-written and practical reference that will help the reader enter the exciting world of acoustical numerical simulation.

Sheldon Imaoka
Principal Engineer
ANSYS, Inc.

Preface

The use of finite element analysis (FEA) to solve acoustic problems has enabled investigation of complex situations that would otherwise be too cumbersome or time consuming to solve using analytical methods. Many analytical methods are only suitable for solving regular-shaped objects such as ducts, hard-walled rectangular cavities, and so on.

Although finite element analysis can be used to solve complex problems, there is a steep learning curve for practitioners. One must have a good grasp of the science of acoustics. They must understand many concepts and limitations of finite element analysis. Even if they have all this knowledge, they must also know the nuances of a particular finite element analysis software package and its particular quirks. Lastly, if a practitioner has been able to calculate answers using finite element analysis, they need to have a sense of whether the answers predicted by the software are reasonable. The Garbage-In-Garbage-Out (GIGO) principle applies as it is easy to generate misleading results.

The contents of this book attempt to address only the last few of these hurdles: “how to drive” the ANSYS[®] finite element analysis software to solve a variety of acoustic problems. The fundamentals and applications of acoustics are covered in many other textbooks and are not the focus of this book. As for training in finite element analysis, many books are written by mathematicians or academics and their target audience seems to be for other mathematicians or academics. These books contain derivations of shape functions for various finite elements and the nuts-and-bolts of various matrix inversion algorithms so that someone with a lot of time on their hands can create their own finite element software. Whilst these are important topics, a practicing engineer has no spare time and is not going to create his or her own finite element software. Instead, an engineer wants a short sharp bullet list of instructions to get the job done.

We are both mechanical engineers and our backgrounds are in consulting engineering, academic research, and university training of students to become professional engineers. This book contains examples with flavors from these arenas. The goal was to provide instruction in solving acoustic problems starting with simple systems such as a duct, and then progressively more involved problems such as acoustic absorption and fluid–structure interaction. The theory of the acoustic problem is presented and then implemented in MATLAB[®] code, which is included with this book. An ANSYS finite element model of the problem is described and the completed models are included with this book. The combination of these three aspects provides the practitioner with

benchmark cases that can be used as starting points for the analysis of their own acoustic problems.

At times a reader might find the instructions in this book to be verbose or repetitive. Although this might irritate some readers, it is better to provide detailed instructions rather than frustrate a new analyst, or someone that has started halfway through the book. We have tried to avoid using expressions such as “clearly,” or “it is obvious,” as what might be obvious for some readers is baffling to another and instead provide detailed instructions and comprehensive explanations.

The release of the ACT Acoustics extension for ANSYS Workbench has made the use of the software significantly easier for a new analyst to solve acoustic problems. The extension is essentially a toolbar that enables the user to select the relevant acoustic feature that he or she wants to include in the analysis, such as an acoustic mass source, an absorbing boundary, and so on.

We trust that you will find this book a useful resource for learning how to conduct acoustic analyses using ANSYS and MATLAB[®] and will enable you to solve your own acoustic problems.

Carl Howard and Ben Cazzolato
Adelaide

MATLAB[®] and Simulink[®] are registered trademarks of The MathWorks, Inc. For product information, please contact:

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098 USA
Tel: 508 647 7000
Fax: 508-647-7001
E-mail: info@mathworks.com
Web: www.mathworks.com

Acknowledgments

The authors wish to acknowledge the support of the following people that have enabled the completion of this book: David Roche, Sheldon Imaoka, Grama Bhashyam at ANSYS, Inc., for the numerous technical discussions; Sam Nardella; Srini Bandla, Jindong Yang, and Greg Horner at LEAP Australia, for technical assistance; Boyin Ding for proofreading the book; Colin Hansen, our mentor, for encouraging us to write this book; Chenxi Li, for assistance with the micro-perforated panel material; and John Pearse, for hosting the first author at the University of Canterbury while writing this book.

We also wish to acknowledge and thank our families for the unwavering support and encouragement: Nicole, Natalie, and Sarah; Thu-Lan, Toby, and Marcus.

Contents

Foreword	xxxiii
Preface	xxxv
Acknowledgments	xxxvii
1 Introduction	1
1.1 About This Book	1
1.1.1 MATLAB Code	1
1.1.2 ANSYS	2
1.1.3 ANSYS Workbench Models	2
1.1.4 ANSYS Mechanical APDL Code	3
1.2 A Philosophy for Finite Element Modeling	3
1.3 Analysis Types	6
1.3.1 Modal	7
1.3.2 Harmonic	8
1.3.3 Transient Dynamic Analysis	9
1.3.4 Spectrum Analysis	10
2 Background	11
2.1 Learning Outcomes	11
2.2 Introduction	11
2.3 Pressure-Formulated Acoustic Elements	13
2.4 Fluid–Structure Interaction	13
2.5 Displacement-Formulated Acoustic Elements	17
2.6 Practical Aspects of Modeling Acoustic Systems with FEA	19
2.7 Element Types in ANSYS for Acoustic Analyses	22
2.7.1 FLUID29 2D Acoustic Fluid Element	23
2.7.2 FLUID30 3D Acoustic Fluid Element	24
2.7.3 FLUID129 2D Infinite Acoustic Element	26
2.7.4 FLUID130 3D Infinite Acoustic Element	28
2.7.5 FLUID220 3D Acoustic Fluid 20-Node Solid Element	30
2.7.6 FLUID221 3D Acoustic Fluid 10-Node Solid Element	31
2.8 ACT Acoustics Extension	32
2.8.1 Acoustic Body	32
2.8.2 Excitation	36
2.8.2.1 Wave Sources	36

2.8.2.2	Normal Surface Velocity	47
2.8.2.3	Mass Source	48
2.8.2.4	Surface Velocity	49
2.8.2.5	Normal Surface Acceleration	49
2.8.2.6	Mass Source Rate	51
2.8.2.7	Surface Acceleration	51
2.8.3	Body Force Loads	51
2.8.3.1	Static Pressure	52
2.8.3.2	Impedance Sheet	53
2.8.3.3	Temperature	53
2.8.4	Boundary Conditions	54
2.8.4.1	Acoustic Pressure	54
2.8.4.2	Impedance Boundary	55
2.8.4.3	Thermo-viscous BLI Boundary	58
2.8.4.4	Free Surface	58
2.8.4.5	Radiation Boundary	59
2.8.4.6	Absorbing Elements	59
2.8.4.7	Attenuation Surface	60
2.8.4.8	Equivalent Source Surface	61
2.8.5	Results	62
2.8.5.1	Acoustic Pressure	62
2.8.5.2	Acoustic Sound Pressure Level	65
2.8.5.3	Acoustic Velocity	66
2.8.5.4	Acoustic Pressure Gradient	67
2.8.5.5	Acoustic Far Field	67
2.8.5.6	Acoustic Near Field	70
2.8.5.7	Acoustic Time Frequency Plot	73
2.8.5.8	Muffler Transmission Loss	74
2.8.5.9	Tools	75
2.8.5.10	Insertion of Boundary Conditions Based on Named Selections	76
2.8.5.11	Insertion of FSI Interfaces Based on Contacts	77
2.9	Other Acoustic Loads	77
2.9.1	Displacement	78
2.9.2	Flow	78
2.10	Other Measures of Acoustic Energy	79
2.10.1	Sound Intensity	80
2.10.2	Sound Power	82
2.10.3	Acoustic Potential Energy	84
2.10.4	Acoustic Energy Density	85
2.10.5	Structural Kinetic Energy	86
2.11	Mesh Density	87
2.12	Use of Symmetry	90

3	Ducts	101
3.1	Learning Outcomes	101
3.2	Theory	101
3.2.1	Natural Frequencies	102
3.2.2	Four-Pole Method	103
3.2.3	Acoustic Performance Metrics	105
3.3	Example of a Circular Duct	106
3.3.1	ANSYS Workbench	107
3.3.2	Results: Effect of Mesh Density	130
3.3.3	Natural Frequencies of Open–Rigid and Open–Open Ducts	134
3.3.4	Pressure and Velocity Distribution along the Duct . .	138
3.3.5	Results: Pressure and Velocity along the Duct	144
3.3.6	Infinite and Semi-Infinite Loss-Less Ducts	146
3.3.7	Radiation from an Open-Ended Duct	147
3.3.7.1	Theory	148
3.3.7.2	ANSYS Workbench	149
3.3.7.3	Results	159
3.3.7.4	Impedance Varying with Frequency	161
3.3.7.5	Results	164
3.4	Resonator Silencers	166
3.4.1	Geometries	166
3.4.2	Example: Quarter-Wavelength Tube Silencer	167
3.4.2.1	Theory	167
3.4.2.2	MATLAB	170
3.4.2.3	ANSYS Workbench	170
3.4.3	Example: Expansion Chamber Silencer	186
3.4.3.1	Theory	187
3.4.3.2	MATLAB	188
3.4.3.3	ANSYS Workbench	189
3.4.3.4	Results	191
3.5	Non-Plane Waves	193
3.6	Gas Temperature Variations	200
3.6.1	Theory	200
3.6.2	MATLAB	203
3.6.3	ANSYS Workbench	204
3.6.4	ANSYS Mechanical APDL	220
4	Sound Inside a Rigid-Walled Cavity	225
4.1	Learning Outcomes	225
4.2	Description of the System	225
4.3	Theory	225
4.3.1	Natural Frequencies and Mode Shapes	226
4.3.2	Harmonic Response	227
4.4	Example	228

4.4.1	MATLAB	228
4.4.2	ANSYS Workbench	229
4.4.3	ANSYS Mechanical APDL	246
4.4.4	Results	249
5	Introduction to Damped Acoustic Systems	255
5.1	Learning Outcomes	255
5.2	Introduction	255
5.2.1	Viscous or Linear Damping	256
5.2.2	Hysteretic or Structural Damping	258
5.2.3	Air Damping	258
5.2.4	Coulomb Damping	259
5.3	General Discussion of Damping of Vibro-Acoustic Systems in ANSYS	259
5.4	Theory	266
5.5	Example: 2D Impedance Tube with a Real Admittance	269
5.5.1	Description of the System	269
5.5.2	Theory	270
5.5.3	Model	272
5.5.4	MATLAB	273
5.5.5	ANSYS Mechanical APDL	273
5.6	Example: 2D Impedance Tube with a Complex Termination Impedance	279
5.6.1	Description of the System	279
5.6.2	ANSYS Mechanical APDL	280
5.7	Example: 2D Impedance Tube	284
5.7.1	Theory	285
5.7.2	Example	286
5.7.3	MATLAB	287
5.7.4	ANSYS Mechanical APDL	287
5.8	Example: 3D Impedance Tube	290
5.8.1	Model	290
5.8.2	ANSYS Workbench	290
5.8.3	Discussion	300
5.9	Example: 3D Waveguide with Visco-Thermal Losses	302
5.9.1	Theory	303
5.9.2	Model	305
5.9.3	MATLAB	306
5.9.4	ANSYS Workbench	306
5.9.5	ANSYS Mechanical APDL	313
5.10	Application of Spectral Damping to a Rigid-Walled Cavity	313
5.10.1	Spectral Damping Types	314
5.10.2	Example: Damping in a Rigid-Walled Cavity	316
5.10.3	MATLAB	316
5.10.4	ANSYS Mechanical APDL	316