# Vibro-Acoustics

## Fundamentals and Applications

Dhanesh N. Manik

CRC Press
Taylor & Francis Group

Engineering - Mechanical

The subject of vibro-acoustics is important for the better design of machine elements and structures, to minimize sound generated by them. In view of the design cycles of machines becoming shorter, designers need to design quiet machines at the drawing-board stage rather than applying "band-aid" techniques after the machine has been built. Those interested in low-frequency vibration are generally concerned with the modal approach of using natural frequencies and mode shapes, whereas those interested in vibro-acoustics in medium and high frequencies are generally concerned with the wave approach. Since both approaches have their advantages, it is a good idea to study both together to get the best out of them. This is useful for a better understanding of the physics of vibro-acoustics. Written for students and professionals, this book systematically integrates the relevant aspects of vibro-acoustics from various viewpoints and

- Covers fundamental aspects of noise and vibration and their mutual interaction
- Discusses both modal and wave approaches for studying dynamic systems
- Simplifies circuit theory concepts
- Provides a solid understanding of the physics of vibro-acoustics through seamless integration of vibration and acoustics
- A good primer for statistical energy analysis (SEA) users

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

6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

K18860

ISBN: 978-1-4665-8093-0

90000

9 781466 580930

www.crcpress.com

Manik

# Vibro-Acoustics

# Vibro-Acoustics
## Fundamentals and Applications

Dhanesh N. Manik
Professor, Mechanical Engineering
IIT Bombay
Powai, Mumbai, India


CRC Press
Taylor & Francis Group
Boca Raton London New York

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

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



Printed by CPI on sustainable paper
Version Date: 20161117

International Standard Book Number-13: 978-1-4665-8093-0 (Hardback)



**Library of Congress Cataloging-in-Publication Data**

Names: Manik, Dhanesh N., author.
Title: Vibro-acoustics : fundamentals and applications / Dhanesh N. Manik.
Description: Boca Raton : CRC Press, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2016043113| ISBN 9781466580930 (hardback : alk. paper) |
ISBN 9781466580947 (ebook)
Subjects: LCSH: Sound-waves--Damping. | Damping (Mechanics) | Machine design. | Noise control.
Classification: LCC TA355 .M295 2017 | DDC 620.3/7--dc23
LC record available at https://lccn.loc.gov/2016043113

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

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

# Vibro-Acoustics
## Fundamentals and Applications

*Dedicated to my wife, Nisha*

# *Preface*

This book is mainly focused on the viewpoint of those interested in modeling vibro-acoustic systems for designing quiet machines at the drawing-board stage. It is well known that modeling is always cost-effective and is much superior to cut-and-try empirical methods that are not expected to give definite results. The subject matter of vibro-acoustics is very vast and is, therefore, difficult to compress it into about 500 pages of print. But the main objective is to provide all the necessary fundamentals for the reader who can very easily move to other reference books and then comprehend material that is available in the literature; in short, the main objective is to give an easier learning curve for those interested in vibro-acoustics, especially those students at the advanced undergraduate stage.

Background in the following areas is expected: mechanics, circuit theory, fluid mechanics, and mathematics. Therefore, those from any of the engineering disciplines should be able to follow this book. The style adapted in writing this book is pedagogical and hence very easy to follow without any secondary reading. The entire book can be taught as a semester course or some parts of this book can be used to teach a course on noise control.

Most parts of this book have evolved based on the postgraduate elective on vibro-acoustics I have taught at the Indian Institute of Technology (IIT) Bombay for the past 5 years. Therefore, it has undergone many useful changes over a period of time, based on the feedback from students. The course, taught over a period of 14 weeks with tutorials, quizzes, exams, and so on, generated content for this book. Hence, sufficient care has been taken to write this book so the student can easily comprehend the basics of vibro-acoustics through independent reading, supplemented by classroom teaching. I have also used most parts of this book to teach continuing education programs for practicing engineers. Therefore, practicing engineers can also benefit from using this as a reference book, as there are many illustrated practical applications.

The contents have been carefully selected based on my extensive experience of teaching industry professionals and students for the past 23 years. I would have rather preferred to directly use an existing textbook to teach vibro-acoustics. But unfortunately, it was hard to find a book that could give all the necessary information that is required for a beginner to master vibro-acoustics. In addition, many of the authors of reference material in vibro-acoustics are from a physics or electrical engineering background and, therefore, have a different perception of their audience. Due to these reasons, I decided to write this book so that someone interested in vibro-acoustics can get most of it from a cover to cover reading.

Another important reason for writing this book is the division among those working in various aspects of vibration and noise; some of them use only the modal approach and others the wave approach. There are a chosen few who use both of them, for example, Norton. Since each of these approaches has their own advantages, I have used both approaches extensively wherever relevant, so the reader feels much more comfortable to expand the horizons of learning without any difficulty. This approach, therefore, will help to spread the knowledge of vibro-acoustics to a wider audience, rather than being restricted to a chosen few.

The book is divided into 10 chapters. Beginning with a single-degree-of-freedom system, the vibratory behavior of multidegree-of-freedom systems and continuous systems are discussed using both the modal and wave approaches. The basic principles of airborne sound are then discussed along with their measurement techniques. Random vibration,

which is commonly encountered in many vibro-acoustic systems, is discussed to emphasize the basic concept of broadband excitation. Acoustic sources like monopoles, dipoles, and baffled pistons are discussed, which will help in objective description of the source strength. This will also help relating how vibration can produce airborne sound and vice versa. The physics of sound–structure interaction with respect to flexible vibrating structure is clearly explained without using too much mathematics. The basic information for studying information on statistical energy analysis (SEA) is organized systematically in sequence in the first 9 chapters to prepare for the final chapter. In Chapter 10, the basics of SEA are presented along with many applications.

The book is organized in such a way that information related to vibration and noise is logically presented so that they can be eventually unified to determine the extent of noise radiation due to vibration. The sequence is such that all the chapters can be sequentially studied without having to go back and forth. The physics of dynamic systems is emphasized throughout so that the reader in not just lost in mathematics. Therefore, the information presented here will be very useful for modeling vibro-acoustic systems. After going through this book, many other reference books and journal papers in this area can be easily studied. The main objective of this book is to prepare a new graduate student in vibro-acoustics.

**Dhanesh N. Manik**
*Mumbai, India*

# *Acknowledgments*

I thank my PhD supervisor at Auburn University, Dr. Malcolm J. Crocker, for introducing me to these wonderful subjects of vibration and acoustics. I thank my students who had taken my elective course on vibro-acoustics all these years for their valuable feedback. I thank IIT Bombay for providing support in preparing the manuscript.

# *Author*

**Dhanesh N. Manik** was born in Mysore, India. He graduated with a bachelor's degree in mechanical engineering from Mysore University in 1982; a master's degree in mechanical engineering from Indian Institute of Science (IISc), Bangalore, in 1985; and a PhD in mechanical engineering from Auburn University in Alabama in 1991. He also briefly worked at Hindustan Aeronautics (Helicopter Division), Bangalore, from 1985 to 1986. He joined the faculty of Indian Institute of Technology Bombay in 1992 and is currently a professor in mechanical engineering. His main areas of research are statistical energy analysis (SEA) and machinery diagnostics. He is a member of the International Institute of Acoustics and Vibration; Acoustical Society of India; and National Committee on Noise Pollution Control, Central Pollution Control Board, India. He is a consultant to many projects from industry related to vibration and noise, and regularly conducts continuing education programs to industry professionals on vibration and noise. He has authored a book on control systems (Cengage India, 2012).

# Contents


Preface ..... xiii
Acknowledgments ..... xv
Author ..... xvii

**1. Single-Degree-of-Freedom (SDOF) System** ..... 1
1.1 Undamped Single-Degree-of-Freedom (SDOF) ..... 2
1.1.1 Free Vibration ..... 3
1.1.2 Differential Equations of Undamped Free Vibration ..... 3
1.1.2.1 Method of Differential Operators ..... 4
1.1.2.2 Complex Exponential Method ..... 6
1.2 Damped SDOF ..... 11
1.2.1 Differential Equation ..... 11
1.2.2 Phasor of a Damped System ..... 12
1.3 Logarithmic Decrement ..... 13
1.4 Impulse Response Function ..... 16
1.5 Force Excitation ..... 17
1.5.1 Convolution Integral ..... 18
1.5.2 System Transfer Function ..... 19
1.5.3 Harmonic Excitation ..... 19
1.5.4 Complex Mechanical Impedance ..... 21
1.5.5 Phasor Representation of Harmonic Response ..... 24
1.6 Electromechanical Analogy ..... 27
1.7 Power Input ..... 28
1.7.1 Average Power Input to an SDOF ..... 28
1.7.2 General Power Input Equation ..... 30
1.7.3 Power Input and Resonance ..... 31
1.7.4 Power Input Frequency Characteristics ..... 32
1.7.5 Half-Power Frequencies ..... 33
1.7.6 Quality Factor and Damping Ratio ..... 34
1.8 Frequency Regions ..... 34
1.8.1 Input Power versus Frequency ..... 35
1.8.2 Mechanical Phase Angle versus Frequency ..... 36
1.9 Phase Relations ..... 41
1.9.1 Phase Relations in Terms of $\phi_m$ ..... 41
1.9.2 Phase between Displacement and Force ..... 41
1.9.3 Phase between Velocity and Force ..... 42
1.9.4 Phase between Acceleration and Force ..... 43
1.10 Frequency Response ..... 44
1.10.1 Displacement Frequency Response ..... 44
1.10.2 Velocity Frequency Response ..... 46
1.10.3 Acceleration Frequency Response ..... 47
1.11 Admittance ..... 48
1.12 Vibration Transducers ..... 50
1.12.1 Seismic Instrument ..... 50

1.12.2 Piezoelectric Transducer ..... 53
1.12.3 Piezoelectric Accelerometer ..... 53
1.12.4 Charge Amplifier ..... 55
1.13 Conclusions ..... 55

**2. Multidegree of Freedom (MDOF) Systems and Longitudinal Vibration in Bars ..... 61**
2.1 Multidegree-of-Freedom Discrete System ..... 62
2.1.1 Undamped MDOF ..... 62
2.1.2 Natural Frequencies ..... 64
2.1.3 Mode Shapes ..... 65
2.1.4 Mass Normalized Modes ..... 70
2.2 Longitudinal Waves in Bars ..... 85
2.2.1 Wave Equation ..... 85
2.2.2 Solution to the Longitudinal Wave Equation ..... 87
2.3 Fixed-Fixed Bars ..... 91
2.3.1 Natural Frequencies ..... 91
2.3.2 Mode Shapes ..... 92
2.4 Free-Free Bar ..... 99
2.4.1 Natural Frequencies ..... 99
2.4.2 Mode Shapes ..... 100
2.5 Orthogonality Condition ..... 109
2.6 Force Excitation ..... 110
2.7 Conclusions ..... 114

**3. Airborne Sound ..... 121**
3.1 Piston Propagated Disturbance ..... 121
3.2 Pulsating Piston ..... 123
3.3 Pressure Density Relationships due to Acoustic Disturbance ..... 124
3.4 One-Dimensional Wave Equation ..... 127
3.4.1 Conservation of Mass ..... 127
3.4.2 Conservation of Momentum ..... 128
3.4.3 Wave Equation ..... 129
3.4.4 Integral Equations ..... 129
3.5 Wave Equation Solution for Plane Waves ..... 130
3.6 Sound Pressure Level ..... 135
3.6.1 Addition of Sound Pressure Levels ..... 137
3.6.2 Difference between Two Sound Sources ..... 141
3.6.3 Equivalent Sound Pressure Level, $L_{eq}$ ..... 142
3.7 Sound Power Level ..... 145
3.8 Sound Intensity Level ..... 146
3.8.1 Sound Intensity of Plane Waves ..... 147
3.9 Spherical Waves ..... 148
3.9.1 Spherical Wave Equation ..... 148
3.9.2 Solution of Spherical Wave Equation ..... 148
3.9.3 Particle Velocity of Spherical Waves ..... 150
3.9.4 Sound Intensity of Spherical Waves ..... 153
3.10 Frequency Analysis of Airborne Sound Signals ..... 159
3.10.1 Octave and 1/3 Octave Bands ..... 160