IISc Lecture Notes Series

M L Munjal

Noise and Vibration Control

IISc Press

World Scientific

IISc Lecture Notes Series

Noise and Vibration Control

M L Munjal
Indian Institute of Science, India

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

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

IISc Lecture Notes Series — Vol. 3
NOISE AND VIBRATION CONTROL

ISBN 978-981-4434-73-7

Printed in Singapore by World Scientific Printers.

Noise and Vibration Control

IISc Lecture Notes Series **ISSN: 2010-2402**

Published:

Vol. 1: Introduction to Algebraic Geometry and Commutative Algebra
by Dilip P Patil & Uwe Storch

Vol. 2: Schwarz's Lemma from a Differential Geometric Veiwpoint
by Kang-Tae Kim & Hanjin Lee

Vol. 3: Noise and Vibration Control
by M L Munjal

In pursuit of Quietness

Series Preface

World Scientific Publishing Company - Indian Institute of Science Collaboration

IISc Press and WSPC are co-publishing books authored by world renowned scientists and engineers. This collaboration, started in 2008 during IISc's centenary year under a Memorandum of Understanding between IISc and WSPC, has resulted in the establishment of three Series: IISc Centenary Lectures Series (ICLS), IISc Research Monographs Series (IRMS), and IISc Lecture Notes Series (ILNS).

This pioneering collaboration will contribute significantly in disseminating current Indian scientific advancement worldwide.

The **"IISc Centenary Lectures Series"** will comprise lectures by designated Centenary Lecturers - eminent teachers and researchers from all over the world.

The **"IISc Research Monographs Series"** will comprise state-of-the-art monographs written by experts in specific areas. They will include, but not limited to, the authors' own research work.

The **"IISc Lecture Notes Series"** will consist of books that are reasonably self-contained and can be used either as textbooks or for self-study at the postgraduate level in science and engineering. The books will be based on material that has been class-tested for most part.

Preface

Noise is defined as unwanted sound. Excessive or persistent noise may cause annoyance, speech interference and hearing damage. In working environment, noise may lead to several physiological disorders like high blood pressure, heart problems, headache, etc. Noise is also known to cause accidents at the work place and loss of efficiency and productivity.

Vibration is caused by unbalanced inertial forces and moments. Resonant vibrations may lead to fatigue failures. Flexural vibrations of the exposed surfaces of a machine radiate audible noise, and in fact represents one of the primary sources of noise. Excessive vibration and noise characterize all rotating, reciprocating and flow machinery. This makes automobiles, aeroplanes, thermal power stations, etc. excessively noisy. Thus, the problems of noise and vibration are ubiquitous, cutting across all disciplines of engineering. This book deals primarily with industrial and automotive noise, its measurement and control. The control of noise from vibrating bodies at the source involves control of vibration. Therefore, two of the six chapters deal with vibration, its measurement and control.

It is now well understood that a quieter machine is in every way a better machine. Lesser vibration ensures manufacturing to closer tolerances, lesser wear and tear, and longer fatigue life. Hence, a quieter machine is more cost-effective in the long run. Designing for quietness is known to be most cost-effective. Noise control of existing machinery, while often necessary, calls for stoppage of the machinery and excessive retrofit costs.

The All India Council for Technical Education (AICTE) has listed a course on "Noise and Vibration Control" as a possible elective course for senior undergraduates of the engineering colleges in the country. Such a course would need an appropriate textbook. Hence this presentation.

The author has been teaching this course at the graduate level at the Department of Mechanical Engineering of the Indian Institute of Science (IISc) for over three decades. With a good number of solved as well as unsolved exercises, the present textbook lays stress on design methodologies, applications and exercises. Analytical derivations and techniques are eschewed. Nevertheless, references are provided at the end of each chapter for further study.

This textbook stresses on physical concepts and the application thereof to practical problems. The author's four decades experience in teaching, research and industrial consultancy is reflected in the choice of the solved examples and unsolved problems. The book targets senior undergraduate mechanical engineering students as well as designers of industrial machinery and layouts. It can readily be used for self study by practicing designers and engineers. This is why mathematical derivations have been avoided. The illustrations, tables and empirical formulae have been offered for ready reference.

As Chairman and Member Secretary of the Steering Committee of the Facility for Research in Technical Acoustics (FRITA), Professor D. V. Singh and Mr. S. S. Kohli have played an important role in conceptualizing and supporting this book writing project.

This book has been influenced substantially by Professor Colin H. Hansen whose book 'Engineering Noise Control' I have been following in my graduate course at IISc, and Mr. D. N. Raju with whom I have been collaborating on many of my consultancy projects — in pursuit of quietness. I wish to acknowledge the personal inspiration of Professors Malcolm J. Crocker, M. V. Narasimhan, B. V. A. Rao, S. Narayanan, B. C. Nakra, A. K. Mallik and D. N. Manik, among others. I have drawn heavily from the joint publications of my past as well as present graduate students and research students. My sincere thanks to all of them, particularly, Dr. Prakash T. Thawani and Professor Mohan D. Rao.

I thank Professor R. Narasimhan, Chairman of the Department of Mechanical Engineering, Indian Institute of Science for providing all

facilities as well as a conducive environment for research, teaching, consultancy and book writing.

I wish to thank my wife Vandana alias Bhuvnesh for bearing with me during long evenings and weekends that were needed to complete the book.

This text book has been catalyzed and supported by the Department of Science and Technology (DST), under its Utilization of Scientific Expertise of Retired Scientists (USERS) scheme.

Bangalore, April 2013 *M. L. Munjal*

Contents

Chapter 1

Noise and Its Measurement

Sound is a longitudinal wave in air, and wave is a traveling disturbance. Mass and elasticity of the air medium are primary characteristics for a wave to travel from the source to the receiver. A wave is characterized by two state variables, namely, pressure and particle velocity. These represent perturbations on the static ambient pressure and the mean flow velocity of wind, respectively. The perturbations depend on time as well as space or distance.

Noise is unwanted sound. It may be unwanted or undesirable because of its loudness or frequency characteristics. Excessive or prolonged exposure to noise may lead to several physiological effects like annoyance, headache, increase in blood pressure, loss of concentration, speech interference, loss of working efficiency, or even accidents in the workplace. Persistent exposure of a worker to loud noise in the workplace may raise his/her threshold of hearing.

The study of generation, propagation and reception of audible sound constitutes the science of Acoustics. There are several branches of acoustics, namely, architectural acoustics, electroacoustics, musical acoustics, underwater acoustics, ultrasonics, physical acoustics, *etc.* The field of industrial noise, automotive noise and environmental noise constitutes engineering acoustics or technical acoustics. This in turn comprises sub-areas like duct acoustics, vibro-acoustics, computational acoustics, *etc.*

The speed at which the longitudinal disturbances travel in air is called sound speed, c. It depends on the ambient temperature, pressure and density as follows.

$$c = (\gamma RT)^{1/2} = (\gamma p_0 / \rho_0)^{1/2} \tag{1.1}$$

Here γ is the ratio of specific heats C_p and C_v, R is gas constant, p_0 is static ambient pressure, ρ_0 is mass density, and T is the absolute temperature of the medium. For air at standard pressure ($\gamma = 1.4$, $R = 287.05\ J/(kg.K)$, $p_0 = 1.013\times10^5$ Pa), it can easily be seen that

$$c \simeq 20.05(T)^{1/2} \tag{1.2}$$

where T is the absolute temperature in Kelvin.

Symbol T is used for the time period of harmonic disturbances as well. It is related to frequency f as follows:

$$T = 1/f \text{ or } f = 1/T \tag{1.3}$$

Frequency f is measured in Hertz (Hz) or cycles per second. Wavelength λ of moving disturbances, of frequency f, is given by

$$\lambda = c/f \tag{1.4}$$

where c denotes speed of sound.

1.1 Plane Wave Propagation

Plane waves moving inside a wave guide (a duct with rigid walls) are called one- dimensional waves. These are characterized by the following one-dimensional wave equation [1]:

$$\frac{\partial^2 p}{\partial t^2} - c^2 \frac{\partial^2 p}{\partial z^2} = 0 \tag{1.5}$$

where p, z and t are acoustic pressure, coordinate along direction of wave propagation and time, respectively.

For harmonic waves, the time dependence is given by $e^{j\omega t}$ or $\cos(\omega t)$ or $\sin(\omega t)$, where $\omega = 2\pi f$ is the circular frequency in rad/s.

General solution of Eq. (1.5) may be written as

$$p(z,t) = \left(Ae^{-jkz} + Be^{jkz}\right)e^{j\omega t} \tag{1.6}$$

or as

$$p(z,t) = A\, e^{j\omega(t-z/c)} + B e^{j\omega(t+z/c)} \tag{1.7}$$

where $k = \omega / c = 2\pi / \lambda$ is called the wave number.

It can easily be seen that A is amplitude of the forward progressive wave and B is amplitude of the reflected or rearward progressive wave. Algebraic sum of the two progressive waves moving in opposite directions is called a standing wave. Thus, Eq. (1.6) represents acoustic pressure of a one-dimensional standing wave. The corresponding equation for particle velocity is given by

$$u(z,t) = \frac{1}{\rho_0 c}\left(A e^{-jkz} - B e^{jkz}\right) e^{j\omega t} \tag{1.8}$$

$\rho_0 c$, product of the mean density and sound speed, represents the characteristic impedance of the medium

For an ambient temperature of 25^0 C and the standard atmospheric pressure (corresponding to the mean sea level), we have

$$p_0 = 1.013 \times 10^5\ Pa, \quad T = 298\ K, \quad \rho_0 = 1.184\ kg/m^3, \quad c = 346\, m/s,$$
$$\rho_0 c = 410\, kg/(m^2 s)$$

One-dimensional wave occurs primarily in the exhaust and tail pipe of automotive engines and reciprocating compressors. These waves are characterized by a plane wave front normal to the axis of the pipe or tube, and therefore they are called plane waves.

The forward wave is generated by the source and the rearward wave is the result of reflection from the passive termination downstream. In particular, $B/A = R$ is called the Reflection Coefficient, and may be determined from the termination impedance [1]. In particular, $R = 0$ for anechoic termination, 1 for rigid (closed) termination, and -1 for expansion into vacuum. In general, R is a function of frequency.

In view of the plane wave character of the one-dimensional waves, the acoustic power flux W of a plane progressive wave may be written as

$$W = IS = \langle p\ u \rangle S = \langle p\ v \rangle,\ v = S\, u \tag{1.9}$$