Acoustics for Engineers

Macmillan titles of interest to mechanical engineers

Turner	<i>Instrumentation for Engineers</i>
Simonson	<i>Engineering Heat Transfer</i> , 2nd edition
Hull and John	<i>Non-Destructive Testing</i>
Stone	<i>Introduction to Internal Combustion Engines</i>
Stone	<i>Motor Vehicle Fuel Economy</i>
Hall	<i>Polymer Materials</i> , 2nd edition
Goodger	<i>Principles of Engineering Thermodynamics</i> , 2nd edition
John	<i>Introduction to Engineering Materials</i> , 2nd edition
John	<i>Work Out Engineering Materials</i>
Drabble	<i>Work Out Dynamics</i>
Boxer	<i>Work Out Thermodynamics</i>
Boxer	<i>Work Out Fluid Mechanics</i>

Foundations of Engineering series

Drabble	<i>Dynamics</i>
Hulse and Cain	<i>Structural Mechanics</i>
Powell	<i>Electromagnetism</i>
Silvester	<i>Electric Circuits</i>

Acoustics for Engineers

J. D. Turner and A. J. Pretlove

M
MACMILLAN

© J. D. Turner and A. J. Pretlove 1991

All rights reserved. No reproduction, copy or transmission of this publication may be made without written permission.

No paragraph of this publication may be reproduced, copied or transmitted save with written permission or in accordance with the provisions of the Copyright, Designs and Patents Act 1988 or under the terms of any licence permitting limited copying issued by the Copyright Licensing Agency, 33–4 Alfred Place, London WC1E 7DP.

Any person who does any unauthorised act in relation to this publication may be liable to criminal prosecution and civil claims for damages.

First edition 1991

Published by
MACMILLAN EDUCATION LTD
Houndmills, Basingstoke, Hampshire RG21 2XS
and London
Companies and representatives
throughout the world

British Library Cataloguing in Publication Data
Turner, J. D. (John David), 1955–
Acoustics for engineers.

1. Acoustic engineering

I. Title II. Pretlove, A. J.
620.2

ISBN 978-0-333-52143-4

ISBN 978-1-349-21267-5 (eBook)

DOI 10.1007/978-1-349-21267-5

To our children,

Jack,

Gareth,

John,

Steve,

and James,

***who, very early in their lives,
taught us the importance of noise control.***

Contents

<i>Preface</i>	xi
<i>Acknowledgements</i>	xv
1. Basic concepts of noise and vibration	1
1.1 The general nature of sound	2
1.1.1 Derivation of the one-dimensional wave equation	4
1.1.2 Sound in air	8
1.1.3 Relationship between pressure and velocity: the energy in a sound wave	10
1.1.4 Electric circuit analogy	12
1.1.5 The decibel scale	14
1.1.6 Adding decibels	17
1.2 Basic vibration theory for single degree of freedom systems	19
1.2.1 Free vibration	19
1.2.2 Forced vibration	22
1.2.3 Control of forced vibration	24
1.2.4 Vibration isolation	25
1.2.5 Continuous systems and their single degree of freedom equivalents	27
References	31
2. The human effects of noise: criteria and units	32
2.1 Introduction	32
2.2 The ear	33
2.3 Audiometry	36
2.4 Loudness	36

2.5	Weighting functions	39
2.6	Noise-related hearing loss	40
2.7	Noise exposure limits and noise units	41
2.8	Noise criterion (NC) and noise rating (NR) curves	41
2.9	L_{10} and L_{90}	42
2.10	Equivalent continuous sound level (L_{eq} dBA)	44
2.11	Community noise annoyance criteria	44
2.12	Aircraft noise measurements: units and criteria	47
2.13	Hearing damage risk criteria	48
2.14	Masking	50
2.15	Speech interference criteria	52
	References	54
3.	Sound in three dimensions	55
3.1	Introduction	55
3.2	Spherical waves	55
3.3	Directionality	64
3.4	Membrane microphones: a more quantitative theory	66
3.5	Directivity	70
3.6	Screens	71
3.7	Sound in the open air	75
3.8	Summary	77
4.	Analysis of acoustic and vibration signals	78
4.1	Introduction	78
4.2	Fourier series	83
4.3	Even and odd functions	87
4.4	The complex form of the series	89
4.5	The Fourier Transform	90
4.6	Summary	94
	References/further reading	95
5.	Digital methods of spectrum analysis	96
5.1	Introduction	96
5.2	The digital Fourier Transform and the FFT	96
5.3	Practical use of the FFT for spectral analysis	98
5.4	Aliasing and Shannon's Sampling Theorem	100
5.5	Windowing	103
5.6	Choice of window	111
5.7	Glossary of FFT analyser terminology	114
	References/further reading	115
6.	Acoustic instrumentation	116
6.1	Introduction	116

6.2	Microphones	119
6.3	Measurements in an airstream	123
6.4	Hydrophones	125
6.5	Microphone and hydrophone calibration	125
6.6	Sound intensity measurement	129
6.7	Amplifiers and weighting filters	134
6.8	Signal storage equipment	136
6.9	Analogue spectrum analysis	137
	References	141
7.	Reflection and transmission: sound in confined spaces	142
7.1	Introduction	142
7.2	Reflection of plane waves at a boundary	143
7.3	Expansion chamber silencers	147
7.4	Dissipative silencers	150
7.5	Acoustic absorption at surfaces in rooms	151
7.6	Sound in enclosed spaces: room acoustics	155
7.7	RT calculations in problem solving	159
7.8	Case study: acoustic treatment of Reading central swimming baths	159
7.9	Estimating the SPL for a room of known RT, for a source of given power	162
7.10	Sound transmission	166
	References	173
8.	Noise control	174
8.1	Introduction	174
8.2	Noise-conscious design	175
8.3	Existing noise problems	175
8.4	Acoustic systems	176
8.5	Analysis using the series-parallel method	180
8.6	Case study of the noise from a wood fibre mill	182
8.7	Cost analysis of noise control measures	184
	Reference	187
	<i>Index</i>	188

Preface

Sound is a phenomenon which all human beings live with from birth, and perhaps even before. It is a familiar medium of communication with our fellow man and it includes speech and the pleasures of music. Hearing is one of our primary senses, at once vitally valuable to our development and of infinitely varied interest. Sound can also be an irritating nuisance. All of this is taken for granted by most people. Because it is so familiar, relatively few will question how it works. Indeed, the basic physics of sound was not understood at all two hundred years ago. The pioneering work of early physicists such as Helmholtz (1821–1894) and Lord Rayleigh (1842–1919) defined sound as a form of wave motion and the wave theory explained various well-known phenomena such as diffraction (hearing a sound round a corner) and echoes (reflected sound with time delay). Once sound was recognised as a form of wave motion it could be brought into the family of wave phenomena and analogies could then be made with light, electromagnetic radiation and so forth, to the mutual benefit of all. An understanding of the physics of sound is particularly essential to the practising engineer whose task is often to design noise control devices for the factory, the office and at home.

Noise can be just as damaging as any other form of pollution. It may cause irritation or annoyance, and can be a danger to health. For these reasons, legal limits on the exposure to and emission of noise exist in most countries. As well as these health and safety aspects of noise, our acoustic environment is under constant threat from the increase in use and power of vehicles and machinery of all sorts. The benefits of a quiet environment, which was once accepted as the norm, are increasingly appreciated. The preference therefore is for quieter products whenever possible, and this is often reflected by the selling advantage the quiet product has over its noisy competitor.

Noise measurement is an important weapon in the armoury of the engineer concerned with diagnosing or monitoring the condition of machinery. The wheel-tapper who used to be employed on railways is a familiar example. We all know that faulty machines often emit unusual sounds prior to failure. The sounds made by machinery in normal use can be monitored to give advance warning of maintenance requirements. Measurement is therefore a subject of fundamental importance to the noise control engineer. Without it, there is no means of quantifying the extent of a noise problem. A modern measurement system is considerably different from its counterpart of even ten years ago. The only component which is the same is the microphone itself. The rest of the system has, with the advent of the ubiquitous microprocessor or microcomputer, gone digital. In acoustical analysis, digital signal processing is now of paramount importance because of its power, accuracy and speed. For this reason, a considerable proportion of this book is devoted to the fundamental principles of measurement and analysis. This includes not only Fourier analysis but also other useful aspects of signal processing.

Noise costs money. Processes which are inevitably noisy will require expenditure on noise insulation. Excessive noise levels can lead to annoyance or to a loss of concentration, and productivity may fall. The control of noise is therefore important not only to prevent hearing damage and maintain a pleasant environment, but also from the economic point of view. A novel strategy for tackling noise control problems is given in the last chapter of this book. The task of diagnosing and correcting noise problems in the most effective manner is one which, in the past, has received little attention in a formal way. It is hoped that this will provide the reader with an accurate method for defining the best medicine to be prescribed for the noisy patient.

The book is therefore unusual in integrating modern measurement techniques with fundamentals of applied acoustics and the determination of the most effective treatment of noise problems. By this means an up-to-date statement of the basics of noise and noise control is presented. The book aims to describe the basic theory and its practical applications in an easily digestible way with plenty of examples drawn from a wide variety of backgrounds.

Apart from being of general interest, the book is intended to be of value to students on courses of higher education and perhaps particularly to student engineers who, in their later professional lives, will often be faced with problems associated with noise. Many engineering degree courses now recognise the importance of noise control to the practising engineer and this book is designed to fulfil a need for a text which covers, in reasonably concise and up-to-date form, the major aspects of the subject.

The authors acknowledge the constructive comment and informed criticism of their many interested colleagues at Reading, Southampton and

elsewhere in the preparation of this book. Particular thanks are due to Martyn Hill, who patiently read the manuscript and made many helpful comments.

Acknowledgements

The authors wish to thank Professors M. T. Thew of Southampton University and A. G. Atkins of Reading University, for their encouragement of the work on which this book is based. We would also like to acknowledge the assistance provided by Mr M. Hill and Professor F. Fahy.

The index was produced with the aid of an extremely efficient piece of software called MACREX. The authors were lent a copy of MACREX by its creators, and would like to record their gratitude.

Permission for the reproduction of a number of figures and tables is acknowledged from Bruel and Kjaer Ltd. These are indicated in the text.

Every effort has been made to trace all copyright holders but if any have been inadvertently overlooked the publishers will be pleased to make the necessary arrangement at the first opportunity.