Fundamentals of Noise and Vibration Analysis for Engineers

Noise and vibration affects all kinds of engineering structures, and is fast becoming an integral part of engineering courses at universities and colleges around the world. In this second edition, Michael Norton's classic text has been extensively updated to take into account recent developments in the field. Much of the new material has been provided by Denis Karczub, who joins Michael as second author for this edition.

This book treats both noise and vibration in a single volume, with particular emphasis on wave–mode duality and interactions between sound waves and solid structures. There are numerous case studies, test cases and examples for students to work through. The book is primarily intended as a text book for senior level undergraduate and graduate courses, but is also a valuable reference for practitioners and researchers in the field of noise and vibration.

Fundamentals of Noise and Vibration Analysis for Engineers

Second edition

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To
our parents,
the first author's wife Erica,
and his young daughters Caitlin and Sarah

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M. P. Norton and D. G. Karczub
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Preface

The study of noise and vibration and the interactions between the two is now fast becoming an integral part of mechanical engineering courses at various universities and institutes of technology around the world. There are many undergraduate text books available on the subject of mechanical vibrations and there are also a relatively large number of books available on applied noise control. There are also several text books available on fundamental acoustics and its physical principles. The books on mechanical vibrations are inevitably only concerned with the details of vibration theory and do not cover the relationships between noise and vibration. The books on applied noise control are primarily designed for the practitioner and not for the engineering student. The books on fundamental acoustics generally concentrate on physical acoustics rather than on engineering noise and vibration and are therefore not particularly well suited to the needs of engineers. There are also several excellent specialist texts available on structural vibrations, noise radiation and the interactions between the two. These texts do not, however, cover the overall area of engineering noise and vibration, and are generally aimed at the postgraduate research student or the practitioner. There are also a few specialist reference handbooks available on shock and vibration and noise control – these books are also aimed at the practitioner rather than the engineering student.

The main purpose of this second edition is to attempt to provide the engineering student with an updated unified approach to the fundamentals of engineering noise and vibration analysis and control. Thus, the main feature of the book is the bringing of noise and vibration together within a single volume instead of treating each topic in isolation. Also, particular emphasis is placed on the interactions between sound waves and solid structures, this being an important aspect of engineering noise and vibration. The book is primarily designed for undergraduate students who are in the latter stages of their engineering course. It is also well suited to the postgraduate student who is in the initial stages of a research project on engineering noise and vibration and to the practitioner, both of whom might wish to obtain an overview and/or a revision of the fundamentals of the subject.

This book is divided into eight chapters. Each of these chapters is summarised in the introductory comments. Because of the wide scope of the contents, each chapter has its own nomenclature list and its own detailed reference list. A selection of problems relating to each chapter is also provided at the end of the book together with solutions. Each of the chapters has evolved from lecture material presented by the first author to (i) undergraduate mechanical engineering students at the University of Western Australia, (ii) postgraduate mechanical engineering students at the University of Western Australia, and (iii) practising engineers in industry in the form of short specialist courses. The complete text can be presented in approximately seventy-two lectures, each of about forty-five minutes duration. Suggestions for subdividing the text into different units are presented in the introductory comments.

The authors hope that this book will be of some use to those who choose to purchase it, and will be pleased and grateful to hear from readers who identify some of the errors and/or misprints that will undoubtedly be present in the text. Suggestions for modifications and/or additions to the text will also be gratefully received.

M. P. Norton and D. G. Karczub

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This book would not have eventuated had it not been for several people who have played an important role at various stages in our careers to date. Whilst these people have, in the main, not had any direct input into the preparation of this book, their contributions to the formulation of our thoughts and ideas over the years have been invaluable to say the least.

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Last, but not least, special acknowledgements are due to our families: our parents for encouraging us to pursue an academic career; and the first author's wife Erica, for enduring the very long hours that we had to work during the gestation period of this second edition, and his young daughters, Caitlin and Sarah.

Introductory comments

A significant amount of applied technology pertaining to noise and vibration analysis and control has emerged over the last thirty years or so. It would be an impossible task to attempt to cover all this material in a text book aimed at providing the reader with a fundamental basis for noise and vibration analysis. This book is therefore only concerned with some of the more important fundamental considerations required for a systematic approach to engineering noise and vibration analysis and control, the main emphasis being the industrial environment. Thus, this book is specifically concerned with the fundamentals of noise and vibration analysis for mechanical engineers, structural engineers, mining engineers, production engineers, maintenance engineers, etc. It embodies eight self-contained chapters, each of which is summarised here.

The first chapter, on mechanical vibrations, is a review of some fundamentals. This part of the book assumes no previous knowledge of vibration theory. A large part of what is presented in this chapter is covered very well in existing text books. The main difference is the emphasis on the wave–mode duality, and the reader is encouraged to think in terms of both waves and modes of vibration. As such, the introductory comments relate to both lumped parameter models and continuous system models. The sections on the dynamics of a single oscillator, forced vibrations with random excitation and multiple oscillator are presented using the traditional 'mechanical vibrations' approach. The section on continuous systems utilises both the traditional 'mechanical vibrations' approach and the wave impedance approach. It is in this section that the wave–mode duality first becomes apparent. The wave impedance approach is particularly useful for identifying energy flow characteristics in structural components and for estimating energy transmission and reflection at boundaries. A unique treatment of dynamic stress and strain has been included due to the importance of considering dynamic stress in a vibrating structure given the risk of fatigue failure. The treatment provided uses travelling wave concepts to provide a consistent theoretical framework for analysis of dynamic stress in beams, plates and cylindrical shells. The contents of chapter 1 are best suited to a second year or a third year course unit (based on a total course length of four years) on mechanical vibrations.

The second chapter, on sound waves, is a review of some fundamentals of physical acoustics. Like the first chapter, this chapter assumes no previous working knowledge of acoustics. Sections are included on a classical analysis of the homogeneous wave equation, fundamental sound source models and the inhomogeneous wave equation associated with aerodynamic sound, with particular attention being given to Lighthill's acoustic analogy and the Powell–Howe theory of vortex sound. The distinction between the homogeneous and the inhomogeneous acoustic wave equations is continually emphasised. The chapter also includes a discussion on how reflecting surfaces can affect the sound power characteristics of sound sources (this important practical point is often overlooked), and the use of one-dimensional acoustics to analyse sound transmission through a duct with mean flow (with applications including muffler/exhaust system design, air conditioning ducts, and pulsation control for reciprocating compressor installations) based on the use of acoustic impedance and travelling wave concepts developed earlier in the chapter. The contents of chapter 2 are best suited to a third year or a fourth year course unit on fundamental acoustics.

The third chapter complements chapters 1 and 2, and is about the interactions between sound waves and solid structures. It is very important for engineers to come to grips with this chapter, and it is the most important fundamental chapter in the book. Wave–mode duality concepts are utilised regularly in this chapter. The chapter includes discussions on the fundamentals of fluid–structure interactions, radiation ratio concepts, sound transmission through panels, the effects of fluid loading, and impact noise processes. The contents of chapter 3 are best suited to a third year or a fourth year course unit. The optimum procedure would be to combine chapters 2 and 3 into a single course unit.

The fourth chapter is a fairly basic chapter on noise and vibration measurements and control procedures. A large part of the contents of chapter 4 is readily available in the noise and vibration control handbook literature with three exceptions: firstly, constant power, constant volume and constant pressure sound source concepts are discussed in relation to the effects of rigid, reflecting boundaries on the sound power characteristics of these sound sources; secondly, the economic issues in noise and vibration control are discussed; and, thirdly, sound intensity techniques for sound power measurement and noise source identification are introduced. The contents of chapter 4 are best suited to a fourth year course unit on engineering noise and vibration control. By the very nature of the wide range of noise and vibration control procedures, several topics have had to be omitted from the chapter. Some of these topics include outdoor sound propagation, community noise, air conditioning noise, psychological effects, etc.

The fifth chapter is about the analysis of noise and vibration signals. It includes discussions on deterministic and random signals, signal analysis techniques, analogue and digital signal analysis procedures, random and bias errors, aliasing, windowing, and measurement noise errors. The contents of chapter 5 are best suited to a fourth year unit on engineering noise and vibration noise control, and are best combined with chapters 4 and 8 for the purposes of a course unit.

The sixth and seventh chapters involve specialist topics which are more suited to postgraduate courses. Chapter 6 is about the usage of statistical energy analysis procedures for noise and vibration analysis. This includes energy flow relationships, modal densities, internal loss factors, coupling loss factors, non-conservative coupling, the estimation of sound radiation from coupled structures, and relationships between dynamic stress and strain and structural vibration levels. Chapter 7 is about flow-induced noise and vibrations in pipelines. This includes the sound field inside a cylindrical shell, the response of a cylindrical shell to internal flow, coincidence, and other pipe flow noise sources. These two chapters can be included either as optional course units in the final year of an undergraduate course, or as additional reading material for the course unit based on chapters, 4, 5 and 8.

The eighth chapter is a largely qualitative description of noise and vibration as a diagnostic tool (i.e. source identification and fault detection). Magnitude and time domain signal analysis techniques, frequency domain signal analysis techniques, cepstrum analysis techniques, sound intensity analysis techniques, and other advanced signal analysis techniques are described here. The chapter also includes five specific practical test cases; discussions on new techniques used in condition monitoring such as expert systems and performance monitoring; and a review of design concepts for a plant-wide condition monitoring system integrating performance monitoring, safety monitoring, and on-line and off-line condition monitoring. The contents of chapter 8 are best suited to a fourth year unit on engineering noise and vibration noise control, and are best combined with chapters 4 and 5 for the purposes of a course unit.

Based upon the preceding comments, the following subdivision of the text is recommended for the purposes of constructing course units.

(1) 2nd year unit	mechanical vibration (∼14 hrs) chapter 1 (sections 1.1–1.8)
(2) 3rd year unit	waves in structures and fluids (∼14 hrs) chapter 1 (section 1.9), chapter 2 (sections 2.1, 2.2)
(3) 3rd or 4th year unit	structure–sound interactions (∼18 hrs) chapter 2 (sections 2.3, 2.4), chapter 3
(4) 4th year unit*	engineering noise control (∼18 hrs) chapters 4, 5, 8
(5) optional specialist units and/or additional reading	statistical energy analysis and pipe flow noise (∼8 hrs) chapters 6, 7.

* Chapters 2 and 3 should be a prerequisite for the engineering noise control unit.