

ENGINEERING NOISE CONTROL

FIFTH EDITION



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DAVID A. BIES
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Dedication

This book is dedicated to our families.

The second and third authors would also like to dedicate this edition to the first author, David Bies, who sadly passed away and was thus unable to contribute to this edition. His knowledge and insights will be sorely missed.



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Preface to the First Edition

This book grew out of a perceived need for a textbook on engineering noise control suitable for use in an undergraduate or postgraduate course in Engineering or Applied Physics and which, at the same time, would be useful as a practical yet rigorous and up-to-date reference for practising engineers, architects and acoustical consultants.

Preliminary versions of this volume have been used for the past eight years as a basis of an engineering noise control course for final year Mechanical Engineering students at the University of Adelaide, and also for short courses on industrial noise control for practising engineers and industrial design personnel.

The book begins with an introduction to terminology and basic concepts of acoustic wave description and propagation. Included is a discussion of acoustical flow resistance, a simple but fundamental property of porous materials which is basic to the understanding of a variety of acoustical phenomena. Use is made of previously unpublished algorithms and flow resistance information to calculate accurately properties of porous sound absorbing materials.

A discussion of the ear, the subject of Chapter 2, is used as a basis for the understanding of such matters as acoustical masking and hearing damage due to excessive noise exposure. A practical guide to instrumentation follows in Chapter 3. Microphone calibration is considered in some detail and similarities between the microphone and the ear, in the perception of the aural field, are pointed out. Criteria which always form the basis for a noise control solution are considered in Chapter 4. Particular care has been given to the discussion of ambient level specification for spaces where a number of different methods of specification are commonly encountered in practice. A review of long accepted data is used to show that hearing loss due to noise exposure is related to the integral of pressure, which is expressed in this book in terms of a hearing deterioration index (HDI), and not the integral of energy (pressure squared), as universally assumed and implemented in legislation throughout Europe and Australia.

In Chapter 5 a variety of commonly used idealised sources are briefly but comprehensively considered. This information provides the basis for source identification; it also provides the basis for understanding active (that is, noise-cancelling) control techniques. Also included is a comprehensive discussion of outdoor sound propagation. The concept of flow resistance as applied to ground reflection has only recently been recognised in the literature and is incorporated in the discussion.

The importance of the internal impedance of sound sources is emphasised and discussed in the first part of Chapter 6. This is followed by a consideration of the radiation field of sources, its significance, and criteria for identification of the field. In particular, source directivity as a far field phenomenon is emphasised and carefully defined. The remainder of this chapter is concerned with the many methods of laboratory and field measurement of source sound power and the uses of such information.

In Chapter 7 the elements of sound fields in enclosed spaces are considered. Some effort is expended in establishing that rooms of any shape will exhibit modal response; use of splayed walls or odd shaped rooms will not change the basic room behaviour. The point is also made that the traditional description of the sound field in terms of sound absorption, being a property of the wall treatment, is a gross simplification which makes tractable an otherwise very difficult problem, but at the expense of precision. Within the limitations of the analysis the optimisation of reverberation control is discussed.

In the discussion of barriers and enclosures of Chapter 8, new procedures are provided for estimating sound transmission loss of single and double panel wall constructions. Similarly new procedures are provided for investigating diffraction around barriers located either out-of-doors

or indoors where wall and ceiling reflections must be taken into account. While these discussions are based upon published literature, such sources are generally not understandable except to the specialist, so that the authors have made a special effort to put the information into simple and usable textbook form.

Muffling devices are considered in Chapter 9. Simple new procedures for estimating expected attenuation of lined ducts of both rectangular and circular cross section are presented. These procedures are based upon exact analyses and make use of the algorithms introduced in Chapter 1 and presented in an appendix for describing accurately the acoustical properties of porous materials in terms of flow resistance. The analysis of insertion loss for the commonly used side branch resonator, low pass filter and small engine exhaust muffler has been prepared especially for this book. Results are given in terms of insertion loss for various types of source and termination, thus providing an estimate of the expected difference in noise level obtained before and after insertion of the muffler. This analysis is much more useful than the commonly used transmission loss analysis which gives no indication of insertion loss. Consideration is also given to both flow noise generation and pressure drop. Exhaust duct directivity information is new and is based upon previously unreported model studies.

Chapter 10 is concerned with vibration control from the point of view of noise suppression. Vibration isolation and the use of vibration absorbers are discussed in detail. The concepts of resonant and nonresonant vibration modes, and how they contribute to sound radiation, are discussed with reference to the appropriate use of vibration damping material. Semi-empirical prediction schemes for estimating the sound power radiated by a number of commonly encountered industrial noise sources are presented in Chapter 11.

The book concludes with Chapter 12 in which several recently developed analytical techniques for the estimation of radiated sound power of complex structures are reviewed.

Problems suitable for students using the text are included in Appendix A. Appendix B lists important properties of a number of materials. The final three appendices are concerned with the measurement and prediction of the statistical absorption coefficients and normal acoustic impedances of constructions commonly used for sound absorption.

Where possible, references are given within the text to books, reports and technical papers which may provide the reader with a more detailed treatment of their subject matter than is possible here. The reference list at the end of the book is intended as a first source for further reading and is by no means claimed to be comprehensive; thus, omission of a reference is not intended as a reflection on its value.

We have spent considerable effort in the elimination of errors in the text but in the event that more are found we will be grateful for notification from our readers.

David A. Bies
Colin H. Hansen

Preface to the Fourth Edition

Although this fourth edition follows the same basic style and format as the first, second and third editions, the content has been considerably updated and expanded, yet again. This is partly in response to significant advances in the practice of acoustics and in the associated technology during the six years since the third edition and partly in response to improvements, corrections, suggestions and queries raised by various practitioners and students. The major additions are outlined below. However, there are many other minor additions and corrections that have been made to the text but which are not specifically identified here.

The emphasis of this edition is purely on passive means of noise control and the chapter on active noise control that appeared in the second and third editions has been replaced with a chapter on practical numerical acoustics, where it is shown how free, open source software can be used to solve some difficult acoustics problems, which are too complex for theoretical analysis. The removal of Chapter 12 on active noise control is partly due to lack of space and partly because a more comprehensive and a more useful treatment is available in the book, *Understanding Active Noise Cancellation* by Colin H. Hansen.

Chapter 1 includes updated material on the speed of sound in compliant ducts and the entire section on speed of sound has been rewritten with a more unified treatment of solids, liquids and gases.

Chapter 2 has been updated to include some recent discoveries regarding the mechanism of hearing damage.

Chapter 3 has been considerably updated and expanded to include a discussion of expected measurement precision and errors using the various forms of instrumentation, as well as a discussion of more advanced instrumentation for noise source localisation using near field acoustic holography and beamforming. The discussion on spectrum analysers and recording equipment has been completely rewritten to reflect more modern instrumentation.

In Chapter 4, the section on evaluation of environmental noise has been updated and rewritten.

Additions in Chapter 5 include a better definition of incoming solar radiation for enabling the excess attenuation due to meteorological influences to be determined. Many parts of Section 5.11 on outdoor sound propagation have been rewritten in an attempt to clarify some ambiguities in the third edition. The treatment of a vibrating sphere dipole source has also been considerably expanded.

In Chapter 7, the section on speech intelligibility in auditoria has been considerably expanded and includes some guidance on the design of sound reinforcement systems. In the low frequency analysis of sound fields, cylindrical rooms are now included in addition to rectangular rooms. The section on the measurement of the room constant has been expanded and explained more clearly. In the section on auditoria, a discussion of the optimum reverberation time in classrooms has now been included.

In Chapter 8, the discussion on STC and weighted sound reduction index has been revised. The prediction scheme for estimating the transmission loss of single isotropic panels has been extended to low frequencies in the resonance and stiffness controlled ranges and the Davy method for estimating the Transmission Loss of double panel walls has been completely revised and corrected. The discussion now explains how to calculate the TL of multi-leaf and composite panels. Multi-leaf panels are described as those made up of different layers (or leaves) of the same material connected together in various ways whereas composite panels are described as those made up of two leaves of different materials bonded rigidly together. A procedure to calculate the transmission loss of very narrow slits such as found around doors with weather seals has

also been added. A section on the calculation of flanking transmission has now been included with details provided for the calculation of flanking transmission via suspended ceilings. The section on calculating the Insertion Loss of barriers according to ISO9613-2 has been rewritten to more clearly reflect the intention of the standard. In addition, expressions are now provided for calculating the path lengths for sound diffracted around the ends of a barrier.

Chapter 9 has had a number of additions: Transmission Loss calculations (in addition to Insertion Loss calculations) for side branch resonators and expansion chambers; a much more detailed and accurate analysis of Helmholtz resonators, including better estimates for the effective length of the neck; an expanded discussion of higher order mode propagation, with expressions for modal cut-on frequencies of circular section ducts; a number of new models for calculating the Transmission Loss of plenum chambers; and a more detailed treatment of directivity of exhaust stacks.

In Chapter 10, the effect of the mass of the spring on the resonance frequency of isolated systems has been included in addition to the inclusion of a discussion of the surge phenomenon in coil springs. The treatment of vibration absorbers has been revised and expanded to include a discussion of vibration neutralisers, and plots of performance of various configurations are provided. The treatment of two-stage vibration isolation has been expanded and non-dimensional plots provided to allow estimation of the effect of various parameters on the isolation performance.

Chapter 11 remains unchanged and Chapter 12 has been replaced with Chapter 13, where the previous content of Chapter 13 now serves as an introduction to a much expanded chapter on practical numerical acoustics written by Dr Carl Howard. This chapter covers the analysis of complex acoustics problems using boundary element analysis, finite element analysis and MATLAB[®]. Emphasis is not on the theoretical aspects of these analyses but rather on the practical application of various software packages including a free open source boundary element package.

Appendix A, which in the first edition contained example problems, has been replaced with a simple derivation of the wave equation. A comprehensive selection of example problems tailored especially for the book are now available on the internet for no charge at: <http://www.causalsystems.com>.

Appendix B has been updated and considerably expanded with many more materials and their properties covered.

In Appendix C, the discussion of flow resistance measurement using an impedance tube has been expanded and clarified. Expressions for the acoustic impedance of porous fibreglass and rockwool materials have been extended to include polyester fibrous materials and plastic foams. The impedance expressions towards the end of Appendix C now include a discussion of multi-layered materials.

Preface to the Fifth Edition

The fifth edition of the book has been thoroughly updated and reorganised. It also contains a considerable amount of new material. We have tried to keep the book as a suitable text for later undergraduate and graduate students, while at the same time extending content that will make the book more useful to acoustical consultants and noise control engineers.

Chapter 1 now has a section on the Doppler shift caused by moving sources and receivers as well as a section on amplitude modulation and amplitude variation to complement the section on beating.

Chapter 2 is now a combination of Chapters 2 and 4 of the earlier editions. It made sense to us to combine the description of the ear, hearing response and loudness with criteria. New measures for quantifying noise have been included as well as a section on low-frequency loudness and the response of the hearing mechanism to infrasound. The discussion on weighting networks has been extended to the G-weighting and Z-weighting networks and the frequency range covered by weighting networks has been extended at the low end to 0.25 Hz.

Chapter 3 is now an updated version of what was in Chapter 3 in earlier editions. It has been updated to reflect current digital instrumentation and current methods of data acquisition and recording.

Chapter 4 has been rearranged so that it only includes the sound source descriptions that were in Chapter 5 of earlier editions and it now includes sound power estimation schemes for various sources that were previously considered in a separate Chapter 6 of the previous editions.

The new Chapter 5 is entirely devoted to outdoor sound propagation. The chapter has been rearranged to first discuss principles underlying outdoor sound propagation calculations (including infrasound propagation) and second to discuss the various sound propagation models that are currently in use, with particular emphasis on the new model to be used by the European Union and the detailed Harmonoise model. The required input data for each model and the limitations of each model are also discussed. Finally a section is dedicated to uncertainty analysis as we believe that it is very important that any noise level predictions are presented with an associated uncertainty.

Chapter 6 on room acoustics and sound absorption is similar in content to Chapter 7 in previous editions except that auditorium acoustics has been excluded, as there was insufficient space available to do justice to such a complex topic that has been the sole subject of a number of other excellent books.

Chapter 7 (Chapter 8 in previous editions) on sound transmission loss calculations and enclosure design has been updated to reflect recent advances in Davy's prediction model for double panel walls and a more accurate model on the inclusion of the flexibility of connecting studs. In addition, the European model (EN12354-1) for sound transmission loss calculations has been included as well as a section on the effects of various stud spacings on the sound transmission loss of double panel walls.

Chapter 8, which was Chapter 9 in previous editions, has been extended to include an expanded treatment of the calculation of the insertion loss for splitter silencers in both circular and rectangular section ducts, as well as an expanded treatment of pressure loss due to flow through lined ducts and splitter silencers. The self-noise produced by silencers is now discussed in more detail and procedures are now provided for its estimation. Noise generated by flow through silencers is now discussed in more detail, including a discussion of pin noise in gas turbine exhausts. Calculation procedures are provided for the estimation of noise generated by flow through silencers and past pins holding on heat insulating material. The treatment of exhaust stack directivity in previous editions did not mention the effects of exhaust stack temperature.

In this edition, a qualitative description is provided of how exhaust stack temperature may be taken into account. Finally a section, with a number of examples, has been added on 4-pole analysis, which is an excellent technique for the analysis of sound propagation through duct and muffler systems.

In Chapter 9, which was Chapter 10 in previous editions, the treatment of vibration absorbers has been expanded; otherwise, not much else has changed from the fourth edition.

The Chapter 10 (Chapter 11 in previous editions) sections on fan noise and transportation noise have been updated. In particular, the sections on the calculation of train noise and road traffic noise have been extended and a number of models in current use have been described in detail.

Chapter 11, which was Chapter 12 in the fourth edition, has been updated, but the content has not changed much from the fourth edition.

Chapter 12 is a new chapter concerned entirely with frequency analysis. It is a very much expanded version of Appendix D in previous editions. This material, which was partly covered in an Appendix in previous editions, is an important part of understanding noise and vibration problems and, as such, it deserves a chapter of its own.

Appendix A is new and has been included to provide the background material on matrix algebra needed to fully appreciate the 4-pole material in Chapter 8 and the acoustic material property measurement procedures in Appendix D.

Appendices A and B of the fourth edition are now Appendices B and C in this edition. Appendix D (which was Appendix C in the fourth edition) has been updated with a description of the two-microphone method for measuring the normal incidence absorption coefficient and the normal impedance over a wide frequency range in a very short measurement time.

Appendix E is new and includes background material needed to appreciate the material on the Harmonoise propagation model in Chapter 5. This appendix includes explanations of how the Fresnel weighting coefficient for ground reflected waves, as well as the effects of ground reflections and barriers on sound propagation, may be calculated.

Colin H. Hansen
Carl Q. Howard

May, 2017

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