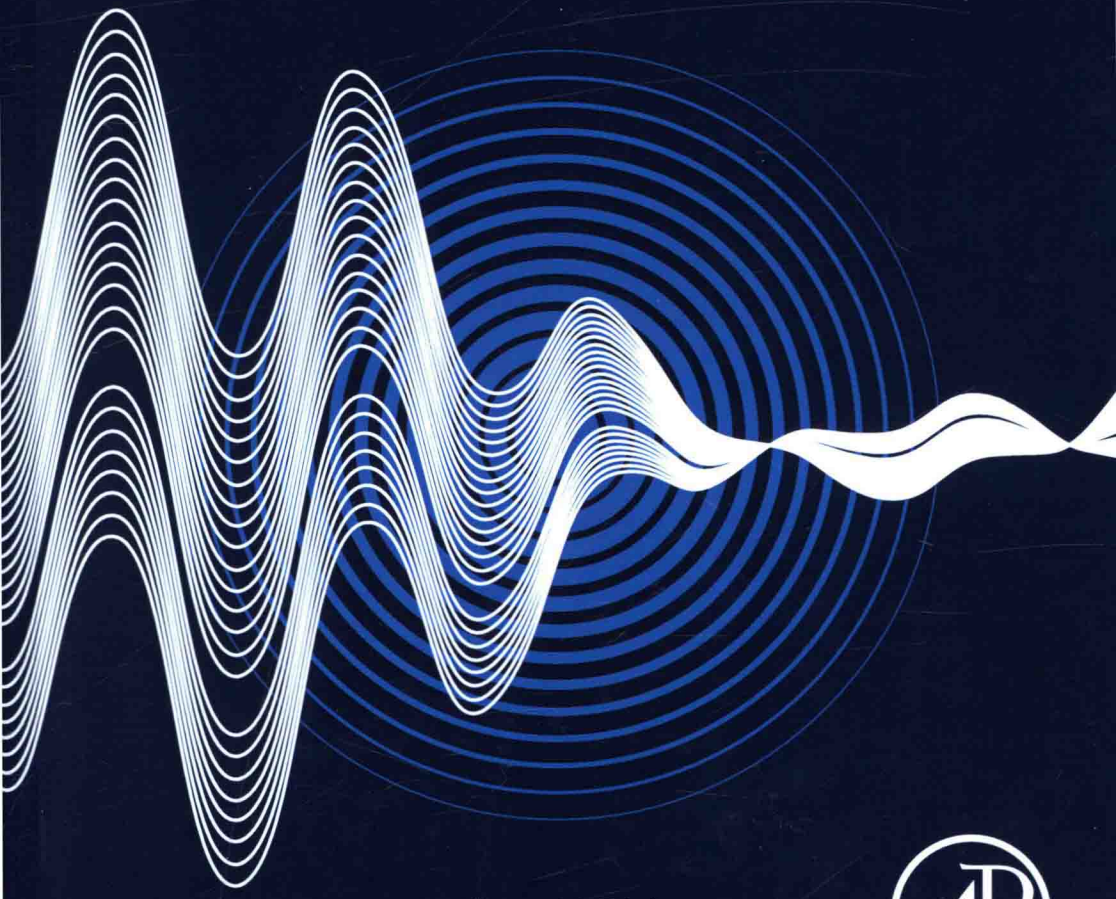
Volume 1

Mechanics of Flow-Induced Sound and Vibration

Second Edition

General Concepts and Elementary Sources



William K. Blake

Mechanics of Flow-Induced Sound and Vibration, Volume 1

William K. Blake

Introduces the theory and concepts of flow-induced sound and vibration relating to various types of fluid motion.

- Presents every important topic in flow-induced sound and vibration.
- Covers all aspects of the topics addressed, from fundamental theory, to the analytical formulas used in practice.
- Provides the building blocks of computer modeling for flow-induced sound and vibration.

Mechanics of Flow-Induced Sound and Vibration, Volume 1: General Concepts and Elementary Sources, Second Edition, enables readers to fully understand flow-induced vibration and sound, unifying the disciplines of fluid dynamics, structural dynamics, vibration, acoustics, and statistics in order to classify and examine each of the leading sources of vibration and sound induced by various types of fluid motion.

Starting with classical theories of aeroacoustics and hydroacoustics, a formalism of integral solutions valid for sources near boundaries is developed and then broadened to address different source types, including jet noise, flow tones, dipole sound from cylinders, and cavitation noise. Step-by-step derivations clearly identify any assumptions made throughout. Each chapter is illustrated with comparisons of leading formulas and measured data.

Along with its companion, *Mechanics of Flow-Induced Sound and Vibration, Volume 2: Complex Flow-Structure Interactions,* the book covers everything an engineer needs to understand flow-induced sound and vibration. This book will be essential reading for postgraduate students, and for engineers and researchers with an interest in aerospace, ships and submarines, offshore structures, construction, and ventilation.

About the Author

William K. Blake is currently a consultant to the U.S. Navy, as well as to the commercial marine and consumer industries. He is also an adjunct professor at the University of Notre Dame, Indiana, and at Johns Hopkins University, Baltimore, Maryland. Blake spent many years at the Naval Surface Warfare Center (formerly David Taylor Model Basin) at Bethesda, Maryland. His numerous contributions to US sea power and naval systems include research in ship hydroacoustics physics, development and application of advanced technology in submarine hull and propulsor ship components, and developing computational procedures. Blake was awarded the Doctor of Engineering, honoris causa, at the University of Notre Dame, in 1996, and the American Society of Naval Engineers Gold Medal in 2002, and he is a Fellow of the Acoustical Society of America in recognition of his achievements.

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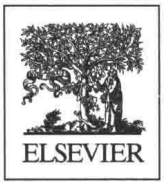

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Mechanics of Flow-Induced Sound and Vibration, Volume 1

Dedication

To my wife, Donna

Preface to the Second Edition

It has been 31 years since the publication of the first edition of this book and I believe that the foundations and fundamentals of the combined subject of aero-hydro acoustics were well established at the time of the first edition. However, in the time since then while there have been developments in those fundamentals there has also been an extensive growth in applications and methods of applications. This growth has been made possible by the development of computational tools, personal computers, data acquisition hardware and software, and sensors. These were not available at the time of Edition 1. In fact personal tools such as, *Matlab, Mathematica, Mathcad*, and *Labview*, now widely used in academic and commercial applications were not available to the reader either. The science of aero-hydro acoustic phenomena has really benefitted from the use of simultaneously-collected multichannel sensor arrays as well. Finally the range of applications has grown under the combined pulls of consumer awareness and intolerance of noise and vibration, public legislation requiring noise control, and military needs.

Computational tools have made possible both direct numerical simulations for research and detailed design engineering applications. I have attempted to selectively extend the coverage of Edition 1 into these new growth areas while at the same time maintaining the structure and philosophy of the book and not substantially increasing its size. In some areas, the newly developed numerical technologies have made it possible to conduct "numerical experiments" that parallel and complement physical experiments, thereby leveraging the capabilities of both. I have used some of these in the areas of jet noise, boundary layer noise, and rotor noise as examples to address the application of numerical techniques. I have avoided going into numerical methods, however, since there are now numerous books on the techniques of computational fluid mechanics, large eddy simulations, and finite element methods making it duplicative to address these techniques, themselves.

The formalisms developed here are suitable for evaluation on a personal computer, but closed-form asymptotic solutions are also given for immediate interpretation for understanding trends in data. The book is written principally as a reference work, although it may be used as a teaching aid. The reader will always find theoretical results supported by step-by-step

derivations that identify any assumptions made. For as many sources of sound as possible, each chapter is illustrated with comparisons of leading-order formulas, measured data, and results of numerical simulations.

In writing the first Edition 1 provided a comprehensive list of references in each focus area. Each of these I read and integrated into the text. This was intended in Edition 2, but I soon faced the reality that the number of papers published in any area is now too large to treat in this manner. One journal has a search engine that provides the user with a year-by-year distribution of papers published in a selected area. The annual publication rate in one area increased in that journal by a factor of 10 beginning in 1999–2000. Accordingly in this edition, the list of references has been expanded, but admittedly less exhaustively than in the first.

As noted previously the presentation philosophy and organization of the first edition has been maintained in this second edition with fundamentals central to Volume 1 and more complex geometry and fluid-structure interaction the subjects of Volume 2. Considering Volume 1, an area of addition and change is in Chapter 3, Shear Layer Instabilities, Flow Tones, and Jet Noise, where the discussion of turbulence statistics and jet noise have been changed and expanded; this required an additional section in Chapter 2, Theory of Sound and Its Generation by Flow, on the effects of source convection and the Doppler effect. Chapter 4, Dipole Sound From Cylinders, and Chapter 5, Fundamentals of Flow-Induced Vibration and Noise, have been updated to meet the needs of the other chapters for which they provide fundamentals. Chapter 6, Introduction to Bubble Dynamics and Cavitation, has been revised to present the latest views on bubble dynamics, cavitation inception, and acoustic transmission in bubbly media. Regarding Volume 2, we have changed chapter numbering, but not the chapter subjects. Accordingly, Chapter 1 of Volume 2 now addresses the phenomena related to hull pressure fluctuations on ships due to extensive propeller cavitation and recent measurements of cavitation noise from full scale ships. Chapters 2 and 3 of Volume 2 have been extensively re-worked. The section on the use of sensors and arrays has been moved from Chapter 2 to Chapter 3 of Volume 2; Chapter 2 of Volume 2 now deals exclusively with the science of boundary layer pressure and Chapter 3 of Volume 2 deals with response of sensors, sensor arrays, and elastic structures. Together these chapters now present the modern views of turbulent boundary layer wall pressure fluctuations at low wave number, radiated sound, rough wall boundary layers, and the effects of steps and gaps on sound. Chapter 4 of Volume 2, presents a comprehensive treatment of flow-excitation and radiated sound from elastic cylinders, both ducts and shells. This coverage recognizes the capability of obtaining modal solutions on personal computers. Chapters 5 and 6 of Volume 2 have also been revised, although less extensively so. Turbulence ingestion noise was not well understood when Edition 1 was written; Edition 2 provides an expanded treatment for lifting surfaces and propeller fans.

Chapter 6 of Volume 2 provides more examples of comparisons between theory and measurement than were possible for Edition 2.

A work of this scope could not have been possible, except for the continued collaboration, benefit, and support of a large number of professionals in the field and with whom I have had the pleasure of working; unfortunately many of whom are no longer active. Of these my late mentors, Patrick Leehey, Maurice Sevik, Gideon Maidanik, George Chertock, and Murry Strasberg were particularly close. In their place is a host of contemporary friends and collaborators with whom I have both held discussions and published research that has contributed to the development of the many concepts presented herein. Among these are Hafiz Atassi, David Feit, Stewart Glegg, Marvin Goldstein, Jason Anderson, Rudolph Martinez, John Muench, Ki Han Kim, Robert Minnitti, Denis Lynch, John Wojno, Joseph Katz, Theodore Farabee, Lawrence Maga, Irek Zawadzki, Jonathan Gershfeld, Matthew Craun, William Devenport, Meng, Wang, Douglas Noll, Peter Chang, Yu Tai Lee, Thomas Mueller, Scott Morris, Yaoi Guan, and William Bonness. I am especially grateful to Christine Kuhn who has provided a thoughtful and thorough critique of parts of the work. Thanks are also due to Kiruthika Govindaraju and the Elsevier editorial team.

Finally the main debts are owed to my wife Donna, who has endured yet another writing of this book with enduring gifts of love, support, and patience, and to our daughters Kristen and Helen; all of whom enthusiastically supported this revision.

Preface to the First Edition

Flow-induced vibration and sound occur in many engineering applications, yet it is one of the least well known of all the engineering sciences. This subject area is also one of the most diverse, incorporating many other narrower disciplines: fluid mechanics, structural dynamics, vibration, acoustics, and statistics. Paradoxically it is also this diverse nature that causes this subject to be widely regarded as one reserved for experts and specialists. The main purpose of this book, therefore, is to classify and examine each of the leading sources of vibration and sound induced by various types of fluid motion and unifies the disciplines essential to describing each source.

This book treats a broad selection of flow sources that are widely encountered in many applications of subsonic flow engineering and provides combined physical and mathematical analyses for each of these sources. The sources considered include jet noise, flow-induced tones and self-excited vibration, dipole sound from rigid and flexible acoustically compact surfaces, random vibration of flow-excited plates and cylindrical shells, cavitation noise, acoustic transmission characteristics and sound radiation from bubbly liquids, splash noise, throttling and ventilation system noises, lifting surface flow noise and vibration, and tonal and broadband sounds from rotating machinery. The formalisms developed are suitable for computer modeling, but closed-form asymptotic solutions are emphasized. Many features of the book have evolved, in part, from the author's own requirements for integrating the fundamentals of the subject with the many practicalities of the design of quiet vibration-free machinery.

To achieve the objective of the book to unify the subject, the second chapter provides comprehensive analytical developments of the classical theories of aeroacoustics and hydroacoustics. These developments begin with the equations of motion, progress through derivations of various forms of the wave equation, and end with the setting down of the formalism of integral solutions that are valid for sources near boundaries. The formal treatment is then broadened and applied to various practical source types throughout the remainder of the book. An important feature of the treatment of real sources is the random nature of the exciting flows in both space and time. Thus statistical methods are introduced in these chapters to describe the sound and vibration generation process in such cases. In summary the book treats the essentials of how flow disturbances generate sound in the absence of local

surfaces, how flows of practical importance excite bodies into vibration, and then how these excited surfaces radiate sound.

Once a mathematical description of the flow-induced surface motion exists, it is a straightforward matter for design engineers to extend the modeling of this book to address other problems such as flow-induced stress and fatigue in structures. In every case presented the derived relationships in this book are tested against whatever empirical data were made available to the author, from either laboratory or field test results, in order to examine the limitations to the theory. The results are also examined to elucidate effective methods for sound and vibration control by considering both the nature of the flow as well as the classical noise control methods. The results of the book may thus also be used to give insights into how entire processes may be designed for fundamentally quiet operation.

The book is written principally as a reference work, although it may be used as a teaching aid. The reader will always find reasonably sophisticated results supported by step-by-step derivations that clearly identify any assumptions made. Each chapter is illustrated with comparisons of leading formulas and measured data. The reference lists, though not meant to be exhaustive, are extensive and are intended to support all phases of the book with up-to-date background and additional information. Because the physical sources of sound and vibration are developed from fundamental principles, readers who are also well versed in machine design or in any of the related engineering sciences should be able to apply the principles in this book in their work. An attempt has been made to use mathematical notation that is standard in other fields of engineering.

The first six chapters (the contents of Volume I) have been written with emphasis on the elements of fluid mechanics, vibration, and acoustics. These chapters deal with the more fundamental sources of flow noise. Thus this volume might fit into a curriculum that offers courses in applied mathematics, acoustics, vibration, and strength of materials and lacks a relatively generalized course in the physical principles of vibration and sound abatement. Volume II, on the other hand, deals with more advanced and practical subject areas. Both volumes could serve as reference books for graduate courses in vibration, noise control, acoustics, and process design engineering. Draft versions of parts of the book have been used by the author in a graduate course in special topics in acoustics at the Catholic University of America and in short courses.

Due to the interdisciplinary nature of the subject of flow-induced vibration and sound as treated in this book, it is unlikely that the average reader will be equally well versed in all the component disciplines: applied mathematics, fluid mechanics, vibrations, strength of materials, acoustics, and statistical methods. Accordingly readers of the book should be accomplished in senior-level applied mathematics as well as in strength of materials and in at least one of the remaining disciplines listed. An attempt has been made to

provide at least a cursory review of certain concepts where it is felt that prior training might be lacking. Readers lacking familiarity in any of the areas will find references to currently available representative texts. An attempt has been made to consolidate the various mathematical developments so that readers who do not seek familiarity with analytical details may focus on the physical properties of the sources. The illustrations will in these cases often provide those readers with insights concerning the parametric dependencies of the various sources.

The author is indebted to his colleagues at the David Taylor Naval Ship Research and Development Center, in academia, and in industry for continuing interest in the project. Special thanks go to Professor Patrick Leehey of the Massachusetts Institute of Technology who provided me with both instruction and inspiration and to Dr. Maurice Sevik who provided encouragement as the work progressed. The book has benefited from conversations with and information provided by A. Powell, J. T. C. Shen, G. Maidanik, G. Franz, M. Strasberg, F. C. DeMetz, W. T. Reader, S. Blazek, A. Paladino, T. Brooks, L. J. Maga, R. Schlinker, J. E. Ffowcs Williams, I. Ver, A. Fagerlund, and G. Reethoff. From time to time, I imposed on a variety of experts to review selected chapters; gratitude is extended to M. Casarella, D. Crighton, M. S. Howe, R. E. A. Arndt, R. Armstrong, F. B. Peterson, A. Kilcullen, D. Feit, M. C. Junger, F. E. Geib, R. Henderson, R. A. Cumming, W. B. Morgan, and R. E. Biancardi. Thanks are also due to C. Knisely, D. Paladino, and J. Gershfeld who read all or part of the manuscript and located many of the inconsistencies and errors.

Finally the main debts are owed to my wife Donna, who initially suggested the project and whose enduring gifts of love, support, and patience made possible its completion, and to our daughters Kristen and Helen for their cheerfulness as they virtually grew up with the book around them.