Mechanics of Flow-Induced Sound and Vibration

VOLUME I

General Concepts and Elementary Sources

William K. Blake

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To my wife, Donna

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Preface

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. A 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 unify 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 of 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.

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Organization of the Book

Volume I is organized by topic and generally deals with fundamentals and basic analytical formulations. Chapter 2 concentrates on the analytical fundamentals that are required throughout the remainder of the work. In order to enhance its usefulness as a teaching aid, Volume I might well be used with a slightly modified organization in which the analytical formulations are worked into the various treatments of sources. The accompanying table therefore organizes the various sections in an order which the author has preferred in lectures. Certain sections are regarded as supplementary to the main theme, although the identification of those sections may be a matter of taste.

Volume II gives more advanced and applied topics, and it requires that the reader be somewhat accomplished with the material of Volume I. The author has used various sections of Chapters 7, 9, 11, and 12 as extensions of the fundamentals. Instructors who from their work are familiar with one or more of the topics of Volume II should be acclimated to the treatments given. Chapter 9 has a section that draws a connection between the flow-induced and acoustically induced vibration of two dimensional structures. This topic is expanded to problems involving cylindrical shells in Chapter 10. Chapters 11 and 12 give an in-depth examination of not only the fundamentals of lifting surface noise, but also the practical aspects of quieting fans, propellers, and blowers.

Organization of Volume 1 into Course Topics

Topic	Core sequence	Supplementary material
Mathematical formulations of aeroacoustics	Ch. 1, 2.1, 2.2, 2.3	
Analytical models of stochastic processes	2.6, 3.5	
Correlation models	3.6.3.3	
Spatially random excitation of structures	5.3.1	
Flow-tones	3.1–3.4	
Jet noise	3.6.1, 3.6.2	3.6.3, 3.7
Dipole sound		
Analytical modeling	2.1.3, 2.4, 2.5, 4.5	
Ducted sources		2.7, 4.7.4
Vortex shedding	4.1–4.4	4.6, 4.7
Vortex-induced vibration	5.7	
Non-linear vibration	5.7.4	
Random vibration	5.1–5.4	5.6
Structural radiation	5.5	
Noise control fundamentals	5.7	5.8
Two-phase flow noise		
Bubble dynamics	6.1.1	
Acoustic propagation	6.1	
Cavitation noise	6.2–6.4	Appendix

List of Symbols

$\mathcal{R}$	Aspect ratio
A_p	Area of a panel, or hydrofoil
B	Number of blades in a rotor or propeller
b	Gap opening (Chapter 3)
C	Blade chord
C_D, C_L, C_f, C_p	Drag, lift, friction, and pressure coefficients, respectively
c	Wave speed, subscripted: 0, acoustic; b, flexural bending; g, group (Chapter 5), gas (Chapters 6 and 7); L, bar; l longitudinal; m, membrane (Chapter 5), mixture (Chapters 3, 5, and 6)
$\mathcal{D}$	Steady drag
D	Diameter (jet; propeller, rotor in Chapters 3, 7, 12)
d	Cylinder diameter, cross section
$E(x)$	Expected value of $x(=\bar{x})$
f	Frequency
$F_i(t)$	Force in i direction
F_i'', F_i'''	Force per unit area, volume
$\mathcal{F}_r$	Froude number
$G(\mathbf{x}, \mathbf{y}), G(\mathbf{x}, \mathbf{y}, \omega)$	Green's functions. Subscripted m for monopole, d_i for dipole oriented along i axis.
$H_n(\xi)$	Cylindrical Hankel function, nth order
h	Thickness of plate, or of trailing edge, hydrofoil, propeller blade
h_m	Maximum thickness of an airfoil section
I	Acoustic intensity
J	Propeller advance coefficient
$J_n(\xi)$	Bessel's function, first kind, nth order
K	Cavitation index $(P_\infty - P_v)/q_\infty$
k, k_i	Wave number; i, ith direction; k_{13}, in the 1, 3 plane
k_g	Geometric roughness height

k_n, k_{mn}	Wave numbers of nth or m, n modes
k_p	Plate bending wave number, $k_p = \omega/c_b$
k_s	Equivalent hydrodynamic sand roughness height
k_T, k	Thrust and torque coefficients for propellers and rotors, Eqs. (12-20) and (12-21).
k_0	Acoustic wave number ω/c_0
$\mathscr{L}$	Steady lift
L, L'	Unsteady lift and lift per unit span, Chapter 12, usually subscripted
L, L_3	Length across the stream, span
L_i	Geometric length in ith direction
l_c, l_f	Spanwise correlation length, eddy formation length
l_0	Length scale pertaining to fluid motion without specification
$\mathscr{M}$, $\mathscr{M}_c$, $\mathscr{M}_T$, $\mathscr{M}_\infty$	Mach numbers: convection (c), tip (T), free stream (∞)
M	Mass
m_m, m_{mn}	Fluid added mass per unit area for m or mn vibration mode
m_s	Structural plating mass per unit area
N	Number of bubbles per unit fluid volume
$n(k)$, $n(\omega)$	Mode number densities
$\mathbf{n}$, n_i	Unit normal vector
n	Shaft speed, revolutions per second
$n(R)$	Bubble distribution density number of bubbles per fluid volume per radius increment
$\mathbb{P}$, $\mathbb{P}(\omega, \Delta\omega)$	Power, total and in bandwidth $\Delta\omega$, respectively
$\mathbb{P}_{rad}$	Radiated sound power
P	Average pressure
P_i	Rotor pitch
P_∞	Upstream pressure
p	Fluctuating pressure; occasionally subscripted for clarity: a, acoustic; b, boundary layer, h, hydrodynamic
$\mathscr{Q}$	Torque
q	Rate of mass injection per unit volume
q_∞, q_T	Dynamic pressures based on U_∞ and U_T
$\mathscr{R}_L$	Reynolds number based on any given length scale L, $= U_\infty L/\nu$
R	Radius; used in Chapters 7 and 8 for general bubble radius and in Chapter 12 for propeller radius coordinate
R_b	Bubble radius
R_{ij}	Normalized correlation function of velocity fluctuations u_i and u_j
R_{pp}	Normalized correlation function of pressure
$\hat{R}$	Nonnormalized correlation function Section 2.6.2
R_T, R_H	Fan tip and hub radii
$\mathbf{r}$, r_i	Correlation point separation, the distinction from r is clear in the text
r	Acoustic range, occasionally subscripted to clarify special source point-field identification
$\mathscr{S}$	Strouhal number $f_s l_0/U$ where l_0 and U depend on the shedding body
$\mathscr{S}_e$, $\mathscr{S}_{2D}$	One- and two-dimensional Sear's functions
$S_{mn}(\mathbf{k})$	Modal spectrum function

$S_p(r, \omega)$	Spectrum function used in Chapter 6 defined in Section 6.4.1
T	Averaging time
T, $T(t)$	Thrust, steady and unsteady
T_{ij}	Lighthill's stress tensor Eq. (2-47)
t	Time
U	Average velocity, subscripted: a, advance, c, convection; s, shedding ($= U_\infty \sqrt{1 - C_{pb}}$); T, tip, τ, hydrodynamic friction ($= \sqrt{\tau_w/\rho_0}$); ∞, free stream
$\mathbf{u}$, u_i	Fluctuating velocities
V	Stator vane number in Chapter 12
v	Volume fluctuation
$v(t)$	Transverse velocity of vibrating plate, beam, hydrofoil
$\mathscr{W}_e$	Weber number, Chapter 7
$\mathbf{x}$, x_i	Acoustic field point coordinate
$\mathbf{y}$, y_i	Acoustic source point coordinate
$y_{\rm i}$	Cross-wake shear layer thickness at point of maximum streamwise velocity fluctuation in wake, Figs. 11-1, 11-18
α	Complex wave number, used in stability analyses and as dummy variable
α_s	Stagger angle
β	Volumetric concentration (Chapters 3 and 7), fluid loading factor $\rho_0 c_0/\rho_p h\omega$ (Chapters 1, 5, 9, and 11), hydrodynamic pitch angle (Chapter 12)
Γ, Γ_0	Vortex circulation (0), root mean square vortex strength in Chapter 11
γ	Adiabatic gas constant (Chapter 6), rotor blade pitch angle (Chapter 12)
δ	Boundary layer or shear layer thickness, also $\delta(0.99)$ and $\delta(0.995)$
$\delta(x)$	Either of two delta functions, see p. 41
δ^*	Boundary (shear) layer displacement thickness
$\eta_{\rm i}$, $\eta_{\rm p}$	Powering efficiencies; i, ideal; p, propeller
$\eta_{\rm T}$, $\eta_{\rm rad}$, $\eta_{\rm m}$, $\eta_{\rm v}$, $\eta_{\rm h}$	Loss factors: T, total; rad, radiation; m, mechanical; v, viscous; h, hydrodynamic
θ	Angular coordinate
θ_τ	Integral time scale of turbulence
$\theta_{\rm m}$	Moving-axis time scale
κ	von Karman constant (Chapter 8), radius of gyration of vibrating plate $h/\sqrt{12}$, beam, hydrofoil (Chapters 9, 10, and 11)
κ, κ_{13}	Dummy wave number variables
Λ	Integral correlation length; for spatial separations in i direction Λ_i
λ	Wavelength (also turbulent microscale in Chapter 11)
μ	Viscosity
$\mu_{\rm p}$	Poisson's ratio, used interchangeably with μ when distinction with viscosity is clear
$\pi(\omega)$	Power spectral density

ρ	Density; ρ_0 average fluid; ρ_g, gas; ρ_m, mixture; ρ_p, plate material
σ_{mn}	Radiation efficiency of *mn* mode, also σ_{rad}
τ	Time delay, correlation
τ_w	Wall shear
τ_{ij}	Viscous shear stress
$\Phi_{pp}(\mathbf{k}, \omega)$	Wave number, frequency spectrum of pressures
$\Phi_{vv}(\omega)$	Auto-spectral density of $v(t)$; subscripted: p for $p(t)$; i for $u_i(t)$, f for $F(t)$
$\Phi_{vv}(\mathbf{y}, \omega)$	Auto-spectral density of $v(t)$ with dependence on location y emphasized; other subscripts as above
ϕ	Angular coordinate
$\phi(\mathbf{y}), \phi(y_i)$	Potential functions
$\phi_i(k_j)$	Wave number spectrum (normalized) of velocity fluctuation u_i
$\phi_{ij}(\mathbf{r}, \omega)$	Cross-spectral density (normalized) between $u_i(\mathbf{y}, t)$ and $u_j(\mathbf{y} + \mathbf{r}, t)$
$\phi_m(\omega - \mathbf{U}_c \cdot \mathbf{k})$	Moving axis spectrum
$\Psi_{mn}(\mathbf{y}), \Psi_m(\mathbf{y})$	Mode shape functions
$\psi(\mathbf{y})$	Stream function
Ω	Shaft rate
ω	Circular frequency
$\boldsymbol{\omega}, \omega_i$	Vorticity vector, component in i direction
ω_c	Coincidence frequency
ω_{co}	Cutoff frequency of an acoustic duct mode
ω_R	Circular cylinder ring frequency

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