AEROACOUSTICS OF FLIGHT VEHICLES

Theory and Practice

Volume 1: Noise Sources

Edited by
Harvey H. Hubbard

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Preface

The field of aeroacoustics has matured dramatically in the past two decades. Researchers have gained significant theoretical and experimental understanding of the noise generated by aircraft power plants and their components. In addition, airframe noise and interior noise have been investigated extensively. The physical understanding obtained from these efforts has resulted in the development of hardware capable of reducing community noise and of meeting strict noise certification requirements. Reductions in overall sound pressure level of 20 to 30 dB have been obtained for some types of power plants, while in the same period their installed power has increased significantly.

Current quiet flight vehicle designs are based on information reported in a multitude of journals, conference proceedings, research reports, and specialized books. Each of these scientific publications represents only incremental steps in the evolution of our present understanding of the various aeroacoustic noise generation and propagation mechanisms and procedures for noise control. There is thus a need for a reference document summarizing the current status of aeroacoustics. It is recognized that some other fine books on aeroacoustics are already available. The reader is referred to the classic handbooks by Harris on noise and vibration control; to Goldstein's "Aeroacoustics," which provides a general theoretical treatment of most aeroacoustic noise sources; to the text "Noise and Acoustic Fatigue in Aeronautics" by Richard and Mead; and to the AIAA Preprint Series volume entitled "Aerodynamic Noise." The current book represents an attempt to integrate and update the information in previous related publications, to provide a balanced viewpoint with both fundamental and applied aspects being considered, and to focus on those topics that are significant for the design and operation of quiet flight vehicles.

In July 1982, the Continuing Education Subcommittee of the Institute of Aeronautics and Astronautics (AIAA) Aeroacoustics Technical Committee identified a critical need for a reference book summarizing and interpreting the status of research in aeroacoustics. The full Aeroacoustics Technical Committee agreed with this conclusion and enthusiastically supported the concept of publishing such a book. The book would have a scope consistent with that of the Technical Committee and would include physics of noise produced by motion of fluids and bodies through the atmosphere and by chemical reaction processes; it would also include the responses of human beings, structures, and the atmosphere to aerodynamic noise. The subcommittee was then instructed to prepare an initial outline of the book for planning purposes and to procure financial support for its printing. This effort has been given generous support by the Langley, Lewis, and Ames Research Centers of the National Aeronautics and Space Administration (NASA); the U.S. Air Force Wright Research and Development Center; and the U.S. Army Aviation Systems Command.

This book is planned as a reference publication, easily readable by persons with scientific or engineering training who have completed a bachelor degree study program. It serves as an authoritative resource book for teachers, students, and researchers, but it is not designed for use directly as a textbook. It provides recommended methodology to evaluate aeroacoustics-related problems and suggests approaches to their solutions, without extensive tables, nomographs, and derivations. It is oriented toward flight vehicles and emphasizes underlying physical concepts. Theoretical, experimental, and applied aspects are covered, including the main formulations and comparisons of theory and experiment.

The preparation of the material for this book has been carried out under the general supervision of the AIAA Technical Committee on Aeroacoustics. The Committee elected the editor (Harvey H. Hubbard), two associate editors (Christopher K. W. Tam and Robert H. Schlinker), and six additional editors (Charles E. Feiler, James C. Yu, Walter K. Eversman, Marvin E. Goldstein, Robert E. Kraft, and Yung H. Yu). Donald L. Lansing and John Laufer (until his untimely death) also served for short terms. They functioned as an editorial board to establish the overall policy for the organizing, reviewing, and editing of the book. Each was selected because of his expert knowledge of at least one of the specialty areas covered in the book. They collectively comprise a team of experts who represent industry, government, and academia viewpoints.

The editorial board members chose by vote the lead authors for each chapter based on their stature and expertise in particular technical areas and on their proven ability to communicate. In all cases, contributing authors were selected and enlisted by the lead authors and on the basis of the same criteria. An outline of each chapter was first approved by the editorial board as a means of defining the overall scope of that chapter. Technical reviewers were chosen by vote of the editorial board based on their expertise of subject matter and the nature of their experience. Two to four persons were selected to provide technical reviews for each manuscript. These technical reviews were then provided to the appropriate authors as a basis for the preparation of their final manuscripts. Final editing was accomplished by Mary K. McCaskill and Thomas H. Brinkley of the NASA Langley Research Center Technical Editing Branch. This latter effort involved skilled technical editors closely associated with the publication profession. Their work included checking for accuracy, grammar, consistency of style, compliance with editorial instructions, and assembly for printing.

Authors and reviewers contributed their time for this project without receiving compensation. Draft manuscript preparation, typing, and graphics were supported partially or wholly by the participant's employer. All these contributions were vital to the success of this project and are greatly appreciated.

Supporting reference information cited in this book is limited to publications available at the time of the text preparation. No proprietary or classified information is included in order to protect the interests of authors' companies and governments. In order to enhance its utility, this book is divided into two volumes, each of which has a list of symbols, an index, and a separate glossary of terms. Reference lists for each chapter contain the key available supporting documents.

Volume 1 includes all the chapters that relate directly to the sources of flight vehicle noise: Propeller and Propfan Noise; Rotor Noise; Turbomachinery Noise; Jet Noise Classical Theory and Experiments; Noise From Turbulent Shear Flows; Jet Noise Generated by Large-Scale Coherent Motion; Airframe Noise; Propulsive Lift Noise; Combustion and Core Noise; and Sonic Boom. Volume 2 includes those chapters that relate to flight vehicle noise control and/or operations: Human Response to Aircraft Noise; Atmospheric Propagation; Theoretical Models for Duct Acoustic Propagation and Radiation; Design and Performance of Duct Acoustic Treatment; Jet Noise Suppression; Interior Noise; Flyover-Noise Measurement and Prediction; and Quiet Aircraft Design and Operational Characteristics.

This book was published initially in August 1991 as NASA Reference Publication 1258, Vols. 1 and 2, and with a companion United States Air Force Wright Research and Development Center designation as Technical Report 90-3052, Vols. 1 and 2. It was printed in soft cover and carried the appropriate NASA, U.S. Air Force, and U.S. Army logos on its covers.

In November 1993, the Acoustical Society of America agreed to reprint it in a hard-cover version but with modifications to the covers and title pages and with minor changes and corrections to the text. Elaine Moran of the Acoustical Society of America and Andrew Prince of the American Institute of Physics have coordinated the preparation of materials for this reprinting.

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Symbols

A	cross-sectional area; acoustic admittance
b	chord
C_D	drag coefficient
C_L	lift coefficient
C_p, c_p	specific heat at constant pressure
C_v	specific heat at constant volume
c	speed of sound
D, d	diameter
d	distance, e.g., from source to receiver
F	fuel-air ratio; force
f	frequency
G_p	cross spectral density of acoustic pressure
H, h	height
h	enthalpy
I	intensity
i	imaginary number, $\sqrt{-1}$
k	wave number
L_A	A-weighted sound level
L_D	D-weighted sound level
L_{dn}	day-night average sound level
L_{EPN}	effective perceived noise level
L_{eq}	equivalent continuous sound level

L_{PN}	perceived noise level
l, ℓ	length
M	Mach number
m	mass
$\dot{m}$	mass flow ratio
N_{Pr}	Prandtl number
N_{Re}	Reynolds number
N_{St}	Strouhal number
P	power
p	sound pressure
R	reflection coefficient; acoustic resistance; gas constant; duct radius; jet radius
$\Re$	distance from arbitrary point on rotating rotor blade to observer
r	rotor radial position
S	wing area
$S(\sigma)$	Sears function
T	temperature
t	time; wing thickness
U	flight velocity
u	particle velocity; mean velocity; axial velocity
V	velocity
V_e	exit velocity of jet
X	acoustic reactance
x, r, θ	cylindrical coordinates
Z	impedance
α	sound absorption
β	$= \sqrt{M^2 - 1}$
γ	ratio of specific heats
δ_f	flap deflection

δ_{ij}	Kronecker delta
ζ	ratio of characteristic impedances
λ	wavelength
ν	viscosity
ξ	cutoff ratio
ρ	density
σ	reduced frequency of gust
ϕ	phase angle
Ω	rotor rotational rate
ω	circular frequency, $2\pi f$

Abbreviations:

BPF	blade-passage frequency
BVI	blade-vortex interaction
DNL	day-night average sound level
EPNL	effective perceived noise level
FAR	Federal Aviation Regulations
HSI	high-speed impulsive
ICAO	International Civil Aviation Organization
LEQ	equivalent continuous sound level
LL_S	Stevens loudness level
LL_Z	Zwicker loudness level
NR	noise reduction
OASPL	overall sound pressure level
PNL	perceived noise level
PWL	power level
rms	root-mean-square
SLA	A-weighted sound level
SLD	D-weighted sound level
SLE	E-weighted sound level

Symbols

SPL	sound pressure level
SWR	standing wave ratio
TL	transmission loss

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1 Propeller and Propfan Noise

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Introduction

Propellers are familiar devices. Indeed, these were the first means of powering airplanes, preceding all other means of propulsion by about 40 years. Propellers were used extensively through the 1940's. Although there have been many refinements to propellers through the years, such as variable pitch and the application of composite materials to reduce weight, the general appearance of the propeller has changed little.

A propeller can be generally described as an open (unshrouded), rotating, bladed device. Although there are many differences in details among various designs and applications, such as number of blades, blade shape, and airfoil section, the noise-generating process is basically the same for all. The major propeller noise components are thickness noise (due to the volume displacement of the blades), steady-loading noise (due to the steady forces on the blades), unsteady-loading noise (due to circumferentially nonuniform loading), quadrupole (nonlinear) noise, and broadband noise. Although the relative importance of these sources depends on design and operating conditions, defining them will completely describe the acoustic signature of a propeller.

One important consideration is the effect of installation on the noise produced by a propeller. This effect is essentially the difference between the laboratory environment and the real world. It is generally assumed that in a laboratory environment conditions are ideal, that is, the propeller is operating in perfectly uniform flow. For an operational propeller, this is never the case. Propellers are always operating in a flow field that has some distortion. This can be from the wing upwash, the pylon wake, the airplane angle of attack, or the inflow turbulence. Since this distortion leads to additional noise, it is a factor which must be considered in defining the total noise of an operational propeller.