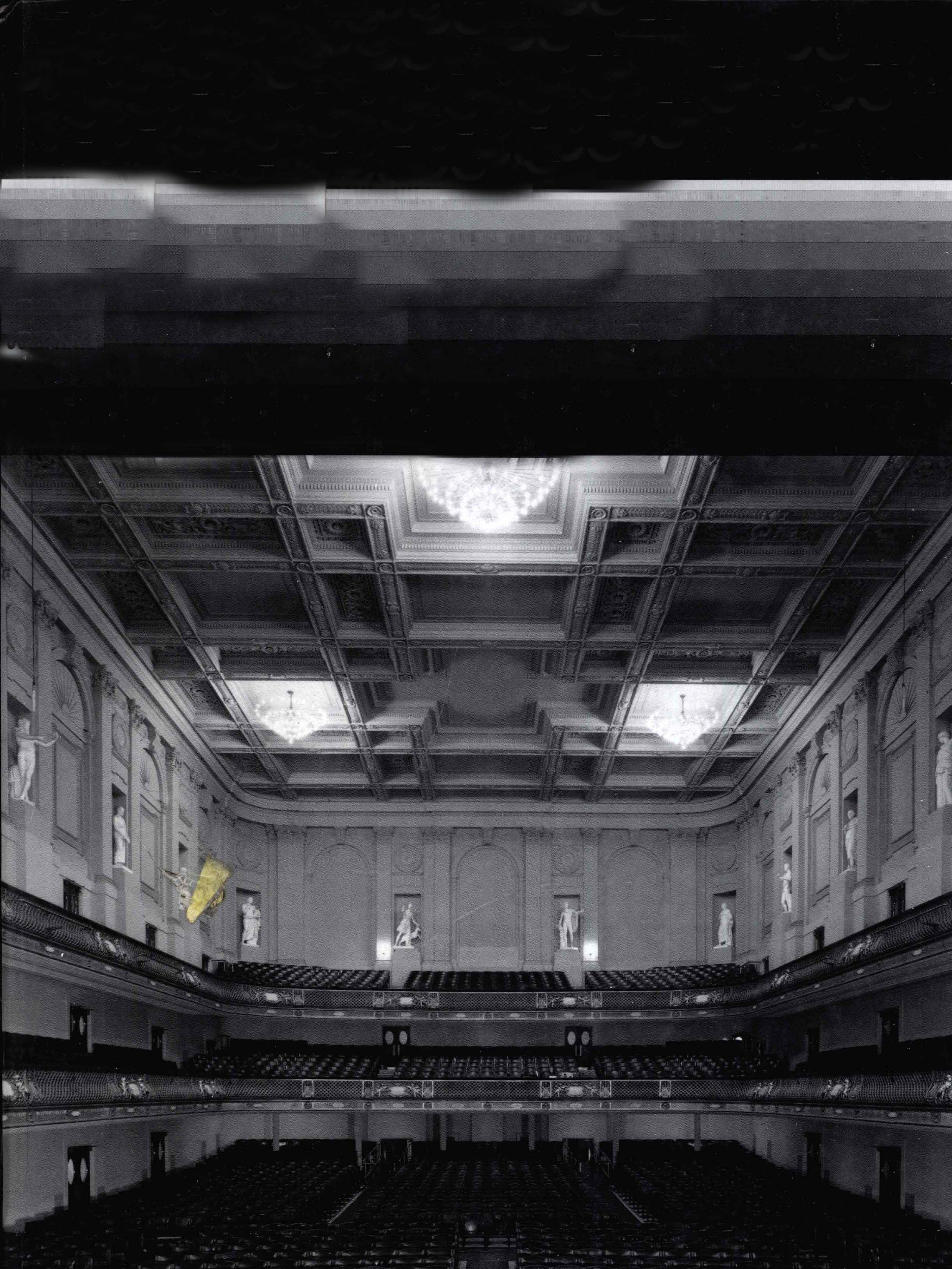

ARCHITECTURAL ACOUSTICS

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About the Author

M. David Egan, P.E., is a consultant in acoustics and part-time professor at the College of Architecture, Clemson University. He has worked as a consultant in acoustics for Bolt Beranek and Newman (BBN) in Cambridge, Massachusetts, and has been principal consultant of his own firm in Anderson, South Carolina for over 15 years. His firm has consulted on over 400 building projects in the United States and abroad. A graduate of Lafayette College (B.S.) and the Massachusetts Institute of Technology (M.S.), where he studied acoustics under the late Professor Robert B. Newman, Professor Egan also has taught at Tulane University, Georgia Institute of Technology, University of North Carolina at Charlotte, and Washington University (St. Louis), and has lectured at numerous schools of design. He is the author of several books in the area of architectural technologies, including *Concepts in Architectural Acoustics* (McGraw-Hill, 1972), *Concepts in Thermal Comfort* (Prentice-Hall, 1975), *Concepts in Building Firesafety* (Wiley-Interscience, 1978 and Kajima Institute, Tokyo, 1981), and *Concepts in Architectural Lighting* (McGraw-Hill, 1983). In addition to consulting, teaching, and writing, Professor Egan is a fellow of the Acoustical Society of America (ASA), former director and two-term vice president of the National Council of Acoustical Consultants (NCAC), associate editor for NOISE/NEWS published by the Institute of Noise Control Engineering (INCE), and national awards coordinator for The Robert Bradford Newman Student Award Fund, Lincoln Center, Massachusetts.

Foreword

The need for practical working knowledge in the environmental sciences for those in the building professions will continue for the foreseeable future. Acoustics, like lighting and the thermal environment, is an environmental science that has become a recognized and respected discipline within the past half century. The fruits of these expanding bodies of scientific knowledge, i.e., practical engineering applications, are increasingly being taken seriously on a widespread basis by architects, engineers, and planners in the solutions of acoustical problems in and around buildings.

Although there are a few exceptions, adequate courses in acoustics have been notably lacking in schools of architecture and engineering. A number of us, including Professor M. David Egan, were fortunate in learning about acoustics at the Massachusetts Institute of Technology through the pioneering and inspirational teaching of the late Professor Robert B. Newman and his colleagues, Professors Leo Beranek and Richard Bolt. Some of their former students, like M. David Egan, have gone on to spread the word not only through design applications of their knowledge but also through lecturing and teaching efforts.

With his earlier book *Concepts in Architectural Acoustics* (McGraw-Hill, 1972), Professor Egan identified the pressing need for a textbook which would cut through to the core of the information needed to understand acoustics problems and to develop practical solutions. The book could hardly be called a textbook in the traditional sense, since the verbal descriptions were few and the major emphasis was on graphic displays of concepts as well as engineering data and problem-solving techniques. This unique approach, as he has found with his students at the Clemson University College of Architecture and elsewhere, appealed to most students of architecture and engineering (of all ages) who need comprehensive yet encapsulated treatments of the environmental sciences. *Concepts in Architectural Acoustics* became a widely used text not only in architectural schools but in the offices of practicing professionals as well. Indeed, many acoustical consultants recommend the book to clients when the need for a little more understanding of technical details exists.

In this new text, *Architectural Acoustics,* Professor Egan has retained all the desirable features of its predecessor and has updated the material with the experience gained this past decade, as well as added several new useful features such as checklists on design and problem areas in building acoustics. The clarity of the illustrations and format of tables of engineering data greatly enhance the usefulness of the book for reference. Like its predecessor, *Architectural Acoustics* emphasizes concepts and aids the designer/decisionmaker in judging the relative importance of acoustical considerations in the context of the overall building environmental system.

This book is an important contribution to the better understanding of building acoustics problems in a growing multidisciplinary design environment.

William J. Cavanaugh
Fellow, Acoustical Society of America
Natick, Massachusetts

Preface

The goal of this book is to present in a highly illustrated format the principles of design for good hearing and freedom from noise in and around buildings. The over 540 illustrations are not merely supplements to the text as with nearly all traditional books. In this book, the illustrations are the core of the coverage of basic principles of sound and hearing, sound absorption and noise reduction, sound isolation and criteria for noise, control of HVAC systems noise and vibrations, auditorium acoustics design, and electronic sound systems.

The book is written for architects, interior designers, engineers, and all others concerned with the design and construction of buildings who need to know the basics of architectural acoustics, but who do not have the time needed to digest wordy presentations. The book is a successor to *Concepts in Architectural Acoustics* (McGraw-Hill, 1972) with the overwhelming majority of the illustrations, case histories, and example problem solutions either entirely new or substantially revised.

The late Professor Robert B. Newman was the author's mentor and teacher in graduate school. His course on architectural acoustics was the inspiration to become an acoustical consultant. The message of that course, offered by Professor Newman for nearly four decades at the MIT School of Architecture and Planning and at the Harvard University Graduate School of Design, was that designers who understand the basic principles of acoustics possess an important new tool for shaping the built environment. The intentions of this book, therefore, are similar. That is, to diffuse knowledge of acoustics and to promote its creative applications in design. Hopefully, not only better acoustical environments, but also better buildings should result.

The book also contains numerous checklists of design aids, data tables of sound absorption and sound isolation properties for a wide variety of modern building materials, case study examples, and step-by-step practical problem solutions. Extensive references are provided so that the interested reader can dig deeper. The appendix includes a metric system conversion table for common building acoustics terms and a summary of useful formulas.

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It would be nearly impossible to name all the people who have influenced me in the fields of architecture and acoustical design, and thereby contributed to the preparation of this book, without inadvertently overlooking someone. Nevertheless, thanks are due to the following persons who provided reviews of portions of chapters in their area of special professional interest: James J. Abernethy, Eric Neil Angevine, Elliott H. Berger, John S. Bradley, Daniel R. Flynn, Ernest E. Jacks, John W. Kopec, Jerry G. Lilly, L. Gerald Marshall, James B. Moreland, Bynum Petty, Gregory C. Tocci, Keith W. Walker, Brian L. Williams, and Randolph E. Wright.

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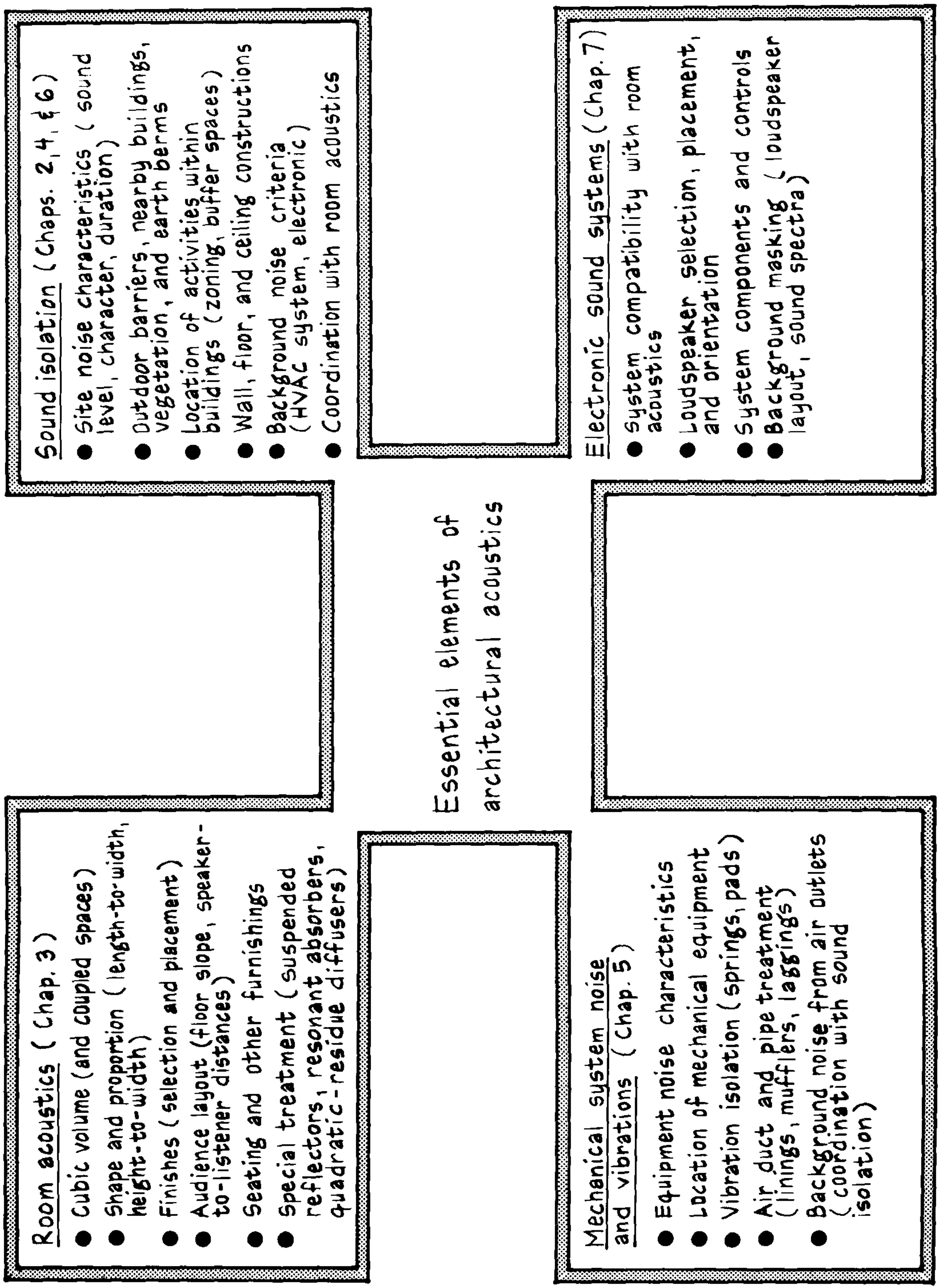
Introduction

Almost all acoustical situations can be described by three parts: source, path, and receiver. Sometimes the *source* (human speech, HVAC equipment) can be made louder or quieter. For example, strategic placement of reflecting surfaces near the speaker in lecture rooms, churches, and auditoriums can reinforce and evenly distribute sound to all listeners. The *path* (air, earth, building materials) can be made to transmit more or less sound. When required, double-wall and other complex constructions can be designed to interrupt the sound path, thereby providing satisfactory sound isolation and privacy. The *receiver* (usually humans, although sometimes animals or sensitive medical equipment) also can be affected. Usually building occupants will hear better, or be more comfortable, if distracting HVAC system noise can be controlled or if intruding environmental noise can be isolated or removed. In most situations, it is best to focus on all three parts. For example, concentrating only on the direct path for sound travel through common walls may at best result in costly overdesign or at worst, no solution at all!

Acoustical requirements always should be considered during the earliest stages of design. Even though corrections can be accomplished during the mid- and latter stages of design, it usually is very difficult to change shapes, room heights, and adjacencies within buildings when spatial relationships and budgets have been fixed. Similarly, deficiencies in completed spaces are often extremely difficult and costly to correct. For example, the addition of an electronic, sound-reinforcing system to an auditorium which is excessively reverberant may exaggerate deficiencies rather than improve listening conditions. This kind of acoustical surprise should not occur if designers understand the basic principles of acoustics. Successful designers provide the spatial relationships, cubic volumes, shapes, and the like so their buildings maintain design quality while best serving their intended purposes, whether it be for work, play, or rest.

Designers should not rely on oversimplified articles in trade magazines, misleading advertisements and incomplete technical data from manufacturers, or highly specialized texts written in technical jargon. The goal of this book, therefore, is to provide a comprehensive framework for the study of acoustics as well as a long-term resource for designers. The designer should be able to anticipate the acoustical problems inherent to most buildings, solve those of a routine nature, and determine when professional assistance is required. A reference source for information on qualified acoustical consultants is the biennial *Directory* of the National Council of Acoustical Consultants (NCAC). The Acoustical Society of America (ASA) also maintains a listing of persons and firms offering acoustical consulting services.

The designer who understands the essential elements of architectural acoustics will be able to best collaborate with acoustical consultants by asking the right questions, identifying alternative solutions, and implementing successful designs. The illustration below identifies essential elements of architectural acoustics and the corresponding chapters in the book.



Contents

Chapter 1

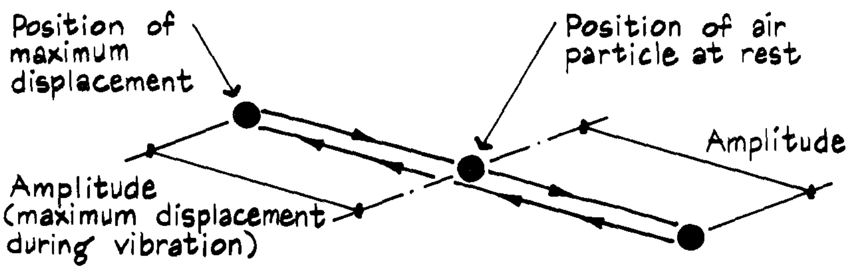
Basic Theory

SOUND AND VIBRATION

Sound is a vibration in an elastic medium such as air, water, most building materials, and the earth.* An elastic medium returns to its normal state after a force is removed. *Pressure* is a force per unit area. Sound energy progresses rapidly, producing extremely small changes in atmospheric pressure, and can travel great distances. However, each vibrating particle moves only an infinitesimal amount to either side of its normal position. It "bumps" adjacent particles and imparts most of its motion and energy to them. A full circuit by a displaced particle is called a *cycle* (see illustration below). The time required for one complete cycle is called the *period* and the number of complete cycles per second is the *frequency* of vibration. Consequently, the reciprocal of frequency is the period. Frequency is measured in cycles per second, the unit for which is called the hertz (abbreviated Hz).

Vibration of Particle in Air

The back and forth motion of a complete cycle is shown below.



Pure Tones

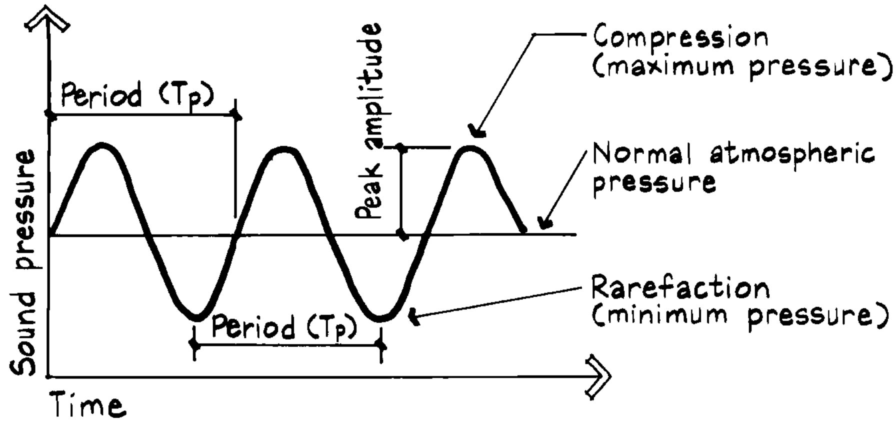
A *pure tone* is vibration produced at a single frequency. Shown below is the variation in pressure caused by striking a tuning fork, which produces an almost pure tone by vibrating adjacent air molecules. Symphonic music consists of numerous tones at different frequencies and pressures (e.g., a tone is composed of a fundamental frequency with multiples of the fundamental, called *harmonics*). To find the period corresponding to a frequency of vibration, use the following formula:

$$T_p = \frac{1}{f}$$

where T_p = period (s/cycle)
f = frequency (cycles/s or Hz)

**Noise* is unwanted sound (e.g., annoying sound made by other people or very loud sound which may cause hearing loss).

For example, a frequency of 63 Hz has a period T_p of $1/63 \simeq 0.02$ s/cycle (roughly 30 times longer than the period at 2000 Hz).



Complex Sounds

The variation in pressure caused by speech, music, or noise is shown below. Most sounds in the everyday world are complex, consisting of a variety of pressures which vary with time. The threshold of hearing for humans is one-millionth of normal atmospheric pressure.