INDUSTRIAL NOISE AND VIBRATION CONTROL

J. D. IRWIN
and
E. R. GRAF

Department of Electrical Engineering
Auburn University, Alabama

PRENTICE-HALL, INC., *Englewood Cliffs, New Jersey 07632*

ACKNOWLEDGMENTS

The authors wish to gratefully acknowledge many of their colleagues who have contributed to this text. In particular, we are especially indebted to Mr. Donald E. Bently, Bently Nevada Corporation, Minden, Nevada, and Mr. Kenneth A. Ramsey, Hewlett-Packard Corporation, Santa Clara, California, for their constructive help and criticism of the vibration material and for allowing us to use some of their work in this text. Special thanks are also expressed to Dr. Charles E. Hickman, Southern Company Services, Inc., Birmingham, Alabama, for providing an appendix and other selected material. We also extend our thanks to Mr. Robert E. Perry, Barron Air Systems Engineers, Birmingham, Alabama, who provided some examples, and Mr. Charles Jackson, Monsanto, Texas City, Texas, who reviewed the vibration material. Also, we thank the Industrial Acoustics Company for providing pictures of various pieces of noise control equipment.

Finally, we are deeply indebted to the many graduate and undergraduate students whose suggestions were extremely helpful in the review and correction of the entire text. Expecially, we wish to thank Gregory H. Williams, Theodore R. Serota, Alan H. Bissinger, and Arnold Geeslin, Jr., for their assistance with the problems and the production of the solutions manual.

PREFACE

This textbook was developed from notes used for a number of years in teaching an undergraduate course in industrial noise and vibration control. Furthermore, additional material was added to the notes as a result of numerous industrial short courses taught on the subject. The topics have been judiciously selected and every attempt has been made to present the material in a fashion that is readily usable both for an undergraduate course or for self-study by a practicing engineer.

The mathematics has intentionally been maintained at a level easily handled by college sophomores; however, juniors are probably better prepared in most instances for a rapidly moving treatment. Considerable detail has been included in selected derivations. This was done to clarify certain critical equations that are of great importance to the entire text. However, this extra detail may be skipped at the discretion of the instructor without a serious loss to practical problem solving.

Both English and metric systems of units are used throughout. A table of conversion factors is provided in an appendix to allow for quick conversion where it is desirable. No effort has been made to designate each and every equation, table, and figure in both sets of units. Only in critical instances are both given. All the remaining ones are left as exercises. Weight is given in newtons as a simplification of units.

The text is replete with examples, and drill problems appear after most sections in which an important formula or concept has been introduced. For the most part, the drill problems are straightforward and relatively simple. The answers to the drill problems appear with the problems. Additional problems at the end of each chapter are generally more difficult than the drill problems and are intended to exercise and demonstrate the new concepts presented in the chapter which they follow. The answers to the odd problems are given in at the end of the book. A complete solutions manual with all drill problems and chapter problems solved is available as an instructor's aid.

J. D. IRWIN
E. R. GRAF

Auburn University
Auburn, Alabama

CONTENTS

5 SOURCES OF NOISE *114*

1

SOUND LEVELS, DECIBELS, AND DIRECTIVITY

1.1 INTRODUCTION

Sound may be described as a propagating disturbance through a physical medium. It is perceived by the ear as a pressure wave superimposed upon the ambient air pressure at the listener. The *sound pressure* is therefore the incremental variation about the ambient atmospheric pressure.

We shall now proceed to a mathematical description of those pressure waves that we designate as sound.

1.2 SOUND WAVE CHARACTERISTICS

Sound wave characteristics are readily described upon examining the attributes of a pure tone. A *pure tone* is a sinusoidal pressure wave of a specific frequency and amplitude, propagating at a velocity determined by the temperature and pressure of the air.

Let us now consider a hypothetical sound generator, as shown in Figure 1.1. The source may be thought of as an elastic sphere that expands and contracts sinusoidally at a frequency, f. As the sphere expands, the air molecules are compressed. Then as the sphere contracts, the air molecules spread apart; that is, the gas is rarefied. The *sound wave* thus generated will have a frequency equal to the number of times per second which the sphere expands and contracts. The peak pressure amplitude is a function of the maximum excursion of the sphere.

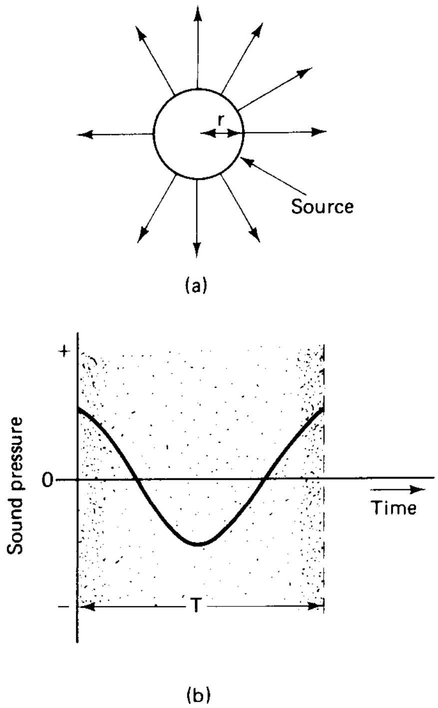

FIGURE 1.1 *(a) Spherical source oscillating at a frequency, f, to generate a spherical acoustic wave; (b) pressure vs. time for the sinusoidal wave with the compression and rarefaction of the gas depicted*

1.2.1 Frequency, Period, and Wavelength

The concept of *frequency* is common to both electrical and mechanical oscillations. The frequency, f, of an oscillating disturbance is equal to the number of times per second that the disturbance passes through both its positive and negative excursions. The number of cycles per second is termed *hertz* (Hz). For example, in the United States our electrical utility systems supply electrical power at 60 Hz, which simply means that a voltage is delivered with a sinusoidal waveform varying at 60 cycles per second.

The frequency of a simple pure-tone sound wave is recognized as the *pitch* of the tone. The human ear responds to a range of frequencies from approximately 20 to 16,000 Hz, with a maximum sensitivity at about 3,000 Hz.

In the area of industrial noise reduction we shall be interested primarily in the range of frequencies from about 63 Hz to 16,000 Hz. This is because the sensitivity of the human ear is greatly reduced below 63 Hz and above 16,000 Hz compared to its peak sensitivity.

The *period*, *T*, of the sinusoidal wave is depicted in Figure 1.1. Period is related to the frequency, *f*, by

$$\boxed{T = \frac{1}{f} \quad \mathrm{s}} \tag{1.1}$$

We note that the period is the time required for one complete cycle.

The *wavelength*, *λ*, is the distance between like points on two successive waves. Wavelength is related to the frequency and velocity of propagation by

$$\boxed{\lambda = \frac{c}{f} = cT \quad \text{ft} \quad \text{or} \quad \text{m}} \tag{1.2}$$

where the *velocity of propagation*, *c*, is in turn a function of the characteristics of the propagation supporting medium.

1.2.2 Velocity of Sound

The speed of sound in air is given by

$$c = \sqrt{\frac{\gamma p_0}{\rho}} \quad \text{ft/s} \quad \text{or} \quad \text{m/s} \tag{1.3}$$

where $\gamma = \dfrac{\text{specific heat (constant pressure)}}{\text{specific heat (constant volume)}}$

p_0 = ambient or equilibrium pressure

ρ = ambient or equilibrium density

In the case of air, within the range of conditions of interest, γ is taken as 1.4. Equation (1.3) then becomes

$$c = \sqrt{\frac{1.4 p_0}{\rho}} \quad \text{ft/s} \quad \text{or} \quad \text{m/s} \tag{1.4}$$

which can be further simplified by taking advantage of the fact that the ratio p_0/ρ is related to the temperature of the gas. Upon assuming that the air behaves virtually as an ideal gas, the velocity, *c*, is related to the absolute temperature in degrees Rankine by

$$\boxed{c = 49.03\sqrt{R} \quad \text{ft/s}} \tag{1.5}$$

where *R*, the temperature in degrees Rankine, is

$$R = [459.7^\circ + (\text{degree Fahrenheit})] \quad \text{degrees} \tag{1.6}$$

The velocity as related to degrees Kelvin is

$$\boxed{c = 20.05\sqrt{T} \quad \text{m/s}} \tag{1.7}$$

where T, the temperature in degrees Kelvin, is

$$T = [273.2^\circ + (\text{degree Celsius})] \quad \text{degrees} \tag{1.8}$$

EXAMPLE 1.1 Calculate the velocity of sound in air at 70°F (21.1°C) in both English and metric units. Then determine the wavelength of a 1000-Hz tone at the same temperature.

SOLUTION

$$R = (459.7^\circ + 70^\circ) = 529.7^\circ \text{ Rankine}$$

$$c = 49.03\sqrt{529.7} = 1128 \text{ ft/s}$$

$$T = (273.2^\circ + 21.1^\circ) = 294.3^\circ \text{ Kelvin}$$

$$c = 20.05\sqrt{294.3} = 344 \text{ m/s}$$

$$\lambda = \frac{c}{f} = \frac{1128}{1000} = 1.128 \text{ ft} \quad \text{at 1 kHz}$$

$$\lambda = \frac{c}{f} = \frac{344}{1000} = 0.344 \text{ m} \quad \text{at 1 kHz}$$

It is also important to note that the velocity of sound in common building materials is generally quite different from that for air. This, in turn, means that the wavelength in these materials is proportionately different from that in air. This becomes of particular importance to us when we consider the isolation of low-frequency sounds. Table 1.1 lists the approximate veloc-

TABLE 1.1

Approximate velocity of sound in certain common media at room temperature (70°F or 21.1°C)

Material	Velocity of Sound ft/s	Velocity of Sound m/s
Air	1,128	344
Water	4,500	1,372
Concrete	10,000	3,048
Glass	12,000	3,658
Iron	17,000	5,182
Lead	4,000	1,219
Steel	17,000	5,182
Wood (hard)	14,000	4,267
Wood (soft)	11,000	3,353