

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. Especially, 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.

Auburn University
Auburn, Alabama

J. D. IRWIN
E. R. GRAF

CONTENTS

ACKNOWLEDGMENTS *xvii*

PREFACE *xix*

1 SOUND LEVELS, DECIBELS, AND DIRECTIVITY 1

1.1 Introduction 1

1.2 Sound Wave Characteristics 1

1.2.1 Frequency, period, and wavelength 2

1.2.2 Velocity of sound 3

1.3 Levels and Decibels 5

1.3.1 Sound power level 6

1.3.2 Sound pressure level 8

1.3.3 Adding, subtracting, and averaging decibels 9

1.3.3.1 Adding decibels 9

1.3.3.2 Subtracting decibels 13

1.3.3.3 Averaging decibels 15

1.3.3.4 Approximation of \bar{L}_p 16

1.4 Directivity 18

1.4.1 Directivity factor, Q 18

1.4.2 Directivity Index 20

1.4.3 Determination of \bar{L}_p 21

1.4.3.1 Measurements in anechoic full space 22

1.4.3.2 Measurements in anechoic hemispherical space 26

PROBLEMS 30

BIBLIOGRAPHY 31

**2 HEARING, HEARING LOSS, AND
PSYCHOLOGICAL EFFECTS OF NOISE 32**

2.1 Introduction 32

2.2 The Human Ear 32

2.2.1 Anatomy 32

2.2.2 Frequency and loudness response 34

2.3 Hearing Loss 36

2.4 Psychological Response to Noise 36

2.4.1 Loudness interpretation 36

2.4.2 Perceived noise level 41

2.4.3 Noise-criteria curves 45

2.4.4 Sound level 47

2.4.5 Speech interference level 51

2.4.6 Masking 53

PROBLEMS 54

REFERENCES 56

BIBLIOGRAPHY 57

**3 NOISE CONTROL CRITERIA
AND REGULATIONS 58**

3.1 Introduction 58

3.2 The Occupational Safety and Health Act of 1970 59

3.3 Noise Control Act of 1972 61

3.4 Performance Indices for Environmental Noise 61

3.5 Major Sources of Noise 66

3.6 Noise from Industrial Plants 67

3.7 Trends in State and Local Governments 68

PROBLEMS 69

REFERENCES 70

4 INSTRUMENTATION 72

4.1 Introduction 72

4.2	Measurement Environment	73
4.2.1	Indoor measurements	73
4.2.2	Outdoor measurements	77
4.3	Microphones	77
4.3.1	Types of microphones	77
4.3.2	Sensitivity	79
4.3.3	Special application considerations	81
4.4	Sound Level Meter	83
4.5	Spectrum Analyzers	84
4.5.1	Octave-band analyzers	91
4.5.2	Narrow-band analyzers	92
4.6	Magnetic Tape Recorders	99
4.7	Real-Time Analyzers	103
4.8	Environmental Noise Measurements	109
4.9	Laboratory Instrumentation	111
	PROBLEMS	111
	REFERENCES	112
	BIBLIOGRAPHY	113

5 SOURCES OF NOISE 114

5.1	Introduction	114
5.2	Estimation of Noise-Source Sound Power	115
5.3	Fan or Blower Noise	116
5.4	Electric Motors as a Source of Noise	123
5.5	Pump Noise	124
5.6	Air Compressor Noise	126
5.7	Noise Produced by Typical Building and Construction Equipment	129
5.8	Home Appliance Noise	132
	PROBLEMS	133
	REFERENCES	134

6 ROOM ACOUSTICS 136

- 6.1 Introduction 136
- 6.2 Sound Field Designation 136
- 6.3 Energy Density 138
 - 6.3.1 Potential energy 138
 - 6.3.2 Kinetic energy 140
 - 6.3.3 Total energy density 140
 - 6.3.4 Energy density as a function of the room 143
 - 6.3.4.1 Absorption coefficient and the steady-state energy density 146
 - 6.3.4.2 Direct and reverberant energy 151
 - 6.3.4.2.1 Room configuration consideration 152
 - 6.3.4.2.2 Energy density in a progressive spherical wave 153
 - 6.3.4.2.3 Sum of the energy density in the direct and reverberant fields 155
- 6.4 Pressure and Power Levels 159
 - 6.4.1 Air attenuation by atmospheric absorption 166
 - 6.4.2 Sound level 167
 - 6.4.3 Sound power level 168
 - 6.4.3.1 Sound power level by means of a reference source 171
- 6.5 Reverberation 173
 - 6.5.1 Reverberation time 175
 - 6.5.2 Room-constant determination from the reverberation time 180
- PROBLEMS 182**
- REFERENCES 184**

7 ACOUSTICS OF WALLS, ENCLOSURES, AND BARRIERS 185

- 7.1 Introduction 185
- 7.2 Transmission Loss and Transmission Coefficients 185
 - 7.2.1 Transmission-loss frequency dependence 187
 - 7.2.2 Sound transmission class 189

7.3	Noise Reduction of a Wall	190
7.3.1	Sound pressure level away from the wall	198
7.4	Composition and Multiple Construction of Walls	200
7.5	Indirect Sound Paths	202
7.6	Enclosures	203
7.6.1	Factors that affect the performance of enclosures	203
7.6.2	Full enclosures or hoods	205
7.6.2.1	Noise reduction of a hood	205
7.6.2.2	Hood insertion loss	208
7.6.3	Small enclosures	212
7.6.4	Partial enclosures	213
7.7	Acoustic Barriers	213
7.7.1	Sound pressure level without the barrier	214
7.7.2	Sound pressure level with the barrier	214
7.7.3	Barrier insertion loss	216
7.7.3.1	Reverberant field with the barrier	216
7.7.3.2	Barrier diffracted field	217
7.7.3.3	Barrier insertion loss formulation	219
7.7.3.4	Special cases of the insertion loss	221
7.7.3.5	Insertion loss approximation for barriers	226
PROBLEMS	230	
REFERENCES	234	
BIBLIOGRAPHY	235	

8 ACOUSTICAL MATERIALS AND STRUCTURES 237

8.1	Introduction	237
8.2	Sound-Absorbing Materials	237
8.2.1	Porous materials	238
8.2.2	Noise-reduction coefficient	239
8.2.3	Panel absorbers	247
8.3	Duct Noise	248
8.3.1	Flow noise in ducts	248
8.3.2	Duct design considerations	249

8.4	Mufflers	249
8.4.1	Absorptive mufflers	250
8.4.1.1	Lined ducts	250
8.4.1.2	Parallel and blocked-line-of-sight baffles	251
8.4.1.3	Lines bends	251
8.4.1.4	Plenum chambers	253
8.4.2	Reactive mufflers	255
8.4.2.1	Expansion chambers	255
8.4.2.2	Cavity resonators	258
8.4.3	Prefabricated mufflers	262
8.5	Pipe-Wrapping Materials	263
PROBLEMS		264
REFERENCES		265
BIBLIOGRAPHY		266

9 VIBRATION CONTROL SYSTEMS FOR INDUSTRIAL APPLICATIONS 267

9.1	Introduction	267
9.2	Vibration Systems	268
9.2.1	The model	268
9.2.2	Free vibration	269
9.2.3	Forced vibration	279
9.2.3.1	Harmonic excitation	279
9.2.3.2	Impulse excitation	283
9.2.3.3	Static deflection	284
9.3	Vibration Control	285
9.3.1	Transmissibility	285
9.3.1.1	Force excitation	285
9.3.1.2	Motion excitation	286
9.3.2	Design curves	287
9.3.2.1	Transmissibility vs. damping ratio	287
9.3.2.2	Isolation efficiency vs. ω and ω_n	289
9.3.2.3	Static deflection vs. natural frequency	290
9.3.3	Control techniques	293
9.3.3.1	Source alteration	293
9.3.3.2	Isolation	294
9.3.3.2.1	<i>Metal springs</i>	294

9.3.3.2.2	<i>Elastomeric mounts</i>	297
9.3.3.2.3	<i>Isolation pads</i>	301
9.3.3.3	<i>Inertia blocks</i>	303
9.3.3.4	<i>Absorption</i>	303
9.3.3.5	<i>Active systems</i>	306
9.3.3.6	<i>Damping</i>	307
9.3.3.6.1	<i>Measures of damping</i>	308
9.3.3.6.2	<i>Damping mechanisms</i>	310
9.4	Structural Support Considerations	314
9.5	Critical Shaft Speeds	317
9.6	Vibration in Ducts	318
9.7	Vibration Measurements	321
9.7.1	<i>Measurement quantities</i>	321
9.7.2	<i>Measurement systems</i>	324
9.7.2.1	<i>Transducers</i>	325
9.7.2.1.1	<i>Velocity pickups</i>	326
9.7.2.1.2	<i>Accelerometers</i>	327
9.7.2.2	<i>Preamplifiers</i>	328
9.7.2.3	<i>Processing and display equipment</i>	329
9.7.2.4	<i>Overall measurement system performance</i>	330
9.7.2.5	<i>Mechanical impedance and mobility</i>	333
9.8	Measurement of Structural Dynamics	335
	PROBLEMS	351
	REFERENCES	353
	BIBLIOGRAPHY	354

10 MACHINE PROTECTION AND MALFUNCTION DIAGNOSIS 356

10.1	Introduction	356
10.2	Causes of Vibration	356
10.2.1	<i>Unbalance</i>	357
10.2.2	<i>Rubs in rotating machinery</i>	358
10.2.3	<i>Misalignment</i>	359
10.2.4	<i>Looseness</i>	360
10.2.5	<i>Excitation of resonances due to insufficient damping</i>	360
10.2.6	<i>Oil whirl and oil whip</i>	360

10.3	Basic Rotor Dynamics	362
10.3.1	Modeling	362
10.3.2	Critical speed	364
10.3.3	System response	366
10.3.4	Stability	371
10.4	Instrumentation	374
10.4.1	Transducer	375
10.4.2	Processing and display equipment	376
10.4.2.1	Vibration monitor	376
10.4.2.2	Eccentricity monitor	376
10.4.2.3	Axial position monitor	376
10.4.2.4	Tachometers	377
10.4.2.5	Oscilloscope	377
10.4.2.6	Tape recorders	378
10.4.2.7	Filters and phase meters	378
10.4.2.8	Real-time analyzers	379
10.4.2.9	Computer systems	379
10.5	Diagnostic Analyses	380
10.5.1	Rotor balancing	380
10.5.1.1	Instrumentation	380
10.5.1.2	Orbits	382
10.5.1.3	Balancing procedure	384
10.5.2	Rotating-machinery rubs	396
10.5.3	Misalignment	398
10.5.4	Looseness and oil whirl	399
10.5.5	Summary	400
PROBLEMS		400
REFERENCES		401
BIBLIOGRAPHY		402

APPENDIX A 403

Conversion Factors 403

APPENDIX B 406

Solution of Ordinary Differential Equations
by Use of Laplace Transforms 406

APPENDIX C 417

Detailed Summary of Noise Control Act of 1972 417

ANSWERS TO ODD-NUMBERED PROBLEMS 425

INDEX 429

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.

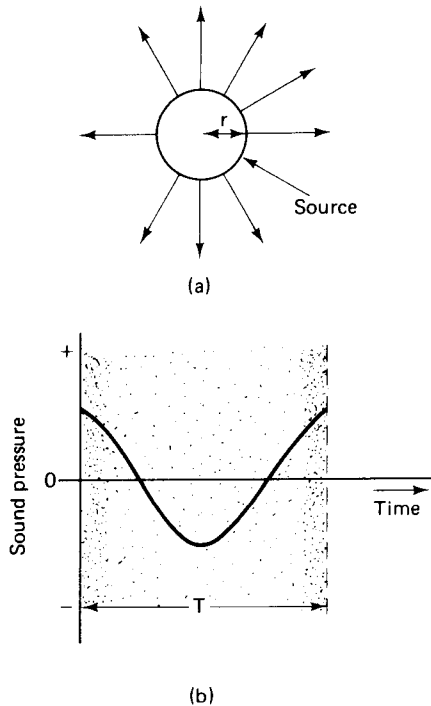


FIGURE 1.1 (a) Spherical source oscillating at a frequency, f , to generate a spherical acoustic wave; (b) pressure vs. time for the sinusoidal wave with the compression and rarefaction of the gas depicted

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

$$T = \frac{1}{f} \text{ s} \quad (1.1)$$

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

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

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

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

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

$p_0 =$ ambient or equilibrium pressure

$\rho =$ 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

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

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

$$c = 49.03 \sqrt{R} \text{ ft/s} \quad (1.5)$$

where R , the temperature in degrees Rankine, is

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

The velocity as related to degrees Kelvin is

$$c = 20.05\sqrt{T} \text{ m/s} \quad (1.7)$$

where T , the temperature in degrees Kelvin, is

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

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

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

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

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

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

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

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

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	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