

Thomas D. Rossing  
Neville H. Fletcher

# Principles of Vibration and Sound

With 140 Illustrations



Springer-Verlag

New York Berlin Heidelberg London Paris  
Tokyo Hong Kong Barcelona Budapest

# Contents

Preface	v
<b>PART I</b>	
<b>Vibrating Systems</b>	<b>1</b>
<b>CHAPTER 1</b>	
<b>Free and Forced Vibrations of Simple Systems</b>	<b>3</b>
1.1. Simple Harmonic Motion in One Dimension	4
1.2. Complex Amplitudes	6
1.3. Superposition of Two Harmonic Motions in One Dimension	7
1.4. Energy	10
1.5. Damped Oscillations	10
1.6. Other Simple Vibrating Systems	12
1.7. Forced Oscillations	16
1.8. Transient Response of an Oscillator	20
1.9. Two-Dimensional Harmonic Oscillator	22
1.10. Graphical Representations of Vibrations: Lissajous Figures	23
1.11. Normal Modes of Two-Mass Systems	25
1.12. Nonlinear Vibrations of a Simple System	26
<b>APPENDIX</b>	
A.1. Alternative Ways of Expressing Harmonic Motion	29
A.2. Equivalent Electrical Circuit for a Simple Oscillator	30
References	32
<b>CHAPTER 2</b>	
<b>Continuous Systems in One Dimension: Strings and Bars</b>	<b>33</b>
2.1. Linear Array of Oscillators	33
2.2. Transverse Wave Equation for a String	35
2.3. General Solution of the Wave Equation: Traveling Waves	36
2.4. Reflection at Fixed and Free Ends	36

2.5.	Simple Harmonic Solutions to the Wave Equation	37
2.6.	Standing Waves	38
2.7.	Energy of a Vibrating String	39
2.8.	Plucked String: Time and Frequency Analyses	39
2.9.	Struck String	42
2.10.	Bowed String	45
2.11.	Driven String Impedance	47
2.12.	Motion of the End Supports	48
2.13.	Damping	50
2.14.	Longitudinal Vibrations of a String or Thin Bar	53
2.15.	Bending Waves in a Bar	54
2.16.	Bars with Fixed and Free Ends	57
2.17.	Vibrations of Thick Bars: Rotary Inertia and Shear Deformation	60
2.18.	Vibrations of a Stiff String	61
2.19.	Dispersion in Stiff and Loaded Strings: Cutoff Frequency	61
2.20.	Torsional Vibrations of a Bar	63
	References	64

## CHAPTER 3

	Two-Dimensional Systems: Membranes and Plates	65
3.1.	Wave Equation for a Rectangular Membrane	65
3.2.	Square Membranes: Degeneracy	68
3.3.	Circular Membranes	69
3.4.	Real Membranes: Stiffness and Air Loading	70
3.5.	Waves in a Thin Plate	71
3.6.	Circular Plates	72
3.7.	Elliptical Plates	74
3.8.	Rectangular Plates	75
3.9.	Square Plates	78
3.10.	Square and Rectangular Plates with Clamped Edges	81
3.11.	Rectangular Wood Plates	82
3.12.	Bending Stiffness in a Membrane	85
3.13.	Shallow Spherical Shells	86
3.14.	Nonlinear Vibrations in Plates and Shallow Shells	88
3.15.	Driving Point Impedance	89
	References	92

## CHAPTER 4

	Coupled Vibrating Systems	95
4.1.	Coupling Between Two Identical Vibrators	95
4.2.	Normal Modes	96
4.3.	Weak and Strong Coupling	98
4.4.	Forced Vibrations	100
4.5.	Coupled Electrical Circuits	103
4.6.	Forced Vibration of a Two-Mass System	107
4.7.	Systems with Many Masses	109

4.8. Graphical Representation of Frequency Response Functions	110
4.9. Vibrating String Coupled to a Soundboard	112
4.10. Two Strings Coupled by a Bridge	114

**APPENDIX**

A.1. Structural Dynamics and Frequency Response Functions	117
A.2. Modal Analysis	121
A.3. Finite Element Analysis	122
References	123

**CHAPTER 5**

<b>Nonlinear Systems</b>	<b>125</b>
5.1. A General Method of Solution	126
5.2. Illustrative Examples	128
5.3. The Self-Excited Oscillator	130
5.4. Multimode Systems	131
5.5. Mode Locking in Self-Excited Systems	133
References	135

**PART II**

<b>Sound Waves</b>	<b>137</b>
--------------------	------------

**CHAPTER 6**

<b>Sound Waves in Air</b>	<b>139</b>
6.1. Plane Waves	139
6.2. Spherical Waves	143
6.3. Sound Pressure Level and Intensity	145
6.4. Reflection and Transmission	147
6.5. Absorption	151
6.6. Normal Modes in Cavities	153
References	156

**CHAPTER 7**

<b>Sound Radiation</b>	<b>157</b>
7.1. Simple Multipole Sources	157
7.2. Pairs of Point Sources	160
7.3. Arrays of Point Sources	162
7.4. Radiation from a Spherical Source	164
7.5. Line Sources	166
7.6. Radiation from a Plane Source in a Baffle	167
7.7. Unbaffled Radiators	170
7.8. Radiation from Large Plates	172
References	174

<b>CHAPTER 8</b>	
<b>Pipes and Horns</b>	<b>175</b>
8.1. Infinite Cylindrical Pipes	175
8.2. Wall Losses	178
8.3. Finite Cylindrical Pipes	181
8.4. Radiation from a Pipe	186
8.5. Impedance Curves	186
8.6. Horns	189
8.7. Finite Conical and Exponential Horns	194
8.8. Bessel Horns	197
8.9. Compound Horns	199
8.10. Perturbations	201
8.11. Numerical Calculations	203
8.12. The Time Domain	203
References	206
<b>CHAPTER 9</b>	
<b>Acoustic Systems</b>	<b>209</b>
9.1. Low-Frequency Components and Systems	209
9.2. High-Frequency Components and Systems	216
9.3. Finite Horns	219
9.4. Coupled Mechanical Components	222
9.5. Multi-Port Systems	224
9.6. Conclusion	226
References	227
Selected Bibliography	229
Problems	231
Answers to Selected Problems	239
Name Index	241
Subject Index	243