

FOUNDATIONS OF

Engineering Acoustics

Frank Fahy



Contents

<i>Preface</i>	xiii
<i>Acknowledgements</i>	xix
Chapter 1 Sound Engineering	1
1.1 The importance of sound	1
1.2 Acoustics and the engineer	2
1.3 Sound the servant.....	3
Chapter 2 The Nature of Sound and Some Sound Wave Phenomena	6
2.1 Introduction	6
2.2 What is sound?	6
2.3 Sound and vibration.....	7
2.4 Sound in solids	9
2.5 A qualitative introduction to wave phenomena.....	9
2.5.1 Wavefronts.....	9
2.5.2 Interference	12
2.5.3 Reflection	14
2.5.4 Scattering	16
2.5.5 Diffraction	17
2.5.6 Refraction	18
2.5.7 The Doppler effect.....	20
2.5.8 Convection	20
2.6 Some more common examples of the behaviour of sound waves	21
Chapter 3 Sound in Fluids	23
3.1 Introduction	23
3.2 The physical characteristics of fluids	23
3.3 Molecules and particles.....	24
3.4 Fluid pressure	25
3.5 Fluid temperature	25
3.6 Pressure, density and temperature in sound waves in a gas	26
3.7 Particle motion	29
3.8 Sound in liquids	29
3.9 Mathematical models of sound waves.....	30
3.9.1 The plane sound wave equation.....	30
3.9.2 Solutions of the plane wave equation	34
3.9.3 Harmonic plane waves: sound pressure	35

3.9.4	Plane waves: particle velocity	38
3.9.5	The wave equation in three dimensions.....	39
3.9.6	Plane waves in three dimensions	41
3.9.7	The wave equation in spherical coordinates	43
3.9.8	The spherically symmetric sound field	44
3.9.9	Particle velocity in the spherically symmetric sound field	45
3.9.10	Other forms of sound field	46
Chapter 4 Impedance		48
4.1	Introduction	48
4.2	Some simple examples of the utility of impedance.....	50
4.3	Mechanical impedance	52
4.3.1	Impedance of lumped structural elements	53
4.4	Forms of acoustic impedance.....	56
4.4.1	Impedances of lumped acoustic elements	57
4.4.2	Specific acoustic impedance of fluid in a tube at low frequency	63
4.4.3	Normal specific acoustic impedance	66
4.4.4	Radiation impedance	67
4.4.5	Acoustic impedance	68
4.4.6	Line and surface wave impedance	68
4.4.7	Modal radiation impedance	71
4.5	An application of radiation impedance of a uniformly pulsating sphere	72
4.6	Radiation efficiency	72
Chapter 5 Sound Energy and Intensity		74
5.1	The practical importance of sound energy	74
5.2	Sound energy	75
5.3	Transport of sound energy: sound intensity	76
5.4	Sound intensity in plane wave fields	78
5.5	Intensity and mean square pressure	82
5.6	Examples of ideal sound intensity fields.....	82
5.6.1	The point monopole.....	82
5.6.2	The compact dipole.....	84
5.6.3	Interfering monopoles	85
5.6.4	Intensity distributions in orthogonally directed harmonic plane wave fields	87
5.7	Sound intensity measurement.....	88
5.8	Determination of source sound power using sound intensity measurement ..	91
5.9	Other applications of sound intensity measurement	92
Chapter 6 Sources of Sound		96
6.1	Introduction	96
6.2	Qualitative categorization of sources	97
6.2.1	Category 1 sources	98
6.2.2	Category 2 sources	100
6.2.3	Category 3 sources	103
6.3	The inhomogeneous wave equation	103
6.3.1	Sound radiation by foreign bodies	104
6.3.2	Boundary ‘sources’ can reflect or absorb energy	105

6.4	Ideal elementary source models.....	106
6.4.1	The Dirac delta function	106
6.4.2	The point monopole and the pulsating sphere	108
6.4.3	Acoustic reciprocity	111
6.4.4	External forces on a fluid and the compact dipole.....	112
6.4.5	The oscillating sphere.....	116
6.4.6	Boundary sources	118
6.4.7	Free-field and other Green's functions	121
6.4.8	The Rayleigh integrals	122
6.5	Sound radiation from vibrating plane surfaces.....	124
6.6	The vibrating circular piston and the cone loudspeaker.....	126
6.7	Directivity and sound power of distributed sources	129
6.7.1	Sound power of a source in the presence of a second source.....	131
6.8	Zones of a sound field radiated by a spatially extended source	134
6.9	Experimental methods for source sound power determination	135
6.10	Source characterization.....	136
Chapter 7 Sound Absorption and Sound Absorbers		140
7.1	Introduction	140
7.2	The effects of viscosity, thermal diffusion and relaxation processes on sound in gases	141
7.2.1	The origin of gas viscosity	141
7.2.2	The effects of thermal diffusion	142
7.2.3	The effect of molecular relaxation.....	143
7.2.4	Sound energy dissipation at the rigid boundary of a gas	143
7.2.5	Acoustically induced boundary layers in a gas-filled tube	146
7.3	Forms of porous sound absorbent material	147
7.4	Macroscopic physical properties of porous sound-absorbing materials	149
7.4.1	Porosity.....	149
7.4.2	Flow resistance and resistivity	150
7.4.3	Structure factor	151
7.5	The modified equation for plane wave sound propagation in gases contained within rigid porous materials	153
7.5.1	Equation of mass conservation.....	153
7.5.2	Momentum equation	154
7.5.3	The modified plane wave equation.....	154
7.5.4	Harmonic solution of the modified plane wave equation	154
7.6	Sound absorption by a plane surface of uniform impedance	156
7.6.1	The local reaction model	156
7.6.2	Sound power absorption coefficient of a locally reactive surface.....	158
7.6.3	Wave impedance	162
7.7	Sound absorption by thin porous sheets.....	163
7.7.1	The immobile sheet in free field	163
7.7.2	The limp sheet in free field	164
7.7.3	The effect of a rigid wall parallel to a thin sheet	166
7.8	Sound absorption by thick sheets of rigid porous material	167
7.8.1	The infinitely thick 'sheet'	167
7.8.2	The sheet of finite thickness	168

7.8.3	The effect of a backing cavity on the sound absorption of a sheet of porous material	169
7.9	Sound absorption by flexible cellular and fibrous materials.....	171
7.10	The effect of perforated cover sheets on sound absorption by porous materials	172
7.11	Non-porous sound absorbers.....	174
	7.11.1 Helmholtz resonators	174
	7.11.2 Panel absorbers	176
7.12	Methods of measurement of boundary impedance and absorption coefficient	178
	7.12.1 The impedance tube	178
	7.12.2 Reverberation room method	179
Chapter 8 Sound in Waveguides		181
8.1	Introduction	181
8.2	Plane wave pulses in a uniform tube.....	183
8.3	Plane wave modes and natural frequencies of fluid in uniform waveguides...	187
	8.3.1 Conservative terminations	187
	8.3.2 Non-conservative terminations.....	191
8.4	Response to harmonic excitation	194
	8.4.1 Impedance model.....	194
	8.4.2 Harmonic response in terms of Green's functions	196
8.5	A simple case of structure-fluid interaction.....	199
8.6	Plane waves in ducts that incorporate impedance discontinuities	201
	8.6.1 Insertion loss and transmission loss.....	201
	8.6.2 Transmission of plane waves through an abrupt change of cross-sectional area and an expansion chamber.....	202
	8.6.3 Series networks of acoustic transmission lines	205
	8.6.4 Side branch connections to uniform acoustic waveguides.....	206
	8.6.5 The side branch tube	208
	8.6.6 The side branch orifice.....	210
	8.6.7 The Helmholtz resonator side branch.....	210
	8.6.8 Bends in otherwise straight uniform waveguides	211
8.7	Transverse modes of uniform acoustic waveguides	211
	8.7.1 The uniform two-dimensional waveguide with rigid walls	211
	8.7.2 The uniform two-dimensional waveguide with finite impedance boundaries	217
	8.7.3 The uniform waveguide of rectangular cross-section with rigid walls.....	218
	8.7.4 The uniform waveguide of circular cross-section with rigid walls ...	218
8.8	Harmonic excitation of waveguide modes.....	220
8.9	Energy flux in a waveguide of rectangular cross-section with rigid walls	222
8.10	Examples of the sound attenuation characteristics of lined ducts and splitter attenuators.....	224
8.11	Acoustic horns	227
	8.11.1 Applications.....	227
	8.11.2 The horn equation	228

Chapter 9 Sound in Enclosures	236
9.1 Introduction	236
9.2 Some general features of sound fields in enclosures.....	239
9.3 Apology for the rectangular enclosure	243
9.4 The impulse response of fluid in a reverberant rectangular enclosure	243
9.5 Acoustic natural frequencies and modes of fluid in a rigid-walled rectangular enclosure.....	245
9.6 Modal energy	248
9.7 The effects of finite wall impedance on modal energy-time dependence in free vibration	249
9.8 The response of fluid in a rectangular enclosure to harmonic excitation by a point monopole source	251
9.9 The sound power of a point monopole in a reverberant enclosure	253
9.10 Sound radiation into an enclosure by the vibration of a boundary	254
9.11 Probabilistic wave field models for enclosed sound fields at high frequency .	256
9.11.1 The modal overlap factor and response uncertainty.....	256
9.11.2 High-frequency sound field statistics	257
9.11.3 The diffuse field model	258
9.12 Applications of the diffuse field model	262
9.12.1 Steady state diffuse field energy, intensity and enclosure absorption	262
9.12.2 Reverberation time	263
9.12.3 Steady state source sound power and reverberant field energy.....	265
9.13 A brief introduction to geometric (ray) acoustics.....	267
Chapter 10 Structure-borne Sound	270
10.1 The nature and practical importance of structure-borne sound	270
10.2 Emphasis and content of the chapter	274
10.3 The energy approach to modelling structure-borne sound	276
10.4 Quasi-longitudinal waves in uniform rods and plates.....	278
10.5 The bending wave in uniform homogeneous beams	279
10.5.1 A review of the roles of direct and shear stresses.....	279
10.5.2 Shear force and bending moment	281
10.5.3 The beam bending wave equation.....	284
10.5.4 Harmonic solutions of the bending wave equation.....	284
10.6 The bending wave in thin uniform homogeneous plates	285
10.7 Transverse plane waves in flat plates.....	286
10.8 Dispersion curves, wavenumber vector diagrams and modal density	287
10.9 Structure-borne wave energy and energy flux.....	290
10.9.1 Quasi-longitudinal waves	290
10.9.2 Bending waves in beams	291
10.9.3 Bending waves in plates.....	293
10.10 Mechanical impedances of infinite, uniform rods, beams and plates	293
10.10.1 Impedance of quasi-longitudinal waves in rods	293
10.10.2 Impedances of beams in bending	294
10.10.3 Impedances of thin, uniform, flat plates in bending.....	296
10.10.4 Impedance and modal density	297
10.11 Wave energy transmission through junctions between structural components	297

10.12	Impedance, mobility and vibration isolation	298
10.13	Structure-borne sound generated by impact	301
10.14	Sound radiation by vibrating flat plates.....	304
10.14.1	The critical frequency and radiation cancellation	304
10.14.2	Analysis of modal radiation	306
10.14.3	Physical interpretations and practical implications.....	310
Chapter 11	Transmission of Sound through Partitions	315
11.1	Practical aspects of sound transmission through partitions	315
11.2	Transmission of normally incident plane waves through an unbounded partition.....	315
11.3	Transmission of sound through an unbounded flexible partition	320
11.4	Transmission of diffuse sound through a bounded partition in a baffle.....	328
11.5	Double-leaf partitions.....	330
11.6	Transmission of normally incident plane waves through an unbounded double-leaf partition	331
11.7	The effect of cavity absorption	336
11.8	Transmission of obliquely incident plane waves through an unbounded double-leaf partition	338
11.9	Close-fitting enclosures	342
11.10	A simple model of a noise control enclosure	347
11.11	Measurement of sound reduction index (transmission loss).....	348
Chapter 12	Reflection, Scattering, Diffraction and Refraction	352
12.1	Introduction	352
12.2	Scattering by a discrete body.....	354
12.3	Scattering by crowds of rigid bodies.....	355
12.4	Resonant scattering	359
12.4.1	Discrete scatterers	359
12.4.2	Diffusors.....	360
12.5	Diffraction.....	362
12.5.1	Diffraction by plane screens	362
12.5.2	Diffraction by apertures in partitions	370
12.6	Reflection by thin, plane rigid sheets	373
12.7	Refraction	375
12.7.1	Refracted ray path through a uniform, weak sound speed gradient	375
12.7.2	Refraction of sound in the atmosphere	377
Appendix 1	Complex exponential representation of harmonic functions	380
A1.1	Harmonic functions of time	380
A1.2	Harmonic functions of space.....	382
A1.3	CER of travelling harmonic plane waves	382
A1.4	Operations on harmonically varying quantities represented by CER	383
Appendix 2	Frequency Analysis	384
A2.1	Introduction	384
A2.2	Categories of signal	385
A2.3	Fourier analysis of signals	386
A2.3.1	The Fourier integral transform	386
A2.3.2	Fourier series analysis	387

A2.3.3 Practical Fourier analysis	388
A2.3.4 Frequency analysis by filters	390
A2.4 Presentation of the results of frequency analysis.....	392
A2.5 Frequency response functions.....	392
A2.6 Impulse response.....	393
Appendix 3 Spatial Fourier Analysis of Space-Dependent Variables	394
A3.1 Wavenumber transform	394
A3.2 Wave dispersion.....	394
Appendix 4 Coherence and Cross-Correlation	397
A4.1 Background.....	397
A4.2 Correlation.....	397
A4.3 Coherence	398
A4.4 The relation between the cross-correlation and coherence functions	399
Appendix 5 The Simple Oscillator	401
A5.1 Free vibration of the undamped mass–spring oscillator	401
A5.2 Impulse response of the undamped oscillator.....	401
A5.3 The viscously damped oscillator.....	402
A5.4 Impulse response of the viscously damped oscillator.....	403
A5.5 Response of a viscously damped oscillator to harmonic excitation	403
Appendix 6 Measures of Sound, Frequency Weighting and Noise Rating Indicators	406
A6.1 Introduction	406
A6.2 Pressure–time history.....	406
A6.3 Mean square pressure	407
A6.4 Sound pressure level	408
A6.5 Sound intensity level.....	408
A6.6 Sound power level	408
A6.7 Standard reference curves.....	409
Appendix 7 Demonstrations and Experiments	411
A7.1 Introduction	411
A7.2 Demonstrations	411
A7.2.1 Noise sources	411
A7.2.2 Sound intensity and surface acoustic impedance.....	412
A7.2.3 Room acoustics	413
A7.2.4 Miscellaneous	413
A7.3 Formal laboratory class experiments	415
A7.3.1 Construct a calibrated volume velocity source (CVVS).....	415
A7.3.2 Source sound power determination using intensity scans, reverberation time measurements and power balance	415
A7.3.3 Investigation of small room acoustic response.....	416
A7.3.4 Determination of complex wavenumbers of porous materials	417
A7.3.5 Measurement of the specific acoustic impedance of a sheet of porous material	418
A7.3.6 Measurement of the impedance of side branch and in-line reactive attenuators	418

A7.3.7 Sound pressure generation by a monopole in free space and in a tube.....	419
A7.3.8 Mode dispersion in a duct	419
A7.3.9 Scattering by a rough surface	419
A7.3.10 Radiation by a vibrating plate	420
<i>Answers</i>	421
<i>Bibliography</i>	430
<i>References</i>	432
<i>Index</i>	435