

Table of Contents

Preface	13
Chapter 1. Equations of Motion in Non-dissipative Fluid	15
1.1. Introduction.	15
1.1.1. Basic elements	15
1.1.2. Mechanisms of transmission	16
1.1.3. Acoustic motion and driving motion	17
1.1.4. Notion of frequency	17
1.1.5. Acoustic amplitude and intensity.	18
1.1.6. Viscous and thermal phenomena.	19
1.2. Fundamental laws of propagation in non-dissipative fluids	20
1.2.1. Basis of thermodynamics	20
1.2.2. Lagrangian and Eulerian descriptions of fluid motion	25
1.2.3. Expression of the fluid compressibility: mass conservation law	27
1.2.4. Expression of the fundamental law of dynamics: Euler's equation.	29
1.2.5. Law of fluid behavior: law of conservation of thermomechanic energy	30
1.2.6. Summary of the fundamental laws.	31
1.2.7. Equation of equilibrium of moments	32
1.3. Equation of acoustic propagation	33
1.3.1. Equation of propagation	33
1.3.2. Linear acoustic approximation	34
1.3.3. Velocity potential.	38
1.3.4. Problems at the boundaries	40
1.4. Density of energy and energy flow, energy conservation law	42
1.4.1. Complex representation in the Fourier domain	42
1.4.2. Energy density in an "ideal" fluid	43
1.4.3. Energy flow and acoustic intensity	45
1.4.4. Energy conservation law.	48

Chapter 1: Appendix. Some General Comments on Thermodynamics	50
A.1. Thermodynamic equilibrium and equation of state	50
A.2. Digression on functions of multiple variables (study case of two variables)	51
A.2.1. Implicit functions	51
A.2.2. Total exact differential form	53
Chapter 2. Equations of Motion in Dissipative Fluid	55
2.1. Introduction.	55
2.2. Propagation in viscous fluid: Navier-Stokes equation	56
2.2.1. Deformation and strain tensor	57
2.2.2. Stress tensor	62
2.2.3. Expression of the fundamental law of dynamics	64
2.3. Heat propagation: Fourier equation.	70
2.4. Molecular thermal relaxation	72
2.4.1. Nature of the phenomenon	72
2.4.2. Internal energy, energy of translation, of rotation and of vibration of molecules	74
2.4.3. Molecular relaxation: delay of molecular vibrations	75
2.5. Problems of linear acoustics in dissipative fluid at rest	77
2.5.1. Propagation equations in linear acoustics.	77
2.5.2. Approach to determine the solutions	81
2.5.3. Approach of the solutions in presence of acoustic sources.	84
2.5.4. Boundary conditions	85
Chapter 2: Appendix. Equations of continuity and equations at the thermomechanic discontinuities in continuous media.	93
A.1. Introduction	93
A.1.1. Material derivative of volume integrals	93
A.1.2. Generalization	96
A.2. Equations of continuity	97
A.2.1. Mass conservation equation	97
A.2.2. Equation of impulse continuity	98
A.2.3. Equation of entropy continuity.	99
A.2.4. Equation of energy continuity	99
A.3. Equations at discontinuities in mechanics	102
A.3.1. Introduction	102
A.3.2. Application to the equation of impulse conservation.	103
A.3.3. Other conditions at discontinuities	106
A.4. Examples of application of the equations at discontinuities in mechanics: interface conditions	106
A.4.1. Interface solid – viscous fluid	107
A.4.2. Interface between perfect fluids	108
A.4.3. Interface between two non-miscible fluids in motion.	109

Chapter 3. Problems of Acoustics in Dissipative Fluids.	111
3.1. Introduction.	111
3.2. Reflection of a harmonic wave from a rigid plane.. . . .	111
3.2.1. Reflection of an incident harmonic plane wave	111
3.2.2. Reflection of a harmonic acoustic wave	115
3.3. Spherical wave in infinite space: Green's function	118
3.3.1. Impulse spherical source.	118
3.3.2. Green's function in three-dimensional space.	121
3.4. Digression on two- and one-dimensional Green's functions in non-dissipative fluids	125
3.4.1. Two-dimensional Green's function	125
3.4.2. One-dimensional Green's function	128
3.5. Acoustic field in "small cavities" in harmonic regime	131
3.6. Harmonic motion of a fluid layer between a vibrating membrane and a rigid plate, application to the capillary slit.	136
3.7. Harmonic plane wave propagation in cylindrical tubes: propagation constants in "large" and "capillary" tubes.	141
3.8. Guided plane wave in dissipative fluid.	148
3.9. Cylindrical waveguide, system of distributed constants.	151
3.10. Introduction to the thermoacoustic engines (on the use of phenomena occurring in thermal boundary layers)	154
3.11. Introduction to acoustic gyrometry (on the use of the phenomena occurring in viscous boundary layers)	162
 Chapter 4. Basic Solutions to the Equations of Linear Propagation in Cartesian Coordinates.	 169
4.1. Introduction.	169
4.2. General solutions to the wave equation	173
4.2.1. Solutions for propagative waves	173
4.2.2. Solutions with separable variables	176
4.3. Reflection of acoustic waves on a locally reacting surface	178
4.3.1. Reflection of a harmonic plane wave	178
4.3.2. Reflection from a locally reacting surface in random incidence	183
4.3.3. Reflection of a harmonic spherical wave from a locally reacting plane surface	184
4.3.4. Acoustic field before a plane surface of impedance Z under the load of a harmonic plane wave in normal incidence	185
4.4. Reflection and transmission at the interface between two different fluids.	187
4.4.1. Governing equations	187
4.4.2. The solutions	189
4.4.3. Solutions in harmonic regime.	190
4.4.4. The energy flux	192

4.5. Harmonic waves propagation in an infinite waveguide with rectangular cross-section.	193
4.5.1. The governing equations.	193
4.5.2. The solutions	195
4.5.3. Propagating and evanescent waves	197
4.5.4. Guided propagation in non-dissipative fluid	200
4.6. Problems of discontinuity in waveguides	206
4.6.1. Modal theory	206
4.6.2. Plane wave fields in waveguide with section discontinuities	207
4.7. Propagation in horns in non-dissipative fluids	210
4.7.1. Equation of horns	210
4.7.2. Solutions for infinite exponential horns.	214
Chapter 4: Appendix. Eigenvalue Problems, Hilbert Space	217
A.1. Eigenvalue problems	217
A.1.1. Properties of eigenfunctions and associated eigenvalues	217
A.1.2. Eigenvalue problems in acoustics	220
A.1.3. Degeneracy	220
A.2. Hilbert space.	221
A.2.1. Hilbert functions and \mathcal{L}^2 space	221
A.2.2. Properties of Hilbert functions and complete discrete ortho-normal basis	222
A.2.3. Continuous complete ortho-normal basis	223
Chapter 5. Basic Solutions to the Equations of Linear Propagation in Cylindrical and Spherical Coordinates.	227
5.1. Basic solutions to the equations of linear propagation in cylindrical coordinates	227
5.1.1. General solution to the wave equation	227
5.1.2. Progressive cylindrical waves: radiation from an infinitely long cylinder in harmonic regime	231
5.1.3. Diffraction of a plane wave by a cylinder characterized by a surface impedance.	236
5.1.4. Propagation of harmonic waves in cylindrical waveguides	238
5.2. Basic solutions to the equations of linear propagation in spherical coordinates	245
5.2.1. General solution of the wave equation	245
5.2.2. Progressive spherical waves	250
5.2.3. Diffraction of a plane wave by a rigid sphere	258
5.2.4. The spherical cavity	262
5.2.5. Digression on monopolar, dipolar and 2n-polar acoustic fields.	266

Chapter 6. Integral Formalism in Linear Acoustics	277
6.1. Considered problems	277
6.1.1. Problems	277
6.1.2. Associated eigenvalues problem	278
6.1.3. Elementary problem: Green's function in infinite space	279
6.1.4. Green's function in finite space	280
6.1.5. Reciprocity of the Green's function	294
6.2. Integral formalism of boundary problems in linear acoustics	296
6.2.1. Introduction	296
6.2.2. Integral formalism	297
6.2.3. On solving integral equations.	300
6.3. Examples of application	309
6.3.1. Examples of application in the time domain	309
6.3.2. Examples of application in the frequency domain.	318
Chapter 7. Diffusion, Diffraction and Geometrical Approximation.	357
7.1. Acoustic diffusion: examples	357
7.1.1. Propagation in non-homogeneous media	357
7.1.2. Diffusion on surface irregularities	360
7.2. Acoustic diffraction by a screen.	362
7.2.1. Kirchhoff-Fresnel diffraction theory.	362
7.2.2. Fraunhofer's approximation.	364
7.2.3. Fresnel's approximation.	366
7.2.4. Fresnel's diffraction by a straight edge	369
7.2.5. Diffraction of a plane wave by a semi-infinite rigid plane: introduction to Sommerfeld's theory.	371
7.2.6. Integral formalism for the problem of diffraction by a semi-infinite plane screen with a straight edge	376
7.2.7. Geometric Theory of Diffraction of Keller (GTD)	379
7.3. Acoustic propagation in non-homogeneous and non-dissipative media in motion, varying "slowly" in time and space: geometric approximation	385
7.3.1. Introduction	385
7.3.2. Fundamental equations	386
7.3.3. Modes of perturbation	388
7.3.4. Equations of rays	392
7.3.5. Applications to simple cases	397
7.3.6. Fermat's principle	403
7.3.7. Equation of parabolic waves	405
Chapter 8. Introduction to Sound Radiation and Transparency of Walls . .	409
8.1. Waves in membranes and plates	409
8.1.1. Longitudinal and quasi-longitudinal waves.	410
8.1.2. Transverse shear waves	412

8.1.3. Flexural waves	413
8.2. Governing equation for thin, plane, homogeneous and isotropic plate in transverse motion	419
8.2.1. Equation of motion of membranes	419
8.2.2. Thin, homogeneous and isotropic plates in pure bending	420
8.2.3. Governing equations of thin plane walls	424
8.3. Transparency of infinite thin, homogeneous and isotropic walls	426
8.3.1. Transparency to an incident plane wave	426
8.3.2. Digressions on the influence and nature of the acoustic field on both sides of the wall	431
8.3.3. Transparency of a multilayered system: the double leaf system	434
8.4. Transparency of finite thin, plane and homogeneous walls: modal theory	438
8.4.1. Generally	438
8.4.2. Modal theory of the transparency of finite plane walls	439
8.4.3. Applications: rectangular plate and circular membrane	444
8.5. Transparency of infinite thick, homogeneous and isotropic plates	450
8.5.1. Introduction	450
8.5.2. Reflection and transmission of waves at the interface fluid-solid.	450
8.5.3. Transparency of an infinite thick plate	457
8.6. Complements in vibro-acoustics: the Statistical Energy Analysis (SEA) method	461
8.6.1. Introduction	461
8.6.2. The method	461
8.6.3. Justifying approach.	463
Chapter 9. Acoustics in Closed Spaces	465
9.1. Introduction.	465
9.2. Physics of acoustics in closed spaces: modal theory	466
9.2.1. Introduction	466
9.2.2. The problem of acoustics in closed spaces	468
9.2.3. Expression of the acoustic pressure field in closed spaces.	471
9.2.4. Examples of problems and solutions	477
9.3. Problems with high modal density: statistically quasi-uniform acoustic fields	483
9.3.1. Distribution of the resonance frequencies of a rectangular cavity with perfectly rigid walls	483
9.3.2. Steady state sound field at “high” frequencies	487
9.3.3. Acoustic field in transient regime at high frequencies	494
9.4. Statistical analysis of diffused fields	497
9.4.1. Characteristics of a diffused field	497
9.4.2. Energy conservation law in rooms	498
9.4.3. Steady-state radiation from a punctual source	500
9.4.4. Other expressions of the reverberation time	502

9.4.5. Diffused sound fields.	504
9.5. Brief history of room acoustics	508

Chapter 10. Introduction to Non-linear Acoustics, Acoustics in Uniform Flow, and Aero-acoustics. 511

10.1. Introduction to non-linear acoustics in fluids initially at rest	511
10.1.1. Introduction	511
10.1.2. Equations of non-linear acoustics: linearization method	513
10.1.3. Equations of propagation in non-dissipative fluids in one dimension, Fubini's solution of the implicit equations.	529
10.1.4. Bürger's equation for plane waves in dissipative (visco-thermal) media	536
10.2. Introduction to acoustics in fluids in subsonic uniform flows	547
10.2.1. Doppler effect	547
10.2.2. Equations of motion	549
10.2.3. Integral equations of motion and Green's function in a uniform and constant flow	551
10.2.4. Phase velocity and group velocity, energy transfer – case of the rigid-walled guides with constant cross-section in uniform flow	556
10.2.5. Equation of dispersion and propagation modes: case of the rigid-walled guides with constant cross-section in uniform flow	560
10.2.6. Reflection and refraction at the interface between two media in relative motion (at subsonic velocity)	562
10.3. Introduction to aero-acoustics	566
10.3.1. Introduction	566
10.3.2. Reminder about linear equations of motion and fundamental sources	566
10.3.3. Lighthill's equation	568
10.3.4. Solutions to Lighthill's equation in media limited by rigid obstacles: Curle's solution	570
10.3.5. Estimation of the acoustic power of quadrupolar turbulences	574
10.3.6. Conclusion	574

Chapter 11. Methods in Electro-acoustics 577

11.1. Introduction	577
11.2. The different types of conversion	578
11.2.1. Electromagnetic conversion	578
11.2.2. Piezoelectric conversion (example)	583
11.2.3. Electrodynamic conversion	588
11.2.4. Electrostatic conversion	589
11.2.5. Other conversion techniques	591
11.3. The linear mechanical systems with localized constants	592
11.3.1. Fundamental elements and systems	592
11.3.2. Electromechanical analogies	596

12 Fundamentals of Acoustics

11.3.3. Digression on the one-dimensional mechanical systems with distributed constants: longitudinal motion of a beam.	601
11.4. Linear acoustic systems with localized and distributed constants	604
11.4.1. Linear acoustic systems with localized constants	604
11.4.2. Linear acoustic systems with distributed constants: the cylindrical waveguide	611
11.5. Examples of application to electro-acoustic transducers.	613
11.5.1. Electrodynamical transducer.	613
11.5.2. The electrostatic microphone	619
11.5.3. Example of piezoelectric transducer	624
Chapter 11: Appendix	626
A.1 Reminder about linear electrical circuits with localized constants.	626
A.2 Generalization of the coupling equations	628
Bibliography	631
Index	633