Contents

Preface ix

Chapter 1. Fluid–Structure Interaction 1

1.1. Introduction 1
1.2. Fluid–structure interaction problem 2
1.2.1. Fluid–structure coupling methods 5
1.2.2. Temporal coupling 8
1.2.3. Spatial coupling 11
1.3. Vibroacoustics 14
1.3.1. Vibrations of three-dimensional solids 15
1.3.2. Acoustics of fluids 17
1.3.3. Numerical methods for calculating a structure coupled with a stagnant fluid 18
1.4. Aerodynamics 21
1.4.1. Aeroelastic problems 23
1.4.2. Aerodynamic loads 26
1.4.3. Problem equations 29

Chapter 2. Fluid–Structure Interaction with Ansys/Fluent . . . 35

2.1. Presentation of Ansys 35
2.2. Coupling with Ansys 37
2.2.1. Types of coupling analysis 38
2.3. Example of fluid–structure interaction using the “physics” environment 40
2.3.1. Fluid in motion 40
2.3.2. Stagnant fluid 48
2.4. Example of interaction using Fluent 54

Chapter 3. Vibroacoustics 59

3.1. Introduction 59
3.2. Equations of the acoustic and structure problems 60
3.2.1. Equation of the acoustic problem 60
3.2.2. Boundary conditions of the acoustic problem 61
3.2.3. Equation of the structure problem 62
3.2.4. Boundary conditions of the structure problem 62
3.3. Vibroacoustic problem 63
3.3.1. Problem statement 64
3.3.2. Boundary conditions at the interface 65
3.3.3. Finite element approximation 66
3.4. Study of an elastic plate coupled with a fluid cavity 86
3.4.1. Equations of the coupled fluid–structure problem 87
3.4.2. Variational formulation of the fluid 88
3.4.3. Variational formulation of the plate 92
3.4.4. Numerical results 94
3.5. Study of the propeller of a boat 97
3.5.1. Numerical results 99

Chapter 4. Aerodynamics 103

4.1. Introduction 103
4.2. Computational method 104
4.2.1. Conformal mesh 104
4.2.2. Immersed boundary methods 105
4.2.3. Volume-based fictitious domain methods 106
4.3. Aerodynamic problem's resolution 107
4.3.1. Mobile domain 107
4.3.2. Weak formulation 108
4.3.3. Evaluating the energy of the system 111
4.3.4. Numerically solving the system 116
4.3.5. Discretization by finite elements 120
4.4. Finite element method for the solid 123
4.4.1. Discretization 124
4.4.2. Assembling the system 126
4.4.3. Solving the system of algebraic equations 126
4.4.4. Integration by Gaussian quadrature 126
4.4.5. Advancing the time step using the Hilbert–Hugues–Taylor algorithm 127
4.4.6. Linearization using the Newton–Raphson algorithm 129
4.5. Finite volumes for the fluid 130
4.5.1. Generic transport equation 130

4.5.2. Conservation property of the method 131
4.5.3. The different steps in the method 131
4.5.4. Integrating the model equation 132
4.5.5. Control volumes 133
4.5.6. Physical interpolation 135
4.5.7. Evaluating the flux through the faces 135
4.5.8. Centered scheme 136
4.5.9. Upwind scheme 138
4.5.10. Hybrid scheme 139
4.5.11. Discretization 139
4.6. Coupling procedures 141
4.6.1. Coupling strategies 141
4.6.2. Implicit partitioned coupling 142
4.7. Numerical results 145
4.7.1. Static analysis 145
4.8. Study of a 3D airplane wing 150
4.8.1. Modal analysis 153
4.9. Transient analysis 154

Chapter 5. Modal Reduction for FSI 163

5.1. Introduction 163
5.2. Dynamic substructuring methods 164
5.2.1. Linear problems 165
5.2.2. Nonlinear problems 167
5.3. Nonlinear substructuring method 169
5.3.1. Vibrational equations of a substructure 170
5.3.2. Fixed-interface problem 171
5.3.3. Static bearing problem 172
5.3.4. Representing the system with the linear Craig–Bampton basis 173
5.3.5. Model reduction using the approach of Shaw and Pierre . . 174
5.3.6. Assembling the substructures 176
5.4. Proper orthogonal decomposition for flows 178
5.4.1. Properties of POD modes 179
5.4.2. Snapshot POD 179
5.4.3. Finding low-order expressions for dynamic systems 180
5.5. Dynamic substructure/acoustic subdomain coupling 185
5.5.1. Basic equations 187
5.5.2. Variational formulations 190
5.5.3. Discretization by finite elements 191
5.5.4. Calculating the local modes 194

5.5.5. Modal synthesis 196
5.6. Numerical simulation 199
5.6.1. Elastic ring 199
5.6.2. Boat propeller 206

Chapter 6. Reliability-based Optimization for FSI 211

6.1. Introduction 211
6.2. Reliability in mechanics 212
6.2.1. Random variables 212
6.2.2. Reliability function 214
6.3. Failure in mechanics 215
6.3.1. Failure scenarios 216
6.3.2. Expression of the failure probability 217
6.4. Reliability index 217
6.4.1. Rjanitzyne–Cornell index 217
6.4.2. Hasofer–Lind index 218
6.5. Mechanoreliability coupling 218
6.5.1. Reliability-based calculation methods 219
6.5.2. Monte Carlo method 220
6.5.3. FORM/SORM approximation methods 221
6.6. Reliability-based optimization in mechanics 224
6.6.1. Deterministic optimization 225
6.6.2. Different approaches to RBDO 226
6.6.3. Classical approach 228
6.6.4. Hybrid approach 229
6.6.5. Frequency-based hybrid approach 231
6.7. SP method 234
6.7.1. Formulation of the problem 234
6.8. Numerical results 237
6.8.1. Reliability calculation for an airplane wing 237
6.8.2. Application of RBDO to the airplane wing 239

Bibliography 253

Index 263