

## Table of Contents

<b>Foreword</b> . . . . .	xiii
<b>Preface</b> . . . . .	xv
<b>Part I. Sources of Vibrations</b> . . . . .	1
<b>Chapter 1. Unbalance and Gyroscopic Effects</b> . . . . .	5
1.1. Introduction . . . . .	5
1.1.1. Physico-mathematical model of a rotating system . . . . .	7
1.1.2. Formation of equations and analysis . . . . .	7
1.2. Theory of balancing . . . . .	10
1.2.1. Balancing machine or “balancer” . . . . .	12
1.2.1.1. The soft-bearing machine . . . . .	12
1.2.1.2. The hard-bearing machine . . . . .	17
1.2.2. Balancing <i>in situ</i> . . . . .	17
1.2.2.1. The method of separate planes . . . . .	19
1.2.2.2. The method of simultaneous planes – influence coefficients . . . . .	24
1.2.3. Example of application: the main rotor of a helicopter . . . . .	26
1.2.3.1. Bench test phase on the ground . . . . .	27
1.2.3.2. Test phase on a helicopter in flight . . . . .	30
1.3. Influence of shaft bending . . . . .	32
1.3.1. The notion of critical speed . . . . .	33
1.3.2. Forward precession of the flexible shaft . . . . .	38
1.3.2.1. Subcritical speed ( $\Omega < \omega_{cr}$ ) . . . . .	39
1.3.2.2. Resonance ( $\Omega = \omega_{cr}$ ) . . . . .	41
1.3.2.3. Supercritical speed ( $\Omega > \omega_{cr}$ ) . . . . .	41
1.3.3. Balancing flexible shafts . . . . .	42
1.3.4. Example of application: transmission shaft of the tail rotor of a helicopter . . . . .	44

1.4. Gyroscopic effects . . . . .	44
1.4.1. Forward or backward motion . . . . .	44
1.4.2. Equations of motion . . . . .	47
1.4.2.1. Natural angular frequencies (shaft off motion) . . . . .	51
1.4.2.2. Critical speeds during forward precession . . . . .	51
1.4.2.3. Critical speeds during retrograde precession . . . . .	51
<b>Chapter 2. Piston Engines . . . . .</b>	<b>53</b>
2.1. Introduction. . . . .	53
2.2. Excitations generated by a piston engine . . . . .	54
2.2.1. Analytic determination of an engine torque . . . . .	55
2.2.2. Engine excitations on the chassis frame. . . . .	59
2.2.2.1. Knocking load. . . . .	60
2.2.2.2. Pitch torque . . . . .	63
2.2.2.3. Review of actions for a four phase cylinder engine . . . . .	64
2.2.3. The notion of engine balancing. . . . .	64
2.2.3.1. Balancing the knocking loads. . . . .	64
2.2.3.2. Balancing the galloping torque . . . . .	67
2.3. Line shafting tuning . . . . .	67
2.3.1. The notion of tuning . . . . .	67
2.3.2. Creation of the equations . . . . .	68
2.3.3. Line shafting optimization . . . . .	71
2.3.3.1. Results for a non-optimized line shafting. . . . .	71
2.3.3.2. Results for an optimized line shafting. . . . .	73
<b>Chapter 3. Dynamics of a Rotor . . . . .</b>	<b>75</b>
3.1. Introduction. . . . .	75
3.2. Description of the blade/hub relationship . . . . .	75
3.2.1. Some historical data . . . . .	75
3.2.2. Hinge link of the blade and the hub . . . . .	76
3.2.2.1. Formation of the equations for blade motion. . . . .	77
3.2.2.2. Homokinetic rotor . . . . .	86
3.3. Rotor technologies. . . . .	87
3.3.1. Articulated rotors . . . . .	88
3.3.1.1. Conventional articulated rotors. . . . .	88
3.3.1.2. Starflex® and Spheriflex® rotors . . . . .	89
3.3.2. Hingeless rotors . . . . .	91
3.3.3. Hingeless rotor . . . . .	92
3.4. Influence of alternate aerodynamic loads . . . . .	93
3.4.1. Load characterization . . . . .	94
3.4.1.1. Loads on a blade . . . . .	94
3.4.1.2. Dynamic response of a blade . . . . .	99

3.4.1.3. Loads transmitted by a mode $i$ . . . . .	100
3.4.2. Analysis of loads transmitted to the rotor hub . . . . .	102
3.4.2.1. Loads transmitted to the rotor. . . . .	103
3.4.2.2. Synthesis of rotor loads on the rotor mast . . . . .	109
3.4.3. Dynamic optimization of a blade. . . . .	111
3.4.3.1. Introduction . . . . .	111
3.4.3.2. Study of the example of an optimized blade . . . . .	111
3.4.3.3. Contribution of the second flapping mode . . . . .	116
<b>Chapter 4. Rotor Control</b> . . . . .	<b>119</b>
4.1. Introduction. . . . .	119
4.2. Blade motions . . . . .	121
4.2.1. Flapping equation – general case. . . . .	121
4.2.2. The case of a rotor without eccentricity and flapping stiffness . . . . .	123
4.3. Control through cyclic and collective swashplates. . . . .	127
4.4. Control through flaps . . . . .	129
4.4.1. Description. . . . .	129
4.4.2. Modeling. . . . .	131
4.4.2.1. Flapping equation. . . . .	131
4.4.2.2. Torsion equation . . . . .	134
4.4.3. Ways to control the blade . . . . .	136
<b>Chapter 5. Non-Homokinetic Couplings</b> . . . . .	<b>141</b>
5.1. Introduction. . . . .	141
5.2. Analysis of operation . . . . .	142
5.2.1. Parametric transformation. . . . .	143
5.2.2. Effects of non-homokinetics: modulation of acceleration . . . . .	144
5.2.3. Effects of non-homokinetics: variation of the motor torque . . . . .	146
5.3. Solutions to make the link homokinetic . . . . .	150
5.3.1. Double Cardan . . . . .	150
5.3.2. Introduction of high flexibility . . . . .	151
5.3.3. Homokinetic drive system of a tilt rotor . . . . .	152
<b>Chapter 6. Aerodynamic Excitations</b> . . . . .	<b>159</b>
6.1. Introduction. . . . .	159
6.2. Excitations caused by the Karman vortices – fuselage effects . . . . .	160
6.3. Aerodynamic excitations generated by the main rotor of a helicopter . . . . .	164
6.4. Practical solutions for tail-shake . . . . .	168

<b>PART II. Vibration Monitoring Systems</b> . . . . .	171
<b>Chapter 7. Suspensions</b> . . . . .	177
7.1. Introduction . . . . .	177
7.2. Filtering effects of the interface link . . . . .	177
7.2.1. Stiffness modification for an excitation in force . . . . .	177
7.2.1.1. Modeling . . . . .	177
7.2.1.2. Response to a harmonic excitation . . . . .	179
7.2.1.3. Response to an unbalanced excitation . . . . .	183
7.2.2. Stiffness modification for displacement excitation . . . . .	185
7.2.2.1. Modeling . . . . .	186
7.2.2.2. Analysis of the results . . . . .	187
7.2.2.3. Example: vehicle suspension . . . . .	188
7.2.3. Damping modification . . . . .	190
7.2.3.1. Principle . . . . .	190
7.2.3.2. Modeling . . . . .	191
7.2.4. Complex case of the rotor/fuselage link of a helicopter . . . . .	195
7.3. Acting on the interface through kinematic coupling . . . . .	202
7.3.1. The example of the DAVI system . . . . .	202
7.3.1.1. Principle . . . . .	202
7.3.1.2. Formulation of the equations . . . . .	203
7.3.1.3. Implementation . . . . .	206
7.3.1.4. Experimental analysis . . . . .	207
7.3.2. Example of the Aris system . . . . .	209
7.3.2.1. Mechanical system . . . . .	209
7.3.2.2. Hydraulic system . . . . .	210
7.3.3. Example of a fluid inertia resonator . . . . .	214
7.3.3.1. Principle . . . . .	214
7.3.3.2. Formation of the equations . . . . .	214
7.3.3.3. Example of application: integration of the system on a helicopter . . . . .	216
<b>Chapter 8. Self-Tuning Systems</b> . . . . .	219
8.1. Introduction . . . . .	219
8.2. Modification of link characteristics (stiffness or damping) . . . . .	220
8.3. Modification of the kinematic coupling: example of self-tuning Sarib® . . . . .	221
8.3.1. Modeling of the suspension behavior . . . . .	222
8.3.1.1. Degrees of freedom of the system . . . . .	222
8.3.1.2. Formulation of the equations . . . . .	224
8.3.1.3. Analysis of the general behavior of the suspension . . . . .	225
8.3.1.4. Conclusion . . . . .	227
8.3.2. Presentation of the control algorithm . . . . .	228

8.3.3. Performances . . . . .	231
8.3.3.1. Simulation and behavior analysis . . . . .	231
8.3.3.2. Tests conducted on a model. . . . .	234
8.3.3.3. Flight tests on a real structure. . . . .	237
<b>Chapter 9. Active Suspensions . . . . .</b>	<b>239</b>
9.1. Principle. . . . .	239
9.2. Formulation of system equations and analysis of the system. . . . .	240
9.3. Technological application . . . . .	244
<b>Chapter 10. Absorbers . . . . .</b>	<b>253</b>
10.1. Introduction . . . . .	253
10.2. Optimization of the structure. . . . .	253
10.3. Dynamic absorbers. . . . .	254
10.3.1. Coupling with preponderant stiffness . . . . .	255
10.3.1.1. Translation system . . . . .	255
10.3.1.2. Rotating system: torsion resonator . . . . .	264
10.3.2. Coupling using damping and stiffness. . . . .	266
10.3.2.1. Operation of the equations. . . . .	266
10.3.2.2. Tuning method. . . . .	270
10.3.2.3. Industrial application: resonator used on a helicopter for the tail boom vibrations . . . . .	272
10.3.2.4. Industrial application: resonator for torsion movements . . . . .	274
10.3.3. Coupling with preponderant damping . . . . .	274
<b>Chapter 11. Self-Adjusting Absorbers . . . . .</b>	<b>279</b>
11.1. Introduction . . . . .	279
11.2. Implementation. . . . .	279
11.3. System coupling . . . . .	281
11.3.1. Analog algorithm . . . . .	281
11.3.2. Digital algorithm . . . . .	282
<b>Chapter 12. Active Absorbers. . . . .</b>	<b>289</b>
12.1. Introduction . . . . .	289
12.2. Active control with a resonator . . . . .	289
12.2.1. Electromagnetic actuator. . . . .	290
12.2.1.1. Single stage resonator . . . . .	290
12.2.1.2. Two-stage electromagnetic resonator . . . . .	295
12.2.2. Hydraulic actuator. . . . .	300
12.2.2.1. Technological principle . . . . .	300

12.2.2.2. Control algorithm . . . . .	303
12.2.2.3. Results of lab tests . . . . .	304
12.3. Active control through external loads. . . . .	305
12.3.1. Mechanical load generator. . . . .	305
12.3.1.1. Description of the mechanism. . . . .	305
12.3.1.2. Positioning of the generator . . . . .	307
12.3.2. Active control through the anti-torque rotor . . . . .	309
<b>Chapter 13. Resonators.</b> . . . .	<b>319</b>
13.1. Introduction . . . . .	319
13.2. Kinematic coupling . . . . .	319
13.2.1. Pendular masses . . . . .	319
13.2.1.1. Principle . . . . .	319
13.2.1.2. Modeling . . . . .	320
13.2.1.3. Analysis of the results . . . . .	323
13.2.2. Coplanar resonators. . . . .	323
13.3. Stiffness coupling . . . . .	325
13.3.1. Principle . . . . .	325
13.3.2. Modeling . . . . .	327
13.3.3. Forced response of the system . . . . .	331
13.3.4. Analysis of the results . . . . .	332
<b>Chapter 14. Self-Adapting Resonators</b> . . . . .	<b>335</b>
14.1. Introduction . . . . .	335
14.2. Acting near the source: hub resonator . . . . .	335
14.2.1. Principle . . . . .	335
14.2.2. Control algorithm . . . . .	339
14.2.2.1 Type 1 controller. . . . .	339
14.2.2.2. Type 2 controller . . . . .	339
14.2.3. Experiment . . . . .	340
<b>Chapter 15. Active Systems</b> . . . . .	<b>343</b>
15.1. Introduction . . . . .	343
15.2. Principle of the active system in the fixed frame of reference . . . . .	345
15.2.1. Principle . . . . .	345
15.2.2. Control algorithm . . . . .	346
15.2.3. Experiment . . . . .	349
15.2.4. Conclusions . . . . .	350
15.3. Principle of the active system in a rotating frame of reference . . . . .	350
15.3.1. Introduction . . . . .	350
15.3.2. Individual blade control . . . . .	352

15.3.2.1. Principle . . . . .	352
15.3.2.2. Design. . . . .	352
15.3.2.3. Hydraulic actuators of the IBC system . . . . .	353
15.3.2.4. Implementation . . . . .	353
15.3.3. Individual control by servo-flaps . . . . .	354
15.3.3.1. Principle of the rotor with blade flaps operated by piezoelectric actuators . . . . .	354
15.3.3.2. Technological solutions . . . . .	355
<b>Bibliography</b> . . . . .	359
<b>Index</b> . . . . .	365