Contents

Foreword to the First Edition *XVII*
Preface to the First Edition *XIX*
Preface to the Second Edition *XXIII*
Acknowledgements *XXV*

1 Introduction *1*
1.1 Classification of Rotor Systems *1*
1.2 Historical Perspective *3*
References *8*

2 Vibrations of Massless Shafts with Rigid Disks *11*
2.1 General Considerations *11*
2.2 Rotor Unbalance *11*
2.3 Lateral Vibrations of an Elastic Shaft with a Disk at Its Center *13*
2.3.1 Derivation of Equations of Motion *13*
2.3.2 Free Vibrations of an Undamped System and Whirling Modes *14*
2.3.3 Synchronous Whirl of an Undamped System *16*
2.3.4 Synchronous Whirl of a Damped System *20*
2.3.5 Energy Balance *22*
2.4 Inclination Vibrations of an Elastic Shaft with a Disk at Its Center *23*
2.4.1 Rotational Equations of Motion for Single Axis Rotation *23*
2.4.2 Equations of Motion *23*
2.4.3 Free Vibrations and Natural Angular Frequency *27*
2.4.4 Gyroscopic Moment *29*
2.4.5 Synchronous Whirl *33*
2.5 Vibrations of a 4 DOF System *34*
2.5.1 Equations of Motion *34*
2.5.1.1 Derivation by Using the Results of 2 DOF System *35*
2.5.1.2 Derivation by Lagrange's Equations *37*
2.5.2 Free Vibrations and a Natural Frequency Diagram *40*
2.5.3 Synchronous Whirling Response *42*
2.6 Vibrations of a Rigid Rotor *43*
2.6.1 Equations of Motion *43*

2.6.2 Free Whirling Motion and Whirling Modes *45*
2.7 Approximate Formulas for Critical Speeds of a Shaft with Several Disks *46*
2.7.1 Rayleigh's Method *47*
2.7.2 Dunkerley's Formula *48*
References *48*

3 Vibrations of a Continuous Rotor *49*
3.1 General Considerations *49*
3.2 Equations of Motion *50*
3.3 Free Whirling Motions and Critical Speeds *55*
3.3.1 Analysis Considering Only Transverse Motion *56*
3.3.2 Analysis Considering the Gyroscopic Moment and Rotary Inertia *58*
3.3.3 Major Critical Speeds *59*
3.4 Synchronous Whirl *60*
References *65*

4 Balancing *67*
4.1 Introduction *67*
4.2 Classification of Rotors *67*
4.3 Balancing of a Rigid Rotor *69*
4.3.1 Principle of Balancing *69*
4.3.1.1 Two-Plane Balancing *69*
4.3.1.2 Single-Plane Balancing *70*
4.3.2 Balancing Machine *71*
4.3.2.1 Static Balancing Machine *71*
4.3.2.2 Dynamic Balancing Machine *71*
4.3.3 Field Balancing *75*
4.3.4 Various Expressions of Unbalance *77*
4.3.4.1 Resultant Unbalance U and Resultant Unbalance Moment V *77*
4.3.4.2 Dynamic Unbalance (U_1, U_2) *79*
4.3.4.3 Static Unbalance U and Couple Unbalance $[U_c, -U_c]$ *80*
4.3.5 Balance Quality Grade of a Rigid Rotor *82*
4.3.5.1 Balance Quality Grade *82*
4.3.5.2 How to Use the Standards *84*
4.4 Balancing of a Flexible Rotor *86*
4.4.1 Effect of the Elastic Deformation of a Rotor *86*
4.4.2 Modal Balancing Method *87*
4.4.2.1 N-Plane Modal Balancing *88*
4.4.2.2 (N + 2)-Plane Modal Balancing *90*
4.4.3 Influence Coefficient Method *90*
References *92*

5 Vibrations of an Asymmetrical Shaft and an Asymmetrical Rotor *93*
5.1 General Considerations *93*

5.2 Asymmetrical Shaft with a Disk at Midspan *94*
5.2.1 Equations of Motion *94*
5.2.2 Free Vibrations and Natural Frequency Diagrams *95*
5.2.2.1 Solutions in the Ranges $\omega > \omega_{c1}$ and $\omega < \omega_{c2}$ *98*
5.2.2.2 Solutions in the Range $\omega_{c1} > \omega > \omega_{c2}$ *99*
5.2.3 Synchronous Whirl in the Vicinity of the Major Critical Speed *100*
5.3 Inclination Motion of an Asymmetrical Rotor Mounted on a Symmetrical Shaft *102*
5.3.1 Equations of Motion *103*
5.3.2 Free Vibrations and a Natural Frequency Diagram *108*
5.3.3 Synchronous Whirl in the Vicinity of the Major Critical Speed *109*
5.4 Double-Frequency Vibrations of an Asymmetrical Horizontal Shaft *110*
References *113*

6 Nonlinear Vibrations *115*
6.1 General Considerations *115*
6.2 Causes and Expressions of Nonlinear Spring Characteristics: Weak Nonlinearity *115*
6.3 Expressions of Equations of Motion Using Physical and Normal Coordinates *121*
6.4 Various Types of Nonlinear Resonances *123*
6.4.1 Harmonic Resonance *124*
6.4.1.1 Solution by the Harmonic Balance Method *124*
6.4.1.2 Solution Using Normal Coordinates *128*
6.4.2 Subharmonic Resonance of Order 1/2 of a Forward Whirling Mode *130*
6.4.3 Subharmonic Resonance of Order 1/3 of a Forward Whirling Mode *132*
6.4.4 Combination Resonance *133*
6.4.5 Summary of Nonlinear Resonances *136*
6.5 Nonlinear Resonances in a System with Radial Clearance: Strong Nonlinearity *139*
6.5.1 Equations of Motion *141*
6.5.2 Harmonic Resonance and Subharmonic Resonances *142*
6.5.3 Chaotic Vibrations *144*
6.6 Nonlinear Resonances of a Continuous Rotor *145*
6.6.1 Representations of Nonlinear Spring Characteristics and Equations of Motion *146*
6.6.2 Transformation to Ordinary Differential Equations *149*
6.6.3 Harmonic Resonance *150*
6.6.4 Summary of Nonlinear Resonances *151*
6.7 Internal Resonance Phenomenon *152*
6.7.1 Examples of the Internal Resonance Phenomenon *152*
6.7.2 Subharmonic Resonance of Order 1/2 *153*

6.7.3 Chaotic Vibrations in the Vicinity of the Major Critical Speed *156*
References *158*

7 Self-Excited Vibrations due to Internal Damping *161*
7.1 General Considerations *161*
7.2 Friction in Rotor Systems and Its Expressions *161*
7.2.1 External Damping *162*
7.2.2 Hysteretic Internal Damping *162*
7.2.3 Structural Internal Damping *167*
7.3 Self-Excited Vibrations due to Hysteretic Damping *168*
7.3.1 System with Linear Internal Damping Force *169*
7.3.2 System with Nonlinear Internal Damping Force *171*
7.4 Self-Excited Vibrations due to Structural Damping *173*
References *176*

8 Nonstationary Vibrations during Passage through Critical Speeds *177*
8.1 General Considerations *177*
8.2 Equations of Motion for Lateral Motion *178*
8.3 Transition with Constant Acceleration *179*
8.4 Transition with Limited Driving Torque *183*
8.4.1 Characteristics of Power Sources *183*
8.4.2 Steady-State Vibration *184*
8.4.3 Stability Analysis *187*
8.4.4 Nonstationary Vibration *188*
8.5 Analysis by the Asymptotic Method (Nonlinear System, Constant Acceleration) *189*
8.5.1 Equations of Motion and Their Transformation to a Normal Coordinate Expression *190*
8.5.2 Steady-State Solution *192*
8.5.3 Nonstationary Vibration *194*
References *196*

9 Vibrations due to Mechanical Elements *199*
9.1 General Considerations *199*
9.2 Ball Bearings *199*
9.2.1 Vibration and Noise in Rolling-Element Bearings *199*
9.2.1.1 Vibrations due to the Passage of Rolling Elements *200*
9.2.1.2 Natural Vibrations of Outer Rings *202*
9.2.1.3 Geometrical Imperfection *204*
9.2.1.4 Other Noises *205*
9.2.2 Resonances of a Rotor Supported by Rolling-Element Bearings *205*
9.2.2.1 Resonances due to Shaft Eccentricity *205*
9.2.2.2 Resonances due to the Directional Difference in Stiffness *206*
9.2.2.3 Vibrations of a Horizontal Rotor due to the Passage of Rolling Elements *208*

9.2.2.4 Vibrations due to the Coexistence of the Passage of Rolling Elements and a Shaft Initial Bend *208*
9.3 Bearing Pedestals with Directional Difference in Stiffness *209*
9.4 Universal Joint *211*
9.5 Rubbing *215*
9.5.1 Equations of Motion *217*
9.5.2 Numerical Simulation *218*
9.5.3 Theoretical Analysis *220*
9.5.3.1 Forward Rubbing *220*
9.5.3.2 Backward Rubbing *221*
9.6 Self-Excited Oscillation in a System with a Clearance between Bearing and Housing *222*
9.6.1 Experimental Setup and Experimental Results *223*
9.6.2 Analytical Model and Reduction of Equations of Motion *224*
9.6.3 Numerical Simulation *226*
9.6.4 Self-Excited Oscillations *227*
9.6.4.1 Analytical Model and Equations of Motion *227*
9.6.4.2 Stability of a Synchronous Whirl *228*
9.6.4.3 Mechanism of a Self-Excited Oscillation *229*
References *232*

10 Flow-Induced Vibrations *235*
10.1 General Considerations *235*
10.2 Oil Whip and Oil Whirl *235*
10.2.1 Journal Bearings and Self-Excited Vibrations *236*
10.2.2 Reynolds Equation *239*
10.2.3 Oil Film Force *240*
10.2.3.1 Short Bearing Approximation *241*
10.2.3.2 Long Bearing Approximation *243*
10.2.4 Stability Analysis of an Elastic Rotor *243*
10.2.5 Oil Whip Prevention *246*
10.3 Seals *248*
10.3.1 Plain Annular Seal *248*
10.3.2 Labyrinth Seal *251*
10.4 Tip Clearance Excitation *251*
10.5 Hollow Rotor Partially Filled with Liquid *252*
10.5.1 Equations Governing Fluid Motion and Fluid Force *254*
10.5.2 Asynchronous Self-Excited Whirling Motion *256*
10.5.3 Resonance Curves at the Major Critical Speed (Synchronous Oscillation) *257*
References *261*

11 Vibration Suppression *263*
11.1 Introduction *263*
11.2 Vibration Absorbing Rubber *263*

11.3 Theory of Dynamic Vibration Absorber *263*
11.4 Squeeze-Film Damper Bearing *264*
11.5 Ball Balancer *266*
11.5.1 Fundamental Characteristics and the Problems *266*
11.5.2 Countermeasures to the Problems *268*
11.6 Discontinuous Spring Characteristics *271*
11.6.1 Fundamental Characteristics and the Problems *271*
11.6.2 Countermeasures to the Problems *273*
11.6.3 Suppression of Unstable Oscillations of an Asymmetrical Shaft *274*
11.7 Leaf Spring *276*
11.8 Viscous Damper *277*
11.9 Suppression of Rubbing *278*
References *280*

12 Some Practical Rotor Systems *283*
12.1 General Consideration *283*
12.2 Steam Turbines *283*
12.2.1 Construction of a Steam Turbine *283*
12.2.2 Vibration Problems of a Steam Turbine *286*
12.2.2.1 Poor Accuracy in the Manufacturing of Couplings *286*
12.2.2.2 Thermal Bow *287*
12.2.2.3 Vibrations of Turbine Blades *287*
12.2.2.4 Oil Whip and Oil Whirl *290*
12.2.2.5 Labylinth Seal *290*
12.2.2.6 Steam Whirl *290*
12.3 Wind Turbines *290*
12.3.1 Structure of a Wind Turbine *290*
12.3.2 Campbell Diagram of a Wind Turbine with Two Teetered Blades *292*
12.3.3 Excitation Forces in Wind Turbines *294*
12.3.4 Example: Steady-State Oscillations of a Teetered Two-Bladed Wind Turbine *295*
12.3.4.1 Wind Velocity *296*
12.3.4.2 Vibration of the Tower *296*
12.3.4.3 Flapwise Bending Vibration of the Blade *297*
12.3.4.4 Chordwise Bending Vibration of the Blade *297*
12.3.4.5 Torque Variation of the Low-Speed Shaft *297*
12.3.4.6 Variation of the Teeter Angle *297*
12.3.4.7 Variation of the Pitch Angle *297*
12.3.4.8 Gear *297*
12.3.5 Balancing of a Rotor *298*
12.3.6 Vibration Analysis of a Blade Rotating in a Vertical Plane *299*
12.3.6.1 Derivation of Equations of Motion *299*
12.3.6.2 Natural Frequencies *302*
12.3.6.3 Forced Oscillation *302*

12.3.6.4 Parametrically Excited Oscillation *303*
References *305*

13 Cracked Rotors *307*
13.1 General Considerations *307*
13.2 Modeling and Equations of Motion *309*
13.2.1 Piecewise Linear Model (PWL Model) *309*
13.2.2 Power Series Model (PS Model) *311*
13.3 Numerical Simulation (PWL Model) *312*
13.3.1 Horizontal Rotor *312*
13.3.2 Vertical Rotor *313*
13.4 Theoretical Analysis (PS Model) *313*
13.4.1 Forward Harmonic Resonance $[+\omega]$ (Horizontal Rotor) *313*
13.4.2 Forward Harmonic Resonance $[+\omega]$ (Vertical Rotor) *315*
13.4.3 Forward Superharmonic Resonance $[+2\omega]$ (Horizontal Rotor) *315*
13.4.4 Other Kinds of Resonance *317*
13.4.4.1 Backward Harmonic Resonance $[-\omega]$ *317*
13.4.4.2 Forward Superharmonic Resonance $[+3\omega]$ *317*
13.4.4.3 Forward Subharmonic Resonance $[+(1/2)\omega]$ *318*
13.4.4.4 Forward Super-Subharmonic Resonance $[+(3/2)\omega]$ *319*
13.4.4.5 Combination Resonance *320*
13.5 Case History in Industrial Machinery *321*
References *324*

14 Finite Element Method *327*
14.1 General Considerations *327*
14.2 Fundamental Procedure of the Finite Element Method *327*
14.3 Discretization of a Rotor System *328*
14.3.1 Rotor Model and Coordinate Systems *328*
14.3.2 Equations of Motion of an Element *329*
14.3.2.1 Rigid Disk *329*
14.3.2.2 Finite Rotor Element *330*
14.3.3 Equations of Motion for a Complete System *336*
14.3.3.1 Model I: (Uniform Elastic Rotor) *336*
14.3.3.2 Model II: Disk–Shaft System *340*
14.3.3.3 Variation of Equations of Motion *343*
14.4 Free Vibrations: Eigenvalue Problem *345*
14.5 Forced Vibrations *347*
14.6 Alternative Procedure *349*
References *350*

15 Transfer Matrix Method *351*
15.1 General Considerations *351*
15.2 Fundamental Procedure of the Transfer Matrix Method *351*
15.2.1 Analysis of Free Vibration *351*

15.2.2 Analysis of Forced Vibration *355*
15.3 Free Vibrations of a Rotor *359*
15.3.1 State Vector and Transfer Matrix *359*
15.3.2 Frequency Equation and the Vibration Mode *364*
15.3.3 Examples *365*
15.3.3.1 Model I: Uniform Continuous Rotor *365*
15.3.3.2 Model II: Disk–Shaft System *366*
15.4 Forced Vibrations of a Rotor *367*
15.4.1 External Force and Extended Transfer Matrix *367*
15.4.2 Steady-State Solution *370*
15.4.3 Example *371*
References *371*

16 Measurement and Signal Processing *373*
16.1 General Considerations *373*
16.2 Measurement and Sampling Problem *374*
16.2.1 Measurement System and Digital Signal *374*
16.2.2 Problems in Signal Processing *375*
16.3 Fourier Series *376*
16.3.1 Real Fourier Series *376*
16.3.2 Complex Fourier Series *376*
16.4 Fourier Transform *378*
16.5 Discrete Fourier Transform *379*
16.6 Fast Fourier Transform *383*
16.7 Leakage Error and Countermeasures *383*
16.7.1 Leakage Error *383*
16.7.2 Countermeasures for Leakage Error *384*
16.7.2.1 Window Function *384*
16.7.2.2 Prevention of Leakage by Coinciding Periods *385*
16.8 Applications of FFT to Rotor Vibrations *386*
16.8.1 Spectra of Steady-State Vibration *386*
16.8.1.1 Subharmonic Resonance of Order 1/2 of a Forward Whirling Mode *386*
16.8.1.2 Combination Resonance *388*
16.8.2 Nonstationary Vibration *388*
References *391*

17 Active Magnetic Bearing *393*
17.1 General Considerations *393*
17.2 Magnetic Levitation and Earnshaw's Theorem *393*
17.3 Active Magnetic Levitation *394*
17.3.1 Levitation Model *394*
17.3.2 Current Control with PD-Control *396*
17.3.2.1 Physical Meanings of PD Control *397*
17.3.2.2 Transfer Function and Stability Condition *397*

17.3.2.3 Determination of Gains *398*
17.3.2.4 Case with a Static Load *399*
17.3.3 Current Control with PID-Control *399*
17.3.3.1 Transfer Function and Stability Condition *399*
17.3.3.2 Determination of Gains *400*
17.3.3.3 Case with a Static Load *400*
17.3.4 Practical Examples of Levitation *401*
17.3.4.1 Identification of System Parameters *401*
17.3.4.2 Digital PD-Control with DSP *402*
17.3.5 Current Control with State Feedback Control *403*
17.4 Active Magnetic Bearing *405*
17.4.1 Principle of an Active Magnetic Bearing *405*
17.4.2 Active Magnetic Bearings in a High-Speed Spindle System *405*
17.4.3 Dynamics of a Rigid Rotor system *406*
References *408*

Appendix A Moment of Inertia and Equations of Motion *409*

Appendix B Stability above the Major Critical Speed *413*

Appendix C Derivation of Equations of Motion of a 4 DOF Rotor System by Using Euler Angles *415*

Appendix D Asymmetrical Shaft and Asymmetrical Rotor with Four Degrees of Freedom *421*
D.1 4 DOF Asymmetrical Shaft System *421*
D.2 4 DOF Asymmetrical Rotor System *423*
Reference *425*

Appendix E Transformation of Equations of Motion to Normal Coordinates: 4 DOF Rotor System *427*
E.1 Transformation of Equations of Motion to Normal Coordinates *427*
E.2 Nonlinear Terms *428*
References *429*

Appendix F Routh–Hurwitz Criteria for Complex Expressions *431*
References *432*

Appendix G FFT Program *433*
References *435*

Index *437*