

Contents

Abstract	iii
Kurzfassung	v
Acknowledgments	vii
Table of Contents	ix
List of Figures	xiii
List of Tables	xix
Nomenclature	xxi
1. Introduction	1
1.1. Motivation	1
1.2. Aeroelastic Phenomena in Turbomachinery	2
1.3. State of the Art	4
1.3.1. Aeroelastic Stability Analysis in Turbomachinery	4
1.3.2. Previous Investigations on the Limitations of the Energy Method	6
1.4. Research Objective	8
1.5. Outline of the Thesis	10
2. Theory	11
2.1. Free Vibration of the Harmonic Oscillator in the Time Domain	11
2.1.1. Damping and Excitation	13
2.1.2. Structural Energy	14
2.2. Aeroelastic Modeling for Turbomachinery	15
2.2.1. Equation of Motion and Forces Acting on Structure	15
2.2.2. Prestressed Modal Analysis	16
2.2.3. Mechanics of Rotationally Symmetric Structures	18
2.2.4. Traveling Waves: The Inter-Blade Phase Angle	21
2.2.5. Generalized Aerodynamic Forces	22
2.2.6. Reduced Frequency	25
2.2.7. Aeroelastic Stability Equation in Modal Form	26
2.3. The Energy Method	26
2.3.1. Rationale of the Energy Method	26
2.3.2. Aerodynamic Work per Cycle	27

2.3.3. Logarithmic Decrement of Aerodynamic Damping	28
2.3.4. Local Excitation	30
2.4. Aerodynamic Coupling of Modeshapes	30
2.4.1. Aeroelastic Eigenvalue Problem	31
2.4.2. Solving the Flutter Equation	33
2.4.3. Physical Representation of Aeroelastic Modeshapes	36
2.5. Parameters in Coupled-Mode Flutter Analysis	37
2.5.1. Mass Ratio	37
2.5.2. Solidity	39
2.5.3. Frequency Separation and Distance	40
2.5.4. Normalized Logarithmic Decrement	41
3. Numerical Approach	43
3.1. Computational Fluid Dynamics	43
3.2. Computational Structural Mechanics	45
3.3. Aeroelastic Coupling	45
3.4. Aeroelastic Toolchain	46
4. Geometries and Test Cases	51
4.1. FUTURE-EPFL 2D Linear Cascade	51
4.2. NACA3506 2D Linear Cascade	55
4.3. CRISPMulti Fan Stage	58
5. Verification and Validation of the P-K Method	65
5.1. General Remarks on Time-Marching Simulations	66
5.1.1. General Observations	67
5.1.2. Post-Processing the Time History of Deflections	68
5.1.3. Disclaimer on Used Non-Reflecting Boundary Conditions	70
5.2. FUTURE-2D-LC	70
5.2.1. GAF Matrix Generation	71
5.2.2. Subsonic Operating Point with Frequency Separation 1:2	73
5.2.3. Subsonic Single-Mode Flutter vs. Low Frequency Separation	79
5.2.4. Operating Point Transonic I	81
5.2.5. Operating Point Transonic II	86
5.3. NACA3506-2D-LC	88
5.3.1. Subsonic	88
5.3.2. Transonic	89
5.4. CRISPMulti	92
5.4.1. Time-Marching FSC Simulations	92
5.4.2. P-K Analysis	93
5.5. Mode Tracking Strategies	98
5.5.1. Mode Crossing	98
5.5.2. Frequency Coalescence	98

5.6. Summary	101
6. Aerodynamically Coupled Modeshapes in a Linear Compressor Cascade	103
6.1. General Remarks	104
6.2. Subsonic Operating Point	104
6.2.1. Influence of Mass Ratio and Frequency Separation	104
6.2.2. Aerodynamic Resonance and Effect on Modal Coupling	109
6.2.3. Influence of Solidity	114
6.3. Transonic Operating Point	117
6.3.1. Influence of Mass Ratio and Frequency Separation	117
6.3.2. Aerodynamic Resonance and Effect on Modal Coupling	121
6.3.3. Influence of Solidity	126
6.4. Summary	129
7. Application to Low Mass Ratio Fan Blade	131
7.1. General Remarks	131
7.2. Modal Coupling at a Specific Operating Point	132
7.2.1. Generalized Aerodynamic Forces	132
7.2.2. Energy Method and Coupled-Mode Analysis Compared	135
7.2.3. Modal Participations	135
7.2.4. Considering Different Modeshapes in P-K Analysis	139
7.3. Flutter Boundary above Working Line	141
7.3.1. Overview	141
7.3.2. Subsonic to Transonic Flow at Medium Rotational Speed	142
7.3.3. Transonic Flow at Medium-High Rotational Speed	143
7.3.4. Higher Rotational Speed	146
7.4. Mechanism of Modal Coupling	149
7.5. Summary and Outlook	156
8. Conclusion	157
8.1. Aerodynamic Coupling of Modeshapes in Turbomachinery	157
8.2. Occurrence of Aerodynamically Coupled-Mode Flutter	158
8.3. The P-K Method: Verification vs. Validation	159
Bibliography	161
A. Appendix	171
A.1. IBPA Patterns	171
A.2. Additional Validation for FUTURE-2D-LC Case Transonic I	173
A.3. Computational Efficiency: Time-Marching Simulation vs. P-K Method Analysis	177
A.3.1. Natural Frequencies of Modeshapes	183

A.4. CRISPMulti: Parameter Changes Throughout the Compressor
Map 185
A.4.1. Twist-to-Plunge Ratio of Modeshapes 185

Curriculum Vitae **187**