

[A Modern Course in Aeroelasticity](#)

Fifth Revised and Enlarged Edition

von
Earl H. Dowell

5. überarbeitete und erweiterte Auflage

Springer Verlag Berlin; Heidelberg 2014

Verlag C.H. Beck im Internet:
www.beck.de
ISBN 978 3 319 09452 6

Zu [Leseprobe](#)

Contents

1	Introduction	1
2	Static Aeroelasticity	3
2.1	Typical Section Model of an Airfoil	3
2.1.1	Typical Section Model with Control Surface	8
2.1.2	Typical Section Model—Nonlinear Effects	13
2.2	One Dimensional Aeroelastic Model of Airfoils	15
2.2.1	Beam-Rod Representation of Large Aspect Ratio Wing	15
2.2.2	Eigenvalue and Eigenfunction Approach	19
2.2.3	Galerkin's Method	22
2.3	Rolling of a Straight Wing	24
2.3.1	Integral Equation of Equilibrium	24
2.3.2	Derivation of Equation of Equilibrium	25
2.3.3	Calculation of $C^{\alpha\alpha}$	27
2.3.4	Sketch of Function $S(y_1, \eta)$	27
2.3.5	Aerodynamic Forces (Including Spanwise Induction)	28
2.3.6	Aeroelastic Equations of Equilibrium and Lumped Element Solution Method	31
2.3.7	Divergence	32
2.3.8	Reversal and Rolling Effectiveness	34
2.3.9	Integral Equation Eigenvalue Problem and the Experimental Determination of Influence Functions	36
2.4	Two Dimensional Aeroelastic Model of Lifting Surfaces	39
2.4.1	Two Dimensional Structures—Integral Representation	40
2.4.2	Two Dimensional Aerodynamic Surfaces—Integral Representation	41
2.4.3	Solution by Matrix-Lumped Element Approach	42

2.5	Other Physical Phenomena	43
2.5.1	Fluid Flow Through a Flexible Pipe	43
2.5.2	(Low Speed) Fluid Flow Over a Flexible Wall	46
2.6	Sweptwing Divergence	47
	References	50
3	Dynamic Aeroelasticity	53
3.1	Hamilton's Principle	54
3.1.1	Single Particle	54
3.1.2	Many Particles	56
3.1.3	Continuous Body	56
3.1.4	Potential Energy	56
3.1.5	Nonpotential Forces	59
3.2	Lagrange's Equations	60
3.2.1	Example—Typical Section Equations of Motion	61
3.3	Dynamics of the Typical Section Model of An Airfoil	64
3.3.1	Sinusoidal Motion	65
3.3.2	Periodic Motion	67
3.3.3	Arbitrary Motion	67
3.3.4	Random Motion	73
3.3.5	Flutter—An Introduction to Dynamic Aeroelastic Instability	81
3.3.6	Quasi-Steady, Aerodynamic Theory	85
3.4	Aerodynamic Forces for Airfoils—An Introduction and Summary	87
3.4.1	Aerodynamic Theories Available	91
3.4.2	General Approximations	94
3.4.3	Slender Body or Slender (Low Aspect Ratio) Wing Approximation	96
3.5	Solutions to the Aeroelastic Equations of Motion	97
3.5.1	Time Domain Solutions	98
3.5.2	Frequency Domain Solutions	99
3.6	Representative Results and Computational Considerations	102
3.6.1	Time Domain	102
3.6.2	Frequency Domain	104
3.6.3	Flutter and Gust Response Classification Including Parameter Trends	105
3.6.4	Gust Response	119
3.7	Generalized Equations of Motion for Complex Structures	124
3.7.1	Lagrange's Equations and Modal Methods (Rayleigh-Ritz)	124
3.7.2	Kinetic Energy	126
3.7.3	Strain (Potential Elastic) Energy	127

3.7.4	Natural Frequencies and Modes-Eigenvalues and Eigenvectors	131
3.7.5	Evaluation of Generalized Aerodynamic Forces	132
3.7.6	Equations of Motion and Solution Methods	134
3.7.7	Integral Equations of Equilibrium	135
3.7.8	Natural Frequencies and Modes	137
3.7.9	Forced Motion Including Aerodynamic Forces	140
3.8	Other Fluid-Structural Interaction Phenomena.	151
3.8.1	Fluid Flow Through a Flexible Pipe: “Firehose” Flutter	151
3.8.2	(High Speed) Fluid Flow Over a Flexible Wall— A Simple Prototype for Plate or Panel Flutter.	154
	References.	159
4	Nonsteady Aerodynamics of Lifting and Non-lifting Surfaces	161
4.1	Basic Fluid Dynamic Equations	163
4.1.1	Conservation of Mass	163
4.1.2	Conservation of Momentum.	164
4.1.3	Irrotational Flow, Kelvin’s Theorem and Bernoulli’s Equation	165
4.1.4	Derivation of a Single Equation for Velocity Potential	168
4.1.5	Small Perturbation Theory	170
4.2	Supersonic Flow.	176
4.2.1	Two-Dimensional Flow	177
4.2.2	Simple Harmonic Motion of the Airfoil.	177
4.2.3	Discussion of Inversion.	180
4.2.4	Discussion of Physical Significance of the Results . . .	183
4.2.5	Gusts	184
4.2.6	Transient Motion	185
4.2.7	Lift, Due to Airfoil Motion	186
4.2.8	Lift, Due to Atmospheric Gust	187
4.2.9	Three Dimensional Flow	191
4.3	Subsonic Flow	196
4.3.1	Derivation of the Integral Equation by Transform Methods and Solution by Collocation	197
4.3.2	An Alternative Determination of the Kernel Function Using Green’s Theorem.	200
4.3.3	Incompressible, Three-Dimensional Flow.	202
4.3.4	Compressible, Three-Dimensional Flow.	206
4.3.5	Incompressible, Two-Dimensional Flow.	211
4.4	Representative Numerical Results	230

4.5	Transonic Flow	235
4.6	Concluding Remarks	260
	References	262
5	Stall Flutter	265
5.1	Background	265
5.2	Analytical Formulation	266
5.3	Stability and Aerodynamic Work	268
5.4	Bending Stall Flutter	269
5.5	Nonlinear Mechanics Description	271
5.6	Torsional Stall Flutter	272
5.7	General Comments	275
5.8	Reduced Order Models	277
5.9	Computational Stalled Flow	278
	References	284
6	Aeroelasticity in Civil Engineering	285
6.1	Fundamentals	287
6.1.1	Vortex-Induced Oscillation	287
6.1.2	Galloping	298
6.1.3	Torsional Divergence	308
6.1.4	Flutter and Buffeting in the Presence of Aeroelastic Effects	309
6.2	Applications	316
6.2.1	Suspension-Span Bridges	316
6.2.2	Tall Chimneys and Stacks, and Tall Buildings	335
	References	342
7	Aeroelastic Response of Rotorcraft	349
7.1	Blade Dynamics	351
7.1.1	Articulated, Rigid Blade Motion	351
7.1.2	Elastic Motion of Hingeless Blades	360
7.2	Stall Flutter	371
7.3	Rotor-Body Coupling	375
7.4	Unsteady Aerodynamics	394
7.4.1	Dynamic Inflow	394
7.4.2	Frequency Domain	400
7.4.3	Finite-State Wake Modelling	401
7.5	Summary	403
	References	404
8	Aeroelasticity in Turbomachines	409
8.1	Aeroelastic Environment in Turbomachines	410
8.2	The Compressor Performance Map	411

8.3	Blade Mode Shapes and Materials of Construction	415
8.4	Nonsteady Potential Flow in Cascades	416
8.5	Compressible Flow	421
8.6	Periodically Stalled Flow in Turbomachines	425
8.7	Stall Flutter in Turbomachines	428
8.8	Choking Flutter	430
8.9	Aeroelastic Eigenvalues	431
8.10	Recent Trends	434
	References.	437
9	Modeling of Fluid-Structure Interaction.	439
9.1	The Range of Physical Models	439
9.1.1	The Classical Models	439
9.1.2	The Distinction Between Linear and Nonlinear Models	442
9.1.3	Computational Fluid Dynamics Models	443
9.1.4	The Computational Challenge of Fluid Structure Interaction Modeling	443
9.2	Time-Linearized Models	444
9.2.1	Classical Aerodynamic Theory	444
9.2.2	Classical Hydrodynamic Stability Theory	444
9.2.3	Parallel Shear Flow with an Inviscid Dynamic Perturbation	445
9.2.4	General Time-Linearized Analysis.	446
9.2.5	Some Numerical Examples	447
9.3	Nonlinear Dynamical Models	447
9.3.1	Harmonic Balance Method.	449
9.3.2	System Identification Methods	450
9.3.3	Nonlinear Reduced-Order Models	451
9.3.4	Reduced-Order Models	451
9.3.5	Constructing Reduced Order Models	452
9.3.6	Linear and Nonlinear Fluid Models	453
9.3.7	Eigenmode Computational Methodology	453
9.3.8	Proper Orthogonal Decomposition Modes	454
9.3.9	Balanced Modes	455
9.3.10	Synergy Among the Modal Methods	455
9.3.11	Input/Output Models	455
9.3.12	Structural, Aerodynamic, and Aeroelastic Modes	456
9.3.13	Representative Results	458
9.4	Concluding Remarks and Directions for Future Research	470
	References.	475

10	Experimental Aeroelasticity	479
10.1	Review of Structural Dynamics Experiments	479
10.2	Wind Tunnel Experiments	480
10.2.1	Sub-critical Flutter Testing	481
10.2.2	Approaching the Flutter Boundary	481
10.2.3	Safety Devices	481
10.2.4	Research Tests Versus Clearance Tests	482
10.2.5	Scaling Laws	482
10.3	Flight Experiments	482
10.3.1	Approaching the Flutter Boundary	482
10.3.2	When Is Flight Flutter Testing Required?	483
10.3.3	Excitation	483
10.3.4	Examples of Recent Flight Flutter Test Programs	483
10.4	The Role of Experimentation and Theory in Design	483
	References	486
11	Nonlinear Aeroelasticity	487
11.1	Introduction	487
11.2	Generic Nonlinear Aeroelastic Behavior	488
11.3	Flight Experience with Nonlinear Aeroelastic Effects	490
11.3.1	Nonlinear Aerodynamic Effects	491
11.3.2	Freeplay	491
11.3.3	Geometric Structural Nonlinearities	492
11.4	Physical Sources of Nonlinearities	492
11.5	Efficient Computation of Unsteady Aerodynamic Forces: Linear and Nonlinear	493
11.6	Correlations of Experiment/Theory and Theory/Theory	495
11.6.1	Aerodynamic Forces	495
11.7	Flutter Boundaries in Transonic Flow	499
11.7.1	AGARD 445.6 Wing	499
11.7.2	HSCT Rigid and Flexible Semispan Models	500
11.7.3	Benchmark Active Control Technology Model	501
11.7.4	Isogai Case A Model	503
11.8	Limit Cycle Oscillations	505
11.8.1	Airfoils with Stiffness Nonlinearities	505
11.8.2	Nonlinear Internal Resonance Behavior	506
11.8.3	Delta Wings with Geometrical Plate Nonlinearities	508
11.8.4	Very High Aspect Ratio Wings with Both Structural and Aerodynamic Nonlinearities	509
11.8.5	Nonlinear Structural Damping	511
11.8.6	Large Shock Motions and Flow Separation	511
11.8.7	Abrupt Wing Stall	521
11.8.8	Uncertainty due to Nonlinearity	522

11.9	Concluding Remarks	523
	References.	524
12	Aeroelastic Control.	531
12.1	Introduction	531
12.2	Linear System Theory	532
12.2.1	System Interconnections	532
12.2.2	Controllability and Observability.	535
12.3	Aeroelasticity: Aerodynamic Feedback	536
12.3.1	Development of a Typical Section Model	537
12.3.2	Aerodynamic Model, 2D	539
12.3.3	Balanced Model Reduction	541
12.3.4	Combined Aeroelastic Model	543
12.3.5	Development of a Delta Wing Model	546
12.3.6	Transducer Effects	548
12.3.7	Aerodynamic Model, 3D	551
12.3.8	Coupled System	552
12.4	Open-Loop Design Considerations	554
12.4.1	HSVs and the Modal Model.	555
12.4.2	Optimization Strategy	556
12.4.3	Optimization Results	559
12.5	Control Law Design	560
12.5.1	Control of the Typical Section Model	561
12.5.2	Control of the Delta Wing Model	563
12.6	Parameter Varying Models.	564
12.6.1	Linear Matrix Inequalities	565
12.6.2	LMI Controller Specifications.	566
12.6.3	An LMI Design for the Typical Section.	569
12.7	Experimental Results.	571
12.7.1	Typical Section Experiment	571
12.7.2	LPV System Identification	572
12.7.3	Closed-Loop Results	574
12.7.4	Delta Wing Experiment	575
12.8	Closing Comments on Aeroelastic Control	581
	References.	582
13	Modern Analysis for Complex and Nonlinear Unsteady Flows in Turbomachinery	585
13.1	Linearized Analysis of Unsteady Flows	586
13.2	Analysis of Unsteady Flows in Multistage Machines	592
13.3	The Harmonic Balance Method for Nonlinear Unsteady Aerodynamics	596
13.4	Conclusions	605
	References.	606

14	Some Recent Advances in Nonlinear Aeroelasticity	609
14.1	Introduction	610
14.2	Motivation and Goals	610
14.3	Current Examples of Recent Advances	612
14.3.1	Transonic and Subsonic Panel Flutter	612
14.3.2	Freeplay Induced Flutter and Limit Cycle Oscillations	615
14.3.3	Reduced Order Modeling of Unsteady Aerodynamics	619
14.4	Transonic Flutter and LCO of Lifting Surfaces	622
14.4.1	Generic Nonlinear Aeroelastic Behavior	622
14.4.2	Flight Experience with Nonlinear Aeroelastic Effects	624
14.4.3	Physical Sources of Nonlinearities	626
14.4.4	Efficient and Accurate Computation of Unsteady Aerodynamic Forces: Linear and Nonlinear	627
14.4.5	Experimental/Theoretical Correlations	627
14.5	Aerodynamic LCO: Buffet, AWS and NSV	639
14.6	Concluding Remarks	645
	References	645
	Appendix A: A Primer for Structural Response to Random Pressure Fluctuations	651
	Appendix B: Some Example Problems	659
	Index	697

A Modern Course in Aeroelasticity

Fifth Revised and Enlarged Edition

Dowell, E.H.

2015, XXX, 700 p. 331 illus., 30 illus. in color., Hardcover

ISBN: 978-3-319-09452-6