

A Modern Course in Aeroelasticity

SOLID MECHANICS AND ITS APPLICATIONS

Volume 116

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A Modern Course in Aeroelasticity

Fourth Revised and Enlarged Edition

by

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The authors would like
to pay tribute to
Robert H. Scanlan, a
superb aeroelastician,
an inspiring teacher,
and a consummate
mentor and friend. He
is greatly missed.

Contents

Preface	xvii
Preface to the First Edition	xvii
Preface to the Second Edition	xix
Preface to the Third Edition	xx
Preface to the Fourth Edition	xxi
Short Bibliography	xxiii
1. INTRODUCTION (DOWELL)	1
2. STATIC AEROELASTICITY (DOWELL)	5
2.1 Typical Section Model of An Airfoil	5
Typical section model with control surface	10
Typical section model—nonlinear effects	16
2.2 One Dimensional Aeroelastic Model of Airfoils	18
Beam-rod representation of large aspect ratio wing	18
Eigenvalue and eigenfunction approach	22
Galerkin's method	24
2.3 Rolling of a Straight Wing	26
Integral equation of equilibrium	26
Derivation of equation of equilibrium	27
Calculation of $C^{\alpha\alpha}$	28
Sketch of function $S(y_1, \eta)$	28
Aerodynamic forces (including spanwise induction)	30
Aeroelastic equations of equilibrium and lumped element solution method	32
Divergence	33
Reversal and rolling effectiveness	34

	Integral equation eigenvalue problem and the experimental determination of influence functions	37
2.4	Two Dimensional Aeroelastic Model of Lifting Surfaces	41
	Two dimensional structures—integral representation	41
	Two dimensional aerodynamic surfaces—integral representation	42
	Solution by matrix-lumped element approach	43
2.5	Other Physical Phenomena	44
	Fluid flow through a flexible pipe	44
	(Low speed) fluid flow over a flexible wall	47
2.6	Sweptwing Divergence	47
	References for Chapter 2	51
3.	DYNAMIC AEROELASTICITY (DOWELL)	53
3.1	Hamilton's Principle	54
	Single particle	54
	Many particles	56
	Continuous body	56
	Potential energy	56
	Nonpotential forces	59
3.2	Lagrange's Equations	60
	Example—typical section equations of motion	61
3.3	Dynamics of the Typical Section Model of An Airfoil	64
	Sinusoidal motion	64
	Periodic motion	67
	Arbitrary motion	67
	Random motion	73
	Flutter - an introduction to dynamic aeroelastic instability	81
	Quasi-steady, aerodynamic theory	85
3.4	Aerodynamic Forces	87
	Aerodynamic theories available	91
	General approximations	95
	'Strip theory' approximation	95
	'Quasisteady' approximation	95
	Slender body or slender (low aspect ratio) wing approximation	96
3.5	Solutions to the Aeroelastic Equations of Motion	97
	Time domain solutions	98
	Frequency domain solutions	100

3.6	Representative Results and Computational Considerations	103
	Time domain	103
	Frequency domain	103
	Flutter and gust response classification including parameter trends	105
	Flutter	105
	Gust response	121
3.7	Generalized Equations of Motion for Complex Structures	128
	Lagrange's equations and modal methods (Rayleigh-Ritz)	128
	Kinetic energy	129
	Strain (potential elastic) energy	130
	Examples	133
	(a) Torsional vibrations of a rod	133
	(b) Bending-torsional motion of a beam-rod	134
	Natural frequencies and modes-eigenvalues and eigenvectors	135
	Evaluation of generalized aerodynamic forces	136
	Equations of motion and solution methods	137
	Integral equations of equilibrium	139
	Natural frequencies and modes	141
	Proof of orthogonality	143
	Forced motion including aerodynamic forces	144
	Examples	147
	(a) Rigid wing undergoing translation responding to a gust	147
	(b) Wing undergoing translation and spanwise bending	153
	(c) Random gusts-solution in the frequency domain	155
3.8	Other Fluid-Structural Interaction Phenomena	156
	Fluid flow through a flexible pipe: "firehose" flutter	156
	(High speed) fluid flow over a flexible wall - a simple prototype for plate or panel flutter	158
	References for Chapter 3	165
4.	NONSTEADY AERODYNAMICS (DOWELL)	169
4.1	Basic Fluid Dynamic Equations	169
	Conservation of mass	170
	Conservation of momentum	171
	Irrotational flow, Kelvin's theorem and Bernoulli's equation	172
	Derivation of a single equation for velocity potential	174
	Small perturbation theory	175

	Reduction to classical acoustics	177
	Boundary conditions	178
	Symmetry and anti-symmetry	180
4.2	Supersonic Flow	182
	Two-dimensional flow	182
	Simple harmonic motion of the airfoil	183
	Discussion of inversion	185
	Discussion of physical significance of the results	187
	Gusts	189
	Transient motion	190
	Lift, due to airfoil motion	191
	Lift, due to atmospheric gust	192
	Three dimensional flow	195
4.3	Subsonic Flow	201
	Derivation of the integral equation by transform methods and solution by collocation	201
	An alternative determination of the Kernel Function using Green's Theorem	204
	Incompressible, three-dimensional flow	207
	Compressible, three-dimensional flow	211
	Incompressible, two-dimensional flow	215
	Simple harmonic motion of an airfoil	218
	Transient motion	224
	Evaluation of integrals	229
4.4	Representative Numerical Results	232
4.5	Transonic Flow	238
	References for Chapter 4	270
5.	STALL FLUTTER (SISTO)	275
	5.1 Background	275
	5.2 Analytical formulation	276
	5.3 Stability and aerodynamic work	278
	5.4 Bending stall flutter	279
	5.5 Nonlinear mechanics description	281
	5.6 Torsional stall flutter	282
	5.7 General comments	285
	5.8 Reduced order models	288

5.9	Computational stalled flow	289
	References for Chapter 5	294
6.	AEROELASTICITY IN CIVIL ENGINEERING (SCANLAN AND SIMIU)	299
6.1	Vortex-induced Oscillation	301
	Vortex shedding	301
	Modeling of vortex-induced oscillations	305
	Coupled two-degree-of-freedom equations: wake oscillator models	306
	Single-degree-of- freedom model of vortex-induced response	310
6.2	Galloping	314
	Equation of motion of galloping bodies. The Glauert-Den Hartog necessary condition for galloping instability	314
	Description of galloping motion	320
	Chaotic galloping of two elastically coupled square bars	321
	Wake galloping : physical description and analysis	321
6.3	Torsional Divergence	327
6.4	Flutter and Buffeting in the Presence of Aeroelastic Effects	328
	Formulation and analytical solution of the two- dimensional bridge flutter problem in smooth flow	330
	Bridge section response to excitation by turbulent wind in the presence of aeroelastic effects	334
6.5	Suspension-Span Bridges	336
	Wind tunnel testing of suspended-span bridges	336
	Torsional divergence analysis for a full bridge	338
	Locked-in vortex-induced response	340
	Flutter and buffeting of a full-span bridge	350
	Reduction of bridge susceptibility to flutter	360
6.6	Tall Chimneys and Stacks, and Tall Buildings	361
	Tall chimneys and stacks	361
	Tall buildings	365
	References for Chapter 6	367
7.	AEROELASTIC RESPONSE OF ROTORCRAFT (CURTISS AND PETERS)	377
7.1	Blade Dynamics	379
	Articulated, rigid blade motion	379
	Elastic motion of hingeless blades	390

7.2	Stall Flutter	403
7.3	Rotor-Body Coupling	409
7.4	Unsteady Aerodynamics	433
	Dynamic inflow	434
	Frequency domain	440
	Finite-state wake modelling	441
	Summary	444
	References for Chapter 7	444
8.	AEROELASTICITY IN TURBOMACHINES (SISTO)	453
8.1	Aeroelastic Environment in Turbomachines	454
8.2	The Compressor Performance Map	455
8.3	Blade Mode Shapes and Materials of Construction	460
8.4	Nonsteady Potential Flow in Cascades	462
8.5	Compressible Flow	467
8.6	Periodically Stalled Flow in Turbomachines	471
8.7	Stall Flutter in Turbomachines	475
8.8	Choking Flutter	477
8.9	Aeroelastic Eigenvalues	479
8.10	Recent Trends	481
	References for Chapter 8	487
9.	MODELING OF FLUID-STRUCTURE INTERACTION (DOWELL AND HALL)	491
9.1	The Range Of Physical Models	491
	The classical models	491
	The distinction between linear and nonlinear models	494
	Computational fluid dynamics models	495
	The computational challenge of fluid structure interaction modeling	495
9.2	Time-Linearized Models	496
	Classical aerodynamic theory	496
	Classical hydrodynamic stability theory	497
	Parallel shear flow with an inviscid dynamic perturbation	497
	General time-linearized analysis	498
	Some numerical examples	500
9.3	Nonlinear Dynamical Models	500
	Harmonic balance method	503

System identification methods	503
Nonlinear reduced-order models	504
Reduced-order models	504
Constructing reduced order models	505
Linear and nonlinear fluid models	506
Eigenmode computational methodology	507
Proper orthogonal decomposition modes	508
Balanced modes	509
Synergy among the modal methods	509
Input/output models	509
Structural, aerodynamic, and aeroelastic modes	511
Representative results	512
The effects of spatial discretization and a finite computational domain	512
The effects of mach number and steady angle of attack: subsonic and transonic flows	516
The effects of viscosity	521
Nonlinear aeroelastic reduced-order models	522
9.4 Concluding Remarks	524
References for Chapter 9	529
Appendix: Singular-Value Decomposition, Proper Orthogonal Decomposition, & Balanced Modes	538
10. EXPERIMENTAL AEROELASTICITY (DOWELL)	541
10.1 Review of Structural Dynamics Experiments	541
10.2 Wind Tunnel Experiments	543
Sub-critical flutter testing	543
Approaching the flutter boundary	544
Safety devices	544
Research tests vs. clearance tests	544
Scaling laws	544
10.3 Flight Experiments	545
Approaching the flutter boundary	545
When is flight flutter testing required?	545
Excitation	545
Examples of recent flight flutter test programs	546
10.4 The Role of Experimentation and Theory in Design	546
References for Chapter 10	548

11. NONLINEAR AEROELASTICITY (DOWELL, EDWARDS AND STRGANAC)	551
11.1 Introduction	551
11.2 Generic Nonlinear Aeroelastic Behavior	552
11.3 Flight Experience with Nonlinear Aeroelastic Effects	554
Nonlinear aerodynamic effects	556
Freeplay	556
Geometric structural nonlinearities	557
11.4 Physical Sources of Nonlinearities	557
11.5 Efficient Computation of Unsteady Aerodynamic Forces: Linear and Nonlinear	558
11.6 Correlations of Experiment/Theory and Theory/Theory Aerodynamic forces	560
11.7 Flutter Boundaries in Transonic Flow	566
11.8 Limit Cycle Oscillations	573
Airfoils with stiffness nonlinearities	573
Nonlinear internal resonance behavior	575
Delta wings with geometrical plate nonlinearities	577
Very high aspect ratio wings with both structural and aerodynamic nonlinearities	578
Nonlinear structural damping	581
Large shock motions and flow separation	581
Abrupt wing stall	594
Uncertainty due to nonlinearity	595
References for Chapter 11	598
12. AEROELASTIC CONTROL (CLARK AND COX)	611
12.1 Introduction	611
12.2 Linear System Theory	612
System interconnections	612
Controllability and observability	615
12.3 Aeroelasticity: Aerodynamic Feedback	617
Development of a typical section model	617
Aerodynamic model, 2D	619
Balanced model reduction	622
Combined aeroelastic model	623
Development of a delta wing model	627
Transducer effects	630

Aerodynamic model, 3D	633
Coupled system	634
12.4 Open-Loop Design Considerations	636
HSVs and the modal model	637
Optimization strategy	638
Optimization results	641
12.5 Control Law Design	642
Control of the typical section model	644
Control of the delta wing model	647
12.6 Parameter Varying Models	647
Linear matrix inequalities	648
LMI controller specifications	649
An LMI design for the typical section	652
12.7 Experimental Results	654
Typical section experiment	655
LPV system identification	656
Closed-loop results	658
Delta wing experiment	664
12.8 Closing Comments	667
References for Chapter 12	669
13. MODERN ANALYSIS FOR COMPLEX AND NONLINEAR UNSTEADY FLOWS IN TURBOMACHINERY (HALL)	675
13.1 Linearized Analysis of Unsteady Flows	676
13.2 Analysis of Unsteady Flows	683
13.3 Harmonic Balance Method	688
13.4 Conclusions	699
References for Chapter 13	701
Appendices	705
Appendix A: A Primer For Structural Response To Random Pressure Fluctuations	705
A.1 Introduction	705
A.2 Excitation-Response Relation For The Structure	705
A.3 Sharp Resonance or Low Damping Approximation	709
Nomenclature	710
References for Appendix A	710

Appendix B: Some Example Problems	711
B.1 For Chapter 2	711
B.2 For Section 3.1	724
B.3 For Section 3.3	730
B.4 For Section 3.6	735
B.5 For Section 4.1	738
Index	743

Preface

Preface to the First Edition

A reader who achieves a substantial command of the material contained in this book should be able to read with understanding most of the literature in the field. Possible exceptions may be certain special aspects of the subject such as the aeroelasticity of plates and shells or the use of electronic feedback control to modify aeroelastic behavior. The first author has considered the former topic in a separate volume. The latter topic is also deserving of a separate volume.

In the first portion of the book the basic physical phenomena of divergence, control surface effectiveness, flutter and gust response of aeronautical vehicles are treated. As an indication of the expanding scope of the field, representative examples are also drawn from the non-aeronautical literature. To aid the student who is encountering these phenomena for the first time, each is introduced in the context of a simple physical model and then reconsidered systematically in more complicated models using more sophisticated mathematics.

Beyond the introductory portion of the book, there are several special features of the text. One is the treatment of unsteady aerodynamics. This crucial part of aeroelasticity is usually the most difficult for the experienced practitioner as well as the student. The discussion is developed from the fundamental theory underlying numerical lifting surface analysis. Not only the well known results for subsonic and supersonic flow are covered; but also some of the recent developments for transonic flow, which hold promise of bringing effective solution techniques to this important regime.

Professor Sisto's chapter on Stall Flutter is an authoritative account of this important topic. A difficult and still incompletely understood phenomenon, stall flutter is discussed in terms of its fundamental aspects

as well as its significance in applications. The reader will find this chapter particularly helpful as an introduction to this complex subject.

Another special feature is a series of chapters on three areas of advanced application of the fundamentals of aeroelasticity. The first of these is a discussion of Aeroelastic Problems of Civil Engineering Structures by Professor Scanlan. The next is a discussion on Aeroelasticity of Helicopters and V/STOL aircraft by Professor Curtiss. The final chapter in this series treats Aeroelasticity in Turbomachines and is by Professor Sisto. This series of chapters is unique in the aeroelasticity literature and the first author feels particularly fortunate to have the contributions of these eminent experts.

The emphasis in this book is on fundamentals because no single volume can hope to be comprehensive in terms of applications. However, the above three chapters should give the reader an appreciation for the relationship between theory and practice. One of the continual fascinations of aeroelasticity is this close interplay between fundamentals and applications. If one is to deal successfully with applications, a solid grounding in the fundamentals is essential.

For the beginning student, a first course in aeroelasticity could cover Chapters 1-3 and selected portions of 4. For a second course and the advanced student or research worker, the remaining Chapters would be appropriate. In the latter portions of the book, more comprehensive literature citations are given to permit ready access to the current literature.

The reader familiar with the standard texts by Scanlan and Rosenbaum, Fung, Bisplinghoff, Ashley and Halfman and Bisplinghoff and Ashley will appreciate readily the debt the authors owe to them. Recent books by Petre* and Forsching† should also be mentioned though these are less accessible to an English speaking audience. It is hoped the reader will find this volume a worthy successor.

*Petre, A., *Theory of Aeroelasticity. Vol. I Statics, Vol. II Dynamics.* In Romanian Publishing House of the Academy of the Socialist Republic of Romania, Bucharest, 1966.

†Forsching, H. W., *Fundamentals of Aeroelasticity.* In German. Springer-Verlag, Berlin, 1974.

Preface to the Second Edition

The authors would like to thank all those readers who have written with comments and errata for the First Edition. Many of these have been incorporated into the Second Edition. They would like to thank Professor Holt Ashley of Stanford University who has been most helpful in identifying and correcting various errata.

Also the opportunity has been taken in the Second Edition to bring up-to-date several of the chapters as well as add a chapter on unsteady transonic aerodynamics and aeroelasticity. Chapters 2,5,6 and 8 have been substantially revised. These cover the topics of Static Aeroelasticity, Stall Flutter, Aeroelastic Problems of Civil Engineering Structures and Aeroelasticity in Turbomachines, respectively. Chapter 9, Unsteady Transonic Aerodynamics and Aeroelasticity, is new and covers this rapidly developing subject in more breadth and depth than the First Edition. Again, the emphasis is on fundamental concepts rather than, for example, computer code development per se. Unfortunately due to the press of other commitments, it has not been possible to revise Chapter 7, Aeroelastic Problems of Rotorcraft. However, the Short Bibliography has been expanded for this subject as well as for others. It is hoped that the readers of the First Edition and also new readers will find the Second Edition worthy of their study.

Preface to the Third Edition

The authors would like to thank all those readers of the first and second editions who have written with comments and suggestion. In the third edition the opportunity has been taken to revise and update Chapters 1 through 9. Also three new chapters have been added, i.e., Chapter 10, Experimental Aeroelasticity, Chapter 11, Nonlinear Aeroelasticity; and Chapter 12, Aeroelastic Control. Chapter 10 is a brief introduction to a vast subject; Chapter 11 is an overview of a frontier of research; and Chapter 12 is the first connected, authoritative account of the feedback control of aeroelastic systems. Chapter 12 meets a significant need in the literature. The authors of the first and second editions welcome two new authors, David Peters who has provided a valuable revision of Chapter 7 on rotorcraft, and Edward Crawley who has provided Chapter 12 on aeroelastic control. It is a privilege and a pleasure to have them as members of the team. The author of Chapter 10 would also like to acknowledge the great help he has received over the year from his distinguished colleague, Wilmer H. "Bill" Reed, III, in the study of experimental aeroelasticity. Mr. Reed kindly provided the figures for Chapter 10. The author of Chapter 12 would like to acknowledge the significant scholarly contribution of Charrissa Lin and Ken Kazarus in preparing the chapter on aeroelastic control. Finally the readers of the first and second editions will note that the authors and subject indices have been omitted from this edition. If any reader finds this an inconvenience, please contact the editor and we will reconsider the matter for the next edition.

Preface to the Fourth Edition

In this edition several new chapters have been added and others substantially revised and edited. Chapter 6 on Aeroelasticity in Civil Engineering originally authored by Robert Scanlan has been substantially revised by his close colleague, Emil Simiu. Chapter 9 on Modeling of Fluid-Structure Interaction by Earl Dowell and Kenneth Hall is entirely new and discusses modern methods for treating linear and nonlinear unsteady aerodynamics based upon computational fluid dynamics models and their solution. Chapter 11 by Earl Dowell, John Edwards and Thomas Strganac on Nonlinearity Aeroelasticity is also new and provides a review of recent results. Chapter 12 by Robert Clark and David Cox on Aeroelastic Control is also new and provides an authoritative account of recent developments. Finally Chapter 13 by Kenneth Hall on Modern Analysis for Complex and Nonlinear Unsteady Flows in Turbomachinery is also new and provides an insightful and unique account of this important topic. Many other chapters have been edited for greater clarity as well and author and subject indices are also provided.

Dr. Deman Tang has provided invaluable contributions to the production of the text and all of the authors would like to acknowledge his efforts with great appreciation.

Useful comments on Chapter 6 by Professor Nicholas P. Jones of the Whiting School of Engineering, John Hopkins University, are gratefully acknowledged.

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EARL H. DOWELL

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In parentheses, abbreviations for the above books are indicated which are used in the text.

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- 21 Eastep, Franklin E. (editor), "Flight Vehicle Aeroelasticity," a series of invited articles by several authors in the *Journal of Aircraft*, Vol.40, No.5, 2003, pp.809-874.

Journals

AHS Journal

AIAA Journal

ASCE Transactions, Engineering Mechanics Division

ASME Transaction, Journal of Applied Mechanics

International Journal of Solids and Structures

Journal of Aircraft

Journal of Fluids and Structures

Journal of Sound and Vibration

Other journals will have aeroelasticity articles, of course, but these are among those with the most consistent coverage.

The impact of aeroelasticity on design is not discussed in any detail in this book. For insight into this important area the reader may consult the following volumes prepared by the National Aeronautics and Space Administration in its series on SPACE VEHICLE DESIGN CRITERIA. Although these documents focus on space vehicle application, much of

the material is relevant to aircraft as well. The depth and breadth of coverage varies considerably from one volume to the next, but each contains at least a brief State-of-the-Art review of its topics as well as a discussion of Recommended Design Practices. Further some important topics are included which have not been treated at all in the present book. These include, as already mentioned in the Preface.

Aeroelasticity of plates and shells (panel flutter) (NASA SP-8004) and Aeroelastic effects on control systems dynamics (NASA SP-8016, NASA SP-8036 NASA SP-8079) as well as Structural response to time-dependent separated fluid flows (buffeting) (NASA SP-8001) Fluid motions inside elastic containers (fuel sloshing) (NASA SP-8009, NASA SP-8031) and Coupled structural - propulsion instability (POGO) (NASA SP-8055)

It was intended to revise these volumes periodically to keep them up-to-date. Unfortunately this has not yet been done.

- 1 NASA SP-8001 1970
Buffeting During Atmospheric Ascent
- 2 NASA SP-8002 1964
Flight Loads Measurements During Launch and Exit
- 3 NASA SP-8003 1964
Flutter, Buzz and Divergence
- 4 NASA SP-8004 1972
Panel Flutter
- 5 NASA SP-8006 1965
Local Steady Aerodynamic Loads During Launch and Exit
- 6 NASA SP-8008 1965
Prelaunch Ground Wind Loads
- 7 NASA SP-8012 1968
Natural Vibration Wind Analysis
- 8 NASA SP-8016 1969
Effect of Structural Flexibility on Spacecraft Control System
- 9 NASA SP-8009 1968
Propellant Slosh Loads
- 10 NASA SP-8031 1969
Slosh Suppression

- 11 NASA SP-8035 1970
Wind Loads During Ascent
- 12 NASA SP-8036 1970
Effect of Structural Flexibility on Launch Vehicle Control System
- 13 NASA SP-8050 1970
Structural Vibration Prediction
- 14 NASA SP-8055 1970
Prevention of Coupled Structure - Propulsion Instability (POGO)
- 15 NASA SP-8079 1971
Structural Interaction with Control Systems.

Chapter 1

INTRODUCTION

Several years ago, Collar suggested that aeroelasticity could be usefully visualized as forming a triangle of disciplines, dynamics, solid mechanics and (unsteady) aerodynamics.

Aeroelasticity is concerned with those physical phenomena which involve significant mutual interaction among inertial, elastic and aerodynamic forces. Other important technical fields can be identified by pairing the several points of the triangle. For example,

- Stability and control (flight mechanics) = dynamics + aerodynamics
- Structural vibrations = dynamics + solid mechanics
- *Static* aeroelasticity = steady flow aerodynamics + solid mechanics

Conceptually, each of these technical fields may be thought of as a special aspect of aeroelasticity. For historical reasons only the last topic,

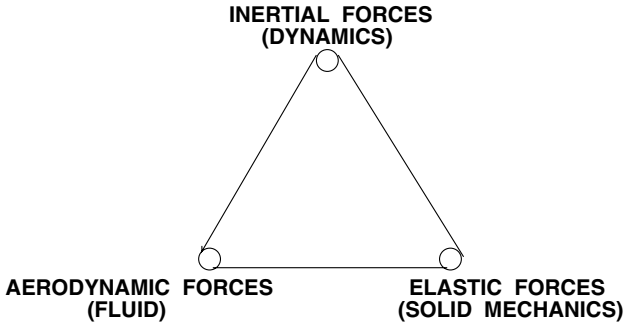


Figure 1.1. Collar diagram.

static aeroelasticity, is normally so considered. However, the impact of aeroelasticity on stability and control (flight mechanics) has increased substantially in recent years.

In modern aerospace vehicles, the relevant physical phenomena may be even more complicated. For example, stresses induced by high temperature environments can be important in aeroelastic problems, hence the term

‘aerothermoelasticity’

In other applications, the dynamics of the guidance and control system may significantly affect aeroelastic problems, or vice versa, hence the term

‘aeroservoelasticity’

For a historical discussion of aeroelasticity including its impact on aerospace vehicle design, consult Chapter 1 of Bisplinghoff and Ashley [2] and AGARD CP No.46, “Aeroelastic Effects from a Flight Mechanics Standpoint” [6].

We shall first concentrate on the dynamics and solid mechanics aspects of aeroelasticity with the aerodynamic forces taken as given. Subsequently, the aerodynamic aspects of aeroelasticity shall be treated from first principles. Theoretical methods will be emphasized, although these will be related to experimental methods and results where this will add to our understanding of the theory and its limitations. For simplicity, we shall begin with the special case of static aeroelasticity.

Although the technological cutting edge of the field of aeroelasticity has centered in the past on aeronautical applications, applications are found at an increasing rate in civil engineering, e.g., flows about bridges and tall buildings; mechanical engineering, e.g., flows around turbomachinery blades and fluid flows in flexible pipes; and nuclear engineering; e.g., flows about fuel elements and heat exchanger vanes. It may well be that such applications will increase in both absolute and relative number as the technology in these areas demands lighter weight structures under more severe flow conditions. Much of the fundamental theoretical and experimental developments can be applied to these areas as well and indeed it is hoped that a common language can be used in these several areas of technology. To further this hope we shall discuss subsequently in some detail several examples in these other fields, even though our principal focus shall be on aeronautical problems. Separate chapters on civil engineering, turbomachinery and helicopter (rotor systems) applications will introduce the reader to the fascinating phenomena which arise in these fields.

Since most aeroelastic phenomena are of an undesirable character, leading to loss of design effectiveness or even sometimes spectacular structural failure as in the case of aircraft wing flutter or the Tacoma Narrows Bridge disaster, the spreading importance of aeroelastic effects will not be warmly welcomed by most design engineers. However, the mastery of the material to be discussed here will permit these effects to be better understood and dealt with if not completely overcome. Moreover in recent years, the beneficial effects of aeroelasticity have received greater attention. For example, the promise of new aerospace systems such as uninhabited air vehicles (UAVs) and morphing aircraft will undoubtedly be more fully realized by exploiting the benefits of aeroelasticity while mitigating the risks.

Chapter 2

STATIC AEROELASTICITY

2.1. Typical Section Model of An Airfoil

We shall find a simple, somewhat contrived, physical system useful for introducing several aeroelastic problems. This is the so-called ‘typical section’ which is a popular pedagogical device.* This simplified aeroelastic system consists of a rigid, flat, plate airfoil mounted on a torsional spring attached to a wind tunnel wall. See Figure 2.1; the airflow over the airfoil is from left to right.

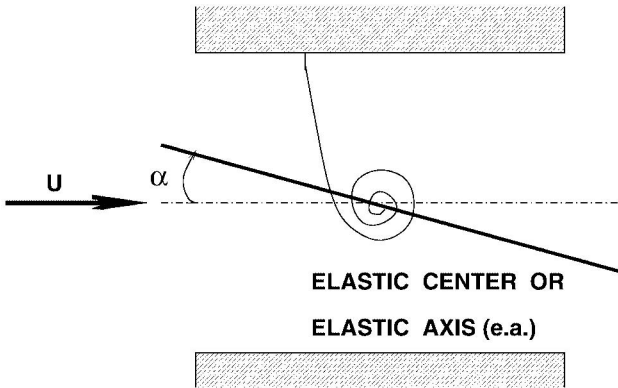


Figure 2.1. Geometry of typical section airfoil.

The principal interest in this model for the aeroelastician is the rotation of the plate (and consequent twisting of the spring), α , as a function

*See Chapter 6, BA, especially pp. 189–200.

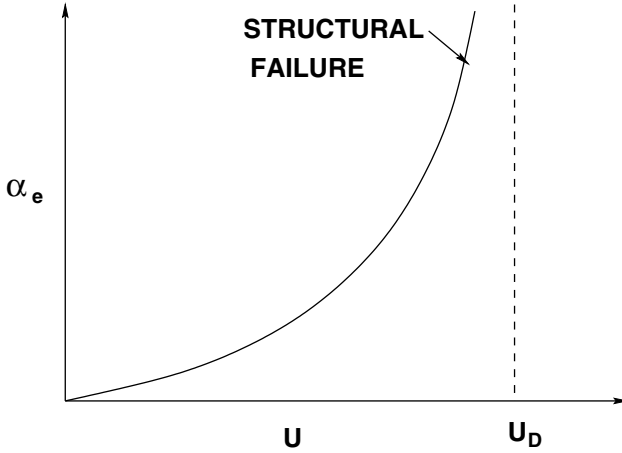


Figure 2.2. Elastic twist vs airspeed

of airspeed. If the spring were very stiff or airspeed were very slow, the rotation would be rather small; however, for flexible springs or high flow velocities the rotation may twist the spring beyond its ultimate strength and lead to structural failure. A typical plot of elastic twist, α_e , vs airspeed, U , is given in Figure 2.2. The airspeed at which the elastic twist increases rapidly to the point of failure is called the ‘divergence airspeed’, U_D . A major aim of any theoretical model is to accurately predict U_D . It should be emphasized that the above curve is representative not only of our typical section model but also of real aircraft wings. Indeed the primary difference is not in the basic physical phenomenon of divergence, but rather in the elaborateness of the theoretical analysis required to predict accurately U_D for an aircraft wing versus that required for our simple typical section model.

To determine U_D theoretically we proceed as follows. The equation of static equilibrium simply states that the sum of aerodynamic plus elastic moments about any point on the airfoil is zero. By convention, we take the point about which moments are summed as the point of spring attachment, the so-called ‘elastic center’ or ‘elastic axis’ of the airfoil.

The total aerodynamic angle of attack, α , is taken as the sum of some initial angle of attack, α_0 (with the spring untwisted), plus an additional increment due to elastic twist of the spring, α_e .

$$\alpha = \alpha_0 + \alpha_e \quad (2.1.1)$$