A Modern Course in Aeroelasticity

SOLID MECHANICS AND ITS APPLICATIONS
Volume 116

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For a list of related mechanics titles, see final pages.

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

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 in 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.

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*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 Noninearity 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 Nocholas P. Jones of the Whiting School of Engineering, John Hopkins University, are gratefully acknowledged.

Figures 6.4, 6.24, 6.28, 6.33, 6.34, 6.35, 6.36, and 6.37 are reprinted with permission from Elsevier.

EARL H. DOWELL

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Books

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3 Bisplinghoff, R. L., and Ashley, H., *Principles of Aeroelasticity*, John Wiley and Sons, Inc., New York, N.Y., 1962. Also available in Dover Edition. (BA)

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5 Scanlan, R. H. and Rosenbaum, R., *Introduction to the Study of Aircraft Vibration and Flutter*, The Macmillan Company, New York, N.Y., 1951. Also available in Dover Edition.

6 AGARD Manual on Aeroelasticity, Vols. I-VII, Beginning 1959 with continual updating. (AGARD)

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

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3 Rodden, W. P., *A Comparison of Methods Used in Interfering Lifting Surface Theory*, AGARD Report R-643, March 1976.

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5 Abramson, H. N., "Hydroelasticity: A Review of Hydrofoil Flutter", *Applied Mechanics Reviews*, February 1969.

6 Many Authors, "Aeroelastic Effects From a Flight Mechanics Standpoint", AGARD, Conference Proceedings No. 46, 1969.

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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,

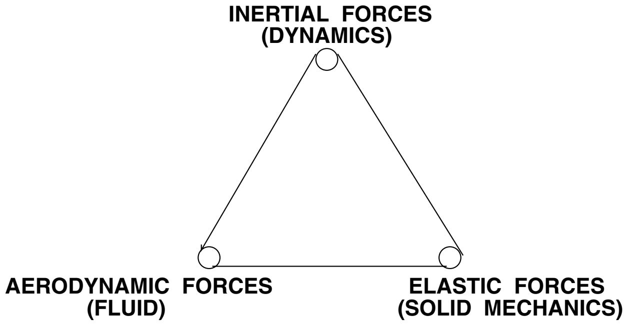

Figure 1.1. Collar diagram.

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.

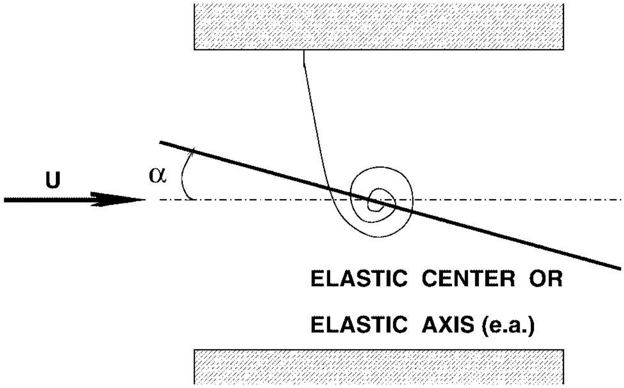

Figure 2.1. Geometry of typical section airfoil.

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.

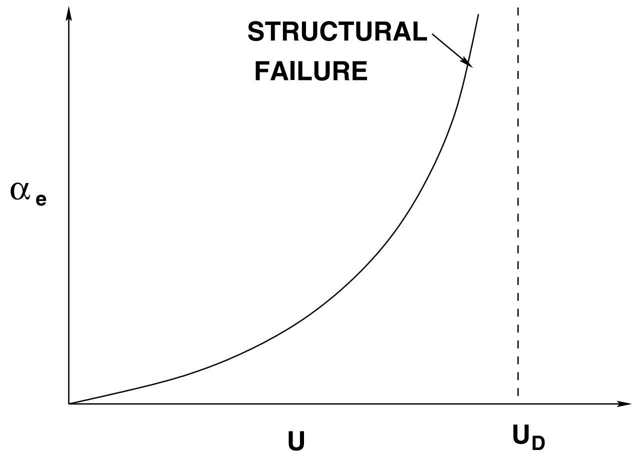

Figure 2.2. Elastic twist vs airspeed

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.

$$\alpha = \alpha_0 + \alpha_e \tag{2.1.1}$$