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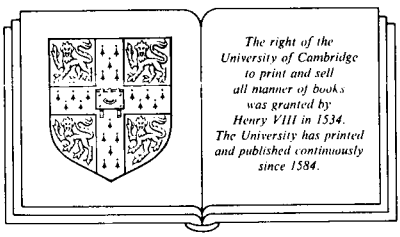

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PREFACE

THE present volume is essentially a collection of papers on the title subject by the author and others during recent years. The interest in unsteady transonic flow arises mainly in connection with calculation of flutter which is more likely to occur in the transonic range than in any other speed range. Most of the work done up to now has been based on linearized theory. Although linearized theory breaks down for steady transonic flow it is known to be valid for unsteady flow provided the unsteadiness is sufficiently large. Unfortunately there is one important type of transonic flutter, namely control surface flutter or "buzz", for which non-linear effects are very important, notably the presence of shock waves. However, recent developments, as those described in Chapter 11, offer some hope for methods of analysis of this phenomenon. Nevertheless, other types of transonic flutter may be adequately treated by use of linearized theory and it is hoped that this monograph will be of some use to aeroelasticians as well as of assistance for further research in this field.

Although the flutter aspect of the problem has been stressed, another related problem, namely that of calculating dynamic stability derivatives (for which linearized theory seems to be valid for wings with highly swept leading edges) is also covered. Other interesting problem areas, like those of transient air forces and forces on accelerating bodies, have been left out completely. Of the content, parts of Chapters 1, 2, 4 and 11 are new and have not been published previously.

I would like to express my sincere thanks to Professors Sune B. Bernt and Holt Ashley for their encouragement and helpful advice during the course of my work on the subject in recent years and also for their careful reading of the part that constituted my doctoral thesis at the Royal Institute of Technology in Stockholm. Also, I would like to express my gratitude to Dr. D. E. Davies of the Royal Aircraft Establishment, Farnborough, for his helpful criticism of the original publications and for going through all my calculations and discovering several algebraic mistakes. Miss Ingrid Jonason typed the manuscript and Miss Elisabeth Redlund and Miss Ulla-Britt Anderson drew all the figures. Thanks are due to them and to all others at the Aeronautical Research Institute of Sweden who helped me with the manuscript in various ways.

Most of the work presented here was done during my stay at the Aeronautical Research Institute of Sweden and supported by the Swedish Air Board through Saab Aircraft Company. The part reported in Chapter 5 was supported by the U.S.A.F. Office of Scientific Research. The support of these organizations is gratefully acknowledged.

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PREFACE TO THE PAPERBACK EDITION

This is a reprint of the original 1961 monograph which was based on the doctoral thesis of the author. It deals with the analysis of the unsteady aerodynamic forces acting on oscillating thin two- and three-dimensional wings in transonic flow. Such forces are needed for the prediction of flutter, which tends to occur more readily at transonic speeds than in any other speed regime. The book emphasizes analytical methods for treating the linearized problem for simple planforms such as rectangular and delta wings. It also includes a treatment of slender wing-body combinations.

There is a thorough discussion of the limitations of the validity of linearized acoustical theory showing how this theory becomes valid for large reduced frequencies. At transonic speeds, strong coupling arises between the unsteady flow and the steady flow due to thickness and lift as manifested in the behavior of the slow moving, ''receding'' wave part of the pressure with a variable wavelength as it propagates through the nonuniform steady flow. This difficulty does not arise for subsonic and supersonic small-perturbation unsteady flows, for which the linear theory of acoustical disturbances propagating through the uniform free stream holds. An important finding in the book is that the contribution of the receding wave part of the pressure to the overall lift and moment becomes negligible at high frequencies, as the positive and negative portions of the receding short-wave pressure contributions then tend to cancel. At transonic speeds, complications also arise from shock waves impinging on the moving wing surface, and the boundary conditions that apply on an unsteadily moving shock wave are considered in the book.

Nowadays the standard engineering practice is to carry out transonic flow calculations directly on the computer using numerical techniques based on finite differences or finite volume and the like. Computer codes for both two- and three-dimensional unsteady transonic flow calculations are available and routinely used in industry for flutter predictions. Analytical treatments of the simplified equations presented in this monograph may nevertheless still be of value because of the physical insight gained through them. Also, the 'exact' solutions for special planforms provided may serve as useful reference solutions for validation of complicated computer codes. Many of the numerical methods developed for steady transonic flow also start from the formulation for an unsteady flow and seek the steady flow as the limit as $t \to \infty$, so that an understanding of transonic unsteady flow phenomena is of value for the steady flow problem as well.

A large number of papers on unsteady transonic flow have of course appeared in the literature since this monograph was originally published. For example, the comprehensive review by Borland (USAF AFFDL-TR-78-189, Vol. 1, Fluid Dynamics Lab., Wright-Patterson AFB, Ohio, 1979) lists more than 200 articles published between 1970 and 1979. Tijdeman and Seebass (*Ann. Rev. Fluid Mech.*, **12,** 1980) reviews the two-dimensional problem and also discusses the effects of viscosity. The author's own review article in Symposium Transsonicum II (ed. K. Oswatitsch, Springer Verlag, 1976) pays special attention to the propagation of acoustical waves in a nonuniform transonic flow and their importance for the related problem of the stability of a smoothly decelerating shock-free flow, a problem originally treated by Spee (NLR TR 69122 U, Amsterdam 1969). Many examples of unsteady transonic flow calculations for both two- and three-dimensional wings can be found in the aeronautical literature, for example in the AIAA Journal and the AIAA Journal of Aircraft.

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INTRODUCTION

In recent years a large amount of work has been expended on the study of aerodynamic forces on oscillating wings. These forces are needed for the investigation of the dynamic or aeroelastic stability of an airplane. Such problems have received increased attention with the advent of transonic and supersonic airplanes.

There are two reasons why the phenomenon of flutter has become more important as airplanes have surpassed sonic speed. Firstly, of course, the more slender shapes required for supersonic flight have made the airplanes more flexible and therefore more prone to aeroelastic instabilities. Secondly, the aerodynamic forces at transonic speeds are such as to favor the occurrence of flutter, so that the critical speed usually has a minimum at or near $M = 1$. For an excellent discussion of transonic flutter problems the reader is referred to a paper by Garrick (Ref. 18).

The affinity to flutter in the transonic speed range may be explained from well-known aerodynamic properties of transonic flow. The lifting pressures due to a given amount of deflection are known to be at maximum at or near $M = 1$ (cf. the lift curve slope). This must lower the flutter velocity since an increase of all aerodynamic derivatives by the same amount has the same effect as, for example, increasing the air density. However, an effect which is probably even more important is that due to the large phase lags between motion and unsteady air pressures that occur at transonic speeds. When an object travels at a speed near that of sound the flow perturbations created move forward at about the same speed as the object itself. Hence there will be a slow accumulation of disturbances and, if the flow is given sufficient time to build up, the well-known typical transonic non-linearities will occur. Since a pressure wave set up at a point will spend a long time before it travels off the object, it is evident that large and possibly destabilizing phase differences between motion and pressure can easily be created. These are directly responsible for one-degree-of-freedom flutter of control surfaces (control surface "buzz") and also for the low or negative damping in pitch sometimes encountered by tailless aircraft of high or medium aspect ratios.

Because the computation of aerodynamic forces on oscillating three-dimensional wings is so complicated, even on the basis of linearized theory, most flutter calculations in industry today are made by use of aerodynamic derivatives obtained from two-dimensional (strip theory) analysis. For high supersonic Mach numbers or for large-aspect-ratio wings in subsonic flow this procedure may be justified. At transonic speeds, however, cross-flow effects are always very large as is well known in the case of steady flow. Therefore, the use of strip theory can lead to large errors in the computed flutter speed near $M = 1$. For example, a strip-theory flutter calculation of a configuration involving a

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control surface will always show one-degree-of-freedom flutter of the control surface at transonic speeds unless the hinge stiffness is very high or artificial damping is provided. As shown in Chapter 7, however, the three-dimensional theory, on the contrary, gives positive hinge moment damping at $M = 1$ for rectangular control surfaces of aspect ratio less than 3.5.

Since there is no prospect of integrating the full non-linear transonic equations of fluid motion, any three-dimensional lifting-surface theory would have to be based on the linearized equations. For sub- or super-sonic flow linearized theory is known to hold well for thin wings. For transonic flow, however, the above-mentioned non-linear accumulation of disturbances precludes the use of linearized theory in the steady, non-lifting case no matter how thin the wing is. In the oscillating wing case the situation is somewhat better, though. Firstly, one is concerned with the lifting part of the flow. According to the transonic equivalence law, Ref. 54, linearized theory is capable of describing the steady lifting flow for wings of low aspect ratio, and wind tunnel experiments do, indeed, confirm fairly well the predictions of the theory at least for wings with swept leading edges. Secondly, if the wing oscillates rapidly the non-linear disturbance accumulation will not have time to develop and hence the linearized equations will be applicable. The conditions necessary for this to apply are discussed in Chapter 1.

The main part of the present monograph is devoted to the study of lifting surface theories. Most of this is based on recent theoretical work by the writer (Refs. 30–39) but available investigations by other workers in the field have also been included for completeness. The writer's methods have been developed with the aim of covering the reduced frequencies of interest in flutter research. For the sake of simplicity, however, most numerical results given are those for stability derivatives, i.e. for rigid-body wing motions, but evaluated at frequencies of interest in flutter work. One exception to this is Chapter 5 on wing-body interference at sonic speed in which only results for stability derivatives at low reduced frequencies are given.

No comprehensive treatment of the present subject would be complete without reference to experimental results. In Chapter 11 material available in the open literature is collected on the subject for cases where direct comparisons with theory are possible.

The writer realizes that there are transonic unsteady-flow problems that merit attention other than the oscillating wing problem and which have been left out in this monograph. In principle, the oscillating case can be considered as the Fourier transform with respect to time of an arbitrary time dependent motion so that it is possible to make use of the given results for any type of motion. However, such a method is seldom practical. References dealing with transient phenomena at transonic speeds can be found, for example, in Miles' recent book (Ref. 49).

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