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13. ABSTRACT (Maximum 200 words)

The present work was mainly concerned with the fundamental processes that occur on a two-dimensional airfoil undergoing a maneuver which normally produces dynamic stall. The results show that, in a high Reynolds number flow, a separation process initiates in the leading-edge region once a certain critical angle of attack is exceeded (for a thin airfoil). Much of the work has concentrated on the leading edge region, since a general analysis incorporating the effects of the airfoil wake has shown that for a thin airfoil at angle of attack, the most important separation effects occur in the leading edge region. A number of possible control processes have been considered on a computational basis of the leading-edge region, including selective localized suction and a small moveable portion of the wall. These indicate that the onset of separation can be inhibited at angles of attack beyond the critical value leading to significant increases in lift.

Extensive computations have also been carried out for unsteady three dimensional boundary layers induced by vortex motion. The results show that complex separation events occur that involve complicated topologies and multiple critical points. A Lagrangian method has been developed which computes the solution at high Reynolds number up to the evolution of a separation singularity.

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Executive Summary

The objective of this research was to identify the principal cause and effect relationships in dynamic stall that occurs on airfoils at large Reynolds numbers, as well as possible means for controlling the onset of the event. Extensive work has been carried out to investigate the leading-edge region of a general airfoil shape that is set into motion having an increasing angle of attack to the mainstream flow. It has been found that the primary dynamic stall vortex initiates at high Reynolds number through an unsteady separation process that occurs near the leading-edge. The primary stall vortex then eventually provokes separation of the surface layer near mid-chord, in a process that leads to full stall. The influence of altering the pitch rate on the airfoil as a control means has been investigated and has been found to significantly influence the separation process and, hence, the formation of the dynamic stall vortex.

The influence of suction and/or a moving portion of the surface have been considered as well; it has been found that significant increases in lift are possible with this type of control. As a full airfoil is pitched up from rest, a thin wake emanates from the sharp trailing edge. A general procedure to determine the influence of this developing wake on the flow around the airfoil was developed; this work includes incorporating a calculation procedure for the unsteady boundary layer over the entire surface of the thin airfoil.

Supplementary work on this contract has also been carried out with Professor Anatoly Ruban on the stability of compressible flow near a compression ramp, as well as the effects of strong wall cooling on hypersonic boundary layer separation. The work on supersonic instability has revealed the presence of an absolute instability at relatively modest angles for a compression ramp. The work on hypersonic boundary layers has shown that the influence of wall cooling can be extremely effective at suppressing both instabilities and boundary-layer separation.

Overview

The onset of dynamic stall has been identified with a process of unsteady separation that develops near the leading-edge of an airfoil shape. Results have been obtained for an airfoil which is abruptly changed to a new angle of attack, and also for an airfoil which is pitched up gradually to a new angle of attack. General results for the time of separation for an arbitrary thin airfoil shape have been obtained, which predict the time and location of separation in the leading-edge region over a range of pitching rates. The influence of reversing the pitching rate on the separation process has been examined and found, in general, to weaken the separation effect, but not eliminate it. A general theory to account for the influence of the wake on a maneuvering airfoil has been developed, and work is continuing to determine the influence of this wake on separation processes over a complete two-dimensional airfoil undergoing an unsteady maneuver. This work forms a portion of the Ph.D. thesis work of K. Zalutsky.

The feasibility of employing suction and/or a moving portion of the airfoil surface as a separation control device has been examined. The objective is to consider turning on the control at a critical phase of the airfoil cycle and at a critical location on the airfoil surface to determine what is the minimum level of control that can be effective in delaying separation. The results indicate that judicious use of a limited amount of suction (and/or a moving surface) can have a dramatic effect on the separation characteristics, delaying separation up to three times the angle of attack (as compared to an airfoil without control); hence up to three times the lift appears to be possible before a catastrophic separation can occur. This work is a portion of the Ph.D. thesis work of C. Y. Kim.

Vortex motion in three dimensions is commonplace once such vortices are observed to provoke a viscous-inviscid interaction with viscous boundary layers on solid walls. The development of unsteady separation in three-dimensional boundary layers at high Reynolds number is very complex and poorly understood. In the present work three-dimensional unsteady solutions have been obtained for a vortex-like external flow near a solid wall both in Eulerian and Lagrangian coordinates. The development of a three-dimensional Lagrangian numerical procedure has been especially challenging. Work is still in progress to refine this computational algorithm and to visualize the complex evolving boundary-layer phenomena. A series of completed calculations shows that prior to separation, multiple critically points occur in the flow giving rise to complex, evolving flow topologies. This work forms a portion of the Ph.D. thesis of C. Y. Kim.

Extensive work has been carried out to determine the stability characteristics and influence of a cold wall in separation induced by a shockwave boundary-layer interaction in compressible high-speed flow. At supersonic speeds, and under normal wall conditions, the separated flow region is found to be unstable. Wall cooling has been found to substantially inhibit separation on a cold wall, as well as lead to stabilization of the flow.

<u>Accomplishments/New Findings</u>

(1) Through a series of new calculations and theoretical developments, it has been demonstrated that the onset of dynamic stall occurs in the leading edge region of a thin airfoil at high Reynolds numbers. These results have shown that this is the case for an airfoil whose angle of attack is either abruptly changed to a new value or whose angle of attack changes continuously as the airfoil is pitched up. These results indicate that attempts at control of the dynamic stall process would best be concentrated in the leading-edge region of the airfoil.

(2) General results for the time and location of separation for an airfoil whose angle of attack increases linearly with time have been obtained. The results pertain to any thin airfoil. The influence of decreasing the angle of attack once separation is detected has been considered on a computational basis. It has been demonstrated that it is difficult to inhibit the separation process once it initiates. However, if the angle of attack is held constant at a certain stage or decreased, the strength of the separation

phenomena (and presumably the strength of the resulting primary stall vortex) can be weakened significantly.

(3) As an airfoil undergoes an unsteady maneuver, the wake of the airfoil develops from the trailing-edge region and changes with time. A general theory for the influence of this wake on the inviscid flow around the airfoil has been used to evaluate the unsteady boundary-layer development along the entire surface of the airfoil. The results confirm that the leading edge region is the most important concerning the onset of dynamic stall.

(4) Extensive calculations have been carried out to determine the influence of suction through a finite slot on the airfoil surface, as well as introducing a moving portion of the wall, the control is only necessary during a critical part of the separation process. The results indicate that under certain circumstances the angle of attack (and hence the lift) can be tripled before separation occurs.

(5) Calculated results for vortex-induced separation in three-dimensional boundary layers reveal the presence of multiple critical points in a complex evolving flow. The separation process involves the evolution of focused three-dimensional plumes of vorticity, as predicted by modern theories of the event. The present calculation method is one of the first successful applications of a Lagrangian method to a fully three-dimensional unsteady flow.

(6) It has been demonstrated for the first time that supersonic boundary layer flow on a compression ramp can develop an absolute instability. This instability is associated with the reverse flow region in the corner of the compression ramp and it can be expected when the ramp angle exceeds relatively modest values. The instability is novel and of the absolute type; it develops as a standing wave packet near the reverse flow region in the corner. This suggests that the small separation bubbles may be potential sites for abrupt transition to turbulence.

Personnel Supported

Professor J. D. A. Walker
Professor A. I. Ruban
Professor Q. Li
Michael P. Johnson (Graduate Research Assistant)
Konstantin Zalutsky (Graduate Research Assistant)
C.-Y. Kim (Graduate Research Assistant)

Publications

A. T. Degani, Q. Li and J. D. A. Walker 1994 "Unsteady Separation from the Leading Edge of an Airfoil", AIAA Paper 94-2338, Colorado Springs, Colorado, June, 1994.

M. P. Johnson 1994 "Unsteady Boundary-Layer Separation from the Leading Edge of an Airfoil", M.Sc. Thesis, Lehigh University.

R. M. Kerimbekov, A. I. Ruban and J. D. A. Walker 1994 "Hypersonic Boundary-Layer Separation on a Cold Wall", *Journal of Fluid Mechanics*, Vol. 274, pp. 163-195.

K. W. Cassel, A. I. Ruban and J. D. A. Walker 1995 "An Instability in Supersonic Boundary-Layer Flow Over a Compression Ramp", *Journal of Fluid Mechanics*, Vol. 300, pp. 265-285.

A. T. Degani, Q. Li and J. D. A. Walker 1996 "Unsteady Separation from the Leading Edge of an Airfoil", *Physics of Fluids*, Vol. 8, pp. 704-714.

M. P. Johnson and J. D. A. Walker 1997 "Separation on a Pitching Airfoil at High Reynolds Number", in review.

C. Y. Kim and J. D. A. Walker 1997 "Separation Control on a Maneuvering Airfoil", in review.

Interactions

J. D. A. Walker, "Unsteady Separation from the Leading Edge of an Airfoil", 25th AIAA Fluid Dynamics Conference, Colorado Springs, June 20-23, 1994

J. D. A. Walker, "Control of Unsteady Separation on a Pitching Airfoil", APS Meeting, Division of Fluid Dynamics, Atlanta, Georgia, November 20-23, 1994.

J. D. A. Walker, "Aspects of Unsteady Separation", City College, New York, October 4, 1995.

New Discoveries, Inventions, or Patent Disclosures

None

Honors/Awards

Honor/Award: Fellow, American Physical Society — Year Received: 1991
Honor/Award Recipient(s): J. David A. Walker
Awarding Organization: American Physical Society

Honor/Award: Associate Fellow, AIAA — Year Received: 1993
Honor/Award Recipient: J. David A. Walker
Awarding Organization: American Institute of Aeronautics and Astronautics

Honor/Award: Alexander von Humboldt Senior Scientist Year Received: 1994
Honor/Award Recipient: J. David A. Walker
Awarding Organization: Alexander von Humboldt Foundation

Honor/Award: Chairman, AIAA Fluid Dynamics Technical Committee Year Received: 1993-1996
Honor/Award Recipient: J. David A. Walker
Awarding Organization: American Institute of Aeronautics and Astronautics