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Effect of Initial Acceleration on the Development of the Flow Field of an Airfoil Pitching at Constant Rate

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Introduction

We present results from a series of experiments where an airfoil is pitched at constant rate from 0 to 60 degrees angle of attack. It is well documented (e.g. references 1-4) that the dynamic stall behavior of such an airfoil strongly depends on the nondimensional pitch rate $K = \dot{\alpha}C/(2U_\infty)$, where C is the chord, $\dot{\alpha}$ the constant pitch rate, and U_∞ the free stream speed. In reality, the actual motion of the airfoil deviates from the ideal ramp due to the finite acceleration and deceleration periods imposed by the damping of drive system and response characteristics of the airfoil (see Figure 1). It is possible that the pitch rate alone may not suffice in describing the flow and that the details of the motion trajectory before achieving a desired constant pitch rate may also affect the processes involved in the dynamic stall phenomenon. We note that the flux of vorticity for attached flow at the airfoil surface, $(\partial\omega/\partial y)_s$, is given by [5]

$$\nu \left(\frac{\partial \omega}{\partial y}\right)_s = \frac{1}{\rho}\left(\frac{\partial p}{\partial x}\right)_s + \frac{\partial U_s}{\partial t}$$

The details of the acceleration phase may, therefore, modify the surface vorticity flux by altering the time-varying surface pressure gradient $(\partial p/\partial x)_s$, and also directly through the surface acceleration term $(\partial U_s/\partial t)$.

To our knowledge, a systematic investigation of the effects of acceleration/deceleration periods on dynamic stall characteristics of nominally constant pitch rate motions has not been reported. Studying these effects should give further insight into the processes of vorticity generation and accumulation on unsteady surfaces. The study is expected to also provide clues to how these processes may be modified/controlled by the deliberate shaping of the pitch motion trajectory. Practical applications of the study are to be noted since in real devices infinite (i.e. extremely large) acceleration/deceleration is neither possible nor desirable.

In the present experiments, we investigate the effects of acceleration and deceleration periods by systematically varying the acceleration magnitude and its duration through the initial acceleration phase to constant pitch rate. The magnitude and duration of deceleration needed to bring the airfoil motion to rest are similarly controlled. Our preliminary results indicate that the elapsed time (from start of motion) until the first indication of leading edge separation is affected by the acceleration period; the airfoil angle of attack where leading edge separation occurs is, however, practically unchanged. Many of the details of the dynamic stall vortex formation and its interactions appear to be also insensitive to the details of the acceleration period for the range of parameters studied so far. We provide a scaling argument for the acceleration period which may explain the insensitivity of the angle of attack for leading edge separation observed here. This scaling further suggests the conditions under which acceleration effects may become important.

Experimental Setup and Results

The experiments were performed in a water tunnel with a NACA 0012 airfoil (chord length $C = 8$ cm) pivoted about the 1/4-chord point. For the results described here, the free stream speed was set to $U_\infty = 10$ cm/s resulting in a chord Reynolds number of 8000. A DC servo motor in conjunction with a digital servo controller were used to pitch the airfoil. A schematic of the type of motion considered is shown in Figure 1. The airfoil starts at zero angle of attack, reaches the desired constant pitch rate of $\dot{\alpha}$ during an acceleration period of T_a, and stops at the final angle of attack of 60 degrees through a deceleration period of T_d. We characterize the pitch trajectory by the usual nondimensional pitch rate, K, and the parameter $e = 0.5(T_a + T_d)/T_c$, where T_c is the "ideal" constant pitch rate time scale needed for the motion. The acceleration parameter e gives an indication of the fraction of the motion time used for acceleration/deceleration. The magnitudes of the acceleration and deceleration were the same for the present results so that $T_a = T_d$ and $e = T_d/T_c$.

We present flow visualization results for the case $K = 0.4$ and different values of e. The actual pitch trajectories recorded during the experiment for the two cases of $e = 0.6$ and 0.15 are shown for comparison in Figure 2. The evolution of the flow field for $K = 0.4$, $e = 0.6$ is illustrated in Figure 3. For each picture, the elapsed time from the start of the motion and the instantaneous angle of attack are indicated. This sequence of pictures was obtained using the Hydrogen-bubble technique and laser sheet illumination at the airfoil mid-span location. Images were sensed by a CCD camera at a rate of 60 fields/sec with an exposure time of 2 msec/field and acquired by a digital image acquisition system into hard disk in real time.

Figure 3 shows that the first visual indication of separation and vortex formation near the leading edge occurs between (t = 0.73 s, α = 27 deg.) and (t = 0.83 s, α = 32 deg.). The actual elapsed time and angle of attack were determined to be (t = 0.80 s, α = 31 deg.) after close inspection of the image sequence versus time. There are many interesting features in the flow development shown in Figure 3. Note, for example, the number of vortices formed and their interaction and also the upstream (reversed) flow near the airfoil surface at (t = 2.17, 2.37 s).

Reducing the acceleration period by a factor of four to e = 0.15 resulted in the flow development shown in Figure 4. The first visual appearance of leading edge separation and vortex formation was determined to be at (t = 0.64 s, α = 32 deg.). In fact many of the details of flow development are nearly the same in Figures 3 and 4 except for a time shift between the occurrence of the events. Reducing the value of e by another factor of four to 0.037 confirmed the observation that while the elapsed time for leading edge separation and vortex formation is affected by e, the angle of attack where this occurs remains unchanged. Similar conclusion was reached when the two cases of e = 0.037, 0.15 at a reduced frequency of K = 0.2 were compared. We should note that our results and conclusions only address the timing of the various events in the flow field development. We do not know, at this time, how the vorticity flux into the separated zone, the circulation of the dynamic stall vortex, and forces on the airfoil are affected as we change the acceleration period.

We now present a scaling argument which suggests that our lowest acceleration corresponds to a time scale that may be too fast for the flow to respond to. For an airfoil reaching a constant pitch rate $\dot{\alpha}$ at a constant acceleration $\ddot{\alpha}$, the acceleration time scale T_a can be defined as

$$T_a = \frac{\dot{\alpha}}{\ddot{\alpha}}$$

The flow convection time scale T_{flow} corresponds to the time it takes for the flow to travel the length of the chord and can be written as

$$T_{flow} = \frac{C}{2U_\infty}$$

A nondimensional acceleration time scale K_{acc} can now be defined and simplified as follows

$$K_{acc} = \frac{T_{flow}}{T_a} = \frac{K}{\alpha_{\max}\, e}$$

where K is the reduced frequency, α_{max} the maximum angle of attack, and e the acceleration parameter defined earlier.

Carta [6] has shown that unsteady inviscid effects lead to a reduction of the chordwise pressure gradient which he proposed as the mechanism responsible for dynamic stall delay. These ideas were later extended by McCroskey [7] who showed that unsteady attenuation of the inviscid pressure gradient near the leading edge could explain the dynamic delay in laminar boundary-layer separation. Carta's results, which were derived for oscillating airfoils, show that for high enough reduced frequencies, $2\pi fC/(2U_\infty) > 0.5$, the unsteady reduction of the inviscid pressure gradient reaches an asymptotic value. We interpret this to mean that if the motion time scale is short enough relative to the convection time scale, the inviscid pressure gradient over the airfoil reaches an asymptotic state. We, therefore, suggest that for our experiment the condition $K_{acc} > 0.5$ corresponds to a "frozen" inviscid pressure gradient. According to McCroskey's [7] results, we expect laminar separation to be mostly dictated by the inviscid pressure gradient with little influence from unsteady boundary-layer response.

In all the cases we have presented here, the value of K_{acc} exceeds 0.6. Based on the argument above, for all three cases of $e = 0.6, 0.15, 0.037$, the airfoil boundary layer is exposed to the same "frozen" inviscid pressure gradient. This may be the reason why all three cases show the first indication of leading edge separation at the same angle of attack. The scaling argument also suggests that at low values of K_{acc} the effects of acceleration period may become important. Since the maximum value of e is unity, low values of reduced frequency K would be required for this to happen.

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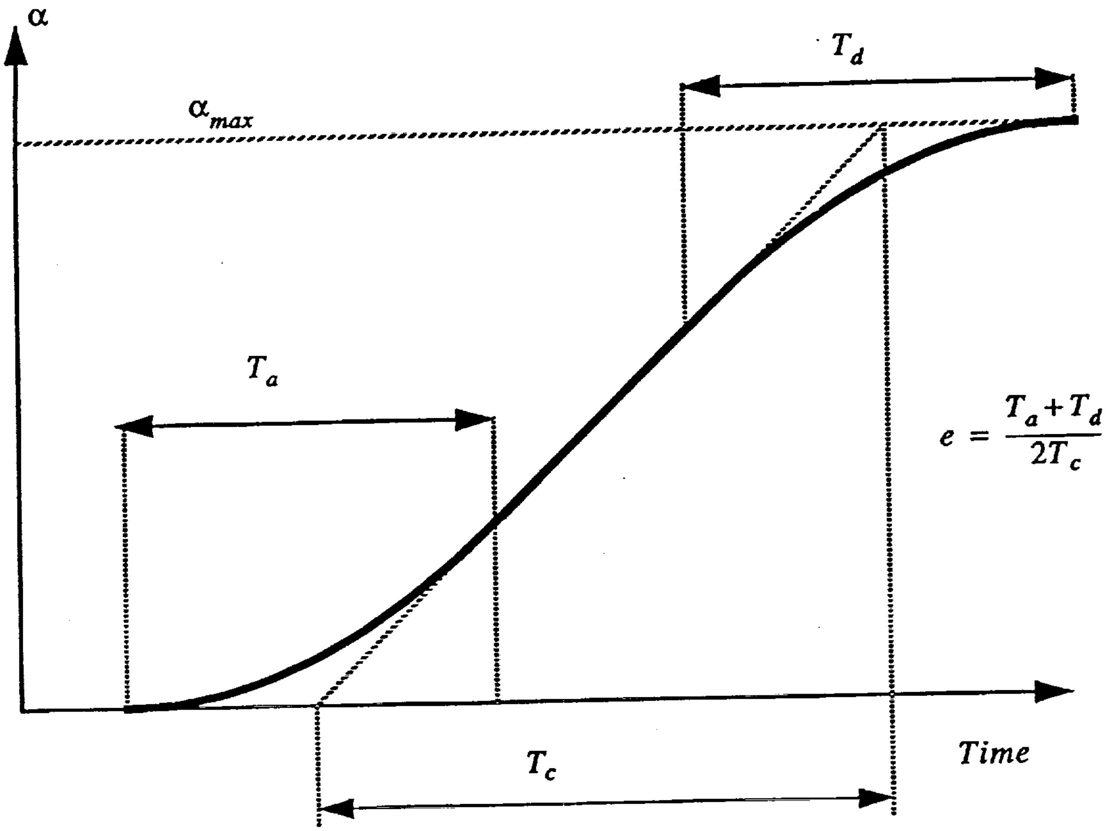


Figure 1. Constant pitch rate motion with finite acceleration and deceleration.

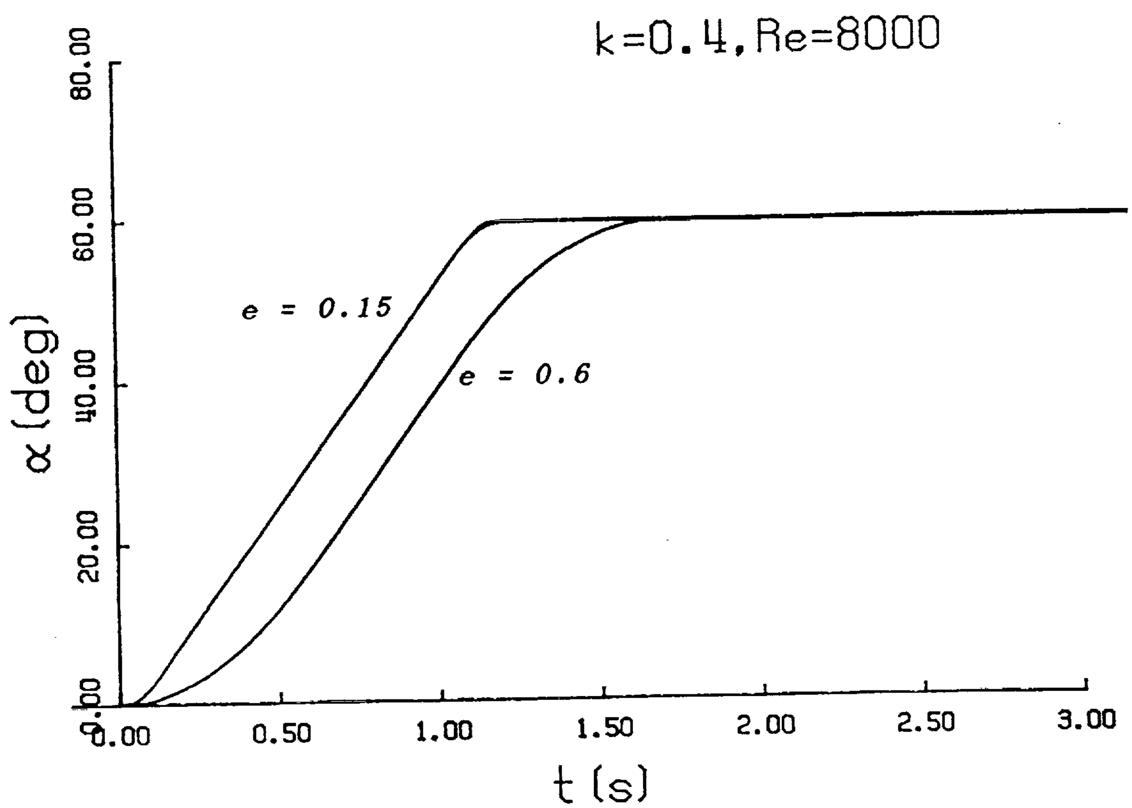


Figure 2. Time history of the airfoil pitch angle recorded during the experiment. Both trajectories reach the same constant pitch rate but with different constant accelerations.

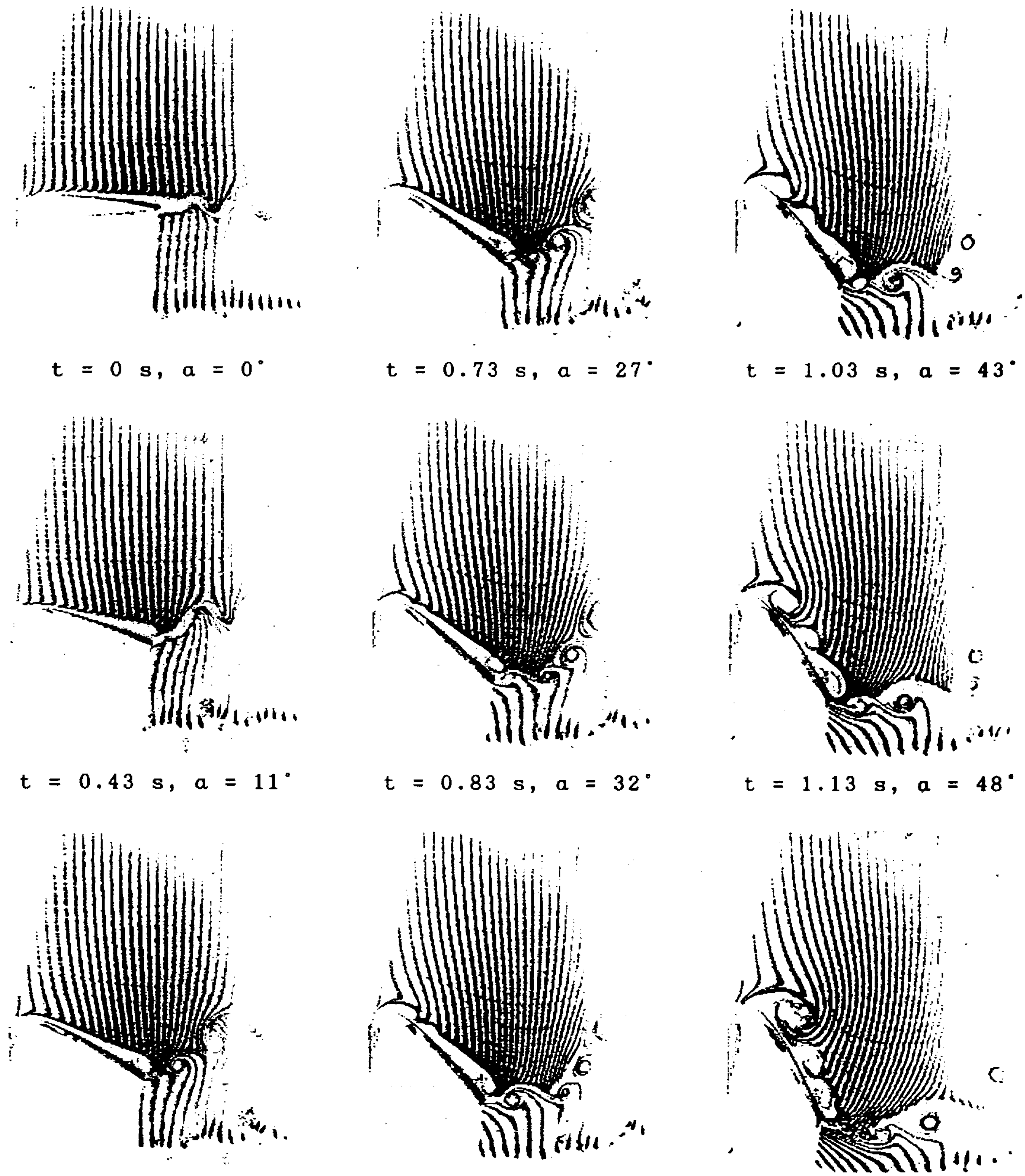


Figure 3. Evolution of the flow field on the airfoil suction side. (K = 0.4, e = 0.6)

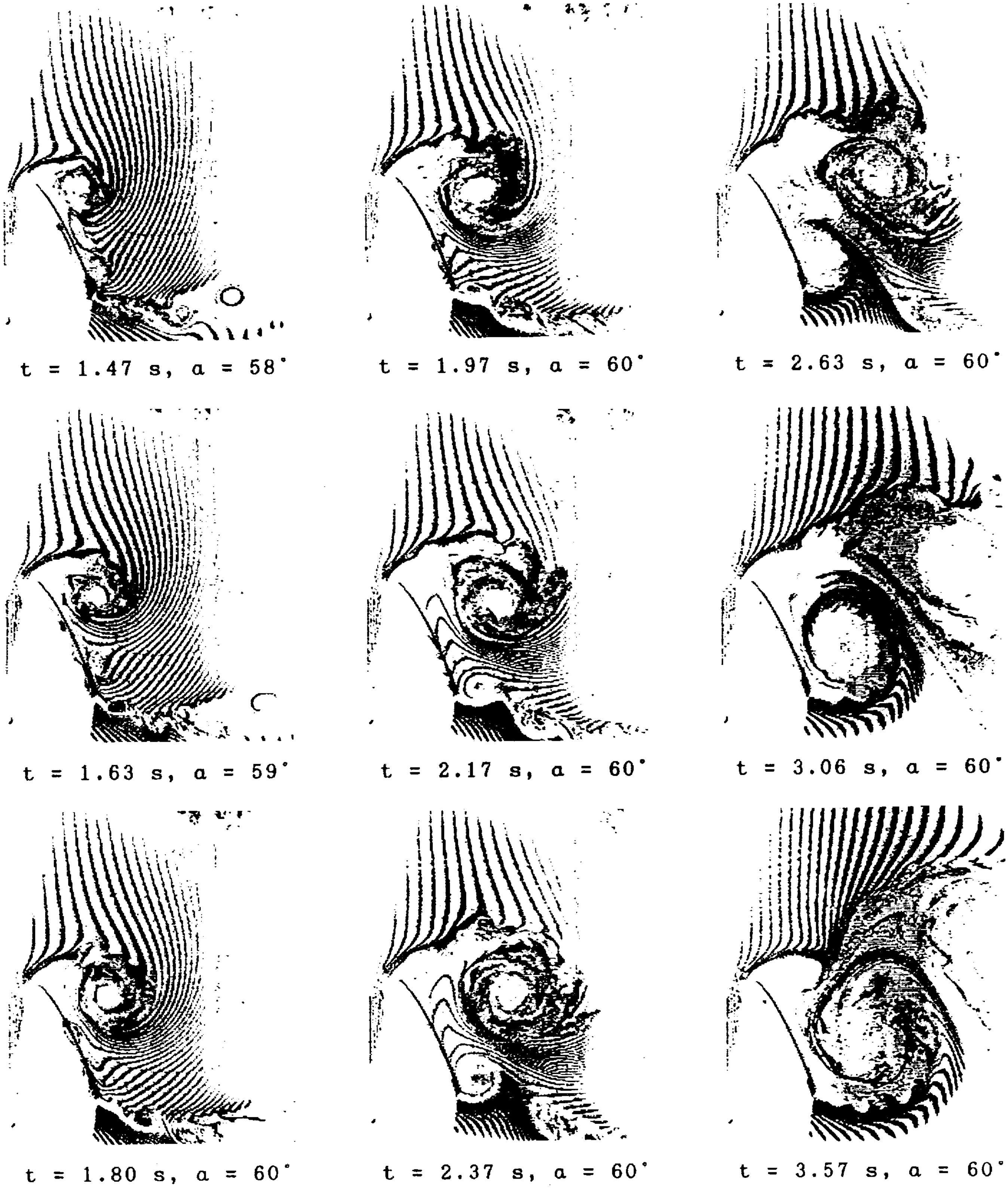


Figure 3. Continued.

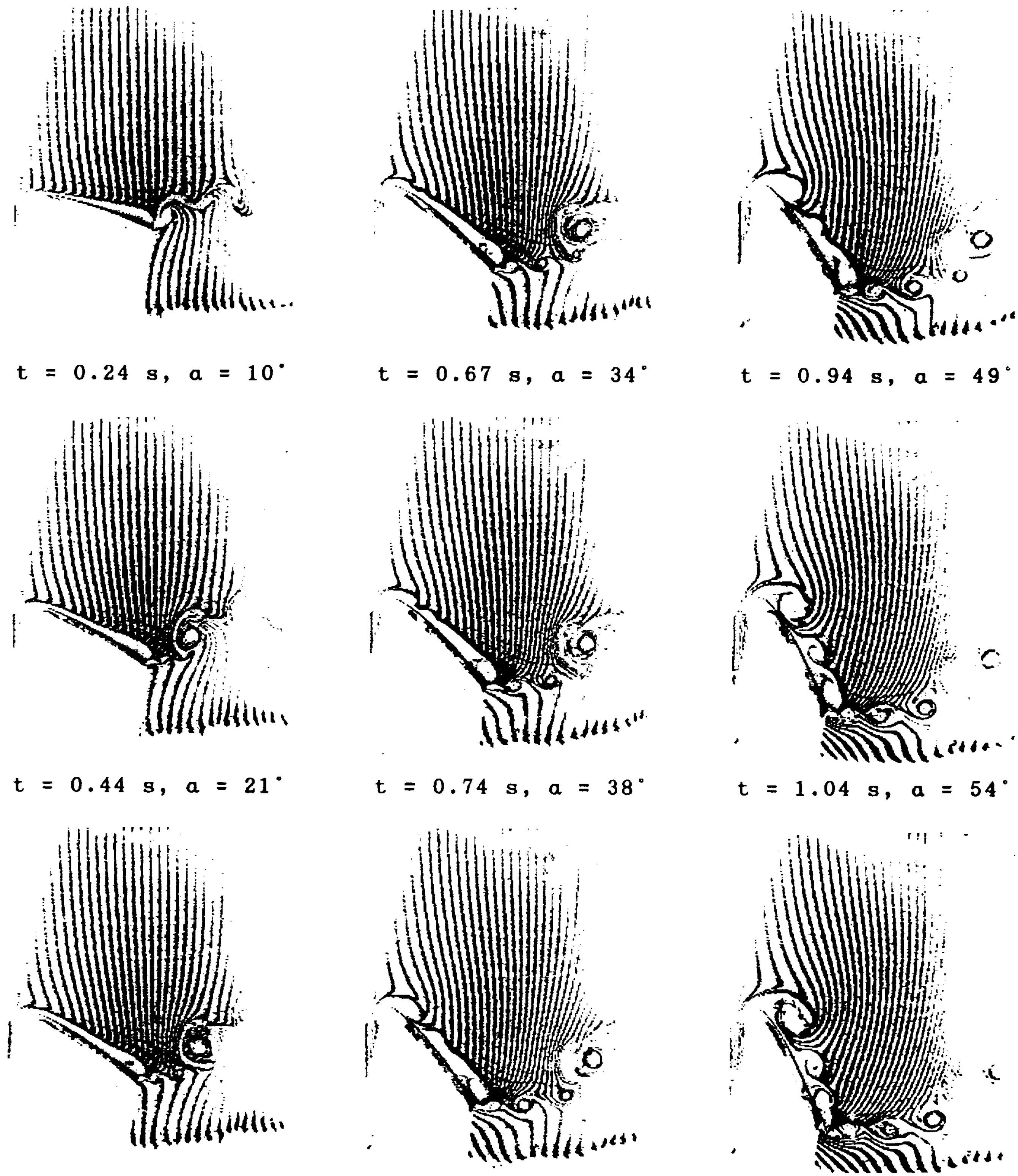
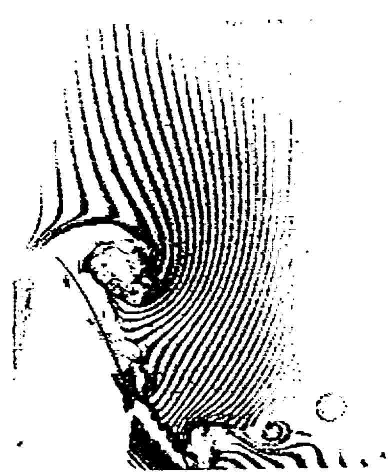


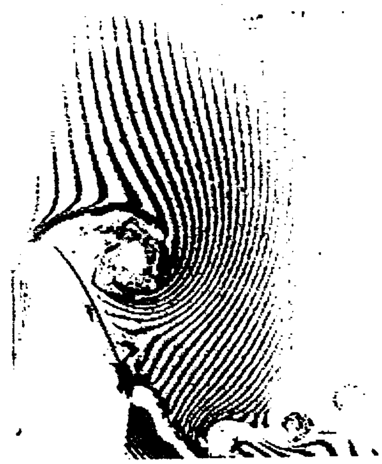
Figure 4. Evolution of the flow field on the airfoil suction side. ($K = 0.4$, $e = 0.15$)

t = 1.21 s, a = 60°

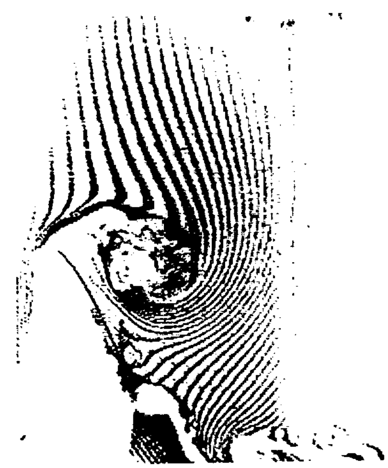
t = 1.27 s, a = 60°



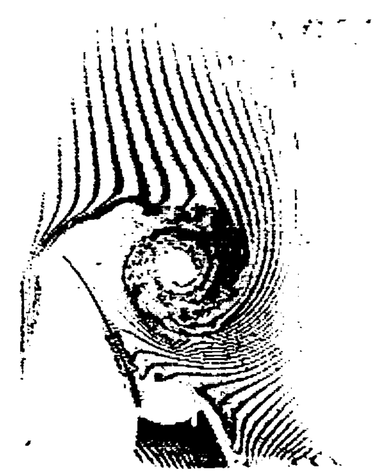
t = 1.34 s, a = 60°



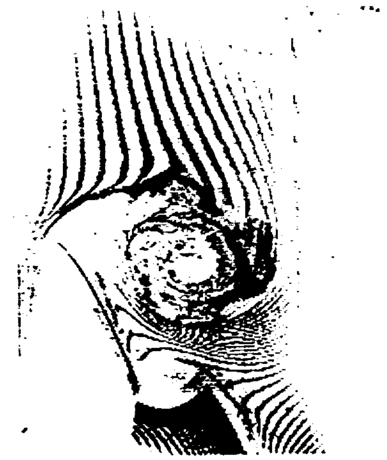
t = 1.44 s, a = 60°



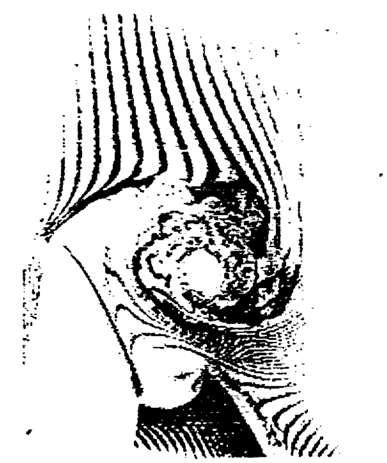
t = 1.57 s, a = 60°



t = 1.84 s, a = 60°



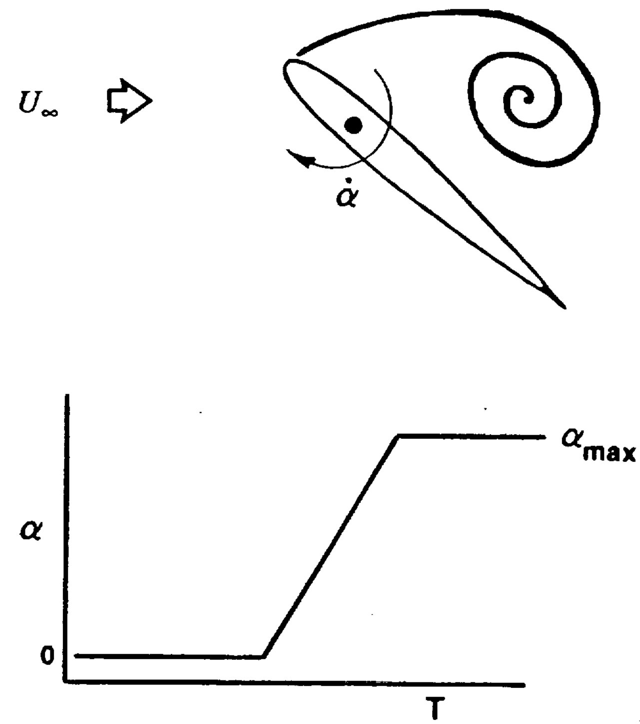
t = 1.97 s, a = 60°



t = 2.11 s, a = 60°

t = 2.27 s, a = 60°

Figure 4. Continued.



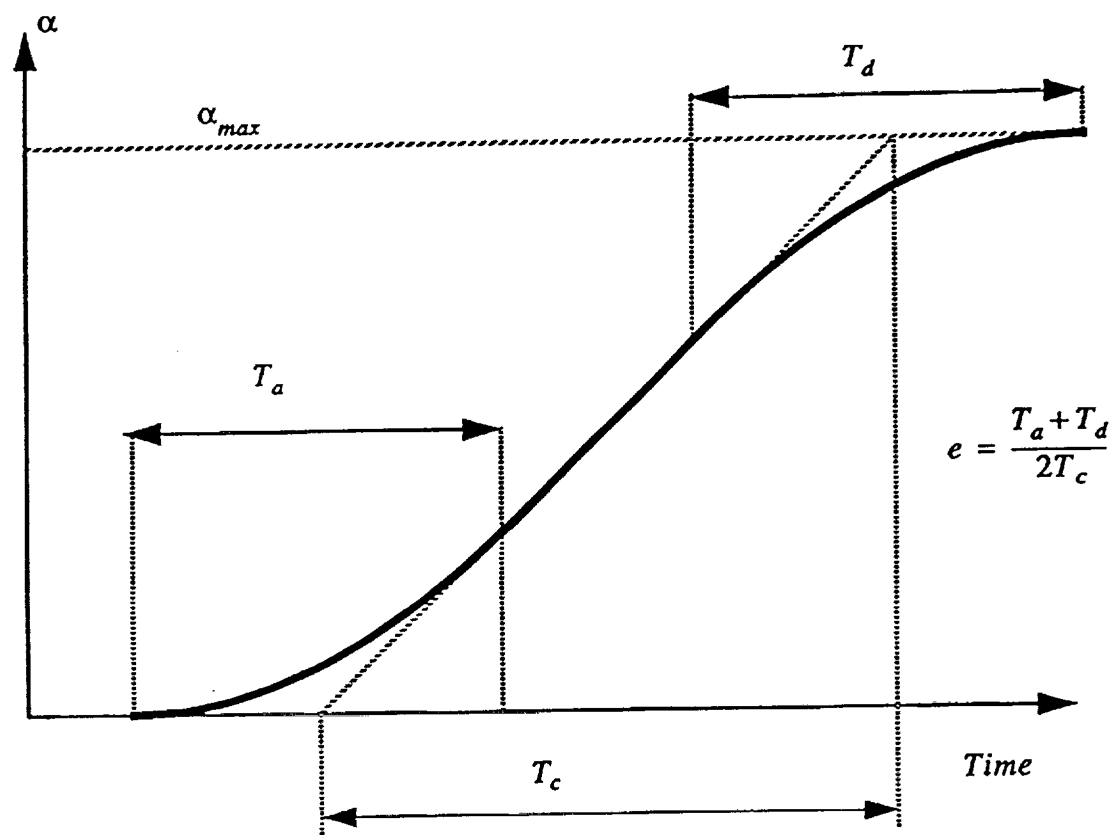
Schematic of constant pitch rate motion.

$$\text{Nondimensional pitch rate } K = \frac{\dot{\alpha} C}{2U_\infty}$$

In reality, the actual motion of the airfoil deviates from the ideal ramp due to the finite acceleration and deceleration periods imposed by the damping of drive system and response characteristics of the airfoil. The flux of vorticity for attached flow at the airfoil surface, $(\partial\omega/\partial y)_s$, is given by

$$\nu \left(\frac{\partial\omega}{\partial y}\right)_s = \frac{1}{\rho}\left(\frac{\partial p}{\partial x}\right)_s + \frac{\partial U_s}{\partial t}$$

The details of the acceleration phase may, therefore, modify the surface vorticity flux by altering the time-varying surface pressure gradient $(\partial p/\partial x)_s$, and also directly through the surface acceleration term $(\partial U_s/\partial t)$.



Constant pitch rate motion with finite acceleration and deceleration.

Experimental Setup

Airfoil	NACA 0012
Chord length	C = 8 cm
Pitch axis	1/4-chord
Free stream speed	U_∞ = 10 cm/s
Chord Reynolds number	8,000
Angle of attack variation	0 to 60 degrees
Nondimensional pitch rate	$K = 0.2$, $e = 0.15$, 0.037
	$K = 0.4$, $e = 0.6$, 0.15, 0.037

Flow visualization	Hydrogen-bubble technique
Illumination	Laser sheet at airfoil mid-span
Image sensing	CCD camera, 60 fields/s, 2 msec exp.
Image acquisition	Digitized in real-time into hard disk

Summary of Results

T_s = elapsed time for leading edge separation (sec).
α_s = angle of attack at leading edge separation (degrees).

	T_s	α_s
$K = 0.2$, $e = 0.15$	0.97	24
$K = 0.2$, $e = 0.037$	0.90	25
$K = 0.4$, $e = 0.6$	0.80	31
$K = 0.4$, $e = 0.15$	0.60	30
$K = 0.4$, $e = 0.037$	0.57	31

Flow convection time scale $T_{flow} = \frac{C}{2U_\infty}$

"Constant" pitch rate time scale $T_c = \frac{1}{\dot{\alpha}}$

Acceleration time scale $T_a = \frac{\dot{\alpha}}{\ddot{\alpha}}$

$$T_a = e\ T_c$$

Nondimensional pitch rate $K = \frac{T_{flow}}{T_c} = \frac{\dot{\alpha} C}{2U_\infty}$

Nondimensional acceleration time $K_{acc} = \frac{T_{flow}}{T_a} = \frac{K}{e}$

It is suggested that for large enough value of K_{acc} (i.e. $K_{acc} > 0.5$), the inviscid pressure gradient remains "frozen".

Conclusions

For the range of parameters studied, the finite acceleration period does not affect the angle of attack where leading edge separation occurs. Many of the details of dynamic stall vortex formation and its interactions appear to be also unaffected.

It is suggested that the value of $K_{acc} = K/e$ must be low enough before the finite acceleration period affects the flow development.

What Next ?

Test the proposed hypothesis by performing experiments at low values of K_{acc}.

Current results are qualitative and only address the timing of various events in the flow field development. Quantify the study by measuring the velocity field and determining the evolution of the circulation of the dynamic stall vortex.

REPORT ON THE WORKSHOP ON ANALYTICAL METHODS IN UNSTEADY SEPARATION

by

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A workshop centered around the use of analytical techniques in the computation of unsteady separated flow was held at the Ramada university Hotel and Conference Center on January 25 and 26, 1990. The meeting was sponsored by the U.S. Army Research Office in Research Triangle Park, North Carolina and was hosted by the Departments of Aeronautical and Astronautical Engineering and Mechanical Engineering of The Ohio State University. Meeting Co-Chairmen were R. J. Bodonyi and A. T. Conlisk. During this presentation the Workshop will be summarized and the main conclusions of the Workshop participants will be discussed.

The organization of such a workshop focused on the use of analytical methods in computing unsteady separated flows was motivated by the fact that until the last several years, little was known about the structure of large-scale unsteady separation. Indeed, in problems where the precise details of the unsteady separation boundary layer have been required, such as in the high Reynolds number flow past a bluff body where vortex shedding occurs, ad hoc procedures have generally been used to determine the separation point and the magnitude of the shed vorticity. Furthermore, the computation of accurate solutions to the full time-dependent Navier-Stokes equations at high Reynolds numbers, especially in three-dimensions, remains a difficult, if not impossible, task because of the many different scales of motion which can occur in such a large-scale separated flow. Given these difficulties, a natural question to ask is whether analytical techniques could profitably be used to reduce the amount of numerical computation required or to render untractable numerical problems tractable.

The first day of the workshop consisted of presentations by the invited speakers who were: Professor F. T. Smith, The Ohio State university and University College London, Professor O. R. Burggraf, The Ohio State University, Professor S.F. Shen, Cornell University, Professor J.D.A. Walker, Lehigh University, Dr. P. W. Duck, University of Manchester, Professor N. Riley, University of East Anglia, Professor S. J. Cowley, Imperial College of Science and Technology, and Professor L. Van Dommelen, Florida State University.. The second day consisted of a session wherein the other participants presented short discussions of their particular research in the area., This rather informal session was followed by a panel discussion led by the invited speakers and involving all participants ® unsteady separated flow problems involving eruptions of boundary layer fluid from the wall layer into the main flow. F. T. Smith discussed a possible structure for such a eruptive behavior in general terms within an interactive framework and he defined a sequence of stages of the flow leading to formation of a vortex structure all involving quite distinct length and time scales (all scaling with an inverse power of the Reynolds number); the numerical problems associated with computing such a flow are obvious. The other speakers addressed the above question through discussion of a particular problem. J.D.A. Walker focused on the emergence of a singularity in the boundary layer flow induced by a potential vortex; he discussed computations of the flow up to the singular time using a Lagrangian scheme. Professors Shen and Riley addressed the problem of high Reynolds number unsteady flow past a cylinder while Professor Burggraf addressed the problem of propagating stall in compressors. Professor Duck considered the problem of unsteady separation in a local region near a line of symmetry and Professors Cowley and Van Dommelen discussed the unsteady separation process in three-dimensions.

The main conclusions of the Workshop were that although we know much more about unsteady separation than we did say ten years ago, the numerical methods which must be employed to bridge the gap between small and large scale separation have not been developed. Indeed, while there seems little doubt that there does exist a singularity in the boundary layer equations at finite time in these unsteady separated flow problems, the concensus of the workshop was that considerable effort should be directed to developing methods by which computation of the flow may be effected beyond the singularity.

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13. ABSTRACT *(Maximum 200 words)*

This report contains the proceedings of a workshop held at NASA Ames Research Center in April 1990. This workshop was jointly organized by NASA, the Air Force Office of Scientific Research (AFOSR), and the Army Research Office (ARO), and was directed toward improved understanding of the physical processes that cause unsteady separation to occur. The proceedings contain the written contributions for the workshop, and include selected viewgraphs used in the various presentations.

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