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A study of compressibility effects on dynamic stall of rapidly pitching airfoils

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Results of recent experimental studies into the effect of compressibility on dynamic stall of oscillating airfoils are reviewed. Stroboscopic schlieren images of the strongly unsteady flow field are presented, showing the development of the dynamic stall vortex, and its progression down the airfoil. The effect of varying free-stream Mach number, and frequency of oscillation of the airfoil are demonstrated, and examples of local supersonic flow are presented including the presence of a shock near the leading edge of the airfoil.

1. Introduction

Dynamic pitching of helicopter airfoils past the static stall angle can produce significant increases in lift; unfortunately, it also produces very strong pitching moments that preclude use of the extra lift, and even results in complete avoidance of the flight conditions that could introduce the conditions known as "dynamic stall". Accurate modeling of the details of the unsteady separation and the dramatically changing flow field associated with dynamic stall of airfoils is one of the most challenging tasks for computational aerodynamicists today. The unsteady flow combines regions of highly viscous flow with large regions of unsteady potential flow. When the additional aspects of unsteady effects on transition, low-Reynolds-number turbulent flow, and compressibility are introduced into the modeling process, the task is well beyond the state of the art. However, it is just this task that is facing fluid dynamicists who try to model the rapidly changing flow that exists on model and full-scale helicopter rotor blades.

As can be seen in fig. 1, the dynamic delay of stall during rapid pitch-up past the static stall boundary is a complex case of inviscid and viscous interactions which include significant delay of boundary layer separation, regions of unsteady, reversed flow (with no disturbance of the outer flow field), and vorticity-dominated major interactions with the surrounding flow field, culminating in a dramatically increased maximum lift coefficient for a short period of time before complete flow separation occurs. This dynamic flow condition has been studied for a wide range of conditions (see Carr [1] for a detailed review).

Recent studies have identified compressibility as a primary factor in the stall development (see

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Chandrasekhara and Carr [2], Lorber and Carta [3], Visbal [4], Carr et al [5], and Fung and Carr [6]). The present effort is directed toward documentation of the unsteady compressible flow field on oscillating and ramp motion airfoils, so that better modeling of this flow field can be accomplished. This paper reviews the progress that has been made in this test program, and identifies several issues of significance in modeling of this interesting problem.

2. Research facility

As part of this continuing study of the influence of compressibility, the Compressible Dynamic Stall Facility (CDSF) was constructed at the NASA Ames Research Center Fluid Mechanics Laboratory (FML). The CDSF is an in-draft wind tunnel with a 25 cm × 35 cm test section, driven by the FML compressor, which is connected to the tunnel-exit throat (for details see

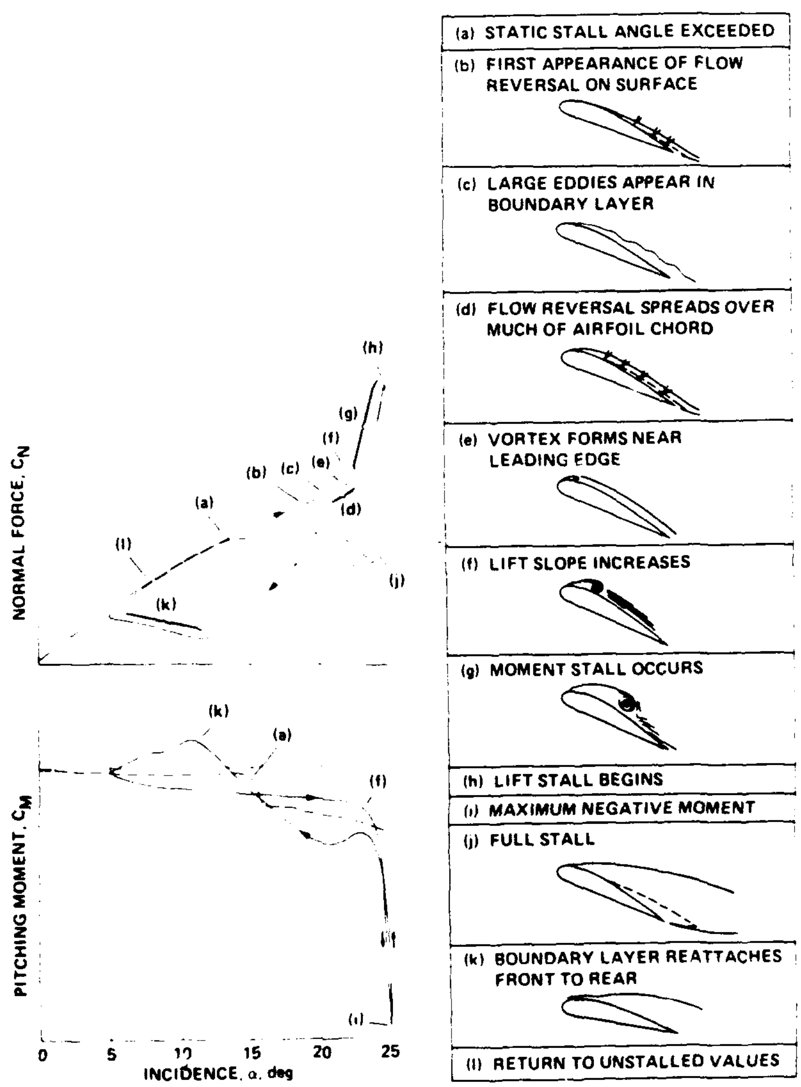

Fig. 1. Events of dynamic stall on NACA 0012 Airfoil.

Carr and Chandrasekhara [7]). The compressor maintains a vacuum sufficient to create sonic velocity at the throat which is located downstream of the test section. The tunnel velocity is controlled by varying the area of this throat; the velocity can range from $M = 0.10$ to $M = 0.50$.

The CDSF is unique in that it has been specifically designed for dynamic stall flow visualization at high speeds. Unobstructed viewing of the complete flow field surrounding the airfoil during unsteady motion is made possibly by mounting the test airfoil between optical glass windows which support the airfoil on pins embedded in the windows. The window–airfoil–window combination is driven in oscillating, or ramp motion by two separate, specially designed drive systems. For oscillating airfoil tests, the windows are driven in unison by a 4-bar, push-rod–flywheel system, pivoting about the quarter-chord point of the airfoil as shown in fig. 2; this system can produce sinusoidal oscillations with a maximum amplitude of 10° at up to 100 Hz over a mean angle of attack ranging from 0–15°. For ramp motion, the windows are driven by a hydraulic system mounted on the tunnel roof, which drives the window–airfoil–window combination through a bell-crank linkage; this drive can produce constant-pitch-rate motion from $\alpha = 0°$ to $60°$ at up to 3600 degrees/second.

Flow visualization and analysis is obtained using a variety of non-intrusive diagnostic systems including a stroboscopic schlieren system, laser velocimetry, holographic interferometry, and point-diffraction interferometry. The results presented here will be based mostly on stroboscopic schlieren. The schlieren system consists of a stroboscopic light source which can be triggered either manually or by computer control at any desired

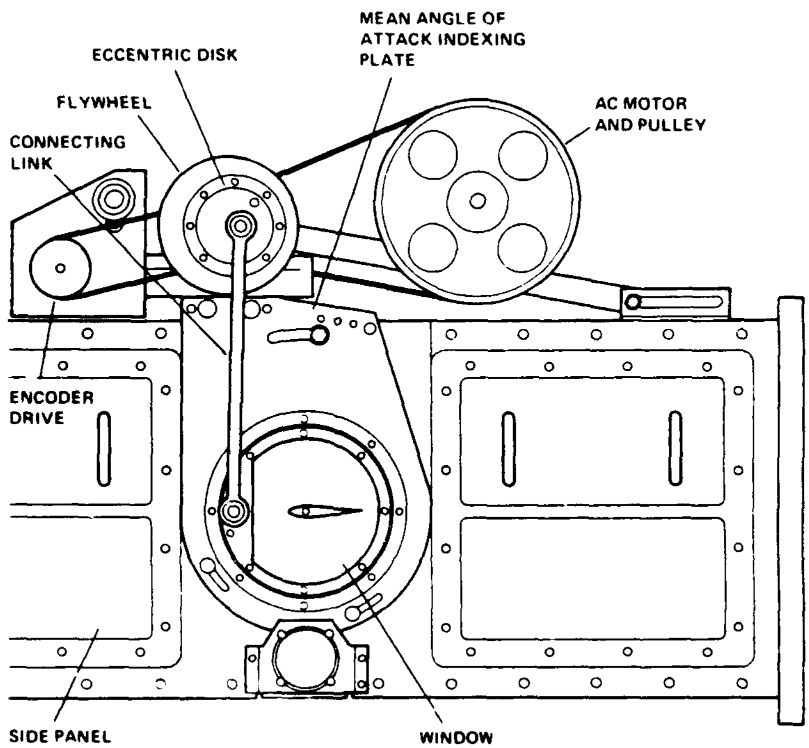

Fig. 2. Diagram of compressible dynamic stall facility.

point in the cycle; both single and repetitive triggering are available. The schlieren system uses two large spherical mirrors (45 cm in diameter with a 3 m focal length) located 3 m from the test section. This offers a very sensitive system, and has allowed visualization of shear layer characteristics, even in $M = 0.10$ flows.

Stroboscopic schlieren offers a new view of the character of unsteady flows. Each picture is a recording of the instantaneous density-gradient field, thus showing the imprint of the changing flow field at the instant the photograph is taken. This is in strong contrast to more conventional techniques such as smoke, which record particle pathlines that present an image of the flow history up to the time of the photograph, and thus give only a limited indication of the strength of the dynamic stall vortex at the time the photograph is taken.

3. Results and discussion

3.1. Effect of compressibility on stall angle

The location of the dynamic stall vortex has been measured from the schlieren photographs for a variety of conditions (Chandrasekhara and Carr [2]); fig. 3 shows that the influence of compressibility is first observed in the decrease of the angle at which the dynamic stall vortex appears on the airfoil. As can be seen, the path of the vortex is virtually unchanged for Mach numbers up to 0.25. However, for Mach numbers of 0.30 and above, there is a pronounced decrease in the angle at which the vortex starts to move down the airfoil and eventually into the wake.

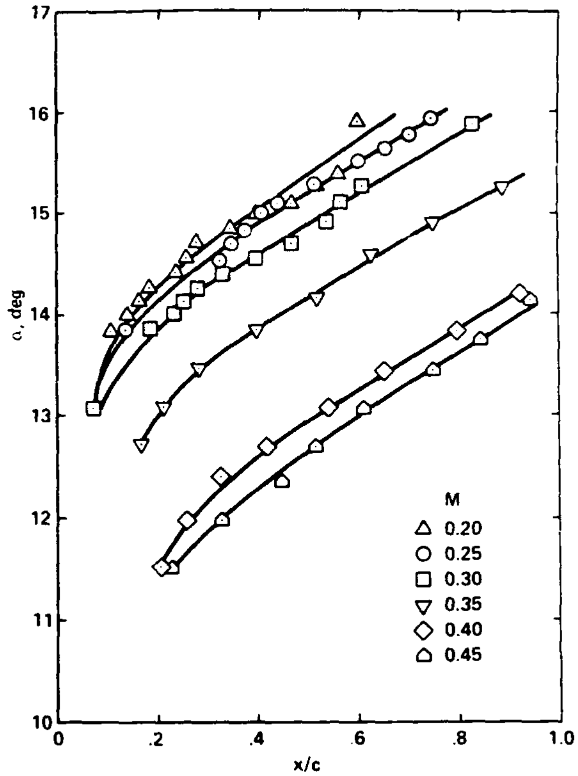

Fig. 3. Effect of Mach number on the position of dynamic stall vortex at $k = 0.05$.

3.2. Presence of embedded shocks on upper surface

As the free-stream velocity increases beyond $M = 0.20$, the flow on the leading edge exceeds sonic speed. This region of the upper surface of the oscillating airfoil can reach speeds sufficient to induce shocks on the surface, even though the free-stream velocity is fully subsonic. We have now verified (fig. 4) the presence of a strong, short shock, which can induce separation on the airfoil through an additional mechanism not present in low-speed dynamic stall (see Chandrasekhara and Brydges [8]).

3.3. Motion-history effects on dynamic stall vortex

The dynamic lift overshoot that an airfoil experiences during an oscillating or ramp-type motion depends on the vorticity that is produced during the unsteady motion. Since this vorticity is primarily generated in the region of strong pressure gradient near the leading edge of the airfoil, and these gradients are directly dependent on the angle of attack history, a study of the impact of motion history on the vortex development has been performed. Figure 5 shows the development

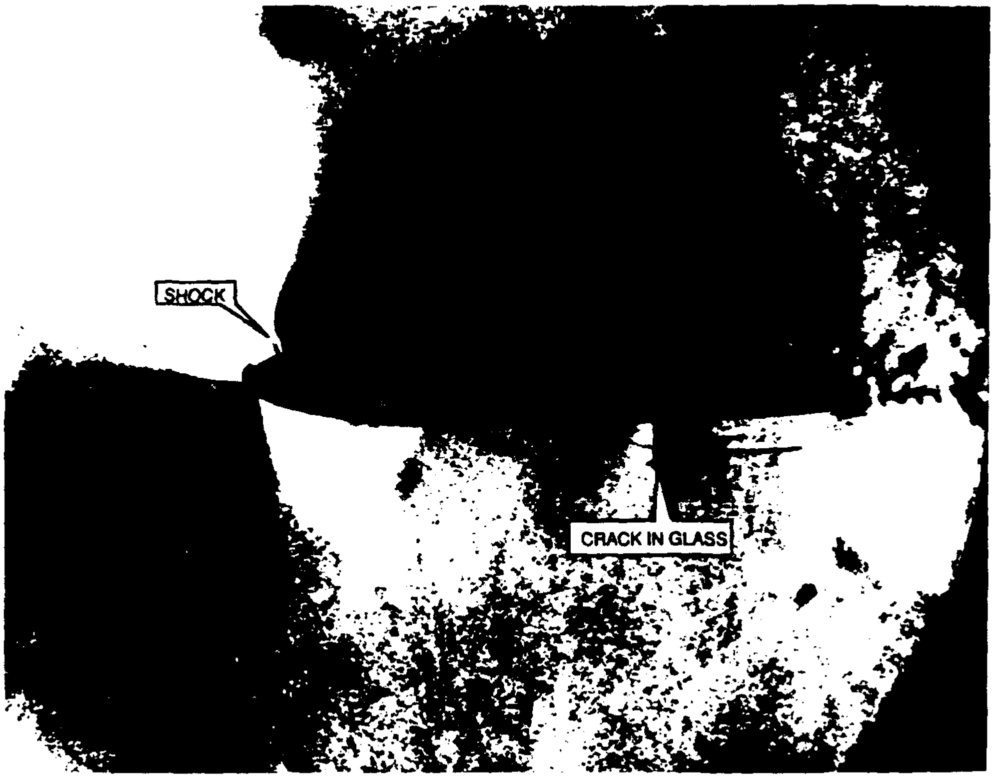

Fig. 4. Schlieren photograph showing presence of shock during dynamic stall.

of the dynamic stall vortex on a NACA 0012 airfoil experiencing ramp motion (on left) compared to the flow on the same airfoil during oscillation.

Comparisons in each case are made at the angle at which the *instantaneous* nondimensional pitch rates match, but the *time histories* are different. Both cases start at alpha = 0°; the ramp achieves the required nondimensional pitch rate within 6° of rotation, and maintains a constant pitch rate thereafter. In contrast, the oscillating motion achieves the required pitch rate twice during its cycle of $\alpha = 10° + 10° \sin \omega t$; the comparison in fig. 5 is made in each case at the higher-angle match. In the lower pair of photographs in fig. 5, the two motions are compared at 15° angle of attack; as can be seen, both flows are showing the same flow development – the images are virtually identical. In contrast, the comparison made at 17° (the middle set of photographs, at the nondimensional pitch rate of 0.025) shows that the dynamic stall vortex for the airfoil experiencing ramp motion is at mid-chord, as is the vortex for the oscillating case; however, note that the ramp-induced vortex is much less well defined. Now consider the images for 18° angle of attack (the upper images). Here the dynamic stall vortex caused by ramp motion has been completely diffused, and the airfoil is entering the stall condition; the vortex for the oscillatory motion airfoil is still well defined, and lift can be expected to remain for some more time on this airfoil.

4. Concluding remarks

It can be seen that there are many physical factors competing for dominance of the unsteady

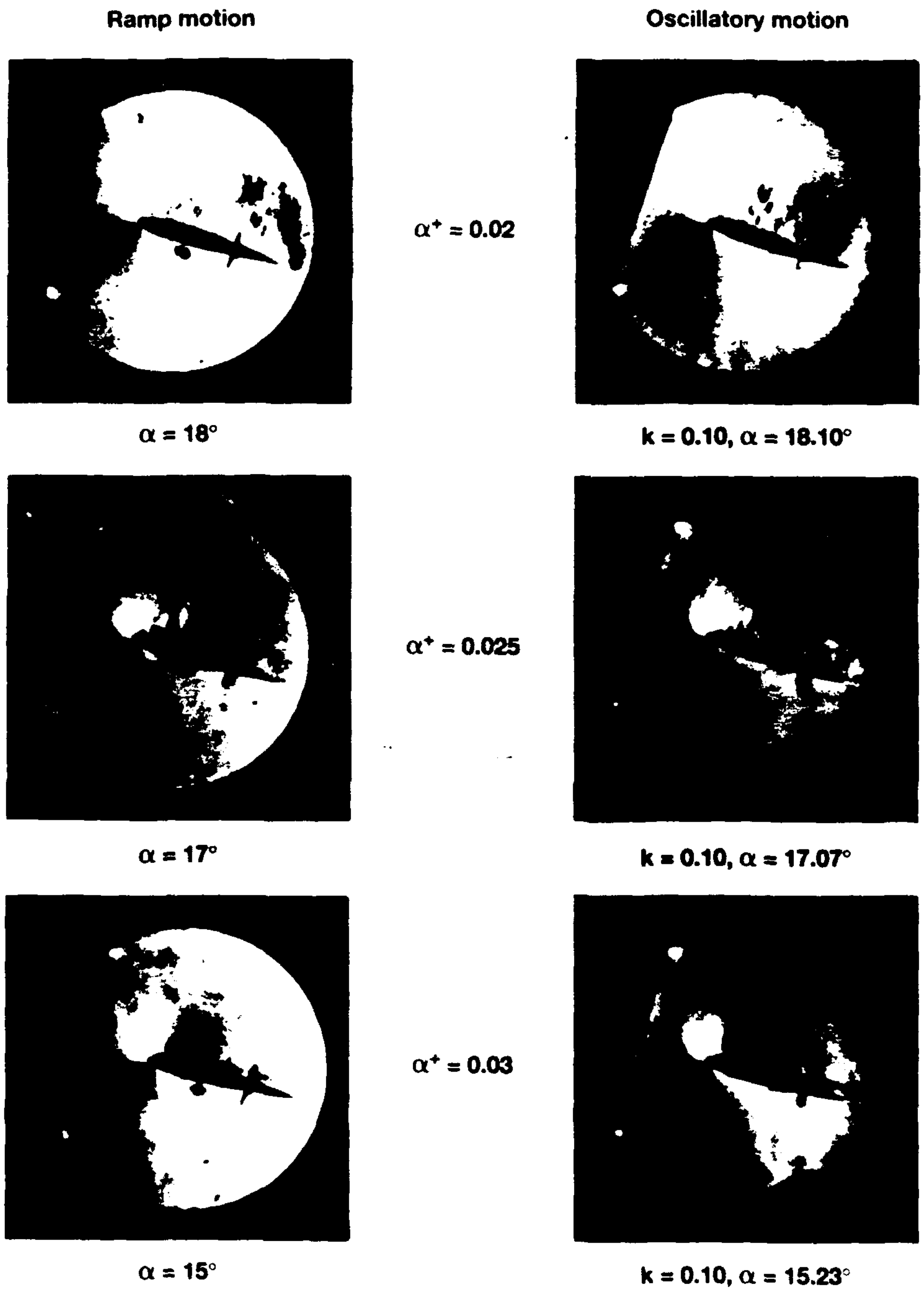

Fig. 5. Schlieren photographs of dynamic stall due to ramp compared to oscillation.

flow field on rapidly pitching airfoils, including regions of supersonic flow, embedded shocks, and the effects of motion history. Lack of detailed knowledge of the interaction between phenomena has meant that virtually all design effort applied to dynamic-stall-resistant airfoils has been experimental and empirical in nature. However, the gains that can be made through such "ad hoc" approaches are reaching a plateau; any significant additional improvements will require a much better ability to model the physics of the dynamic stall process.

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