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FLUID MECHANICS OF WING ADAPTATION FOR SEPARATION CONTROL

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ABSTRACT The unsteady fluid mechanics associated with use of a dynamically deforming leading edge airfoil for achieving compressible flow separation control has been experimentally studied. Changing the leading edge curvature at rapid rates dramatically alters the flow vorticity dynamics which is responsible for the many effects observed in the flow.

1. Introduction

It is well known that the performance of fluid flow systems is limited by onset of separation. Hence, control of flow separation has become an important problem in fluid mechanics. Previously attempted separation control methods have ranged from use of suction to acoustic perturbation. The major limitation of these approaches is the increasing power requirement with increasing freestream velocity for effective control. Furthermore, most do not work at compressible conditions. When an airfoil operates at or near maximum lift conditions, the local flow over it can reach compressible conditions even at $M_\infty = 0.2$ and thus, most flow control schemes fail precisely when they are needed. Hence, a novel flow control method has been developed at the Navy-NASA Joint Institute of Aeronautics. It involves dynamically modifying the airfoil leading edge curvature, the cause of the strong local fluid acceleration and the subsequent adverse pressure gradient. With advances in smart materials and actuators, such a method can even become practical. As can be expected, dynamical deformation of an airfoil introduces dramatic changes in the unsteady potential flow over it and hence in the unsteady vorticity dynamics that governs the flow development. The paper addresses these issues by demonstrating the resulting changes in the fluid physics and the flow control envelope in attached and separated compressible flows.

2. Description of the Experiment

The 15.24cm chord airfoil developed for the purpose is referred to as the dynamically deforming leading edge (DDLE) airfoil. Its leading 25% is made from a carbon-fiber composite, the rest is machined from solid metal. The leading edge is about 50μm thick and is attached to a mandrel shaped to the NACA 0012 profile. It is housed *inside* the airfoil and is connected to a computer controlled brushless servomotor drive system. The mandrel translates in the chordwise direction moving the leading edge by a maximum of 2mm to introduce up to 400% continuous change in the airfoil leading edge radius. The mechanism is designed to work synchronously with an airfoil oscillating in the

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compressible dynamic stall facility (CDSF) located at the Fluid Mechanics Laboratory of NASA ARC. The airfoil is held between the CDSF test section walls with glass inserts providing optical access to the region $-0.15 \leq x/c \leq 0.35$. The displacement of the leading edge, rate of its curvature change and its phasing with the oscillating airfoil are fully controllable. Ref. 1 provides a detailed description of the DDLE airfoil. In the present experiments, the airfoil angle of attack was varied from 8 to 18 deg in a steady freestream flow at $M_\infty = 0.3$. With the airfoil held at fixed angle of attack, the leading edge curvature was varied at different rates -V1, V2 and V10- to produce the shape changes shown in Fig. 1. Each shape change represents about 75μm displacement of the leading edge. Point diffraction interferograms (PDI) were recorded for shapes 0 to 18 as the airfoil passed through these shapes, with shape 0 nearly corresponding to the basic NACA 0012 profile. When each shape was tested separately in steady flow with no real-time leading edge deformation, the rate is referred to as V0.

3. Results and Discussion

3.1. Characterization of Flow Regimes

Figure 2a shows the various flow regimes that result in steady flow (V0) over different shapes. The shape 0 airfoil exhibits characteristics largely identical to the 15.24cm chord NACA 0012 airfoil which stalls at $\alpha \approx$14 deg. However, as the airfoil becomes more rounded (e.g. shape 8 airfoil) α_{ss} increases to about 19 deg. The figure shows that a "window of opportunity" exists in which separation can be prevented and separated flow can also be *made to reattach* by an **extremely small** movement of the leading edge, thus validating the DDLE concept. At high angles, attached flow with a laminar separation bubble forms over the airfoil. Stall occurs as the bubble bursts. Leading edge stall is the general feature of the DDLE airfoil at the test Mach number for most shapes. The boundary layer vorticity is shed by convection for this condition. For α =14-16 deg, mixed flow, defined as attached flow at the leading edge with some trailing edge separation (as deduced from the interference fringes lifting-off into the outer flow) is present for shapes 0-4.

Figure 2b shows the flow regimes that appear for the slowest deformation rate V1 used at different angles of attack. Interestingly, the attached flow regime shrinks considerably relative to that seen in Fig. 2a and an attached flow regime "with a nascent vortex" develops. Together, these two regimes roughly correspond to the attached flow regime seen for the V0 case. The vortex eventually grows and is shed in a manner akin to that observed in dynamic stall flow, but at *higher angles* for shapes up to 8 and at *very low angles* for rounder shapes. This is a completely different stall mechanism compared to steady flow, even though the rate of change of nose curvature is very small. A comparison of the reduced frequencies of the oscillatory airfoil flow and the DDLE airfoil flow based on the leading edge velocity indicates that the values for the latter case are $O(1)$ lower. In Ref. 2 it was shown that there is no quasi-steady state for the dynamic stall flow and a vortex forms even for the lowest reduced frequency tested. In the present case, even for the initial condition of attached flow (at low α), the vorticity field changes from diffusion dominated to convection dominated once the vortex forms. At high angles of attack (e.g. $\alpha = 15$ deg), the flow over the airfoil is initially separated for shape 0, but a slight rounding of the nose quickly reattaches the leading edge flow with an incipient vortex. Even though trailing edge flow may have partially separated for shape 4, it could not be confirmed for shapes 5-8 and hence, the flow was treated as attached for these shapes. Thus, it was concluded that the outer inviscid unsteady flow pressure distribution, and hence its vorticity dynamics, were favorably influenced by dynamically changing the nose geometry. Another interesting feature observed in this flow is the presence of significant peak suction pressure in the post-stall flow regime (see Sec. 3.2) when the vortex convected. The suction peak was not fully lost even when leading edge stall finally ensued. The time scales for the re-creation of the vorticity in the flow, its subsequent diffusion, coalescence into a vortex, its growth and shedding, are all factors that determine the degree of control effectiveness that can be obtained from the geometry change used.

A similar map for the case of DDLE movement at V10, Fig. 2c, generally shows a large reduction in both the attached flow regimes. The stall angle for shape 0 has also decreased to 12 deg. A scan along the different shapes at a fixed angle of attack (e.g. 15 deg) shows that the flow reattaches with a vortex forming for shape 6 and shortly afterwards leading edge stall develops abruptly. However, at the lower angle of attack of 13 deg, a mixed flow regime exists followed by the regime in which a vortex forms. Subsequently, vortex growth and convection occur. Once again, a region of vortex flow with moderately large suction peaks is present. The narrower window of opportunity in this case of fast leading edge retraction suggests that for flow control to be effective, the rate of change of leading edge curvature should be carefully tailored to the flow conditions of interest. Sudden and rapid changes may even result in undesirable consequences and hence should be avoided.

3.2. Development of Airfoil Peak Suction Pressure

Figure 3a shows the peak suction pressure contours over the DDLE airfoil for the V0 case. The rapid loss of suction with the occurrence of leading edge stall is clear. Stall is seen at very low angles for shape 9 and higher. For shapes 6-8, a very strong suction peak is present, with $C_{p_{min}}$ values reaching -6.0. For the case of V1, Fig. 3b shows that the airfoil develops the strongest suction for shape 8, but the region of $C_{p_{min}} = -4.0$ extends over a wider range of shapes than that seen in Fig. 3a. The most important difference is seen for the flow regime with a vortex present (see also Fig. 2b) and also for post-stall shapes. The values here are -3.0 to -4.0 unlike those seen in Fig. 3a for the V0 case. This indicates that even at slow rates of curvature change, the separated flow over a deforming airfoil reattaches over the leading edge which enables vorticity production. Other data in hand (but not presented here) shows that the suction gradually decreases with increasing deformation rate. However, when the deformation starts from the attached flow state ($\alpha \leq 8$deg) no differences are observed in the peak suction development. But, even passing through shape 8 (where mildly separated flow is seen for V0 at $\alpha = 10$ deg) results in dramatic changes in the peak suction development for all subsequent shapes at all speeds tested.

From these data it seems important to remain within the stall-boundaries seen for the V0 case while carrying out dynamic flow control. However, reaching the desired shape should be done carefully to ensure that the vorticity does not coalesce. It appears best to rapidly change the leading edge curvature and stop at a shape where the flow reattaches without a vortex, yet the rate should be slow enough in order that no imbalances in the flow time scales are introduced. In such a case, the vorticity produced from the flow control effort is gradually diffused providing a better control authority by avoiding the pitching moment associated with the vortex that is otherwise produced.

4. Conclusions

A novel and practical method of compressible separated flow control through active manipulation of the vorticity field by leading edge curvature change has been demonstrated. The unsteady effects of dynamic surface deformation places some restrictions on the process. The study revealed that the slowest rate of altering the nose curvature used in the experiments was the most effective in controlling flow separation.

References

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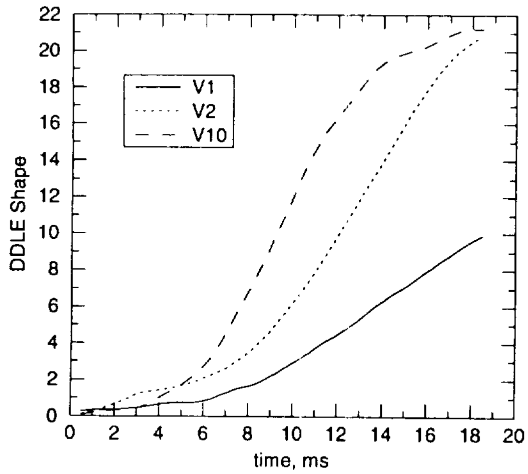

Fig. 1. DDLE Shape Change History.

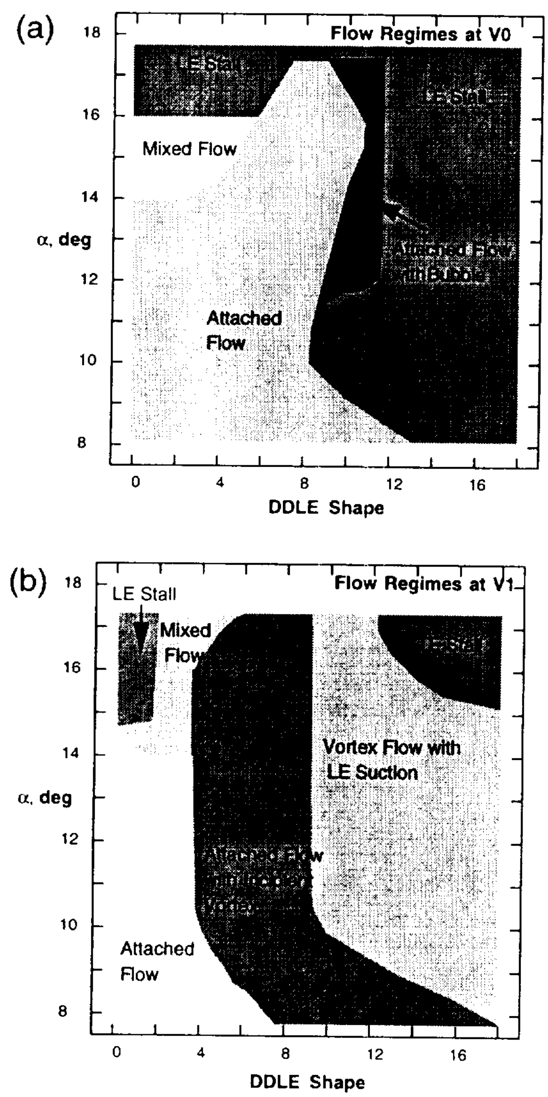

Fig. 2. Flow Regimes over DDLE Airfoil: M = 0.3; (a) V0; (b) V1.

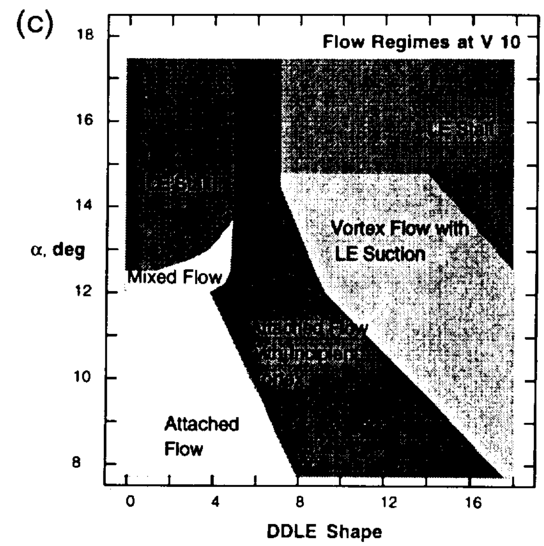

Fig. 2. (concluded); (c) V10.

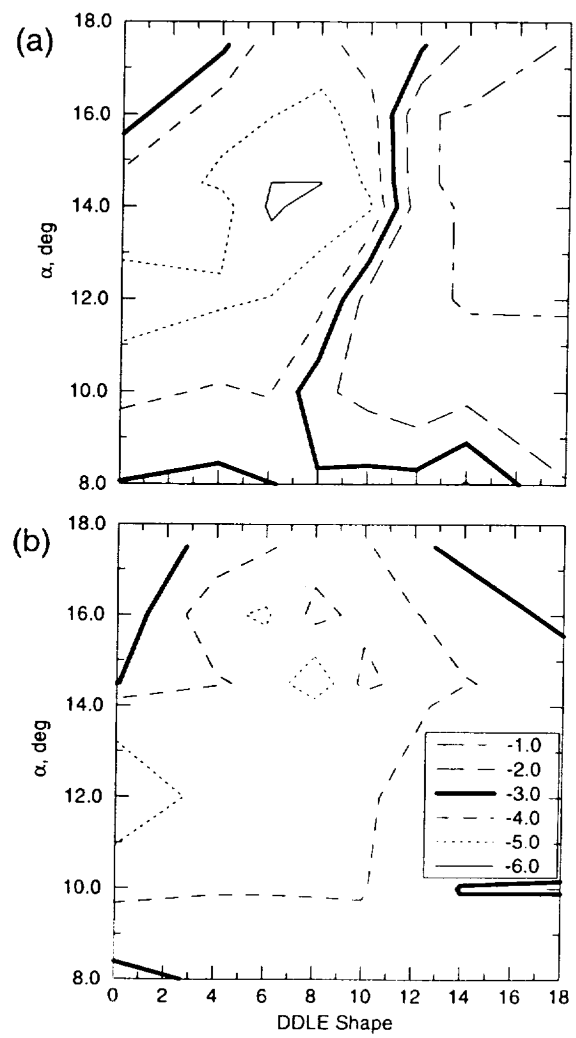

Fig. 3. Contours of $C_{p_{min}}$ for Flow over DDLE Airfoil: M = 0.3; (a) V0; (b) V1.

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