Engineering Notes

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Some Recent MIT Research on Dynamic Stall

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SOME recent research on airfoil dynamic stall by members of the MIT Aeroelastic and Structures Research Laboratory is summarized below. This work tentatively defines the boundary-layer flow processes during dynamic stall.

The initial work investigated the forward movement of the laminar separation point of an unsteady laminar boundary layer during rapid changes of angle of attack.[1] The separation mechanism considered is shown in Fig. 1. The boundary layer is laminar initially, separates when it encounters the adverse pressure gradient in the vicinity of the airfoil leading edge, becomes turbulent, and reattaches, forming a separation bubble. The analysis included the calculation of the potential flow and the computation of the laminar boundary layer. In the unsteady calculations, a Joukowsky airfoil having the same leading-edge radius as the NACA 0012 airfoil was considered. A plot of the movement of the laminar separation point forward over the airfoil upper surface as angle of attack is increased at various rates is shown in Fig. 2. It is seen that the laminar separation point reached the airfoil leading edge at an angle of attack of about 9° for all rates considered. This result is due to the large adverse pressure gradient near the leading edge at large angles of attack; the boundary layer for either the steady or unsteady case cannot overcome this large gradient and thus separates. Theoretical variation of the airfoil pitching axis location from the airfoil leading edge to the three-quarter chord point had negligible influence on the position of the laminar separation point for the typical rates and pitching axis locations considered, since the effect of pitching-axis location on the potential flow was small.

One purpose of these calculations was the prediction of the unusual dynamic stalling behavior of the wing tested by Garelick.[2] The wing tested had an NACA 0012 airfoil section, 5-in. chord and 42-in. span between side-walls, with 8 NACA Type 49 pressure transducers installed at chordwise locations from 10–80% chord. The object of the test was to simulate the nearly linear, nonoscillatory angle-of-attack change on a helicopter blade on the downwind side of the disk, and to record the time varying pressures. The freestream velocity was held at a constant 132 fps for all of the tests and the freestream Reynolds number was 3.44×10^5 based upon the chord length. In the various tests performed, dynamic stall occurred at angles of attack ranging from 15–20°. Dynamic stall was defined in the tests to occur the instant the suction at the 10% chord station no longer increased with increasing angle of attack. These angles are well above the static stall value of around 10° angle of attack. The results showed that both the location of pitching axis and the rate of change of angle of attack affected the angle of dynamic stall.

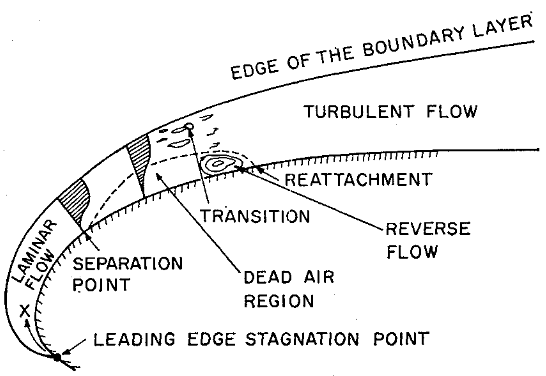

Fig. 1 Bubble structure on a thin airfoil.

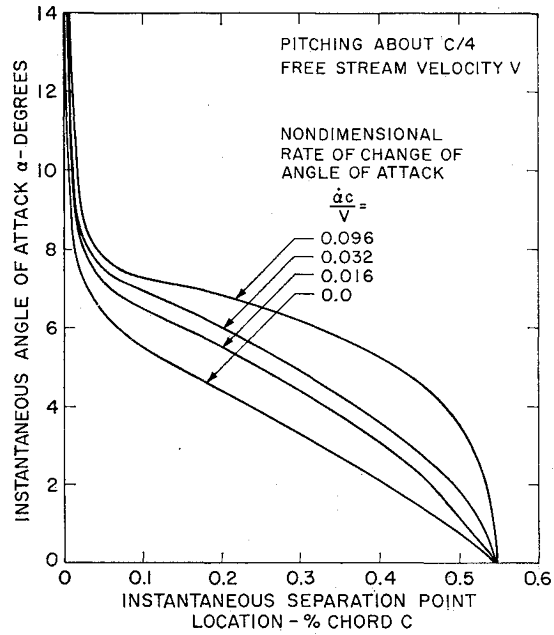

Fig. 2 Movement of the unsteady laminar boundary-layer separation point on a 12% Joukowsky airfoil.

These large effects of rate and pitching-axis location on stall angle of attack were not predicted by the theory described above. It was concluded that the observed dynamic stall effects must be associated with the dynamics of the laminar separation bubble.

A short bubble formed on an airfoil surface moves toward the leading edge as the angle of attack slowly increases, contracting in length, and finally bursting suddenly at the stalling angle. The bursting of the short bubble depends on various factors such as the pressure distribution on the airfoil surface, Reynolds number, freestream turbulence, etc., but full understanding of this phenomenon has not yet been attained.

This is the stall process of the leading-edge type in the steady-state case where much experimental evidence exists. But the process is unknown in the unsteady case, when the angle of attack is changed rapidly. Although no definitive experimental study has yet been made concerning the behavior of the short bubble in the unsteady case, it seems likely that the short bubble is formed in the unsteady case also; it moves toward the leading edge with increasing angle of

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attack, and finally bursts at an angle of attack which is considerably higher than the static stalling angle.

Bubble dynamics were studied experimentally for the case of an airfoil pitching linearly to a large angle of attack.[3] The time history of forward movement of the separation bubble reattachment point was determined by detecting the sudden pressure rise at the point of reattachment as it passed over the airfoil upper surface during pitching motion at various rates.[4]

A wing of NACA 0012 airfoil section, 6-in. chord and 36-in. span was mounted between two vertical panels in the 7 × 9 ft Wright Brothers Wind Tunnel at MIT.[3] Pitching motion around the quarter-chord position was produced by a spring-mass system at various pitch rates ranging from 0.5 rad/sec to 11 rad/sec. Initial and final angles of attack were 3.4° and 35°, respectively. In order to measure the rather small pressure difference at the reattachment point, three miniature inductance-type difference pressure transducers were installed in the model and each was connected to two of the six pressure taps on the upper surface through tubes; this arrangement cancelled out most of the absolute pressure at each tap, which decreases with the increase of the angle of attack, and therefore detected only the pressure difference between two adjacent pressure taps on the upper surface. Pressure taps were located at the 15%, 25%, 35%, 55%, 65%, and 75% chord points. Each pressure transducer experienced a sudden pressure variation at the instant when the reattachment point passed over one of the pressure taps connected with it.

Events occurring at two different instants are of interest in the present discussion. The first event is the passage of the bubble reattachment point forward over the airfoil 15% chord point, at instant *A*. The second event is the formation of the leading-edge vortex following bubble bursting, and its subsequent influence on the pressure at the 15% chord point, at instant *B*. The variation of instantaneous angles of attack α_A and α_B (corresponding to instants *A* and *B*, respectively) with rate of change of angle of attack is shown in Fig. 3. Note that the increases in both α_A and α_B with rate of change of angle of attack are almost identical. If the same amount of time is required in each case for the leading-edge vortex to grow sufficiently to affect the pressure at the 15% chord point, then the delay in the initiation of leading-edge stall is almost identical to the delay in the forward movement of the bubble reattachment point. Note that when $\dot{\alpha}c/V = 0.20$, the reattachment point is at 15% chord at an angle of attack of 14°, which is double the value when the reattachment point

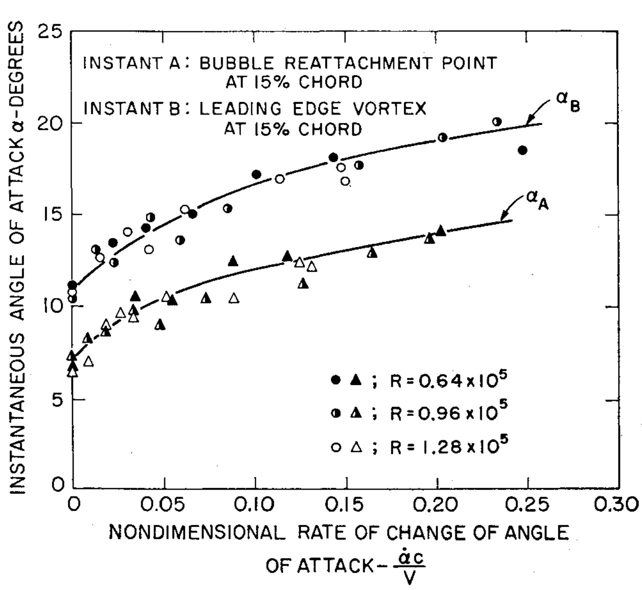

Fig. 3 Variation in the angles of attack α_A and α_B with rate of change of angle of attack.

passed over the 15% chord point in the steady state ($\dot{\alpha}c/V = 0$). Although comparison of the short bubble lengths at the same angle of attack for different values of $\dot{\alpha}c/V$ is not possible with the data obtained in this experiment, it is implied that short bubbles elongate with increasing $\dot{\alpha}c/V$.

These results are of considerable significance in understanding the nature of the airfoil dynamic stall. They suggest that the delay in the occurrence of leading-edge separation is due to the delay in the forward movement of the reattachment portion of the separation bubble as the angle of attack is increased. Thus, the turbulent reverse flow portion of the separation bubble, Fig. 1, is delayed in experiencing the highly adverse pressure gradient on the forward upper surface of the airfoil. The pressure rise across the separation bubble is therefore maintained below the critical value to a higher angle of attack, depending upon the rate of change of angle of attack. Still unknown is the reason for the delay in the forward movement of the aft portion of the bubble; it appears that the theoretical determination of airfoil dynamic stall angle of attack requires the consideration of bubble dynamics.

As a result of the preceding research it is believed that the boundary-layer processes during dynamic stall are now tentatively defined. As in the static case, a separation bubble is formed on the airfoil upper surface as angle of attack is increased. The forward end of the bubble is defined by the laminar separation point and the aft end by the turbulent reattachment point. As the rate of change of angle of attack is increased, there is negligible delay before the laminar separation point reaches the airfoil leading edge, while the forward movement of the turbulent reattachment point is retarded, suggesting that the bubble elongates. Finally, the bubble contracts as the reattachment point approaches the leading edge, and as the shortened bubble encounters the large adverse pressure gradient it bursts, and leading-edge vortex shedding commences, as described in Ref. 5. The delay of rotor blade dynamic stall due to the rate of change of angle of attack appears to be related to the delay of forward movement of the reattachment portion of the separation bubble into the region of high-adverse pressure gradient in the vicinity of the blade leading edge.

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