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Engineering Notes

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Dynamic Stall of Pitching Airfoils and Delta Wings, Similarities and Differences

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Introduction

HIGH-PERFORMANCE aerospace vehicles operating at high angles of attack are subject to unsteady separated flowfields that generate highly nonlinear aerodynamics. Although experimental dynamic stall characteristics for wings with straight and highly swept leading edges exhibit striking similarities, an analysis shows that the underlying flow physics are very different. The two sets of oscillatory dynamic stall characteristics in Fig. 1 look very similar, in spite of the fact that Fig. 1a is for dynamic stall of the VERTOL 23010-1.58 airfoil section,[1] and Fig. 1b is for a sharp-edged 70-deg delta wing.[2]

Delta Wing Dynamic Stall

In the case of the slender delta wing (Fig. 1b), the dominating unsteady flow mechanism, causing the dynamic overshoot of static aerodynamic characteristics, is the pitch-rate-induced camber effect (Fig. 2). Lambourne and Bryer[3] have shown that the effect of camber on delta wing vortex breakdown is extremely large (Fig. 3). The fact that the angle of attack at 60% chord is much higher in Fig. 3a than in Fig. 3b would on a planar delta wing cause earlier vortex breakdown in the former case, contrary to the experimental results[3] (Fig. 3). Apparently, the difference in camber dominates, causing breakdown to be delayed to occur aft of the trailing edge in Fig. 3a, whereas it occurs close to the apex in Fig. 3b. That is, the pitch-rate-induced camber $c\dot{\alpha}/U_\infty$ (Fig. 2) will control the overshoot of static lift maximum and undershoot of static flow reattachment on delta wings (Fig. 1b).

Dynamic Airfoil Stall

Although airfoil camber and nose droop have an effect on maximum airfoil lift[4] (Fig. 4), the pitch-rate-induced camber (Fig. 2) has only a moderate effect on the dynamic overshoot of static lift maximum. This is demonstrated by experimental results[5] for the effect of pitch axis location ξ_{CG} on the dynamic overshoot $\Delta c_{n\,\max}$ of the maximum static normal force on an oscillating NACA 0012 airfoil (Fig. 5). As the effect of $c\dot{\alpha}/U_\infty$ is not dependent on ξ_{CG} (Fig. 2), it and the accelerated flow effect[6] together account for the intercept $\Delta c_{n\,\max} > 0$ at $\xi_{CG} = 0$ in Fig. 5. Because most of that intercept is

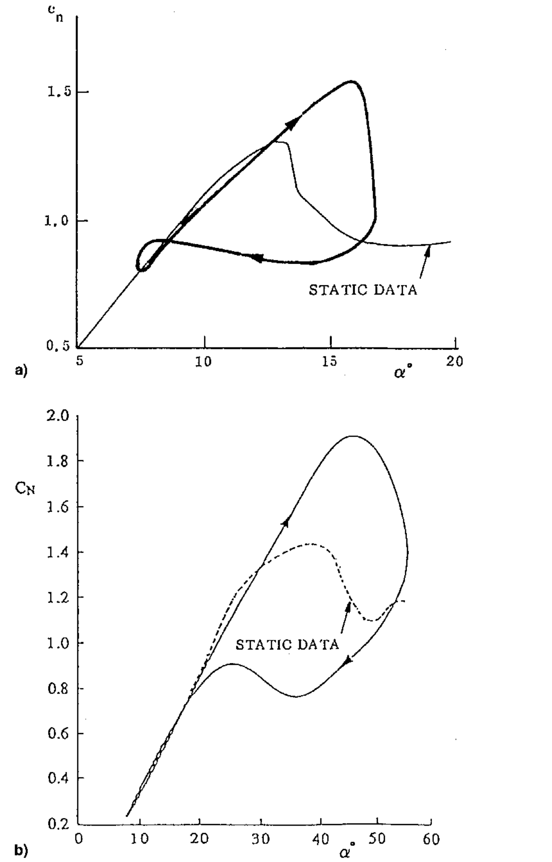

Fig. 1 Dynamic c_n (α) characteristics of stalling wings: a) VERTOL 2300-1.58 airfoil section[1] and b) sharp-edged 70-deg delta wing.[2]

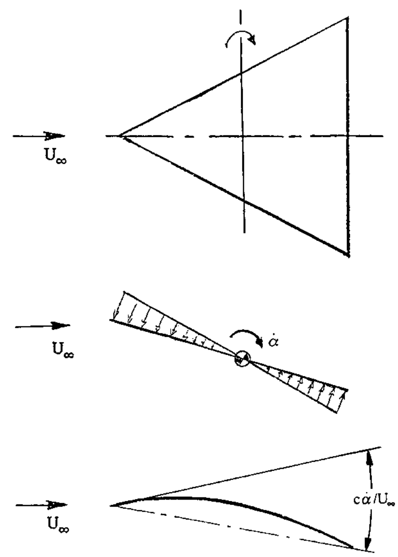

Fig. 2 Pitch-rate-induced camber effect.

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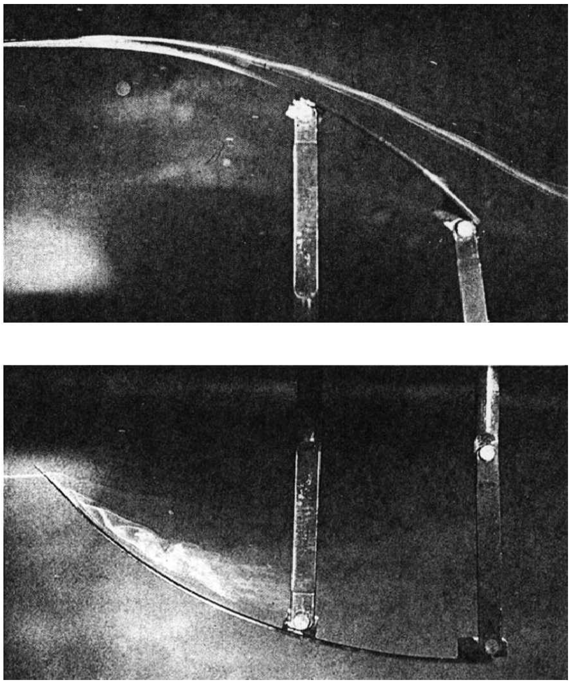

Fig. 3 Effect of static camber on the vortex breakdown of an 80-deg delta wing.[3] Local incidence a) increasing and b) decreasing with distance from apex.

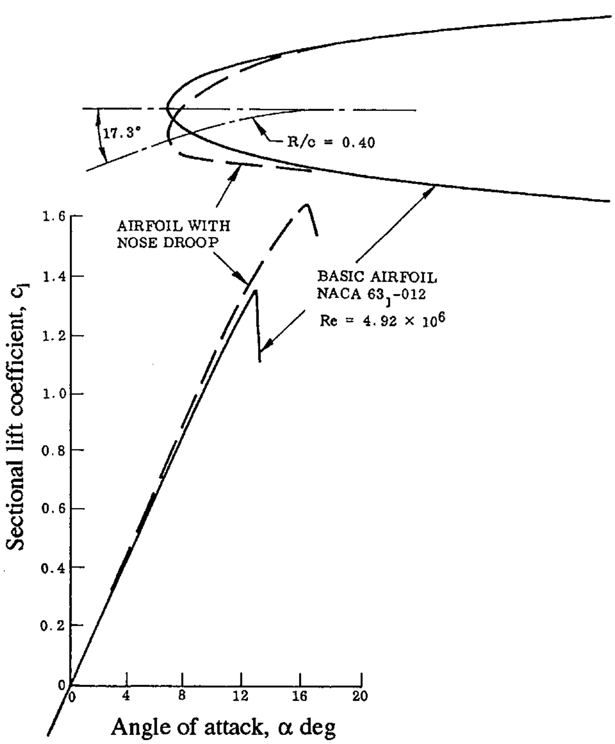

Fig. 4 Effect of leading-edge droop on maximum airfoil lift.[4]

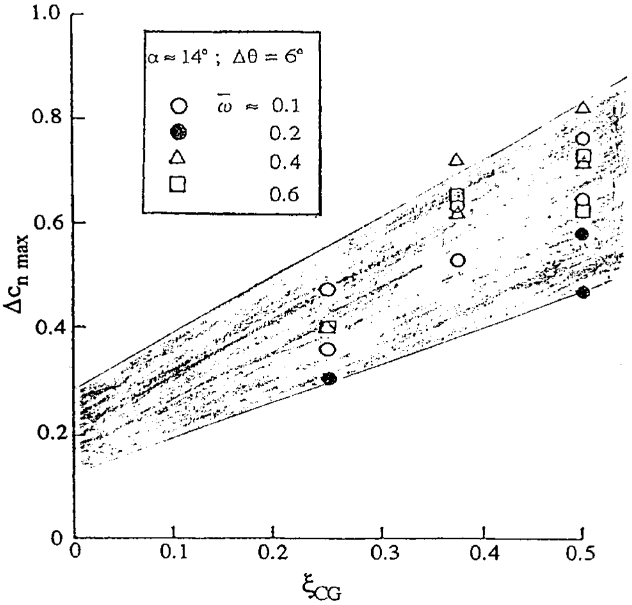

Fig. 5 Effect of pitch axis location ξ_{CG} on dynamic overshoot $\Delta c_{n\,\max}$ of maximum static normal force on NACA 0012 airfoil for 6-deg amplitude oscillations at α = 14 deg and different reduced frequencies.[5]

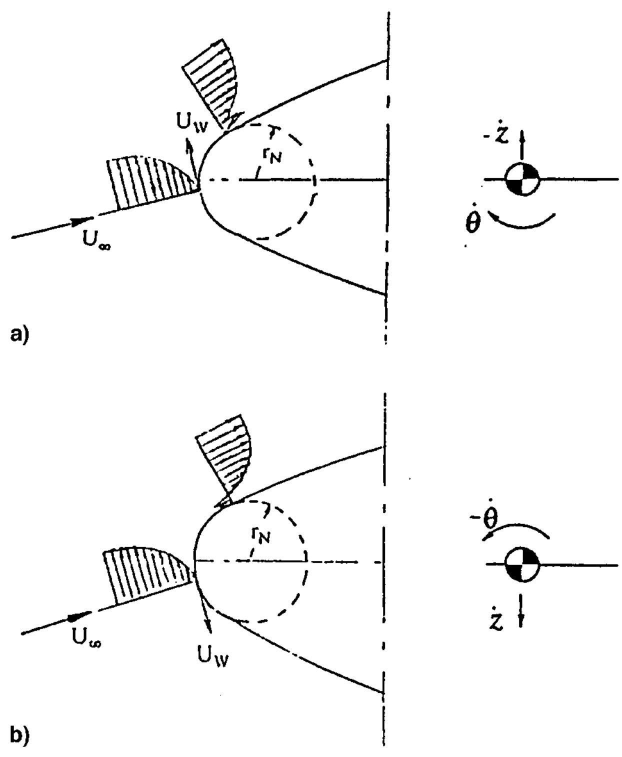

Fig. 6 Leading-edge-jet effect: a) upstroke and b) downstroke.

accounted for by the accelerated flow effect,[6] the effect of the pitch-rate-induced camber is not significant in the case of dynamic airfoil stall.

The increased overshoot $\Delta c_{n\,\max}$ for $\xi_{CG} > 0$ in Fig. 5, e.g., for the standard oscillation center $\xi_{CG} = 0.25$, is caused by the moving-wall effect, the so-called leading-edge-jet effect[7] (Fig. 6). At the stagnation point, the flow velocity is the same as the pitch-rate-induced moving wall velocity at the leading edge. As the wall velocity decreases rapidly relative to the increasing ambient flow velocity with increasing distance from the stagnation point, the boundary-layer profile is changed as sketched in Fig. 6, attaining a wall-jet-like shape near the wall, creating the leading-edge-jet effect first discussed in Ref. 7. As Fig. 6 illustrates, this moving-wall effect[8] will influence the dynamic stall characteristics in opposite directions for pitching and plunging airfoils.[9] The moving-wall velocity at the stagnation point $\dot{z}_{LE}$ is proportional to ξ_{CG} for a pitching airfoil, explaining the experimental data trend in Fig. 5.

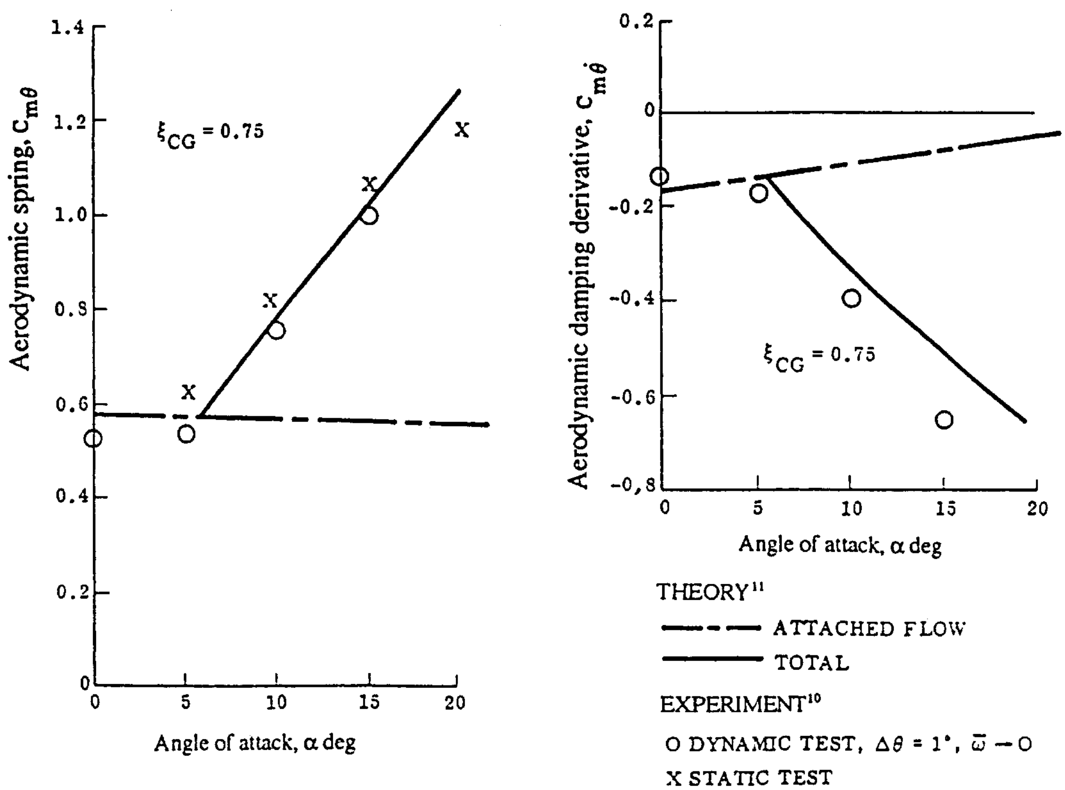

Fig. 7 Static and dynamic stability characteristics of 69.6-deg delta wing with rounded leading edges describing 1-deg amplitude pitch oscillations around 75% chord.[10,11]

Discussion

Thus, in the case of dynamic airfoil stall, the moving-wall effect dominates above the pitch-rate-induced camber effect. In view of this, the measured small-amplitude dynamic characteristics of a 69.6-deg delta wing with rounded leading edges[10,11] (Fig. 7) were at first very surprising. The predictions[11] only considered the effect of the leading-edge roundness to delay static crossflow separation and the associated start of the generation of leading-edge vortices.[12] That is, any additional delay of crossflow separation due to the moving-wall effect was neglected in the prediction.[11] The results are in basic agreement with the dominance of apex flow conditions on downstream vortex development, both in the absence[13] and presence[3] of vortex breakdown, observations that have been corroborated in more recent investigations.[14] The prediction[11] was obtained by using the analytic method derived in Ref. 15 for sharp-edged delta wings, modified to account for the delay of static crossflow separation caused by the leading-edge roundness.[12] The agreement between prediction[11] and experiment[10] indicates that there was no significant moving-wall effect associated with the rounded leading edge.

Conclusions

Analysis of experimental results for dynamic stall on airfoils and delta wings demonstrates that, although the dynamic stall characteristics in relation to static characteristics look very similar in the two cases, the fluid-mechanical processes causing the dynamic overshoot of static stall and undershoot of static flow reattachment are very different. In the case of dynamic stall of a straight wing, the moving-wall effect dominates over the pitch-rate-induced camber effect; whereas in the case of a pitching delta wing, the roles are reversed and the pitch-rate-induced camber effect dominates.

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