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Engineering Notes

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Response of Free-to-Roll Slender Delta Wings to Pitching and Plunging

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I. Introduction

WING rock of slender delta wings at high angles of attack is a well-documented phenomenon. These limit-cycle oscillations in roll are due primarily to instability of the leading-edge vortices. Some of the undesirable consequences of this aerodynamic instability are uncommanded roll and tail fin buffet. Since this phenomenon occurs at high alpha, it results in reduced combat effectiveness and compromised stability. Wing rock of slender wings has therefore been studied widely to understand the physics of this flow regime. Various explanations for the aerodynamic instability have been reported. A large body of literature is available on the subject; pertinent results from a few representative investigations provide a flavor of the issues. In an experimental investigation of an 80-deg free-to-roll delta wing, Levin and Katz[1] noted that a possible cause of random-disturbance-initiated oscillation is that it is sustained by reduced distance between the up-moving semiwing and the leading-edge vortex emanating from the same side. They further noted that damping of the roll was a consequence of vortex breakdown. Based on the data of Nguyen et al., Ericsson[2] noted discontinuities induced by vortex breakdown and for very slender delta wings by vortex asymmetry (liftoff) that occurred before the vortex breakdown. Ng et al.[3] note that asymmetric vortex breakdown over wings with variation in sideslip angle or roll angle has been suggested as a direct cause of aerodynamic instability resulting in wing rock. Both spiral and bubble modes of vortex breakdown have been observed. Wing rock has also been attributed to vortex shedding by Redinniotis et al.[4] They also noted the phenomenon to be independent of Reynolds number.

One of the earliest investigations of vortex breakdown over a pitching but constrained-in-roll delta wing was by Gad-el-Hak and Ho,[5] who noted oscillation of the breakdown location with angle of attack, which moved toward the apex with increasing angle of attack and moved toward the trailing edge with decreasing angle of attack. Gursul and Yang[6] have noted that the two important parameters affecting vortex breakdown are the ratio of the tangential and axial velocities in the vortex and the pressure gradient exterior to the vortex; for a pitching wing both these parameters vary. Increase in either of these parameters accelerates the breakdown process. They correlated pressure fluctuations with the pitching angle and determined that a phase lag existed between the breakdown and pitch motion; the breakdown occurred not at the maximum angle of attack but rather when the wing started a pitch-down motion. Ericsson,[7] however, has identified the influence of pitching as a change in effective camber. He has referred to the results of Lambourne et al.,[8] who investigated a chordwise-deforming delta wing. Lemay et al.[9] reported hysteresis in the vortex breakdown location for a pitching delta wing as a function of angle of attack. They observed widening of the hysteresis loop with increasing reduced frequency and finally its becoming symmetric around the static breakdown characteristics. They also noted minimal influence of reduced frequency and of Reynolds number on the propagation of the breakdown location, whereas it was sensitive to pitching frequency. Thompson et al.[10] studied transient pitching motion of a delta wing. They compared the effects of ramp motion to those of Ref. 5 and observed that the ramp-up closely followed the leg of the hysteresis loop of the upstroke of the oscillating wing whereas the pitch-down lagged the downstroke of the oscillating wing. Miau et al.[11] reported the effect of a ramp pitching delta wing, noting that the movement of the breakdown location was strongly dependent on the pitching rate. They attributed delays in the propagation of the breakdown locations to the underdeveloped primary vortex in the process of pitching.

Several methodologies have been proposed and investigated to control and/or to modify the vortex-burst location. These methods include suction, blowing, and mechanical flaps. Details of experiments conducted for vortical flow management, including leading edge extensions for roll control at high angles of attack and forebody vortex manipulation to alleviate uncontrolled vortex asymmetry using deployable strakes, have been reported by Rao and Campbell.[12] The effect of spanwise blowing on control of vortex breakdown on a static delta wing was reported by Johari et al.[13] to be moderate. Mitchell et al.[14] used trailing-edge symmetric and asymmetric injection to control vortex breakdown, reporting positive influence over control of the breakdown location. Vorobieff and Rockwell[15] applied trailing-edge blowing to control vortex breakdown over a large-amplitude pitching delta wing, observing that intermittent blowing during the upstroke of the pitching cycle was most effective. Walton and Katz[16] conducted experiments on the response of a free-to-roll doubledelta wing to asymmetrically deflected leading-edge flaps. Similar experiments were also conducted by Ize and Arena[17] for an 80-deg delta wing and compared the experimental results with a computational model. Gursul et al.[18] investigated the effects of leading-edge oscillating flaps and variable sweep, reporting hysteresis of breakdown locations. They noted that sweep oscillations equal to wing pitching frequency minimized vortex-breakdown-location excursion.

It was thus observed from a review of the literature that most investigations have primarily focused on understanding the flow physics of vortex bursts and its management for cases where the wing was

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constrained in roll. Of course, an important element of the flow regime is to be able to determine techniques of minimizing the influence of vortex bursts on the lift-producing capabilities of the wing. In a wing free to roll, the complexity of the physics of flow is obviously increased. This paper presents the results of an experimental investigation to understand the response of wing rock to global manipulation of the flowfield through pitching and plunging of the wing.

II. Experimental Setup and Procedure

The experiments were carried out in a water tunnel with a test section of 2×3 ft and a freestream turbulence level of 1% of the maximum velocity. The delta-wing model was made from 0.063-in.-thick steel plate with a leading edge bevel of 30 deg, sweep of 80 deg, root chord of 12.00 in., and span of 4.25 in. The model mounting mechanism (Fig. 1) was designed for motion in three modes, a free-rolling mode, a forced pitching mode, and a forced plunging mode. Teflon blocks were used as bearings to allow free rolling of the wing. Hinges on the pitching and plunging rods allowed free roll as well in the latter two modes. The plunging and pitching were effected through an Hewlett Packard signal generator, a Bruel & Kjaer amplifier, a shaker, and mechanical linkages. The plunging and pitching schedule was

$$d = d_0 \sin \omega t \qquad \text{(plunging)}$$

$$\alpha = \alpha_0 + \Delta\alpha \sin \omega t \qquad \text{(pitching)}$$

where $d_0 = 2$ in., $\Delta\alpha = 2.5$ deg, and ω is the frequency of oscillation.

White fluorescent markers were attached to the trailing edge (wingtips and midspan) for use as targets for image analysis. Leading-edge vortices were visualized with the help of air bubbles introduced at the apex of the wing through flexible tubing. Tests were conducted at a tunnel speed of $U_0 = 1.62$ ft/s resulting in a Reynolds number of 133×10^3 based on root chord. The angle of attack (α_0) of the model was 36 deg, which resulted in classical wing rock. The pitch axis was about the midchord.

The base-line wing-rock characteristics were first established by allowing the wind to rock freely. The wing was then plunged at 1) half the free wing-rock frequency, 2) the free wing-rock frequency, and 3) twice the free wing-rock frequency. The wing was then pitched similarly at the same three frequencies. The leading-edge vortex response and wing oscillations were video taped at 60 frames/s using two Fairchild–Weston high-speed (maximum 200 frames/s) cameras placed aft and at the port and starboard of the wing. Flow visualization data were evaluated to understand the vortex-burst behavior and estimate the vortex-burst locations. The wing rock was analyzed to yield the time histories of roll angles, velocities, and accelerations using the Expert Vision system from Motion Analysis Corp. This system consisted of two high-speed cameras (Fairchild–Weston 200 frames/s) and a video processor (VP320). The image analysis software allowed highly accurate position and higher derivative estimates by tracking designated targets. The masking editor of the expert vision system was used to track only the fluorescent marker, thereby minimizing the memory requirements for processing. The known distance between the spanwise locations of the markers was used to calibrate the system and calculate the maximum roll angle. The midspan marker track was used to subtract out the pitching/plunging to yield the roll-angle variations. The resulting target track was numerically differentiated to determine the roll rate.

III. Results and Discussion

At an angle of attack of 36 deg a stable limit-cycle roll oscillation (Figs. 2a and 2b) was observed to be rapidly established due to asymmetric aerodynamics of the leading-edge vortices, similarly to what has been reported in other investigations. The time period was determined to be 1.033 s and frequency $\omega_f = 6.08$ rad/s, resulting in a reduced frequency $k = 1.36$ based on wingspan. The maximum amplitude of the wing rock was approximately 30 deg. The vortex-burst locations were observed to be at a distance of approximately 0.21 (nondimensionalized by root chord) from the trailing edge.

The influence on the amplitude and frequency of the wing rock due to a pure plunging motion at the three frequencies is shown in Fig. 3. As can be observed, the reduction in amplitude of wing rock was not significant at plunge frequencies equal to the free wing-rock frequency (an equivalent $\Delta\alpha = \omega d / U_0$ of 1.27 deg). Similarly, the wing-rock response to a plunge frequency at half the free wing-rock frequency was also not significant. The phase portraits for these frequencies show a stable limit cycle (Figs. 4a and 4b). No reduction in wing-rock frequency was observed. However, when the wing was plunged at a frequency twice the free wing-rock frequency, the wing rock was almost completely attenuated, which can be clearly seen in Fig. 3.

Flow visualization of the phenomenon provided insight into the response. For free wing rock the vortex burst moves rapidly upstream from the wake to over the wing. In the case of plunging the wing

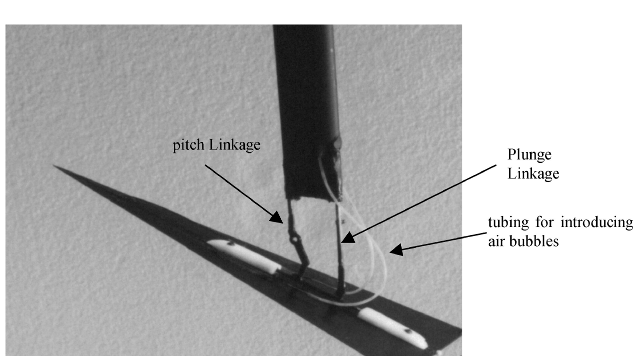
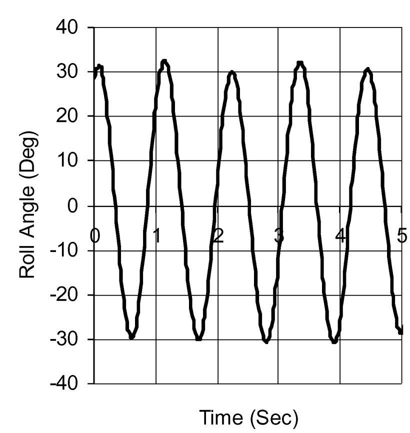
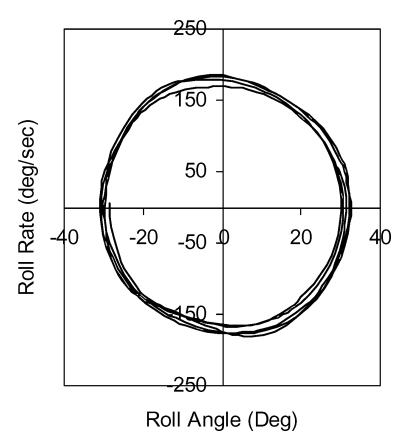


Fig. 1 Model and linkage mechanism.



a) Amplitude



b) Phase portrait

Fig. 2 Free wing rock.

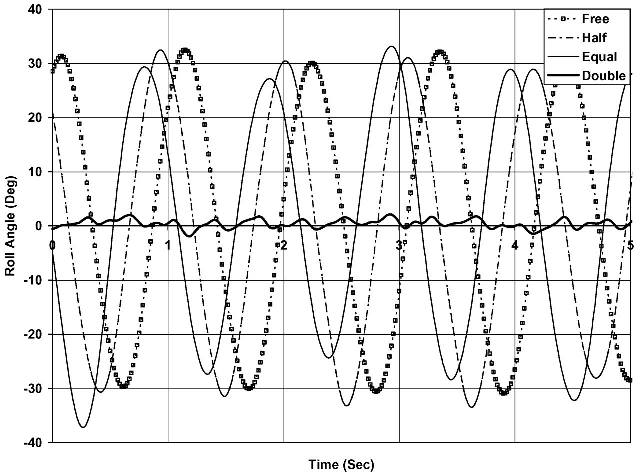
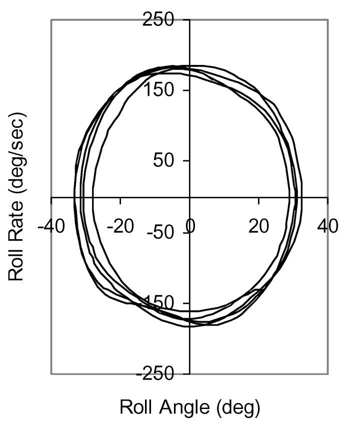
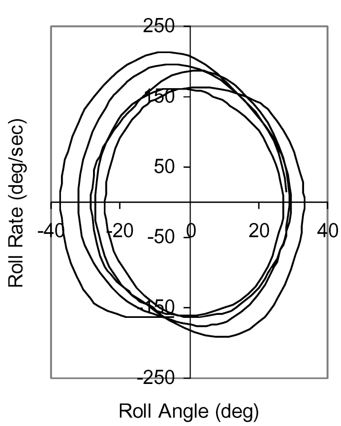


Fig. 3 Wing rock response to plunging.



a) At half the free wing-rock frequency



b) At the free wing-rock frequency

Fig. 4 Phase portrait of wing rock for plunging wing.

at half the free wing-rock frequencies, the asymmetric vortex-burst locations were observed to move upstream on the wing surface in a manner similar to that in the free wing. The leading-edge vortices for the wing being plunged at a frequency equal to the free wing-rock frequency are shown in Fig. 5 for maximum plunge. In this case vortex burst was still asymmetric, with the maximum upstream excursion location in the wake but closer to the wing trailing edge. However, in the case of plunging at twice the free wing-rock frequency, not only were the vortex burst locations moved downstream of the wing (Figs. 6a–6d), but also there was a minimal excursion of burst location with wing rock.

The response of the wing rock to pitching (Fig. 7) was observed to be different in character from that to plunging. The pitching of the wing at half the free wing-rock frequency resulted in almost

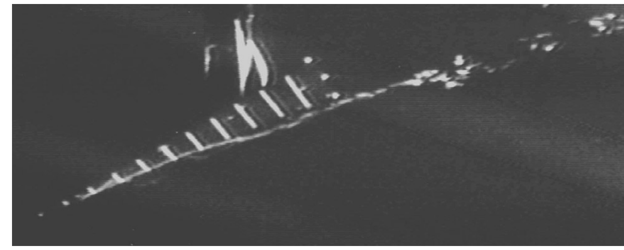
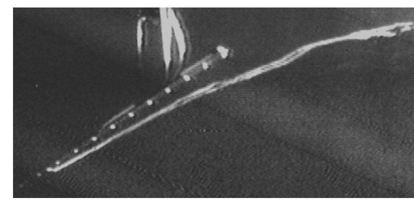
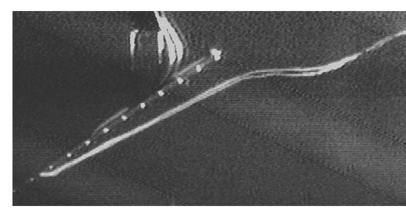


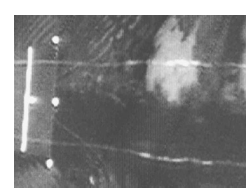
Fig. 5 Response of leading-edge vortices to plunging at free wing-rock frequency.



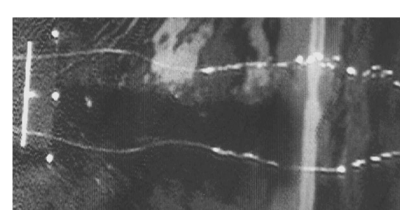
a) Maximum plunge amplitude



b) Minimum plunge amplitude



c) Maximum plunge amplitude



d) Minimum plunge amplitude

Fig. 6 Response of leading-edge vortices to plunging at double the free wing-rock frequency.

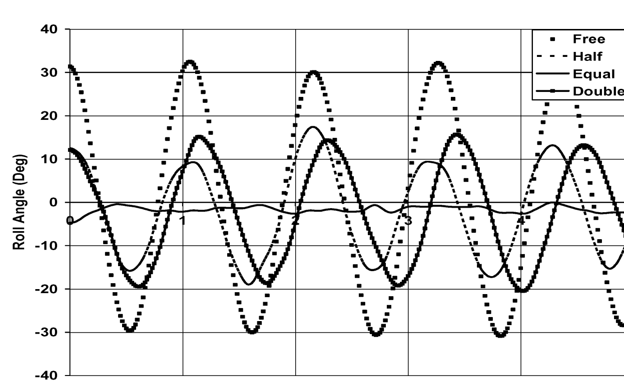
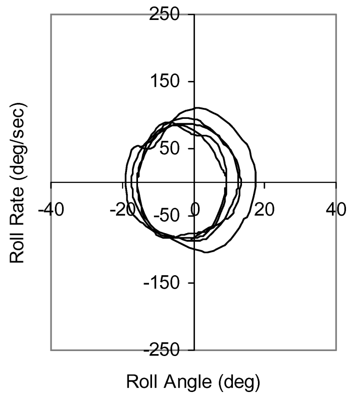
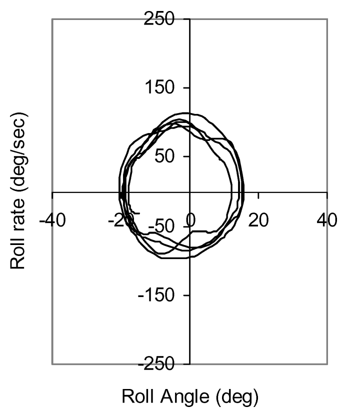


Fig. 7 Wing-rock response to pitching.



a) At half the free wing-rock frequency



b) At double the free wing-rock frequency

Fig. 8 Phase portrait of wing rock for pitching wing.

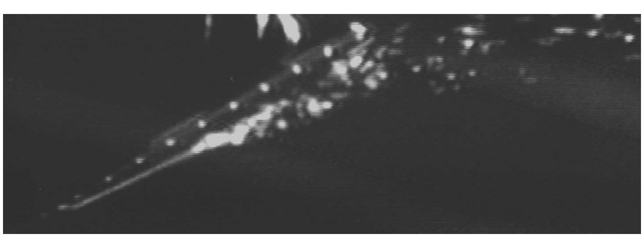


Fig. 9 Response of leading-edge vortices to pitching at free wing-rock frequency.

50% attenuation of amplitude of the wing rock. However, unlike the plunging case, for response to pitching at twice the free wing-rock frequency, the attenuation was again only about 50%. A slight reduction in wing-rock frequency was observed for the two cases. The wing rock was observed to be effectively attenuated when the wing was pitched at the free wing-rock frequency, as seen in Fig. 7. Reduction in amplitudes and roll rates can be observed from the phase portraits for the wing rock when pitched at half and double the free wing-rock frequency (Figs. 8a and 8b).

It was observed from the flow visualization results that at half the free wing-rock frequency, the vortex-burst locations oscillated over the wing surface with the asymmetric bursting phenomenon still present. This excursion was between nondimensional distances of 0.33 and 0.67 from the leading edge. Thus the amount of vortex lift generated was lesser than for to the free wing rock, resulting in reduced amplitude of wing rock. The downstream burst location was at maximum pitch amplitude, whereas the upstream burst location was at minimum amplitude, in contrast to earlier investigations. This is perhaps due to flow being subjected to both pitching and rolling of the wing. By pitching the wing at the free wing-rock frequency, excursion of the vortex-burst location was reduced to between 0.46 and 0.625 from the leading edge. However, almost symmetric vortex breakdown was observed (Fig. 9), resulting in completely, attenuation of the wing rock.

IV. Conclusions

Various techniques have been investigated to determine optimal strategies to control wing rock. The present study has determined that the free wing-rock characteristics play an important role in the design of such control strategies.

Specifically, as a result of this experimental investigation the following conclusions are made:

1) The response of the leading vortices is different for the pitching wing from that for the plunging wing.

2) Plunging the wing at twice the free wing-rock frequency resulted in.

a) vortex breakdown location excursions in the wake far downstream of the trailing edge,

b) wing rock being effectively attenuated.

3) Pitching the wing at a frequency equal to the free wing-rock frequency caused

a) vortex breakdown becoming symmetric, whereas the burst-location excursion was not beyond the trailing edge,

b) wing rock being effectively attenuated.

The pitching/plunging of the free-to-roll slender delta wing was observed to influence the asymmetry in the leading-edge vortex flow. A manipulation technique resulting in leading-edge vortex response similar to the plunging at double the free wing frequency would not only ameliorate the unwanted wing rock but also maintain the ability of the wing to produce vortex lift.

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