Yaw-Roll Coupled Oscillations of a Slender Delta Wing

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Reported are the results of experiments conducted on a slender delta wing designed to undergo roll and yaw oscillations simultaneously. Wind tunnel and water tunnel results indicate that the yaw oscillations always preceded roll oscillations. Time histories show coupling between roll and yaw motions. A significant drop in lift coefficient was observed during these motions. There exists a bifurcation angle of attack at which coupled yaw and roll oscillations force the moment coefficients to switch sign. Pertinent results of the ongoing research work are presented.

I. Introduction

UNMANNED aerial vehicles with delta wing plan forms of uniform thickness and camber distributions offer good maneuverability and low speed handling qualities due to additional vortex-generated lift. However, at high angles of incidence slender delta wings undergo roll oscillations because of vortex asymmetry[1-3]. Furthermore, the vortex asymmetry also manifests itself in the form of wing rock. Since this phenomenon is due to the imbalance of lift on the wing, roll divergence sets in with subsequent nose slicing and uncontrolled spin.

It is evident that in actual free flights there exists a strong coupling between the roll oscillations and yawing motion. A large body of previous work on delta wings has focused on roll oscillations and control with the wing constrained in yaw[4-5]. Only limited studies have modeled yaw effects, but only as static sideslips[6-7] and the dynamics of yaw-roll coupling is still missing because of the complexity of machining the model and the measurements involved. Additional problems arise due to model mounting. As the angle of attack of the model changes, the location of the center of pressure relative to the central pivot point changes which in turn significantly alters the response of the model once the motion sets in. The objective of the present work therefore was to experimentally investigate the effects of yaw and roll coupled motions on the aerodynamics of a delta wing pivoted at its center of gravity.

II. Experimental Setup

A. Model Geometry

In order to understand the dynamical yaw-roll coupling, both a wind tunnel and water tunnel model were designed and built in the Auburn University machine shop. Both of the models were constructed with similar geometries, however due to size limitations the water tunnel model was scaled down. The basic model design shown in Figure 1 consisted of a 75-deg leading edge sweep slender delta wing. The wind tunnel model had a root chord of 17 inches (43 cm), span of 5 inches (13 cm) and uniform thickens of 1 inch (25.4 mm). The water tunnel model was scaled down from this by about a factor of 3. Both models were made from a solid aluminum blocks that were hollowed out to accommodate a yaw-bearing and a mounting collar attached to the model at the center of mass. A 0.3 inch (8 mm) diameter hardened stainless steel rod passed through a set of two ball bearings spaced 8 inches (20 cm) apart in a bronze housing. This rod was rigidly attached to the yaw-bearing and thus allowed the model to achieve independent yaw and roll motions in two orthogonal planes without producing coning motion. A close-up of the models is shown in Figure 2.

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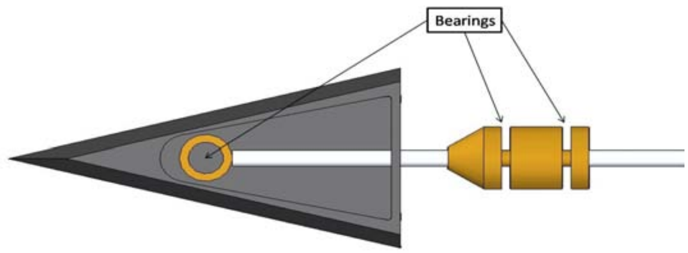

Figure 1. Slender delta wing model geometry.

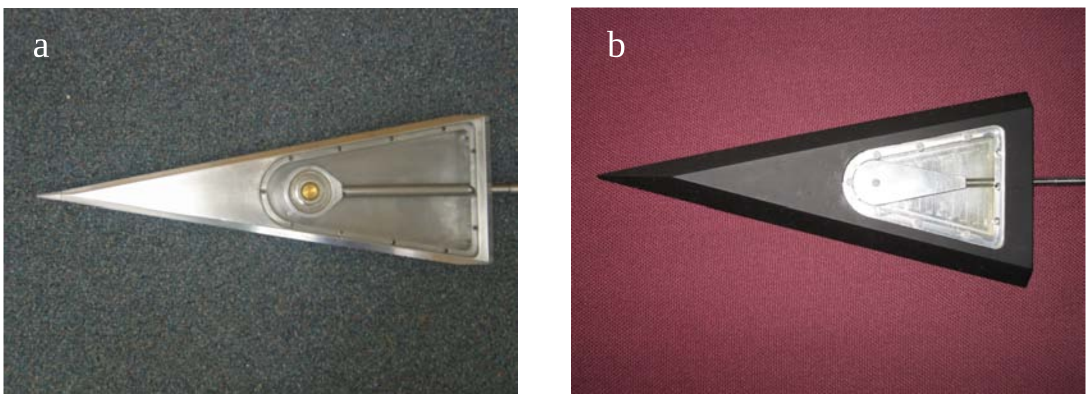

Figure 2. Close-up of the models: a.) Wind Tunnel, b.) Water Tunnel.

B. Wind Tunnel Model Support System

To prevent proximity effects between the delta wing vortices and the top wall of the test section, the model was mounted on a specially designed support system that allowed for the position of the model in the test section to be held at a fixed location at high angles of attack. The upper limit of the tunnel angle of attack system was extended by incorporating manual adjustment of the initial setting of the model incidence as shown in Figure 3. After securing to the wind tunnel balance, the support system was enclosed in a shroud that prevented direct impingement of the oncoming wind.

Figure 3. Slender delta wing model with tunnel support and mounting system.

C. Test Setup

Tests were conducted in the Auburn University 3ft x 4ft test section closed circuit low speed wind tunnel capable of a maximum test section velocity of 180 ft/sec. The model was mounted on the six-component external pyramidal strain gage balance. Data was acquired using National Instruments 16 bits A/D converter and LabView software. Data sampling rate was 1 kHz and depending on the nature of tests, the time series records of 1 to 4 seconds were recorded. Post processing of data was accomplished using Excel and Matlab software.

Tests consisted of the measurement of forces and moments for the baseline case with model constrained in both roll and yaw and for increasing angles of attack. This is referred to as “None-Free” in the figures legends. Three additional sets of data consisted of model:

1). Free to roll with constrained yaw, (Roll-Free)
2). Free to yaw with constrained roll, (Yaw-Free)
3). Free to yaw and roll. (All-Free)

Force and moment coefficients were calculated for a wide range of angles of attack and were correlated with the model displacements. Model motion was measured with the help of a tri-axial accelerometer mounted at the mid-span and near the trailing edge of the model. Accelerations were simultaneously obtained from the outputs of three Endevco Inc. charge amplifiers. Acceleration data was numerically integrated to obtain out of plane displacements and velocities.

Due to time constraints, there has been no quantitative data collected with the water tunnel. However, video captures showing proof of concept have been made. A diagram of the setup used in the water tunnel is shown in Figure 4. This setup will be later used for flow visualization on the same data sets used in the wind tunnel.

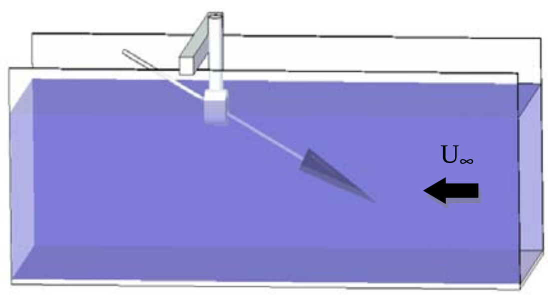

Figure 4: Water Tunnel setup.

III. Results and Discussion

Results showed sensitivity to the initial model orientation and perturbations in the flow. A detailed survey of test section flow revealed slight flow angularity along the vertical plane of the tunnel. The effect of this was seen in the integrated output of the accelerometer. It may however be noted that the accelerometer signals also included model, support and tunnel vibrations

The results presented below have been compared to the baseline case (None-Free) in order to determine the synergy of the aerodynamic forces and motions.

Figure 5 shows variation of the lift force as the model is allowed to oscillate in yaw and roll motions at $\alpha = 25$ degrees (angle of attack) and is compare to the All-Free case. The model showed a uniform cyclic variation when the roll motion was unconstrained. It was observed that the mean lift force reduced when the model was allowed a yaw motion and the results differed from the roll free motion in a limit cycle oscillation[5]. For the All-Free case, a cyclic amplification and attenuation of amplitude was observed and is attributed to the yaw-roll coupling. With increasing angle of attack it was noted that the yawing motion always preceded the rolling motion and at the onset of rolling motion the coupled yaw-roll motion became similar to a Dutch roll. When a wand with a tuft of yarn was introduced into the flow, for the determination of vortex burst and trajectory, the delta wing motions also began to vary in amplitude suggesting that these motions were sensitive to the free-stream disturbances.

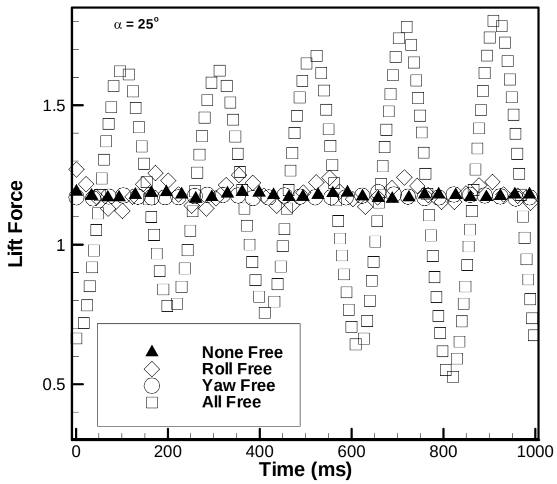

Figure 5. Variation in lift force for all cases, α = 25°.

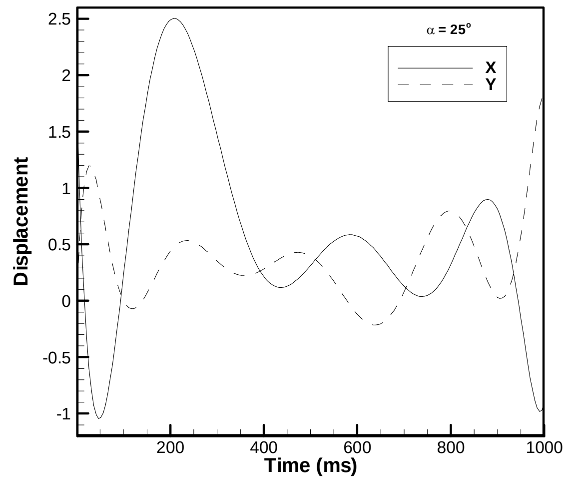

Figure 6. Displacements obtained from the transducer mounted near trailing edge, α = 25°.

Figure 6 shows the lateral and vertical displacements for the all-free case of the delta wing as measured near the trailing edge at α = 25 degrees. Here x is the direction of displacement in the vertical plane and y is the direction of displacement in the span-wise direction. The x-displacements indicate that as the wing rolled, and because of the dynamic pressure, the trailing edge motions remained positive but oscillatory. The displacements in yaw consisted of a combination of long and short wavelengths that repeated in time.

The asymmetrical motion of the model had profound effect on the aerodynamic moments. Figure 7, for example, shows that the pitching moment was not affected by the None-Free and Yaw-Free motions but did respond to the All-Free and Roll-Free cases. Sensitivity of pitching moment to Roll-Free is understandable due to limit cycle oscillations. For the Yaw-Free case only a slight change in pitching moment suggests that an in plane motion did not alter the lateral stability. The All-Free motion had greater impact as it appeared to have extracted energy from roll motions and dissipated into yaw motions indicating strong yaw-roll coupling. The trends for the rolling and yawing moments were similar to the pitching moments and are shown in Figure 8 and Figure 9 respectively.

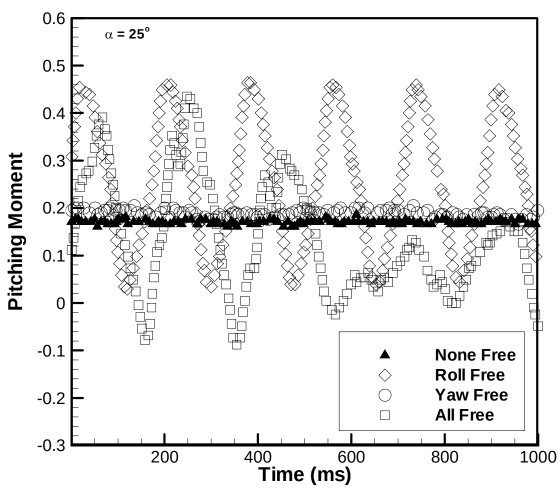

Figure 7. Pitching Moment variations for all cases, α = 25°.

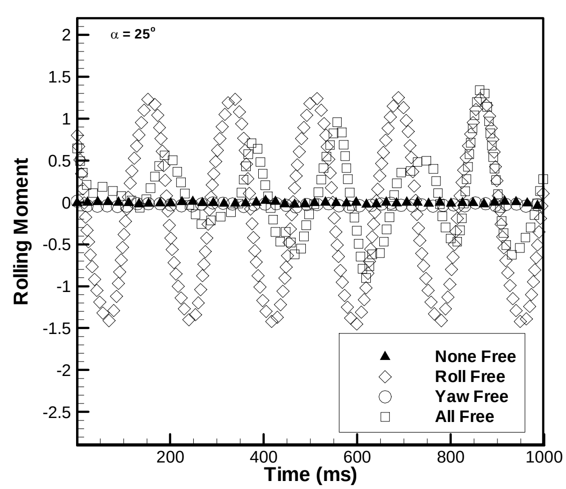

Figure 8. Rolling Moment variations for all cases, α = 25°.

Results of the lift coefficient for all cases are presented in Figure 10 starting from the angle of attack for the onset of motion. For the Roll-Free case α_{CLmax} and C_{Lmax} were considerably higher than the None-Free case, indicating effects of proximity of vortices to the wing surface due to motion. Slightly lower C_L trends were observed for the Yaw-Free case that followed the None-Free data well until $\alpha = 25^o$ and beyond that point no further increase in C_L was observed. For the All-Free case a very distinct drop in lift was observed for the entire range of angles of attack but only a slight change in α_{CLmax} and C_{Lmax}. This shows that due to yaw-roll coupling, a delta wing platform is likely to experience severe stability problems.

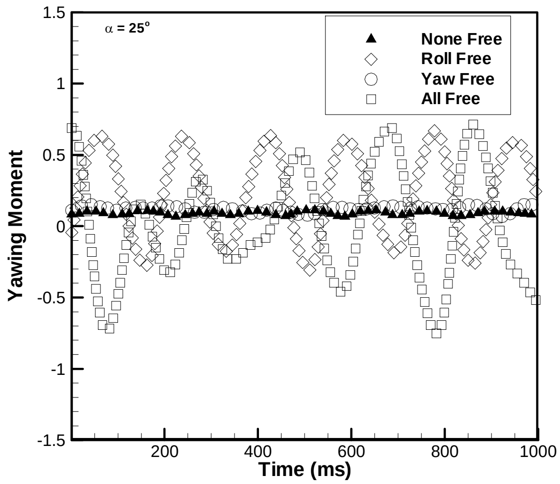

Figure 9. Yawing Moment variations for all cases, α = 25°.

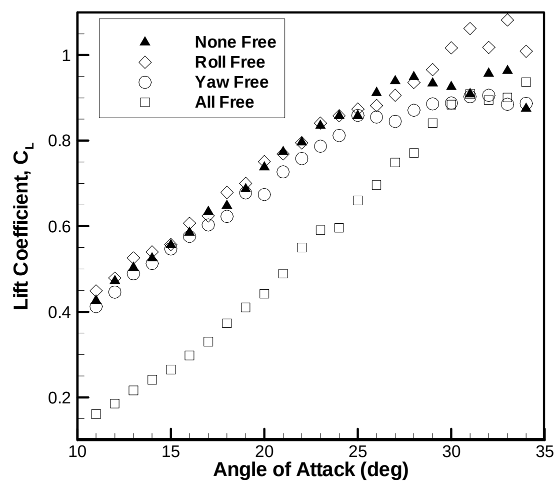

Figure 10. Lift Coefficient vs. α for all cases.

Rolling and yawing moment coefficients presented in Figures 11 and 12 clearly show that around $\alpha = 25°$ there was a sign change in the moments for the All-Free case. From Figure 10 this angle of attack corresponds to a bifurcation point where a yaw-free wing produces less lift but a roll-free wing produces more lift. Therefore in the pressence of both motions i.e. yaw-free and roll-free, there is a synergistic effect which is evident in the results presented.

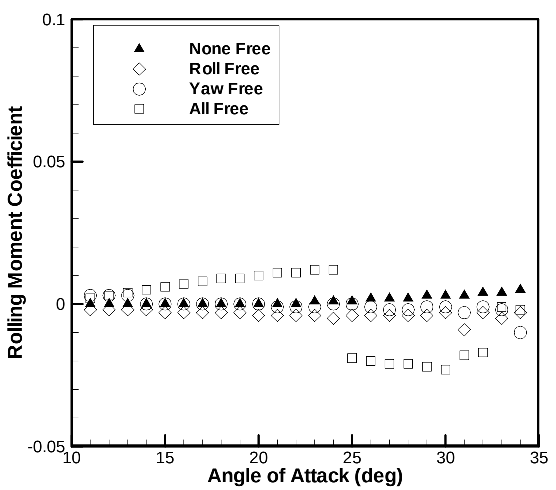

Figure 11. Rolling Moment Coefficient vs. α for all cases.

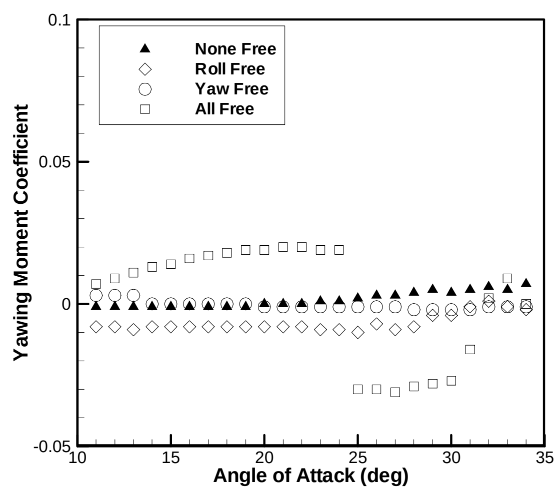

Figure 12. Yawing Moment Coefficient vs. α for all cases.

IV. Conclusions

Aerodynamics of a slender delta wing capable of two-degrees of freedom was investigated. A strong yaw-roll coupling was observed. The yaw-roll coupling was responsible for a significant drop in the mean lift coefficient for the entire range of angles of attack tested. It is also concluded that for such a coupling there exists a bifurcation angle of attack (α_B) where a drop in lift due to yawing motion interplays with an increase in lift due to rolling motion. Consequently, at this α_B the moment coefficients switch sign and therefore can strongly influence the overall stability of the delta wing aircraft.

Acknowledgments

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