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EFFECT OF DORSAL FIN ON THE STABILITY OF VORTICES OVER A DELTA WING

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Cai *et al.*[5] developed a vortex stability theory for slender conical bodies and analyzed the stability of vortex pairs over slender conical wing-body combinations under small perturbations. An experimental study is presented in this paper to verify the validity of the theoretical predictions. A sharp-edged flat-plate delta wing is tested in a low-speed wind tunnel. A smoke-laser-sheet visualization technique is used to visualize and measure the positions of the vortex pair, which are found to be symmetric and conical over the wing. The same tests are performed on an identical delta wing model but with a flat-plate dorsal fin mounted vertically in the incidence plane of the wing. Two fin heights are tested. The ratios of the local fin height to the local wing semi-span are 0.75 and 1.50. The test results clearly indicate that the vortices become asymmetric and non-conical over the model with the fin height ratio of 0.75 and recover symmetry and conicity over the model with the fin height ratio of 1.50, providing direct experimental evidence of the theoretical predictions.

Keywords: Vortex stability; high angle of attack; fin; slender body; flat-plate delta wing.

1. Introduction

Symmetric separation vortices over slender bodies may become asymmetric as the angle of attack is increased beyond a certain value, causing asymmetric forces even at symmetric flight conditions. The transition of the vortex pattern from being symmetric to asymmetric over symmetric bodies is a fascinating fluid dynamics problem.[1,2]

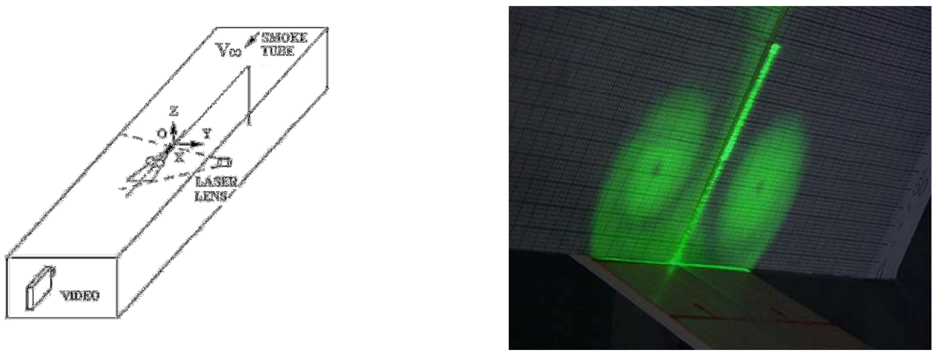
Shanks[3] performed tests of highly swept delta wings and showed the appearance of significant rolling moments at angles of attack above 248 whose semi-apex angles are less than 128. Later, Stahl, Mahmood, and Asghar[4] concluded based on their force measurements and flow visualization that the vortex flow over slender delta wings with sharp leading edges remained symmetric at all angles of attack until vortex breakdown occurred. Ericsson[1] claimed that the vortex asymmetry observed in Shanks' experiment was not due to hydrodynamic instability but rather likely due to asymmetric reattachment in the presence of a centerline spline on the leeside of the wing in the Shanks' model.

Cai *et al.*[5] developed a vortex stability theory for slender conical bodies and showed by analytical methods that vortices over a flat-plate delta wing at zero sideslip are conical, symmetric, and stable for all angles of attack but a low dorsal fin would destabilize the vortices and therefore render the originally symmetric vortices non-conical, unsteady, or both. The flow would recover symmetry only when the fin height is increased to a critical level. Cai *et al.* suggested that the vortex asymmetries observed in Shanks' experiments were caused by the destabilizing effect of the center spline.

The purpose of this work is to perform such an experimental study guided by the theoretical predictions.[6]

2. Experimental Setup and Results Discussions

Tests are conducted in the NF-3 wind tunnel at Northwestern Polytechnical University. Test Section is 3.0 m wide and 1.6 m high. The turbulence level is 0.33% at wind speed of 4.5 m/s. The sweep angle of the wing is 82.58 and the root chord $c_0 = 990.6$ mm. The leading and trailing edges are beveled with a 208 from the windward side. For visualization purpose, the dorsal fins are made of clear float glass, which has a thickness of 2 mm. The measurement accuracy of α and β is within ±0.098. The Reynolds number based on the root chord of the wing c_0 is $Re = 2.99 \times 10^5$.



(a) (b)

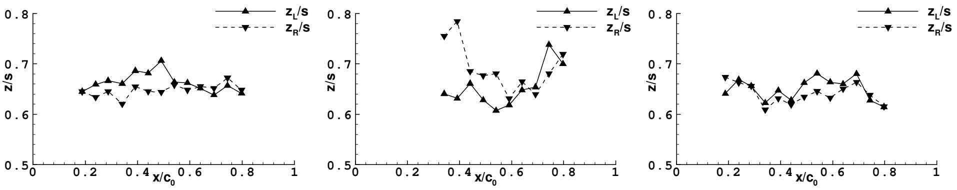
Fig. 1. (Color online) The smoke-laser sheet method.

The smoke-laser-sheet technique is shown in Fig. 1(a). Quantitative measurements of the vortex streamwise locations are made by digitally overlapping the laser sheet vortex patterns to a grid board with all other settings unchanged (Fig. 1(b)). The minimum scale of the grid board is 2 mm. Due to the restriction of manual processing, only ten readings are read from the first 10-second video recording at equal intervals.

3. Results and Discussions

The (time-averaged) transverse coordinates (y/s, z/s) of the vortex cores at a given axial location are obtained by an average of the readings from 10 laser-sheet photographs.

These coordinates z/s of the vortex centers are plotted against their axial location x/c_0 in Fig. 2 for the wing-alone, 0.75s-fin and 1.50s-fin models, respectively. The subscripts L and R denote the left- and right-hand sides respectively. A comparison of Figs. 2(a)–2(c) shows that although the left and right vortices over the wing-alone model and 1.50s-fin model are not perfect mirror images, the deviations are not large. The slight scatter of the left and right vortices shown in Figs. 2(a) and 2(c) is about the measurement uncertainties (which is estimated as ±2% at $x/c_0 = 54\%$). The locations of the left and right vortices of the 0.75s-fin model, however, exhibit significant and consistent asymmetry as compared to those of the wing-alone and the 1.50s-fin models beyond the measurement uncertainties.



(a) (b) (c)

Fig. 2. z/s coordinates of the vortex core centers vs. x/c_0.

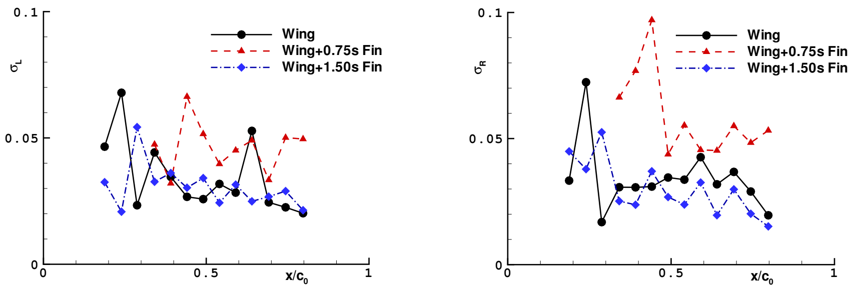
Let $(y/s)_i$ and $(z/s)_i$ be the (time-averaged) local dimensionless coordinates of the vortex centers for the i-th cross-section of the wing. Their arithmetic mean values, are denoted here as $\bar{y}$ and $\bar{z}$. For strictly conical vortices, the $((y/s)_i, (z/s)_i)$ coordinate pairs should be identical for all cross-sections, and equal to their mean values. The standard deviation γ of those measured dimensionless coordinate pairs from their arithmetic mean pair is used to quantify the deviation of the vortices from being strictly conical. The ratios of asymmetry δ are defined by the ratio of the difference between the left and right dimensionless coordinates and the average of the two.

The vortex mean dimensionless coordinates $(\bar{y}, \bar{z})$, the ratios of asymmetry δ, and the conicity parameter γ, are calculated and listed in Table 1 for the three models. The values of the asymmetry parameter δ for the wing-alone model and the 1.50s-fin model are as small as the average measurement uncertainty, whereas those of the 0.75s- fin model are much larger than the uncertainty. The asymmetry occurs in both z- and y-coordinates. Table 1 shows that the values for the 0.75s-fin model are much larger than those for the wing-alone and the 1.50s-fin models, indicating that the vortex pair over the 0.75s-fin model is non-conical in comparison with those of the other two models.

Table 1. Mean vortex positions, ratio of asymmetry δ, and conicity parameter.

Model	$(-\bar{y}_L, \bar{z}_L)$	$(\bar{y}_L, \bar{z}_L)$	(δ_y, δ_y)	γ_L	γ_R
Wing	(0.737, 0.663)	(0.743, 0.648)	(0.01, 0.02)	0.038	0.029
0.75s Fin	(0.801, 0.653)	(0.754, 0.692)	(0.06, 0.06)	0.048	0.059
1.50s Fin	(0.792, 0.650)	(0.771, 0.641)	(0.03, 0.01)	0.032	0.028

The standard deviations σ of the instantaneous readings from their arithmetic mean is used to quantify the unsteady motion of the vortices (as shown in Fig. 3). The σ values for the wing-alone model and the 1.50s-fin model vary generally around 3%, whereas the σ values for the 0.75s-fin model vary generally around 5%, going as high as almost 10% in some sections, indicating that the vortex pair over the 0.75s-fin model is much more unsteady in comparison to those of the other two models. The large values of σ occurring near the apex are due to the local large uncertainty of the coordinate measurements. Despite this fact, these test results provide strong evidence to support that adding a thin-plate dorsal fin of $h_L/s = 0.75$ to the delta wing renders the original vortex pair, which is relatively symmetric and conical to become asymmetric, non-conical and unsteady and that a fin of sufficient height restores symmetry and conicity of the vortices.



(a) Left vortex (b) Right vortex

Fig. 3. Unsteadiness parameter σ for the vortex positions vs. x/c_0.

4. Conclusion

Flow visualization and quantitative analysis of the vortex positions clearly demonstrate that the vortices which are symmetric, conical, and steady over the wing-alone model, become asymmetric, non-conical, and unsteady over the model with the fin height ratio of 0.75, and recover symmetry and conicity over the model with the fin height ratio of 1.50, all for the same flow conditions. These results provide direct experimental evidence of the theoretical predictions by Cai *et al*.[5]

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