Experimental Investigations on Stability of Vortex Flow over Slender Delta Wing with Dorsal Fin

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A vortex stability theory for slender conical bodies developed by Cai, Liu, and Luo predicted that vortices over a flat-plate delta wing at high angles of attack with zero sideslip are conical, symmetric, and stable but adding a low dorsal fin to the wing would destabilize the vortices and therefore render the originally symmetric vortices asymmetric and/or non-conical. To verify the validity of the theoretical predictions and show the behaviors of the vortices over the slender delta wing and its combinations when the flowfield-asymmetry onset occurs, a 2-D Particle Image Velocimetry (PIV) study is presented in this paper. A sharp-edged flat-plate delta wing of 82.5° sweep angle is tested in a low-speed wind tunnel at angle of attack of 35° and zero sideslip. The PIV technique is used to visualize and measure the distributions of the vorticity component normal to the cross-flow plane at 60% wing root chord. The same test is 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 0.3 and 0.6 respectively. The PIV results indicate that the vortex pair is symmetric and steady over the wing, but vortex breakdown occurs periodically when adding the low dorsal fin. The results provide direct experimental evidence of the theoretical predictions.

Nomenclature

\begin{itemize}
\item $c_0$ = wing root chord
\item $f$ = vortex breakdown frequency
\item $h_L$ = local height of dorsal fin
\item $K$ = Sychev similarity parameter, $\tan \alpha / \tan \epsilon$
\item $q_\infty$ = free-stream dynamic pressure
\item $Re$ = free-stream Reynolds number based on $c_0$
\item $s$ = local semi-span of wing
\item $\Omega$ = reduced angular frequency of vortex breakdown, $2\pi f c_0 / U_\infty$
\item $U_\infty$ = free-stream velocity
\item $x, y, z$ = body axes of the wing
\item $X, Y, Z$ = balance body axes
\item $\epsilon$ = semi-apex angle of wing
\item $\psi$ = phase angle in a period of vortex breakdown
\item $\omega_x$ = axial vorticity, $\partial w / \partial y - \partial v / \partial z$
\end{itemize}

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I. 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 under symmetric flow conditions is a fascinating fluid dynamics problem and of major importance for the performance and control of high-maneuverability flight vehicles that favor the use of slender bodies. Excellent reviews on this subject can be found in the papers by Ericsson1 and Lowson and Ponton.2

Shanks3 performed tests of highly swept delta wings with semi-apex angles of 6 to 20 degrees at high angles of attack up to 40° over a range of Reynolds numbers from 0.9×10^6 to 2.4×10^6 based on wing root chord. His measurements showed the appearance of significant rolling moments at angles of attack above 24 degrees and zero sideslip for models whose semi-apex angles are less than 12°. Shanks' experiment led to the belief that the vortex flow over a low aspect-ratio delta wing with sharp leading-edges, like the flow over slender pointed bodies of revolution, would become asymmetric at high angles of attack and zero sideslip before vortex breakdown occurs over the wing.4, 5 Later, Stahl, Mahmood, and Asghar6 performed water tunnel and wind tunnel experiments and 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 on the wing. That conclusion seemingly contradicted the observations by Shanks. Ericsson,1 however, noticed that Shanks' wing model differed from that by Stahl et al.6 in that Shanks' model contained a low center spline or 'fuselage bump' on the leeside of the wing. Ericsson 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 the centerline spline.

Cai, Liu, and Luo7 developed a vortex stability theory for slender conical bodies and showed by their analytical methods that vortices over a flat-plate delta wing at zero sideslip are conical, symmetric, and stable for all angles of attack but adding a low dorsal fin to the wing would destabilize the vortices and therefore render the originally symmetric vortices asymmetric or non-conical, or both. The flow would recover symmetry only when the fin height is increased to a critical level. The forward half of the Shanks' models approximated conical bodies. By examining the data in Shanks' test and comparing with their predicted range of fin heights needed to destabilize the vortex flow, Cai et al.7 suggested that the vortex asymmetries observed in Shanks' experiments were caused by the destabilizing effect of the center spline, which functions as a low height dorsal fin on Shanks' flat-plate delta wings.

It may be argued that the 'bump' on Shanks' test model is not exactly a flat-plate fin as assumed in the theory by Cai et al. Models of strictly slender and conical flat-plate fins added to a sharp-edged flat-plate delta wing were made. Investigations by the smoke-laser-sheet visualizations8, the six-component internal strain gage balance measurements9 and the particle image velocimetry10 yielded results agreeable to the theory.7

In order to verify the validity of the theoretical predictions and show the behaviors of the vortices over the slender delta wing and its combinations at higher angle of attack, a 2D PIV study at 35° angle of attack is performed in this paper to promote the validation.

The following sections briefly review the theoretical results6, the force-measurement results9 and the PIV results10. The PIV experimental setup is described. The PIV experimental results at 35° angle of attack are then presented and discussed. Conclusions are lastly drawn.

II. Theoretical Method and Results

In this section, a brief review of the theoretical vortex-flow model and the stability analysis method developed in Refs. 7 and 11 are presented, a delta wing of a semi-vertex angle, $\varepsilon = 7.5^\circ$ with and without a dorsal fin of a height, $h_D = 0.3s$ and 0.6s in the wing's symmetry plane is considered. The theoretical results for the three experimental models are calculated by the modified theory.9

When a vortex is slightly perturbed from its stationary position and then released, its motion follows the vortex velocity. After linearization, the increments of its coordinates as function of time are governed by a system of two linear, homogeneous, first-order, ordinary differential equations. Define the Jacobian and divergence of the vortex velocity field $q = (u, v)$.

$$J = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{pmatrix}, \quad D = \nabla \cdot q = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

(1)

It is shown7 that the eigenvalues of this problem are

$$\lambda_{1,2} = 0.5[D_0 \pm (D_0^2 - 4J_0)^{1/2}]$$

(2)
Where the subscript 0 denotes values at the stationary position of the considered vortex.

The eigenvalues $\lambda_1$ and $\lambda_2$ depend on the Sychev similarity parameter $K_{1,2}$, the sideslip similarity parameter $K_s$, and other geometric parameters such as ratio of $h_L$ to $s$. Any perturbation of the stationary positions of the vortex pair can be decomposed into a symmetric perturbation and an anti-symmetric perturbation. The maximum real part of the two eigenvalues $\lambda_1$ and $\lambda_2$ for each vortex of the stationary vortex pair under small symmetric or anti-symmetric perturbations is used to determine stability in this analysis. A positive value of this variable means perturbation growth (unstable), a negative value means decay of the perturbation (stable), and a zero value means that the perturbation persists with constant amplitude (neutrally stable). A vortex pair is stable if and only if both vortices are stable under both symmetric and anti-symmetric perturbations.

Figure 1(a) presents the maximum real part of the two eigenvalues for the stability of the stationary symmetric vortex pair versus angle of attack at zero sideslip for a at-plate delta wing with a semi-vertex angle, $\varepsilon = 7.5^\circ$. Fig. 1(b)(c) presents the maximum real part of the two eigenvalues for the stability of the stationary symmetric vortex pair for the wing with a dorsal fin of heights, $h_L = 0.3s$ and $0.6s$ at zero sideslip. For the case of wing alone, the stationary symmetric vortex pair is stable and the stability curves under symmetric and anti-symmetric perturbations coincide each other. For the two cases of wing-fin combination, the stability curves under symmetric perturbation remain the same as that of the wing alone as it should be, since the fins are positioned in the symmetry plane of the wing and the perturbation is symmetric. Under anti-symmetric perturbation, the stability curves for the two wing-fin cases deviate from that of the wing alone. The stationary symmetric vortex pair over the wing-fin combination is
When the angle of attack is low and becomes unstable as the angle of attack is increased beyond certain value. The instability onset occurs at \( \alpha = 32^\circ \) and \( 27^\circ \) for \( h_L = 0.3 \) and \( 0.6 \), respectively.

It is fantastic that a low dorsal fin has a destabilizing effect to the originally stable stationary symmetric vortex pair over a slender delta wing, in consideration of that the fin is seated in the symmetry plane of the wing and the sideslip angle is zero. The higher the dorsal fin is, the greater the destabilizing effect will be, and therefore, a lower angle of attack is required for the instability to occur for the higher fin case. The destabilizing effect is caused by the interaction between the vortex pair and the wing with low dorsal fin under small perturbations.

Furthermore, the theory predicts that unlike the case of a slender circular cone, there exist no stationary asymmetric conical vortex solutions for the slender flat-plate delta wing at high angles of attack and zero sideslip. If the stationary symmetric conical vortex pair over the combination of slender conical wing and fin becomes unstable, it is most likely non-conical and unsteady.

III. Review of Force-Measurement Results

The force measurements using a six-component internal strain-gage balance were performed in the NF-3 wind tunnel at Northwestern Polytechnical University. The test section has a width of 3.5 m, a height of 2.5 m. The free-stream turbulence level is 0.08%. The variation of the wind speed is within ±0.5 m/second. The variation of the free-stream velocity direction is within ±0.5°. The accuracy of \( \alpha \) and \( \beta \) measurements is within ±0.09°.

The delta wing of 82.5° swept angle is made of aluminum alloy plate of thickness 15 mm as shown in Fig. 2. \( c_0 = 990.0 \) mm. All edges are beveled with a 20° angle from the windward side of the wing so that the leeward side is perfectly flat. The two fins, \( h/s = 0.3 \) and \( 0.6 \) are made of aluminum alloy plate of thickness 2.0 mm. The fin leading edge is sharpened symmetrically with a 45° angle from both sides. The tip portion of the two models up to a station of 160.0 mm along the wing root chord is separately made to increase the precision in forming an accurate conical nose as assumed by the theory. The rest portion of the wing is common to the three models. The fin is fixed vertically on the upper surface of the wing in its symmetry plane. The six aerodynamic components are referred to a balance coordinate system XYZ. The origin is set at the balance center which is located in the model symmetry plane. The X-axis points upstream, parallel to the wing root chord. The Y-axis points to the wing starboard side. The Z-axis points downward.

The tests are conducted at \( \alpha = 12^\circ \sim 32^\circ \), \( U_e = 35 \) m/second, \( Re = 2.33 \times 10^6 \). Figure 3 presents the rolling moment coefficient \( C_{\ell} \) versus \( \alpha \) at zero sideslip for the wing-alone, the wing+0.3s-fin and the wing+0.6s-fin models from seven repeat runs. The repeatability are fairly good. Similar results are obtained for the side force and yawing moment. A force asymmetry onsets at \( \alpha = 26^\circ \) and \( 22^\circ \) for the wing+0.3s-fin and the wing+0.6s-fin model, respectively, and no asymmetry occurs for the wing model, which agrees with the theoretical predictions.
IV. Experimental Setup for PIV Study

The PIV experiments were conducted in a low-turbulence and low-noise 1.5 m × 1.5 m wind tunnel at Beijing University of Aeronautics and Astronautics. The free-stream turbulence level is 0.08%. The wing and the wing+0.6s-fin models are those used in the force-measurement experiments. The model support is enforced by suspending the model with tension wires to the wind tunnel wall. The wing body coordinates \( xyz \) are introduced for the PIV study. The origin is located at the wing apex, the \( x \)-axis points downstream and parallel to the wing root chord, the \( y \)-axis points to the wing starboard side and the \( z \)-axis points upward.

The PIV system is manufactured by DANTEC Company. Fig. 4 shows a schematic of the experimental setup. The Nd-YAG laser, a product of LABest Company PIV-350, emits double pulses of 350 mJ energy. Through optics, the laser beam is converted into a 220 × 220 mm light sheet of 3 mm thickness. The laser sheet is set normal to the wing root chord. The flow seeds are the smoke particles of approximately 1 \( \mu \)m in diameter commonly used in cinema industry. A CCD camera of 2048×2048 pixels is used to record the cross-flow fields. For each cross-flow field a dual-pulse separated with 30 \( \mu \)s is recorded 50 times at a frequency of 2 Hz. The dual-pulse images are analyzed with the FlowManager software to yield the distribution of the instantaneous velocity vector \( (v, w) \) over the cross-flow plane. The instantaneous vorticity component \( \omega_x \) is calculated from the \( (v, w) \) distribution.
Figure 3. Rolling moment coefficient measured in 7 repeat runs.

Figure 4. Schematic of the PIV experimental setup.
V. Experimental Results Review of PIV Study at $\alpha = 30^\circ$

The PIV measurements at 30° angle of attack are made at only one station at $x/c_0 = 0.6$ for wing-alone model and at various cross-flow planes from $x/c_0 = 0.3$ to 0.8 with an increment of 0.1 for the wing+0.6s-fin model at $\alpha = 30^\circ$, $\beta = 0$, $U_\infty = 35$ m/second, and $Re = 2.33 \times 10^6$.

For the wing-alone model the asymmetric flow is well known. For example, Stahl et al. observed that the leading-edge vortices are symmetric, Verhaagen et al. using a no-nulling five-hole probe showed that the cross-flow velocity components are conical away from the apex and trailing edge regions, and Visser, et al. showed that the axial vorticity is also conical by hot-wire measurements. Thus, only one station at $x/c_0 = 0.6$ is measured for the wing model, while for the wing-fin model a series of stations are studied. No vortex breakdown on the wing surface is observed at the 30° angle of attack.

A. Comparison between the Wing and the Wing-Fin Models at $x/c_0 = 0.6$

Figure 5 shows the contours of the time-averaged axial vorticity $\omega_x$ on the cross-flow plane for the wing model and the wing+0.6s-fin model at $x/c_0 = 0.6$. The free shear layer separated from the sharp leading edge of the wing first extends upward and outbound of the wing and then coils up spirally and finally develops into the concentric circular contours of a vortex core. The magnitude of the axial vorticity increases to maximum at the core center where the cross-flow velocity vanishes.

![Figure 5. Comparison of the time-averaged axial vorticity contours between the wing-alone and the wing-fin models on the cross-flow plane at $x/c_0 = 0.6$, $\alpha = 30^\circ$, $\beta = 0$.](image-url)
Table 1 presents the coordinate \((y/s, z/s)\) of the (primary) vortex center and the axial vorticity at the starboard and port vortex centers from Figure 5 for the wing and the wing-fin models. The magnitudes of the axial vorticity at the starboard and port vortex centers are substantially different for the wing-fin model, while those for the wing-alone model are practically the same.

Therefore, the axial-vorticity distribution over the wing+0.6s-fin model is asymmetric to the symmetry plane of the model. The z/s-coordinates also indicates the asymmetry for the wing-fin model. The PIV study confirms the analytical predictions.

Table 1. Comparison of the vortex center coordinates \((y/s, z/s)\) and the axial vorticity at the vortex center between the wing-alone and the wing+0.6s-fin models at \(x/c_0 = 0.6, \alpha = 30^\circ, \beta = 0\).

<table>
<thead>
<tr>
<th>Model</th>
<th>Port side</th>
<th>Starboard side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(y/s)</td>
<td>(z/s)</td>
</tr>
<tr>
<td>Wing</td>
<td>−0.69</td>
<td>0.59</td>
</tr>
<tr>
<td>Wing+0.6s-fin</td>
<td>−0.73</td>
<td>0.54</td>
</tr>
</tbody>
</table>

B. Chordwise Distributions of Axial Vorticity over the Wing-Fin Model

Chordwise development of the cross flow over the wing+0.6s-fin model are studied. Fig. 6 presents the contours of the time-averaged axial vorticity of the starboard vortex on the cross-flow planes from 0.3\(c_0\) to 0.8\(c_0\). To study the flow conicity, the local semi-span \(s\) is chosen to normalize the axial vorticity. Table 2 presents the distribution of the non-dimensional axial vorticity \(s\omega_x/U_\infty\) along the vortex center line and the coordinates \((y/s, z/s)\) of the vortex center over the wing+0.6s-fin model at Stations \(x/c_0 = 0.3\sim 0.8\). The positions of the two primary vortex center lines are definitely asymmetric, and the axial vorticity distributions along the two vortex center lines are significantly different. Thus, the symmetric vortex flow over the wing alone becomes asymmetric for the wing-fin model.

Table 2. Distribution of the axial vorticity \(s\omega_x/U_\infty\) along the vortex center line and the center coordinates \(y/s, z/s\) over the wing+0.6s-fin model at \(x/c_0 = 0.3\sim 0.8, \alpha = 30^\circ, \beta = 0\).

<table>
<thead>
<tr>
<th>(x/c_0)</th>
<th>(s\omega_x/U_\infty)</th>
<th>(y/s)</th>
<th>(z/s)</th>
<th>(s\omega_x/U_\infty)</th>
<th>(y/s)</th>
<th>(z/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>−13.5</td>
<td>−0.72</td>
<td>0.46</td>
<td>14.2</td>
<td>0.72</td>
<td>0.54</td>
</tr>
<tr>
<td>0.4</td>
<td>−16.7</td>
<td>−0.79</td>
<td>0.51</td>
<td>15.7</td>
<td>0.81</td>
<td>0.58</td>
</tr>
<tr>
<td>0.5</td>
<td>−19.7</td>
<td>−0.77</td>
<td>0.46</td>
<td>18.1</td>
<td>0.72</td>
<td>0.46</td>
</tr>
<tr>
<td>0.6</td>
<td>−26.4</td>
<td>−0.73</td>
<td>0.54</td>
<td>32.5</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>0.7</td>
<td>−42.6</td>
<td>−0.70</td>
<td>0.59</td>
<td>39.4</td>
<td>0.70</td>
<td>0.59</td>
</tr>
<tr>
<td>0.8</td>
<td>−46.1</td>
<td>−0.72</td>
<td>0.58</td>
<td>38.3</td>
<td>0.71</td>
<td>0.60</td>
</tr>
</tbody>
</table>
To study the flow conicity two ray lines passing through the apex of the wing-fin model are chosen in the neighborhood of the vortices. Table 3 shows that the distribution of the non-dimensional axial vorticity along each ray line varies significantly at $x/c_0 = 0.3 \sim 0.8$, $\alpha = 30^\circ$, $\beta = 0$. Therefore, the conical flow over the wing alone becomes non-conical over the wing-fin model.

<table>
<thead>
<tr>
<th>$x/c_0$</th>
<th>$x_\omega/\Omega_u$</th>
<th>$y/s$</th>
<th>$z/s$</th>
<th>$x_\omega/\Omega_u$</th>
<th>$y/s$</th>
<th>$z/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>$-9.9$</td>
<td>$-0.73$</td>
<td>0.54</td>
<td>8.8</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>0.4</td>
<td>$-14.8$</td>
<td>$-0.73$</td>
<td>0.54</td>
<td>13.4</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>0.5</td>
<td>$-16.4$</td>
<td>$-0.73$</td>
<td>0.54</td>
<td>15.2</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>0.6</td>
<td>$-26.4$</td>
<td>$-0.73$</td>
<td>0.54</td>
<td>32.5</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>0.7</td>
<td>$-26.6$</td>
<td>$-0.73$</td>
<td>0.54</td>
<td>27.0</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>0.8</td>
<td>$-35.2$</td>
<td>$-0.73$</td>
<td>0.54</td>
<td>32.4</td>
<td>0.73</td>
<td>0.64</td>
</tr>
</tbody>
</table>

The above results clearly demonstrate that the vortical flow over the wing with the low dorsal fin at 30° angle of attack is asymmetric and non-conical. Therefore, the stable symmetric vortex pair over a slender sharp-edged flat-plate delta wing becomes unstable under small perturbations when combined with a flat-plate dorsal fin of low height.

VI. Experimental Results of PIV Study at $\alpha = 35^\circ$

The PIV measurements are made at only one station at $x/c_0 = 0.6$ for both wing-alone and wing-fin model at $\alpha = 35^\circ$, $\beta = 0$, $U_\infty = 35$ m/second, and $Re = 2.33 \times 10^6$. With 2-D PIV test technique, we recorded the instantaneous vortex flowfield for 50 times with 2 Hz dual-pulse frequency. From these original pictures, we can clearly find that the flowfield keeps steady for wing-alone model and it becomes unsteady and goes through a periodical variation for wing-fin model. The mechanisms of the unsteady flow for the wing-fin models are investigated by phase-locked (locked to the vortex breakdown period) averaged vorticity. The time-averaged vorticity can not resolve the phase-locked vorticity produced by the periodical vortices variations.

A. Behaviors of the vortices over the wing-alone model

The vortices over the wing-alone are investigated by phase-locked (locked to the variation period of the vortices over wing-fin model, which is about 2s) averaged vorticity for convenient comparison with wing-fin model. The dual-pulse is recorded 50 times at a frequency of 2 Hz, there are 4 readings evenly distributed at phase-angle increment of 90° in one period of the variation of vortices. At a given phase angle there are totally 12 samples to be averaged.

Figure 7 show the contours of the phase-locked-averaged axial vorticity $\omega_x$ on the cross-flow plane for the wing model. It indicates that it is practically the same for those contours, and there still is no vortex breakdown at the measured station. The vorticity contours clearly demonstrate that the vortex pair is symmetric and steady.

B. Behaviors of the vortices over the wing+0.3s-fin model

In the present work, we just changed the fin and tip and keep the main portion of the wing after the tips be common to all models, the other test conditions is same to all three model. That is to say, the dual-pulse is still recorded 50 times at a frequency of 2 Hz.

For the wing+0.3s-fin model, the PIV pictures clearly show that the starboard vortex undergoes a periodic variation during the record time, the period is about 2 seconds, the reduced angular frequency $\Omega = 0.06$. There are almost 4 readings at phase-angle increment of 90° in one period of the variation of vortices. At a given phase angle there are almost 7 samples to be averaged, some unclear PIV pictures are given up.

Figure 8 shows the contours of the phase-locked-averaged axial vorticity $\omega_x$ on the cross-flow plane for wing+0.3s-fin model. It indicates that the port vortex keeps almost no change, the starboard vortex goes through a periodic variation.
\begin{align*}
\psi &= 180^\circ \\
\psi &= 90^\circ \\
\psi &= 0^\circ 
\end{align*}
Figure 7. Phase-locked-averaged vorticity distributions with different phase angle for wing-alone

(a) $\psi = 0^\circ$

(b) $\psi = 90^\circ$

(d) $\psi = 270^\circ$
C. Behaviors of the vortices over the wing+0.6s-fin model

For the wing+0.6s-fin model, the period of the vortices variation is about 1.5 seconds. the reduced angular frequency $\Omega=0.13$. There are almost 3 readings at phase-angle increment of 120° in one period of the variation of vortices. At a given phase angle there are almost 7 samples to be averaged, some unclear PIV pictures are gave up.

Figure 9 shows the contours of the phase-locked-averaged axial vorticity $\omega_x$ on the cross-flow plane for the wing+0.6s-fin of different phase angles. The figures indicate that the starboard vortex keeps steady, the port vortex goes through a periodic variation, which is different from wing+0.3s-fin model. We can also notice that the degree of the unsteadiness of the vortex breakdown occurs on the wing+0.6s-fin model is bigger than that of wing+0.3s-fin model, because the vorticity of the port vortex of the wing+0.6s-fin model is more diffuse than that of the starboard vortex of the wing+0.3s-fin model. What is more, the vortex breakdown period of the wing+0.6s-fin model is shorter than that of the wing+0.3s-fin model.

Figure 8. Phase-locked-averaged vorticity distributions with different phase angle for wing+0.3s-fin model at $x/c_0 = 0.6$, $\alpha = 35^\circ$.

(d) $\psi = 270^\circ$
Figure 9. Phase-locked -averaged vorticity distributions with different phase angle for wing+0.6s-fin model at $x/c_0 = 0.6$, $\alpha = 35^\circ$.

(a) $\psi = 0^\circ$

(b) $\psi = 120^\circ$

(c) $\psi = 240^\circ$
D. Vortex Position and Vorticity Comparison between the Wing and the Wing-Fin Models

Figure 10 shows the axial vorticity distribution through the vortex core alone the spanwise lines at different phase angles for three test models. It indicates that the positions of the vortex pair are almost symmetric and the vorticity keeps almost equal for wing-alone model. For wing+0.3s-fin model, it indicates that the positions of the vortex pair are almost symmetric and the vorticity keep almost equal at phase angle of 0°. When the vortex breakdown onset occurs, the position and the vorticity between port and starboard vortex become clearly different. The axial vorticity distribution of wing+0.6s-fin model indicates that the positions of the vortex pair are clearly different at all phase angles.
VII. Conclusions

The stability of vortices over a slender sharp leading-edged flat-plate delta wing with and without a dorsal fin mounted in the symmetry plane of the wing at high angles of attack, zero sideslip and low speed is analyzed and tested. The analysis is based on a linearized stability theory and a slender conical-flow model. The experimental studies by six-component strain gage measurement and particle image velocimetry are performed in parallel with the analytical results.

The PIV measurements are made at only one station at $x/c_0 = 0.6$ for wing-alone model and wing-fin model at $35^\circ$ angle of attack, $\beta = 0$, $U_\infty = 35$ m/second, and $Re = 2.33 \times 10^6$. The distributions of the phase-locked-averaged axial vorticity component obtained from the PIV test clearly demonstrate that the vortex flow over the wing keeps steady and symmetric, but becomes unsteady and undergoes a vortex breakdown periodically. The periods of vortex variation are about $2s$ and $1.5s$ for wing+0.3s-fin model and wing+0.6s-fin model respectively. The vortices over the wing-alone are investigated by phase-locked-averaged, the following flow features are revealed.

1. The vortices changes between wing and wing-fin model show that the stable symmetric vortex pair over a slender sharp-edged flat-plate delta wing become unstable under small perturbations when combined with a flat-plate dorsal fin of low height.

2. Besides vortex asymmetry, unsteady and non-conical, the vortex breakdown is also the behaviors when the vortex instability onset is predicted by the theoretical method.

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