Observation of the instability in the shear layer behind a paraboloidal-nose cylinder

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Abstract. Flow visualization was used to investigate experimentally the evolution process of the instability in the separated shear layer behind an axisymmetric paraboloidal-nose cylinder at high angles of attack. The appearance of instability is observed as uniformly spaced vortex loops showing wavy folds of a shear layer. The distance between the counter-rotating primary and secondary vortices varies with time and the vortex loops always appear first in the region between the primary and secondary vortex at the time and place where these vortices approach closest together. The second vortex loops appear in the downstream of the first ones delayed by the appearance of the first vortex loops. It is suggested that the short wavelength perturbations of the preceding vortex loops advect on the outer surface of the primary vortex along the fluid path accompanied by the dominating vortex loops in downstream region.

1. Introduction
A flow over a paraboloidal-nose cylinder at incidence provides the fundamental example of the simple body flow field seen in most high angle of attack flows and provides the model flow of three-dimensional separated flows. Three-dimensional flow separation about a slender body at incidence has been the subject of many studies, including topological structures for a body of revolution such as a slender cone [1], a round-nosed body [2], and a prolate spheroid [3, 4]. The structures of the symmetric separated flow about a paraboloidal-nose cylinder at incidence with main, primary, and secondary vortices on the lee side has been well established in experiments and is illustrated in figure 1. The feeding shear layers roll up to form a pair of counter-rotating main vortices.

It was shown by Riley & Lowson [5] that steady sub-vortical structures appear in the free shear layer over delta wings. They demonstrated that the smoke filaments formed near the leading edge of the wing spiral into the core of the main vortex as they pass downstream. They suggested that the steady sub-vortices are due to a local three-dimensional Kelvin-Helmholtz instability of the free shear layer.

In the present study, we investigate experimentally the instability of the flow behind a paraboloidal-nose cylinder with appearance of vortex loops in the feeding shear layer encircling the main vortices. This instability is unsteady in contrast to the steady sub-vortical structures over delta wings, and little data on this kind of instability were available in previous works. The present measurements were accomplished using flow visualizations together with PIV measurements in a towing system in a settled air chamber.
2. Experimental setup

The model of a 180mm length cylinder with diameter $D = 75$mm and a paraboloidal nose length 140mm ($1.87D$) was tested in this experiments.

The flow facility used in all the experiments described herein is a towing system in a settled air chamber with a rectangular cross section shown in figure 2. The dimensions of the chamber are 620mm in width $\times$ 820mm in height and a length of 1790mm. A linear actuator enables positioning of a model with the stroke of 1000mm at a maximum speed of 1.5 m/s. The slider of the linear guide, on which a model is fixed at an angle of attack $\alpha$, is driven by the electric motor programmed as a foregoing acceleration with 1.9$D$ in stroke and a steady traveling motion with 9.4$D$ followed by a deceleration with 1.9$D$.

In the following, we will adopt a coordinate system (the same as for the figure shown in section 1) with the $x$-axis along the body axis, the $y$-axis along the symmetric plane, and the $z$-axis perpendicular to them, where the origin is taken at the nose apex.

The evolution of the wake was then measured by a particle image velocimetry (PIV) using cross-sectional and longitudinal cuts produced by the sheet illumination of the Nd:YAG laser. Glycol/water fog droplets (nominally 5 $\mu$m diameter, created with a commercial theatrical fog generator) were seeded into the air chamber and the visualized image was recorded with a CCD camera (1008 $\times$ 1018pixel, 8bit). The cross-sectional cuts of the flow along planes parallel to $yz$-plane performed at various downstream locations, $x/L$, will be referred to as ‘front views’. While the longitudinal cuts along planes parallel to $xz$-plane performed at various locations, $y/R$ ($2R = D$, where $R$ is the radius of the cylinder), will be referred to as ‘top views’.

To visualize the three-dimensional evolution of the wake, we employed a titanium tetrachloride (TiCl$_4$) to produce a dense white smoke (titanium dioxide), as a result of a chemical reaction, due to the presence of moisture in the air. The titanium tetrachloride was applied on a portion of the nose surface, which allowed us to visualize integrated streaklines of a white smoke developing in the wake.
Figure 3. Visualization of vortex loops behind an axisymmetric paraboloidal-nose cylinder. \( Re = 7200 \). Titanium tetrachloride was applied near the nose apex and on the windward symmetry line. Main vortex (M) and primary vortex (P) are seen in the picture. (a) \( \alpha = 40^\circ \), (b) \( \alpha = 70^\circ \).

3. Results

The TiCl\(_4\) visualization was used to study and characterize the instability in the feeding shear layer. A CCD camera (the same as for the PIV measurements described in section 2) and a stroboscope (pulse duration 22 \( \mu \)s) were used to capture snapshots of the flow. Titanium tetrachloride was applied on the portion of the body surface near the nose apex and on the windward symmetry line of the nose. The test speed was \( U = 1.5 \) m/s and Reynolds number was \( Re = 7200 \) (\( Re = UD/\nu \), where \( \nu \) is the kinematic viscosity of the air).

For \( \alpha = 40^\circ \) and \( 70^\circ \) (figures 3a, 3b), the main vortex and the primary vortex (denoted in the picture by the letters ‘M’ and ‘P’, respectively) are seen in the picture with vortex loops, which are encircling the main vortex and extend to the cylinder part of the body from the end of the nose at \( \alpha = 40^\circ \) and from the middle of the nose at \( \alpha = 70^\circ \). The regularity of the vortex loops is quite apparent in the visualization shown in figure 3, where the spacing of the loops is almost uniform. Further downstream, there appear slight irregularity in the instantaneous vortex-loop shapes with turbulence.

To characterize the structure of the vortex loops, we took several pictures at \( \alpha = 40^\circ \) by changing the amounts and the places to apply titanium tetrachloride. Figure 4 shows the close up view of the vortex loops. In this picture, the most outer sheet of white smoke estimates the feeding shear layer and we observed the wavy folds of the shear layer around the main vortex. The waves extend downstream while increasing in magnitude. Figure 5 was taken at a different location, where the main, primary, and secondary vortices (denoted in the picture by the letters ‘M’, ‘P’, and ‘S’, respectively) are seen in this picture. Observe that at the border region between the primary and the secondary vortices, a serial pattern of vortices appear with a constant spacing. The above observations support our assumption that each vortex loop consists of a vortex tube.

To characterize the temporal behavior of the vortex loops, we took sequence of pictures using
Figure 4. Close-up view of the vortex loops showing the wavy folds of a shear layer. $Re = 7200, \alpha = 40^\circ$.

Figure 5. Footprints of the vortex loops between the primary and the secondary vortices. $Re = 7200, \alpha = 40^\circ$.

A high-speed camera moving with the model. The pictures were taken at a frame rate of 240 frames per second with an exposure-time of 1/2000 seconds. A metal halide lamp was used for illumination. Figure 6 presents a representative sequence of TiCl$_4$ visualizations showing the vortex loops that appeared intermittently around $x/L = 1.0$ at $\alpha = 40^\circ$. In these pictures, the main flow is from top to bottom, and the primary and the secondary vortices (denoted in the first frame of the pictures by the letters ‘P’ and ‘S’) are seen. Note that the distance between the primary and the secondary vortices varies with time and the vortex loops first appear between these vortices at the time and place where these two vortices approach closest together. The newly created vortex loops (denoted in the pictures by the letters $A_1$ and $B_1$) are so weak that the surface of the primary and the secondary vortices adjacent to the vortex loops are almost flat.

At the downstream region of these vortex loops, the ripples appear on the upper surface of the primary vortex, delayed by the appearance of the first vortex loops. The ripples propagate downstream while increasing in magnitude, forming new vortex loops (denoted in the picture by the letters $A_2$ and $B_2$). The delayed vortex loops are originated not from the region between the primary and the secondary vortices but from the outward surface of the primary vortex, where the delayed loops are stronger in magnitude than the preceding ones. It is considered that the vortex loops shown in figure 3 correspond to the delayed loops, since the preceding loops are so weak that they are overshadowed by the delayed ones.

Figure 7 shows vorticity distributions at $\alpha = 40^\circ$ obtained using a particle image velocimetry and measured at various cross sections, with $\omega^*$ non-dimensionalized by the velocity of the free stream $U$ and the diameter of the cylinder $D$ as $\omega^* = (D/U)\omega$. The locations of the primary and the secondary vortices (denoted in the figure by the letters ‘P’, and ‘S’ respectively) are obtained from the front views of averaged vorticity distributions from 50 sets of data in various cross sections shown in figure 7a, and are depicted in figures 7c and 7d (data at $x/L = 0.93$ and 1.25 are not presented in figure 7a). In figure 7c, preceding vortex loops and delayed vortex loops (denoted in the figure by the letters ‘L$_1$’ and ‘L$_2$’ respectively) are clearly seen in the
Figure 6. Vortex loop formation around $x/L = 1.0$. $Re = 7200$, $\alpha = 40^\circ$. Time interval between frames is 8.33 ms. ‘P’ and ‘S’ represent the primary and the secondary vortex, respectively. The vortex loops $A_1$ and $B_1$ first appear on the edge between the primary and the secondary vortices, accompanied by ripples in the downstream region near the upper surface of the primary vortex. The ripples grow along the shear layer, forming stronger new vortex loops $A_2$ and $B_2$.

A longitudinal cross section at $y/R = 1.07$ that is above the primary and the secondary vortices corresponding to the line A-A in figure 7a. Note that preceding loops $L_1$ are located between the primary and the secondary vortices, while delayed loops $L_2$ are located in the outward side of the primary vortex. This observation is consistent with the behavior of the vortex loops described above in figure 6. Note also that the preceding loops extends to downstream region in parallel with the delayed ones. In other words, the preceding loops coexist with the delayed ones forming a double loop structure. In such a case, however, the preceding loops are difficult to observe by visualizations, since they are overshadowed by the delayed loops. The vortex tubes constituting the delayed loops are observed also in the other orthogonal cross section at $x/L = 1.43$ in figure 7b, where its direction of rotation is counter clock-wise in the right half of the front view and clock-wise in the right half of the top view. This result confirms that each delayed vortex loop consists of a vortex tube.

To confirm further that we have observed the change in the distance between the primary and the secondary vortices accompanied by the formation of the preceding vortex loops, we visualized the vortex cores on the lee side of the body at $\alpha = 40^\circ$ using TiCl$_4$. In figure 8, a pair of parallel primary and secondary vortices are seen behind the body, where symmetric deformation of the vortex pair appeared in the nose region with an axial wavelength of about $4b \sim 5b$ ($b$ is the distance between the vortex pair). This instability of the counter-rotating vortex pair is due to the Crow instability [6], which cause the temporal change of the distance between the primary and the secondary vortices. Further downstream, the breakdown of the primary and the secondary vortices are occurred as can be seen in figure 8. This vortex breakdown is due to the deceleration of the axial flow behind the cylinder, which causes disorder of the vortex loops as shown in figure 3.

Under the effect of the primary and the secondary vortices approaching each other, we found that the preceding vortex loops appear in the region between the two vortices. This evidence favors the hypothesis that observed vortex loops are a result of the short wavelength instability of
Figure 7. Vorticity distributions. $Re = 7200$, $\alpha = 40^\circ$. (a) front views for averaged vorticity from 50 sets of data, (b) front views for instantaneous vorticity, (c) and (d) top views for instantaneous vorticity in the cross sections corresponding respectively to the lines A-A and B-B in (a).

a counter-rotating vortex pair as shown in figure 9. Leweke & Williamson [7], studying the short wavelength instability, show that the amplitude of the short wavelength instability is larger in the regions where the large-scale Crow instability brings the two vortices closer together. However, it must be considered that the down-wash flow between the primary and the secondary vortices cannot lift up the short wavelength perturbations as vortex tubes. It would be interesting to address the link between the preceding vortex loops and the three-dimensional separation type of foci or spiral nodes [2]. It would be natural that the short wavelength perturbations affect the skin-friction lines and may explain the observed preceding vortex loops.

The formation of the preceding vortex loops has an effect on the development of the ripples in the downstream region. We found, in figure 6, that the second vortex loops appeared in the downstream of the preceding loops delayed by the appearance of the preceding loops. These vortex loops originate from the ripples on the upper surface of the primary vortex, where the strong cross flow lifts up these ripples towards the main vortex along the feeding shear layer. It is important to mention that the organized structure and the wavelength of the preceding loops are retained at the ripples. This result can be explained by assuming that the upstream short wavelength perturbations are advected along the path of the flow on the surface of the primary vortex.

4. Conclusions

We have studied the development of the instability in the shear layer as an appearance of vortex loops. Flow visualization of the temporal properties of the vortex loops revealed that the
Figure 8. Visualization of vortex cores. Re = 7200, α = 40°. Higher order vortices (represented by H and H') are seen in the picture in addition to main (M), primary (P) and secondary (S) vortices.

Figure 9. Vortex skeleton model of a flow behind an axisymmetric paraboloidal-nose cylinder at high angles of attack. Vortices in the other side of the symmetric plane are not shown.

preceding vortex loops always grow first, accompanied by the delayed vortex loops dominating in the wake. We have also shown that the distance between the primary and the secondary vortices varies with time possibly by the Crow instability of a counter-rotating vortex pair and that the preceding loops appear intermittently at the time and place where the primary and the secondary vortices approach closest together. Furthermore, we found that the preceding loops appear in the region between the primary and the secondary vortex, while the delayed loops are originated from the ripples on the upper surface of the primary vortex. This result was further confirmed by the PIV measurements of vorticity distributions. The PIV measurements also revealed that the preceding loops and the delayed loops can coexist in the downstream region. It appears to indicate that the delayed vortex loops are due to the short wavelength perturbations of the preceding vortex loops advected on the surface of the primary vortex.

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