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On Unsteadiness of a Laminar Junction Flow

Jianhua Liu*, Shucheng Zhai, Fangwen Hong and Kai Yan

China Ship Scientific Research Center
National Key Laboratory on Ship Vibration & Noise
Wuxi, China
* jhliu@cssrc.com.cn

Abstract

A wing-body junction flow of a navigating underwater vehicle is considered to be a crucial source of flow radiating acoustic noise, which inspires interests in research on junction flows. Complex interference flow fields and three-dimensional separations are produced by an upstream boundary layer on the vehicle surface that encounters an obstacle attached. To figure out the contribution of unsteady motions of horse-shoe vortices to intensive pressure fluctuations around junctions, a series of experiments are conducted in a low-speed wind tunnel by smoke-wire flow visualizations and time-resolved PIV measurements.

1 Introduction

Junction flows occur in a number of practical aerodynamic and hydrodynamic situations, including external aerodynamic, turbomachinery, underwater vehicle, electronic component cooling, and river/bridge flows. In all of these cases, complex interference flow fields and three-dimensional separations are produced by an upstream boundary layer on a surface that encounters an obstacle attached to that surface, such as a wing, turbine blade, sail or conning tower, electronic chip, or bridge pier. The past experimental and numerical studies of junction flows were extensively reviewed and their underlying physics were discussed. The most striking finding of previous experiments was that the horseshoe vortex was dominated by coherent, low-frequency unsteadiness and characterized by bimodal histograms of velocity probability density functions (PDFs). Especially in turbulent junction flows at a high Reynolds number, these vortices were highly unsteady and were responsible for high turbulence intensities, high surface pressure fluctuations and heat transfer rates, and erosion scour in the nose region of the obstacle.
According to the work quoted above, it was difficult to find out where the unsteadiness came from in a turbulent or laminar junction flow at Re<1000 and it is crucial for the junction flow control. In this paper, a series of images of smoke-wire flow visualizations give details about what is happing at the base of the obstacle and the reverse motion of the corner vortex is considered to lead to the laminar junction unsteadiness. Based on these findings, a novel idea of locating a vertical thin end-plate upstream of circular-cylinder to cut off the corner vortex is proposed and result is discussed in aspects smoke-wire flow visualizations and time-resolved PIV measurements. Finally, effect of unsteadiness of junction flows on flow radiated noise is analyzed correspondingly.

2 Experimental setup

Experiments were carried out in a low-speed open-return wind tunnel with test section dimensions $0.3\times0.3\times1.9$ m^3, which was a through type tunnel with an exhaust that recirculated back into the room via a series of filters. A 10-mm-thick clear acrylic flat-plate with a 2:1 elliptical leading edge and a sharp trailing edge was mounted horizontally in the test section and 0.15 m after a 7:1 area ratio contraction, with a 200-mm-distance left to install a circular cylinder vertically at the centreline of the flat-plate and below the top wall. The cylinder was also made of acrylic, whose diameter was D=31 mm and the height was 195 mm to leave a 5-mm-gap intentionally between the top wall to prevent junction vortices from into being and their impact on the junction flow to be interested in. A sketch of model arrangement and coordinates is shown in Fig. 1 and the flow is from left to right. The plane *o-x'y* is a vertical plane in an angle of 30° to *o-xy* plane.

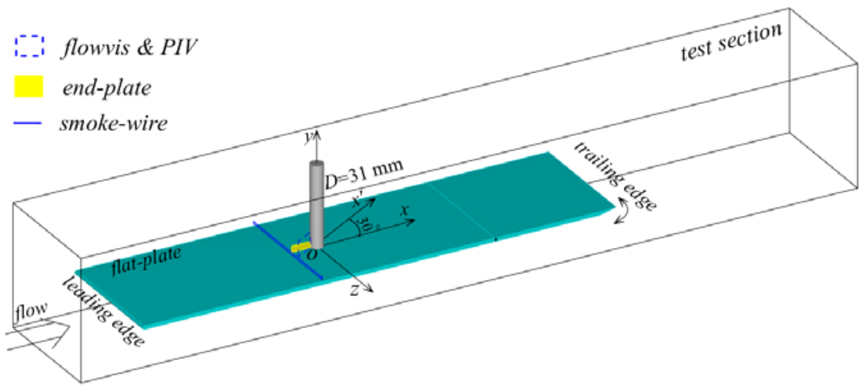

Figure 1: Sketch of model arrangement and coordinates.

3 Unsteady vortex motion of a laminar junction flow

PIV measurements

The flow field around a laminar junction was studied with a Dantec dynamics two-dimensional PIV system in symmetric, 30°planes and horizontal planes at a Reynolds number of Re_D=3306. The streamlines of phase-averaged flow field in symmetric, 30° planes and a horizontal plane y=1.5 mm around the junction are depicted as solid lines in Fig. 2, with contours of pressure fluctuations estimated based on the two-dimensional velocity vectors, at an instant when the corner vortex are impinging into the primary vortex. The freestream is from left to right.

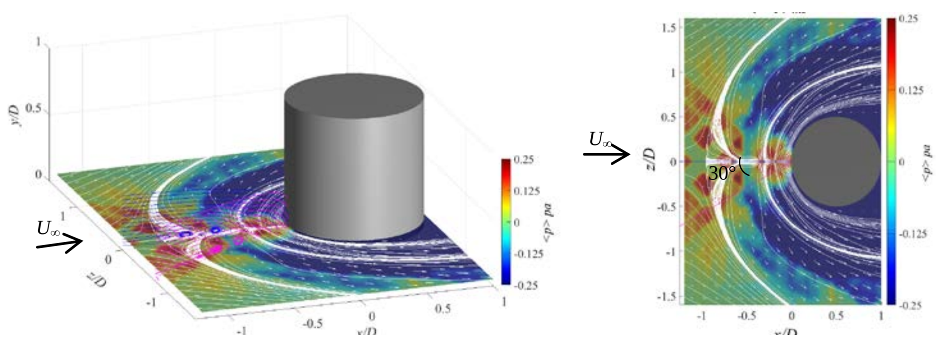

Figure 2: Snapshot of the phase-averaged flow field around a laminar junction by PIV measurements.

Flow visualizations

Smoke-wire flow visualizations were conducted to figure out what was happening at the base of the wing in detail. Two 100-μm-diametered wires were horizontally placed upstream of the cylinder by 55 mm within the incoming boundary layer, with heights of 4 mm and 9 mm above the flat-plate, respectively. The *o-x'y* plane was illuminated by a laser sheet and images were captured at 1 kHz. Therefore, time interval between the two adjacent images is 1 ms.

A process of vortices motion in a cycle is presented by the seven images in Fig. 3(I). As seen from Fig. 3(I), the corner vortex goes downstream together with the primary vortex until when it is extremely close to the cylinder, given in Fig. 3(I)(*d*) and it changes direction to go upstream pointing to the primary vortex in Fig. 3(I)(*d*-*e*). Then, the corner vortex runs into the primary vortex and starts turning around as a part of the primary vortex, which leads to shape changes and oscillations of the primary vortex. Finally, the corner vortex is merged into the primary vortex and they become a new corner vortex of the next cycle. In a cycle, the vortex pattern is changing from six-vortex into four-vortex, which takes on a highly unsteady process. During a cycle, the impact and merging into event as shown in Fig. 3(II) is believed to lead to unsteadiness of junction vortices system and highly oscillation of junction wake flows.

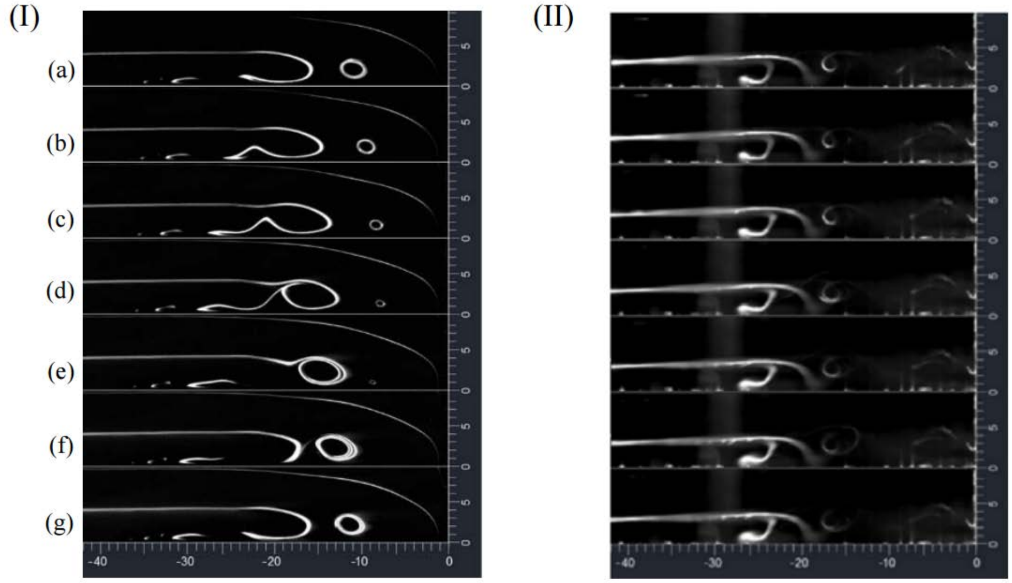

Figure 3: Images of smoke-wire flow visualization in 30° plane in a 14 ms interval. (I) Laminar junction; (II) Upstream vertical splitter control.

Pressure field estimation

Decomposition of the pressure fluctuations associated to the phase-averaged event from the total pressure fluctuations estimated by multi-path integral method is conducted in the laminar junction flow, as shown in FIG. 4. The phase-averaged events contribute nearly all the total pressure fluctuations, except for a small amount of it around x'/D=-0.46 where the secondary counter-rotating vortex appears nearby. And the total pressure fluctuation level grows up from the flat-plate to a vertical location corresponding to the maximum p_{rms}. Beyond it, the total pressure decays, as well as that of the phase-averaged and secondary vortex. While, the total pressure fluctuation of end-plate control case keeps increasing as away from the flat-plate without any apparent peaks at any vertical location. However, the pressure fluctuation is at a comparative or even higher level on the flat-surface. Therefore, the pressure field has been changed from a pressure concentrated pattern into a dispersive pattern by the vertical end-plate placed in the symmetric plane, *i.e.*, pressure fluctuation gradually increases as away from the solid wall.

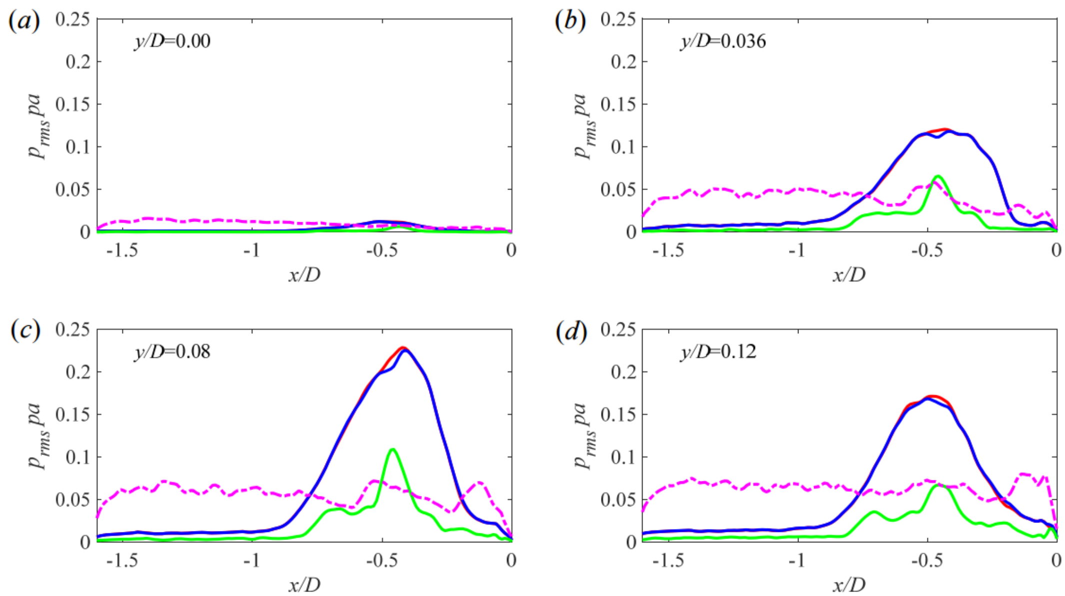

Figure 4: Decomposition of pressure fluctuations. —: total, —:phase-averaged, —: no phase-averaged pressure fluctuations of laminar junction and - ·: pressure fluctuations under end-plate control..

4 Conclusion

The unsteadiness of a laminar junction flow is captured in aspects of topology of instantaneous flow field and smoke-wire flow visualizations. It seems that the flow field is dominated by a six- or four-vortex pattern alternating process.

It is found that the corner vortex of a laminar junction flow stops moving downstream and changes direction to run into and be merged into the primary vortex, which leads to shape changes and oscillations of the primary vortex, which is supposed to be responsible for the laminar junction unsteadiness.

A vertical end-plate located in symmetry plane upstream the nose of circular cylinder successfully avoids unsteadiness of the laminar junction flow by cutting off the corner vortex. In the meanwhile, the flow field becomes a steady four-vortex system according smoke-wire flow visualization. Besides,pressure fluctuation gradually increases as away from the solid wall. The phase-averaged event takes a dominant role of intensive pressure fluctuations in the region of vortex core in laminar junction flow and the flow radiation noise source has been weakened under end-plate control.

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