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Efficient suction control of unsteadiness of turbulent wing-plate junction flows*

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Abstract: A wing-body junction flow of a navigating underwater vehicle is considered to be a crucial source of the flow radiating acoustic noise, which attracts much research interest. In this paper, wing-plate junction flows are experimentally investigated in a low-speed wind tunnel by smoke-wire flow visualizations and time-resolved PIV measurements. To reveal the physical behavior of such flows, smoke-wire flow visualizations are conducted for a laminar wing-plate junction. A novel control strategy is proposed, to accurately locate the suction openings where the streamline is about to roll up to form a vortex in the turbulent junction flows. The control effect is discussed in perspectives of both the time-averaged and instantaneous flow fields.

Key words: Wing-plate junction flow, horseshoe vortex, turbulence, unsteadiness, PIV

Introduction

The 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 these cases, complex interference flow fields and three-dimensional separations are produced by an upstream boundary layer on a surface that encounters an attached obstacle, such as a wing, turbine blade, sail or conning tower, electronic chip, or bridge pier[1]. The past experimental and numerical studies[1] 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 probability density functions (PDFs)[2], meaning that the flow switched between two modes[3]. Especially in the turbulent junction flows at a high Reynolds number, these vortices were highly unsteady and responsible for high turbulence intensities[4], high surface pressure fluctuations[1,5], acoustic noise radiation[6], heat transfer rates[7], and erosion scour in the nose region of the obstacle[1].

As pointed out by Simpson[1], these phenomena that affected juncture flows, caused a number of undesirable effects in practical cases. Because the primary horseshoe vortices were of the rotational sense of the approaching boundary layer, they entrained higher-speed free-stream fluid along the obstacle and increased drag[8] and heat transfer[7] in the junction region. Take horseshoe vortex structure around a bridge pier as an example, it could scour away soil and rocks and weaken the bridge foundation. Control or modification of these juncture flows was mainly aiming at reducing these adverse effects[9]. Additionally, high levels of the mean bed shear stress were observed beneath the primary necklace vortex, especially over the region where the bimodal oscillations were strong, as well as beneath the small junction vortex at the base of the cylinder, according to the large-eddy simulation (LES) results[10].

Passive controls of turbulent junction flows were widely studied to avoid these undesired effects of junction flows. The well-known and classical passive control method for a turbulent junction flow was to modify the pressure field by placing a fillet at the base of the obstacle[11]. And some further developed approaches were put forward later on. For example, Kang et al.[12] indicated that with a cavity (or slot) upstream the circular cylinder, the strength of primary vortex was weakened due to the fluid stream engulfed into

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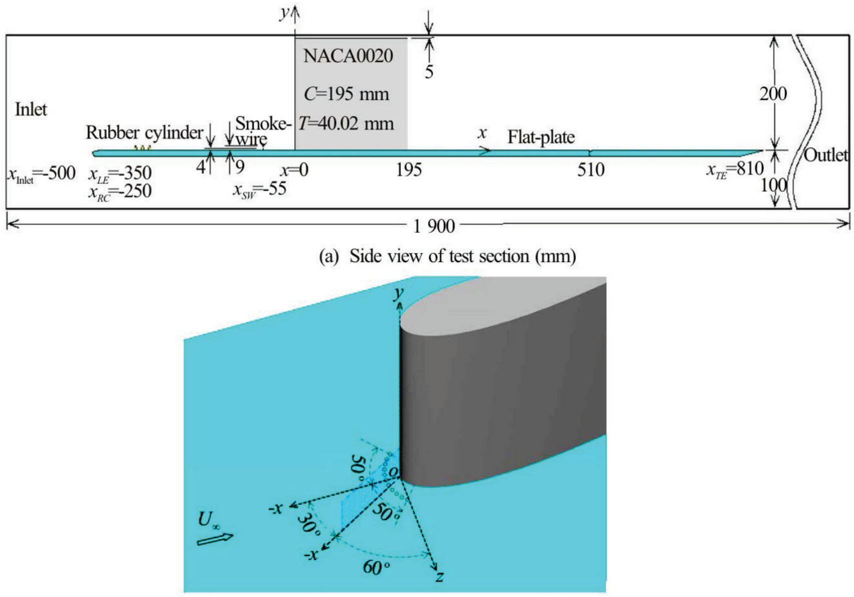

(b) PIV plane and suction orifices at the nose

Fig.1 (Color online) Sketches of test section and model arrangement

the upstream cavity in the turbulent junction flow. While the adverse pressure gradient was weakened upstream the cavity, it was strengthened downstream the cavity. Kairouz and Rahai[13] placed a ribbed plate upstream a NACA0012 airfoil on the flat-plate surface and it was shown that the riblets affected the location of the horseshoe vortex away from the corner with its strength reduced, but horseshoe vortex remained there.

In addition to the passive controls, a few active approaches were also studied. A spatially-limited, constant-rate suction (ranging from 0% to $U_\infty \times 68\%$) through a slot upstream the cylinder was utilized[14]. The PIV results indicated that the surface suction weakened both the instantaneous turbulent vortex and its associated surface interactions in the symmetry plane, effectively eliminated the average turbulent necklace vortex in the symmetry plane and reduced the average downstream extension of the vortex. Another similar study[15] showed that the suction flow rate of $U_\infty \times \delta^* \times D$ through an opening located in the vicinity of the separation lines, with D being the diameter of the obstacle and δ^* the displacement thickness of the boundary layer, reduced the vortex size and moved the separation lines towards the obstacle's leading edge.

According to the above studies, active means seems more effective in turbulent juncture flow control but it is energy consuming for such a high flow rate, even though we could not say exactly where the unsteadiness comes from in a turbulent or laminar junction flow at a Reynolds number larger than 1 000[16]. However, it is indeed really important to junction flow control. In this paper, smoke-wire flow visualizations are conducted in a laminar wing-plate junction to try to find out where the unsteadiness comes from. For a vortex impinging event, a novel active control method is put forward and the control effect is discussed in aspects of mean two-dimensional vector, PDFs, instantaneous streamlines and synchronous fluctuating pressure in turbulent junction flows.

1. Experimental setup

1.1 *Wind tunnel and test model*

Experiments are carried out in a low-speed open-return wind tunnel with test section dimensions of $0.3\times0.3\times1.9\,(L)\,\mathrm{m}^3$, as a through type tunnel with an exhaust that recirculates 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 is mounted horizontally in the test section, 150 mm behind a 7:1 area ratio contraction, with a 200 mm gap between the top wall of the test section and the upper surface of the flat-plate left to install a NACA0020 wing vertically at the centerline. The wing is also made of acrylic, with the chord and the thickness being C = 195 mm and $T = 40.02$ mm and the height being 195 mm to leave a 5 mm gap intentionally between the top wall to prevent the occurrence of junction vortices and their impact on the junction flow of interest. A sketch of the test section and the model arrangement is shown in Fig.1 and the freestream goes from left to right. Figure 1(b) shows a Cartesian coordinate