Phase-averaged scanning stereoscopic PIV measurement for classification of vortex regime of synthetic jet in cross flow

Yasuyo ONO¹, Masahiro MOTOSUKE^{1,2} and Shinji HONAMI¹

¹ Department of Mechanical Engineering, Tokyo University of Science, Tokyo, Japan j4512617@ed.tus.ac.jp

² Research Institute for Science and Technology, Tokyo University of Science, Tokyo, Japan

ABSTRACT

A synthetic jet is one of flow control devices that can topologically disturb surrounding flow field by adding periodic injection and suction of surrounding fluid using an oscillating membrane through an orifice. This device can be applied to the downsized fluid machinery without a net mass injection of fluid for the simplified structure. In this study, the phase-averaged three-dimensional flow structures of the synthetic jet in laminar cross flow were measured by the phase-locked scanning stereoscopic PIV. The synthetic jet has a round orifice with a diameter of D = 1.0 mm. Stokes number and dimensionless stroke length were ranged from 6.3 to 12.7 and from 2.67 to 16.0, respectively. Reynolds number of the cross flow based on channel height was 1300. The vortex structure of the synthetic jet in cross flow was drastically changed depending on these parameters. According to the measured 3D vortex structure, the parameter map for the classification of vortex regime was obtained.

INTRODUCTION

Due to recent progress in downsizing of the fluid machinery, the control of flow separation or mixing promotion in low Reynolds number has been greatly essential. The flow separation in the downsized fluid machinery often causes performance reduction such as pressure loss. The mixing promotion is necessary to mix fuel with air for increasing combustion efficiency or to control the flow separation. Recently, much attention has been paid on synthetic jets on account of that the synthetic jet generates strong and beneficial disturbance without a net mass flow injection and has a potential being easily downsized.

An application of the synthetic jet as a flow control device has been suggested for the control of separated boundary layer in an aerofoil [1]. In consideration of periodicity in the jet operation, the synthetic jet produces higher turbulence intensity than that of a continuous jet [2]. Also, the near wall effect of the synthetic jet in the boundary layer was investigated and types of vortex structure of the synthetic jet were discussed [3]. Though the vortex structure of synthetic jets issued in cross flow was classified into several types [4], the criteria of the classification were qualitative.

The purpose of this study is to provide quantitative classification of vortex structures of synthetic jet in cross flow depending on non-dimensional parameters by three-dimensional measurement. In our previous research, the three-dimensional flow structure of the synthetic jet in low Reynolds number cross flow has been investigated [5], however, the classification of the vortex structure had not been conducted. Then, we classified types of vortex structure of the synthetic jet in quiescent fluid [6]. Based on the these results, this study focuses on types of vortex structure of the synthetic jet in cross flow. In order to obtain the three-dimensional vortex structure of synthetic jet in cross flow, phase-averaged scanning stereoscopic particle image velocimetry (PIV) was applied.

EXPERIMTNTAL

Figure 1 shows a schematic of the synthetic jet and measurement sections. The orifice surface of the synthetic jet was flush mounted to the wall and the jet was injected normal to the wall. The synthetic jet has a round orifice with a diameter of D = 1.0 mm. The synthetic jet was driven by a piezoelectric-actuator with a forcing frequency of f = 100 to 400 Hz. Resultant periodic motion of injection and suction was generated by the vibrating diaphragm. Bulk velocity of the cross flow was set at 2.0 m/s in a wind tunnel with an aspect ratio of 12, and the Reynolds number based on the tunnel height (H = 10 mm) was 1300. In our PIV system, a double-pulsed Nd:YAG laser was used as an illumination source. The thickness of the laser light sheet was approximately 0.5 mm. DEHS (di-ethylhexyl sebacate) droplets with a nominal diameter of about 300 nm were employed as the tracer. This relatively small tracer is effective for our measurement of synthetic jet because smaller particles have better seeding performance inside a cavity of the jet during

10TH INTERNATIONAL SYMPOSIUM ON PARTICLE IMAGE VELOCIMETRY – PIV13 Delft, The Netherlands, July 1-3, 2013

periodic injection and suction. Two CCD cameras have a stereo angle of 15 deg with Scheimpflug arrangement to obtain focused images at whole measurement area of $8.00 \times 10.65 \text{ mm}^2$. Both cameras and illumination optics were simultaneously traversed in the spanwise direction with 0.17 mm spacing that was the same as the practical focal depth in this imaging configuration. Measurement section was divided into three parts to cover the developing behavior of the vortex formed by the synthetic jet. In our experiments, an oscillation phase in the piezoelectric-actuator of the jet, the record timing of images from two CCD cameras and the laser irradiation were synchronized in a measurement cycle so that the phase-locked measurement of the periodic vortex behaviour was possible. The phase angle of the measurement was 2π when a cyclic behavior of injection and suction had finished. Stokes number, *S*, based on the injection condition of the synthetic jet was ranged from 6.3 to 12.7. The velocity at the orifice exit of the synthetic jet U_{jet} was changed from 0.8 to 2.0 m/s. Stroke length, *L*, based on the length of the jet in injected direction was set from 2.67 to 16.0. The jet velocity ratio, *VR*, which was normalized by the bulk velocity of the cross flow ranged from 0.4 to 1.0.



Figure 1 Measurement configuration

RESULTS AND DISCUSSION

Figure 2 shows velocity-vector field and vorticity contour of Ω_2 in X-Y plane at S = 6.3, 9.0, 11.0, 12.7 and VR = 0.8, 1.0. Several cross-sectional vorticity distributions in Y-Z plane under S = 6.3 and VR = 0.8, case as in Figure 2 (a.1) are shown in Figure 3. The formation of a pair of longitudinal vortex is recognized. Thus, in this case, a forward-rotating vortex at the tip of the jet and longitudinal vortex at the leg can be observed. The vortex in this condition forms a hairpin vortex structure [5]. As VR is increased, the vorticity is increased. Vortex structure in S = 11.0 and 12.7 (Figures 2 (c) and (d)) shows different shape having both forward- and backward-rotating vortices compared to that in smaller S (Figures 2 (a) and (b)). The vortex structure in S = 9.0 and VR = 1.0, as in Figure 2 (b.2) is a transition between hairpin and non-hairpin vortex regime; it has weak pair of backward-rotating vortex at X/D = 7.3, forward-rotating one at X/D =9.0 and strong forespin motion at X/D = 5.5.



Figure 2 Velocity and vorticity of synthetic jet in cross flow at phase 2π . (a.1) S = 6.3 and VR = 0.8, (b.1) S = 9.0 and VR = 0.8, (b.2) S = 9.0 and VR = 1.0, (c.1) S = 11.0 and VR = 0.8, (c.2) S = 11.0 and VR = 1.0, (d.1) S = 12.7 and VR = 0.8, (d.2) S = 12.7 and VR = 1.0.



Figure 3 Velocity and vorticity in XY plane and YZ plane (S = 6.3, VR = 0.8)

Figure 4 depicts the three-dimensional vortex structure in the case in Figures 2 (a.1) and (c.1), namely hairpin and nonhairpin vortex. In the latter case, the tip of the jet forms a ring vortex; this is observed as a foreward and backwardrotating vortices in XY-plane (Figure 2 (c.1)). The ring vortex at the tip of the vortex structure is attached to the longitudinal vortex pair. We defined the vortex configuration in Figure 3 (b) as chopstick form vortex pair attached mushroom vortex (MC vortex). To distinguish these MC and hairpin vortices, we focused on whether the vortex structure had the backward-rotating vortex at the upstream part of the jet tip, because the ring vortex did not have the backward-rotating vortex. In this study, the presence of the backward-rotating vortex was used as the criteria of the classification.



Figure 4 Three-dimensional vorticity. (a) Hairpin vortex (S = 6.3, L = 16.0) and (b) MC vortex (S = 11.0, L = 6.7)

10TH INTERNATIONAL SYMPOSIUM ON PARTICLE IMAGE VELOCIMETRY – PIV13 Delft, The Netherlands, July 1-3, 2013

The larger both *S* and *VR* are, the stronger the vorticity of the backward-rotating vortex becomes. Thus, the magnitude of the vorticity is inappropriate parameter to discriminate MC vortex from hairpin vortex. Here, the vorticity ratio of forward-rotating vortex to backward-rotating one in the same *S* and *VR* was employed as the criterion. Figure 5 shows the vorticity ratio in S = 6.3, 11.0, 12.7 and $VR = 0.6 \sim 1.0$. In this study, we have defined MC vortex as a vortex that has the vorticity ratio larger than 0.75.

According to the series of parametric measurements, a parameter map presenting the vortex regimes of the synthetic jet in cross flow based on Stokes number S and non-dimensional stroke length L shown in Figure 6 was obtained. Blank plots presented in the figure are the vortex regime classification of the same synthetic jet in quiescent fluid [6]. The parameter map indicates that MC vortex appears under large S. The vortex roll up in MC vortex in early stage of injection corresponds to roll up in quiescent fluid.



Figure 5 Vorticity ratio at phase 2π



Figure 6 Parameter map of vortex regime of synthetic jet in laminar cross flow compared to that in quiescent fluid

REFERENCES

- [1] Glezer A and Amitay M "Synthetic jets" Annual Review of Fluid Mechanics 34 (2002) pp. 503-29
- [2] Milanovic IM and Zaman KBQ "Synthetic jets in crossflow" AIAA Journal 43 (2005) pp. 929-939
- [3] Jabbal M and Zhong S "The near wall effect of synthetic jet in a boundary layer" International Journal of Heat and Fluid Flow 29 (2008) pp. 119-130
- [4] Zhou J, Tang H and Zhong S "Vortex roll-up criterion for synthetic jets" AIAA Journal 47 (2009) pp. 1252-1262
- [5] Iai T, Motosuke M and Honami S "Behavior of synthetic jet in cross flow at low Reynolds number" Journal of Fluid Science and Technology, 5 (2010) pp. 35-44
- [6] Iwabuchi K, Kurihara K, Motosuke M and Honami S "Classification of vortex regime and three-dimensional vortex structure of synthetic jet in quiescent fluid" Proc. 50th AIAA Aerospace Science Meeting AIAA 2012-1244 (2012)