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On the velocity and pressure statistics during the flapping motion in a planar turbulent jet

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ABSTRACT

The role of a large-scale coherent vortex structure in a planar jet, which is intermittently observed and called "flapping motion", on the turbulent energy transport process is investigated experimentally. The experiment is performed by simultaneously measuring the two components of velocity and pressure in the self-preserving region of the jet. The probe for the simultaneous measurement of the velocity and pressure consists of an X-type hot-wire sensor and a static pressure probe. The measurement data are analyzed using a conditional sampling technique and the phase-averaging technique, on the basis of an intermittency function which shows whether the jet is now flapping or not. This intermittency function is obtained by the measurement results of the streamwise velocity fluctuation by means of the two I-type hot-wire sensors set in the self-preserving region of the jet with applying a continuous wavelet transform analysis to the data. The experimental results show that the phase-averaged velocity field during the flapping motion shows a good agreement with those obtained through the 23 points simultaneous measurement of the streamwise velocity in the previous studies. Further, the phase-averaged pressure field during the flapping motion indicates the existence of a large-scale coherent vortex structure, interpreted as a combination of the flapping and puffing motions in the self-preserving region of the jet. In addition, it is found that the production of the turbulent energy and its diffusion from the inner region to the outer region of the jet are enhanced by the flapping motion. In particular, this enhancement of the turbulent energy diffusion is caused by the combination of an increase of the turbulent diffusion to the outer region of the jet and a decrease of the pressure diffusion to the inner region of the jet.

1. Introduction

In a far field of a planar jet, the similarity law of the statistical value of the flow field is realized and the region is called "self-preserving region"(Rajaratnam, 1976). In the self-preserving region, instantaneous flow structure or vortex structure is very complicated. So that, superimposed vortex structures consist of small scale homogeneous vortex structure and large-scale coherent vortex structure can be observed (Dimotakis et al., 1983).

The first report of the coherent structures in a self-preserving region of a planar jet was performed by Goldschmidt and Bradshow (1973). They indicated there was a flapping which may add a new dimension to the interpretation of a planar turbulent jet. The experimental results casted some doubt on those of Wygnanski and Gutmark (1971) who suggested that there was no flapping in a planar jet. The term "flapping" was named from the visual image of this phenomenon that the jet flaps as a flag does.

After the several useful studies on the large-scale vortex structures (Everitt and Robins, 1978; Gortari and Goldschmidt, 1981; Oler and Goldschmidt, 1982; Mumford, 1982), Antonia et al. (1983) performed the measurements of space–time correlations of longitudinal and normal velocity fluctuations and of temperature fluctuations. The experimental results supported the existence of counter-rotating spanwise structures appearing alternately on opposite sides of the jet centerline in the self-preserving region of the jet. The frequency of these structures closely satisfied the self-preservation. The asymmetric arrangement of the structures was first observed downstream of the position where the jet mixing layers nominally merge but upstream of the onset of self-preservation. Further, closer to the jet exit, the space–time correlations indicated the existence of spanwise structures that were symmetrical about the centerline.

Thomas and Brehob (1986) also investigated the large-scale vortex structural patterns in the self-preserving region of a planar turbulent jet. The experimental results of the two-point correlation and coherence-based measurements obtained from both longitudinal and lateral component velocity fluctuations were supportive of

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the existence of an antisymmetric array of counterrotating vortices in the region. Further, they indicated the structural array propagated at 60% of the mean streamwise velocity on the jet centerline.

Recently, Gordeyev and Thomas (2000, 2002) investigated the coherent structure in the self-preserving region of the planar turbulent jet experimentally by applying POD. In the measurement, twin cross-stream rakes of X-wire probes were used to take cross-spectral measurements with different spanwise separations between the rakes and at several locations throughout the self-preserving region. The measurement results suggested that the flow supported a planar structure aligned in the spanwise direction as well as an essentially three-dimensional structure with asymmetrical shape in the cross-stream direction and pseudo-periodically distributed in the spanwise direction.

Sakai et al. (2006a) performed the simultaneous measurement of the streamwise velocity and the KL (Karhunen–Loève) expansion was applied to the measured data to extract and clarify the coherent structure in a planar turbulent jet. The measurements of the velocity were performed at 21 points in the self-preserving region of a turbulent planar jet by an array of I-type hot-wire probes. They indicated the low-numbered (energetic) modes represented the large-scale coherent structure, the middle-numbered modes represented the finer (small-scale) random structure, and the higher-numbered modes contributed mainly to the intermittent structure in the outer region from the investigation of the random coefficients and the eigen functions (modes). Further, they also showed that there existed a pair of regions with the positive and negative streamwise velocity fluctuation on the opposite sides of the jet centerline, and the signs of velocity fluctuation for those regions changed alternately as time proceeds from the spatio-temporal velocity field reconstructed by the first KL mode. Moreover, these characteristics were consistent with the flapping motion. Consequently, on the basis of the result of KL expansion, a new interpretation of the coherent structure model in the self-preserving region of a planar jet was given from the combination of "flapping motion" and "puffing motion" (Sakai et al., 2006a).

Landel et al. (2012) investigated experimentally the structure of quasi-two-dimensional planar turbulent jet using particle image velocimetry. They found that the jet structure consists of a meandering core with large counter-rotating eddies which develop on alternate sides of the jet core at the large vertical distances. Further, they also found that the jets were self-similar and the mean properties were consistent with both experimental results and theoretical models of the time-averaged properties of fully unconfined planar jet although their study concerned quasi-two-dimensional confined jet. They indicated the dynamics of the interacting core and large eddies accounts for the Gaussian profile of the mean streamwise velocity as shown by the spatial statistical distribution of the core and eddy structure.

By the way, in these days, the pressure statistics in turbulent flows are again actively measured and discussed using high accurate measurement techniques and computational techniques in some researches (Straatman et al., 1998; Yoshizawa, 2002; Suga, 2004; Tsuji and Ishihara, 2003). They investigated and discussed on the important phenomena related to the pressure fluctuation in turbulent flows such as the pressure diffusion process of the Reynolds stress and the $-7/3$ power law for the power spectrum of the pressure fluctuation by numerical simulations and experiments.

In this paper, for the better understanding of the characteristics and the effect of the large-scale coherent vortex structure in a planar jet, simultaneous measurement of two components of the velocity and pressure in the self-preserving region of a planar jet is performed and discussed. Firstly, a method to discriminate the flapping motion and determine the intermittency function about the occurring of the flapping motion by using the continuous wavelet transform with Gabor mother wavelet is presented. Secondly, the phase-averaged velocity and the pressure field on the basis of the intermittency function obtained by the present method is confirmed. Finally, the turbulent energy transport process of a planar jet in the flapping motion is estimated and discussed.

2. Experiment setup and procedure

2.1. Simultaneous measurement of velocity and pressure

Many useful techniques for the simultaneous measurement of the velocity and pressure in turbulent flows have been developed and used to date (Tsuji et al., 2007; Naka et al., 2006; Sakai et al., 2007). In this study, a combined probe which consists of two hot-wire probes and a pressure tube is used for the simultaneous measurement with reference to our previous research (Terashima et al., 2012) because this probe can realize higher spatial resolution and smaller temporal resolution measurement than other measurement techniques.

Fig. 1 shows a schematic view of the combined probe for the simultaneous measurement of two components of the velocity and pressure. The pressure tube is placed between two hot-wires (diameter: 5.0 μm, length: 1.0 mm) which construct the X-type hot-wire sensor for the measurement of two velocity components. The gap between the side wall of the pressure tube and the hot-wire is 0.5 mm, and the streamwise gap between the tip of the pressure tube and the cross point of the two hot-wires is 2.0 mm. These gaps are necessary to eliminate the interference between each probe because the disturbances caused by one probe influenced the measurement accuracy of another probe in some cases. It should be noted here that from the previous experimental results of this planar jet (Sakai et al., 2007), the Taylor transverse microscale and Kolmogorov microscale were estimated to be approximately 3.0 mm and 0.10 mm respectively, in the self preserving region ($x_1/d = 40$). Therefore, judging from the diameters and the arrangement of the probe, it is considered that the spatial resolution of the velocity and the pressure fluctuation by this probe is less than the Taylor microscale.

Fig. 2 shows a schematic view of the pressure tube. The shape of the tip of the pressure tube is hemispherical, like that of a pitot tube. The external diameter and the internal diameter of the pressure tube are 0.50 mm and 0.34 mm, respectively. There are eight pressure holes on the sidewall of the pressure tube, and the

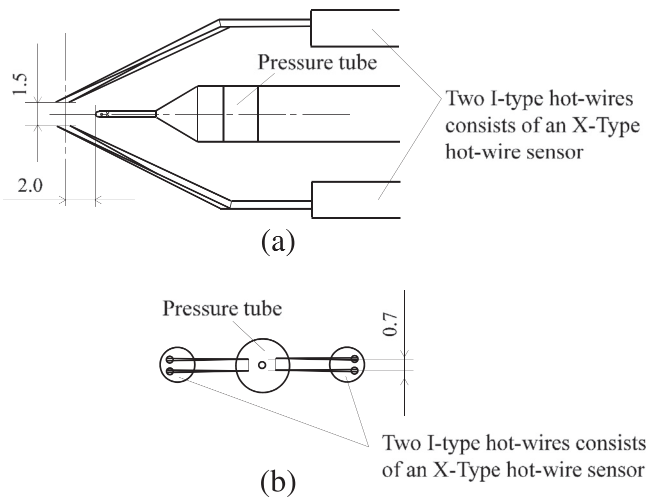

Fig. 1. Schematic view of the combined probe (Unit: mm). (a) Top view. (b) Front view.