End-Effects of a Finite Synthetic Jet on Flow Control

Li-Hao Feng, Li-Qun Ma and Jin-Jun Wang

Abstract The end-effects of a finite synthetic jet used for controlling the flow around a two-dimensional circular cylinder are experimentally investigated in this study. The Reynolds number based on the cylinder diameter is Re = 800, and the corresponding natural vortex shedding frequency f_0 is 0.24 Hz (St = 0.21). The synthetic jet is actuated at excitation frequency $f_e/f_0 = 2.08$, with the equivalent momentum coefficient $C_\mu = 0.139$. Six *x–y* planes of view from the mid-span to one of the slot ends with identical interval 5 mm are measured using two-dimensional time-resolved PIV system. It is found that the end-effects of the finite synthetic jet do not have a crucial influence on flow fields in the mid-span regions, which are independent of the slot length if it is longer than one cylinder diameter.

Keywords Flow control · Finite synthetic jet · Circular cylinder · End-effects

1 Introduction

Synthetic jet is one of the most efficient flow control techniques, which has been applied in various fields (Zhang et al. 2008). Particular attention has been paid to control of flow around a circular cylinder in the previous investigations (Amitay et al. 1997; Tensi et al. 2002; Béra et al. 2000; Wang et al. 2007; Feng and Wang 2010, 2012; Feng et al. 2010, 2011; Ma and Feng 2013). The dimension problem is

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considered as one of the most important issues that potentially affects the global control results. A two-dimensional synthetic jet interacts with a two-dimensional flow filed, which usually is just the ideal situation. However, most of the flow fields in nature are highly three-dimensional, and sometimes the synthetic jet cannot be considered as a two-dimensional one in comparison with the controlled flow. For example, the length of the synthetic jet orifice was about two cylinder diameters in Amitay's et al. (1997) and Tensi's et al. (2002) experiments, while it was one cylinder diameter in Béra's et al. (2000) experiment. Consequently, the interactions between a finite synthetic jet and the flow around a two-dimensional circular cylinder are investigated experimentally in this study, where the particular attention is paid to the end-effects of the finite synthetic jet on the control effect.

2 Experimental Setup

The experiment was conducted in a recirculation water tunnel. The circular cylinder was horizontally mounted across the test section, and end plates were used in order to reduce the effects of the boundary layer developing on the test section walls. The outer diameter of the circular cylinder was $D = 30$ mm, the inner diameter was $d = 22$ mm, and the spanwise length was $L = 500$ mm, giving an aspect ratio of 16.7. The synthetic jet was issuing from a slot with width $h = 1$ mm and length $l = 50$ mm, which was arranged on the external surface of the circular cylinder. The slot was located in the mid-span region of the experimental circular cylinder and paralleled to its axis. During the experiment, the slot was arranged at the front stagnation point of the circular cylinder. Since the ratio of the synthetic jet length to the cylinder outer diameter was only about 1.7, the present synthetic jet could be considered as a finite one. The origin of the coordinate was located at the cylinder center in the mid-span of the slot, while the x-, y-, and z-axes pointed to the streamwise, vertical, and spanwise directions, respectively. More details about the experimental setup can be found in previous studies by the authors (Wang et al. 2007; Feng and Wang 2010, 2012; Feng et al. 2010, 2011; Ma and Feng 2013).

During the experiment, the free-stream velocity was fixed at $U_\infty = 34.5$ mm/s, corresponding to the Reynolds numbers Re = 800 of the circular cylinder and the natural frequency $f_0 = 0.24$ Hz (St = 0.21). The flow around the circular cylinder was belonged to the shear layer transition regime, where three-dimensional vortex structures developed in the wake. The synthetic jet was actuated at about twice of the natural frequency, namely $f_e/f_0 = 2.08$, with the equivalent momentum coefficient $C_\mu = 0.139$. In order to study the end-effects of the synthetic jet on the control effect, six x–y planes of view from the mid-span to one of the slot ends with identical interval 5 mm were measured using two-dimensional time-resolved PIV system.

3 Results and Discussion

The objective of present investigation is to find out how much the flow field near the mid-span is influenced by the three-dimensional end-effects of the finite synthetic jet. To address this issue, by comparing the variances at different x–y planes, two aspects have been considered as follows.

3.1 Characteristics of the Statistical Parameters

Figures 1 and 2 show the distributions of the time-averaged streamwise velocity and its root mean square at different x–y planes along the y-axis and the x-axis, respectively. It is shown that in the near-wake region, the velocities at planes of $z = 0$, 5, and 10 mm are nearly consistent with each other, though the velocities at planes of $z = 15$, 20, and 25 mm exhibit some differences due to the end-effects of the synthetic jet. It is indicated that the end-effects of the synthetic jet do have an influence on the flow fields within half-cylinder-diameter distance from each end. However, it does not have a crucial influence on flow fields in the mid-span regions, namely $-10\ \text{mm} \le z \le 10\ \text{mm}$. The wall visualization experiments conducted by Tensi et al. (2002) also showed the obvious three-dimensional effects near the slot ends; however, such effects decreased toward the mid-span of the slot.

3.2 POD Modes

The proper orthogonal decomposition (POD) is a useful technique to analyze the complex flow phenomenon (Ma et al. 2000; Feng et al. 2010, 2011). Figure 3 presents the first 4 POD modes based on the vertical velocity downstream of the circular cylinder. Since most of the energy concentrates in the first few modes, the variations in the distributions of the first few modes can well reveal the variations in the vortex dynamics. For the control case, the POD modes in all x–y planes are obviously different from the natural case. The modes at $z = 0$ mm show the most differences, which is followed by those at other x–y planes, further indicating that the spanwise scale of the influenced scope of the finite synthetic jet can be at least the same scale as its length. The differences between different x–y planes reveal the end-effects of the synthetic jet on the vortex dynamics.

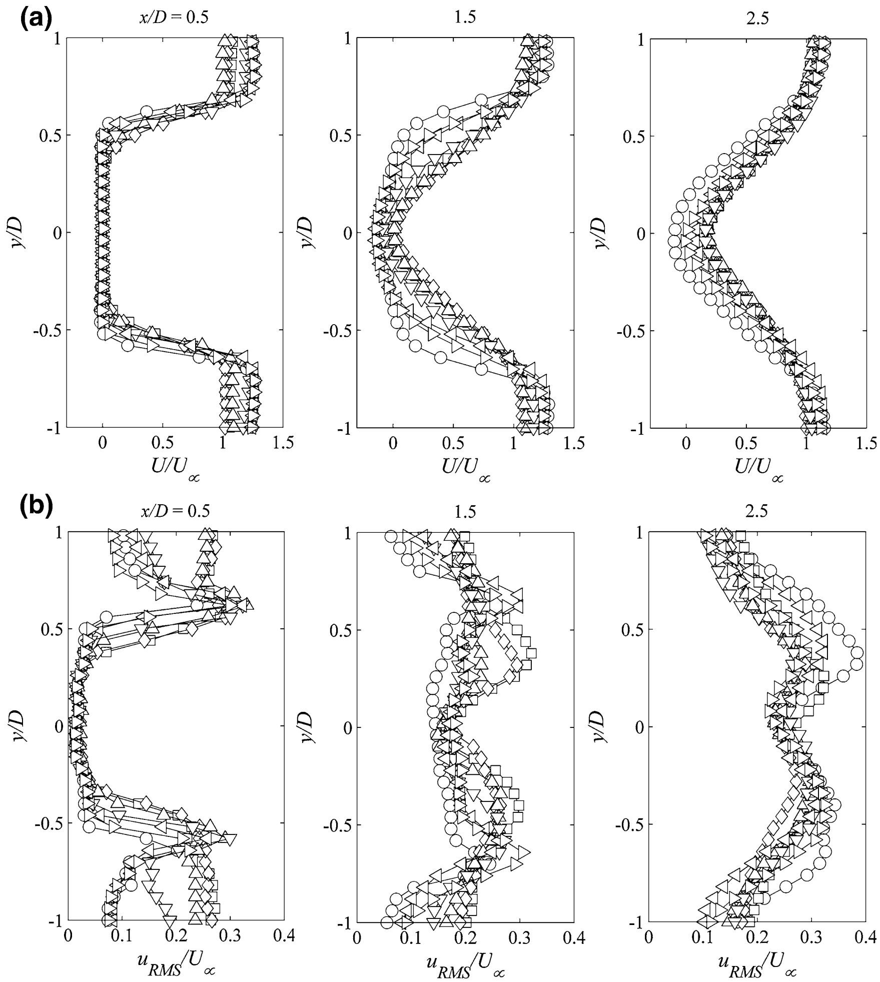

Fig. 1 Vertical sectional distributions of time-averaged streamwise velocity U/U_∞ (**a**) and root mean square of the streamwise velocity u_{RMS}/U_∞ (**b**) at $x/D = 0.5$, 1.5, and 2.5 for different spanwise positions for Re = 800, $f_e/f_0 = 2.08$, $C_\mu = 0.139$. *Empty circle* natural case at $z = 0$, and control case at *empty square* $z = 0$, *empty diamond* 5 mm, *empty up-pointing triangle* 10 mm, *empty down-pointing triangle* 15 mm, *empty left pointing pointer* 20 mm, *empty right pointing pointer* 25 mm

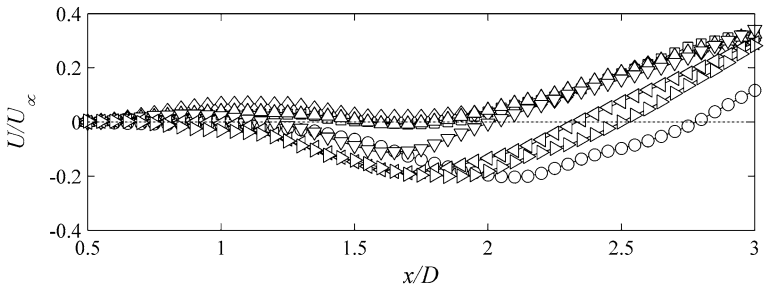

Fig. 2 Streamwise sectional distributions of time-averaged streamwise velocity U/U_∞ at $y/D = 0$ for different spanwise positions for Re = 800, $f_e/f_0 = 2.08$, $C_\mu = 0.139$. *Empty circle* natural case at $z = 0$, and control case at *empty square* $z = 0$, *empty diamond* 5 mm, *empty up-pointing triangle* 10 mm, *empty down-pointing triangle* 15 mm, *empty left pointing pointer* 20 mm, *empty right pointing pointer* 25 mm

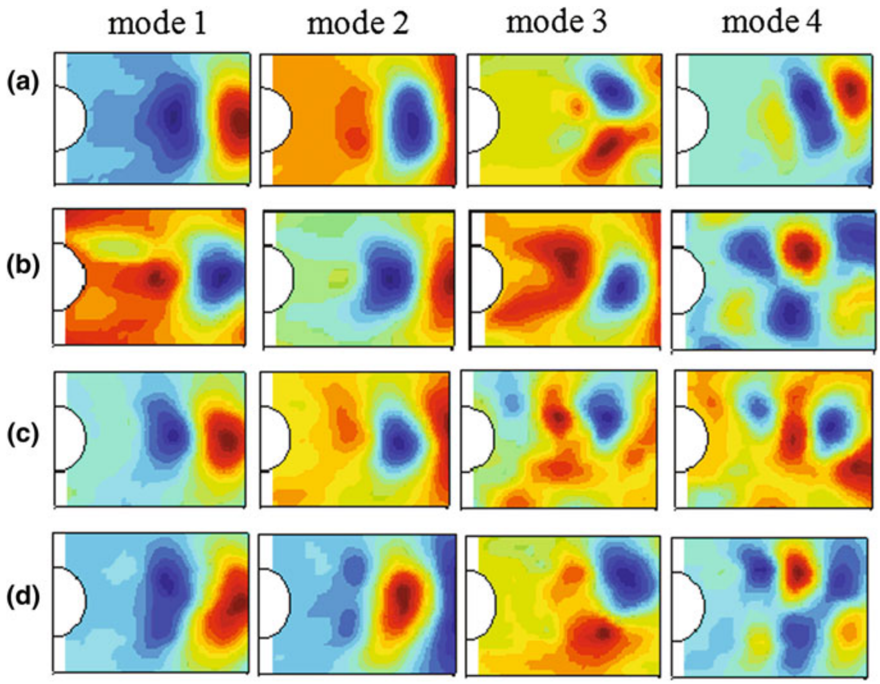

Fig. 3 POD modes of the vertical velocity for the natural and control cases. **a** Natural case at $z = 0$, control case at **b** $z = 0$ mm, **c** $z = 10$ mm, **d** $z = 25$ mm

4 Conclusions

It can be concluded that the end-effects of the finite synthetic jet do have an influence on the flow fields within half-cylinder-diameter distance from each end. However, it does not have a crucial influence on flow fields in the mid-span regions, namely $-10\ \text{mm} \leq z \leq 10\ \text{mm}$. In other words, the flow field in the mid-span is independent of the slot length if it is longer than one cylinder diameter.

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