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Flow structure evolution for laminar vortex rings impinging onto a fixed solid wall

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ABSTRACT

Laser Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV) techniques are used to investigate the synthetic jet actuated laminar vortex rings impinging onto a solid wall. Four cases with different stroke lengths ($19\ \text{mm} \leqslant L_0 \leqslant 50\ \text{mm}$) are adopted to generate laminar vortex rings with Reynolds number ($Re_{V0} \approx 151$) and orifice-to-wall distance ($H = 40$ mm) unchanged. It is found that the dimensionless stroke length normalized by the orifice-to-wall distance (L_0/H) has a significant influence on the evolution of near wall flow structure of the impinging synthetic jet. Specifically, as the stroke length is relatively small ($L_0/H = 0.475$ and 0.775), the impinging vortex ring could only induce a weak secondary vorticity near the wall, which cannot roll up into a coherent structure. It is illustrated with LIF visualization and Finite Time Lyapunov Exponents (FTLEs) that a large-scale spiral vortex ring is generated in the near wall region for these two cases, which is explored for the first time. However, as the stroke length becomes larger ($L_0/H = 0.95$ and 1.25), the strong secondary vorticity rolls up and pairs with the impinging vortex ring to form a vortex dipole. As a result, the impinging vortex rings are prevented to merge with the vorticity clustering near the wall causing a rapid reduction of the near wall vortex strength. The analysis of the radial wall jet shows that the induced large-scale spiral vortex ring at the case of the smaller stroke length could slow down both the decay rates of radial mass flow rate and momentum flux, and this might be of benefit for the mass and heat transfer of wall surface when applying the impinging synthetic jet.

1. Introduction

The interaction between vortex and solid wall appears frequently in nature and engineering application, so the understanding of this interaction is of both fundamental and engineering interests [1,2]. In the past decades, the study of a single vortex ring impinging onto wall has gained interest considerably. Walker et al. [3] presented various phenomena induced by single vortex ring impingement including the vorticity concentration, boundary layer separation, inverse vortex rolling-up and so on. In addition, they also showed that the fluid ejection near the wall becomes large enough as the ring Reynolds number increases. Subsequently, the numerical simulation of Orlandi and Verzicco [4] explained that the reverse vortex pairing was the reason for this fluid ejection. Moreover, they confirmed the prediction developed by Cerra and Smith [5] that the induced secondary vortex ring was more unstable than the impinging vortex ring. Recently, Naguiba and Koochesfahani [6] presented some physical explanations for the wall pressure associated with the single vortex ring impinging onto solid wall.

Synthetic jet is a widely concerned active flow control technique for recent twenty years. It is the most prominent feature of the synthetic jet which can periodically generate vortices but with zero net mass flux. So it is also called zero-net-mass-flux jet. In order to simplify the governing parameters of synthetic jet, Glezer et al. [7] and Smith and Glezer [8] proposed two dimensionless parameters: the dimensionless stroke length (based on the orifice diameter) and Reynolds number. Shuster and Smith [9] concluded that the distance of vortex ring leaving away from orifice increased with the stroke length but it had been little affected by the Reynolds number. Nowadays, the synthetic jet has been shown a potential application in the heat transfer of wall surface due to its stronger mixing and entrainment capacity, so it might become a heat transfer enhancement method to overcome the disadvantage of traditional cooling techniques. Pavlova and Amitay [10] conducted a comprehensive study of the parameter influence on the impinging synthetic jet including the frequency, Reynolds number and orifice-to-wall distance. They found that due to the breakdown and merging of vortices before the impingement, high frequency synthetic jet was better to remove the heat than the low

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frequency for the small orifice-to-wall distance. Conversely, for the large orifice-to-wall distance, low frequency jet was more effective because the vortex rings impinged onto wall separately. Moreover, they reported that the impinging synthetic jet was about three times more effective than the continuous jet at the same Reynolds number. McGuinn et al. [11] found that the stroke length had a significant effect on the mean flow filed and heat transfer of wall surface of the impinging synthetic jet. Moreover, they identified four different flow regimes of the impinging synthetic jet based on the ratio of the stroke length to the orifice-to-wall distance. Krishnan and Mohseni [12] used the hot-wire anemometry to investigated the characteristics of the radial wall jet induced by the synthetic jet impinging onto wall. Their results showed that the radial wall jet was dominated by the excitation frequency and its harmonics of the synthetic jet, and the mean velocity profile of the wall jet exhibited a self-similar behavior. The experiment of Xu et al. [13] illustrated that there existed obvious differences in the impingement process between the first few cycles of vortex rings and the rest. They also observed the generation of a secondary vortex ring near the wall at a low Reynolds number. Xu and Feng [14] showed that the influence of orifice-to-wall distance mainly reflects in the vortex strength and speed before impinging onto wall.

There already have some researches concerned about the impinging synthetic jet, but most of them focus on the influence of Reynolds number. Although McGuinn et al. [11] conducted a study on the stroke length effect on the impinging synthetic jet, little information about the flow structure evolution was provided. The aim of this research is to explore the influence of stroke length on the flow structure evolution of the impinging synthetic jet. Four cases with different stroke lengths ($19\ \text{mm} \leqslant L_0 \leqslant 50\ \text{mm}$) are selected for comparison while both the Reynolds number ($Re_{V0} \approx 151$) and orifice-to-wall distance ($H = 40$ mm) are kept constant. Special attentions are paid to the vortex evolution, the generation of near wall flow structure and the characteristics of the radial wall jet. We hope that this study could deepen our understanding of the impinging synthetic jet and provide some advices for the practical applications.

2. Experimental setup

The experiment is conducted in a cube water tank made of Plexiglas with size $600 \times 600 \times 600\ \text{mm}^3$, which is big enough to avoid interference of the impinging jet with the ambient fluid. A piston-cylinder actuator is used to generate synthetic jet and connected with a hollow circular cylinder by rubber tubing. This connecting rubber tubing is rigid enough to have no deformation during the jet generation. The outer diameter of the hollow circular cylinder is $D_0 = 32$ mm with inner diameter of $R = 24$ mm, and orifice diameter is $D = 10$ mm. An eccentric disk is connected with a rod to transfer the motor's circular motion into the reciprocating motion of the piston (Fig. 1), and the detailed description about this actuator system can be found in the previous study [13]. The length of the connecting rod is $l = 300$ mm and the maximum eccentricity adopted here is $\Delta = 4.4$ mm, apparently $l \gg \Delta$ since $\Delta / l \approx 0.015$. As a result, the instantaneous flow velocity at the orifice $v_0(t)$ can be simplified as Eq. (1) (the centerline of the synthetic jet is defined as y axis in Fig. 1):

$$v_0(t) \approx 2\pi\Delta f (R/D)^2 \sin(2\pi f t) \tag{1}$$

where the excitation frequency is calculated as $f = n/60$, n is the rotation speed of motor. Obviously, the orifice velocity meets the sinusoidal curve. According to Smith and Glezer's slug model [8], the time-averaged blowing velocity over the entire cycle V_0 is expressed as Eq. (2)

$$V_0 = \frac{1}{T}\int_0^{T/2} v_0(t)dt = 2\Delta f (R/D)^2 \tag{2}$$

So the stroke length is expressed as:

$$L_0 = \int_0^{T/2} v_0(t)dt = 2\Delta (R/D)^2 \tag{3}$$

And the Reynolds number is defined as:

$$Re_{V0} = V_0 D/\nu \tag{4}$$

where T is the excitation period and ν is water kinematic viscosity (temperature is about 20 °C).

Then the vortex ring Reynolds number $Re_{\Gamma 0}$ based on the circulation can be evaluated as:

$$Re_{\Gamma 0} \sim p \times \frac{L_0 V_0}{\nu} = p \times \frac{L_0}{D} \times Re_{V0} \tag{5}$$

where p is the velocity program factor. Shuster and Smith [9] pointed out for the sinusoidal velocity program, $p \approx 1.23$. For all the cases, the Reynolds number and orifice-to-wall distance are fixed as $Re_{V0} \approx 151$ and $H = 40$ mm, respectively. In order to ensure a constant Reynolds number, the product of eccentricity and excitation frequency should be the same according to Eqs. (2) and (4). Table 1 describes the main parameters for all the cases of different stroke lengths. Due to the motor speed must be an integer, the excitation frequency $f = 0.5$ (i.e. motor speed 30 rpm) is employed for case 2 resulting in a slightly larger Reynolds number. When comparing the circulation Reynolds number $Re_{\Gamma 0}$ with the results from Shuster and Smith [9], it can be seen that the synthetic jet vortex rings of all the cases are laminar in this experiment. It is worth noting that the orifice-to-wall distance is also used to normalize the stroke length as L_0/H, which is presented in Table 1. The reason is that since L_0 decides the distance of vortex ring traveling from the orifice during the blowing stroke, L_0/H represents the "real" distance of the vortex ring traveling before impinging onto wall (i.e. the distance between the vortex ring and the wall). On the other hand, Eq. (5) shows that $Re_{\Gamma 0}$ increases with L_0/H since H is fixed in this experiment. Therefore, we think that L_0/H could better reflect the role of the stroke length in the impinging synthetic jet.

Laser Induced Fluorescence (LIF) technique is used to visualize the vortex ring evolution. The light source for LIF is a continuous laser with wavelength of 532 nm. The fluorescent material is Rhodamine6G with the emission wavelength of about 590 nm. A CCD camera installed with an optical filter of cutoff wavelength 560 nm is employed to capture the images. The continuous laser provides an illumination plane across the centerline of synthetic jet for the PIV system. The laser sheet is defined as x–y coordinate plane, and the coordinate origin is located at the intersection of the vortex ring centerline with the wall (Fig. 1). The resolution of CCD camera is 640×480 pixels with the view field about $80 \times 60\ \text{mm}^2$. Two hundred velocity fields are captured within one jet cycle resulting in a high enough time resolution for the phase-averaged analysis. In addition, the camera records the evolutions of more than seventy cycle vortex rings for every case. The PIV interrogation window is set as 16×16 pixels with 50% overlap. A background removal technique is employed to reduce the wall reflection and increase the particle contrast ratio. The evaluated particle seeding density is about 0.0568 *ppp* resulting in about 14 particles within an interrogation window, which guarantees the reliability of velocity calculation. The estimated uncertainty of velocity measurement is less than 1.25%.