# FLOW CHARACTERISTICS OF SYNTHETIC JETS DEPENDING ON EXIT CONFIGURATION

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## ABSTRACT

Flow characteristics of synthetic jets have been computationally investigated for different exit configurations under a cross flow condition. The exit configuration of a synthetic jet substantially affects the process of vortex generation and evolution, which eventually determines the mechanism of jet momentum transport. Two types of exit configurations were considered: one is a conventional rectangular exit, and the other is a series of circular holes. The interactions of synthetic jets with a freestream were performed by analyzing the vortical structure characteristics. The effectiveness of flow control was evaluated by examining the behavior of the wall shear stress. Through various comparisons, it was observed that the exit configuration should be regarded as an important design parameter, and the circular exit provides better performance than the rectangular exit in terms of sustainable vortical structure and flow control capability.

## INTRODUCTION

Control of flow separation by means of synthetic jets is known to be quite effective in a variety of flow conditions. Synthetic jets have been widely used in fluid dynamic applications including static and dynamic stall control of airfoils, jet vectoring, jet mixing enhancement, and thermal mixing. There have been numerous studies on the benefits of synthetic jets as a control or mixing device. A synthetic jet periodically transports momentum from a jet cavity to an outside region, thus interacting with an external flow field through a series of jet vortices.

Studies on synthetic jets have been performed by both experimental and numerical methods. Experimental studies have revealed jet characteristics and jet vortex formation. Mittal *et al.* examined the formation and interaction of a synthetic jet with a flat plate boundary layer in a three-dimensional configuration [1]. Rumsey *et al.* performed a study of synthetic jet flows into a turbulent boundary layer crossflow through a circular orifice [2]. Kim and Kim numerically investigated the frequency-dependent flow control mechanisms of synthetic jets on an airfoil, and proposed multi-location synthetic jets to mitigate the unstable flow structures of a high-frequency jet [3]. Subsequently, Kim *et al.* applied synthetic jets to improve the aerodynamic performance of tilt-rotor UAV airfoils in hovering and transition flight modes [4]. They performed a study on the characteristics of synthetic jets for different exit configurations under various flow conditions [5]. Through various comparisons, they observed that the exit configuration should be regarded as an important design parameter.

The focus of the present paper is to study the flow characteristics of synthetic jets dependent on the jet exit configuration under cross flow conditions. The interaction of synthetic jets with a crossflow was analyzed in terms of vortex characteristics, and the effect of synthetic jets on flow control was studied in terms of wall shear stress distributions.

## NUMERICAL METHODS

*1. Governing equations*

Accurate prediction of stall characteristics with or without turbulence models is still an extremely challenging task. By considering available computing power and required numerical accuracy, the present approach relies on solving Unsteady Reynolds-averaged Navier-Stokes (URANS) equations. URANS simulation combined with adequate turbulence models, such as the κ-ω SST turbulence model, can provide reasonably good solutions.

*2. Synthetic jet boundary conditions*

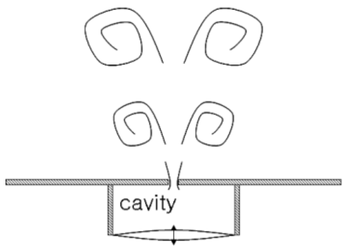


Figure 1. Schematic of a synthetic jet

A synthetic jet actuator is an oscillatory jet generator that requires zero-net mass input yet produces a non-zero momentum output. Figure 1 shows a schematic of a synthetic jet actuator that contains an enclosed cavity with a small orifice on one face. At CFDVAL2004, Rumsey *et al.* reported that, compared to experiment data, the velocity distributions near the orifice exit might exhibit some anomalies neither captured nor modeled by CFD, but they also mentioned that global flow features could be captured with a reasonably good accuracy [3,4].

Based on these results, the suction/blowing-type boundary condition proposed by Kral *et al.*, as in Eq. (1), was applied to the synthetic jet actuator [6]. The 'top hat' condition, wherein the spatial variation of the jet at the orifice was neglected, was employed to obtain computationally efficient results without compromising physical reality. A perturbation to the flow-field was then introduced by the jet velocity where ξ denotes the streamwise direction, η denotes the spanwise direction $\zeta$ denotes normal direction from the wall, $\vec{u}_n$ is a velocity vector, and $\vec{d}_{jet}$ is a unit vector in the jet direction.

$$\vec{u}_n(\xi=0,\eta=0,\zeta,t)=A_{jet}f(\zeta)\sin(\omega t)\vec{d}_{jet},\ \ f(\zeta)=1 \quad (1)$$

## RESULTS AND ANALYSIS

The geometric details and experimental data can be found in Ref. 5. Figure 2 shows the schematic of each exit configuration. The rectangular exit has a width of 0.6 mm and a span of 50 mm, while the circular exit has 17 circular holes of a hole diameter of 1.5 mm, a hole gap of 1.5 mm, and a span of 50 mm. In order to maintain the same geometrical condition, the total exit area, total jet momentum, and the span length were set the same for each jet. The Reynolds number of the circular hole diameter is 1000, the freestream velocity is 10 m/s, the jet frequency is fixed at 50 Hz, and the maximum velocity of the synthetic jet is 40 m/s. The boundary conditions of Eq. (1) can be determined from the flow condition.

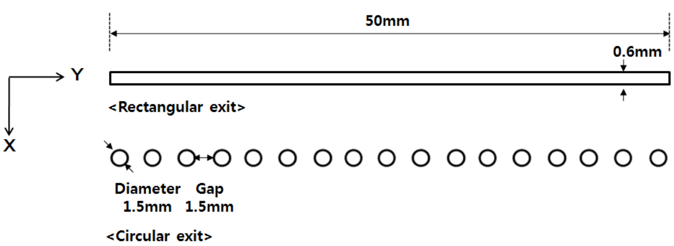
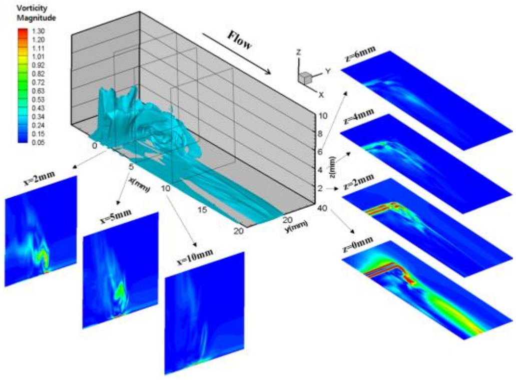


Figure 2. Exit configurations of the rectangular and circular exits

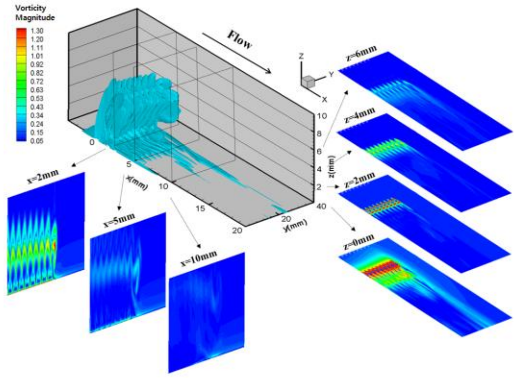
*1. Flow structures*

Figure 3 presents the results of the phase-averaged vortical structures of synthetic jets in cross flow interaction for the rectangular and circular exits. The computed results show very different vortex structures depending on the exit configuration, which affect the characteristics of the subsequent flows. In case of the rectangular exit, a long two-dimensional vortex pair is observed along the spanwise direction, and a semicircular vortex is seen at the end of the slot under quiescent conditions [5]. For the cross flow field, the interaction between the vortex pair and the freestream weakens the vortex strength along X-direction and Z-direction, and the semicircular vortex favorably interacts with the freestream to strengthen the initial vortex, but a vortical structure exists on the flow field for a short duration, as shown in Fig. 3(a).

For the circular exit, a vortex ring is generated at each hole and the overall vortical structure of the circular exit exhibits an additional three-dimensional flow structure under quiescent conditions [5]. This is consistent with the behavior of a vortical structure in cross flow interaction. As shown in Fig. 3(b), the overall vortical structure is stronger and relatively more sustainable from the slot center to the slot end, and its influence on the flow field is much more visible than the rectangular case. This indicates that the circular exit affects local flow characteristics more widely than the rectangular exit.



(a) rectangular exit

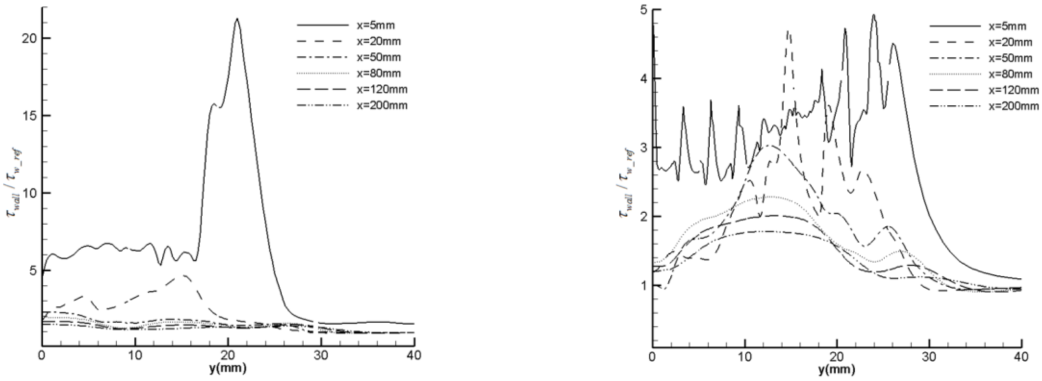


(b) circular exit

Figure 3. Phase-averaged vortical structures (a) rectangular exit; (b) circular exit

*2. Flow control effectiveness*

The flow control effectiveness of the exit configuration is evaluated by comparing the phase-averaged wall shear stress distributions, as shown in Fig. 4. The X-axis is spanwise distance, and the Y-axis is the ratio of the wall shear stress values of the jet-on ( $\tau_{wall}$ ) and the wall shear stress values of the jet-off ( $\tau_{w\_ref}$ ) along the streamwise distance. The variation in wall shear stress is a useful indicator of the effectiveness of a flow control device for flow separation delay. From this perspective, the distributions of wall shear stress were obtained for rectangular and circular exits. For each exit configuration, the wall shear stress ratio was examined along the streamwise and spanwise directions. In case of the rectangular exit, the wall shear stress ratio at the end of the slot is higher than that of the slot center at x = 5 mm, but the values quickly decrease after x = 20 mm. For the circular exit, the wall shear stress distributions are oscillatory. The maximum values coincide with the center of the circular holes, while the minimum values are located between two adjacent holes. Overall, the wall shear stress distributions are relatively preserved along the streamwise direction. This indicates, combined with the result of Fig. 3, that the clockwise rotating flow part at the slot end for the rectangular exit negatively interacts with the freestream, which makes the vortex persistence weaker. However, for the circular exit, serial vortex rings favorably interacts with the freestream to preserve the initial vortex, so it is able to survive longer to have a strong effect on the flow fields. It is noted that the persistence of the jet vortex for the circular exit is better than for the rectangular exit.




(a) rectangular exit (b) circular exit

Figure 4. Phase-averaged distributions of wall shear stress (a) rectangular exit; (b) circular exit

## CONCLUSION

The flow characteristics of synthetic jets with the rectangular and circular exits were numerically investigated. The flow structures and flow control effectiveness were conducted for the cross flow condition at the same jet frequency, total jet momentum, and other parameters. In case of the rectangular exit, the jet vortex is strong near the end of the exit due to the three-dimensional effect. The clockwise rotating flow is then observed from the slot end, which leads to the negative interaction with the freestream, so the effect of the synthetic jet is rapidly decreased further downstream. For the circular exit, on the other hand, the serial vortex rings are uniformly developed in the freestream direction, and the vortical flow effect is far-reaching from the slot exit. The vortical structure favorably interacts to maintain the strength of the initial vortex, and thus, it is able to survive longer and strongly affect the downstream flow field. This is consistent with the results of the wall shear stress distribution, which indicates that the circular exit is relatively more effective for separation delay since the jet vortex of the circular exit produces a more sustainable vortical flow characteristic than the rectangular exit in the cross flow interaction.

## ACKNOWLEDGMENT

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