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Active control of a planar offset attaching jet using synthetic jets

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Abstract

A planar jet issued from a contoured nozzle was forced using a pair of synthetic jet actuators located along the upper and the lower edges of the jet exit. The forcing frequency varied from fH_j/U_o of 0.08 to 0.45 for a fixed forcing amplitude u'/U of 0.3. It was found that the time-averaged re-attachment length was reduced by forcing, the decreases were particularly large when the lower actuator was used. The flow field was modified significantly by the forcing when fH_j/U_o was 0.08, strong vortical structures were observed in the flow which increased the turbulent fluctuations along both shear layers.

Keywords: Active flow control; synthetic jet actuator; offset attaching jet

Nomenclature

f^*	nondimensional forcing frequency, fH/U_o
H_j	height of the jet, m
H_s	height of the step, m
Re	Reynolds number based on the jet height, U_oH_j/ν
U_o	spatial averaged flow velocity across the jet exit, m/s
U, V	local time-averaged stream-wise and vertical velocities, m/s
u'	root-mean-square value of the exit velocity for the synthetic jet, m/s
$\overline{u^2}$	Reynolds stream-wise normal stress, m^2/s^2
$\overline{v^2}$	Reynolds vertical normal stress, m^2/s^2
x, y, z	spatial coordinates, m
y_{max}	vertical location of the maximum mean velocity, m
$y_{i,max}$	vertical location of the maximum $\overline{u^2}$ along inner shear layer, m
$y_{o,max}$	vertical location of the maximum $\overline{u^2}$ along outer shear layer, m
X_r	time-averaged re-attachment length, m

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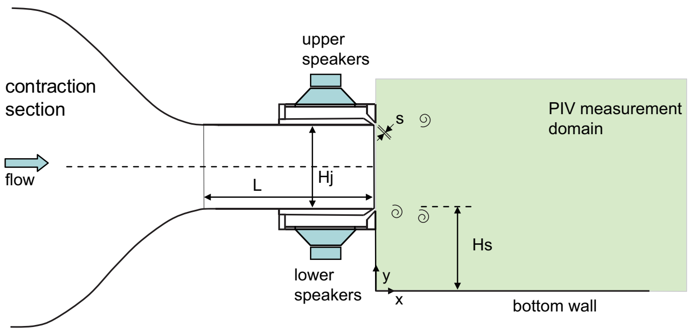

Fig. 1. Schematics of the test rig

1. Introduction

A two-dimensional jet issued parallel to a solid wall with an offset distance (H_s) curves and attaches to the wall. It is often used in cooling or drying applications. There is a shear layer develops along the lower side of the jet, similar to other separated flows, and another shear layer forms along the upper side of the jet. Gao and Ewing [1] studied the distributions of the mean velocity for a planar offset attaching jet issued from two parallel plates with offset distances of 0.2 to $1.0H_j$. They divided the flow into five different stages. The first three stages were related to the attaching process while the jet evolved into a flow similar to a typical wall jet in the last two stages. Gao and Ewing [2] studied the large-scale motions in an offset jet used by [1] by examining the correlations between the fluctuating velocities and the fluctuating wall pressure. They found that the fluctuations of wall pressure distributed uniformly in frequencies (fX_r/U_j) from 0.5 to 1.0. They argued that the pressure fluctuations in this frequency range was related to flow structures developed along the inner shear layer. Gao and Ewing [2] also found that there was a flapping motion with a frequency $fX_r/U_j < 0.2$ in the separation region. After the jet attached to the wall, the impact of flow structures structures in the shear layer on the wall decreased gradually in the stream-wise direction. The flow eventually became similar to a planar wall jet without initial offset height ($H_s/H_j = 0$).

Efforts were also made to modify the development of an offset attaching jet using active flow control methods. Tanaka et al. [5–7] studied the effect of blowing or sucking flow though a gap in the corner of the recirculation region of a turbulent radial attaching jet discharged from a cylindrical nozzle. When the suction flow rate was increased, the maximum stream-wise velocity decayed at a faster rate in the near filed, and the maximum in the static pressure associated with the attachment process was also more pronounced, and the location of this maximum shifted upstream. When the blowing flow rate was increased, the maximum in the stream-wise mean velocity decayed at a slower rate in the region $x/H_s \leq 15$ The maximum static pressure on the wall also decreased and the attachment point shifted to a downstream location. Gao et al. [3,4] used a co-flowing wall jet to control the offset attaching jet they studied in [1,2]. They compared the mean and fluctuating wall pressure, skin friction on the wall and the heat transfer rates from the wall to the jet for different ratios of mass flux ratios and momentum flux ratios between the offset jet and the co-flowing wall jet. Different mean flow patterns were identified. They found wall jet with low momentum was quickly entrained into the offset jet reducing the turbulent fluctuations and the heat transfer rate in the near field of the attaching jet. These changes increased with the mass flow rate of the wall jet. Wall jet with larger momentum flux remained attached to the wall inducing periodic motions that significantly increase the wall normal turbulent fluctuations in the flow.

Control of a planar attaching jet using zero-net-mass-flux(synthetic) jets was not studied before. Here in this investigation, the effect synthetic jets on the development of a offset attaching jet will be examined experimentally.

2. Experimental methods

The experimental facility shown in Fig. 1 is made from $10mm$ thick plexiglas. The jet facility was modified from the facility used by [8]. Air flow from a $0.75kW$ centrifugal fan goes through a diverging section, a setting chamber and a two dimensional contraction section forming a planar jet with a height (H_j) of $30mm$. The profile of the contraction

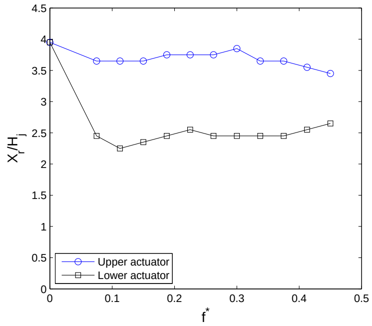

Fig. 2. Distributions of the time-averaged re-attachment location.

section was a 5th polynomial with length of 300mm and a contraction ratio of 10. Two perforated plates were used inside of the setting chamber to condition the flow, the turbulence at the jet exit was less than 0.5%. A 500mm long bottom plate was position in a direction parallel to the jet exit. The vertical distance from the lower edge of the jet to the plate (H_s) is 30mm. The width of the experimental facilities is 300mm, the aspect ratio of the flow was 10. Two side panels with a height of 200mm was used to maintain two dimensional development of the flow.

A 100mm long (L) straight section containing the actuators was added to the exit of contoured nozzle. The synthetic jet produced jet flows through a 1mm-height slot (s) that were directed at a 45 degree to the main jet, the amplitude of the control jets were 30% of the velocity of the main jet ($u'/U_0 = 0.3$). The velocity of the control jet varied periodically at a frequency of $f^* = 0.08$ to 0.45. Two 80mm-diameter 4 Ω 40W speakers were used for each synthetic jet. The driving signal was produced using a signal generator and amplified using a digital amplifier. The performance of the synthetic jet actuators were characterized using a hot-wire probe located at 1mm downstream of the jet exit. It was found the natural frequency of the cavity of the synthetic jet was approximately 80Hz where the jet produced the largest oscillating velocity at the exit with a constant amplitude sinusoidal electric driving signal. The pressure inside of the cavity was also monitored using a pressure transducer with a response time less than 1ms. The variations of u'/U_o produced by the two synthetic jets were within 3%.

The development of the flow field on the centerline-plane ($z = 0$) was characterized using a Lavision 2D PIV system. Droplets of olive oil with a mean particle diameter of 1μm were used as tracer particles. These particles were introduced to the diverging section of the rig using an in-house four-nozzle head droplet generator. A 200 mJ dual-head Nd:YAG Litron Nano pulse laser system was used to illuminate the tracer particles. The laser pulses were triggered at a rate of 25Hz. A Lavision supplied Highspeedstar camera with 1024x1024 pixel resolution was used to capture the images. The separation time between two exposures was 100μs to allow seed particles to travel 6 pixels based on the average jet velocity. 2000 image pairs were collected for processing which resulted in a total PIV error less than 3%. Lavision DaVis 8.1 software package was used for image acquisition and post-processing. Vectors were computed using cross correlation and 50% overlap with a multi-pass of 32x32 pixel and 16x16 pixel interrogation windows. The velocity and pressure measurements were performed with an cross-sectional averaged jet velocity (U_j) of 8.0m/s, determined by integrating the velocity profiles measured at the exit. The corresponding Reynolds number (Re) was 15300.

3. Results and Discussion

The stream-wise position with $U = 0$ at $y/H = 0.05$ interpolated from the time averaged stream-wise velocity (U) was taken as the time-average re-attachment location, shown in Fig. 2. X_r decreased when the jet was forced, the decreases were much larger when the lower actuator was used. It was counter-intuitive that X_r decreased when the upper actuator was used, one would expect the bulk of the jet curve away from the wall when forced at the upper edge.

The distributions of the mean velocity and the stream-wise and the vertical Reynolds normal stresses when the jet was forced using the upper actuator with $u'/U_o = 0.3$ are shown in Fig.4. When there was no control, the bulk of the jet curved toward the wall and attached to the wall near $x/H_j \approx 4.0$. A shear layer developed on each side of the jet, the velocity fluctuations along the shear layers increased after the jet was issued from the exit. The shear layer

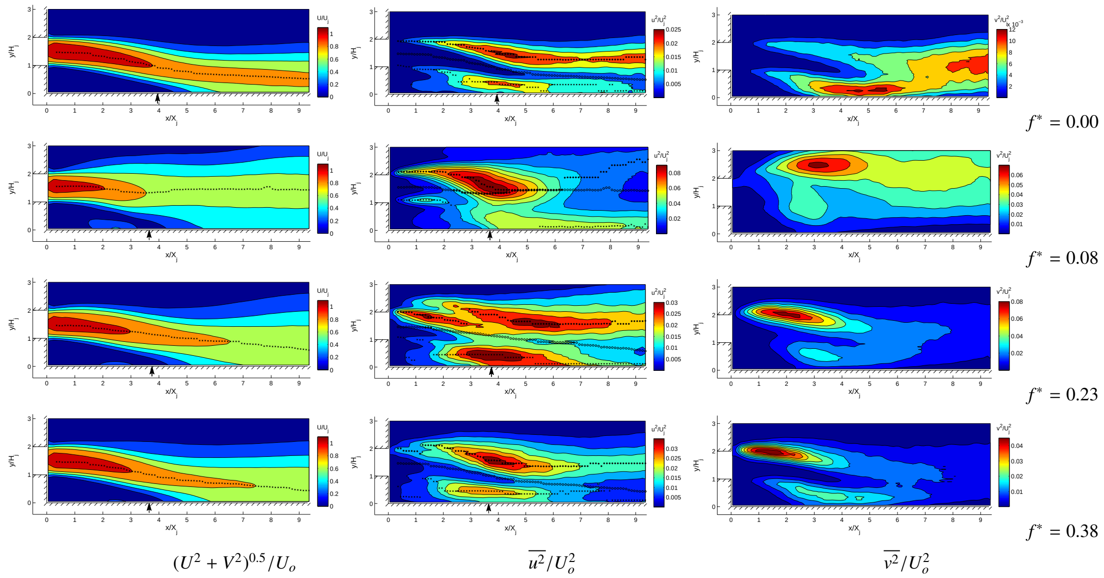

Fig. 3. Distributions of (left) the time-averaged velocity, (middle) stream-wise and (right) vertical normal stresses for forcing frequencies $f^* = 0$(no control) to 0.38 using the **upper** actuator a forcing amplitude of $u'/U_o = 0.3$. Black dots were for visual aid only.

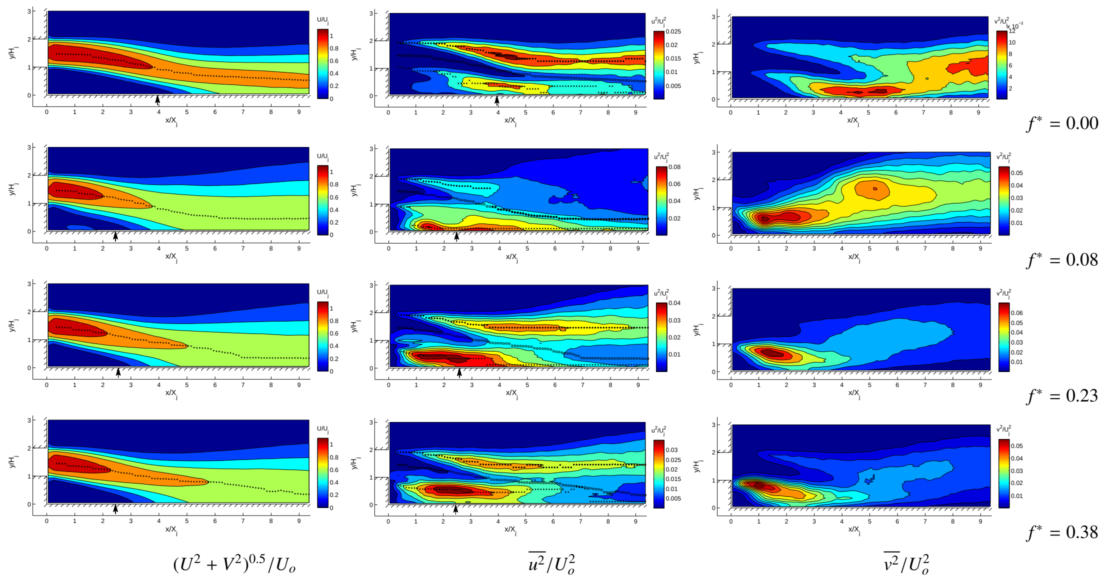

Fig. 4. Distributions of (left) the time-averaged velocity, (middle) stream-wise and (right) vertical normal stresses for forcing frequencies $f^* = 0$(no control) to 0.38 using the **lower** actuator a forcing amplitude of $u'/U_o = 0.3$. Black dots were for visual aid only.

below the jet (or inner shear layer) decreased in strength after the jet attached to the wall. When the jet was forced at the upper edge with a low frequency $f^* = 0.08$, the bulk of the jet was nearly parallel to the wall in the region $x/H_j \geq 3.0$. Forcing also caused strong vertical motion at $x/H \approx 3.0$ and $y/H \approx 2.5$, and strong horizontal motion at $3.0 \leq x/H \leq 4.0$ at $y/H \approx 1.5$. When the jet was forced at $f^* = 0.23$, motions in both shear layer were enhanced. The enhancement was less when a higher forcing frequency ($f^* = 0.38$) was used. When the jet was forced at the lower edge, the fluctuations in the inner shear layer were enhanced.

Comparisons of the stream-wise normal stresses for jet with different forcing frequencies using the upper and lower actuators are shown in Fig. 5 and 6, respectively. The maximum local velocity decreased by forcing, particulary for the

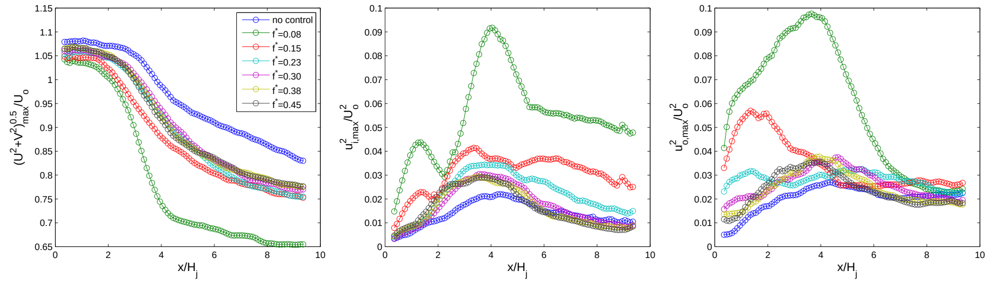

Fig. 5. Distributions of the (left) maximum local velocity and maximum normal stress along the (middle) inner shear layer and (right) outer shear layer using the **upper** actuator with $u'/U_o = 0.3$.

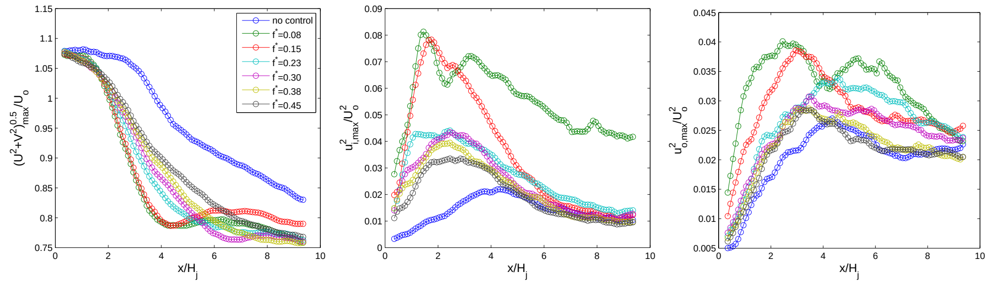

Fig. 6. Distributions of the (left) maximum local velocity and maximum normal stress along the (middle) inner shear layer and (right) outer shear layer using the **lower** actuator with $u'/U_o = 0.3$.

case with low frequency of $f^* = 0.08$ applied at the upper edge, there are also significant increase in the fluctuations in the outer and the inner shear layers. The enhanced flapping motion had a significant impact on the flow.

4. Conclusions

A planar jet issued from a contoured nozzle was forced using a pair of synthetic jet actuators located along the upper and the lower edge of the jet exit. The forcing frequency was varied from fH_j/U_o of 0.08 to 0.45 for a fixed forcing amplitude u'/U of 0.3. It was found that the time-averaged re-attachment length was reduced by forcing. The flapping motion was enhanced significantly when low frequency forcing with fH_j/U_o of 0.08 was applied to the upper edge of the jet, strong vortical structures were observed in the flow which increased the turbulent fluctuations along both shear layers.

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