SUPPRESSION OF UNSTEADY VORTEX SHEDDING FROM A CIRCULAR CYLINDER BY USING A PASSIVE JET FLOW CONTROL METHOD

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ABSTRACT
A passive jet flow control method was employed to suppress the unsteady vortex shedding from a circular cylinder at the Reynolds number level of \( Re = (0.18\sim1.1) \times 10^5 \). The passive jet flow control was achieved by blowing jets from the holes near the rear stagnation point of the cylinder, which are connected to the in-take holes located near the front stagnation point through channels embedded inside the cylinder. Since a part of the oncoming flow would inhale into the in-take holes, flow through the embedded channels, and blow out from the holes near the rear stagnation point to suppress/manipulate the alternating vortex shedding in the wake flow behind the circular cylinder, the present passive jet flow control method does not require any additional energy inputs for the flow control. In the present study, the aerodynamic force (i.e., both lift and drag) acting the circular cylinder model with and without the passive jet flow control were compared quantitatively at different Reynolds numbers (i.e., different inlet mean speed). It was found that, in addition to almost eliminating the fluctuations of the lift forces acting on the cylinder, the passive jet flow control method was also found to reduce the mean drag acting on the cylinder model greatly. The instantaneous vorticity distributions and corresponding streamline patterns were used to reveal the underlying physics about why and how the passive jet flow control method can be used to suppress the alternating vortex shedding and induce a symmetrical wake pattern behind the cylinder model.

Keywords: Passive jet flow control; suppression of alternating vortex shedding; vortex-induced-vibration; wake flows behind circular cylinders.

INTRODUCTION
Vortex-induced-vibrations (VIVs) of circular cables are closely related to the vortex shedding in the wakes behind the bluff bodies (i.e., circular cylinders); a number of studies have been performed in recent years to manipulate the vortex shedding process in order to reduce the VIVs of the bluff bodies. Several passive flow control methods, which depend on the modifications of the geometry shapes of the bluff bodies, have been suggested to manipulate the vortex shedding process behind the bluff bodies. For examples, Roshko (1955, 1961) suggested to mount a splitter plate behind a circular cylinder to change the alternative shedding mode of the vortex structures in the wake flow into a symmetric mode. Owen et al. (2001) attached hemispherical bumps to circular cylinders to control the fluctuating amplitudes of the vortex-induced vibrations of cable models.

Glezer and Amitay (2002) investigated the interactions of synthetic jets with the cross flows and reported that synthetic jets could delay flow separation and reduce the drag acting on bluff bodies. While synthetic jets were usually placed near the separation points for flow control, Feng et al. (2010, 2011) and Feng and Wang (2010, 2012) found that synthetic jets located at the rear stagnation points of circular cylinders would also be used to suppress flow separations and reduce the resultant drags acting the circular cylinders.

Active jet flow control need input external energy to induce the jet flow; however, the present passive jet flow control needn’t consume the external energy and realize as follows: the partial oncoming flow blew into the inlet holes, went through the ring channels and blew from the jet holes into the near wake as a result of breaking/suppressing the alternating vortex shedding in the wake.

MESH GENERATION FOR CFD SIMULATION
The diameter \( D \) of the circular cylinder is 100 mm. The pipe height of the ring channel around the cylinder is 5 mm; as a result, the diameter of the ring channel is 110 mm. Five inlet holes are employed near the front stagnation point and five outlet holes are employed near the back stagnation. The inlet and outlet holes’ location is shown in Fig. 1 and the interval angle between two neighboring holes equals 7.5 deg.
The size of each inlet or outlet hole is the same rectangular to be 8.0mm×6.9mm which are the dimensions along the axial and circumference direction of the cylinder, respectively.

Fig. 1. Mesh generation for the CFD simulation of the flow around a circular cylinder

Figure 1 shows the computation domain for the CFD numerical simulation of the flow field around a circular cylinder. The grid partition was achieved in the pre-processor code ICEM-CFD 13.0, and the structural mesh was chosen in the discretization process. The number of grid cells of the cuboid computational region was roughly 250,000. The first grid normal to the cylinder surface was set as 0.6 mm and 200 grids were equidistantly arranged on the cylinder surface along the circumferential direction. The boundary conditions are defined as follows: left side is the “velocity inlet”; right side is “outflow” which is fully developed outlet boundary; front, back, upper and lower boundaries are “symmetry”; the circular cylinder surface is “wall”; and the surface of the ring channel is “wall”. For the baseline cases (i.e., no control cases), the inlet and outlet holes are set as “wall”; for the control cases, the inlet and outlet holes are set as “opening” which means the flow can enter into or come out from the ring channel.

The shear stress transport (SST) $k-\omega$ turbulent model (Menter, 1993) based on the RANS method was employed to simulate the behavior of turbulent flow in the CFD numerical simulation. The time interval was set as 0.0025 s, the mean wind speed of the inlet was uniform and changed at 2.5, 5.0, 10.0 and 15.0 m/s with a low turbulence intensity of 1%, the corresponding Reynolds number is about (0.18-1.1) ×10^5. The simulation Reynolds number range frequently occurs in the actual engineering.

RESULTS AND DISCUSSIONS

To verify the above-mentioned numerical method and meantime provide baseline cases for the passive jet flow control, the flow past an uncontrolled circular cylinder was first simulated and the aerodynamic coefficients (i.e., the lift and drag coefficients) as shown in Fig. 2. Meantime, the corresponding frequency spectra of the time histories of the lift and drag coefficients were calculated as shown in Fig. 3. The mean drag coefficient and the Strouhal number were compared with well-known benchmark results by previous researchers as shown in Fig. 4. The mean drag coefficient is consistent with the previous results. The Strouhal number is little larger than the previous experimental results, however, is close to the simulation results (Franke, 1990). Therefore, the feasibility and reliability of proposed numerical method and grid can be accepted by the baseline simulation examples.

The numerical simulations of the passive jet flow control were then performed and the controlled aerodynamic coefficients were shown in Fig. 2. Compared with the baseline cases, the fluctuations of the lift and drag coefficients are dramatically suppressed and the mean drag coefficients are simultaneously decreased. As shown in Fig. 3, Comparing with the baseline cases, there is no dominant frequency component in the frequency spectra of the lift and drag coefficients for the controlled cases. The present aerodynamic forces of the controlled cases (i.e., lift or drag) will not bring the flow-induced vibration whatever in the cross-flow direction or the in-line direction.

Based on the time sequences of the unsteady aerodynamic force measurements as shown in Fig. 2, the standard deviations of the instantaneous drag and lift forces acting on the cylinder model can be calculated, which can be used to assess the effectiveness of the passive jet flow control in reducing the unsteadiness of the wind loads acting on the cylinder model for potential VIV suppression more clearly and quantitatively. In the present study, a non-dimensional parameter, called force fluctuation reduction factor, $f_{\text{jet-control}}$, which is defined as the ratio of the standard deviation values of the dynamic aerodynamic forces (either drag or lift) acting on the cylinder for the cases with passive jet flow control, $\sigma_{\text{with-control}}$, to those of the baseline cases without control, $\sigma_{\text{without-control}}$, i.e., $f_{\text{jet-control}} = \frac{\sigma_{\text{with-control}}}{\sigma_{\text{without-control}}}$ is used as a quantitative indicator to assess the effectiveness of the passive jet flow control under different simulation conditions (i.e., different Reynolds number).
Fig. 2. Comparison of aerodynamic coefficients between the baseline and passive control cases

Fig. 3. Comparison of PSD of aerodynamic coefficients between the baseline and passive control cases
It should be noted that the force fluctuation reduction factor, \( f_{\text{jet-control}} \), would have a value of 1.0 for the baseline cases (i.e., the cases without control). When the value of \( f_{\text{jet-control}} \) is smaller than 1.0, it indicates that the fluctuating amplitudes of the dynamic wind loads acting on the cylinder can be reduced by using the passive jet flow control method, thereby, it would offer a great potential for VIV suppression. Smaller the \( f_{\text{jet-control}} \) value is; better performance the passive jet flow control method will have for VIV suppression. Fig. 5 gives the \( f_{\text{jet-control}} \) values based on the simulated lift coefficients of the cylinder with and without the passive jet flow control. The control effectiveness of the \( f_{\text{jet-control}} \) values are 3.28%, 4.24%, 0.04% and 0.01% corresponding to the Reynolds number of \( Re=0.18\times10^5 \), \( Re=0.36\times10^5 \), \( Re=0.71\times10^5 \) and \( Re=1.1\times10^5 \).

Figure 6 shows the measured mean drag reduction factor, which is defined as the ratio of the mean drag forces acting on the cylinder for the cases with the passive jet flow control to that of the baseline case without control (i.e., \( C_{D_{\text{with\ passive\ jet\ control}}} / C_{D_{\text{without\ control}}} \)), as a function of the Reynolds number. The mean drag coefficients of the cylinder were found to decrease rapidly under the passive jet flow control. The drag coefficients of the cylinder were found to become 68.74%, 72.05%, 73.60%, and 75.62% of those of the corresponding baseline cases.

From the simulation results of the force fluctuation reduction factor and the mean drag reduction factor, the passive jet flow control exhibits excellent control effectiveness, meantime, the control effectiveness is stable and no further significant improvements were observed when the Reynolds number changed.

The simulated aerodynamic coefficient results given above reveal many interesting features and global characteristics about the passive jet flow control method in reducing the unsteadiness of the dynamic wind loads acting on the simulation model. Moreover, the quantitative information about the corresponding flow fields around the cylinder with and without passive jet flow control is highly desirable to elucidate the underlying physics to gain further insight about the fundamental mechanism of the passive jet flow control method with isolated jet holes. The vorticity and streamline results were utilized in the present study to quantify the characteristics of the wake flow behind the cylinder.

Figure 7 shows the comparison of the instantaneous vorticity contour with and without the passive jet flow control. The left column is the baseline results and the right one is the controlled results. As the Reynolds number was located in the subcritical region, the wake patterns are “2S” mode for four simulated cases. Under the passive jet flow control, the wake becomes the completely symmetrical pattern for the cases of \( Re=0.71\times10^5 \) and \( Re=1.1\times10^5 \). Comparing with the results of the force fluctuation reduction factor shown in Fig. 5, the lift fluctuation was suppressed to be nearly zero. For the cases of \( Re=0.18\times10^5 \) and \( Re=0.36\times10^5 \), the wake doesn’t completely becomes the symmetrical mode, i.e., an approximately symmetrical pattern; however, the lift fluctuation was suppressed to be about 5% of those of the corresponding
baseline cases. Whatever the case, the instantaneous vorticity contours indicate that the vorticity near the outlet holes are the opposite directions from the main vorticity distribution. It means that the outlet holes can generate small scale of reverse vortices again the main wake vortices. The symmetrically generated small scale of reverse vortices can destroy/suppress the alternating vortex shedding and induce a symmetrical wake pattern as shown in right column of Fig. 7.

In the wall turbulence or shear flow, the strong shear layers existing will cover the virtual turbulence eddies and the shearing motions will make the reliable calculation of the virtual vortices difficulty as shown in right column of Fig. 7. Figure 7 shows that whole shear layer in the far wake are computed as the vorticity under a passive flow control. To overcome this shortcoming, we prefer to use the imaginary part of the complex eigenvalue of the velocity gradient tensor to distinctly visualize vortices (Zhou et al., 1999). Swirling strength is closely related to vorticity but it can discriminate between vorticity due to shear motion and vorticity resulting from rotation as shown in Fig. 8. Figure 8 indicates that the wake vortices are almost eliminated in the far wake for the cases of \( Re=0.71 \times 10^5 \) and \( Re=1.1 \times 10^5 \) and the vortex shedding is greatly weakened in the wake for the cases of \( Re=0.18 \times 10^5 \) and \( Re=0.36 \times 10^5 \).

The streamline distributions in the flow field were then studied as shown in Fig. 9 and Fig. 10; the left column is the baseline results and the right one is the controlled results. The controlled results indicate that the partial fluid (i.e., the air) flows into the inlet holes, goes through the ring channel and then flows out from the outlet holes. The flow from the outlet holes stops the streamline alternate in the vertical direction and separates the wake into the upper and lower parts. Under the passive jet flow control, the recirculation region was suppressed and most of the fluid moves along the main flow direction. Similarly with the results of Fig. 7, the streamline distributions are completely symmetrical for the cases of \( Re=0.71 \times 10^5 \) and \( Re=1.1 \times 10^5 \) and approximately symmetrical for the cases of \( Re=0.71 \times 10^5 \) and \( Re=1.1 \times 10^5 \).

![Fig. 7. Comparison of the instantaneous vorticity contour with and without the passive jet flow control, left: the baseline results, right: the controlled results](image-url)
Fig. 8. Comparison of swirling strength contour with and without control (left: the baseline; right: controlled results)

(a) Re=0.18×10^5
(b) Re=0.36×10^5
(c) Re=0.71×10^5
(d) Re=1.1×10^5

Fig. 9. Comparison of streamlines around the cylinder with and without control (left: baseline; right: controlled results)

(a) Re=0.18×10^5
(b) Re=0.36×10^5
(c) Re=0.71×10^5
(d) Re=1.1×10^5
Fig. 10. Comparison of the instantaneous streamline distribution in the near wake with and without the passive jet flow control, left: the baseline results, right: the controlled results
For further investigation of the control effectiveness of the passive jet flow control method with the Reynolds number, following the work of Chen et al. (2013), the suction/jet momentum coefficient, $C_\mu$, which is defined as the ratio of the suction/jet momentum flux to the oncoming free-stream momentum flux, i.e., 

$$
C_\mu = \left( \frac{U_{\text{suc}}}{U_*} \right)^2 \left( \frac{S_{\text{suc}}}{DL_0} \right),
$$

where $S_{\text{suc}}$ is the area of the suction/jet holes (i.e., the total area of the five suction/jet holes); $L_0$ is the thickness of the circular cylinder and is chosen as $0.2D$ in the simulation. The suction/jet momentum coefficients $C_\mu$ for each simulated case are shown in Fig.11 where $C_{\mu-\text{In}}$ indicates the suction momentum coefficient of the inlet holes and $C_{\mu-\text{Out}}$ denotes the jet momentum coefficient of the outlet holes. The result show when the Reynolds number increases, the suction momentum coefficient increases and the jet moment coefficient decrease. However, the change of suction/jet momentum coefficient is very small with the Reynolds number.

![Fig. 11. The suction/jet momentum coefficients of the passive jet flow control vs. Reynolds number](image)

Figure 12 indicates the velocity of inlet/outlet holes of the passive jet flow control changing with the Reynolds number. The result indicates that the improvement of the control effectiveness is more related to the absolute velocities of the outlet holes.

![Fig. 12. The velocity of inlet/outlet holes of the passive jet flow control vs. Reynolds number](image)

CONCLUSIONS

This paper investigated the passive jet flow control method for suppressing the unsteady vortex shedding from a circular cylinder through numerical simulations. The following conclusions were obtained from this study:

1. The passive jet flow control method can dramatically decrease the lift fluctuation and achieve the control effectiveness exceeding 95%, which means this method can potentially suppress the VIV of the cylinder; simultaneously, this flow control method can decrease the mean drag coefficient to be less than 75% of those corresponding baseline cases. The dominant frequencies in the aerodynamic forces are eliminated under the passive jet flow control.

2. The passive jet flow control can generate small scale of reverse vortices which are symmetrical. These symmetrically reverse vortices can destroy/suppress the alternating vortex shedding and induce a symmetrical wake pattern in the near-wall region. In the far region, the wake vortices are greatly suppressed for smaller Reynolds number cases or entirely eliminated for larger Reynolds number cases.

3. In the present Reynolds number region which locates in the subcritical region, the wake pattern (either vorticity or streamline distribution) will change from the approximate symmetrical mode into the completely symmetrical mode with the Reynolds number increasing. As a result, the lift fluctuations will decrease to nearly zero.

4. The control effectiveness of the passive jet flow control method is improved with increasing the absolute velocities from the outlet holes when the Reynolds number increases.

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REFERENCES


