

## Control of Vortex Shedding at Moderate Reynolds Numbers\*

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### ABSTRACT

The suppression method of vortex shedding from a circular cylinder has been studied experimentally in the Reynolds number range from 300 to 1600. The test is performed in a water channel. The model cylinder is 1 cm in diameter and 38 cm in length. A row of small rods of 0.18 cm in diameter and 1.5 cm in length are perpendicularly connected to the surface of the model cylinder and distributed along the meridian. The distance between the neighboring rods and the angle of attack of the rods can be changed so that the suppression effect on vortex shedding can be adjusted. The results show that vortex shedding can be suppressed effectively if the distance between the neighboring rods is smaller than 3 times and the cylinder diameter and the angle of attack is in the range of  $30^\circ \leq \beta < 90^\circ$ .

**Key words:** control of vortex shedding; vortex-induced vibration; moderate *Re* numbers

### 1. Introduction

It is well known that regular vortex shedding occurs behind a bluff body when fluid flows across it at a certain velocity. The pressure distribution on the surface changes as the vortices shed alternatively from each side of the cylinder. A sinusoidal fluid force is then generated which may cause vibration of the body. Vortex induced vibration (VIV) is dangerous to cylindrical structures, not only for the durable fatigue damage, but also for the possible resonance. The key parameter to vortex induced vibration is the reduced velocity  $U/fD$  (Blevins, 1990), where  $U$  is the oncoming velocity of fluid,  $f$  is the vibrating frequency and  $D$  is the diameter of the cylinder. To a forced oscillating cylinder, the phenomenon of lock-on (Pesce and Fajra, 2000) occurs if the value of  $U/fD$  is in a certain range. The frequency of vortex shedding changes from following  $St-Re$  relation to coinciding with the vibration frequency of the body (Blevins, 1990). On this condition the rms (root-mean-square) value of fluctuating velocity in the wake and the rms value of fluctuating hydrodynamic force acting on the body can be promoted to rather high levels. To a free vibrating cantilevered cylinder, the interaction between vibration and vortex shedding is very complicated (Govardhan and Williamson, 2000). When  $U/fD$  reaches a certain value  $a$ , the amplitude of vibration jumps up abruptly to a much higher level. The amplitude remains at the level as  $U/fD$  further increases from  $a$  to  $b$ . At  $U/fD = b$ , the amplitude falls off abruptly to a much lower level.

There are some instances in wind engineering that large structures were destroyed by vortex induced

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vibration, such as the failure of cooling towers at the power station Ferry-bridge in England and the collapse of Tacoma-Narrows bridge deck in the USA. Vortex-induced vibration also makes troubles in ocean engineering (Vandiver, 1998; Farnes, 1998; Allen, 1998). The risers and tension legs of a deep-sea (hundreds of meters or more in depth) platform vibrate as ocean current flows across them. Resonance occurs at relatively large reduced velocities. To a very long circular cylindrical riser, danger comes from three sides (Allen, 1998):

1. Current velocity is usually larger in deep ocean than that in shallow sea.
2. The increase of length lowers the riser's natural frequency, thus increasing the reduced velocity.
3. The floating type of platform is commonly used in deep-sea, therefore, there is no structure to hold the riser.

Efforts have been made to control vortex-induced vibration (Sumer and Fredsøe, 1997; Blevins, 1990). The control methods may be classified into two categories. One is to change the vibrating characteristics of structures, such as stiffening the structure to avoid resonance; adding mass, hanging hammers and changing the moment of inertia to enhance damping; using active control systems to reduce vibration, etc. Another is to change the hydrodynamic characteristics of structures, such as streamlining the body, using separation control devices, and employing vortex frequency modulation (or called frequency shifting) technique, to avoid resonance.

To suppress the formation of vortex shedding is a direct solution to the control of vortex-induced vibration. Up to now, many kinds of suppression methods have been developed, such as, splitting plate set in the wake (You *et al.*, 1998), fluid blowing at the trailing-edge (Schumm *et al.*, 1994; Wood, 1964), cylinder vibration (Beger, 1961; Tokumaru and Dimotakis, 1991), body heating (Lecordier *et al.*, 1991) and sound interference (Blevins, 1985). But none of them is suitable for solving the engineering problems mentioned above.

Some vortex suppression methods of engineering practicality may be found in literature (Blevins, 1990; Walshe and Woolton, 1970; Sumer and Fredsøe, 1997). In our recent research (Shao *et al.*, 1998), a new and simple method has been developed to control vortex shedding. In this paper, the suppression method and its result for the flow past a circular cylinder at moderate Reynolds numbers will be presented.

## 2. Experimental Method

The experiment was performed in a low turbulence water channel in the State Key Laboratory for Turbulence Study, Peking University, Beijing, China. The test section of the channel was 3 m long, 80 cm high and 40 cm wide. The channel could supply steady and homogeneous stream flow in a range of velocity 0.1 ~ 1.0 m/s in the test section. As shown in Fig. 1, the model circular cylinder was placed horizontally across the channel at a height of 40 cm from the bottom. The cylinder was 38 cm in length and 1 cm in diameter, and each end was mounted with an end plate. The height of the end plate was 20 cm, the thickness was 1 cm and the length was 35 cm. The conterminous place of the cylinder and the end plate was 20 cm from the leading edge of the end plate and 15 cm from the trailing edge. Slopes, started from

the leading and trailing sharp edges respectively and extended to the conterminous place, were formed on the inner side (the side facing the water) of each end plate to reduce the influence of fluid boundary layers over the side walls of the channel.

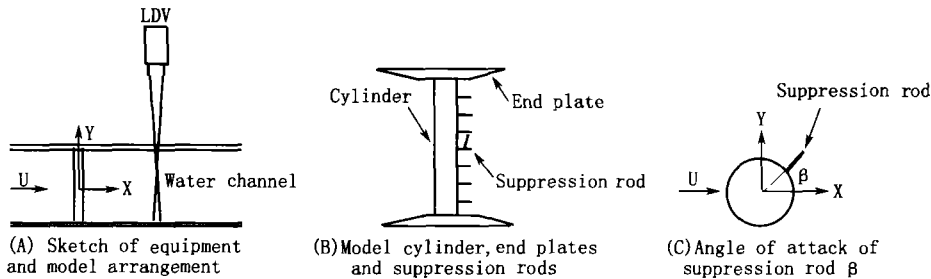


Fig. 1. Sketch of model cylinder and experimental equipment.

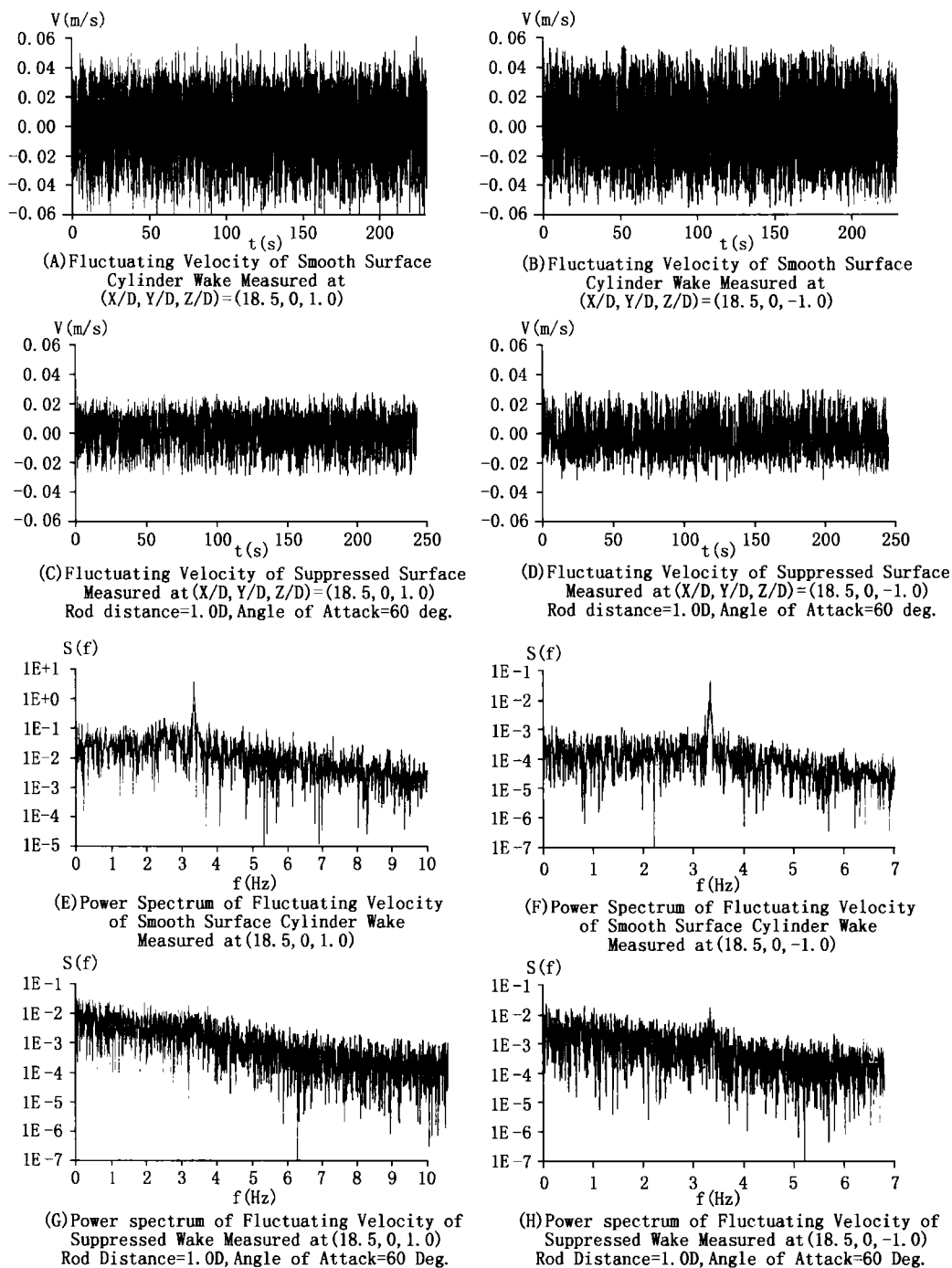
As is known, vortex shedding naturally occurs behind a circular cylinder of a smooth surface if the Reynolds number of flow is larger than about 45. In order to suppress the formation of vortex shedding, a row of small rods of 1.5 cm in length and 0.18 cm in diameter were distributed along a meridian line of the cylinder. One end of each rod was perpendicularly connected with the cylinder surface, and the other end was exposed to the water. The distance between the neighboring rods and the angle of attack of the rods (see Fig. 2(B)) could be changed to adjust the suppression effect in experiment. The model cylinder, end plates and rods were all made of plexiglas, and tightly connected with each other.

The mean and fluctuating velocities of the wake of smooth surface cylinder (SSC for short) and the wake of cylinder with suppression rods (SRC for short) were measured respectively in each run. Before the measurement of SSC wake, the velocity of the oncoming flow was adjusted to a certain value, then kept constant there to allow for stabilization of the flow. The measurement was carried out with a Laser-Doppler Velocity-meter. After the measurement of SSC wake, the model was fitted with suppression rods and fixed at the position. The flow velocity was kept unchanged. A 10-minute re-stabilization of the flow was insured to reduce the influence of disturbance caused by the setting of suppression-rods .

### 3. Results and Discussions

The measurements of fluctuating velocities in the wake of SSC as well as in the wake of SRC with different arrangements of suppression rods have been done. The test Reynolds number ranges between 300 and 1600. The distance between the neighboring rods  $l/D$  changes from 1 to 3 and the angle of attack of the rods changes from  $0^\circ$  to  $90^\circ$ .

The depictions in Fig. 2 show the antitheses of fluctuating velocities of SSC and SRC wakes and their power spectra at a Reynolds number  $Re = 1600$ . Figs. 2(A) and 2(B) are the fluctuating velocity signals of SSC wake measured at  $(X/D, Y/D, Z/D) = (18.5, 0, 1.0)$  and  $(18.5, 0, -1.0)$  respectively. Their power spectra are shown in Figs 2(E) and 2(F) respectively. A peak exists at the frequency  $f = 3.2$  Hz, which means that vortex shedding occurs behind the SSC. The corresponding Strouhal number of the shedding frequency  $St = 0.21$  is close to the values measured by other authors. Figs.

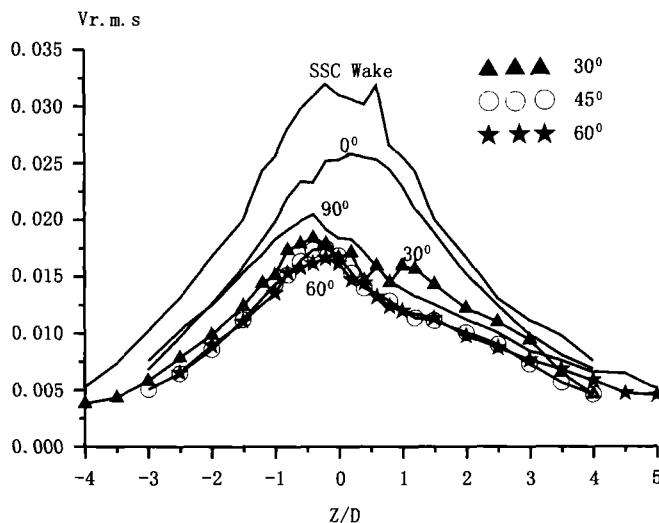


**Fig. 2.** Fluctuating velocities and their power spectra of suppressed and un-suppressed wakes tested at  $Re = 1600$ .

2(C) and 2(D) are the fluctuating velocity signals of a SRC (rod distance  $l/D = 1.0$ , and attack angle of the rods  $\beta = 60^\circ$ ) wake measured at the points  $(18.5, 0, 1.0)$  and  $(18.5, 0, -1.0)$  respectively. Their power spectra are shown in Figs.2 (G) and 2(H) respectively. The amplitudes of fluctuating velocities at both the upper side ( $Z > 0$ ) and the lower side ( $Z < 0$ ) of the SRC wake are much smaller than those of SSC wake. The spectra of fluctuating velocities for SRC wake are broad banded and the peak values are 2-orders lower than those for the SSC wake, indicating that the suppression method is effective.

For check of the span-wise uniformity of suppressed wake flow in the mid-field region  $15D \sim 20D$  from the cylinder, mean and fluctuating velocities were measured along a line parallel to and  $18.5D$  from the  $Y$ -axis. The distance between the neighboring test points is  $\Delta Y = 0.5D$ . The test results show that, except for small regions near the end plates, the changes of mean velocity and the rms value of fluctuating velocity along the line are small. The uniformity is good.

To know the holistic effect of suppression, we measured the fluctuating velocities throughout the wake at section  $X/D = 18.5$ ,  $Y/D = 0$ . The distribution of rms value on the section for different angles of attack is shown in Fig.3, where  $Re = 1600$ , and the rod distance is fixed at  $l/D = 1.0$ . The relative maximum values of fluctuating velocities  $V_{rms\ max} / V_{0rms\ max}$  of the section for different angles of attack are listed in Table 1, where  $V_{rms\ max}$  is the maximum rms value of fluctuating velocity for the wake of SRC and  $V_{0rms}$  is that for the wake of SSC at the same  $Re$  number and the same rod distance. The positions  $Z_m/D$  at which the maximum rms values of fluctuating velocities appear are also listed in the table.



**Fig. 3.** Distributions of rms values of fluctuating velocities at different angles of attack at the Section  $X/D = 18.5$ ,  $Y/D = 0$ .  $Re = 1600$ , rod distance =  $1.0D$ .

The amplitudes of fluctuating velocities in the wake of SRC with various arrangements of suppression rods are all smaller than those in the wake of SSC. When the angle of attack  $\beta$  is small, as seen in the

case  $\beta = 0^\circ$ , the suppression is less effective. The amplitude of fluctuating velocity decreases with increasing  $\beta$ , until the most efficient angle  $\beta_{\min}$  is reached. In this case,  $\beta_{\min}$  is in the vicinity of  $60^\circ$ . From  $\beta_{\min}$  on, the amplitude increases with increasing  $\beta$ . As an example, the fluctuating amplitude at  $\beta = 90^\circ$  is larger than that at  $\beta = 60^\circ$ .

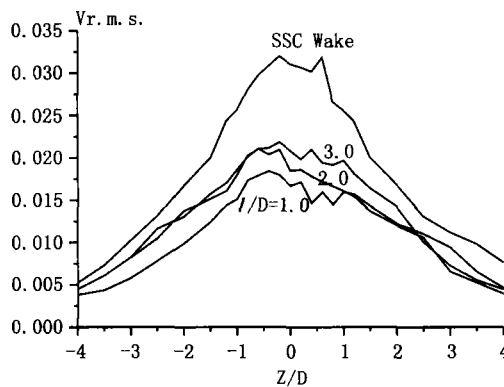
**Table 1** Influence of angle of attack  $\beta$  on the relative maximum rms values of fluctuating velocities

$V_{\text{rms max}}/V_{0\text{rms max}}$  at section  $X/D = 18.5$ ,  $Y/D = 0$ , rod distance =  $1.0D$ ,  $Re = 1600$ ,  
 $V_{0\text{rms max}}$  is the maximum value for the wake of SSC and  $V_{\text{rms max}}$  is that for the wake of SRC

$\beta$	$0^\circ$	$30^\circ$	$45^\circ$	$60^\circ$	$90^\circ$	SSC wake
$V_{\text{rms max}}/V_{0\text{rms max}}$	77%	54%	51%	48%	61%	100%
$Z_m/D$	0.3	-0.5	-0.2	-0.2	-0.5	$\pm 0.4$

From the figure and table it is seen that an effective zone of angle of attack  $\beta_1 \leq \beta \leq \beta_2$  (in this case  $\beta_1 \leq 30^\circ$ ,  $\beta_2 < 90^\circ$ ) exists. If suppression rods are so arranged that the angle  $\beta$  is located in the zone, vortex shedding can be well suppressed. Out of the zone, suppression is less effective.

The influence of rod distance  $l/D$  on the distribution of rms value of fluctuating velocity at section  $X/D = 16.0$ ,  $Y/D = 0$  is shown in Fig.4, where  $Re = 350$ , and the angle of attack of the rods  $\beta = 30^\circ$ . The relative maximum rms values of fluctuating velocities  $V_{\text{rms max}}/V_{0\text{rms max}}$  of the section for different rod distances  $l/D$  and the positions  $Z_m/D$  at which the maximum rms values appear are listed in Table 2.



**Fig. 4.** Distributions of rms values of fluctuating velocities at different rod distances at section  $X/D = 16.0$ ,  $Y/D = 0$ .  $Re = 1600$ , angles of attack of the rods  $= 30^\circ$ .

**Table 2** Influence of rod distance on the relative maximum rms values of fluctuating velocities

$V_{\text{rms max}}/V_{0\text{rms max}}$  at Section  $X/D = 16$ ,  $Y/D = 0$ ; angle of attack  $\beta = 30^\circ$ ,  $Re = 350$

$l/D$	1.0	2.0	3.0	$\infty$
$V_{\text{rms max}}/V_{0\text{rms max}}$	55%	61%	64%	100%
$Z_m/D$	-0.5	-0.6	-0.4	$\pm 0.4$

The amplitudes of the fluctuating velocities at rod distances  $l/D = 1, 2$  and  $3$  are all smaller than that of the SSC wake. The smaller the  $l/D$ , the better the suppression effect. But the difference of suppression effects between  $l/D = 1, 2$  and  $3$  is not very large.

We may recall the experimental results given by Strykowski and Sreenivasan (1990). In their experiment, a very small control wire ( $0.1D$  in diameter) was set beside and parallel to the model cylinder. Vortex shedding could be suppressed only when the position of control wire was restricted in a certain zone. The effective zone contracts with increasing  $Re$  number. If  $Re > 79$ , vortex shedding could not be suppressed. Their two-dimensional numerical simulation also shows the suppression effect. They strongly recommended the theory of absolute instability in explaining their results. It seems that the two-dimensional stability theory is plausible.

In this case, however, the suppression rods are arranged in three dimensions, thus, no two-dimensional theory can give reasonable explanation. It is known that the span-wise co-variation of the flow is strong when vortex shedding occurs. The existence of suppression rods may diminish or even break off the span-wise co-variation relation of the flow, then stop the formation of vortex shedding. A plausible and detailed explanation needs a three-dimensional stability analysis or a three-dimensional numerical simulation, but that is out of the range of this paper.

#### 4. Concluding Remarks

The suppression of vortex shedding from a circular cylinder has been studied experimentally. The suppression method is to use small rods arranged along the meridian of the cylinder. One end of each rod is perpendicularly connected to the surface of the cylinder, and the other end is exposed to the fluid. The diameter of each rod is  $0.18D$  and the length is  $1.5D$  ( $D$  is the diameter of model cylinder). The distance between the neighboring rods  $l/D$  and the angle of attack of the rods  $\beta$  are adjustable. The test range of the Reynolds number is  $300 \sim 1600$ . The results show that the suppression method may be very effective for all the Reynolds numbers tested if the angle of attack is in a certain zone. The rod distance tested is in the range  $l/D = 1 \sim 3$ . The results show a trend that a smaller  $l/D$  leads to more effective suppression. But the difference in suppression effect between  $l/D = 1, 2$  and  $3$  is not very large.

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