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Experimental study on flow structures of a screen cylinder wake using PIV

C. Sun[1], A. Mohd Azmi[2] and T. Zhou[1]

[1]School of Engineering, The University of Western Australia,
35 Stirling Highway, Crawley, Western Australia 6009, Australia
[2]Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

Abstract

Suppression of Vortex-induced Vibration (VIV) holds the key to numerous engineering structures as it can result in high amplitude vibrations of a structure, causing fatigue and eventual failure. Experimental results in a wind tunnel on VIV suppression using a screen shroud of 58% porosity showed that the mesh is effective in VIV suppression by 86%. To further explore the mechanism of VIV reduction using a screen shroud, the flow structure in the near wake around a permeable screen cylinder is investigated using Particle Image Velocimetry (PIV). The tests were conducted at a Reynolds number of about 3200 in a water flume. The screen cylinder was made of a stainless-steel wire mesh rolled into a cylinder shape with 58% porosity. The results are compared with that of a bare cylinder in order to evaluate the effectiveness of a screen cylinder on wake modification in the near wake region. The results illustrated that a 58% porosity cylinder could extend the vortex formation length significantly and effectively reduce vortex intensity by more than 57%. These findings are helpful to explain why a screen cylinder used as a shroud is effective in suppressing VIV.

Introduction

Vortex-induced vibration (VIV) plays a vital role in causing fatigue damage of cylindrical structures, which is one of the most significant issues in all fields of engineering. Therefore, researchers have proposed various methods, either passive or active, to suppress VIV. Unlike active control method which involves external energy input to the control methods, passive methods do not require external energy input but just through changing the structural damping, streamlining a body and applying add-on devices, making it more applicable than the former especially for large structures. Various passive control methods have already been proposed to regularize the vortex shedding and control VIV (Kumar et al. [3]).

Porous shroud is one of the methods which has been proved effective in suppressing VIV. The first use of a screen mesh as a shroud for VIV suppression was introduced by Price and Thompson [4]). They suggested that shroud could break up the flow into a large number of small vortices; hence the periodic asymmetry of flow about the cylinder is minimized. Along the inner passage between the shroud and the cylinder, the growth of vortices would be restricted by forced mixing. Zdravkovich [7] performed experiments using a variety of porous shroud, for example, shroud with circular holes, shroud with square holes and a mesh shroud. The results showed that all shrouds are equally effective in suppressing VIV, with the square holed shroud being only marginally more effective than the circular holed shroud. Zdravkovich and Volk [7] found that cylinders fitted with a fine-mesh gauze shroud were good for suppressing VIV. Oruc *et al.* [5] investigated the flow around a bare cylinder encompassed by a screen cylinder outside, and the screen was made of a streamlined thin-steel mesh with a porosity of 50%, where the porosity is the ratio of the open area over the total area. Both studies showed that the screen cylinder outside a bare cylinder can effectively suppress vortex shedding compared with a bare cylinder only. Ozkan *et al.* [6] did further studies on screen cylinders and suggested that a less VIV amplitude can be achieved by using higher screen porosity. Azmi et al. [1] revealed that a screen gauze shroud of 67% porosity can suppress VIV of a circular cylinder by about 78% at an outer-to-inner diameter ratio of 2. Further study on the intermediate wake region of a screen cylinder with 67% porosity shows that the wake of a screen cylinder can be divided into two regions, a vortex formation region and a decay region (Azmi et al. [2]), with the former being much larger than that of a circular bare cylinder.

Despite the nature of screen flows, limited studies have been reported on the near wake characteristics of a screen cylinder as a promising VIV suppression device. Therefore, the first aim of this paper is to investigate the effectiveness of a 58% porosity shroud on VIV reduction of a circular cylinder. For this purpose, VIV tests were conducted in a wind tunnel by covering a solid cylinder with a screen shroud of 58% porosity at an outer-to-inner diameter ratio of 2. This ratio is chosen based on some previous studies (Ozkan et al. [6]). Further, to explore the mechanism on VIV reduction using a porous shroud, the near wake characteristics and vortex formation of the screen cylinder is investigated in a water flume using PIV at a Reynolds number of 3200. Results are then compared with wakes generated by a solid cylinder.

Experimental details

VIV response of a screen shrouded cylinder

To examine the effect of a screen shroud on the VIV response of a circular cylinder, VIV tests of one degree-of-freedom were conducted in the wind tunnel of The University of Western Australia. Two types of cylinders, including a bare cylinder and a screen shrouded cylinder, were fixed, respectively, onto a test frame using four bolts attached to four 260mm long springs. The springs were initially extended by 60mm to ensure that vibrations of the cylinders were not limited. The diameter of the bare cylinder D was 60 mm and that of the screen cylinder was 120 mm (i.e. with a diameter ratio of 2). The dimensions of the wind tunnel are 2.8 m (width) × 2.2 m (height) × 7 m (length) (Figure 1). The screen cylinder was made of a 58% porosity stainless mesh with a length L of 1600 mm. It was supported by four plastic rings (Figure 1) along the bare cylinder to prevent sagging. The linear variable displacement transformer (LVDT) was fixed to the side of the frame for displacement measurements at a frequency of 200 Hz, and the cylinder was located in the middle of its allowable displacement reading.

Near wake measurements using PIV

This experiment was conducted in an open-channel water flume with dimensions of 400 mm (width) × 500 mm (height) × 15 m (length). Both the bare cylinder and the screen cylinder have a diameter d of 20 mm and length L of 380 mm. The bare cylinder was a plain and smooth transparent cylinder, whereas the screen cylinder was made of stainless steel wire mesh (58% porosity) rolled into a cylinder shape as shown in Figure 2. Particle image velocimetry (PIV) technique was used in order to record the structure of the flow, and the image of the flow was captured by a high-speed camera (Photron, FASTCAM SA3) at a rate of 1000 fps. The flow field is illuminated using a laser sheet with thickness of 1mm.

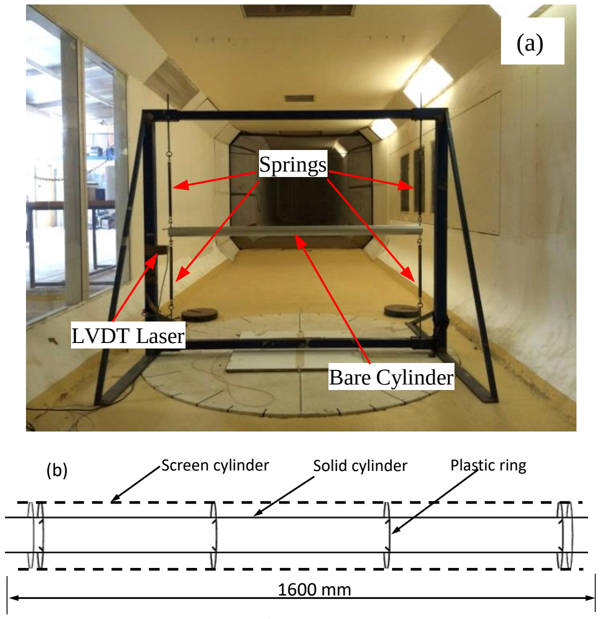

Figure 1. Experimental setup for VIV measurements. (a) Supporting frame; (b) installation of the screen cylinder.

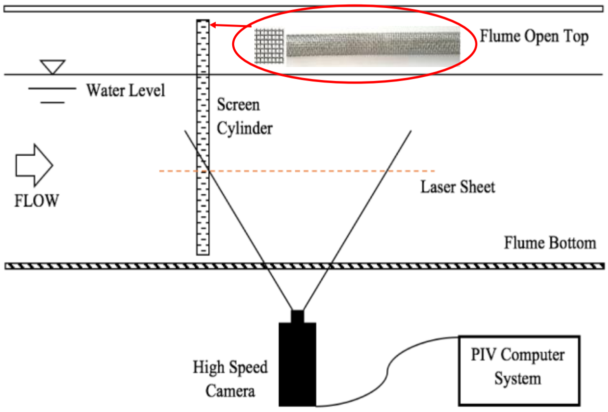

Figure 2. The side view of schematic diagram of the experiment setup.

Results and discussion

Suppression of VIV using a screen shroud

The VIV amplitudes for both a bare cylinder and a screen shrouded cylinder as a function of reduced velocity V_R are shown in Figure 3. The amplitude was obtained after the vibration has become stable by averaging the highest 10% recorded data on the time series of the vibration over about 4 minutes. The reduced velocity, V_R, is defined as:

$$V_R = \frac{U_\infty}{D\ f_N} \quad (1)$$

where f_N is the natural frequency of the cylinder-spring system obtained through free-decay tests. For the solid cylinder, the lock-on region occurs from about V_R = 4.8 to 12 and the maximum amplitude A/D is about 0.48, which agrees well with that published previously (Zhou et al. [8]). Note that in the present study, the amplitude A is obtained by considering the positive or negative vibration only. For the screen shroud cylinder, the cylinder did not vibrate until V_R = 8. The lock-on region has been significantly reduced and the peak amplitude occurred at a higher reduced velocity than for the bare cylinder, delaying the VIV response. The reduction ratio, defined by the ratio of the maximum vibration amplitudes, is about 86%. It is, therefore, confirmed the effectiveness of the mesh shroud in suppressing VIV of a bare cylinder.

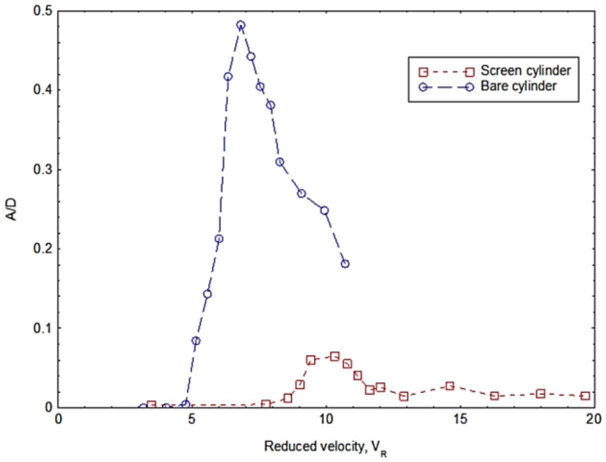

Figure 3. Comparison of VIV amplitude of a bare cylinder and a screen shrouded cylinder.

In order to understand the mechanism of VIV reduction using the screen shroud, PIV measurements on the near wake structures of the bare cylinder and the screen cylinder wakes were conducted and the results are shown as follows.

Mean Velocity Profiles

The mean streamwise velocity profiles at different downstream locations for the two wakes are shown in Figure 4, where a superscript asterisk denotes normalisation by the freestream velocity and the cylinder diameter. It can be seen that at x/d = 1, the mean velocity is positive. This result indicates that there is some fluid passing through the screen cylinder, even though the flow velocity is very low. Further downstream at x/d = 3, the mean velocity becomes negative, indicating a reverse flow at this location. At x/d = 5, the mean velocity at the centreline is about 0.25. This trend seems consistent with that reported by Azmi et al. [2]) for a screen cylinder with 67% porosity.

For the bare cylinder wake, the mean streamwise velocity is negative at x/d = 1, indicating a reverse flow at this location. At x/d = 3, u^* is about 0.6. Further increase in downstream distance will not result in an apparent increase in u^*, indicating the recovering trend of the wake. This is completely different from that of the screen cylinder wake at comparable locations.

RMS transverse velocity

The distributions of the RMS values of the transverse velocity across the wake in the two wakes at different downstream locations are compared in Figure 5. Clearly, there are twin peaks at the locations x/D = 1 and 3, with the centreline values being much lower than the peak values. The peak values are located in the shear layers of the screen cylinder, indicating that the small-scale vortices in the opposite shear layers have not yet merged together at this location. At x/D = 5, there is only one peak occurring at the wake centreline, indicating that the two shear layers have merged together, and a single vortex street may be formed with a more considerable vortex intensity. For x/D = 1 to 5, the values of v^* increase consistently, indicating that the flow structure in the screen cylinder wake may still be under developing. Similar results were obtained by Azmi et al. [1] for a screen cylinder wake with porosity of 67%.

The RMS transverse velocity distributions for the bare cylinder wake show a totally different trend. There is only one peak at the wake centreline. At the locations x/D = 1 and 3, the values of v^* increase significantly, after which they decrease consistently in the streamwise direction. This results indicate that the vortical structures in the bare cylinder wake are formed in the region of x/D = 1 and 3.

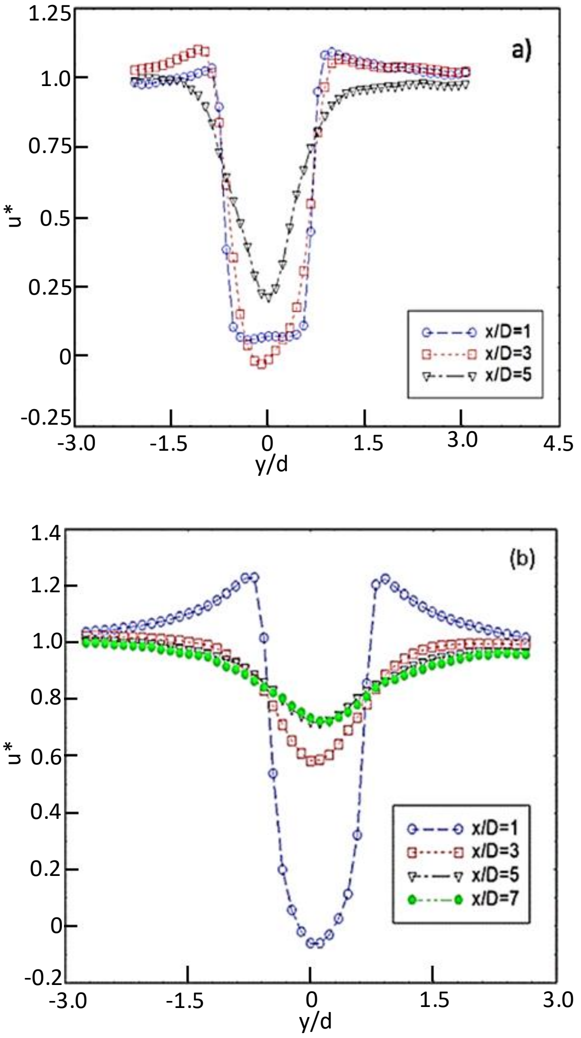

Figure 4. Stream-wise mean flow velocity profiles for a screen cylinder at U_∞=0.16m/s. (a) Solid cylinder; (b) screen cylinder.

The spanwise vorticity contours in the two wakes are shown in Figure 6. For the screen cylinder wake, it can be seen that the shear layers are stretched along the flow direction. Inside the shear layers, small-scale vortices, or the K-H vortices, can be identified clearly. The two shear layers are separated by a buffer zone, which prevents the interaction between them until x/d = 6. These results are similar to those obtained in a screen cylinder wake with 67% porosity although with larger downstream distances of interaction due to the larger porosity and much less freestream turbulent intensity in the latter study. The maximum vorticity magnitude of the small-scale vortices in the shear layers is about 25, which is only about half of that in the bare cylinder wake. As they evolve downstream, the small-scale vortices merge together to form larger vortices in the shear layers. As a result, the frequency of these vortices reduces. The Kármán vortices in the bare cylinder wake are apparent and are formed at about x/d = 1.5, a location which agrees well with previous studies. It is, therefore, believed that in the screen cylinder wake due to the less interaction between the shear layers, the vortex formation region has been significantly extended and the vortex shedding intensity has been suppressed. These effects will make the screen cylinder as an ideal option for VIV suppression.

Contours of Reynolds shear stress

Figure 7 shows the contour plots of the Reynolds shear stress in the two wakes. The Reynolds shear stress immediately downstream of the screen cylinder is very small and can reflect the existence of the small-scale K-H vortices in the shear layers. The contours become apparent only at x/d = 5. This is in apparent contrast to the solid cylinder wake, where the contours become apparent at x/d = 1.5 and are symmetric about the wake centreline.

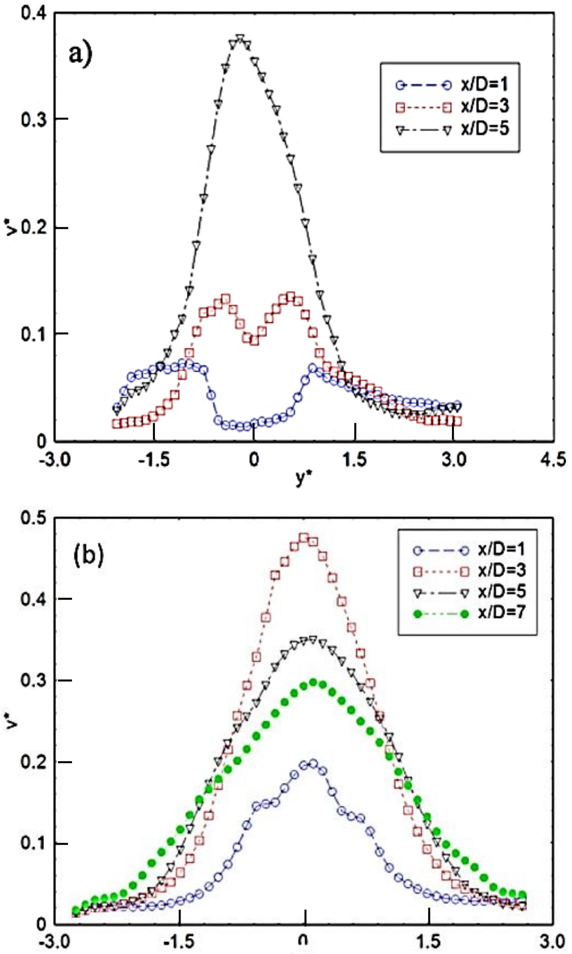

Figure 5. RMS transverse velocity profiles for a screen cylinder at U_∞=0.16m/s. (a) Solid cylinder; (b) screen cylinder.

Conclusions

In the present paper, the effectiveness of a screen shroud with 58% porosity on VIV is examined. To explore the mechanism for this reduction, the near-wake characteristics of a screen cylinder are examined using PIV techniques and the results are compared with those of a bare cylinder. The main conclusions are summarised as follows:

(1) A screen mesh with a porosity of 58% can suppress the magnitude of VIV by 86%. What is more, the screen shroud can delay the onset of VIV to a much higher reduced velocity and also reduce the width of the lock-on region.

(2) Vortex formation length in the screen cylinder wake has been extended further downstream compared with the solid cylinder wake. Small-scale K-H vortices are first generated in the shear layers. They merge together to form larger-scale vortices as they evolve downstream. During this process, they do not interact with each other due to the buffer zone between them until *x/d* = 6. Therefore, the vortex formation region should be larger than this location. What is more, the magnitude of vorticity in the screen cylinder wake is much smaller than that of a solid cylinder wake, indicating a much weaker vortex shedding in the former.

(3) It is believed that due to the extended vortex formation length and weak interaction of vortices, the VIV of a solid cylinder enclosed inside a screen cylinder is suppressed. As a future study, it will be interesting to examine the vortex formation and force characteristics of a solid cylinder enclosed inside a screen cylinder.

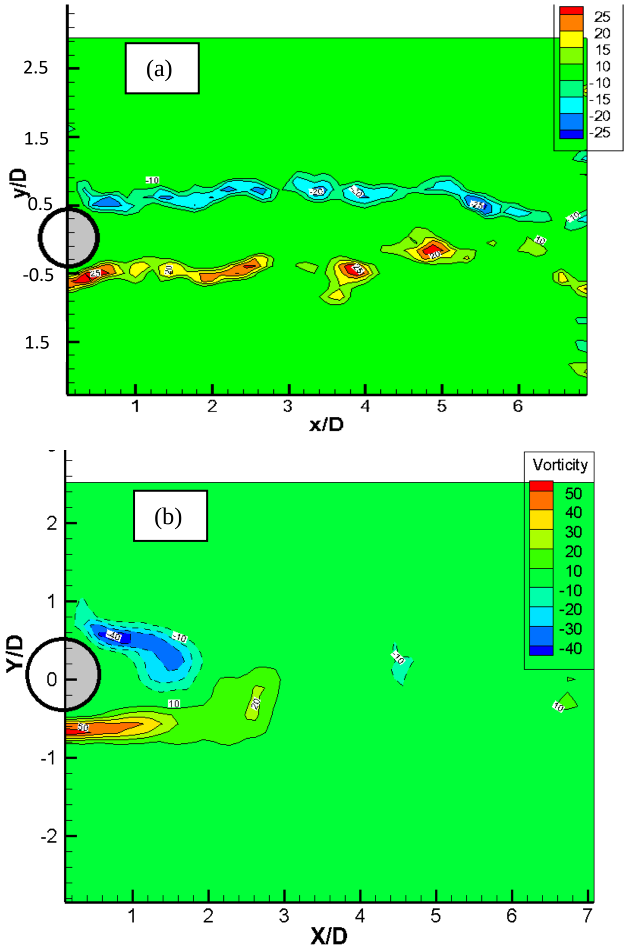

Figure 6. Spanwise vorticity (ω_z^*) contour plots. a) Screen cylinder; b) bare cylinder. (a) Solid cylinder; (b) screen cylinder.

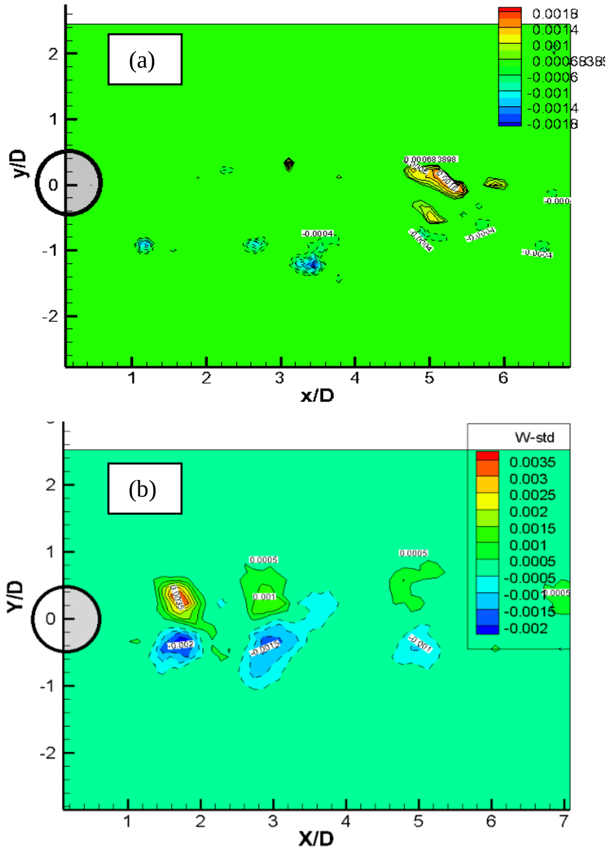

Figure 7. Reynolds shear stress ($\overline{u^*v^*}$) in the wakes of a screen cylinder and a solid cylinder. (a) Screen cylinder; (b) Solid cylinder.

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