The Formation of Vortex Structures in a Screen Cylinder Wake

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Abstract. The formation of vortex structures in a screen cylinder wake was investigated in a wind tunnel at a Reynolds number of 7000. The screen cylinder was made of a stainless steel wire mesh with an open area ratio of 67%. The results showed that the screen cylinder wake could be classified into two distinct regions. The first region was characterised by the development of the shear layer vortices which resulted from Kelvin-Helmholtz instability. At about $x/d = 20$ (where $d$ is the diameter of the cylinder) the shear layer vortices started to interact with each other across the centreline, and evolved downstream to form the alternately arranged ‘large-scale’ coherent structures. These structures were most pronounced at $x/d = 40$. The vortex formation region was therefore extended significantly downstream compared with that of the solid cylinder wake. The second region involved a gradual decay of the fully-formed large-scale structures, evidenced by the weak vorticity exchange across the wake centreline.

1. Introduction

Fluid flow past a circular cylinder may induce vibration of the structure, which is normally known as the vortex-induced vibrations (VIV). VIV of cylindrical structures should be avoided as it will lead to fatigue damage of the structures. VIV can be suppressed using passive methods. Shroud is one of the passive devices which are found effective in suppressing VIV [1] (Zdravkovich 1981). Zdravkovich and Volk [2] (1972) conducted a test for three different shroud types; the square-holed, circular-holed and a fine-mesh gauze, all having 36% porosity, where the porosity is defined as the percentage of the open area over the total area. They found that the shroud made of fine-mesh gauze was the most effective in suppressing vibration of the cylinder, giving the highest reduction in the double-amplitude of vibration. The gauze shroud affected the pressure distribution more significantly than the other shrouds for which there was a radical departure in the pressure distribution over the rear portion of the cylinder (between 80° and 160°). In a recent study by Oruç [3] (2012), a circular cylinder wake was controlled by using a screen with a porosity of 50% formed in a streamlined geometry enclosing the cylinder. The PIV results over the region of $x/d \leq 4$ showed that the existence of the control screen around the cylinder significantly suppressed the interaction of the shear layers and hence the vortex shedding from the surface of the cylinder, resulting in a significant reduction in turbulence intensity, Reynolds shear stress and turbulent kinetic energy. Ozkan et al. [4] (2012) found that a better flow control could be achieved with their screen shroud with an outer-to-inner diameter ratio of 1.6 – 2.0
and porosity of 40 – 60%. While the existing studies proved that the perforated shrouds are effective in suppressing VIV of a circular cylinder, this type of suppression device is largely unexplored, especially the one made of a screen gauze. In the present study, the primary aim is to explore the vortex formation and development in a screen cylinder wake by examining the evolution of its coherent structures. The second aim is to propose a conceptual wake model in its wake, illustrating the formation process and the momentum transport behaviour. The above results will be compared with wakes generated by a solid cylinder and a screen strip. To our knowledge, this is the first attempt to quantify the large-scale structures in the near and intermediate regions of a screen cylinder wake.

2. Experimental Details
The experiments were conducted in a blower type wind tunnel with a test section of 380 mm (width) × 255 mm (height) and 1.8m (long). The free stream velocity was uniform to 0.2% and the longitudinal turbulence intensity was less than 0.5%. Two types of cylinders were used, namely, a solid cylinder and a screen cylinder. The diameters d of the solid and the screen cylinders were 10 mm and 21 mm, respectively. The length l of both cylinders was 380mm, giving an aspect ratio l/d of 38 for the solid cylinder and 18.1 for the screen cylinder. All measurements were performed at Re = 7000, corresponding to a free stream velocity \( U_\infty \) of 10.4 m/s and 5 m/s for the solid and screen cylinders, respectively. Two end plates were used for both cylinders. The thickness of the plates is 1.25mm with the leading and trailing edges being sharpened at an angle of 45°. They were fixed at about 4mm from the tunnel side walls to keep them above the boundary layer. The screen cylinder was made of a stainless steel wire mesh of aperture a = 2 mm and wire diameter dw = 0.45 mm. The porosity of the screen mesh \( \beta \) was 67%. Care was taken to make sure that its diameter was uniform along the cylinder axis (with a tolerance of ±1%). Figure 1 shows the definition of the co-ordinate system, wake profile and the photo of the screen cylinder. The measurement locations were at \( x/d = 10–60 \). To avoid crowding the figures, only results at selected locations are shown. To examine the streamwise evolution of the wakes, an X hot-wire probe was moved across the wake in the y-direction to measure the longitudinal and transverse velocity components, \( u \) and \( v \), respectively. Another X-probe was fixed at the wake edge and at the same streamwise location as the first X-probe to provide a phase reference to the measured velocity signals for phase-averaged analysis. The separation between the two wires of the X-probes was about 1.5mm. The hot wires were 5 \( \mu \)m in diameter and 1 mm in length. The output signals from the anemometers were low-pass filtered at a cut-off frequency \( f_c \) of 2800 Hz and sampled at a frequency \( f_s \) of 5600 Hz using a 16-bit A/D converter. The sampling period \( T_s \) was 30s.

![Figure 1](image-url)

**Figure 1.** Co-ordinate system, wake profile and probe arrangement (a) and the top view of the arrangement of the screen cylinder (b). Please note that the figures are not drawn to scale.

3. Results and Discussion

3.1. Energy spectra in the two wakes
The spectra $\phi_v$ for both cylinders at various downstream locations are shown in Fig. 2. Both spectra are obtained at $y^* = 0.5$ in the two wakes (Figs. 2a and 2b) by calculating the Fast Fourier Transform (FFT) of the velocity signals. The normalized spectral density function is defined such that $\int_0^\infty \phi_v(x)dx = 1$, where $x$ represents the frequency, which is normalized by $U_\infty$ and $d$ i.e. $x = f^* = f d/U_\infty$. With this normalization, the peak frequency on the spectrum corresponds to the Strouhal number. Each spectrum has been shifted downward by one order relative to the one above it for easy viewing. For the solid cylinder wake (Fig. 2a), vortex shedding at $x^* = 10$ is apparent at a single frequency $f$ of 201 Hz, which corresponds to $f^* = 0.2$ as indicated by the sharp peak. This peak location is consistent with previous literatures at subcritical Reynolds numbers. The ratio between the peak height and the plateau region reduces with $f$ although $f^*$ remains the same. This trend indicates that the vortices are decaying in the streamwise direction. On the other hand, the energy spectra of the screen cylinder wake reveal no significant peak at location immediately downstream of the cylinder ($x^* = 10$). This result suggests that vortex shedding is not apparent, which highlights the difference in the near-wake behaviour of both cylinders. A broad-band peak at $f^* = 0.277$ starts to emerge at $x^* = 20$, indicating the emergence of some periodicity of the organised fluid structures in the wake. The peak at $f^* = 0.257$ becomes apparent at $x^* = 30$, indicating the formation of the large-scale structures. Further downstream, the broad-band peak is still apparent with a slightly decreasing frequency trend. For $x^* = 30–60$, the peak frequency decreases from 0.257 to 0.234. On the other hand, the spectra along the outer edge (Fig. 2c) display broad-band peaks even in the near wake, indicating the existence of periodicity at all measured downstream locations. Huang and Keffler [5] (1996) reported the same behaviour for their screen strip wake ($\beta = 40\%$ and $Re = 1.1 \times 10^4$) at $x^* = 1$ and attributed this to the Kelvin-Helmholtz instability of vortex sheets generated at the mesh edge and the subsequent rolled up of the sheets into discrete vortices, similar to the single shear layer development. The periodicity becomes more apparent and the peak magnitude becomes larger from $x^* = 10–30$. The decrease of the broad peak location towards lower frequencies along the streamwise direction indicates the growth of the vortical structures within the shear layers. It is hypothesized that this behaviour is due to an increase in the average wavelength, assuming slowly increasing convective velocity. The above process may imply merging of these vortices, which accounts for the formation of the large-scale structures in the screen cylinder wake, similar to the findings of Huang and Keffler [5] (1996) and Antonia and Mi [6] (1998). The continuous decrease of the peak frequency indicates that the merging process does not occur at a fixed downstream location.
3.2. Phase-averaged coherent vorticity field

A turbulent signal $B$ can be decomposed into a mean value, $\overline{B}$, and a fluctuation component $\beta$ which can further be decomposed into a coherent component $\beta$ and the reminder component $\beta_r$ ([7] Hussain and Reynolds 1970), i.e.

$$B = \overline{B} + \beta = \overline{B} + (\beta + \beta_r). \quad (1)$$

Phase average method allows the coherent structures at a given frequency to be separated. Details of the phase-averaged methods can be found in Zhou et al. [8] (2003). After the detection of the coherent signals $\tilde{u}$ and $\tilde{v}$, the phase-averaged vorticity $\overline{\omega}_x$ is obtained using the following relationship

$$\overline{\omega}_x = \frac{\partial (\overline{\tilde{v}}+\tilde{\phi})}{\partial x} - \frac{\partial (\overline{\tilde{u}}+\overline{\tilde{\phi}})}{\partial y} \approx \frac{\Delta \tilde{\phi}}{\Delta x} - \frac{\Delta (\overline{\tilde{u}}+\overline{\tilde{\phi}})}{\Delta y}, \quad (9)$$

where $\Delta x = -U_c \Delta t = -U_c / \ell_4$ is the separation in the streamwise direction and can be obtained using Taylor’s hypothesis. The average convection velocity $U_c$ of the vortices is given by the velocity $\overline{\tilde{U}} + \tilde{\phi}$ at the vortex centre, which is identified with the location of the maximum phase-averaged vorticity, $\overline{\omega}_x$ max. Meanwhile $\Delta y$ is the distance between two adjacent measurement locations across the wake.

The iso-contours for the phased-averaged vorticity of the solid cylinder and the screen cylinder wakes are shown in Figs. 3 and 4, respectively. The errors in measuring the vorticity components in both wakes depend on that for velocity component measurements and distance measurements, which are estimated at about 13%. Due to regular shedding of the vortices in the wakes, a shedding period can be evaluated, which corresponds to a phase angle from 0 to $2\pi$. Over the measurement period (30 s) at each $y$ location, about 2000 periods of data for both the screen and the solid cylinders were obtained. To use the phase averaged method, we divided one period into 30 phases and then average the measured data at a given phase over the 2000 periods (i.e. corresponding phase angle from 0 to $2\pi$). In the figures showing the contours, we actually plotted also the phase angles over the range -2$\pi$ to 0 by mirroring those from 0–$2\pi$ to show clearer pictures of the flow structures. The phase $\phi$, ranging from $-2\pi$ to $+2\pi$, can be interpreted in terms of a streamwise distance and $\phi = 2\pi$ corresponds to the vortex wavelength $\lambda (=U_c/f)$. The flow direction is from left to right. The positions of the foci and the saddle points associated with the vortices are determined from the sectional streamlines (Figures are not shown here) and denoted by ‘+’ and ‘×’, respectively. The diverging separatrices are shown as dashed lines passing through the saddle points. The diverging separatrices, i.e. the braids, connects the top of a structure to the bottom of an adjoining structure as described in Hussain and Hayakawa [9] (1987). In general, the foci correspond quite well with the maximum vorticity. There are significant variations in terms of the evolution of the shape, strength and size of the vortices in the two wakes. The phase-averaged coherent vorticity contours in the solid cylinder wake (Fig. 3) clearly depict the large-scale vortical structures and their evolution in the streamwise direction, consistent with Zhou et al. [8] (2003), verifying the experimental result of the solid cylinder wake. For example, at $x^* = 10,$

![Figure 2. Energy spectra $\phi_\nu(f^*)$ in the wake of (a) solid cylinder and (b) screen cylinder measured at $y^* = 0.5$ and (c) screen cylinder measured at the wake edge.](image-url)
the $\omega^x_z$ contours display the well-known Kármán vortex street. The maximum concentration for $\omega^x_z$ is 1.1 occurring at $y^* \approx 0.3$. The positive and negative vortices penetrate across the wake centreline to the other side of the wake, showing a staggered vortex pattern. The $\omega^x_z$ contours at $x^* = 20$ display similar vortex structures but with a lower staggered vortex pattern. The $\omega^x_z$ contours at $x^* = 40$ reflecting an apparent reduction in vortex strength as $x^*$ increases. Furthermore, at $x^* = 40$, the staggered pattern of the alternating counter-rotating vortices starts to diminish. For the screen cylinder wake (Fig. 4), the contours of $\omega^x_z$ at $x^* < 30$ are less organized. There are small-scale vortices in the two shear layers, separated by a core layer at the central region. The interaction between the opposite signed vortices starts at $x^* = 20$, where the core layer starts to undulate. At $x^* = 30$, the spanwise vorticity contours become more apparent than that in the region closer to the cylinder, implying an amalgamation process at $x^* < 30$. Vortices still grow thereafter until $x^* = 40$, where the large-scale structures can be seen to be fully formed. Considering the coherent vorticity contours at $x^* \geq 40$, the above results suggest that the decay rate of the fully formed large-scale vortices in the screen cylinder wake is much smaller than that of the large-scale vortices in the solid cylinder wake. For instance, the maximum vorticity concentration decays by about 20% from $x^* = 40$ to 50 and 25% from $x^* = 50$ to 60 in the screen cylinder wake whereas a large decay of 64% is evident only from $x^* = 10$ to 20 in the solid cylinder wake. It can be surmised that due to this slow decay, vortical structures in the screen cylinder wake will persist a long distance downstream. It is interesting to note that at all downstream locations of the screen cylinder wake, there are contours enveloping the vortex cores on each side of the wake and a small amount of vorticity is also found between vortex cores, a feature that is absent in the solid cylinder wake. Huang et al. [10] (1996) also noticed this feature in the screen strip wake on the coherent vorticity contours through pattern-recognition analysis. They noticed that farther downstream at $x^* = 50$ and 100, however, the envelopes were absent and the periodicity was less prominent. The current work indicates that the envelopes are still present at $x^* = 50$ and $x^* = 60$, consistent with the discussion on the persistence of structures downstream in the screen cylinder wake.

4. Conclusions
The formation of the vortical structures in the near and intermediate regions ($10 \leq x^* \leq 60$) of a screen cylinder (with 67% porosity) wake are studied in a wind tunnel using a phase-averaged analysis at a Reynolds number of about 7000. Significant differences about the vortex formation, streamwise evolution and momentum transport are found as compared with that of a solid cylinder wake. The vortex formation region in the screen cylinder wake has been extended significantly. In the near-wake, small-scale vortices are formed in the shear layers due to Kelvin-Helmholtz instability. When evolving downstream, these shear layer vortices merge, grow in size and decrease in frequency. For about $x^* \geq 20$, the size of the vortices in the shear layers are large enough and they interact with each other across the centreline, and evolving downstream to form the large-scale coherent structures. These structures are most pronounced at $x^* = 40$ indicating the completion of the vortex formation process, where vortices are fully formed. After the complete formation of the large-scale structures, vortices decay at a much slower rate in a screen cylinder wake compared with that in the solid cylinder wake, a decay by only about 20% from $x^* = 40$ to 50 in the former, in comparison to a decay of about 61% from $x^* = 10$ to 20 in the latter, which may imply the longer persistence of the large-scale structures in the screen cylinder wake. The transport of vorticity shows that vortices in the solid cylinder wake interact vigorously with those across the centreline, which greatly accelerates its decay, while in the screen cylinder wake, the vorticity exchange across the adjacent vortex border is weak where their vorticity vectors mostly occur along the diverging separatrices, accounting for the slow decay in the streamwise direction. The above results support the two regions of structural evolution in the screen cylinder wake which involve the growth of the shear layer vortices and the slow decay of the fully-formed ‘large-scale’ vortices in comparison to the rapid decay of coherent vortices throughout the solid cylinder wake.
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Figure 3. Phase-averaged coherent spanwise vorticity, $\tilde{\omega}_{z}$, for the solid cylinder wake at (a) $x^* = 10$ (minimum contour value -1.0, maximum contour value 1.1, contour interval 0.1); (b) $x^* = 20$ (-0.35,0.4,0.05) and (c) $x^* = 40$ (-0.12,0.12,0.03) . Vortex centers and saddles are marked by a plus and a cross, respectively. The thick dashed lines represent the diverging separatrices which pass through the saddles.
Figure 4. Phase-averaged coherent vorticity, $\omega_z$, for the screen cylinder wake at (a) $x^* = 10$ (-0.8,0.8,0.1); (b) $x^* = 20$ (-0.5,0.5,0.1); (c) $x^* = 30$ (-0.35,0.35,0.05); (d) $x^* = 40$ (-0.25,0.25,0.05); (e) $x^* = 50$ (-0.2,0.2,0.05) and (f) $x^* = 60$ (-0.15,0.15,0.05). Vortex centers and saddles are marked by a plus and a cross, respectively. The thick dashed lines represent the diverging separatrices which pass through the saddles.