Performance of Vortex Shedding from a Circular Cylinder with a Slit

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Abstract: Flow-field study was conducted concerning vortex shedding from a circular cylinder with a slit. Experiments were carried out in a water channel and a low-speed wind tunnel with emphasis on the impact of the slit width on the quality of the vortex shedding signal measured. It is found that among the cases studied, whose slit widths ranging from 0 to 0.3 *d*, where *d* denotes the diameter of the circular cylinder, an optimal range of slit width, 0.1-0.15 *d*, was identifed, in which not only the vortex shedding signals show the best quality, but also the relation of the Strouhal number against the Reynolds number appears to be the most linear. By spanwise correlation of hot-wire measurements in the wind tunnel, it is further noted that in this situation the vortex shedding flow structures appear to be almost perferctly two-dimensional in the near wake region. Moreover, it is worthwhile to mention that for the cases of the circular cylinders with slits, the signal quality of vortex shedding reamins well acceptable for the Reynolds number as low as 2.4×10^3. Thus, the rangeability of flow measurement is increased significantly.

Keywords: Vortex flow meter, circular cylinder with a slit, PIV

1. Introduction

This study was motivated by recent works [1, 2] on the characteristic behavior of vortex shedding behind a bluff body of uniform cross section, that at Reynolds numbers of 10^4 the vortex shedding flow structures actually show more or less three-dimensional appearances. The present authors subsequently proposed an idea to look into the performance of a circular cylinder with a slit, aiming to improve the two-dimensionality of vortex shedding flow structures. In fact, it was also noted that such a vortex shedder configuration had been extensively considered for vortex flowmeters. [3-8] Hence, the renewal interest on the performance of such a vortex shedder configuration herein is intended to provide new experimental data relevant to the application in flow measurement, meanwhile to gain insights into the physical behaviors of vortex shedding flow structures subjected to the introduction of a slit in a circular cylinder.

A vortex flowmeter works based on a principle that the measured frequency of vortex shedding, an unsteady phenomenon due to flow over a bluff cylinder, is proportional to the speed of the incoming flow. [9] Accordingly, the geometrical shape of a vortex shedder is deemed to play a critical role in determining the performance of a vortex flowmeter. In fact, this is a research area in which a significant amount of research efforts have been made. [3-16] Among those, Igarashi [3-7] has conducted a series of studies on a vortex shedder configuration featured by a circular cylinder with a slit. Igarashi [5, 6] performed experiments in a circular pipe with vortex shedders of different cross-sectional shapes, and found that a circular cylinder with a slit width of 0.1 diameter of the circular cylinder could outperform a trapezoidal cylinder, a configuration adopted in commercial vortex flowmeters, by lower flow resistance and better linearity in the Strouhal values over the range of Reynolds numbers measured. Note that the Igarashi's experiments [5, 6] were performed in a fully-developed turbulent pipe flow, that the blockage ratio due to the presence of the vortex shedder in the pipe was 0.267. The vortex shedding signals were obtained by measuring the pressure fluctuations on the surface of the circular cylinder immediately downstream of the slit, where the fluctuating amplitudes were found to be the most pronounced. [7]

To be somewhat different from the Igarashi's experiments [5, 6], the present study was conducted in both a wind tunnel and a water channel, where a series of circular cylinders with different slit widths were experimented. Based on the criteria proposed by examining the velocity signals measured in the near wake region, an optimal range of slit width was proposed. Note that the present vortex shedder in the wind tunnel or the water channel was lower in blockge ratio and larger in aspect ratio, comapred to the ones studied by Igarashi [5, 6] in fully-developed turbulent pipe flows, thus the vortex shedding flow structures seen in the present experiments were less influenced by the wall boundaries and background turbulent fluctuations. Hence, the veloicty measurement results obtained in the present study not only can complement the previous findings learned from the measurements made in a confined circular pipe, [5, 6] but also allow us to gain further insights into the characteristic behaviors of vortex shedding flow structures, which are found to be intimately associated with the vortex shedding signal quality of concern.

2. Experimental methods

Figure 1 gives a cross-sectional view of the circular cylinder model employed for experiment, where d denotes the diameter of the circular cylinder, d= 40 *mm* and s denoted the width of the slit, which was varied in a range of 0 to 0.3 d. Each of the cylinder models employed was 400 *mm* in length; therefore, the aspect ratio was 10.

Experiments were carried out in an open-type low-speed wind tunnel and a closed-loop water channel, respectively. Figure 2 further indicate the experimental arrangements in these two facilities. In the low-speed wind tunnel, a circular cylinder model was fitted with two end plates in the circular test section, 500 *mm* in diameter, thus the blockage ratio is less than 10 %. Without a circular cylinder model, the maximum turbulence intensity measured at the center of test section was less than 0.4% and the mean velocity could be varied between 2 and 40 *m/s*. The experiments were made at Reynolds numbers, called *Re*, in a range of 1.68×10^4 and 8.70×10^4, based on the freestream velocity measured at the inlet of the test section, denoted as U_0, and d.

Hot-wire velocity measurements were performed in the wind tunnel experiments to obtain the vortex shedding frequencies as well as to examine the two-dimensionality of the vortex shedding flow structures in the near wake region. A single hot-wire was positioned in the wake region, but outside the shear layer, to obtain the vortex shedding signals for analysis. The vortex shedding frequency called f_v, was therefore obtained by the spectral analysis of the signals measured; subsequently the Strouhal number, called St (= $f_v D/U_0$), could be reduced. Moreover, spanwise correlation measurements were carried out with two single hot wire probes in the near wake region, one of which was fixed in the plane z=0, denoting as the reference probe, while the other was traversed to different spanwise locations for a separation distance up to 1.5 d. The results of spanwise correlation allow us to examine the two-dimensionality of the vortex shedding flow structures.

For the experiments in the water channel, the circular cylinder model was fitted in a square test section, whose cross section was 400 *mm* by 400 *mm* shown in Fig. 2b. Without a cylinder model in the test section, the turbulence intensity measured by a particle image velocimeter (PIV) system was about 1 % at U_0 =28 *cm/s.* The maximum velocity in the test section could reach 40 *cm/s*. [17] Note that the blockage ratio due to the presence of the cylinder model in the test section was 10%; the Reynolds numbers corresponding to the experiments performed fell in a range of 2.4×10^3 to 1.14×10^4. Employed for velocity measurements the PIV system consisted of a continuous light sheet powered by an Argon ion laser, a PCO CMOS high speed camera, featuring 1280×1024 pixels per frame with the maximum frame rate of 5000 frames/s, and a PIV View software. During the experiment, the velocity measurements were always conducted in the mid cross-sectional plane of a circular cylinder model.

The coordinate system employed for the present study is shown in Fig. 2. Briefly, x, y and z denote the streamwise, vertical and spanwise directions of flow, where the origin (x, y, z) = (0, 0, 0) is located at the center of the circular cylinder model.

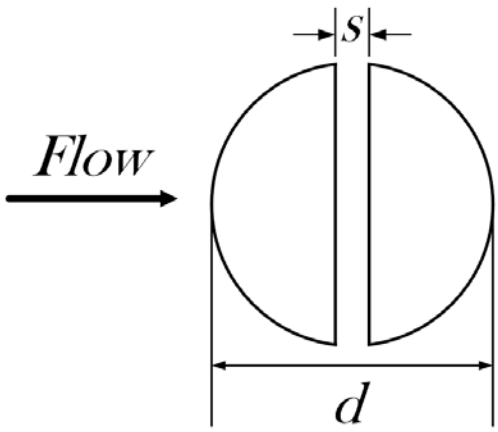
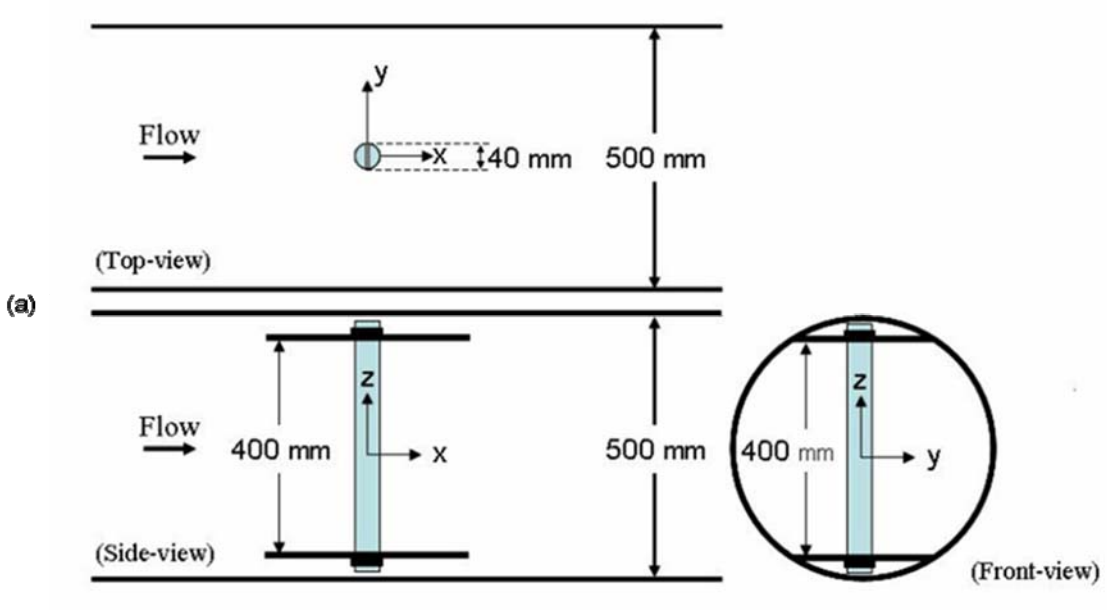


Fig. 1 A cross-sectional view of the circular cylinder model employed for experiment.



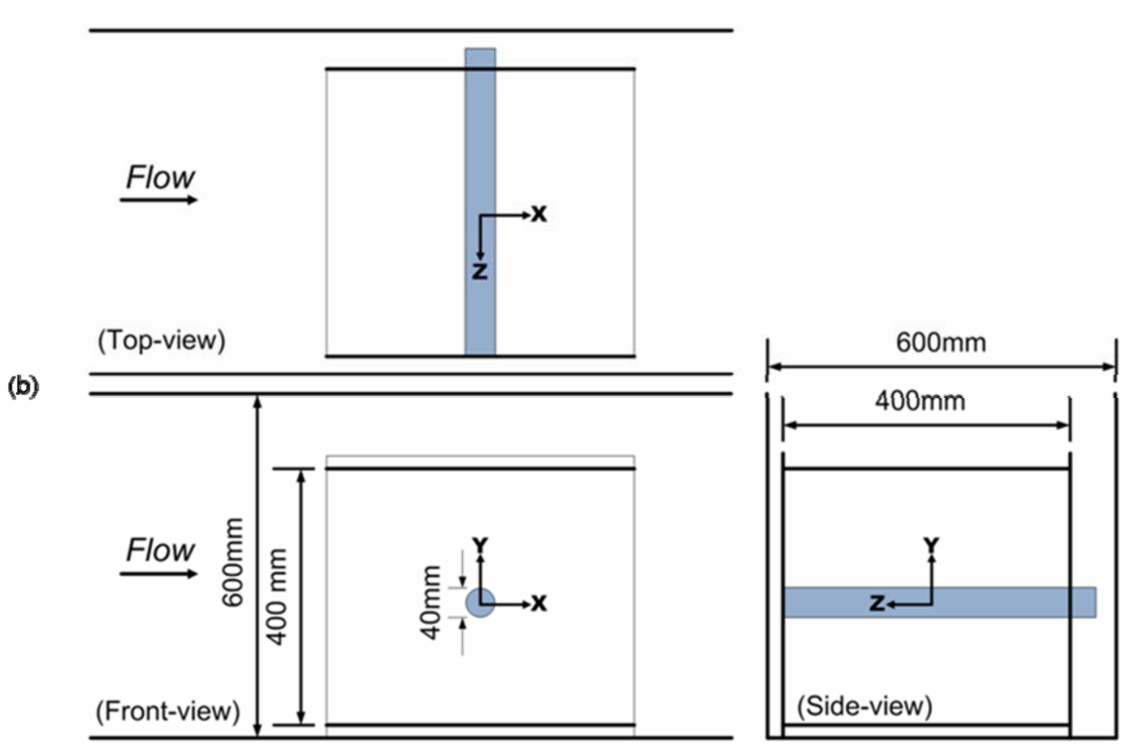


Fig. 2 The experimental setups in (a) the wind tunnel and (b) the water channel.

3. Results and discussion

3.1 Results of the hot-wire measurements made in the wind tunnel

Examples of the real-time hot-wire signal traces obtained with the circular cylinders of *s/d*=0, 0.025, 0.05 and 0.1 at a fixed location in the near wake region, each of which was sampled over one second at *Re*= 3.75×10^4, are presented in Fig. 3 for comparison. As seen in Fig. 3a, fluctuations in the signal trace of *s/d*＝0 appear to be more irregular in time, compared to those in Fig. 3b to d. To be more specific, the irregularity noted is characterized by the presence of amplitude modulations. In a previous study, Wu et al. [1] pointed out that the appearance of amplitude modulations was due to tilting of vortex shedding flow structures behind a bluff cylinder, in a way that the titling angles were varying with time. Accordingly, one can also anticipate that in the present case of *s/d*＝0, the vortex shedding structures behind the circular cylinder show an unsteady, three-dimensional appearance. Moreover, a trend revealed from the signal traces of the cases of *s/d*≠0 in Fig. 3 is that as the slit ratio gets higher, the amplitude modulations get less significant. This observation infers that larger the slit width better is the regularity of fluctuations associated with vortex-shedding, hence two-dimensional appearance of vortex shedding is likely prevailed. Nevertheless, as the slit ratio get further increased, the trend is reversed. This can be seen in Fig. 4, in which the signal traces of the slit ratios varied in a range of 0.15 to 0.3, each of which was sampled over 0.5 seconds, show that the amplitude modulations get more pronounced as the slit ratio gets higher. Therefore, it is fair to say that there exists an optimal width for a circular cylinder, at which the fluctuations associated with vortex shedding appear to be most regular. In the following, it would be of interest to identify the optimal width based on the criteria given, subsequently to gain physical insights into the performance of this vortex shedder configuration from the standpoint of vortex shedding flow structures.

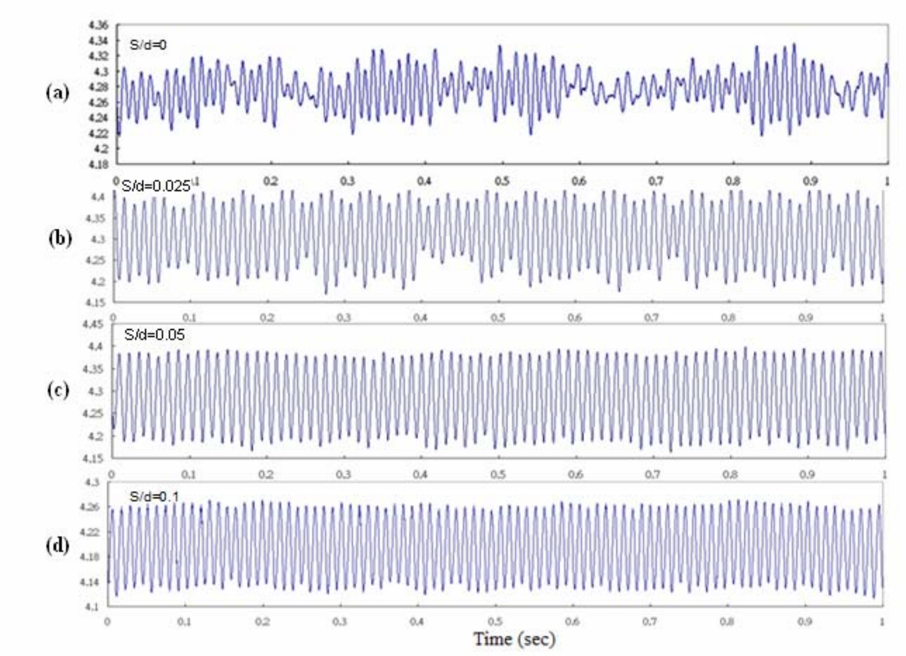


Fig. 3 The real-time hot-wire signal traces of the cases s/d=0,0.025,0.05 and 0.1, at Re= 3.75×10^4

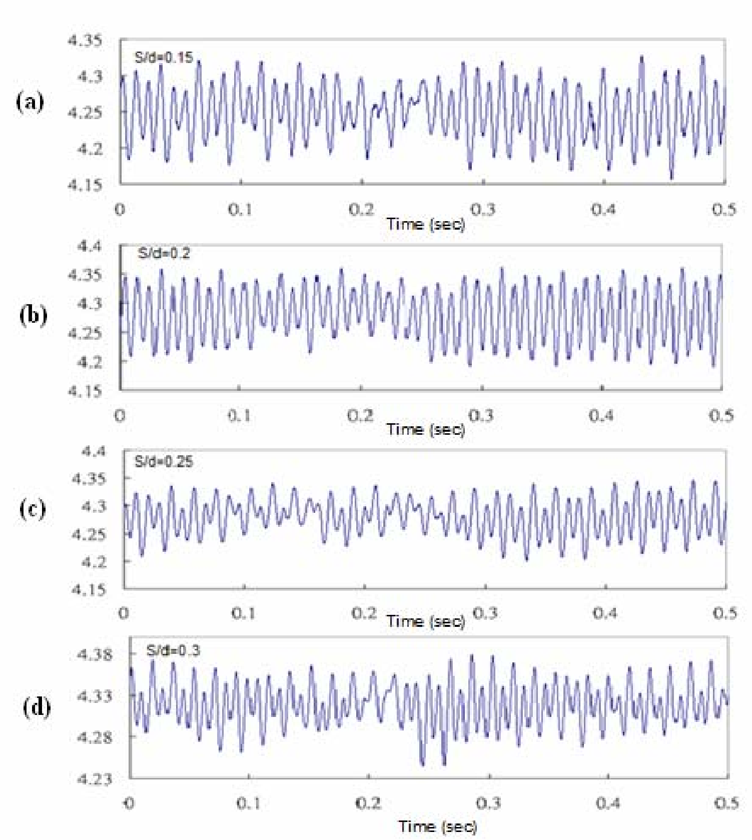


Fig. 4 The real-time hot-wire signal traces of the cases of s/d=0.15 to 0.3, at *Re*= 3.75×10^4.

In this study, the hot-wire signals measured at *Re*= $1.6\text{-}8.7\times10^4$, for *s/d*=0 to 0.3, were analyzed by the technique of Fast Fourier Transformation (FFT) to find the respective vortex shedding frequencies. As a result, the distributions of the Strouhal numbers, *St*, against the Reynolds number range studied, for the six *s/d* cases, are given in Figure 5 for comparison. Noticeable features obtained from this figure can be described below. First, the *St* values of *s/d*=0, irrespective of the Reynolds numbers studied, fall in the range of 0.2-0.21, which are noted in good agreement with Igarashi [4] and Roshko [18], for flows over circular cylinders subjected to negligible blockage at Reynolds numbers in the sub-critical regime. [19] Second, it is noted that for the cases of *s/d*=0.025 and 0.5, the *St* values reduced are lower than those of the reference case, *s/d*=0; conversely, for the cases of higher *s/d* ratios, the *St* values reduced are higher. Therefore, these observations infer a trend that higher the slit ratio, higher is the Strouhal value measured. Above findings are noted in good agreement with the experimental results reported by Igarashi [4]. Specifically, Igarashi [4] showed that for the circular cylinders of *s/d* =0.08 and 0.1, the *St* values are comparable to the reference case of *s/d* =0, below which the *St* values were lower, and above which the *St* values were higher. Third, it is seen in Fig. 5 that each of the *St* distributions appears to be rather insensitive to the Reynolds numbers studied, an indication of the linearity of the *St* values. Later, a quantitative description on the linearity of a *St* curve will be further introduced.

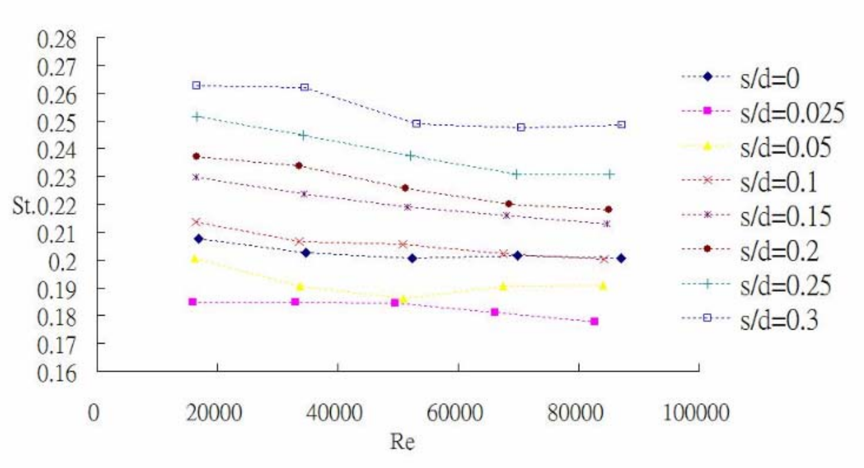


Fig. 5 The distributions of Strouhal numbers over Re=1.6-8.7×10^4 for the six s/d ratios.

Spanwise correlation measurements made with two hot-wires situated outside the wake shear layer were conducted to examine the two-dimensionality of vortex shedding structures, subjected to different flow conditions characterized by *Re* and *s/d*. For example, the results obtained with the cylinder models of *s/d*= 0, 0.05, 0.15, 0.2 and 0.3, at *Re*= 3×10^4, are presented in Fig. 6 for comparison. Note that the four plots in Fig. 6 show the results of the hot-wire measurements obtained at different locations, respectively. Namely, the reference probe was located in the plane z=0, and (x/*d*, y/*d*)= (1, 1.5), (1.5, 1.5), (1, 2) and (2, 2), respectively, whereas the other probe was placed away from the reference probe with a spanwise distance of 0.5 *d*, 1 *d* or 1.5 *d*. It is seen that, irresptive of the hot-wire locations, the spwanwise correlation coefficients obtained consistently show that the best correlation is due to the case of the circular cylinder with the slit width ratio *s/d*= 0.15. For this cylinder model, the correlation coefficient obtained with the largest separation distance 1.5 *d* can reach 0.97. Evidently, the correlation coefficient very close to unity infers that the vortex shedding flow structures would look almost perfectly two-dimensional over the spanwise region measured. It is worthwhile to mention that Peng [17] repeated the experiments at *Re*= 5×10^4, and obtained almost the same results as those in Fig. 6. Thus, it is fair to say that the two-dimensionality of vortex shedding flow structures behind a circular cylinder with a slit is rather insensitive to the Reynolds numbers studied.

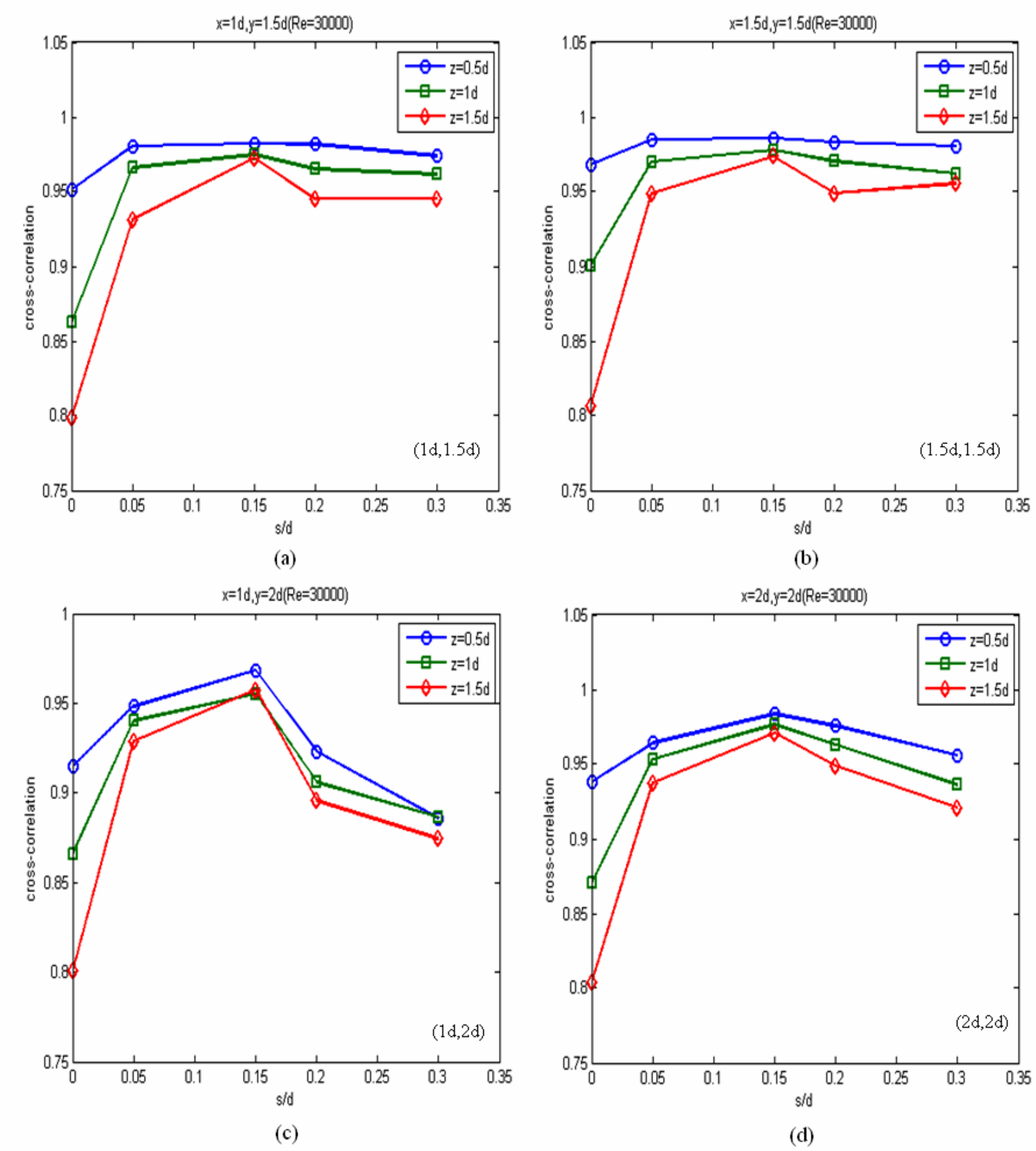


Fig. 6 Spanwise correlation coefficients versus s/d, for the two hot-wires at (x/d, y/d) = (1, 1.5), (1.5, 1.5), (1, 2), and (2, 2), respectively, for spanwise separations of 0.5, 1 and 1.5 d.

3.2. Results of PIV measurements made in the water channel

For the experiments made in the water channel, the real-time signal traces obtained by the PIV at a point in the wake region, (x/*d*, y/*d*, z/*d*) = (1, -0.75, 0), were analyzed by FFT for the vortex shedding frequencies. The frequency spectra obtained with respect to the cases of *s/d*= 0 and 1.5, for *Re*= 2.4×10^3 to 1.14×10^4, are shown in Fig. 7 for comparison. As seen in Fig. 7a (*s/d*=0), the vortex shedding frequency can not be clearly identified from each of the plots. Specifically, the one obtained at Re=2.4×10^3 shows that significant fluctuating energy was distributed over a wide range of frequency, and the fluctuating energy resided in the very low frequency range is remarkable and comparable to that of the vortex shedding frequency component. At higher Reynolds numbers, the frequency spectra show either double-peak appearance or a peak surrounded by a considerable wide band. Referring to Wu et al. [1] and Tu et al. [2], these observations actually infer that the vortex shedding process bears the usteady, three-dimensional appearances mentioned. On the other hand, in Fig. 7b (*s/d*= 0.15), each of the frequency spectra shows a distinct appearance that a peak freqeuncy can be easily identified as the vortex shedding frequency. This difference has an implication that the circular cylinder of *s/d*=0.15 certainly outperforms the reference circular cylinder of *s/d*= 0, as far as the flow measurement application is concerned.

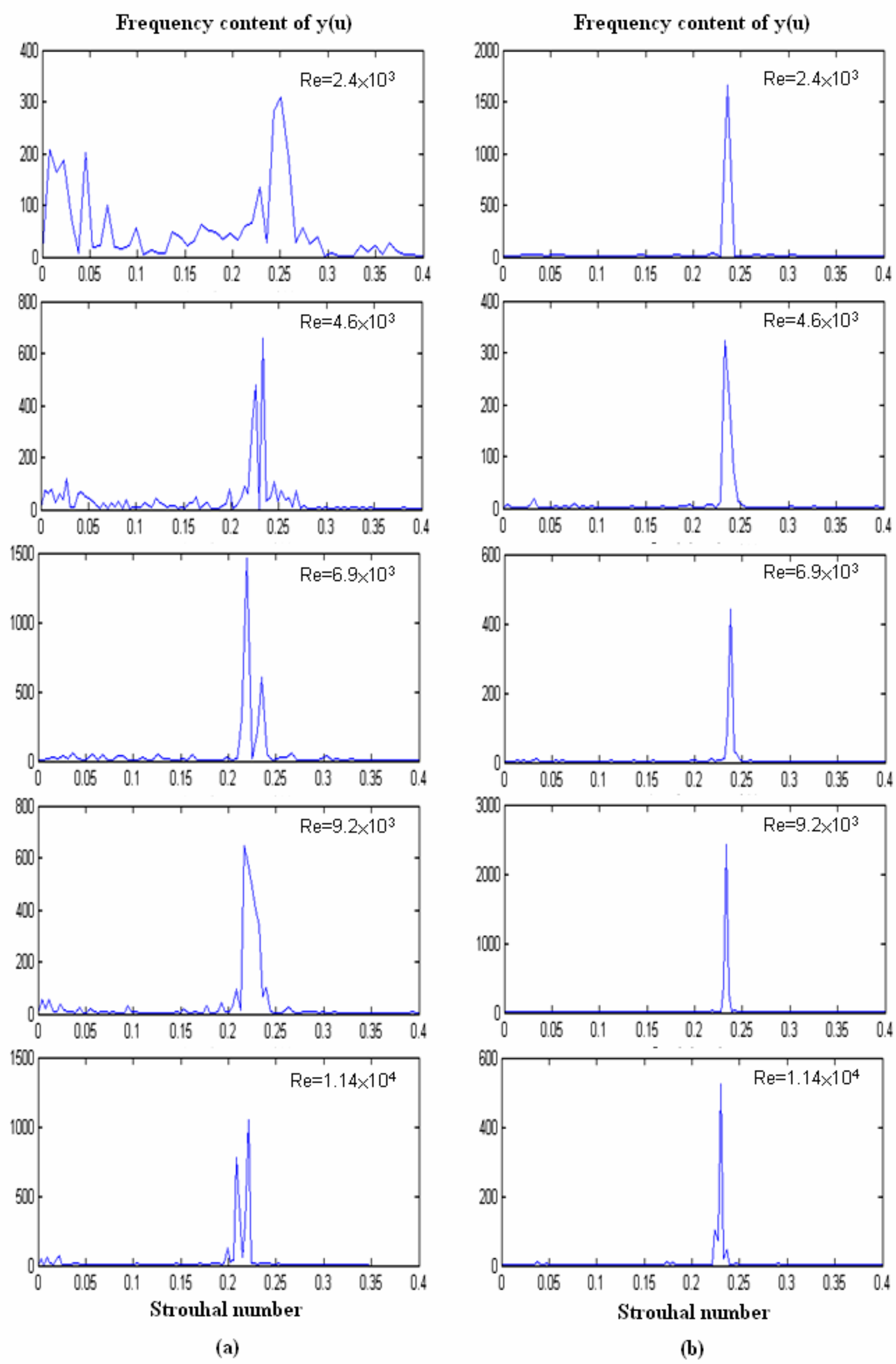


Fig. 7 Frequency spectra of the real-time velocity signals obtained with the cylinder models of (a) s/d=0 and (b) 0.15.

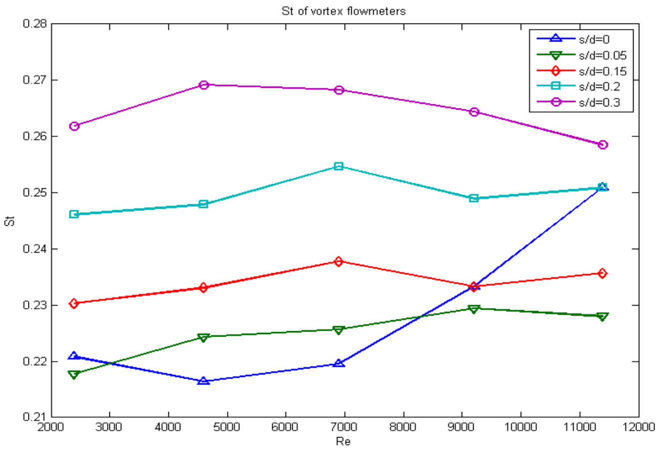


Fig. 8 St versus Re for the five cylinder models studied in the water channel.

Figure 8 presents the distributions of *St* againt *Re* for the five circular cylinders of different slit ratios studied in the water channel experiments. As seen, the nonlinearity in the *St* curve of *s/d*=0 appears to be much more prominent than the others. On the other hand, comparing Figs. 8 and 5 reveals a subtle difference that in Fig. 8 the *St* values of *s/d*=0.05 are higher than the *St* values of *s/d*=0 at *Re*= 4500 and 7000, an indication that at lower Reynolds numbers of 10^3, the effect of blowing and suction due to the slit deserves further investigation.

According to Igarashi [6], the performance a vortex shedder can be described with the nonlinearity of the Strouhal values over the range of Reynolds numbers of interest. The nonliearity defined [6] is shown below.

$$\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|St_i - \bar{St}\right|}{\bar{St}} \qquad (1)$$

ε is called the error of linearity, $\bar{St}$ denotes the mean values of St_i, where the subscript $i=1, N$; St_i denotes the Strouhal value reduced at a flow speed, U_{0i}; N denotes the number of flow speeds studied. According to (1), it is clear that lower the value of ε, better is the linearity of the *St* curve. Figure 9 presents the ε values against *s/d* obtained from the water channel experiments. In the figure, it is found that among the cases studied the most linear *St* curve is due to the circular cylinder with *s/d*=0.15.

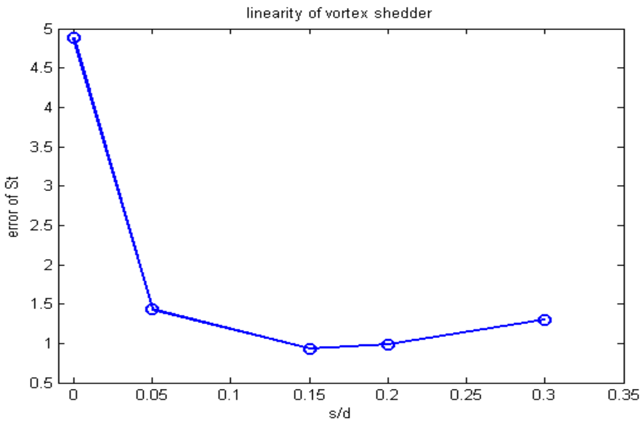


Fig. 9 The ε values versus s/d of the five cylinder models tested in the water channel

Further analysis was carried out to examine the quality of the vortex shedding signal measured. Along this effort, a qauntity called signal-to-noise ratio, Q_S, was defined, which is given below. [20]

$$Q_S = 10 \times \log\left(\frac{P_S}{P_N}\right) \tag{2}$$

where P_S denotes the energy resided within the frequency band between 0.96 f_v to 1.04 f_v; P_N denotes the residual energy that is the total fluctuating energy minus P_S.

As a result, Fig. 10 presents the Q_S values against *Re* for the five circular cylinder models studied. As seen, for any of the cylinder models with slits the signal quality is improved greatly, that the Q_S values are positive and insensitive to *Re*. On the other hand, the Q_S values of *s/d*=0 are much lower and can be negative, which are strongly dependent upon *Re*. This remarkable difference infers that the effect of suction and blowing due to the slit in a circular cylinder shows a stepwise impact on the vortex shedding process.

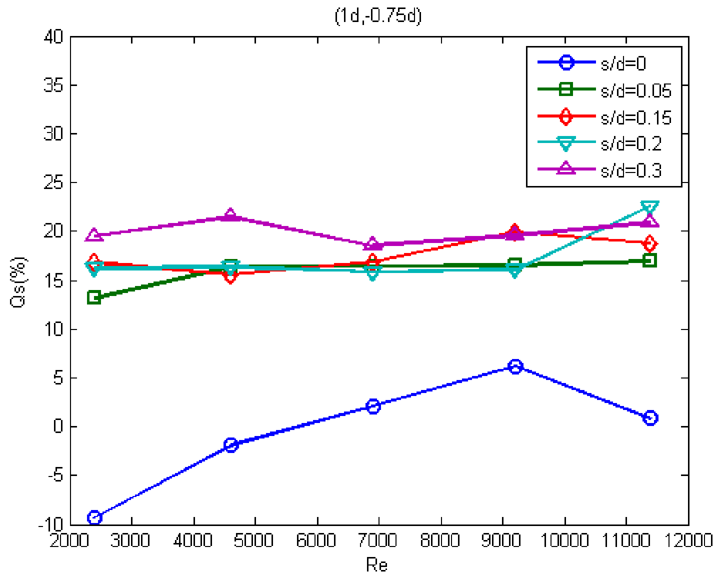


Fig. 10 The Q_S value distributions of the five cylinder models over the range of Reynolds numbers studied.

4. Discussion and Concluding remarks

As noted, above results obtained from the wind tunnel and water channel experiments covered a Reynolds number range of 4×10^3 to 8.7×10^4, corresponding to a ratio more than 30. By taking the *St* values obtained from both experimental facilities into account, the errors of linearity, ε, corresponding to the five circular cylinder models studied were further reduced. The results are presented in Table 1 for comparison. Among those, the case of *s/d*= 0.15 shows the least nonlinearity, ε= 0.966%. In Igarashi [6], several vortex shedders of different cross-section shapes were tested in a fully developed turbulent pipe flows. Igarashi [6] found that the circular cylinder with a slit ratio of *s/d*=0.1 and the blockage ratio 0.267 gave the best performance, ε= 0.06%. While the linearity reported by Igarashi [6] is nearly perfect, it should be mentioned that Igarashi's [6] experiments were carried out over a range of the Reynolds numbers 1.9×10^4 to 2.5×10^4, based on the bulk velocity and the diameter of the pipe, corresponding to a ratio about

13. Apparently, the present Reynolds number range is considerably wider than that in Igarashi [6].

Table. 1 Comparison of the ε values of the five circular cylinder models over the range of Reynolds numbers 2.4×10^3 to 8.7×10^4.

s/d	$\overline{St}$	ε (%)
0	0.225	4.308
0.05	0.22	3.542
0.15	0.234	0.966
0.2	0.25	1.379
0.3	0.266	1.762

In addtion, three major findings obtained from the present study can be summarized below.

(1) Like Igarashi [4-7], the present results obtained substantiate that the introduction of a slit in a circular cylinder improves the quality of the vortex shedding signals measured. Furthermore, the present results obtained from both wind tunnel and water channel facilities, over a Reynolds number range of 2.4×10^3 to 8.7×10^4, suggest an optimal range of width ratio, *s/d*= 0.1 to 0.15, in which the error of linearity, *ε*, in the *St* values obtained and the three-dimensional appearance of vortex shedding structures should be the least.

(2) It is found from the wind tunnel data that the *St* values obtained with the circular cylinders of *s/d*= 0.025 and 0.05 are lower that the reference circular cylinder *s/d*= 0, but those of *s/d*= 0.1 and above are higher. Morevoer, the *St* values of *s/d*=0.1 are noted very close to the reference circular cylinder *s/d*= 0. This has a direct implication that at *s/d*=0.1 the effect of blowing and suction introduced by the slit is likely synchronized with nature vortex shedding, inferring a lock-on situation.

(3) Referrring to the Q_s values given in Fig. 10, one can immediately realize that the effect of blowing and suction introduced by the slit improve the signal quality pronouncedly, but rather insensitive to *s/d*. On the other hand, Table 1 evidences that the *ε* values obtained strongly depend upon *s/d*; meanwhile, the spanwise correlation measurements in Fig. 6 unveil that the two-dimensionality of vortex sheddding flow structures are sensitivet to *s/d* as well. Therefore, the correlation inferred by the results of Table 1 and Fig. 6 unveils a substle link between the lineairty of the *St* values and the two-dimensional appearance of the vortex shedding flow structures.

Acknowledgement

The authors are very grateful to acknowledge the funding supports from National Science Council and Ministry of Education for this research work.

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