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Original Research Article

Experimental Investigation of Flow Interference between Four Circular Cylinders

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ABSTRACT

This paper has investigated the flow interference between four circular cylinders of equal diameters in a square arrangement in a cross-flow. Wind tunnel experiments were conducted to measure the mean force coefficients and Strouhal numbers (St) for six spacing ratios (l/d) varying from 1.5 to 4 at five subcritical Reynolds numbers (Re) ranging from 1.26× 〖10〗^4 to 6.08× 〖10〗^4. The pressure distributions on the surface of the cylinders were measured using pressure transducers. Furthermore, the hot-wire anemometer was employed to measure the vortex vortex-shedding frequencies behind each cylinder. It is revealed that for l/d=1.5, due to severe flow interference between cylinders, there is a difference between lift coefficients for the upstream cylinders. Also, for l/d≤2, the mean drag coefficients for downstream cylinders are negative. In addition, for l/d=2 and l/d=2.5, there is no vortex shedding from the upstream cylinders. Moreover, it is found that the effects of variations in this range of the Reynolds numbers, on the quality of the vortex shedding and Strouhal numbers are negligible; whereas the variations in l/d, strongly affect the flow pattern around the cylinders and aerodynamic coefficients. Also, by decreasing the amount of l/d, the effects of the flow interference between the cylinders increase.

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1 INTRODUCTION

From skyscrapers and chimneys to power lines and nuclear reactor cooling systems, many engineering applications involve groups of bluff bodies, including airfoils, tubes, and blunt shapes. Modeling the intricate flow patterns around these structures, often represented as multi-cylinder arrays in a cross-flow, presents unique challenges due to complex phenomena like vortex shedding, flow interactions, and turbulence.

The flow around a circular cylinder in a cross-flow, a classic in fluid mechanics, holds immense significance due to its diverse applications in engineering and nature. While its fundamental characteristics have been extensively studied, understanding the nuances of this flow remains crucial for optimizing structures and mitigating undesired effects. For example, studies of

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Dobroselsky [1], Nguyen et al. [2], Yao et al. [3], So and Savkar [4], and Holloway et al. [5] While the flow around a single cylinder is well-characterized, introducing multiple cylinders in an array adds a layer of complexity. Fluid interactions, such as vortex shedding synchronization and wake interference, dramatically alter the flow patterns, leading to surprising consequences like drag reduction or flow instabilities. Most previous works have studied multi-cylinder arrays experimentally in high subcritical Reynolds numbers for industrial applications [6-9]. On the other hand, due to the complexity of the flow in these cases, there have been relatively few numerical studies on the circular cylinders which are mostly published just for two cylinders at low Reynolds numbers [10-13].

The fluctuating forces acting on each cylinder in an array are intimately tied to the intricate dance of vortex shedding and flow interference. Imagine each cylinder shedding its own Karman vortex street. These vortex streets, however, don't exist in isolation. The free shear layers, those thin sheets of air separating from the cylinders, interact with each other and with the shed vortices. This interplay can dramatically alter the "vortex shedding quality," such as its frequency or stability. For instance, the merging of shear layers from two cylinders can amplify their vortex shedding, leading to higher force fluctuations. In contrast, the shielding effect of one cylinder on another can suppress vortex shedding altogether. [14-17]. Vortex shedding from each cylinder, vortex shedding on the downstream cylinders and also near-wake are the main parameters affecting the flow-induced vibrations [18]. Major points in multiple-cylinder arrays studies are to find the effects of the flow interference on each cylinder, fluid-structure interactions, classification of the flow pattern around cylinders, and its relation to the flow-induced vibrations.

Some previous studies on flow interference between cylinders have obtained interesting and surprising results that need more consideration. For example, studies of Zdravkovich and Pridden [19] on two circular cylinders in tandem arrangement revealed the fact that minimum drag coefficient doesn't occur on downstream cylinders. Tatsuno et al. [9] found an unsymmetrical flow pattern around three cylinders in an equilateral-triangular arrangement for small spacing ratios (l/d) at zero incident angle. Moreover, in some cases for one cylinder, two Strouhal numbers have been reported [20] and sometimes due to the absence of vortex shedding, the Strouhal number of St has been subjected [8]. On the other hand, for these cases, the main effects of the Reynolds number on the flow pattern around the cylinders are not reported. So, there should be more efforts to get a better perception of the fluid-structure interactions on multi-cylinder arrays in a cross-flow.

Many experimental studies on flow interference between circular cylinders are on two circular cylinders in tandem, side-by-side, and staggered arrangements [14,15,19-24] Some studies have investigated the flow around three circular cylinders in an in-line arrangement [25-28] investigated the mean lift and drag forces acting on two and three cylinders in staggered configurations over a wide range of l/d and suggested that the principle of superposition could be applied in determining the force coefficients. Furthermore, Sayers [29] studied the drag and lift coefficients occurring on one cylinder in a group of three equispaced cylinders. He concluded that the angle of orientation to the free stream will strongly influence the force coefficients acting on each cylinder. Also, Tatsuno et al. [9] investigated the effects of the flow interference between three cylinders in an equidistant triangular arrangement in a cross-flow. They found that the flow interference effects between three cylinders are severe in the case of a low spacing ratio (l/d) and the flow interference effects weaken with higher l/d. They also reported a severe difference between force coefficients of downstream cylinders in side-by-side arrangement for small l/d. Gu and Sun [7] identified four different affected regions i.e. small, transition, medium, and large spacing ratios for the flow pattern on three cylinders in an equilateral-triangular arrangement at 1.4×10^4 as regards different levels of interference of influence of spacing ratio (l/d).

Despite numerous works on two-cylinder arrangements, only a few studies have been reported on multi-cylinder arrays such as four-cylinder arrays. Even among the studies on multi-cylinders many of them were on multi-cylinders in line, side-

by-side, or in tandem [30-32] and studied the interference effects for groups of three or four stacks. A four-cylinder array in a square arrangement is a basic unit in many multi-cylinder arrays such as tube banks. The study of four-cylinder arrays would help understand more complicated flow in much larger cylinder arrays, which are especially evident in shell and tube heat exchangers. It has also many practical applications in offshore structures. Sayers [33,34] studied the flow interference between four circular cylinders in a square arrangement and revealed that the magnitude of the mean lift and drag coefficients is strongly influenced by the orientation of the array group to the free stream. Lam et al. [8] have measured the mean and fluctuating force coefficients of four cylinders in square configuration for different l/d and incidence angles (α) at subcritical Reynolds numbers, using a piezo-electric load cell. They also investigated the frequencies of fluctuating forces acting on each cylinder.

The present work has experimentally investigated force coefficients and Strouhal numbers for four circular cylinders in a square arrangement when subjected to a cross-flow with six spacing ratios (l/d) ranging from 1.5 to 4 at five subcritical Reynolds numbers ranging from 1.26×10^4 to 6.08×10^4. It is hoped that this study could provide a useful database and a better understanding of the flow interference phenomenon for multiple-cylinder arrays in a cross-flow.

EXPERIMENTAL DETAILS

The experiments were performed in the low-speed, open-circuit wind tunnel of the Department of Aerospace Engineering, K.N. Toosi University of Technology, with a closed wall rectangular test section of 1.2 m wide, 1 m high, and 3 m long. The velocity in the test section could be continuously varied using an inverter, which controls the rotation speed of the wind tunnel fan. The deviation of mean wind velocity across the test section was within ±0.5% (velocity non-uniformity) and the longitudinal free-stream turbulence intensity was less than 0.2%.

Figure 1 shows a schematic diagram of the experimental set-up in the wind tunnel. The configuration of the four circular cylinders in a square arrangement is shown in Figure 2. Six spacing ratios (l/d) vary from 1.5 to 4, where d is the cylinder diameter, l is the distance between the centers of adjacent cylinders and l/d is the spacing ratio between two cylinders.

The errors in the spacing and the alignment of the cylinders were within ±0.05 d. Figure 3, (x, y) shows the position of the hot-wire probe behind each cylinder. Moreover, the position of a point on the surface of each cylinder is defined by the azimuthal angle θ, measured from the direction of the free-stream flow. Each cylinder of the group is a 92 cm long hollow aluminum tube of 38 mm external diameter, with a machine-finished surface (by turning and polishing: Ra (μm) = 0.05).

Thirty pressure taps of diameter 0/5 mm were provided every 12° in two parallel rows within 2 cm distance from each other around mid-span in a zigzag manner of each cylinder circumferentially. The aspect ratio is about 24 and the blocking ratio is 2.9% per cylinder. In addition, the total blockage ratio in the present set-up is 5.8%. The tests were carried out at five Reynolds numbers of 1.26×10^4, 2.53×10^4, 3.8×10^4, 5.06×10^4 and 6.08×10^4 (based on the diameter of a single cylinder) at five free-stream velocities of 5, 10, 15, 20 and 24 m/s.

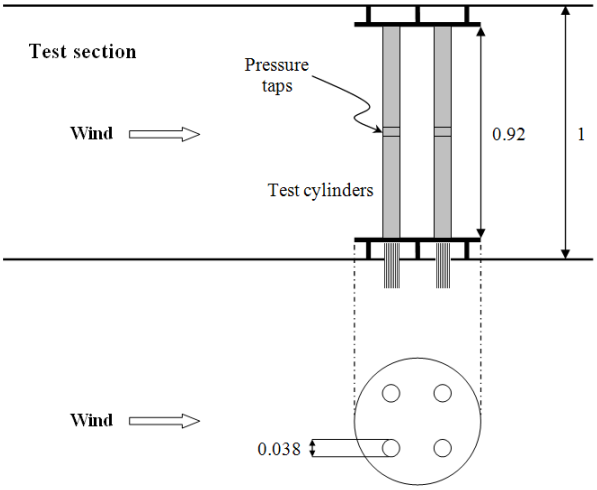

Figure 1. Schematic diagram of the experimental set-up in the wind tunnel, Dimensions are in meters

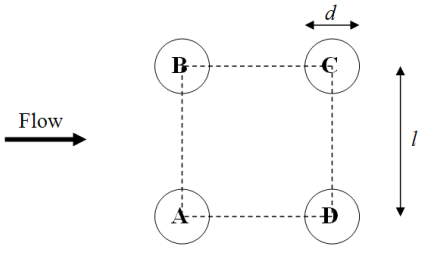

Figure 2. The configuration of four circular cylinders in a square arrangement

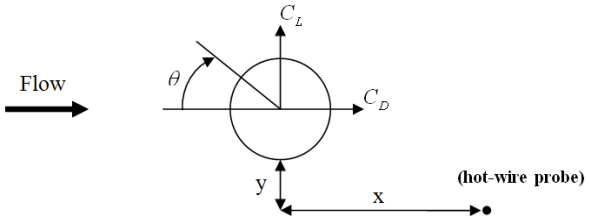

Figure 3. (x, y): the position of the hot-wire probe behind each cylinder; angel θ: the position of a point on the surface of each cylinder

A standard Pitot-static tube was used to monitor the wind speed (free-stream velocity) and the pressure was read using an electronic micro-manometer made by F.S.S (Farasanjesh). All measurements were stored in a computer-controlled data acquisition system. The vortex shedding frequencies were measured using an FSS WU11-SN single-component hot-wire probe, an FSS-CTA constant temperature anemometer, a National Instruments (NI) PCI-6024E 12-bit A/D board with 16analog input channels, and a personal computer. The probe was located at mid-span and downstream of the cylinder of interest using a three-axis computer-controlled traversing system. Furthermore, in the present study, the frequencies of the vortex shedding have been computed using the FFT results (Fast Fourier Transform) by the F.S.S FlowWare program. To investigate all flow frequencies downstream of each cylinder at various Reynolds numbers, different sampling rates were examined from 10 kHz down to 250 Hz. Finally, the sampling rate of 1000 Hz was utilized in which the resolution of the FFT results on shedding frequency was 1 Hz (using 1000 points). The surface pressure measurement system was composed of pressure transducers (Honeywell-DC005NDC4), a National Instruments (NI) PCI-6224 16-bit A/D board with 32 analog input channels, LabVIEW software, and F.S.S PressureField program, and a personal computer. In addition, the duration of each record (specified time interval) was 15s.

The measurement uncertainties in the pressure, lift drag, and coefficients were estimated at $C_P \pm 0.01$, $C_L \pm 0.015$ and $C_D \pm 0.02$, respectively in which the mean force coefficients have been calculated using the pressure distribution method. Moreover, the estimated measurement uncertainty of the Strouhal number was less than $St \pm 0.005$. In the present study, the pressure coefficient C_P, the lift coefficient C_L, the drag coefficient C_D and the Strouhal number St for each cylinder is defined as:

$$C_P = (P - P_\infty)/(0.5\rho V_\infty^2) \quad (1)$$

$$C_L = L/(0.5\rho V_\infty^2 d) \quad (2)$$

$$C_D = D/(0.5\rho V_\infty^2 d) \quad (3)$$

$$St = fd/V_\infty \quad (4)$$

respectively, where P is the mean static pressure on the surface of the cylinder, P_∞ the static pressure of the free-stream flow, L the lift force, D the drag force, ρ the air density, V_∞ the free-stream velocity and f is the frequency.

RESULTS AND DISCUSSION

The results are classified in two major parts illustrated in Figures 4 to 22. In the first part, the pressure coefficient distributions on the surface of the cylinders are presented and then variations of lift and drag coefficients are represented with l/d, using the pressure distribution method. In the second part, diagrams of the spectral analysis of the hot-wire signal are depicted and then the Strouhal number variations are represented versus l/d.

The pressure distributions on the surface of the cylinders were measured by the pressure transducers. In Fig. 4, the distribution of the pressure coefficient on the surface of a single cylinder is presented. Moreover, Figs. 5 to 10 show the pressure coefficient distributions on the surface of four circular cylinders in a square arrangement, at 6.08×10^4, for different values of $l/d = 1.5$ to 4. In Fig. 10, it is clear that by increasing the distance between cylinders for $l/d = 4$ and so weakening the effects of the flow interference between the cylinders, the pressure coefficient distribution on the surface of upstream cylinders (A and B) is somehow similar to that of a single cylinder. In Fig. 4, the distribution of the pressure coefficient on the surface of a single cylinder is presented. The C_P around the cylinder is symmetric, which represents the mean flow pattern is also symmetric. Near the separation point ($\theta_s = 84°$), the minimum value of C_P reaches -1.16, which gives a laminar separation at the subcritical Reynolds number. Also, the value of C_P is almost constant ($C_P \approx -1$) behind the cylinder (downstream of the separation point). In this study, the pressure distribution method has been employed for measuring mean force coefficients in which lift and drag coefficients are only calculated by pressure integration around the cylinders at mid-span.

As depicted in Fig. 4, for a single cylinder at $Re = 6.08 \times 10^4$, it is found that $C_L = 0$ and $C_D = 1.20$, which shows a good agreement with the results

reported by Lam et al. [8] for a single cylinder that has been measured at $Re = 6 \times 10^4$ using a piezo-electric load cell ($C_D = 1.217$ and $C_L = 0$). Also, this graph is rather compatible with the results of Flachsbart [35] and Gu and Sun [7] in which the measurements were performed at $Re = 1.86 \times 10^5$ and $Re = 5.5 \times 10^4$, respectively. There is only a small difference, which may be due to the test conditions and instruments' accuracy.

Figures 11 and 12 show variations of the lift and drag coefficients concerning l/d at 6.08×10^4. In Fig. 11, it is evident that when four cylinders are in a square arrangement, there is a repulsive force between the upstream cylinders A and B which is weakened by increasing l/d.

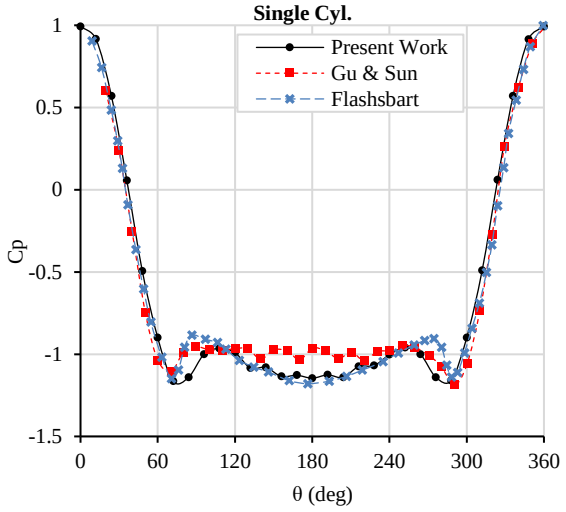

Figure 4. The pressure coefficient (C_P) distribution on the surface of a single cylinder ($Re = 6.08 \times 10^4$)

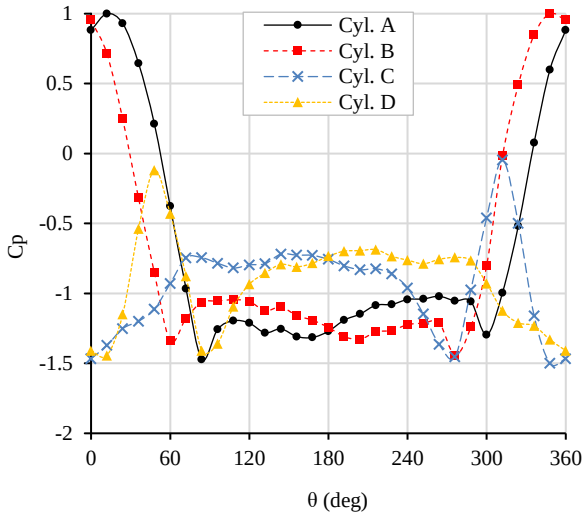

Figure 5. The pressure coefficient (C_P) distribution on the surface of a single cylinder for $l/d = 1.5$ ($Re = 6.08 \times 10^4$)

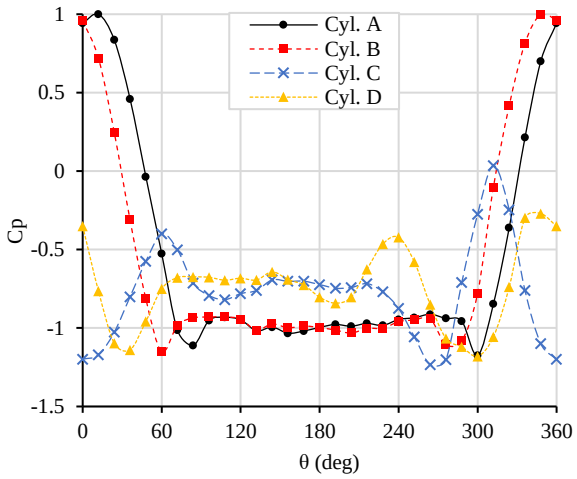

Figure 6. The pressure coefficient (C_P) distribution on the surface of a single cylinder for $l/d = 2$ ($Re = 6.08 \times 10^4$)

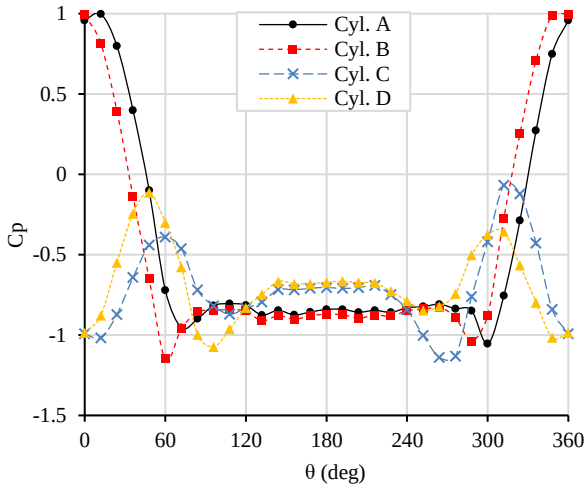

Figure 7. The pressure coefficient (C_P) distribution on the surface of a single cylinder for $l/d = 2.5$ ($Re = 6.08 \times 10^4$)

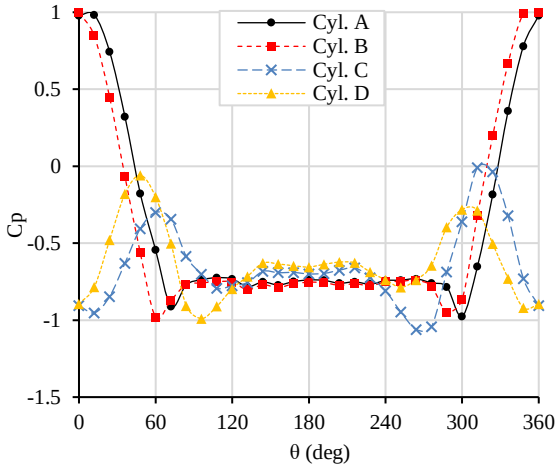

Figure 8. The pressure coefficient (C_P) distribution on the surface of a single cylinder for $l/d = 3$ ($Re = 6.08 \times 10^4$)

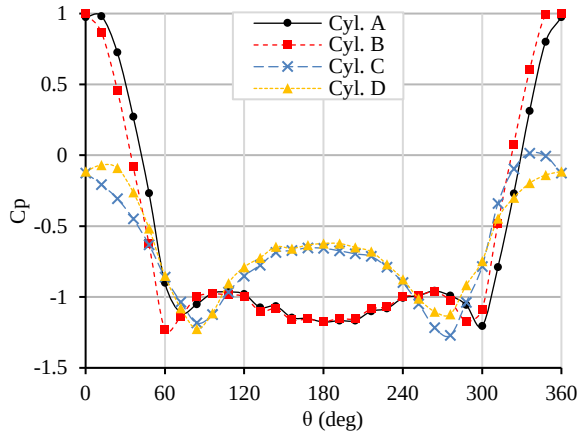

Figure 9. The pressure coefficient (C_P) distribution on the surface of a single cylinder for $l/d = 3.5$ $(Re = 6.08 \times 10^4)$

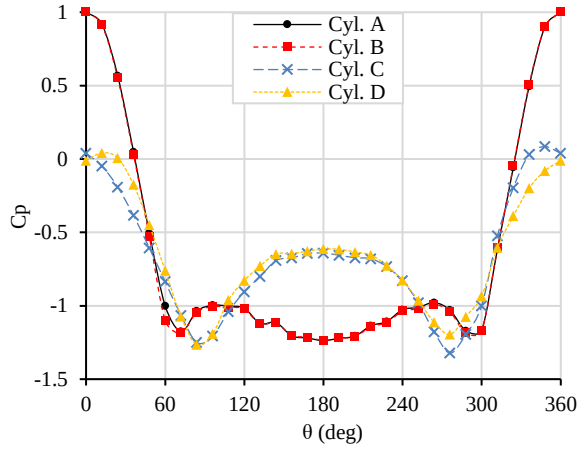

Figure 10. The pressure coefficient (C_P) distribution on the surface of a single cylinder for $l/d = 4$ $(Re = 6.08 \times 10^4)$

Furthermore, it can be seen in Fig. 12 that the downstream cylinders experience lower mean drag coefficients (C_D) than that of the upstream cylinders and the minimum drag coefficient values for the upstream cylinders occur at $l/d = 3$. By increasing l/d, the mean drag coefficients for downstream cylinders are increased. It is notable that for $l/d \leq 2$ these coefficients are negative (see Fig. 12). Also, according to Fig. 11, it is clear that for $l/d = 1.5$, there is a difference between lift coefficients for the upstream cylinders A and B (in a symmetric arrangement) as a result of severe flow interference between the cylinders. This difference is due to the asymmetric pressure distribution, which represents a lack of symmetry in the flow pattern around cylinders A and B. The same phenomenon has been found for three circular cylinders in an equilateral-triangular arrangement which has been reported by Tatsuno et al. [9] and Pouryoussefi et al. [36].

They explained that in these cases, while the effects of flow interference among the cylinders are severe, a very small asymmetry (which is inevitable in experimental studies) can lead to significant changes in obtained results (such as lack of symmetry in the flow pattern around cylinders). From the other viewpoint, by increasing the distance between the cylinders for $l/d = 4$ and weakening the flow interference between the cylinders, it is found that the lift and drag coefficients for the upstream cylinders are almost similar to that of a single cylinder.

The vortex-shedding frequencies behind each cylinder have been measured using a hot-wire anemometer. In Fig. 3, (x, y) is the position of the hotwire probe behind each cylinder. The values of $(x/d\ ,\ y/d)$ for a single as well as four cylinders in $l/d = 1.5$ to 4 are tabulated in Table 1.

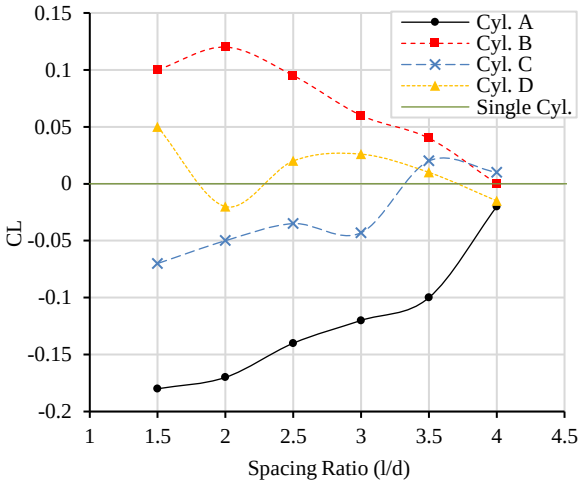

Figure 11. Variation of the mean lift coefficients (C_L) with l/d $(Re = 6.08 \times 10^4)$

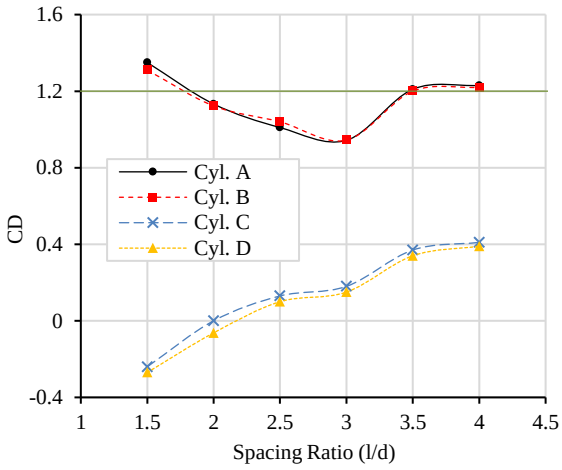

Figure 12. Variation of the mean lift coefficients (C_D) with l/d $(Re = 6.08 \times 10^4)$

To study the effects of Reynolds number on vortex shedding and the flow pattern around the cylinders, the experiments were carried out at five different Reynolds numbers of 1.26×10^4 to 6.08×10^4. Figure 13 illustrates the diagram of the spectral analysis of the hot-wire signal for a single cylinder. Also, the spectral analysis of the hot-wire signal for the four cylinders in various values of $l/d = 1.5$ to 4 is illustrated in Figs. 14 to 21. Fig. 13 illustrates the vortex shedding frequencies behind a single cylinder and indicates that $f = 128$ Hz at $Re = 6.08 \times 10^4$ (Fig. 13(e)).

According to $d = 0.038$ m and $V_\infty = 24$ m/s and defining the Strouhal number as Eq. (4), the Strouhal number for a single cylinder at $Re = 6.08 \times 10^4$ is $St = 0.205$, which shows a good agreement with the results reported by Lam et al. [8] measured at $Re = 6 \times 10^4$ using a piezo-electric load cell ($St = 0.205$). The values of the Strouhal number for a single cylinder at various Reynolds numbers are reported in Table 2.

According to the spectral analysis of the hot-wire signal for cylinders A and D at $l/d = 1.5$, shown in Fig. 14, it is found that due to severe flow interference between the cylinders, there are two distinct frequencies for each cylinder which states simultaneous shedding of two different types of vortex from these cylinders. So it can be said that in this case, there are two different Strouhal numbers for each cylinder.

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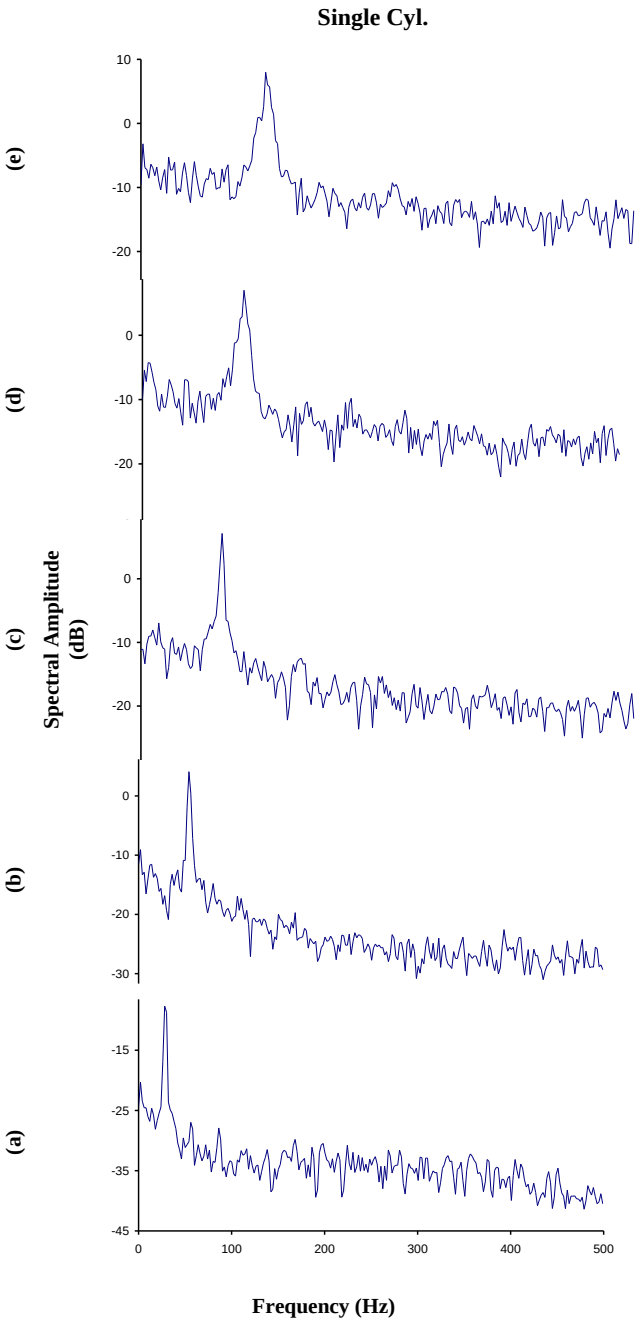


Figure 13. The amplitude spectrum of the hot-wire signal for a single cylinder: (a) $Re = 1.26 \times 10^4$; (b) $Re = 2.35 \times 10^4$; (c) $Re = 3.80 \times 10^4$; (d) $Re = 5.06 \times 10^4$; and (e) $Re = 6.08 \times 10^4$

Table 1: The values of $(x/d\ ,\ y/d)$(x, y): The position of the hot-wire probe behind each cylinder; and d: the cylinder diameter

Single Cyl.	l/d =	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**
(1.68, 0.13)	Cyl. A =	(0.89, 0)	(1.03, -0.26)	(1.29, -0.26)	(1.42, 0)	(1.42, 0)	(1.42, 0)
	Cyl. D =	(1.03, -0.13)	(1.03, -0.13)	(1.03, -0.13)	(1.03, -0.13)	(1.03, -0.13)	(1.03, -0.13)

For example for cylinder A at $Re = 6.08 \times 10^4$ we have: $St = 0.105$ and $St = 0.205$ (see Fig. 14(e)). Also according to the spectral analysis of the hot-wire signal for cylinder A at $Re = 6.08 \times 10^4$ for $l/d = 2$ and $l/d = 2.5$ shown in Figs. 15 and 17, it is found that by varying the hot-wire probe position, the spectral analysis changes significantly. For these two cases, when the hot-wire probe is located in $y/d = -0.26$ (behind cylinder A), spectral analysis diagrams reveal that $St = 0$ which means that there is no vortex shedding from cylinder A; this behavior has been reported by Lam et al [8]. While the hot-wire probe is located at $y/d = 0$ (downstream of cylinder A), each diagram of spectral analysis shows a distinct non-zero frequency. It should be considered that the two frequencies shown in Figs. 15 and 17, are correspond to the flow fluctuation frequencies downstream of cylinder A and are not related to the vortex shedding frequency from cylinder A. The same phenomenon also was observed for other Reynolds numbers. Thus, it should be concluded that for $l/d = 2$ and $l/d = 2.5$, there is no vortex shedding from the upstream cylinders, so Strouhal numbers for these two cylinders are $St = 0$.

Furthermore, by comparing the results of Lam et al. [8], it is found that in these two cases, the fluctuating force frequency acting on each cylinder is equal to the vortex shedding frequency from the same cylinder. In addition, as seen in Fig. 21, by increasing the distance between the cylinders for $l/d = 4$ and so weakening the effects of the flow interference between the cylinders, the spectral analysis of the hot-wire signal for cylinder A is almost the same as that of a single cylinder.

In this study, the Strouhal number has been obtained using the spectral analysis of the hot-wire signal which represents vortex-shedding frequencies behind each cylinder. Figure 22 illustrates the variations of the Strouhal number with l/d. By increasing the distance between the cylinders, consequently weakening the flow interference between the cylinders, it is evident that for $l/d = 4$, the Strouhal number for cylinder A is almost the same as that of a single cylinder (see Fig. 22(a)). On the other hand, by comparing the diagrams of the spectral analysis of the hot-wire signal of each cylinder for various l/d and Re, it is found that the effects of variations in Reynolds number, at high subcritical range ($Re = 1.26 \times 10^4$ to $Re = 6.08 \times 10^4$), on the quality of vortex shedding as well as Strouhal numbers are weak and negligible. Therefore, it can be concluded that the Reynolds number in this range, weakly affects the flow pattern around the cylinders; whereas the effects of variations in l/d, on the flow pattern around the cylinders and aerodynamic coefficients are strong and significant and also by decreasing the l/d, the effects of the flow interference between the cylinders increase.

Table 2: The Strouhal number (St) for a single cylinder

Re =	1.26×10^4	2.53×10^4	3.80×10^4	5.06×10^4	6.08×10^4
St =	0.215	0.210	0.205	0.205	0.205

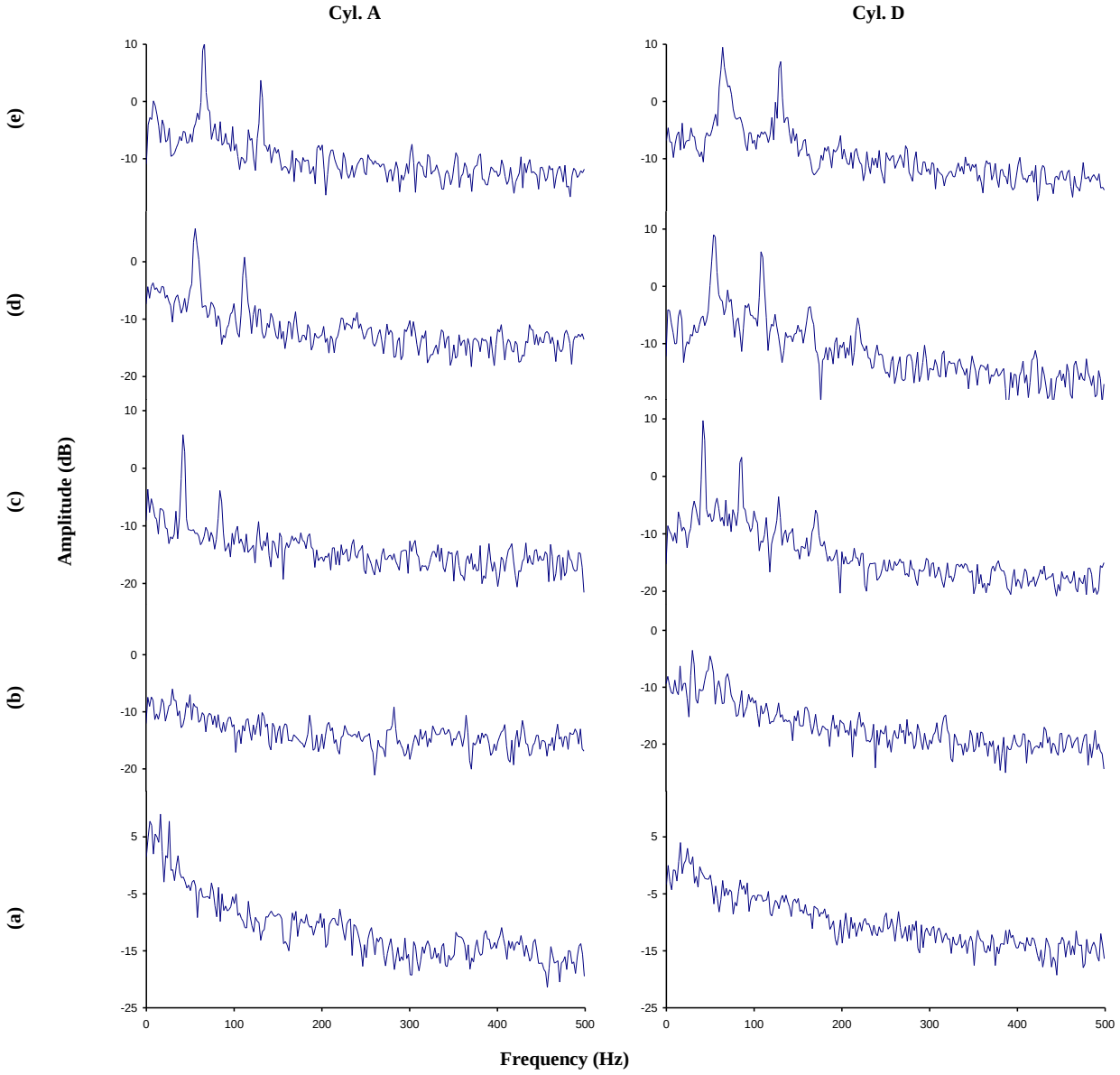


Fig. 14. The amplitude spectrum of the hot-wire signal for $l/d = 1.5$: (a) $Re = 1.26 \times 10^4$; (b) $Re = 2.53 \times 10^4$; (c) $Re = 3.80 \times 10^4$ (d) $Re = 5.06 \times 10^4$and (e) $Re = 6.08 \times 10^4$

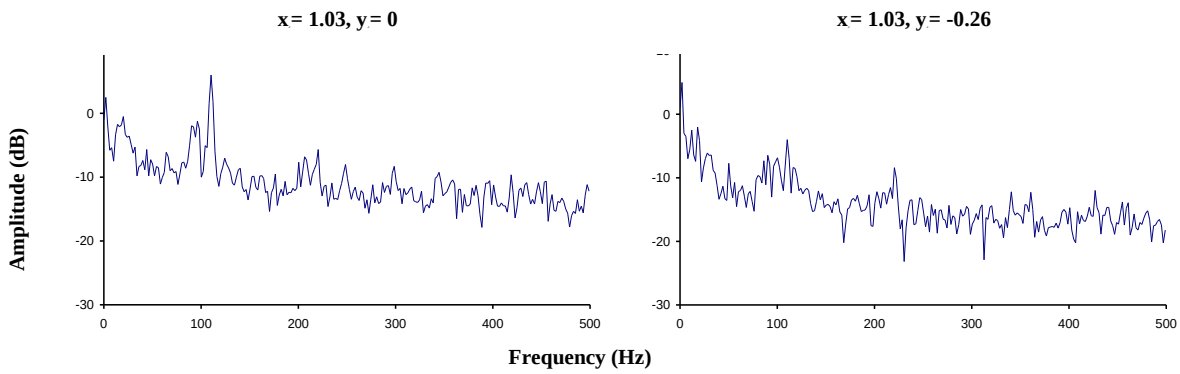


Fig. 15. The amplitude spectrum of the hot-wire signal for cylinder A (at $l/d = 2$ and $Re = 6.08 \times 10^4$)

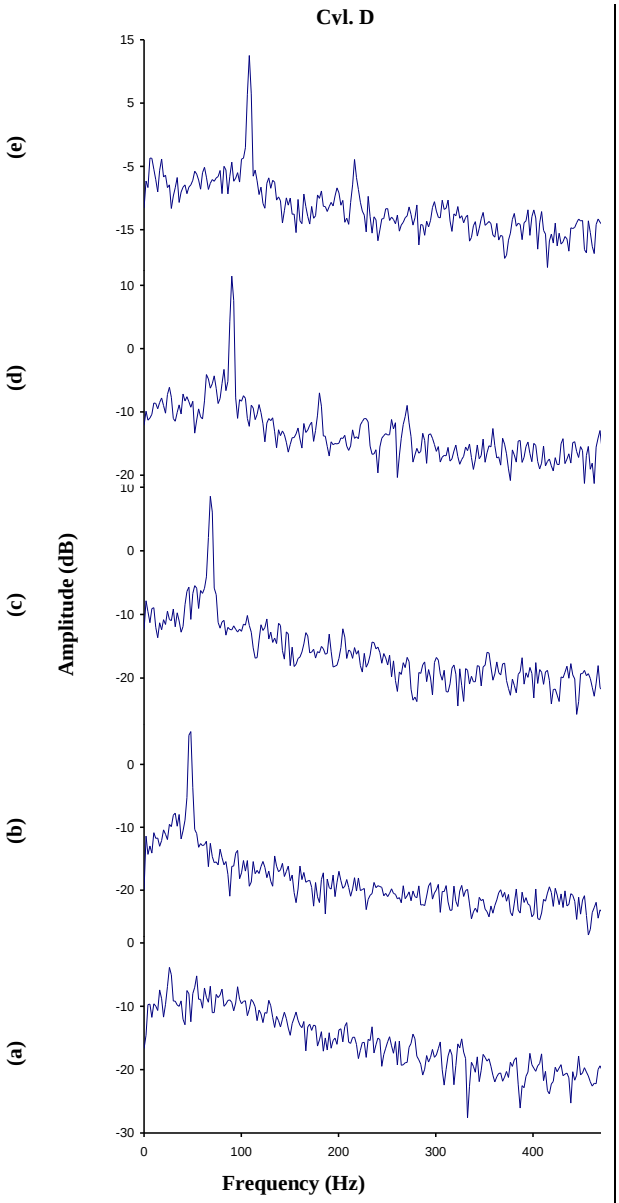


Fig. 16. The amplitude spectrum of the hot-wire signal for cylinder D at $l/d = 2$: (a) $Re = 1.26 \times 10^4$; (b) $Re = 2.53 \times 10^4$; (c) $Re = 3.80 \times 10^4$; (d) $Re = 5.06 \times 10^4$; and (e) $Re = 6.08 \times 10^4$

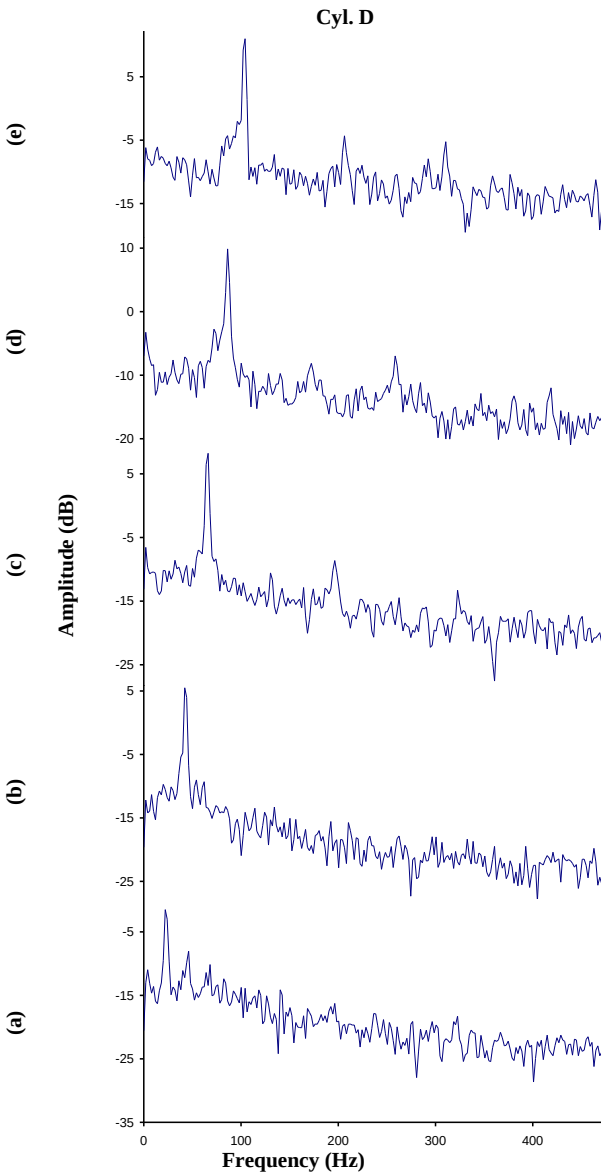


Fig. 18. The amplitude spectrum of the hot-wire signal for cylinder D at $l/d = 2.5$: (a) $Re = 1.26 \times 10^4$; (b) $Re = 2.53 \times 10^4$; (c) $Re = 3.80 \times 10^4$; (d) $Re = 5.06 \times 10^4$; and (e) $Re = 6.08 \times 10^4$

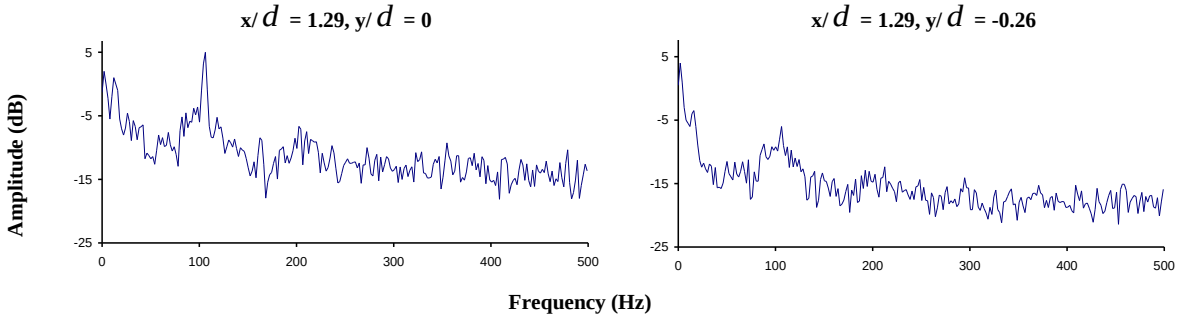


Fig. 17. The amplitude spectrum of the hot-wire signal for cylinder A (at $l/d = 2.5$ and $Re = 6.08 \times 10^4$)

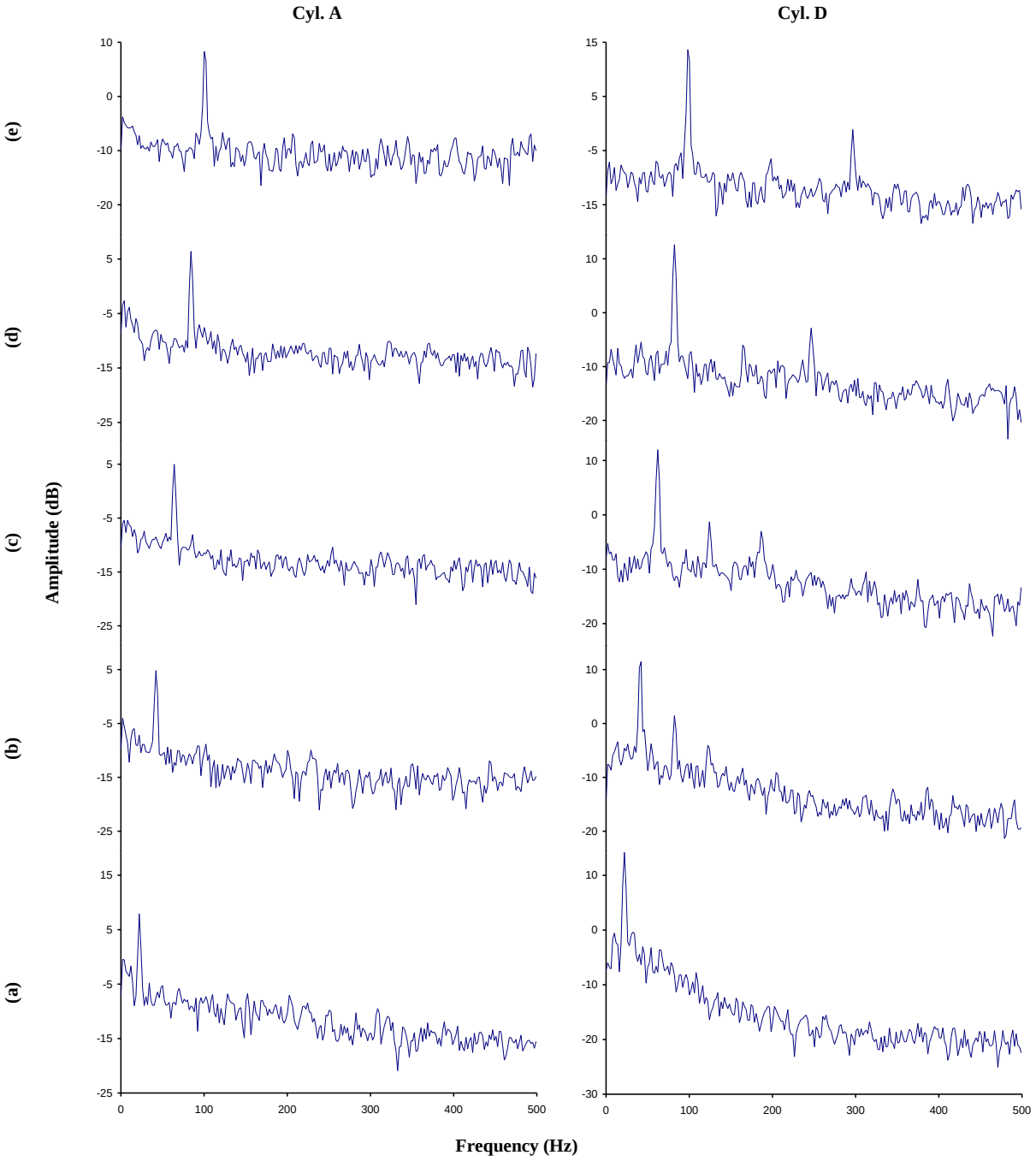


Fig. 19. The amplitude spectrum of the hot-wire signal for $l/d = 3$: (a) $Re = 1.26 \times 10^4$; (b) $Re = 2.53 \times 10^4$; (c) $Re = 3.80 \times 10^4$; (d) $Re = 5.06 \times 10^4$; and (e) $Re = 6.08 \times 10^4$

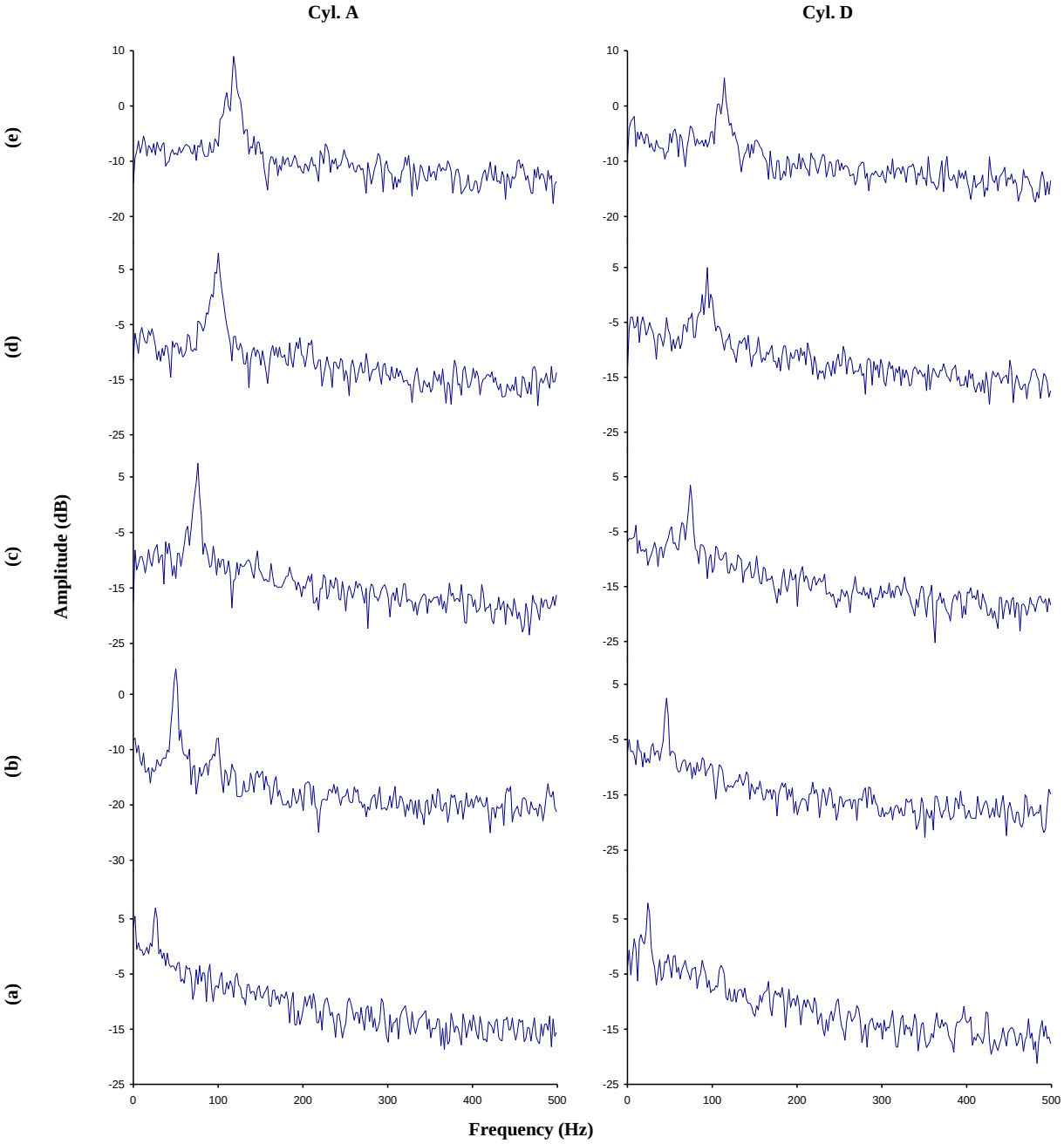


Fig. 20. The amplitude spectrum of the hot-wire signal for $l/d = 3.5$: (a) $Re = 1.26 \times 10^4$; (b) $Re = 2.53 \times 10^4$; (c) $Re = 3.80 \times 10^4$; (d) $Re = 5.06 \times 10^4$; and (e) $Re = 6.08 \times 10^4$

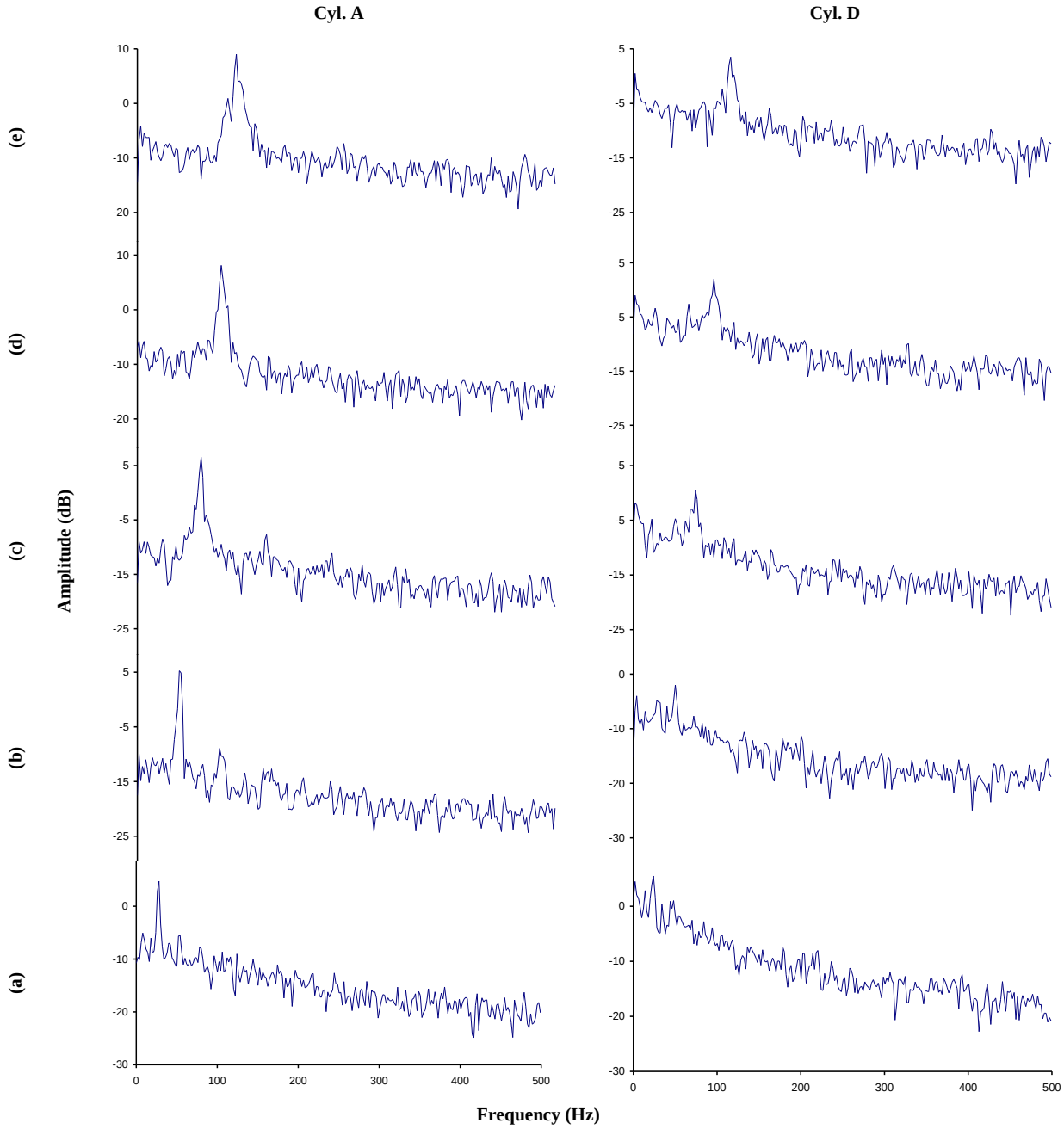
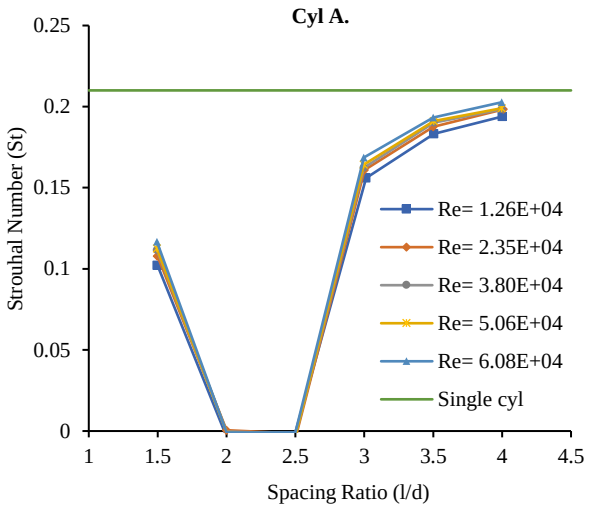
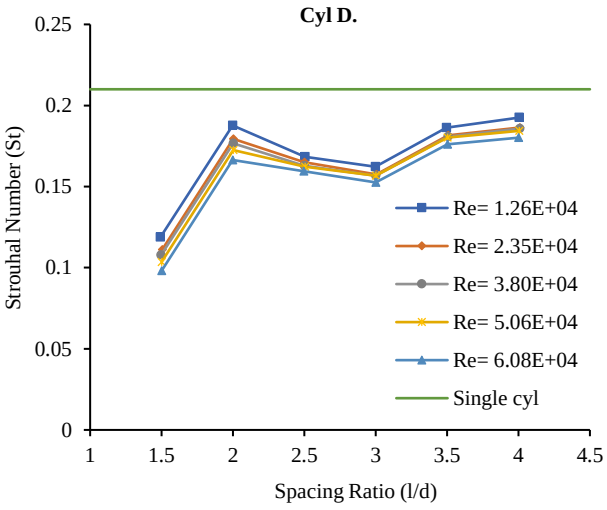


Fig. 21. The amplitude spectrum of the hot-wire signal for $l/d = 4$: (a) $Re = 1.26 \times 10^4$; (b) $Re = 2.53 \times 10^4$; (c) $Re = 3.80 \times 10^4$; (d) $Re = 5.06 \times 10^4$; and (e) $Re = 6.08 \times 10^4$



(a)



(b)

Fig. 22. The variation of the Strouhal number (St) with l/d: (a) cylinder A; and (b) cylinder D

CONCLUSIONS

Flow interference between four circular cylinders in a square arrangement was investigated when subjected to a cross-flow. For this purpose, the mean force coefficients and the Strouhal numbers for six spacing ratios (l/d) varying from 1.5 to 4 were measured experimentally at five subcritical Reynolds numbers of 1.26×10^4 to 6.08×10^4. Some useful conclusions are obtained and they are summarized as follows:

1- When the four cylinders are arranged in the current configuration, upstream cylinders A and B exert a repulsive force on each other which weakens by increasing l/d. Moreover, for $l/d = 1.5$, due to the severe flow interference between cylinders, there is a difference between the lift coefficients for upstream cylinders A and B.

2- The downstream cylinders experience lower mean drag coefficients than that of the upstream cylinders. Also, the minimum drag coefficient values for the upstream cylinders occur at $l/d = 3$. On the other hand, by increasing l/d, the mean drag coefficients for downstream cylinders are increased. It is notable that for $l/d \leq 2$ these coefficients are negative.

3- At $l/d = 1.5$, it is found that due to severe flow interference between the cylinders, there are two different Strouhal numbers for each cylinders which states simultaneous shedding of two different types of vortex from these cylinders.

4- For $l/d = 2$ and $l/d = 2.5$, there is no vortex shedding from the upstream cylinders, so the Strouhal numbers for these two cylinders are $St = 0$. Moreover, in these cases, the fluctuating force frequency acting on each cylinder is equal to the frequency of vortex shedding from the same cylinder.

5- It is found that the effects of variations in Reynolds number, at high subcritical range (1.26×10^4 to 6.08×10^4), on the quality of vortex shedding as well as Strouhal numbers are weak and negligible. Therefore, it can be concluded that the variations in this range of Reynolds numbers weakly affect the flow pattern around the cylinders; whereas the effects of variations in l/d, on the flow pattern around the cylinders and aerodynamic coefficients are strong and significant and also by decreasing the l/d, the effects of the flow interference between the cylinders increase.

6- Increasing the distance between the cylinders, and so weakening the effects of the flow interference, somehow causes the same flow behavior around each upstream cylinder as that of around a single cylinder.

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