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An experimental study of the in-line oscillations of a closely spaced row of cylinders in cross-flow

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Abstract

An experimental study has been carried out, to examine the vibratory motion in the streamwise direction of a closely spaced row of circular cylinders. The cylinders in the flexible row under study, free to respond in-line with the flow, are placed alternately between cylinders of a fixed row in a water channel. The transverse spacing of the cylinders of the same row was 3 cylinder diameters, yielding a cylinder spacing when the two rows were aligned equal to 1.5 diameters. The experiments were carried out at low Reynolds numbers over a range from 700 to 1200. Each programme of measurements started when the flow velocity was maximum, and the flexible row was displaced at a small distance downstream of the fixed row. As the velocity was gradually decreased and the flexible row was moved to a mean position upstream of the fixed in-line oscillations occurred, whose amplitude, which was not constant at different cycles, was dependent on both the stream velocity and the initial displacement between the two rows. For each flow velocity, the time history of the oscillation of the moving row was recorded, from which the response and the frequency of oscillations were obtained and are presented diagrammatically.

Keywords: In-line oscillations; Cylinder row; Response; Oscillation frequency

1. Introduction

Being a typical example of fluid–structure interaction, as well as being important in the design of heat exchangers, the problem of vibration of cylinder arrays (or tube arrays) subjected to cross-flow has received a great amount of attention in recent years. There exist several excitation mechanisms that can cause cylinder vibrations: periodic vortex shedding resonance, turbulence-induced excitation (turbulent buffeting), fluidelastic instability and acoustic resonance. Of these, the self-exciting mechanism of fluidelastic instability is considered to be among the most important, especially from the point of view of damage occurring as a result of the vibration (fretting-wear, fatigue, tube failure).

In the general case of a cylinder array oscillation, the motion of individual cylinders may lead sometimes to abrupt changes in the flow pattern which, in turn, are associated with substantial variations in fluid force. Fluidelastic instability occurs when there is a positive feedback between structural displacements and resulting fluid forces acting in the direction of motion. In such a case, the energy provided by the fluid force exceeds the energy dissipated by damping.

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Nomenclature

A	oscillation amplitude
D	cylinder diameter
f	spectrum of oscillation frequencies
f_n	natural frequency of oscillation in air
f_w	oscillation frequency of the flexible tube row (fundamental frequency in case that other frequencies also exist)
k	spring stiffness coefficient
L_s	submerged length of cylinders
m	effective mass of each cylinder per unit length
m_e	effective mass of the moving cylinders/elastic support arrangement
n	mass parameter for each cylinder
Re	Reynolds number
S	mean displacement of the flexible tube row measured from the fixed row
S_0	initial spacing between the two rows in the streamwise direction
T	distance of the centres of adjacent cylinders (pitch)
U	flow velocity
U_{max}	maximum flow velocity in the channel
U_r	reduced velocity, defined as $U_r = U/f_nD$ or $U_r = U/f_wD$
x	instantaneous displacement of the flexible tube row measured from the fixed row
x'	instantaneous displacement of the flexible tube row from the mean oscillation position

Greek letters

δ	logarithmic decrement
ζ	damping ratio
ρ	fluid density

As a result, the vibration amplitude increases rapidly and, depending on the configuration of the array, may reach high values which can cause severe damage. Naudascher and Rockwell (1994) described this mechanism as a movement-induced excitation, i.e. a motion-dependent mechanism.

For an extensive overview of the variety of models, theories and design guidelines developed to describe and avoid fluidelastic instability, the reader is referred to the works of Païdoussis (1981), Price and Païdoussis (1984), Chen (1987), Weaver and Fitzpatrick (1988), Pettigrew and Taylor (1991), Blevins (1994) and Price (1995, 2002).

A significant contribution is that of Roberts' (1966), who conducted an experimental study in order to investigate the vibratory motion of a cascade of closely spaced circular cylinders. The cascade produces a series of contracting passages which, in principle, form a set of high velocity jets passing between the solid boundaries. When only alternate cylinders are allowed to move in unison in the streamwise direction, the jets issuing downstream of the cascade coalesce in pairs and switch, leading to a time-varying drag force which gives rise to and maintains oscillation.

To understand the dynamics of vibrating cylinders, it would be useful to consider first the steady flow through a stationary cascade of similar geometry. Based on the assumption that the flow field is periodic in the direction across the cascade, Roberts (1966) measured the drag coefficients on two half-cylinders and found that the cylinder with the narrow wake (upstream cylinder) experiences a greater drag than the cylinder with the wide wake (downstream cylinder). This result contradicts the generally accepted relationship between the wake width and the fluid dynamic force acting on an isolated cylinder. Also, from the fluid/structure interaction point of view, such a behaviour of the drag force would have a stabilizing effect, tending to align the cylinders of the cascade. Singh et al. (1989) obtained similar results, but for much lower Reynolds numbers, using a computational approach.

In reality, the phenomenon is more complex than the assumption of a series of flows past two half-cylinders. Zdravkovich (1987) reports that, for the simpler case of flow past two cylinders in a side-by-side arrangement, narrow and wide wakes are formed behind the cylinders when the pitch-to-diameter ratio, T/D, lies between 1.2 and 2.2, and the gap flow forms a jet biased towards the narrow wake. The biased jet can switch to the opposite side at irregular time intervals, and the narrow and wide wakes behind the tubes interchange (bistable flow). Zdravkovich and Stonebanks (1990) examined the flow past a single row and two staggered rows of tubes. They found that the biased gap flow was metastable and could switch intermittently. However, they concluded that the nonuniformity of gap flows was significant in the range $1.1 < T/D \leqslant 1.75$ and disappeared beyond $T/D = 2.1$. They also noted that the drag forces on the cylinders of the upstream row were higher than those of the downstream row, in agreement with the measurement conducted by Roberts.

Thus, the upstream row experiences a higher drag and, in case it is flexible, may start to move in the downstream direction, maintaining narrow cylinder wakes until it reaches a location downstream of the fixed one. At that point, jet switching occurs and the wakes widen, reducing the drag and driving each cylinder upstream. As the cylinders in the moving row are displaced upstream of the fixed ones, the wide wakes persist up to a certain streamwise location, where a sudden switch over to the narrow wakes occurs. In the region between the two switching points, the narrow or wide wake can be attached to either an upstream or a downstream cylinder (bistable situation).

Flows require a finite time to change due to inertia, hence the jet cannot alter its position in space instantaneously. Roberts (1966) found that the speed of jet switching is mainly influenced by the entrainment of the fluid along the separated shear layers. The same author suggests that jet switching may occur for reduced velocities, $U_r = U/f_w D$, sufficiently large, where f_w is the oscillation frequency, which allows adequate time for the switching to take place. The hysteresis introduced by the switch leads to positive work being done on the oscillating cylinders. The energy extracted from the flow is sufficient to offset damping forces and to sustain the motion.

The main focus of Roberts' study was the case of vibrations in which the mean position of the flexible cylinders was the same as that of the fixed cylinders (zero mean stagger). These vibrations were of the "hard-type", requiring an initial finite disturbance to induce a stable oscillation. However, he reports that high amplitude oscillations may also develop if the moving row oscillates about a mean position upstream of the fixed one, whereas the oscillation amplitude is considerably suppressed if the mean oscillation position lies downstream of the fixed row. The oscillations with mean displacement upstream of the fixed row could be of the "hard" or of the "soft" type, the latter developing without an initial disturbance, depending on the damping of the system. For low damping, soft oscillations could build-up to high amplitudes; for larger damping values there was the possibility of one soft and one hard, and for even higher damping only one hard oscillation occurred. In the regime where both soft and hard oscillations were possible a soft-type oscillation was observed, in which the flexible row was aligned with the fixed one when it reached the extreme downstream position. Thus, jet switching does not seem to be the mechanism that sustains this kind of oscillations.

In an attempt to provide further insight into these complicated phenomena, with emphasis on oscillations about a mean position upstream of the fixed row, an experimental study was carried out in a water channel, in order to examine the vibratory motion of a single, closely spaced row of circular cylinders in the streamwise direction. The cylinders of the flexible row, free to respond in the streamwise direction, are placed alternately between cylinders belonging to a fixed row. A direct numerical simulation was to be conducted at similar conditions as in the experiment, thus the experiment was designed in a way that would facilitate the computational simulation. The fixed row comprised four cylinders and the flexible row three cylinders in order to reduce the computational effort, keeping the extent of the computational domain at a minimum. In addition, in an attempt to keep the Reynolds number as low as possible, cylinders of only 3 mm diameter were used.

The initial flow velocity in each experiment was the maximum possible in the channel, and it will be denoted as $U_{\max}$. For that velocity the flexible row was downstream of the fixed one, remaining almost stationary at that initial position. Then, the flow velocity was gradually reduced, so that the flexible row would start to move upstream, passing through the gap between the fixed cylinders. The velocity reduction continued until the flexible row had moved far enough upstream of the fixed one and almost no oscillation was noticeable. For each flow velocity, the time history of the displacement of the flexible row over a long period was obtained. From these response traces the characteristics of the oscillations were evaluated, and are presented diagrammatically.

2. The experimental arrangement

The experiments were carried out in an open water channel 3 meters long, with a working section 0.61 m wide by 0.68 m deep, located in the Department of Aeronautics at Imperial College, London. A cascade of seven smooth metal cylinders of 3 mm diameter was used in the experiment. The cascade was mounted vertically above the channel and normally to the oncoming water stream. Following the definition sketch of Fig. 1, cylinders 2, 4 and 6 were free to move in the streamwise direction in unison, while cylinders 1, 3, 5 and 7 remained fixed. In order to achieve synchronized motion (in phase, with equal amplitude and frequency), separate support mechanisms were used for the fixed and flexible cylinder rows. Thus, cylinders 2, 4 and 6 were mounted vertically on a light horizontal shaft passing through an air-bearing system, as shown in Fig. 2. The required elasticity was achieved by mounting the supporting shaft on two leaf springs constructed from spring steel, in a similar manner to a previous study conducted by Anagnostopoulos and Bearman (1992), which examined the vortex-induced oscillations of a single cylinder. The leaf springs are shown schematically as simple springs in Fig. 2 for a clearer interpretation. Compressed air could be injected to the bearings, circulate through the groove shown in Fig. 2 and come out through the perforation drilled between the groove and the 6 mm diameter hole through which the supporting shaft was sliding. As long as there was no air supply to the air-bearings, the motion of the horizontal shaft was restricted due to friction. When the air-bearings were pressurized from an external compressed air supply, the shaft could move through the air-bearings, since there was no contact between

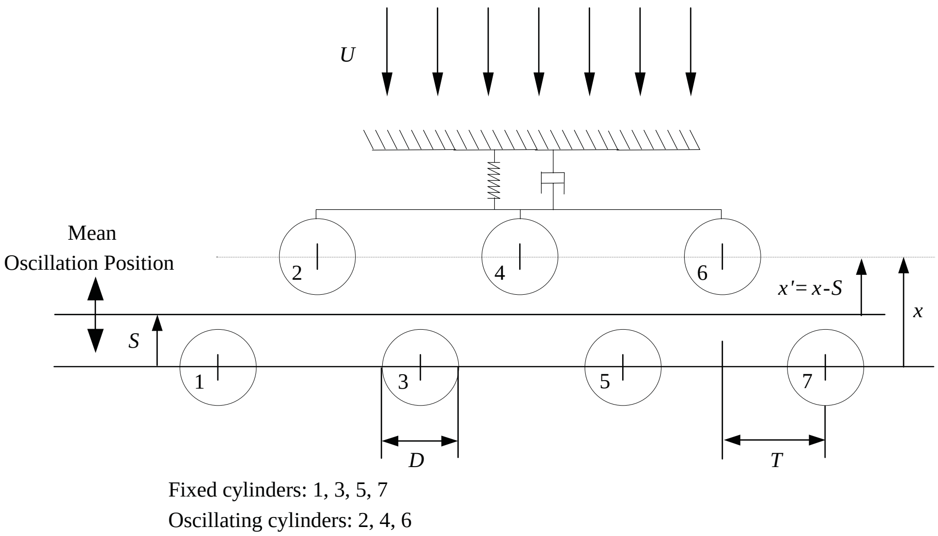


Fig. 1. A closely spaced cascade of cylinders, with alternate cylinders free to oscillate in unison in the streamwise direction. In the beginning of each experimental procedure the flexible tube row is displaced at a distance S_0 downstream of the fixed row. High amplitude oscillations occur when the flexible row oscillates about a mean position located at a distance S upstream of the fixed row of cylinders, as in the case depicted. The instantaneous displacement of the flexible row from the fixed one is denoted by x, and $x' = x - S$ is the displacement of the flexible row from the mean oscillation position. Throughout the paper, the displacement in the downstream direction is considered as positive.

the shaft and the air-bearings and friction was considerably suppressed. The structural damping of the arrangement was extremely small, allowing the streamwise response of the moving cylinders, even for a small exciting force. The response of the row was measured with a noncontact, electronic capacitance displacement transducer. The output signal was digitized and stored in a PC for further processing, and this then yielded the amplitude and frequency of the oscillating row.

A relatively simple system was used to support the fixed cylinders 1, 3, 5 and 7, allowing the adjustment of the initial (before the inception of the experimental procedure) longitudinal spacing, S_0, between the two rows.

The cylinders of each row had a transverse spacing equal to 3; thus, when the two rows were aligned, the ratio T/D became equal to 1.5. The submerged length, L_s, was 165 mm, giving an aspect ratio of 55. Due to the relatively high aspect ratio and low flow velocities we have assumed that we can safely disregard any free-surface effects. The mean flow velocity, U, was measured using a very accurate flow-meter built into the piping system supplying water to the channel. The velocity was controlled by adjusting the flow-rate while keeping the water level unchanged. Design parameters of the channel confined the maximum water velocity to a value of 0.41 m/s. Due to the small size of the cylinder array compared to the width of the channel, the blockage was negligible. Previous investigations (Obasaju et al., 1991; Anagnostopoulos and Bearman, 1992) using the same channel reported a turbulence level of up to 1.5%. The Reynolds numbers in the present experiment were kept deliberately low, significantly lower than in related studies, since one of the purposes of this study was the validation of the results of a numerical simulation at similar conditions to those in the experiment. This is the reason for using cylinders of such small diameter, although the small scale of the experiment imposed difficulty with the whole procedure and prohibited the measurement of hydrodynamic forces, even on the fixed cylinders.

The spring stiffness coefficient, k, was 31.5 N/m and the natural frequency of the oscillating row in air, f_n, was approximately 2.8 Hz. The damping ratio, ζ, determined from the formula $\zeta = \delta/2\pi$, where δ is the logarithmic decrement, was found to be 5.56×10^{-3}.

Due to the high aspect ratio of the cylinders, very stiff rods of stainless steel were employed, in order to avoid deflection of the cylinders along the span due to static hydrodynamic loading. To increase rigidity (minimize whirling) and to avoid deformation and possibly collision of the cylinders during the oscillation, two aluminium end-plates of 1 mm thickness were used to hold the cylinders of each row at a fixed position, relative to each other. The end-plate of the flexible cylinders had the shape shown in Fig. 3 and it was placed slightly above that of the fixed cylinders, which

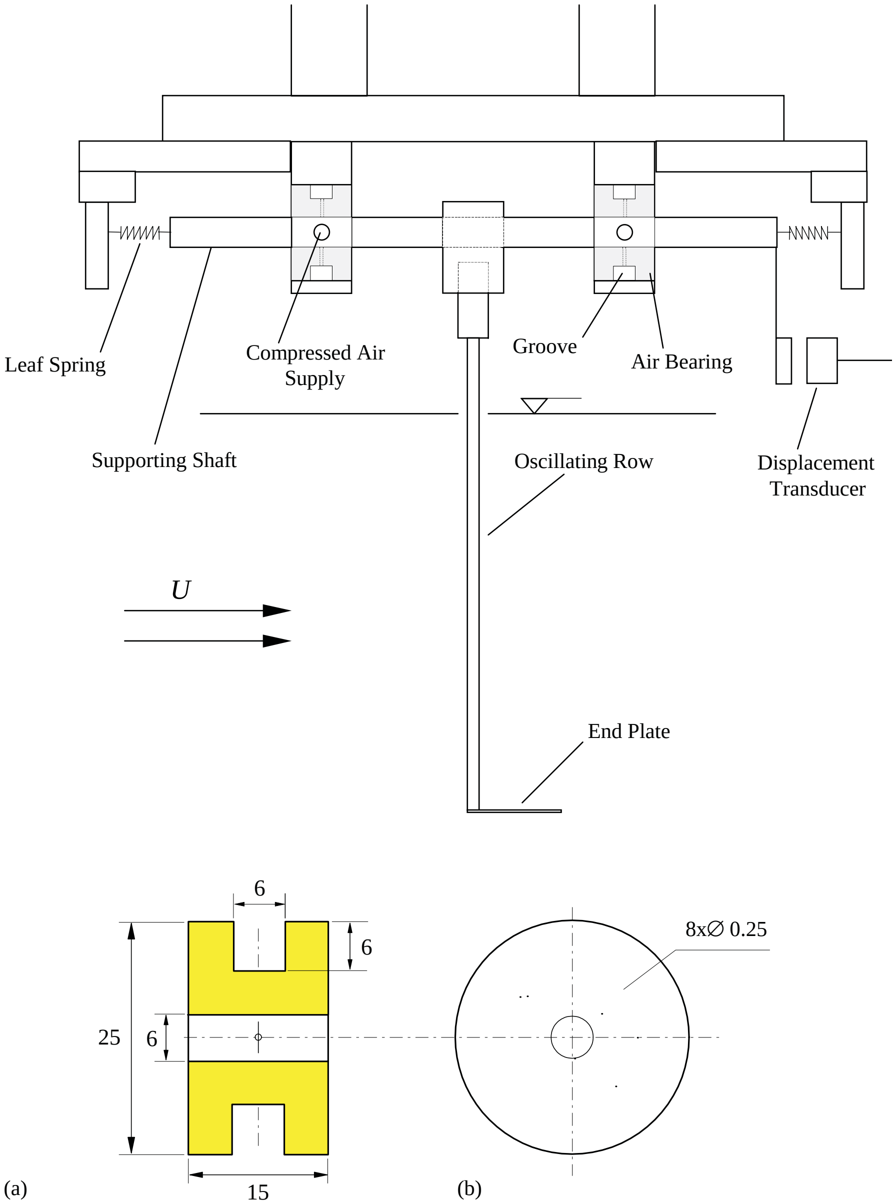


Fig. 2. (Top) The elastic support mechanism suspended over the water channel, and the row of flexible cylinders, that is free to move in-line with the flow (side view). The leaf springs on which the moving row of cylinders is mounted through the supporting shaft are shown schematically as simple springs. (Bottom) Enlarged view of the air-bearing system; (a) cross-section; (b) side view. The dimensions are in mm.

was of rectangular shape. All measurements regarding the estimation of the system natural frequency and damping were carried out with the end-plates attached to the cylinders.

The effective mass of the system comprising the moving cylinders and the support, m_e, was determined in terms of the spring stiffness and the natural frequency from the well-known formula $m_e = k/(2\pi f_n)^2$, and found to be 0.102 kg. The non-dimensional mass parameter, n, defined as $\rho D^2/m$, was equal to 0.04368 for each of the three cylinders of the oscillating row, where m is the effective mass of each cylinder per unit length. The mass-damping parameter, $m\delta/\rho D^2$, was equal to 0.8, a value significantly lower than those reported in Roberts' experiment, which lay in the interval between 200 and 5000.

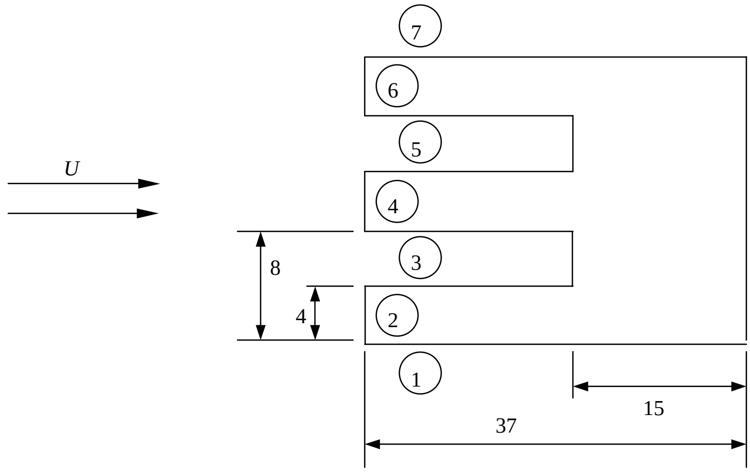


Fig. 3. The end-plate of the flexible cylinders. The dimensions are in mm. The end-plate of the fixed cylinders was placed slightly below that of the flexible cylinders, and it was of rectangular shape.

3. Experimental procedure and data acquisition

Initially only the flexible row was mounted in the channel. Once the air-bearings were pressurized, the row was free to move in the streamwise direction under the hydrodynamic load introduced by the flow stream of velocity U. For each flow velocity, the row was displaced downstream at a position where the net force acting on it was zero, since the drag force acting on the cylinders was balanced by the force exerted by the springs. An increase of the flow velocity yielded a higher hydrodynamic load and a greater deflection of the spring-mounted row. The location of the flexible row at the largest streamwise deflection obtained for maximum flow velocity was taken as the initial position from which all sets of experimental procedures initiated.

The experiments were started at the maximum velocity such that for U_{max} the flexible row was always downstream of the fixed one. Thus, when the maximum deflection of the moving row was accomplished for U_{max}, the fixed row was mounted. As mentioned earlier the initial longitudinal spacing between the two rows, S_0, could be adjusted. After the initial set-up of the two rows, the flow velocity was gradually reduced, so that the flexible row would start to move upstream passing through the gap between the fixed cylinders and eventually oscillate due to the interaction with the fixed row. The velocity reduction continued until the flexible row had moved far enough upstream of the fixed one and no oscillation was notable (the row became stationary again).

During preliminary tests conducted in order to investigate the main features of the phenomenon, it was observed that: (a) marked oscillations occurred only when the mean position of the flexible row was upstream of the fixed one, whereas the flexible row remained practically stationary when it was displaced downstream of the fixed row, and (b) for a constant flow velocity, both the average distance of the oscillating row from the fixed one, S, and the oscillation amplitude, were dependent on the initial displacement between the two rows, S_0.

Data collection was started for U_{max} and it was continued for the whole range of velocities examined. The oscillatory response of the flexible row was not at a constant amplitude, therefore each time record was of sufficient length to predict accurately the oscillation parameters.

4. Results and discussion

Four sets of measurements were performed, for values of S_0/D equal to 0.08, 0.14, 0.15, and 0.16. As noted earlier, the mean location S/D of the oscillating row relative to the fixed one is a function of the free-stream velocity and of the spacing S_0/D. For each flow velocity, the time history of the response of the oscillating row was obtained. From each response trace the mean displacement, S/D, was determined, and the average oscillation amplitude and the r.m.s. value of the normalized in-line response, $x'_{r.m.s}/D$, equal to $(x-S)_{r.m.s.}/D$, were also evaluated.

The position of the centres of the fixed cylinders was taken as the origin of the x-axis, and this axis coincided with the streamwise direction. For displacement, the downstream direction was taken as positive.

Some characteristic traces of the response of the flexible row are displayed in Fig. 4 for $S_0/D = 0.08$, and in Fig. 5 for $S_0/D = 0.16$. Although the recording period was rather long for each flow velocity, equal to 200 seconds, a typical part of the record for an interval of 50 s has been selected for presentation in each case. However, the entire record was considered for the determination of the oscillation parameters. We should mention that the reduced velocity, U_r, quoted in this section is based on the natural frequency of the system, f_n, and not on the actual frequency of oscillation, f_w.

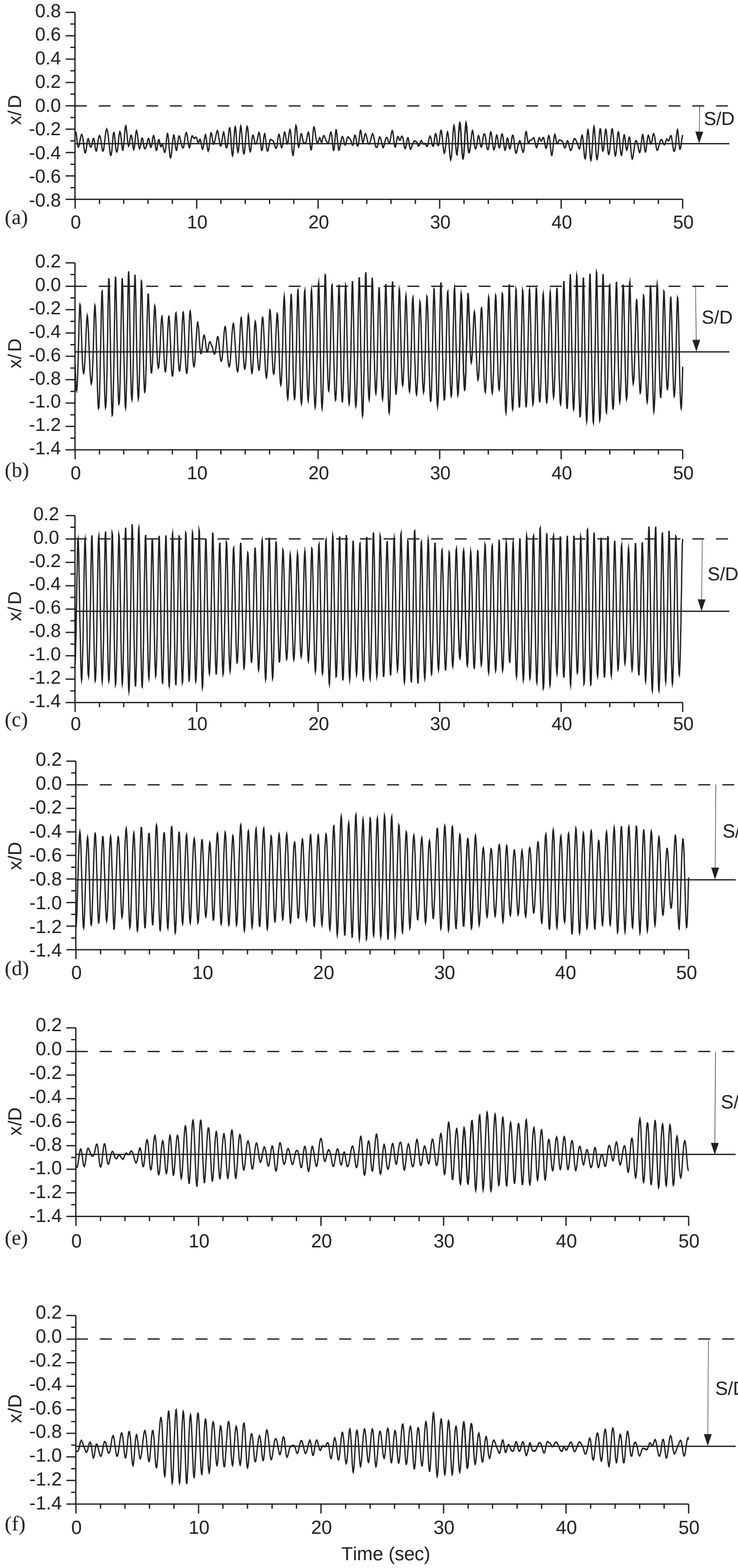
The record of Fig. 4(a) at $U_r = 40.35$ and Re = 1019 illustrates a case of low amplitude oscillations, upstream of the fixed row. The maximum amplitude is 17% of a diameter and $S/D = -0.32$, thus the minimum distance between the rows is 15% of a diameter. The trace of Fig. 4(b) at $U_r = 38.85$ and Re = 981, where high amplitudes have been established, displays an intense modulation. The amplitude fluctuates from almost zero value at some cycles to values as high as 70% of a diameter. The trace portrayed in Fig. 4(c) at $U_r = 38.23$ and Re = 966, corresponding to the highest average amplitude recorded, is less modulated than that of Fig. 4(b). A common characteristic of the two records illustrated in Fig. 4(b,c) is that when the downstream displacement of the moving row becomes maximum, the moving cylinders are located slightly beyond the ones of the fixed row. In addition, the mean amplitude is slightly higher than the absolute value of S in each of the two records. The record of Fig. 4(d) obtained for $U_r = 36.21$ and Re = 915, shows an amplitude fluctuation between 30% to 55% of a diameter. Considering that the mean normalized position, S/D, is -0.806, it is evident that at the lower amplitudes the centres of the cylinders of the flexible row are almost aligned with the leading edge of the cylinders of the fixed row. On the other hand, in the cycles when the amplitude becomes maximum, the minimum distance from the cylinders of the fixed row is equal to 25% of a diameter. The record of Fig. 4(e) when $U_r = 35.70$ and Re = 902 shows an intense amplitude modulation, from very small values at some cycles, to values as high as 37% of a diameter. Considering that $S/D = -0.87$ for this case, it is deduced that at maximum amplitudes the centres of the cylinders of the flexible row are aligned with the leading edge of the cylinders of the fixed row. From the trace of Fig. 4(f) at $U_r = 35.18$ and Re = 889 it is apparent that the flexible row oscillates upstream of the fixed one, since the maximum amplitude is 30% of a diameter and $S/D = -0.91$.

The record of Fig. 5(a) at $U_r = 36.21$ and Re = 915 illustrates a case of low amplitude oscillations. Since the maximum amplitude is 13% of a diameter and $S/D = -0.388$, the minimum distance between the rows is 25% of a diameter. The trace of Fig. 5(b) at $U_r = 35.70$ and Re = 902 displays an intense fluctuation of the oscillation amplitude at different cycles. The maximum downstream displacement corresponds to the alignment with the fixed row. The record of Fig. 5(c) at $U_r = 34.71$ and Re = 877 represents the case of maximum mean amplitude. When the downstream displacement of the moving row becomes maximum, its position is slightly beyond the cylinders of the fixed row. The trace of Fig. 5(d) at $U_r = 33.11$ and Re = 836 shows a case in which the mean amplitude is reduced compared to the previous case of Fig. 5(c). In the cycles where the amplitude is minimum the centres of the cylinders of the moving row are aligned with the leading edge of the fixed cylinders, whereas, at large amplitudes, the distance of the centres of the cylinders of the moving row from those of the fixed cylinders becomes 20% of a diameter. The trace of Fig. 5(e) at $U_r = 32.60$ and Re = 823 shows that, at maximum amplitudes, the centres of the cylinders of the flexible row are slightly displaced downstream of the leading edge of the cylinders of the fixed row. The record of Fig. 5(f) at $\mathrm{U_r} = 31.56$ and Re = 797 illustrates a situation in which the flexible row oscillates upstream of the fixed one, since $S/D = -0.80$ and the maximum amplitude does not exceed 20% of a diameter.

Thus, for both values of the initial displacement, the response of the flexible row portrays similar characteristics. In all cases the displacement signal does not have constant amplitude. This is apparently an effect of the metastable character of the flow, a manifestation of which is the aperiodicity in the traces of the forces exerted on the cylinders at different cycles. Another characteristic is that when the downstream displacement of the moving row becomes maximum in the region of intense oscillations, which is the case depicted in Figs. 4(b,c) and 5(b, c), its location is slightly beyond the fixed row. This is in agreement with the traces of "soft-type" oscillations presented by Roberts, when the flexible row oscillates at a mean position upstream of the fixed one. Figs. 4(d) and 5(d) reveal that when the moving row reaches its extreme downstream position, its distance from the fixed row fluctuates between 20–25% and 50% of a diameter. On the other hand, Figs. 4(e) and 5(e) suggest that at the higher amplitudes, when the downstream displacement of the moving row is maximum, its distance from the fixed row is approximately 50% of a diameter (alignment with the leading edge of the fixed row).

The same conclusions may be drawn for the two remaining runs, namely for S_0/D equal to 0.14 and 0.15. The relevant traces obtained for the case in which S_0/D was 0.14 displayed greater similarities with those of the case $S_0/D = 0.08$, whereas the traces for the case $S_0/D = 0.15$ were closer to those obtained for $S_0/D = 0.16$, as will become evident from a cumulative diagram containing the r.m.s. response for each case.

The variation of the ratio S/D with the Reynolds number and the reduced velocity is illustrated in Fig. 6. We can see that for S_0/D equal to 0.08 and 0.14 the ratio S/D decreases continually with decreasing reduced velocity, due to the


x/D
S/D
(a)
(b)
(c)
(d)
(e)
(f)
Time (sec)

reduction of the mean drag exerted on the cylinders of the moving row. However, for S_0/D equal to 0.15 and 0.16, the flexible row moves back downstream after the alignment with the fixed row, which occurs for $S/D = 0$. After the repulsion, the ratio S/D decreases continually, as the Reynolds number is reduced. Thus, $S_0/D = 0.14$ is the maximum value for which the flexible row moves upstream, without returning downstream after the alignment with the fixed row. It can be seen that for $S_0/D = 0.16$, the flexible row is aligned again with the fixed one at Re = 1040. At the same Reynolds number the ratio S/D for $S_0/D = 0.08$ is equal to −0.25. Thus each initial spacing, S_0/D, yields a different mean stagger position, S/D, for the same Reynolds number, or, equivalently, a different Reynolds number occurs for a constant value of S/D.

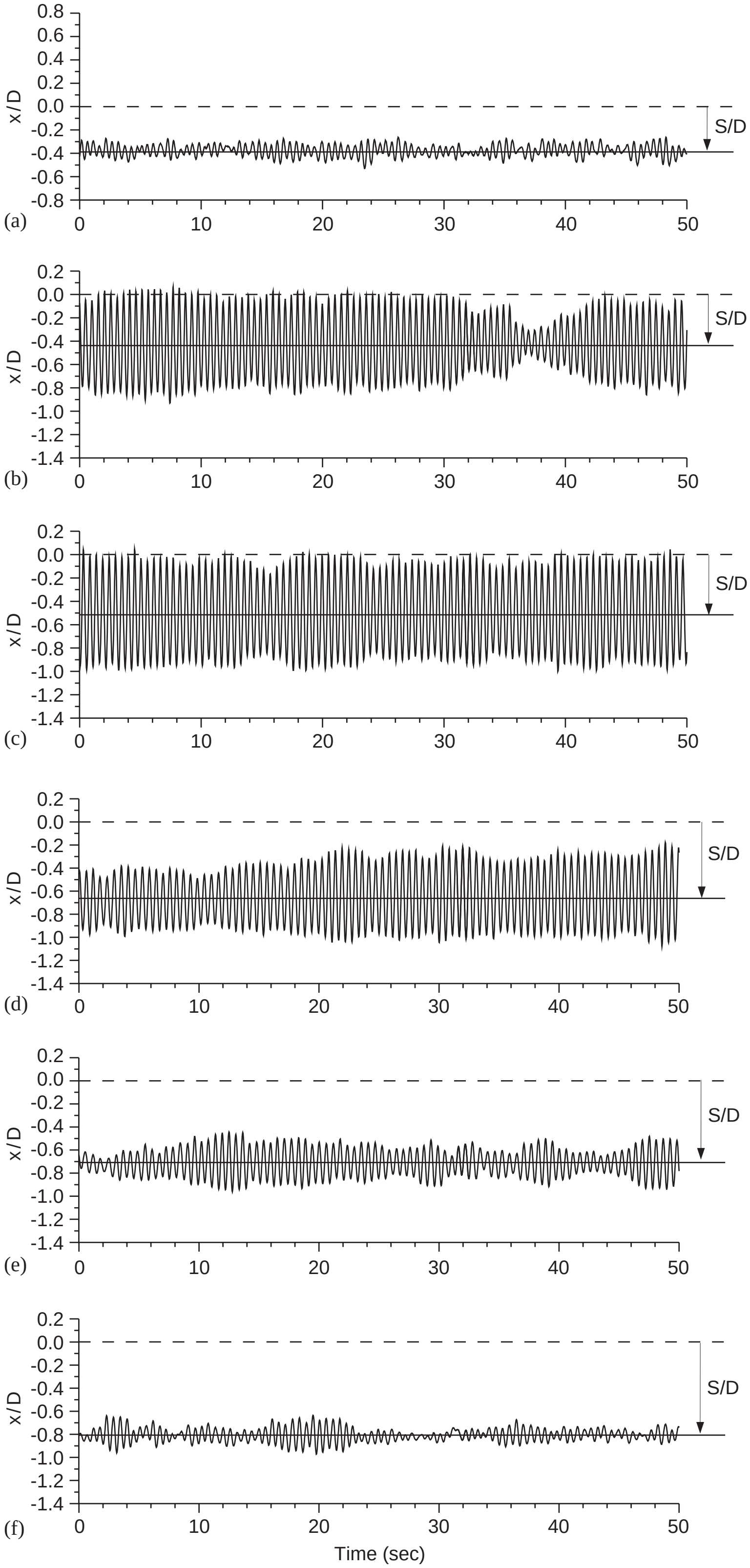
Since significant fluctuations of the oscillation amplitude were observed at different cycles of the same record, the r.m.s. value of the displacement from the mean position, S, was favoured for the evaluation of the response of the moving row, rather than the mean amplitude. The r.m.s. value of the dimensionless in-line response of the flexible row, $x'_{\text{r.m.s.}}/D = (x - S)_{\text{r.m.s.}}/D$, as a function of the Reynolds number and the reduced velocity, is shown in Fig. 7. Each response curve is bell-shaped and has a region of intense oscillations ($x'_{\text{r.m.s.}}/D > 5\%$), the extent of which depends primarily on S_0/D. For S_0/D equal to 0.08 and 0.14, the maximum value of $x'_{\text{r.m.s.}}$ is almost the same, although it occurs at a lower reduced velocity for $S_0/D = 0.14$. For values of S_0/D equal to 0.15 and 0.16, the maximum value of $x'_{\text{r.m.s.}}$ is significantly lower. The reduced velocity at which maximum $x'_{\text{r.m.s.}}$ occurs is lower for $S_0/D = 0.16$, compared to the case $S_0/D = 0.15$. It is evident from Fig. 7 that a slight increase in S_0/D from 0.14 to 0.15 confines the reduced velocity range of intense oscillations and reduces drastically the response. We will see shortly that this result is associated with the downstream repulsion of the flexible row after the alignment with the fixed, which occurs when S_o/D is increased from 0.14 to 0.15.

We can detect from Fig. 7 that the upper limit of Reynolds numbers for which intense oscillations occur increases as S_0/D is reduced. This can be interpreted in combination with Fig. 6, which dictates that the Reynolds number for which a constant value of the ratio S/D occurs is higher for smaller values of S_0/D. A sufficient upstream displacement of the oscillating row from the fixed one is required for the inception of intense oscillations. This critical displacement, corresponding to $S/D \approx -0.25$ in all cases, occurs for a higher Reynolds number as the ratio S_0/D is decreased. We can also notice that for S_0/D equal to 0.08 and 0.14, the maximum r.m.s. response occurs for equal values of S/D in both cases, although at a higher Reynolds number for $S_0/D = 0.08$. The same reasoning applies for the maximum r.m.s. response of the moving row for S_0/D equal to 0.15 and 0.16, which is lower compared to the cases for which S_0/D equals 0.08 and 0.14. It was shown previously that, in the region of intense oscillations, a significant parameter that controls the response is the mean displacement of the moving row, S/D, whose absolute value is very close to the mean oscillation amplitude. This absolute value was greater for the runs when S_0/D was equal to 0.08 and 0.14 than those for S_0/D equal to 0.15 and 0.16, in the region of maximum response.

For the determination of the oscillation frequency, power spectra were generated from the displacement records. Some samples for $S_0/D = 0.16$ are presented in Fig. 8. Fig. 8(a), generated from the trace of Fig. 5(a) at $U_r = 36.21$ and Re = 915, displays a fundamental frequency at $f/f_n = 0.69$, and its first harmonic at a lower level. Fig. 8(b), corresponding to the record of Fig. 5(c) at $U_r = 34.71$ and Re = 877, reveals the existence of the fundamental frequency at $f/f_n = 0.68$ and three harmonics. Fig. 8(c) generated from the trace of Fig. 5(e) at $U_r = 32.60$ and Re = 823 displays two harmonics in addition to the fundamental at $f/f_n = 0.62$, whereas Fig. 8(d) from the record of Fig. 5(f) at $U_r = 31.56$ and Re = 797 shows only the fundamental frequency. We should also note the existence of a component at a frequency equal to about five times the system natural frequency in all cases. A reasonable explanation for this frequency component, which is of low level in all cases, was not possible to be given.

The fundamental frequency of oscillation derived from the frequency spectra, whose contribution is much more important than the higher harmonics in all cases, is denoted as f_w. The variation of the frequency ratio f_w/f_n with the reduced velocity and the Reynolds number is shown in Fig. 9, and with the ratio S/D in Fig. 10. Fig. 9 illustrates that, for each set of experiments (constant S_0/D) the oscillation frequency decreases with the reduced velocity in the region of intense oscillations, and acquires its lowest value by the lower limit of that region. Then an increase occurs, as the reduced velocity approaches its lower values. Fig. 10 reveals a tendency for a collapse of the data obtained for different values of S_0/D, when S/D is the same. When the flexible row oscillates downstream of the fixed one at low amplitude, the oscillation frequency is very close, or even higher, than the natural frequency in air. A drop of the oscillation frequency occurs at S/D around -0.05, which becomes minimum for S/D between −0.8 and −0.9 and then experiences

Fig. 4. Time history of the in-line response for $S_0/D = 0.08$. (a) $U_r = 40.35$ and Re = 1019, $S/D = -0.32$ and $A/D = 0.15$; (b) $U_r = 38.85$ and Re = 981, $S/D = -0.56$ and $A/D = 0.59$; (c) $U_r = 38.23$ and Re = 966, $S/D = -0.62$ and $A/D = 0.63$; (d) $U_r = 36.21$ and Re = 915, $S/D = -0.80$ and $A/D = 0.38$; (e) $U_r = 35.70$ and Re = 902, $S/D = -0.87$ and $A/D = 0.18$; (f) $U_r = 35.18$ and Re = 889, $S/D = -0.91$ and $A/D = 0.14$. The amplitude, A, is the average value obtained from the entire records, and not from their parts depicted in Fig. 4.


(a)
(b)
(c)
(d)
(e)
(f)
x/D
S/D
Time (sec)
0
10
20
30
40
50

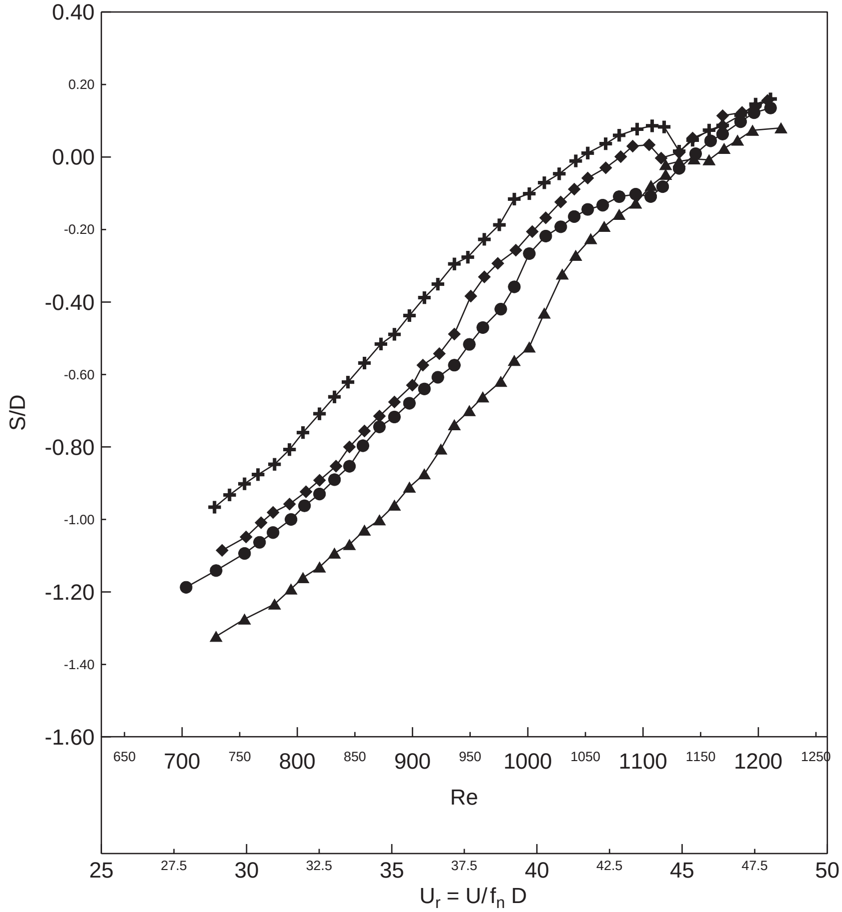


Fig. 6. Mean displacement of the flexible row of cylinders from the fixed row for the various sets of measurements. The positive sign denotes downstream displacement from the fixed row, and the negative sign displacement in the upstream direction. ▲, $S_0/D = 0.08$; ●, $S_0/D = 0.14$; ◆, $S_0/D = 0.15$; +, $S_0/D = 0.16$.

an increase, maintaining lower values than the natural frequency as the mean displacement between the two rows becomes larger. As mentioned previously, the cylinders of the upstream row experience a greater drag than the cylinders of the downstream row. When the flexible row oscillates upstream of the fixed tube row the drag force on the moving cylinders increases as the gap between the moving and fixed rows reduces. This "negative fluid stiffness" effect reduces the total system stiffness and therefore the frequency of vibration is reduced. When the flexible row is downstream of the fixed tube row the effective fluid stiffness is apparently positive, adding to the structural stiffness and therefore increasing the natural frequency of the system.

There seems to be a remarkable similarity to the simpler case of a plug valve studied by D'Netto and Weaver (1987), which Naudascher and Rockwell (1994) call a "press-shut" device, i.e., a device controlling the flow through small openings such that the fluid force tends to press them shut. These investigators found from a stability analysis that the driving mechanism is "negative fluid stiffness" which is a static instability, i.e., the stability threshold can be established from equations which do not contain the dynamic terms. "Press-shut" devices are unstable and lead to self-excited

Fig. 5. Time history of the in-line response for $S_0/D = 0.16$. (a) $U_r = 36.21$ and $\mathrm{Re} = 915$, $S/D = -0.39$ and $A/D = 0.09$; (b) $U_r = 35.70$ and $\mathrm{Re} = 902$, $S/D = -0.44$ and $A/D = 0.30$; (c) $U_r = 34.71$ and $\mathrm{Re} = 877$, $S/D = -0.52$ and $A/D = 0.48$; (d) $U_r = 33.11$ and $\mathrm{Re} = 836$, $S/D = -0.66$ and $A/D = 0.30$; (e) $U_r = 32.60$ and $\mathrm{Re} = 823$, $S/D = -0.71$ and $A/D = 0.16$; (f) $U_r = 31.56$ and $\mathrm{Re} = 797$, $S/D = -0.81$ and $A/D = 0.07$. The mean amplitude, A, was obtained from the entire record lengths.

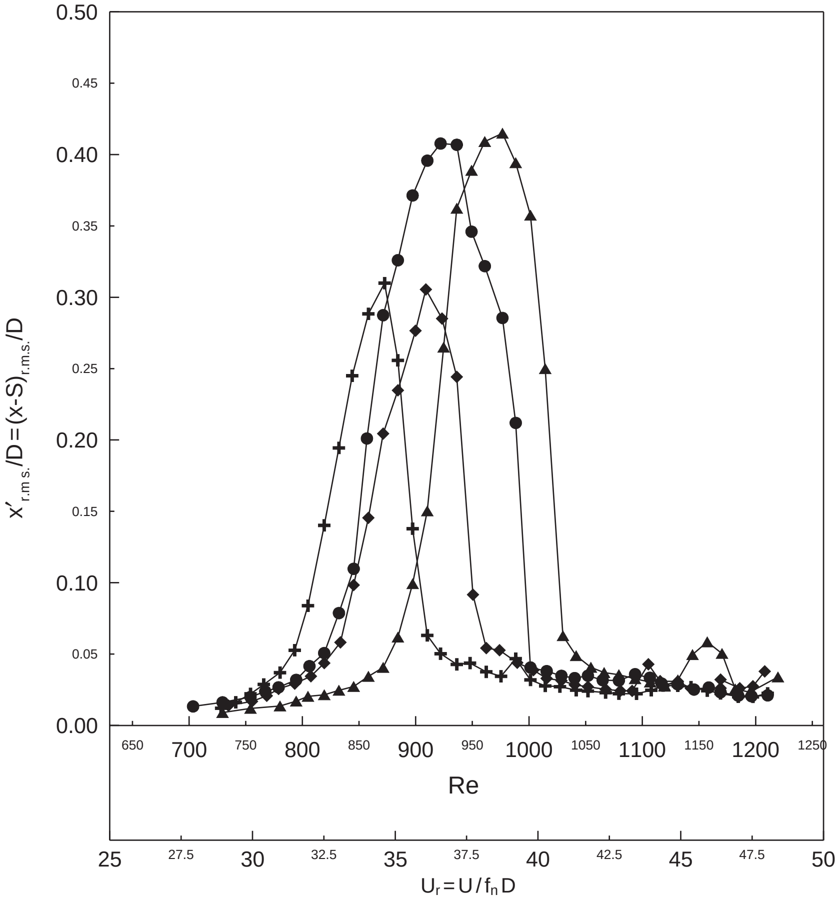


Fig. 7. Variation of the r.m.s. response of the moving row with the Reynolds number and the reduced velocity. ▲, $S_0/D = 0.08$; ●, $S_0/D = 0.14$; ◆, $S_0/D = 0.15$; +, $S_0/D = 0.16$.

vibrations. When the flexible row is downstream of the fixed tube row, the arrangement is a ‘‘press-open’’ device, and the system is stable.

Thus, a case of fluidelastic instability was obtained, in which the flexible row oscillates about a mean position lying upstream of the fixed row. The occurrence of jet switching is not justified even when the flexible row is displaced downstream of the fixed one as it performs oscillations of high amplitude, as happens in some cycles of the records depicted in Fig. 4(b) and (c). In the low amplitude cycles of the same records and in all cases in which the moving row is never aligned with the fixed one, like those depicted in Fig. 4(a,d,e,f), the existence of jet switching should be certainly precluded. Hence, the narrow-wide wake switch does not seem to be the mechanism that sustains the oscillations. Roberts, from experiments in which the moving row was forced to oscillate about a mean position which was the same as that of the fixed row, found that the cylinder motion and the drag force were in phase, thus jet switching is the only mechanism that provides energy to the oscillating row. When the moving row was forced to oscillate upstream of the fixed row, the time history of the drag force lags the cylinder motion, resulting in an extra amount of energy being supplied to the system, apart from that provided by the jet inversion process. Unfortunately, due to the small scale of the experiment, it was not possible to perform force measurements, even on the fixed cylinders. The results of the numerical investigation of the phenomenon with similar parameters as in the experiment, being close to completion, are expected to provide a better understanding to these issues.

Roberts derived, for the onset of oscillations around a zero mean displacement, an approximate equation calibrated from his experimental data, and he presented the results for mass-damping parameter values in the range between 1 and 10^6 in figure 31 of his study. This equation yields for $m\delta/\rho D^2 = 1$ a critical value of reduced velocity, $U_r = U/f_w D$, equal to 30. According to Fig. 7 the critical reduced velocity, $U_r = U/f_n D$, of the present work for $m\delta/\rho D^2 = 0.8$ corresponds to a value equal to 30. Considering from Fig. 9 that for $U_r = 30$ the ratio f_w/f_n ranges between 0.64 and

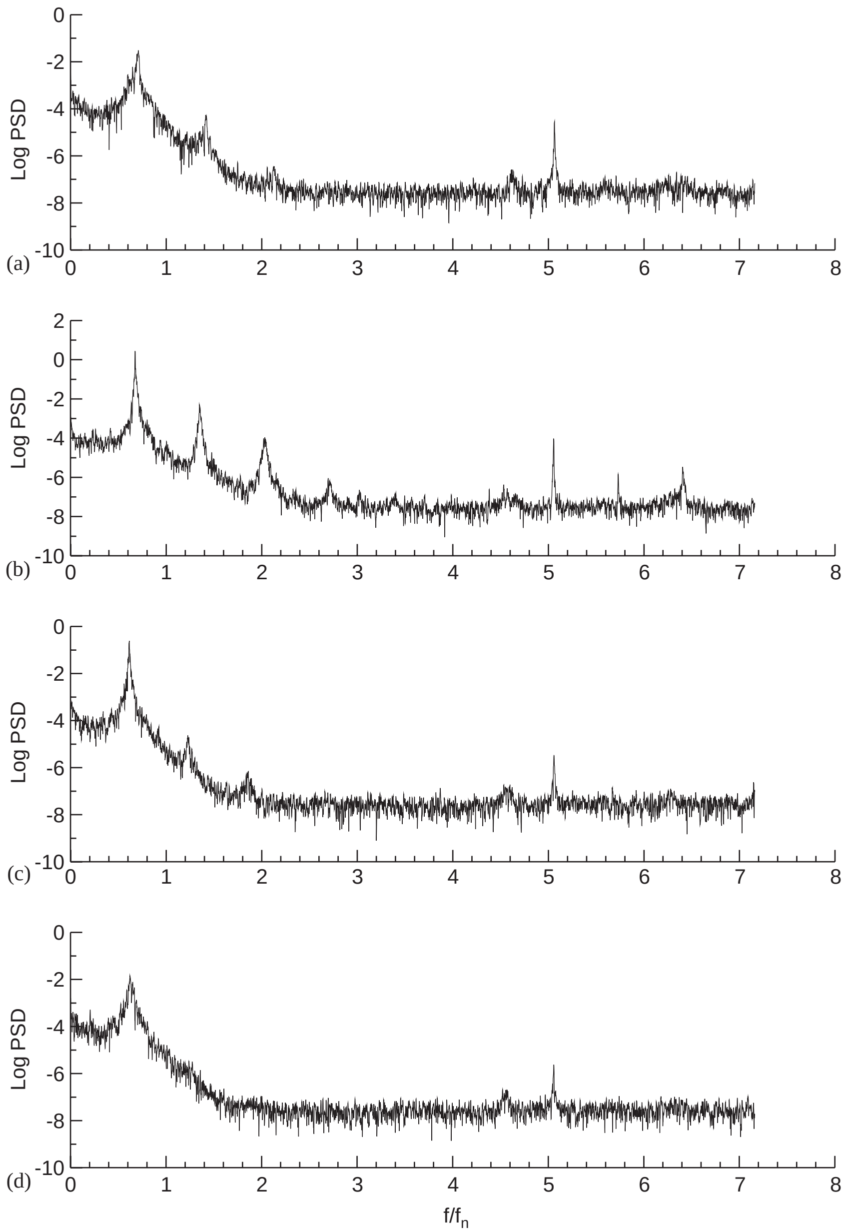


Fig. 8. Power spectra generated from response records displayed in Fig. 5 ($S_0/D = 0.16$). (a) $U_r = 36.21$ and Re = 915, Fig. 5(a); (b) $U_r = 34.71$ and Re = 877, Fig. 5(c); (c) $U_r = 32.60$ and Re = 823, Fig. 5(e); (d) $U_r = 31.56$ and Re = 797, Fig. 5(f).

0.86 for the various values of S_0/D, the critical U/f_wD of the present work lies in the interval between 35 and 47. Thus, in spite of the apparent differences in the excitation mechanisms in the two studies, the critical reduced velocities are of the same order of magnitude.

5. Conclusions

An experimental study was conducted, to investigate the vibratory motion in the streamwise direction of a single, closely spaced row of circular cylinders. The cylinders of the flexible row were placed alternately between cylinders of a

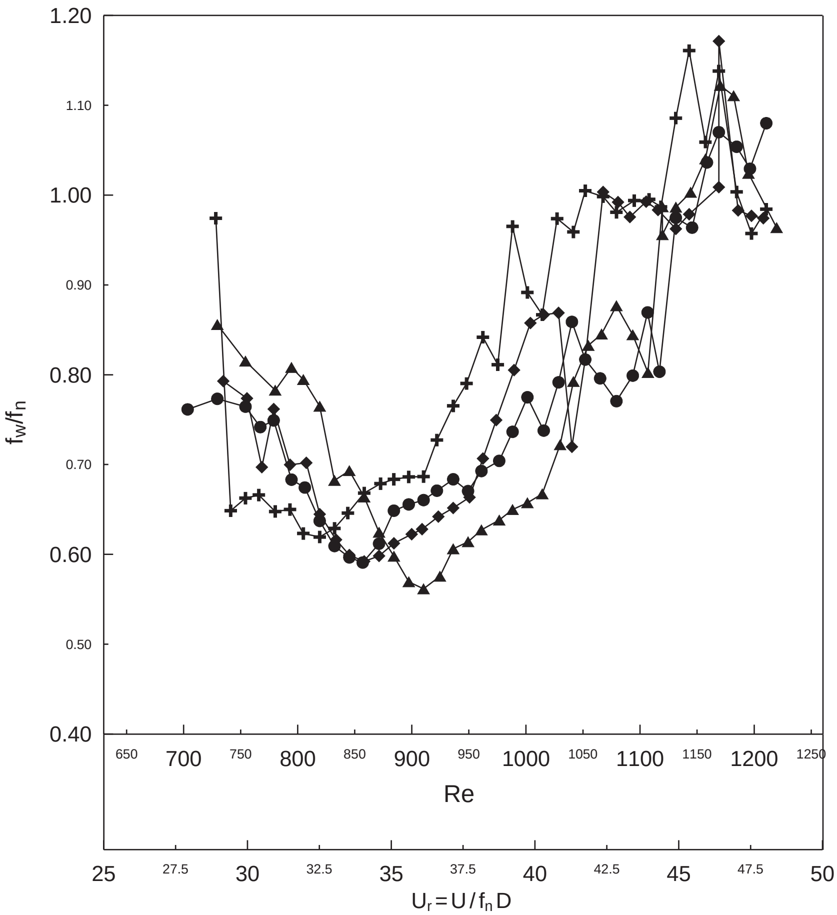


Fig. 9. Variation of the oscillation frequency with the Reynolds number and the reduced velocity. ▲, $S_0/D = 0.08$; ●, $S_0/D = 0.14$; ◆, $S_0/D = 0.15$; +, $S_0/D = 0.16$.

fixed row in a water channel. The experiments started when the flow velocity in the channel was maximum, and the moving row downstream of the fixed one. Marked oscillations of the flexible row were detected when the stream velocity was reduced, inducing displacement of its mean position at a sufficient distance upstream of the fixed row. The response amplitude of the moving row varied from cycle to cycle, requiring long time records for the determination of the mean amplitude, the r.m.s. response and the frequency of oscillation. The mean oscillation amplitude was gradually magnified as the stream velocity was reduced, and then started to decrease, after reaching a maximum. The initial displacement between the two rows was found to play an important role for the determination of both the range of reduced velocities for which intense oscillations occurred and the maximum response. In the range of reduced velocities in which high oscillation amplitudes occurred, the flexible row approached, or even was displaced beyond the fixed one, when it reached the extreme downstream position. However, over a wide range of velocities for which the mean amplitude was smaller, proximity of the oscillating cylinders to those of the fixed row was not attained.

Thus, jet switching does not seem to constitute the dominant mechanism that sustains the oscillations of the flexible row. Rather, it appears that the hydrodynamic interference between the two tube rows is the driving mechanism when the distance between the rows is smaller than a critical value. When the flexible tube row is upstream of the fixed row, the effective hydrodynamic stiffness is negative and static instability leads to limit cycle oscillations. When the flexible tube row is downstream of the fixed row, the effective hydrodynamic stiffness is positive and the system is stable.

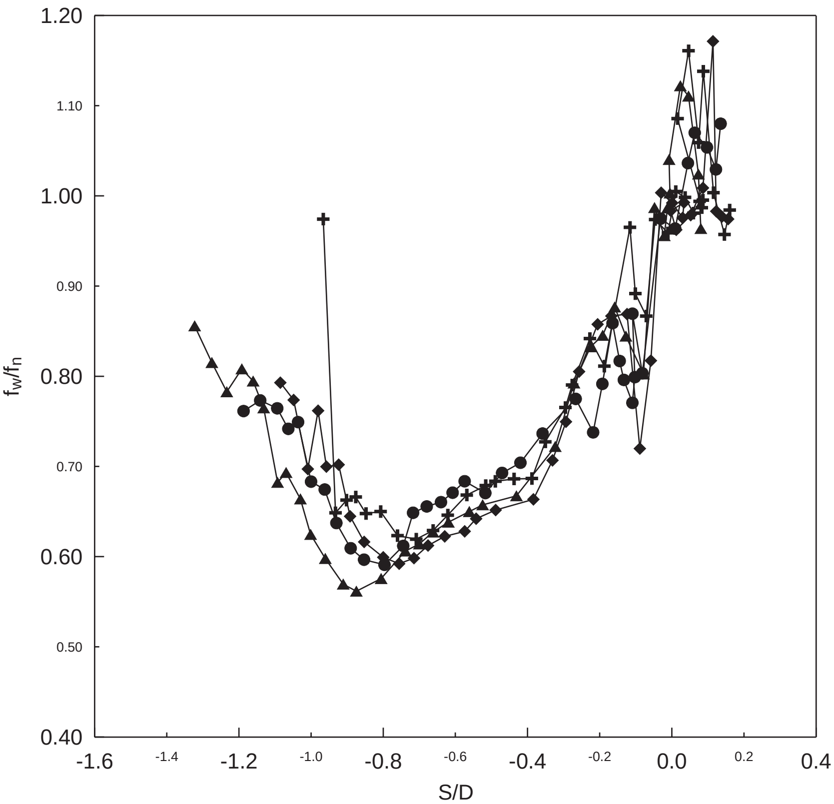


Fig. 10. Oscillation frequency as function of the mean displacement of the moving row. ▲, $S_0/D = 0.08$; ●, $S_0/D = 0.14$; ◆, $S_0/D = 0.15$; +, $S_0/D = 0.16$.

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