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Interference excitation of a square section cylinder

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Abstract

Wind tunnel experiments were conducted to study the interference excitation of a square section cylinder (test cylinder) and the results are reported in this paper. The study was carried out at some specific relative positions identified between the test cylinder (side dimension B) and the interfering cylinder (side dimension b) so that the latter is never upstream of the former. Experiments were carried out for the b/B ratios of 0.5, 1.0, 1.5 & 2.0. In this paper, emphasis is laid on bringing out the influence of b/B ratio on the vibratory response of the test cylinder, considering a few interference positions. The results show that at a particular relative position, the magnitude of vibrations and the response trend of the test cylinder are markedly influenced by the b/B ratio. Under certain combinations of b/B ratio, relative position and reduced velocity, test cylinder vibrations are considerably magnified and in certain other combinations they are suppressed. Flow visualization results are provided in an attempt to bring out the influence of b/B ratio and also to explain the observed vibratory features of the test cylinder.

Keywords: Flow-induced vibration; Relative position; Size ratio; Interference excitation; Flow visualization; Gap flow

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1. Introduction

Flow-Induced Vibration (FIV) of bluff bodies (structures) is of great practical interest in many fields of engineering because of the potential problems associated with this phenomenon. The practical significance of FIV can be markedly seen in the application areas such as heat exchanger tube bundles, buildings, bridges, marine risers etc., wherein a large number of research studies have been performed in the past. Among the bluff sections, the square section is one of the important sections from the aerodynamic point of view being widely employed in structures like buildings and bridges. Also, they seldom occur as isolated structures, but are constructed in groups especially in metro-cities where the wind effects could be very significant. Square sections are used in some of the mechanical engineering applications also, especially in off-shore structures (for example, in the support legs of off-shore jack up rigs where they appear in groups). Hence, it is very relevant to consider their aerodynamic characteristics both in isolation as well as under interference conditions. In this context, square section is chosen for a detailed aero-interference study in this paper. As vibratory response forms one of the major aerodynamic characteristics from the practical point of view, some of those literature contributions relevant to the present study are briefly described for a comprehensive review.

A square section is well known to undergo galloping besides vortex-induced vibrations. Possibly because of this reason, almost all of the studies reported were attempting to disclose various features of these two kinds of oscillation. Parkinson [1] describes different forms of wind-induced instability of structures with bluff sections (including square), including vortex-excitation and galloping. He specifically brought to light the aspect of variation in the configuration of shear layers and the corresponding pressure distribution on the side surfaces. This is a quite interesting result which could possibly explain the multiple am-

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plitude characteristics of a square section reported by Wawzonek [2] (given in Tamura and Shimada [3]). Vortex excitation and galloping were also studied by Nakamura and Tomonari [4] both in smooth as well as in turbulent flows. They could observe a close relationship between the onset of galloping and the peak characteristic of the steady drag coefficient. Parkinson and Sullivan [5] concluded that a square section could gallop at a velocity 2-3 times the resonance velocity for vortex excitation and that the amplitude would increase linearly with velocity as predicted by the quasi-steady theory. Quite interestingly, Parkinson and Wawzonek [6] suggested that a structure could experience the combined effects of these two kinds of oscillations, i.e., vortex excitation and galloping, at low Scruton numbers. This aspect has been clearly noticed in a recent work carried out by the present authors on isolated rectangular cylinders (but not presented in this paper). Bearman et al. [7] have observed that the parameter Uo/Ur (where Uo is the velocity at which galloping is initiated and Ur is the velocity at which system resonance with the wake vortex street takes place) strongly influences the spectrum of excitation. For a square cylinder, Hemon and Santi [8] could observe galloping oscillations at 10 deg. angle of incidence. For flow incident normal to the cylinder, or at zero angle of incidence, they could not locate galloping till a very high reduced velocity value of nearly 60 was reached. In the case of a galloping square section, Luo et al. [9] have shown that there could be intermittent reattachment of shear layers which would possibly lead to the existence of hysteresis in its vibratory response. For a square section, one of the prominent features is its fixed separation points unlike that of a circular cylinder. On the effect of separation points on the fluid-elastic excitation, Wang and Zhou [10] have conducted some interesting studies and results are reported. They have found that fixed separation points give rise to higher amplitude of vibration, for square, when compared to the case where they are movable, as for a circular cylinder. This is because, when the separation points are fixed, there is better spanwise coherence of vortex shedding [10]. Gowda and Kumar [11] also have observed that vibratory amplitude is higher for a square geometry than for a circular one.

On interference effects, literature provides only little information on the flow-induced oscillations of a square section cylinder. Bailey and Kwok [12] have pointed out that under interference conditions, gap flow is a significant factor influencing the oscillatory characteristics of the cylinders, changes in which could even lead to elliptical oscillations. Gap flow could be expected to be very significant in side-by-side arrangement between cylinders, and quite interestingly, Su et al. [13] have observed three modes of excitation (as authors describe, Mode A, Mode B and Mode C) for a pair of flexibly mounted identical square cylinders arranged in this configuration. Besides gap flow velocity, support stiffness also is reported (Su et al. [13]) to be very much contributing in deciding the mode of cylinder excitation. Takeuchi and Matsumoto [14, 15] have studied the vibratory response of tandem square cylinders, wherein they have shown that the vibratory response is very much influenced by the spacing ratio (W/B; W is the distance between the outer faces of the cylinders and B is the side dimension). It is to be specifically mentioned that in almost all of these investigations reported on interference effects, identical square sections are considered and the influence of size ratio (ratio of the sizes of cylinders) on the flow-induced oscillation is not studied.

Zdravkovich [16] and Gowda and Sreedharan [17] have given extensive results for the interference effects on a circular cylinder. Kumar and Gowda [18] and Gowda and Kumar [11] (hereafter referred to as G&A) have studied the interference excitation of a square section cylinder and have reported the vibratory response characteristics of a square cylinder (test cylinder) due to interference effects from another square placed in its vicinity (interfering cylinder). In Kumar and Gowda [18], the results on interference effects are reported only at a particular value of reduced velocity, viz., U/fB=10.0 and hence, the influence of reduced velocity is not revealed. In G&A, the results on interference effects are presented for b/B=0.5, 1.0, 1.5 and 2.0, where B is the side dimension of the test cylinder and b is that of the interfering cylinder (Fig. 2) covering 14 identified relative positions (see Fig. 1) and discussed over a range of reduced velocities. But, in this paper the influence of size ratio (b/B) is not specifically brought to light and discussed. For square sections under interference excitation, size ratio bears significant practical importance because the gap between the cylinders which would influence the near-wake flow pattern, changes considerably with b/B ratio. In the context that it is not dealt with elsewhere, it is felt that this aspect, i.e., the influence of b/B ratio, requires a special focus and

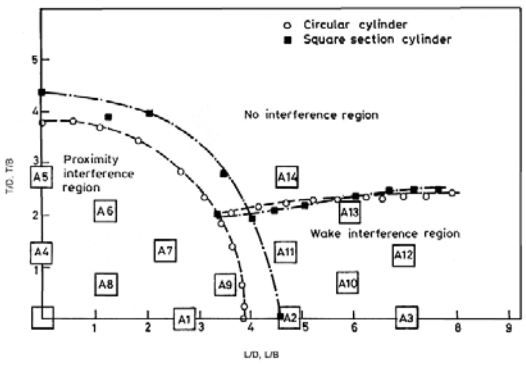


Fig. 1. The various flow regimes and arrangements tested (Gowda and Kumar [11]) (for circular cylinder, results are adopted from Zdravkovich [16]). Reference position, L/B, T/B: (a) A1, 2.35, 0; (b) A2, 4.70, 0; (c) A3, 7.07, 0; (d) A4, 0, 1.30 (e) A5, 0, 2.75; (f) A6, 1.175, 2.05; (g) A7, 2.35, 1.30; (h) A8, 1.175, 0.65; (i) A9, 3.53, 0.65; (j) A10, 5.90, 0.65; (k) A11, 4.70, 1.30; (l) A12, 7.07, 1.30; (m) A13, 5.90, 2.05; (n) A14, 4.70, 2.75.

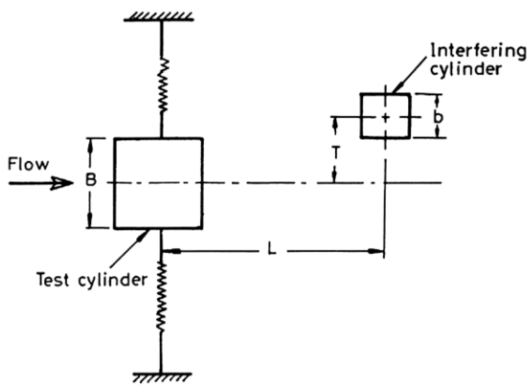


Fig. 2. Schematic sketch of the configuration tested.

hence is considered for discussion in this paper. At some typical positions, flow visualization results are also provided in an attempt to obtain better physical insight into the vibratory features, and in particular on the influence of b/B ratio.

2. Experimental set up

The arrangement is essentially the same as that used by Gowda and Sreedharan [17]. The experimental model features are the same as those described in G&A. However, some salient features are briefly given here for the sake of easy reference. The experiments were conducted on an aluminum tube with a square cross section of side 12 mm, wall thickness 1mm and length 140 mm. The cylinder was positioned vertically at the center of a rectangular frame supported by four identical springs. One of the springs supporting the cylinder was connected to a dynamic pickup (Type 8001; Bruel and Kjaer). The pickup was in turn connected to a storage oscilloscope (Type 1744A; Hewlett Packard) through a charge amplifier (Type 2626; Bruel and Kjaer). The oscilloscope was calibrated to measure the amplitude and frequency of the test cylinder vibrations. The cylinder was capable of vibrating in a direction transverse to the oncoming flow. The natural frequency and the logarithmic decrement of the spring-mounted cylinder were determined to be 54 Hz and 0.00368, respectively. The mass damping parameter k_s (Scruton number) is estimated to be 3.2 (a list of nomenclature is given in the Appendix).

The interfering cylinders were made out of solid aluminum rods with a smooth finish and square cross section, and side dimension ratios (b/B) of 0.5, 1.0, 1.5 and 2.0 were used. Further details are as given in G&A. The response of the test cylinder without any interference was first determined. Then, the interference studies were carried out by varying the flow velocity covering the entire resonance range. The range of Reynolds number referred to the test cylinder side dimension is between 3000 and 11000.

3. Results and discussion

3.1 Interference effects; influence of b/B ratio (vibratory results)

Prior to the interference studies, the response of the test cylinder without any interfering body was conducted. The details of single cylinder response are described in G&A (hence, not presented here to avoid repetition). As mentioned earlier, G&A have presented the vibratory results covering 14 identified relative positions. But, it is noteworthy that, not all 14 positions (namely, A1 to A14) are discussed in G&A, except for b/B=1.0. Furthermore, as indicated earlier, even though the vibratory response characteristics are presented at some selected identified positions, the influence of b/B ratio is not discussed in G&A. This paper is mainly aimed at filling this gap of information as is felt vital. Hence, in this paper, results (a/B Vs U/fB plots) at some selected identified positions (namely A13, A10, A8 and A3) are presented in Figs. 3(a)-(d) and discussed. It is to be specifically pointed out that the results at these positions are not presented and discussed elsewhere, and such an attempt is the first of its kind to reveal the influence of b/B ratio. In all the figures (Figs. 3(a)-(d)), single cylinder response [11] is also incorporated to bring out the interference effects and influence of size ratio more clearly. In Figs. 3(a)-(d), at each position, the vibratory results for all the b/B ratios are put together so as to conveniently discuss the influence of b/B ratio. Even though multiple amplitudes in test cylinder vibrations are observed for all the cases presented here, only the maximum amplitude values are considered and plotted in Fig. 3. For single cylinder response also, only the maximum amplitude values are shown in Fig. 3. Flow visualization results at some typical positions are also presented in an attempt to show the influence of b/B ratio.

At position A13 (L/B=5.9, T/B=2.05), it could be seen that (Fig. 3(a)), for all the b/B ratios, the test cylinder oscillation commences at around a reduced velocity value of 7.0. Further, it could be noticed that for b/B =0.5 and 1.0 (i.e., for b/B≤1.0), cylinder vibratory amplitude follows an increasing-decreasing trend similar to that of single cylinder case. For these cases, even though the vibratory trend is not notably affected due to interference effects, the maximum amplitude is seen to be higher than the single cylinder case. Whereas, for b/B=1.5 and 2.0 (i.e., for b/B>1.0), not only the maximum amplitudes, but also the trends are entirely different. Marked difference in the trend could be seen for U/fB>12.0, wherein the amplitude registers a steep increase followed by a nearly constant oscillatory level (for b/B>1.0) with a small dip at around U/fB=14.5. This is found to be somewhat similar to the response characteristics reported at position A1 [11] wherein amplitude once triggered is not returning to lower levels as the reduced velocity is increased (for b/B>1.0). The response observed at A13 for b/B≤1.0 is typically of vortex-induced vibration (self-limiting characteristic) and for b/B>1.0, quite possibly, the excitation mechanism is due to 'proximity-induced galloping' (Bokain and Geoola [19]; Gowda and Sreedharan [17]). To highlight further, composed with the response of the single cylinder case, considerable interference effects could be observed for the cases with b/B>1.0 wherein they do not exhibit a finite resonance range, unlike the cases with b/B≤1.0. However, it is noteworthy that the onset of oscillations is not significantly affected by the b/B ratio.

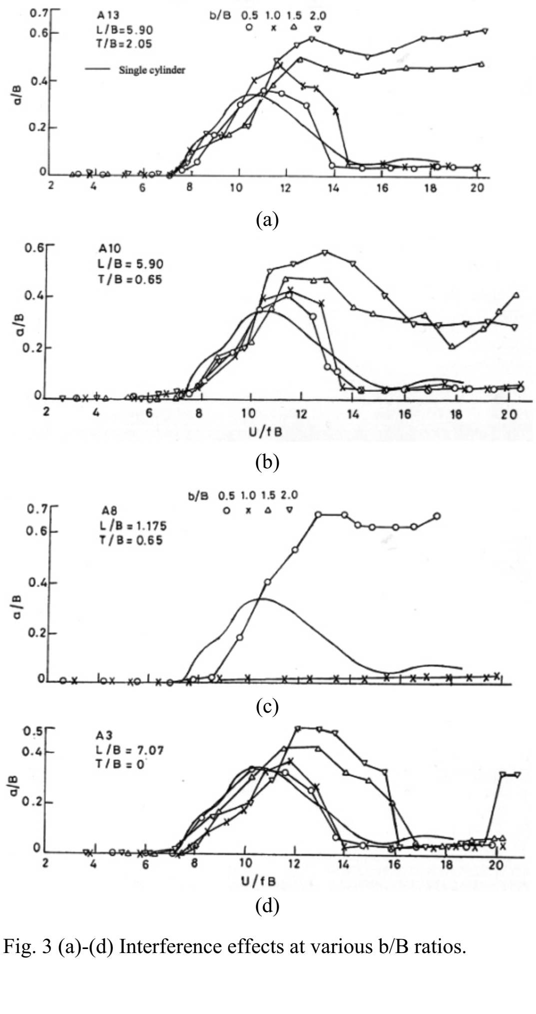


Fig. 3 (a)-(d) Interference effects at various b/B ratios.

At A10 (L/B=5.9, T/B=0.65) which is a slightly staggered position (Fig. 3(b)), the vibratory trends for b/B=0.5 and 1.0 are similar to that of the single cylinder case but with an early end of lock-in. As for position A13, in this case also, for these b/B ratios, the test cylinder amplitude is seen to undergo an amplitude magnification by about 30%. But for b/B=1.5 and 2.0 (b/B>1.0 cases), it can be seen that even the trends are markedly affected signifying intense interference effects. For b/B=1.5, quite interestingly, after an initial increasing-decreasing trend of amplitude in the range 6.5≤U/fB≤18.0, amplitude picks up a linearly increasing trend with reduced velocity. Whereas, for b/B=2.0, after the initial resonance range (6.5≤U/fB≤16.0), vibrations are sustained at a nearly constant amplitude level. Even after U/fB=16.0, oscillation of the test cylinder is not dying out and considerable amplitude persists for both these cases (b/B>1.0). As b/B ratio increases, the reduced velocity at which maximum amplitude occurs seems to shift towards the right. Also, the higher the b/B ratio, the higher is the maximum vibratory amplitude. Except b/B=0.5, at all the other b/B ratios, the test cylinder exhibits an early onset of oscillations. Furthermore, positions A13 and A10 are at the same tandem spacing with the transverse spacing shorter for the latter. Hence, the differences in the vibratory results typically show the influence of relative position on the cylinder excitation process, especially for U/fB>14.0.

As presented, in Figs. 3 (a)-(b), the test cylinder is seen to undergo an amplitude magnification due to interference effects that are severe for higher b/B ratios (>1.0). At some other positions, it has been observed that cylinder excitation is suppressed and, typically, one such case is presented here in Fig. 3(c). At this position (A8), the test cylinder amplitudes are found to be completely suppressed for b/B=1.0 in the entire range of reduced velocity tested. But, for a smaller b/B ratio (=0.5), the cylinder is seen to experience oscillations increasing almost linearly in the range 8.5≤U/fB ≤ 12.0 and exhibiting a nearly constant vibratory amplitude level thereafter. This position (configuration) is not possible to attain with b/B=1.5 and 2.0 and hence, these are not presented. At this slightly staggered position (A8), the cylinders are very close to each other. At some other closer positions A4 (L/B=0, T/B=1.3) and A6 (L/B=1.175, T/B=2.05) also, the test cylinder amplitudes are reported to be suppressed for b/B ratios other than 0.5 [11]. It is noteworthy that all these positions are characterized by small gap widths between the cylinders.

At certain configurations, even higher b/B ratios (b/B>1.0) seem to be not significantly influencing the test cylinder oscillations. Typically, Fig. 3(d) illustrates this point; at position A3 (L/B=7.07, T/B=0), the vibratory trend is not significantly altered for b/B>1.0 (compared to the single cylinder case). However, the interference effects are not completely absent at this position also and are marked by higher amplitudes at higher b/B ratios with a slight shift of maximum amplitude position towards the right (higher reduced velocity). This position is characterized by a relatively large gap width between the cylinders.

Figs. 4 and 5 are based on the vibratory results obtained at all the 14 positions identified (Fig. 1). In Figs. 4(a)-(d), the value of the magnification factor (M) for various b/B ratios at each arrangement is plotted; M is defined as follows:

$$M = \frac{(a/B)_{max} \text{ with interference}}{(a/B)_{max} \text{ for isolated cylinder}}$$

From Fig. 4, it can be seen that in the tandem arrangement (Fig. 1, A1 to A3), the maximum oscillatory amplitude could be nearly three times that for the isolated cylinder. In general, the magnitude of this peak amplitude value and the corresponding reduced velocity increase with b/B ratio, in all the tandem positions tested. For side-by-side arrangement (A4 and A5), the magnification of the oscillations is not that severe when compared to the tandem arrangement; A4 exhibits the least magnification among all the positions. Among the staggered arrangement positions, A9 exhibits the highest magnification, and positions A10 and A12 are seen to exhibit relatively low values of M.

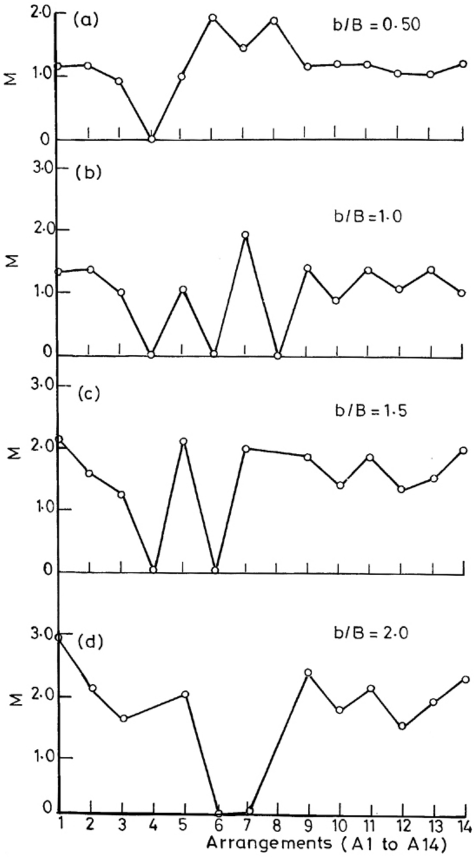


Fig. 4. Magnification factors for various b/B ratios at different arrangements.

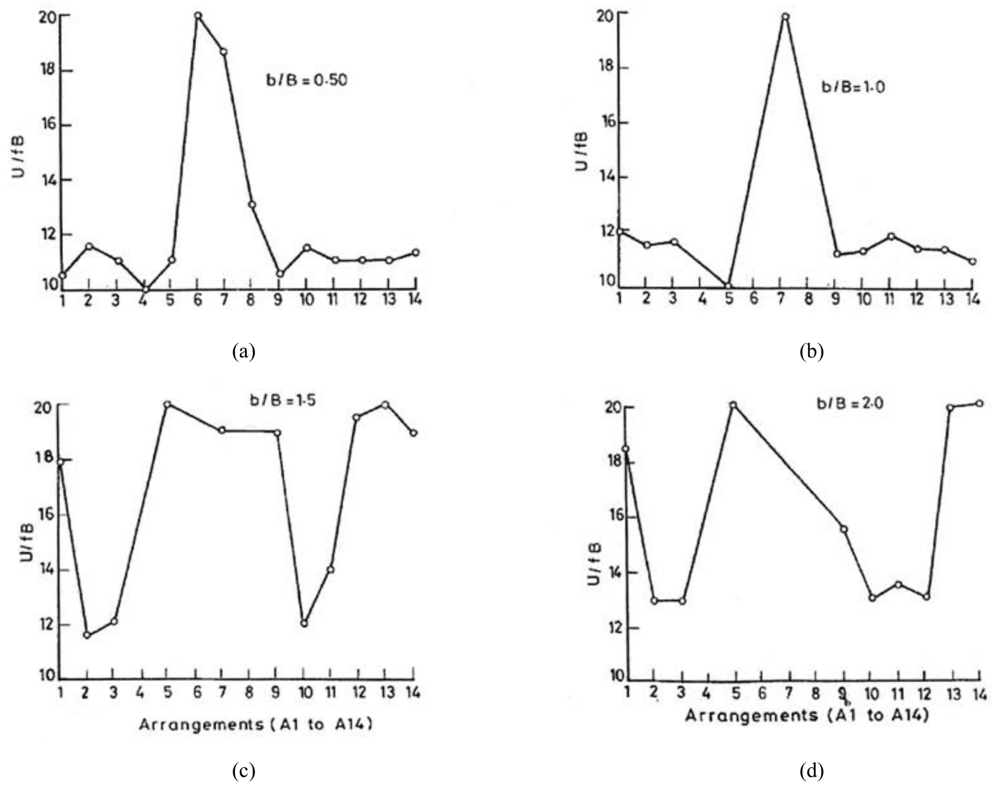


Fig. 5. Reduced velocities corresponding to peak amplitude for various b/B ratios at different arrangements.

One of the aims of this set of experiments was to find out whether the peak amplitude in the cases of interference occurs at any velocity other than that corresponding to the peak amplitude of the isolated cylinder case. With this view, Fig. 5 was plotted which shows the variation of reduced velocity (at which maximum amplitude occurs) with b/B ratio at various relative positions. The maximum amplitude occurs at values of U/fB higher than 10.0; U/fB=10.0 corresponds to the maximum amplitude for an isolated square cylinder [11]. Further, in general, the reduced velocity at which the maximum amplitude occurs is higher for b/B=1.5 and 2.0 (i.e., for b/B>1.0) compared to other b/B ratios (b/B≤1.0). Also, for b/B>1.0, the influence of b/B is felt at a greater number of relative positions, showing a higher reduced velocity for the occurrence of maximum amplitude. It can be seen that (Fig. 5), in general, among all the positions tested, the maximum amplitude is occurring at high reduced velocities at the staggered position A7 and is occurring at low reduced velocities at the tandem positions A2 and A3, irrespective of b/B ratio.

It is worth mentioning that the kind of information provided by Figs. 4 and 5 on interference excitation could be used for practical applications. Typically, in the case of building excitation (for example, high-rise buildings in metro-cities), it could be used in deciding the suitable size ratio and configuration (between buildings) with respect to the existing wind conditions. This is true in the case of square sections utilized in mechanical engineering applications also. As the present results point out (typically at positions A13 and A10), a combination of higher b/B ratio (b/B>1.0) with higher reduced velocity condition (U/fB>12.0) could prove fatal to an upstream square structure under interference excitation, and it is always advisable to avoid such critical combinations from the structural safety point of view.

The response of the test cylinder (Figs. 3 (a)-(d)) can, in general be attributed to the influence of the interfering cylinder on the vortex shedding process and on the flow field around the former coupled with the change in the configuration of the shear layers. Typically, these flow field changes due to interference effects are brought to light in the ensuing section at some selected interference positions.

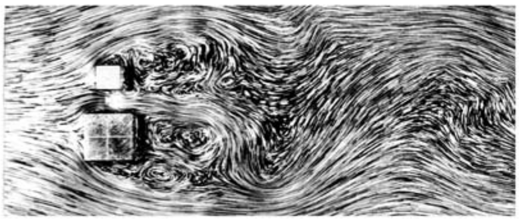
3.2 Flow visualization results

Flow visualization experiments were carried out for the various arrangements by using two solid (and rigid) square cylinders to obtain some insight into the changes in the flow field that occur and their possible influence on the observed response of the test cylinder. The experimental set-up is essentially that used by Kumar and Gowda [18]. The fluid used is water, and fine aluminum powder was used as tracer particles. Experiments were conducted at a Reynolds number of 5200 (with the test cylinder side dimension of 30mm), which corresponds to a reduced velocity at which maximum amplitude occurs for the single cylinder [11]. Tests were conducted for different b/B ratios: 0.5, 1.0, 1.5 and 2.0. The results at some typical positions are presented in Figs. 6 and 7. Flow visualization experiments were carried out at different b/B ratios with stationary cylinders. All these studies have been carried out at a velocity which gives a reduced velocity of U/fB=10.0. This could be considered as a limitation, as the vibratory responses at various relative positions extend over a range of velocities. In spite of this limitation, the results do give a better physical insight into the features of the flow-induced vibratory phenomenon and, in particular, the influence of b/B ratio. In what follows, these results are presented and discussed.

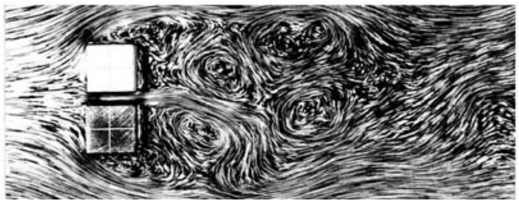
The flow visualization experiments are presented in the form of photographic plates. For the tandem and staggered arrangements, the upstream cylinder represents the test cylinder in air experiments, and in the side-by-side arrangement the test cylinder is represented by the lower cylinder.

Similar to the vibratory results, these results (flow visualization) are also presented here at some typical positions with the same primary objective, i.e., to bring out the influence of b/B ratio.

Figs. 6(a)-(b) show the flow patterns obtained at position A4, which is a side-by-side configuration (T/B=1.3) falling in the proximity interference region (Fig. 1), where, the cylinders are situated in close proximity. At this position, the vibrations are completely suppressed for b/B=0.5, 1.0 and 1.5 (Fig. 4); b/B=2.0 is not possible for this configuration. Typical flow visualization results are presented for b/B = 0.5 and 1.0. In Fig. 6(a) (b/B=0.5), the flow pattern indicates the existence of a strong gap flow pushing the vortex formed by the top shear layer away from the lower cylinder (test cylinder in air experiments) and also stretching this vortex in the longitudinal direction, making it more disorganized. The gap flow observed is biased towards the lower cylinder, reducing its wake width and disrupting the vortex shedding process. This indicates the possibility of very low lift production in the flow field, giving rise to only negligible amplitudes of vibration. Correspondingly, $(a/B)_{max}$ = 0.01 (M=0.03; Fig. 4 (a)).



(a)

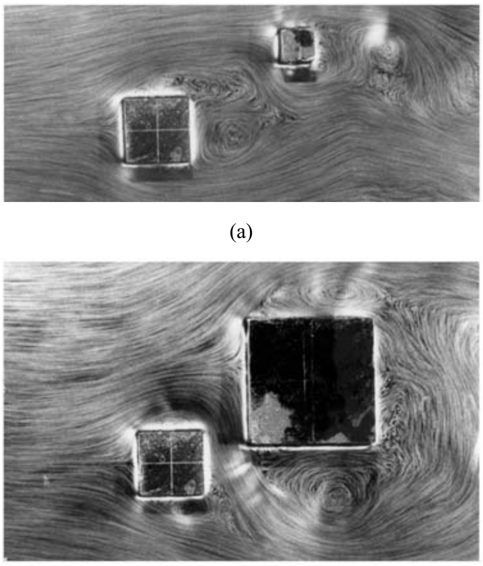


(b)

Fig. 6. Typical flow patterns at position A4 (L/B=0, T/B=1.3) with stationary lower cylinder (a) b/B=0.5, $(a/B)_{max}$ = 0.01 (b) b/B=1.0, $(a/B)_{max}$ = 0.01.

For b/B=1.0 also (Fig. 6(b)), the flow pattern around the lower cylinder is very similar to that of the case with b/B=0.5. The intensity of the gap flow is much more severe, significantly disrupting the vortex shedding process. Correspondingly, as for b/B=0.5, in this case also, $(a/B)_{max}$ =0.01 (M=0.03; Fig. 4(b)). For b/B=1.5, the gap between the cylinders becomes still smaller intensifying the gap flow, further reducing the possibility of vibrations, which is reflected in the vibratory results (Fig. 4(c)).

Fig. 7 shows the flow patterns at position A7 (L/B=2.35, T/B=1.3) for b/B=0.5 and 1.5. For b/B= 0.5 (Fig. 7(a)), the shear layer roll up takes place in the usual manner behind the front cylinder. This near-wake flow situation would possibly induce vibration if the cylinder is flexibly mounted and is reflected in the response amplitude observed with $(a/B)_{max}$ = 0.42 (M=1.3, Fig. 4(a)). For the case with b/B=2.0 (Fig. 7 (b)), the flow field shows that there is hardly any vortex shedding behind the upstream cylinder because of the very strong skewed gap flow occurring between the cylinders. This suggests only negligible lift force



(a)

(b)

Fig. 7. Flow fields for arrangement A7 (L/B=2.35, T/B=1.3) with stationary front cylinder (a) b/B=0.5, $(a/B)_{max}$ = 0.42 (b) b/B=2.0, $(a/B)_{max}$ = 0.02.

generation on the front cylinder and, hence, one could expect only substantially low or near-zero amplitude of vibration to occur, which is the case observed in vibratory results (M= 0.05; Fig. 4(d)). Flow visualization results also indicate that the flow field is affected quite differently for b/B>1.0 (Fig. 7(b)) compared to the case where b/B<1.0 (Fig. 7(a)). Gap flow seems to be critically influencing the flow field of the upstream cylinder for higher b/B ratios (b/B>1.0). However, the major limitation is that the results presented are at U/fB=10.0, whereas the vibratory response is obtained over a range of reduced velocities.

4. Conclusions

From the results presented and discussed, the following conclusions are drawn.

(1) The influence of the b/B ratio is quite significant on the flow-induced oscillation of the square cylinder. Depending upon the relative position, reduced velocity and size ratio, vibrations of the test cylinder could be suppressed or amplified. The vibratory response of the test cylinder is affected both for b/B≤1.0 and b/B>1.0, but quite differently. For b/B≤1.0, the influence on cylinder excitation seems to be relatively less significant. A combination of higher b/B ratios (b/B>1.0) with higher reduced velocities (U/fB>12.0) seems to lead to very high amplitudes.

(2) In general, the magnitude of the peak amplitude and the corresponding reduced velocity (at which it occurs) increase with b/B ratio, in all the tandem positions considered. Among all the b/B ratios, the maximum amplification occurs for b/B=2.0. For the majority of the positions, the reduced velocity at which maximum amplitude occurs is higher for b/B>1.0 cases compared to the cases with b/B≤1.0.

(3) Among the arrangements tested, for b/B≥1.0, the tandem arrangement gives rise to maximum magnification of vibratory amplitude. For b/B<1.0, maximum magnification occurs in staggered arrangements. Overall, it is observed that in the staggered arrangements, amplitude magnification is not that severe when compared to tandem arrangement.

(4) The influence of interfering cylinder on the flow field around the test cylinder is more at higher b/B ratios; gap flow becomes accelerated at higher b/B ratios which seem to critically influence the near-wake of the upstream cylinder.

Acknowledgment

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Nomenclature

a : Peak-to-peak amplitude
B : Side dimension of the test cylinder
b : Side dimension of the interfering cylinder
f : Fundamental natural frequency of the spring-cylinder system
k_s : Scruton number : mass damping parameter ($2m\delta / \rho B^2$)
L : Longitudinal spacing between axes of cylinders
M : Magnification factor
m : Mass per unit length of the test cylinder
T : Transverse spacing between axes of cylinders
U : Free stream velocity
ρ : Density of air
δ : Logarithmic decrement

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