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Comparison of Normal and Parallel Secondary Injection on the Cross Flow Induced Vibration of a Rough and Smooth Single Cylinder

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ABSTRACT. This paper reports an experimental investigation on the effect of a downstream secondary injection in the vicinity of an elastically mounted cylinder on the flow induced vibration. The possibilities of using normal and parallel injection to the cylinder for controlling the flow induced vibration were investigated. Both smooth and rough cylinders were used.

It was found that at reduced velocities less than 8 the effect of both normal and parallel injections on the flow induced vibrations of the cylinder are negligible for all locations of injection and all surface roughnesses used. However at reduced velocities greater than 8 the effect of injection is very much dependent on the blowing rates , the location of the injection and the surface roughness of the cylinder. In general, the normal injection resulted in an increase in the dimensionless vibration amplitude.

1. Introduction

The importance of the interaction occurring between fluid and bluff bodies has been recognized for sometimes by many designers. One adverse result of such an interaction is the phenomena of flow induced vibration which is encountered in various engineering applications such as flow induced vibrations of pipes, cables, heat exchangers, bridges, wings of aircrafts and many more. Although there seems to be numerous amounts of experimental data on the flow induced vibration of a single cylinder such as those reported extensively by Blevins[1], Chen[2], and Parkinson[3], yet the understanding of the various parameters affecting the flow induced vibration of a single cylinder needs more work to be done.

The effects of various system parameters on the stability of the induced oscillation of a single cylinder have been reported by[4-6]. These studies indicate that the lock-in region exhibits a single resonance peak. Jubran *et al.*, Penzin[8] and Durgin *et al.*[9], however, observed a second resonance peak in the frequency curve in the lock-in region. In a recent paper by Shirakashi *et al.*[10], their results suggest that the second peak could be attributed to the end effects of the cylinder. They reported that when blocking plates are mounted in the cylinder only one peak is obtained.

Jubran *et al.*[7] conducted a detailed experimental work on the effects of the free stream turbulence and surface roughness on the dynamic response of a single cylinder elastically mounted at both ends. They reported that increasing the turbulence intensity tends to decrease the dimensionless amplitude in the lock-in region, while increasing the surface roughness tends to reduce the width of the lock-in region. Bearman and Obasju[11] investigated the effect of varying roughness on the flow regimes encountered by the cylinder. Rooney and Peltzer[12] studied the effect of roughness on the shedding characteristics behind circular cylinders. It was concluded that the rough surface acts to homogenize flow conditions over a wide range of area, which would result in a wider range coherence in the shedding pattern, this in turn decreases the range in the Strouhal number for a rough cylinder than for the corresponding smooth cylinder. To the best of the authors knowledge the only work conducted on the flow induced vibration of a single cylinder subjected to more than one stream of the fluid is that of Jubran and Hamdan[13]. They investigated the general effects of a parallel secondary injection on the flow induced vibration of a smooth single cylinder. Their results indicate that for certain combinations of injection velocities and locations, and reduced velocities the dimensionless vibration amplitude may be reduced by as much as 50%.

The present investigation is an extension of the authors previous work[13] in the two main aspects; first the effect of angles of injection on the flow induced vibration for both smooth and rough single cylinder is investigated, which might be encountered in engineering practice when a structural component is subjected to two streams at different angles to each other. Second, the potential of using such a secondary flow injection at the appropriate angle to control the oscillations of a single cylinder is explored.

2. Experimental arrangements

The experimental set up used in this investigation is basically a modified version of that used by the authors[7, 13]. It consists of an open suction type wind tunnel with a square cross section area of 30 cm × 30 cm and of length equal to 217 cm, Figure 1(a). The free stream velocity was varied from 5 to 35 m/s, with the free stream turbulence intensity level of (0.2%). The test cylinder was placed at 1.28 m from the inlet of the test section where the flow was found to be fully developed. The resulting Reynolds number range was about ($6 \times 10^3 - 4.6 \times 10^4$).

The test cylinder was of an aluminum tube with cross section of outer diameter, D = 20 mm wall thickness t = 1.2 mm and length L = 480 mm. This combination yields an aspect ratio L/D of 15 and mass per unit length of $\overline{m}$ of 0.24 kg/m.

The cylinder mountings used in this experiment are similar to those used by Shirakashi *et al.*[4]. The cylinder was suspended by two similar clamped plates at its ends, Figure 1. The plates were placed outside the test section of the wind tunnel to avoid interference with the flow. Jubran *et al.*[7] adopted this mounting to minimize the mode of coupling effects which may arise form the streamwise and rotational motions. Motion in the horizontal direction for this mounting is difficult to excite since the plate axial rigidity is much higher than its rigidity in the vertical direction, i.e the horizontal natural frequency of the cylinder for this mounting is much higher than its natural frequency of vertical vibration. This was confirmed by simply examining the impulsive response of the cylinder. The rotational mode is minimized by carefully adjusting the overhang length of each of the end plates so that the stiffness at both ends of the cylinder is the same. Note that the length of each slot at the sides of the test section of the wind tunnel is 40 mm, less than four times the diameter of the test cylinder, which according to Graham[15] ensures the two dimensionality of the vortex wake. This was confirmed by preliminary tests.

The secondary injection flow is injected from a settling chamber to ensure uniform flow through the injection mechanism, Figure 1(a). The settling chamber is 900 mm × 900 mm in area and 160 mm in depth. The flow is supplied by a fan through two inlet pipes of (20 mm) in diameter fixed at the two sides of the settling chamber at the lower end on the third part of the height. Four sheets of perforated mesh are placed in the upper remaining two thirds of the settling chamber over the supplying pipes. A perspex plate of 3 mm in thickness was used to cover the settling chamber with a perspex pipe of 17 mm in diameter and 300 mm in length fixed at the middle of the roof through which the flow is injected, resulting in a circular jet into the side of the wind tunnel downstream the mounted cylinder in the case of the parallel injection while it is injected from the top of the wind tunnel test section in the case of the normal injection. The arrangement of the injection is shown in Figure 1(b). A movable stand carrying the settling chamber is used to inject air at different locations downstream the mounted test cylinder. The injection velocity was varied by changing the discharge of air from the fan.

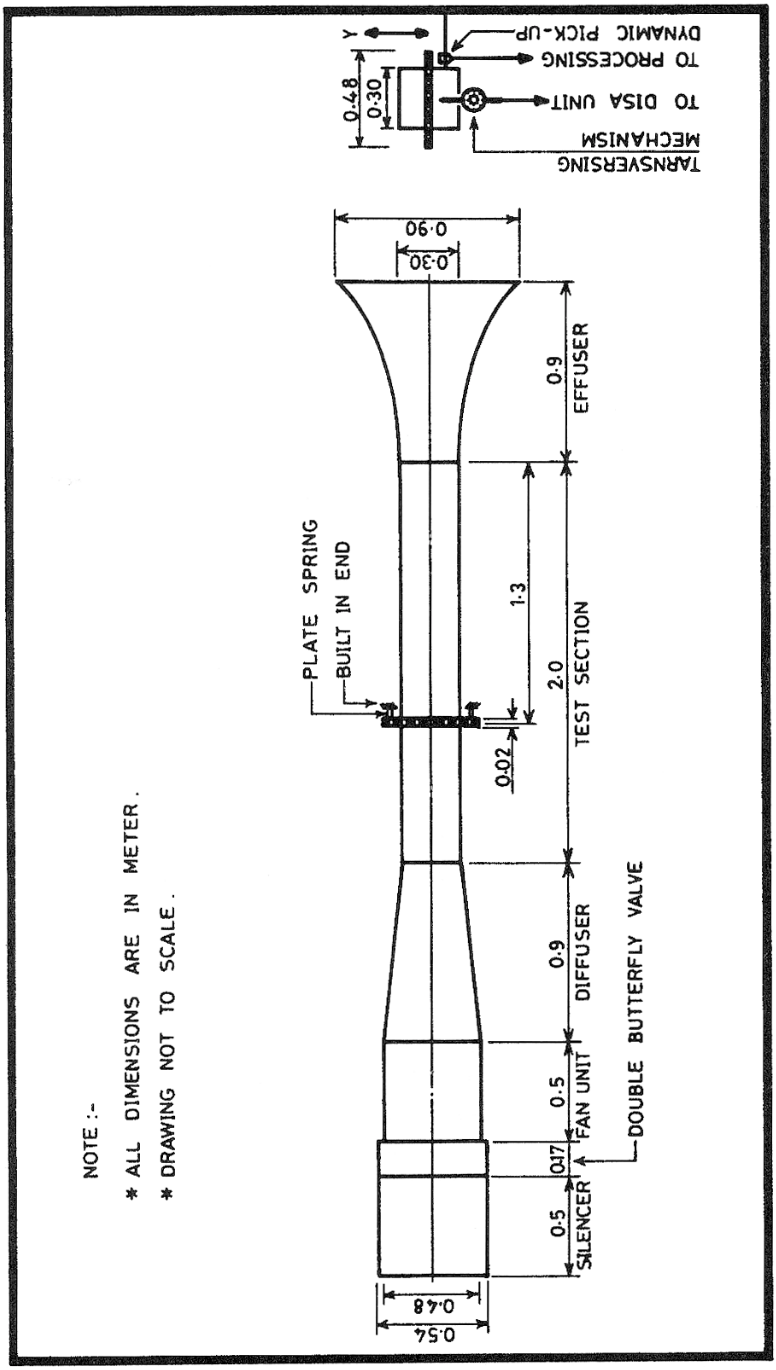

FIG. 1(a). General view of the wind tunnel and the experimental rig.

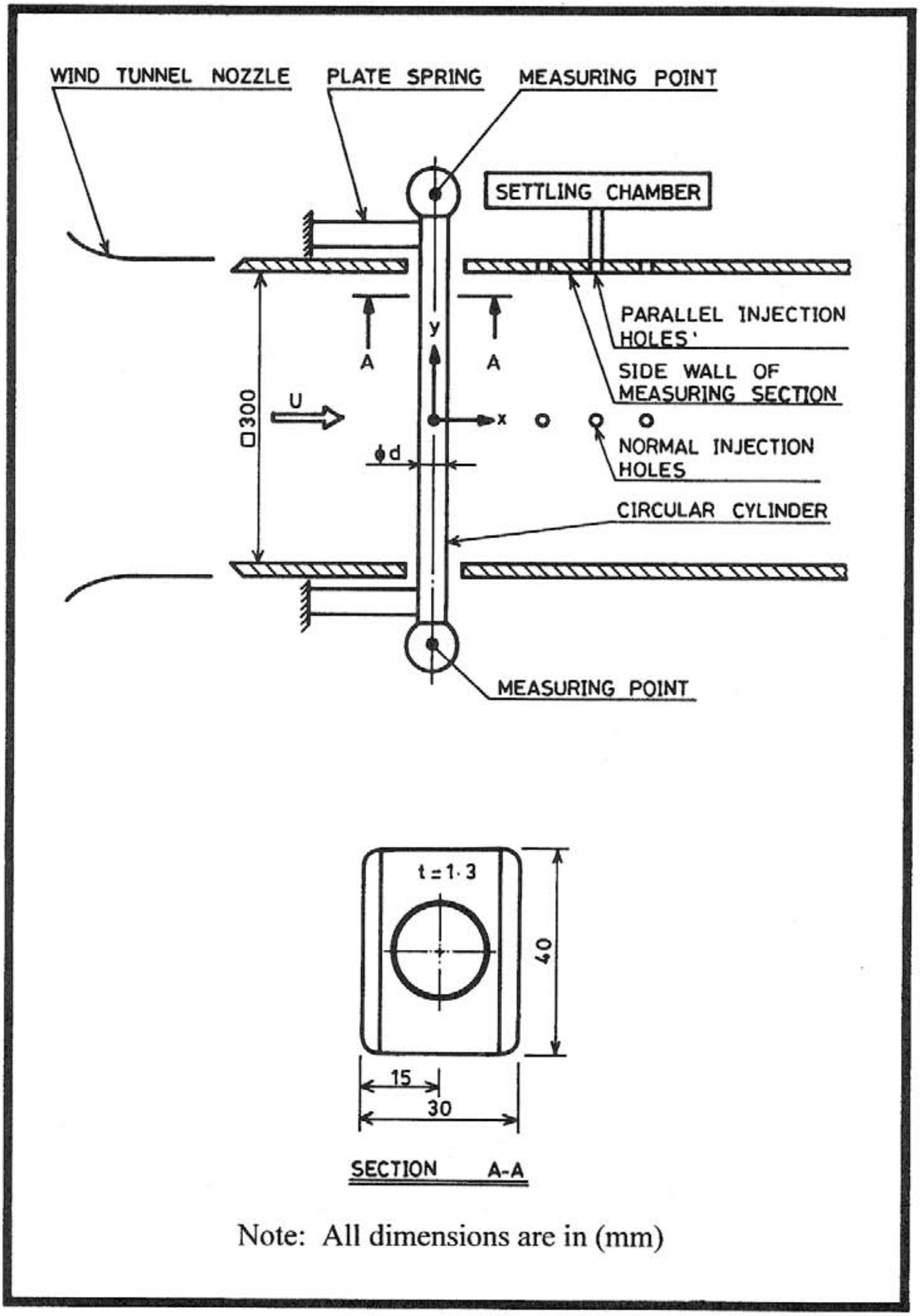

FIG. 1(b). Injection and cylinder arrangements.

Standard sand emery papers with known surface roughness were glued and wrapped to obtain various values for the surface roughness of the cylinder. The grits of sand papers used in the present research are shown in Table 1. For the smooth cylinder, plastic paper was used with an average height of 0.75 µm. The average heights of roughness were measured using the Tallysurf machine.

TABLE 1. Emery papers roughness heights

Grade	*k* (mm)	*k/D*
p 36	0.50	0.0250
p 80	0.20	0.0100
p120	0.13	0.0065
p180	0.07	0.0035

A schematic diagram of the measuring arrangement is shown in Figure 2. The amplitude of vibration was measured by placing a contactless vibration pick up (B&K MM0002) underneath the end of the cylinder. The output signal was simultaneously fed to a digital frequency analyzer (B&K 2131) and to tunable pass band filter (B&K 1621) and then the signal from the tunable filter was also simultaneously fed to a measuring amplifier (B&K 2616) and to a digital storage oscilloscope (OS 4100). Using this arrangement, it was possible to measure the RMS value and to monitor the signal on both frequency and time domains.

The natural frequency (f) and the logarithmic decrement (δ) of the test cylinder were determined by impulsive test, wherein the cylinder was set into vibration by slightly tapping its center.

The free stream velocity was measured using a constant temperature hot wire anemometer (CTA) type (55*MO*1) The frequency spectrum and the waveform of the velocity fluctuation in the wake of the oscillating cylinder, which show the vortex shedding frequency, were monitored by simultaneously feeding the signal from the hot wire probe placed at 1*D* in the horizontal direction and 2*D* in the vertical direction from the static equilibrium position at the mid point of the oscillating cylinder to the frequency analyzer and to a digital oscilloscope.

3. Results and Discussions

Throughout the measurements made to establish the data presented in this paper, care was taken to note possible source of error and an error analysis based on the method of Kline and McClintock[16] was carried out. The error analysis indicated a ± 13% uncertainty in the vibration amplitude and a ± 5% in the velocity. All data are repeated a few times to ensure the repeatability of the results. Reduced velocity within the vortex shedding was obtained by tuning the

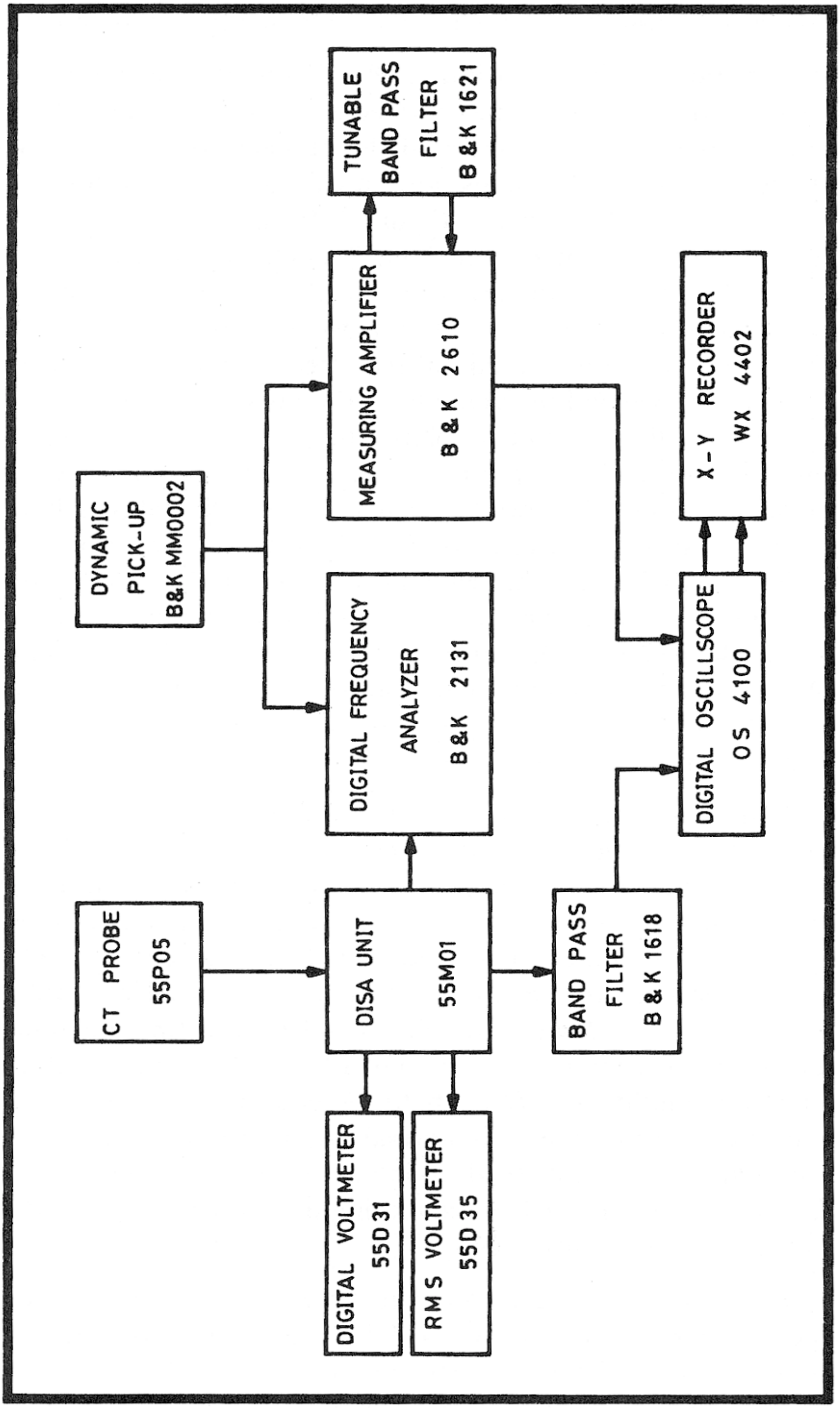

FIG. 2. Signals processing diagram.

natural frequency of the test cylinder to about 76 Hz for which the logarithmic decrement was found to be about 0.018, obtained from a simple impulsive test.

The variation of the non-dimensional RMS vibration amplitude *A/D,* averaged over 20 ms, with the reduced velocity for a smooth cylinder with the injection located normal to the center of the cylinder and the direction of the free stream flow at various locations downstream the center of the cylinder, namely *S/D* =1.5, 3.0 and 5 is shown in Figure 3. It can be seen from Figure 3 that for the injection velocities of 1.9 and 9.8 m/s and the above values of injection locations *S/D,* the effect of injection on the dimensionless amplitude, *A/D* up to about a reduced velocity U_r = 8 seems to be negligible. However for reduced velocities, $U_r > 8$ the magnitude of the effect of injection is very much dependent on the location and the velocity of the injection. At the vicinity of the cylinder increasing the injection velocity from 1.9 to 9.8 m/s, tends to increase the dimensionless vibration amplitude for $U_r > 8$. Increasing the injection distance downstream to *S/D* = 3 showed a decrease in dimensionless vibration amplitude at large values of reduced velocity, $U_r > 12$ when the injection velocity is small, $U_i = 1.9$ = m/s while for the injection velocity of $U_i = 1.9$ m/s the effect of injection is not as predominant as in the case when the injection is in the vicinity of the cylinder (*S/D* = 1.5), however the injection still leads to an increase in the dimensionless vibration amplitude. Far away from the cylinder at *S/D* = 5 the effect of the injection is again to increase the dimensionless vibration amplitude for all reduced velocities investigated.

A dimensionless parameter defined as the blowing rate $M = \rho_i U_i / \rho U$ was introduced where U_i and ρ_i are the secondary flow velocity and the secondary flow density respectively, and ρ and U are the mainstream density and mainstream velocity, is used to investigate the effect of normal blowing rate on the dimensionless amplitude at two reduced velocity namely $U_r = 3.7$ and 6.7, Figure 4. It can be seen from this figure that at low reduced velocity for various injection location, *S/D,* downstream the cylinder increasing the blowing rate tends to decrease the *A/D* up to a blowing rate of $M = 0.8$; for $M > 0.8$ the dimensionless vibration amplitude *A/D* tends to increase with increasing *M.* However at reduced velocity of $U_r = 6.7$ the normal injection has the opposite effect; that is increasing the blowing rate tends to increase the dimensionless vibration amplitude up to $M = 0.6$, after which increasing the blowing tends to decrease the dimensionless vibration amplitude.

The effect of parallel injection on the flow induced vibration of a single rough cylinder with *k/D* = 0.01 and *k/D* = 0.025 are shown in Figures 5 and 6 respectively. At small surface roughness of the cylinder, *k/D* = 0.01, the injection tends to reduce the dimensionless vibration amplitude in the vicinity of the cylinder for the downstream distance at *S/D* = 1.0 and *S/D* = 1.5 for the reduced

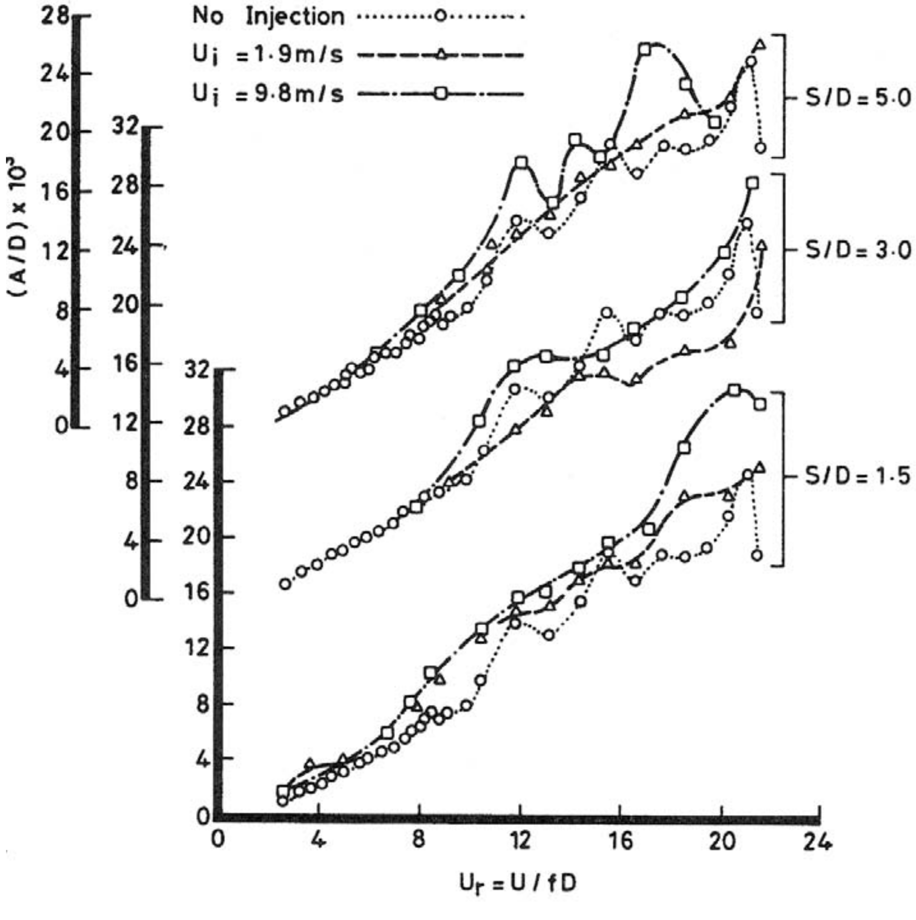

FIG. 3. Effect of normal injection on the dimensionless amplitude (*A/D*) of the smooth cylinder.

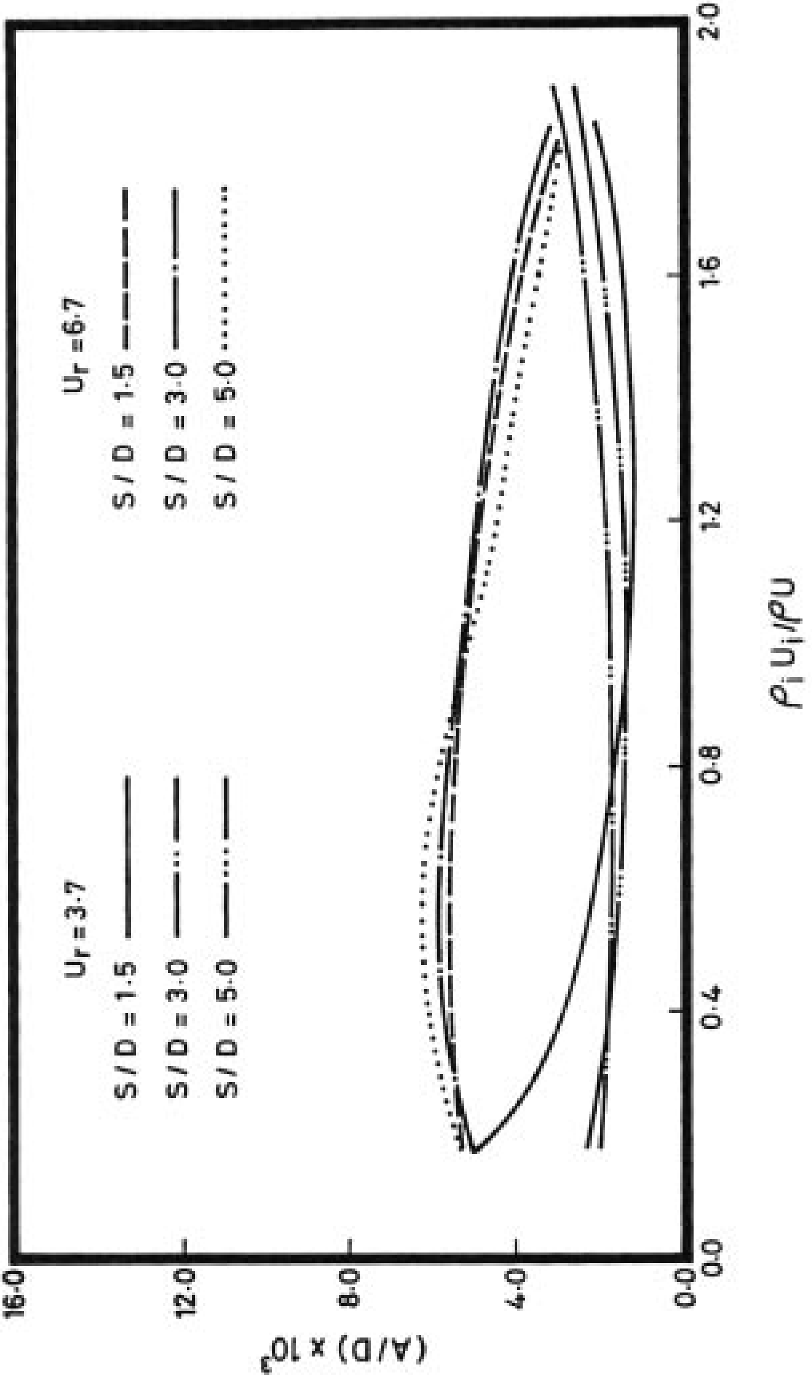

FIG. 4. Effect of normal injection blowing rate on the dimensionless amplitude (*A/D*) of smooth cylinder.

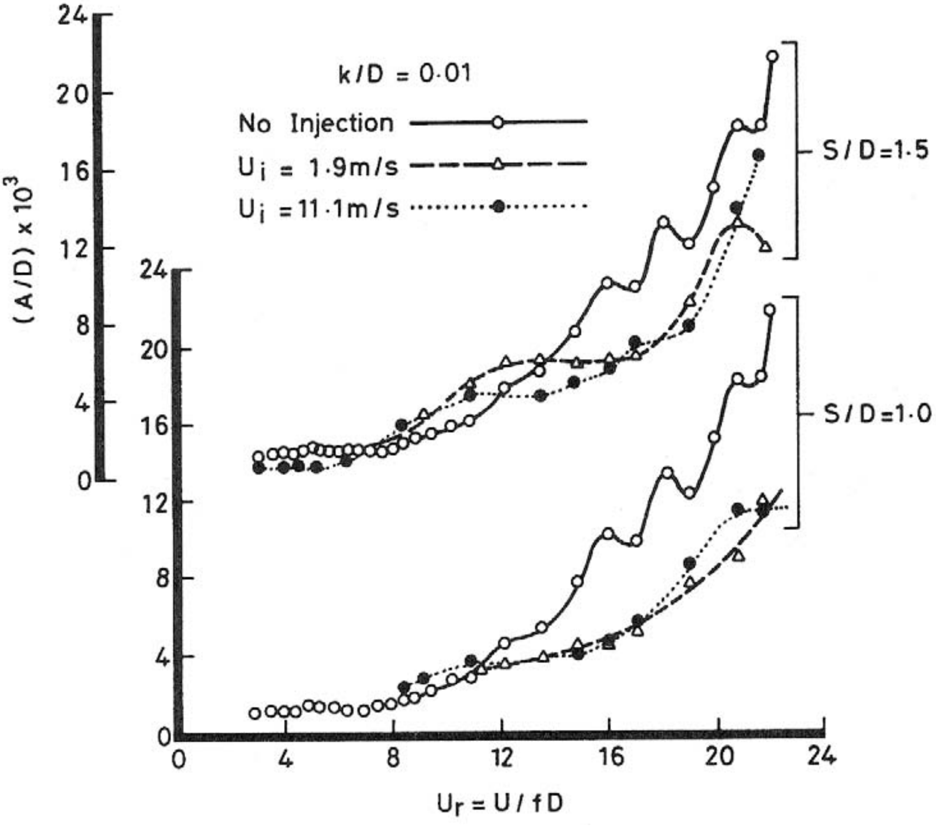

FIG. 5. Effect of parallel injection on the dimensionless amplitude (*A/D*) of a rough cylinder (*k/D* = 0.01).

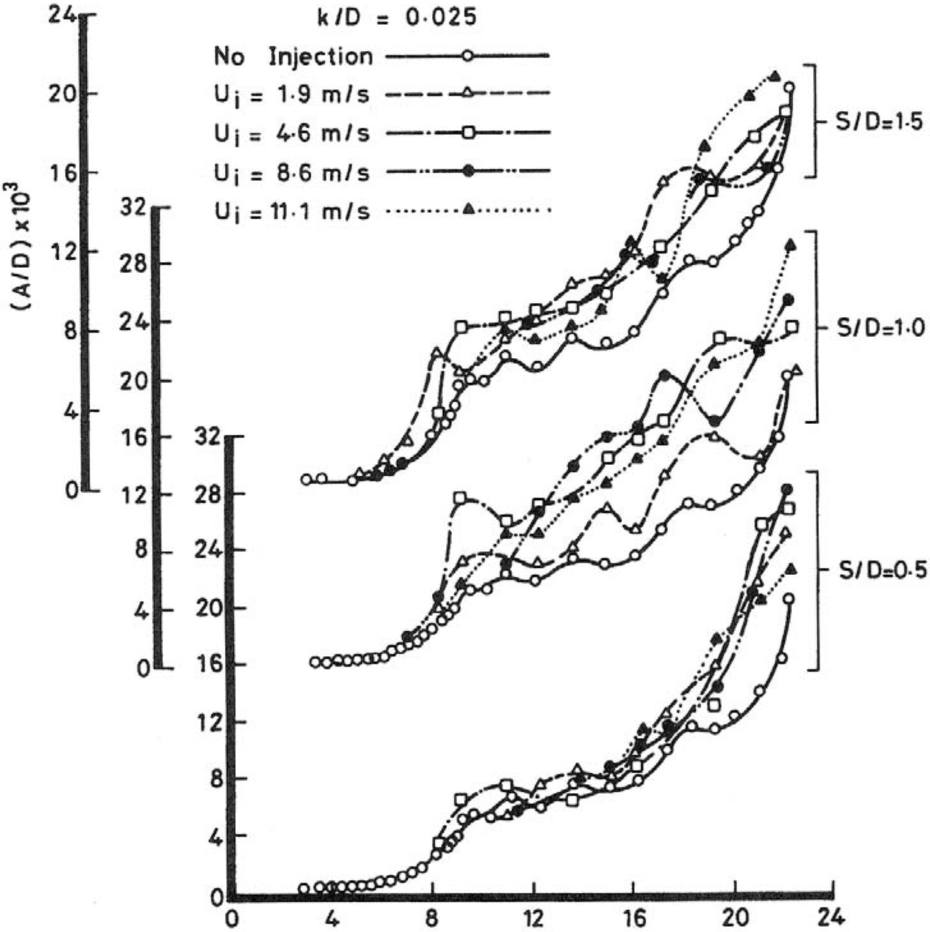

FIG. 6. Effect of parallel injection on the dimensionless amplitude (*A/D*) of a rough cylinder (*k/D* = 0.025).

velocities, $U_r > 8$ regardless of the value of injection velocity, Figure 5. Increasing the surface roughness to k/D = 0.025, resulted in an increase in the dimensionless vibration amplitude for all injection velocities and distances downstream the cylinder, Figure 6.

The effect of blowing rates using normal injection on the dimensionless vibration amplitude of the rough surface cylinder at certain reduced velocities is shown in Figure 7 for $k/D = 0.01$ and $k/D = 0.0065$. Figure 7(a) shows that at $U_i = 8.1$ for injection in the vicinity of the cylinder $S/D = 0.5$ the dimensionless vibration amplitude tends to increase with the increase of the blowing rate up to $M = 0.6$ and then decreases as the blowing rate is increased. As the injection distance, S/D, is increased downstream the effect of injection on A/D at $U_r = 8.1$ seems to be negligible up to $M = 0.5$, on the other hand A/D is increased as M is increased for $S/D > 0.5$. The effect of injection for all blowing rates and S/D is negligible when the reduced velocity $U_r = 3.8$. Figure 7(b) shows the effect of blowing rates on the dimensionless amplitude at $U_r = 3.8$ and $U_r = 8.1$. It can be seen again that at the small reduced velocity, $U_r = 3.8$ the effect for all values of S/D considered is negligible. At $U_r = 8.1$ and $S/D = 0.5$ the effect of blowing rate is similar to that for $k/D = 0.01$.

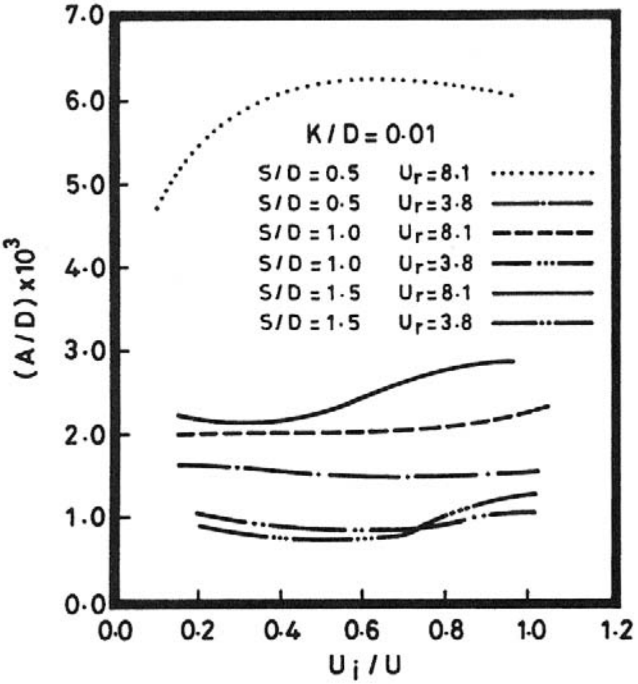

FIG. 7(a). Effect of normal injection blowing rate on the dimensionless amplitude (A/D) of a rough cylinder ($k/D = 0.01$).

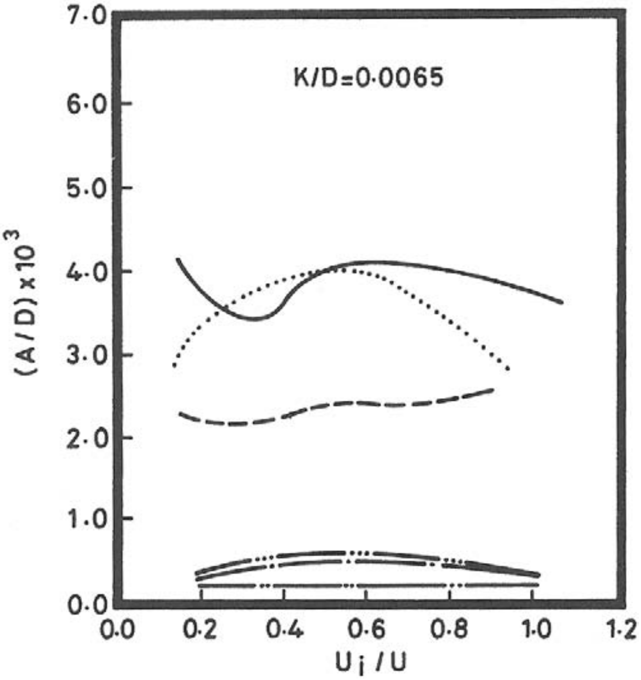

FIG. 7(b). Effect of normal injection blowing rate on the dimensionless amplitude (*A/D*) of a rough cylinder (*k/D* = 0.0065).

Nakagawa[17] has suggested a formation mechanism for the vortex behind a circular cylinder which might be used to explain the reduction of the dimensionless vibration amplitude (*A/D*) in the presence of injection. He has reported that a symmetry of vortex pair with respect to the wake axis behind the cylinder has been found to be necessary for alternate vortex shedding. This results in an unstable vortex system consisting of three vortices in the formation region so that another vortex pair is formed by shedding one of the vortices downstream. In the presence of injection at the vicinity of the cylinder and depending on the momentum of the injection jet, the degree of the symmetry of the formed vortices is altered. The jet tends either to reduce the strength of the alternate vortices and hence reducing the amplitude of vibration or enhancing the strength of the vortices and increase the amplitude of vibration.

4. Conclusion

An experiment investigation was conducted to explore the effect on the flow induced vibration of a smooth and rough cylinder of a secondary flow injected parallel and normal to the cylinder but at 90º to the stream. Based on the experimental results, the effect of injection on an elastically mounted cylinder may be summarized as follows:

1. Injection velocities seem to have negligible effects on the dimensionless vibration amplitude of smooth and rough cylinders for reduced velocities $U_r < 8$ regardless of the values of the blowing rates and the angles of injection
2. For reduced velocity $U_r < 8$ the effect of injection is very much dependent on the angle of injection, location of injection, and roughness of the cylinder.
3. There is a strong evidence that injection of a secondary flow may be used as a means of controlling the flow induced vibration of an elastically mounted cylinder for certain ranges of injection parameters

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Nomenclature

A	RMS vibration amplitude
D	Diameter of test cylinder
A/D	Dimensionless vibration amplitude
f	Natural frequency of the test cylinder
k	Average height of roughness
L	Length of the test cylinder
$\bar{m}$	Mass per unit length of the test cylinder
t	Wall thickness of the cylinder
δ	Logarithmic decrement of the test cylinder
ρ	Density of the fluid of the mainstream flow
ρ_i	Density of the fluid of the secondary injected flow
U	Mainstream velocity
U_i	Injection velocity
U_r	Reduced velocity $\frac{U}{fD}$
M	Blowing rate $\frac{\rho_i U_i}{\rho U}$
S	Downstream distance from the cylinder

مقارنة تأثير الحقن الثانوي العمودي والثانوي الموازي على الاهتزازات الحثية الناتجة عن الجريان العارض لاسطوانة منفردة ملسة واسطوانة خشنة

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المستخلص . تقدم هذه الدراسة نتائج مخبرية لتأثير كل من الحقن الثانوي العمودي والموازي بالقرب من اسطوانة مرنة على الاهتزازات الحثية لهذه الاسطوانة مع دراسة احتمالية استخدام هذا الحقن كوسيلة للتحكم في الاهتزازات الحثية . وقد تم استعمال اسطوانات ملسة وخشنة . ووجد أنه عندما تكون السرعة المقللة أقل من ٨ يكون تأثير كل من الحقن العمودي والموازي على الاهتزازات الحثية قليلا لجميع مواضع الحقن ومقدار خشونة سطح الاسطوانة ، كما وجد أنه عندما تزيد السرعة المقللة عن ٨ فإن تأثير الحقن يعتمد على معدل ، ومكان الحقن وعلى خشونة سطح الاسطوانة . وبشكل عام وجد أن الحقن العمودي يؤدي إلى زيادة في المقدار البعدي للاهتزازات الحثية .