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Effects of Secondary Injection on the Cross Flow Induced Vibration of a Single Cylinder

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Abstract. This paper represents an experimental investigation on the effect of a secondary injection in the vicinity of an elastically mounted smooth cylinder, on the flow induced vibration of such cylinder with the possibilities of using such injection for controlling the flow induced vibration. It was found that the effect is very much dependent on the blowing rate $(\rho_i U_i/\rho U)$, the location of injection downstream, the cylinder and the range of reduced velocities in question.

The results obtained suggest that at certain combination of injection velocities, location of injection downstream and reduced velocity, the dimensionless amplitude of vibration can be reduced by as much as 50%. However, there seems to be other blowing rates, *i.e.* blowing rates greater than 1, which may lead to an increase in the vibration amplitude of the cylinder.The results of this investigation show that secondary flow, if properly used, can be utilized as an effective means for controlling practical flow induced vibration.

Nomenclature

A	RMS vibration amplitude
D	Diameter of the test cylinder
A/D	Dimensionless vibration amplitude
f	Natural frequency of the test cylinder
L	Length of the cylinder
$\overline{m}$	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

Introduction

Flow induced vibration of engineering components, such as arrays of tubes of heat exchanger, power transmission cables, structural components of bridges and industrial tower have been the subject of an enormous research effort. An extensive bibliography of numerous experimental investigations on the classical problem of flow induced vibration of an elastically supported single circular cylinder has been reported by Blevins [1] and Chen [2]. It has been accepted that resonance occurs when the frequency of vortex shedding is equal to the natural frequency of the cylinder. This resonance extends over a reduced velocity range typically between 5 and 10, as a result of the so called "lock-in" phenomenon wherein the frequency of the vortex shedding is synchronized with the resonance frequency of the oscillating cylinder. As the reduced velocity is increased beyond this "lock-in" range the frequency of vortex shedding departs from the frequency of oscillations and the response of the cylinder becomes highly non-linear wherein the vibration amplitude first decreases and then increases with further increase in the reduced velocity to the verge of instability. The effects of various system parameters on the stability of the induced oscillation of a single cylinder have been reported in [3-5]. These studies show that the lock-in region exhibits a single resonance peak. Jubran *et al.* [6], Penzin [7] and Durgin *et al.* [8], however, observed a second resonance peak in the frequency curve in the lock-in region. Shirakashi *et al.* [9] noted that the second resonance may be attributed to the end effects or to the rotation mode of oscillation. Jubran *et al.* [6] conducted a detailed investigation on the effect of the free stream turbulence intensity and surface roughness on the dynamic response of a single cylinder. It has been concluded that in the lock-in region, increasing the free stream turbulence intensity tends to decrease the vibration amplitude, while in the fluid elastic region, increasing the turbulence intensity tends to increase the vibration amplitude. Increasing the surface roughness tends to reduce the width of the lock-in region and to reduce the vibration amplitude. On the other hand, for the fluid elastic region increasing the surface roughness tends to increase the vibration amplitude.

Efforts to develop means for controlling flow induced vibration on bluff bodies have been handicapped by the fact that the understanding of details of steady separated flow are still beyond theoretical modelling *i.e.* the existing numerical models for the most part are based on some empirical correlations of experimental data. Recently William and Zhao [10] have considered acoustic feedback as a means of controlling the vortex formation process in the wake of a single cylinder.

The present investigation has two objectives: **first** the general effect of a secondary injection on the flow induced vibration of a single cylinder is investigated, which might be encountered in engineering practice when a structural component is subjected to two streams at different angle to each other. The **second** is to investigate the possibilities of using this secondary stream injection as a means of controlling the oscillations of a single cylinder.

Experimental Arrangements

The experimental investigation was conducted in an open suction type wind tunnel with a square cross section area of 30 cm × 30 cm and of length equal to 217 cm (Fig. 1). 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 1.3 m from the inlet of the test section where the flow was found to be fully developed.

The test cylinder was of an aluminum tube with cross section of outer diameter $D = 20$ mm, wall thickness $t = 1$ mm and length $L = 480$ mm. This combination yields as aspect ratio L/D of 15 and mass per unit length $\overline{m}$ of 0.239 kg/m.

The cylinder mountings used in this experiment are similar to those used by Shirakashi *et al.* [9]. The cylinder was suspended by two similar clamped plates at its ends (Fig. 1). The plates were placed outside the test section of the wind tunnel to avoid interference with the flow. Jubran *et al.* [6] adopted this mounting to minimize the mode coupling effects which may arise from the streamwise and rotatinal 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 70 mm, less than four times the diameter of the test cylinder, which according to Graham [11] ensures the two dimensionality of the vortex wake. This was confirmed by preliminary tests.

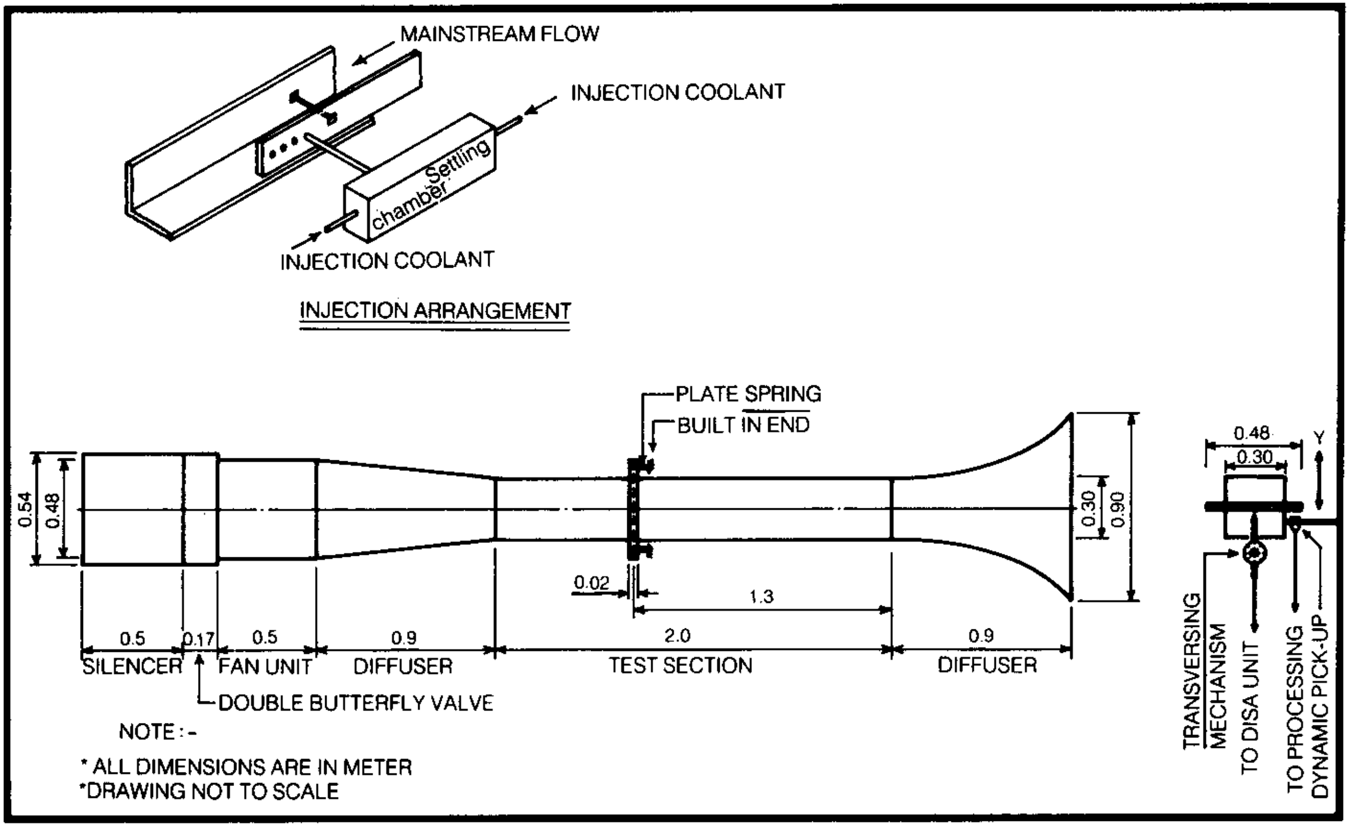

Fig. 1. General view of the wind tunnel and the experimental rig.

The secondary injection flow is injected from a settling chamber to ensure uniform flow through the injection mechanism (Fig. 1). The settling chamber is 900 mm × 650 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 third 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 wind tunnel downstream the mounted cylinder. A movable stand carrying the settling chamber is used to inject air at different distance downstream the mounted test cylinder. The injection velocity was varied by changing the discharge of air from the fan.

A schematic diagram of the measuring arrangement is shown in Fig. 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 a 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 domain.

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 (55MO1). 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 direcion 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.

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 base on the method of Kline and McClintock [12] was carried out. The error analysis indi-

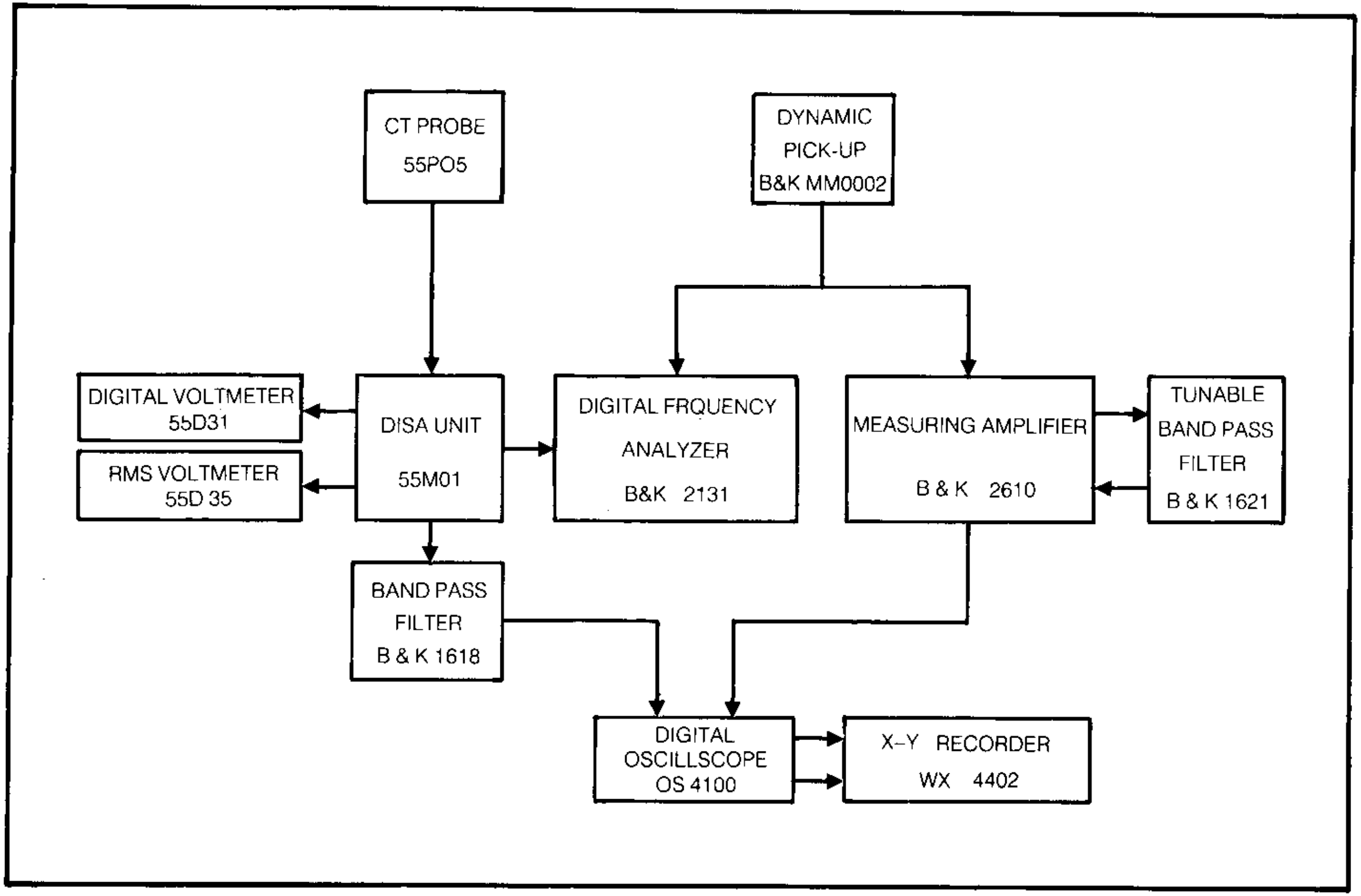

Fig. 2. Signal processing diagram

cated a ±3% 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 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 nondimensional RMS vibration amplitude A/D, averaged over 20 ms, with the reduced velocity for a smooth cylinder with an injection velocity of U_i = 1 m/s at 0.5 D downstream the cylinder (S/D = 0.5) is shown in Fig. 3. The effect of injection on A/D was negligible up to reduced velocity of about 15, however, the curve A/D is seen to be smoother in the presence of the injection. As the reduced velocity is increased to U_r = 24 the injection tends to increase the A/D. Increasing the injection velocity to 8.2 m/s, resulted in a reduction in the nondimensional vibration amplitude A/D where the maximum reduction occurred at a reduced velocity of about 18. Fig. 3 also indicates that a significance reduction in the vibration amplitude A/D is obtained as the injection velocity is increased to 11.8 m/sec.

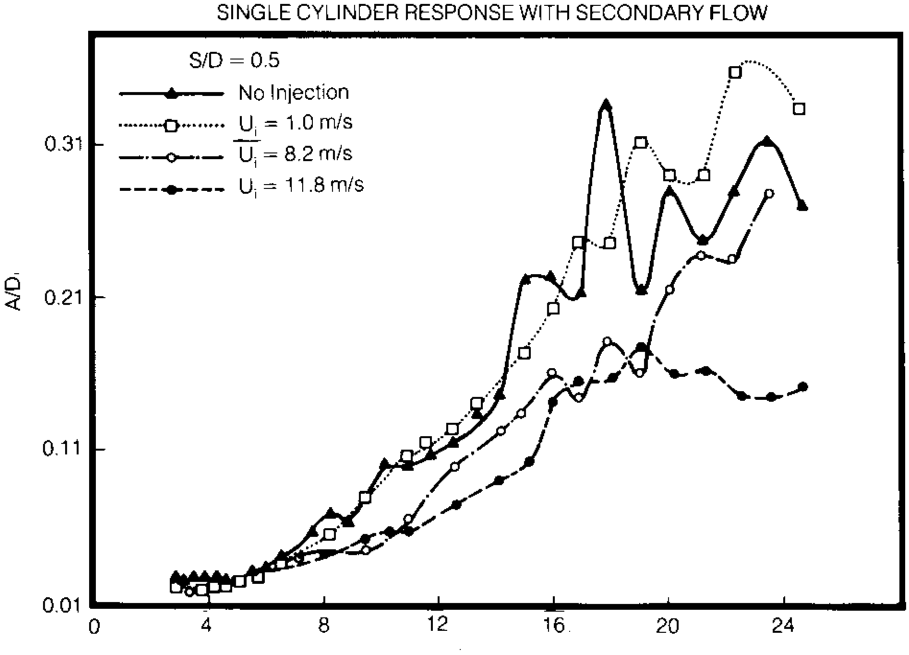

Fig. 3. The effect of injection on A/D at S/D = 0.5 for various U_i of 1 m/s, 8.2 m/s and 11.8 m/s

However, increasing the injection velocities to 27 m/s and 34.5 m/s seems to enhance the induced vibration of the cylinder specially in the region of high reduced velocities (for $U_r > 18$), as shown in Fig. 4.

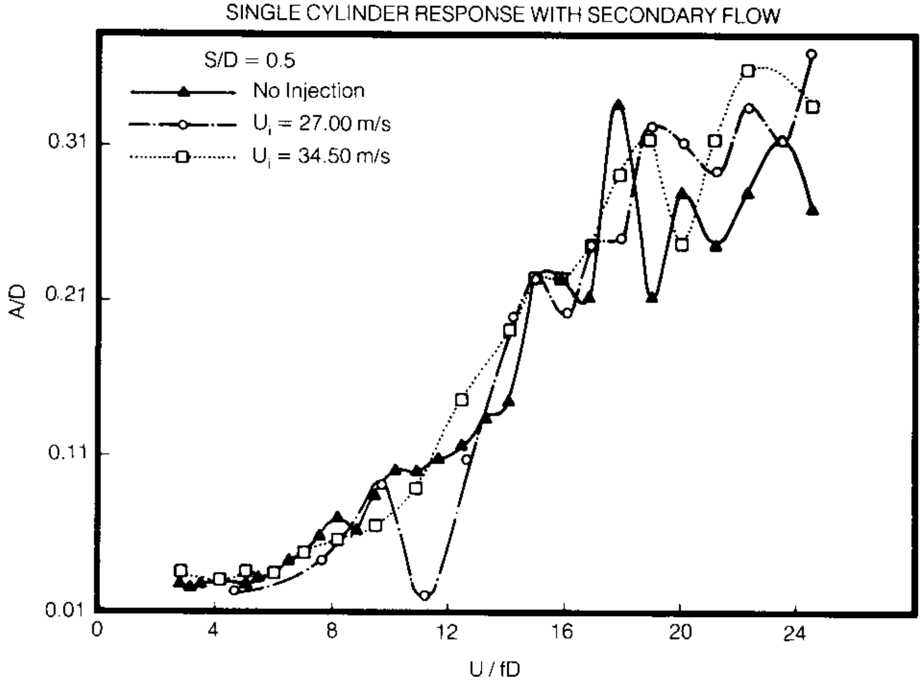

Fig. 4. The effect of injection on A/D at S/D = 0.5 for various U_i of 27 m/s, and 34.5 m/s

Fig. 5 shows the variations of the dimensionless vibration amplitude with reduced velocity at various injection velocities for an injection location of 1.5 D downstream the cylinder. It can be seen that at injection velocity of 1 m/s the injection tends to decrease the (A/D) up to $U_r = 16$, while further increase in the injection velocity in the range 2.2 m/s to 31.9 m/s showed no significance reduction. Nakagawa [13] has suggested a formation mechanism for the vortex behind a circular cylinder which might be used to explain the reduction of the nondimensional 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 hole, 0.5D and dependent on the momentum of the injection jet, the degree of symmetry of the formed vortices is affected. The jet tends either to reduce the strength of the alternate vortices and hence reducing the amplitude or enhancing the strength of the vortices and increase the amplitude.

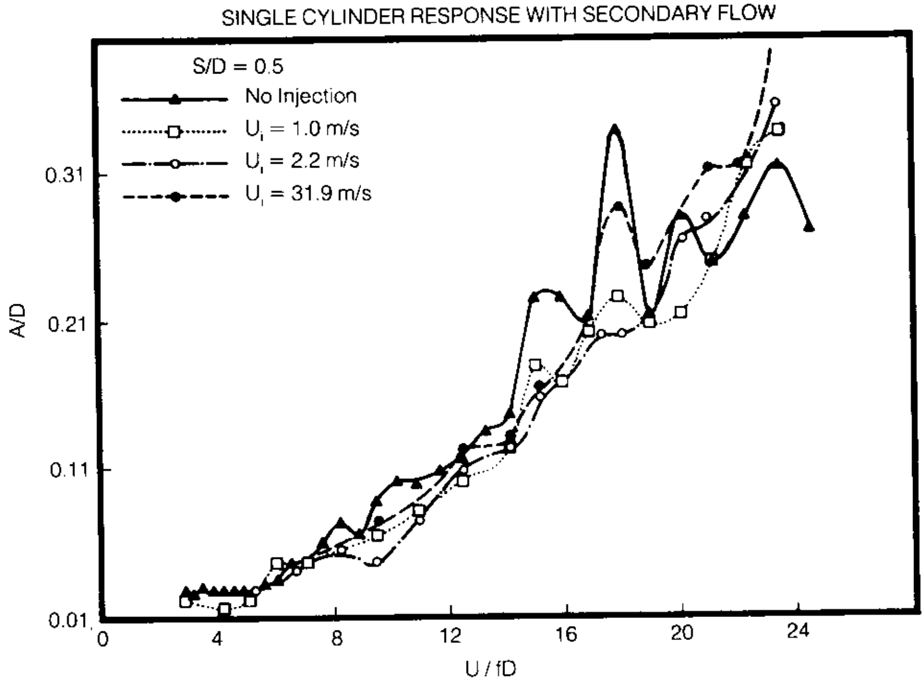

Fig. 5. The effect of injection on A/D at S/D = 0.5 for various U_i of 1 m/s, 2.2 m/s, and 31.9 m/s

The effects of injection on the dynamic response of a single cylinder in the fluid elastic region at different downstream locations, namely 0.5 D and 1D for various injection velocities are shown in Figs. 6 to 8. In order to obtain higher reduced velocities, the natural frequency of the cylinder was changed by adjusting the overhang length of the spring plates. The natural frequency of the system was 14 Hz.

Fig. 6 shows the variation in the dimensionless vibration amplitude A/D with reduced velocity when the secondary injection is placed at S/D = 0.5 for various values of injection velocities U_i. For $U_i = 1$ m/s the vibration amplitude shows a small reduction in the region $80 \leq U_r \leq 120$. This reduction in the vibration amplitude becomes pronounced over the entire range of U_r considered when the injection velocity is increased to 5.7 m/s. However, as the velocity of injection is increased to 8.2 m/sec, the decrease in the dimensionless amplitude A/D is significant for the reduced

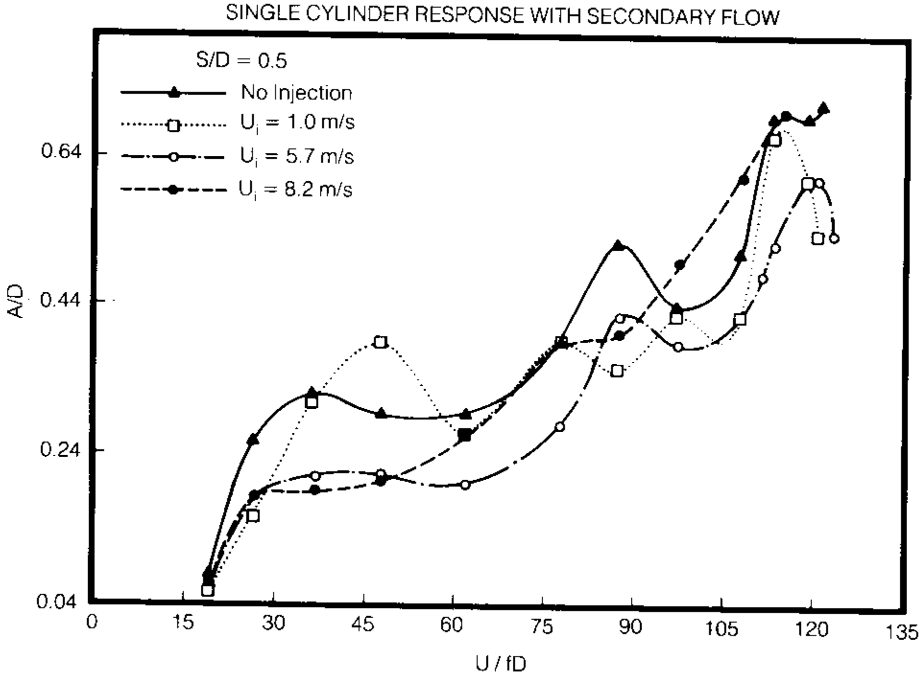

Fig. 6. The effect of injection on A/D at S/D = 0.5 for various U_i of 1 m/s, 5.7 m/s, and 8.2 m/s

velocity range $16 \leqslant U_r \leqslant 60$ and then starts to approach that without injeciton with an increase in A/D for $95 \leqslant U_r \leqslant 110$.

At higher injection velocity of 34.5 m/s the dimensionless vibration amplitude is reduced significantly specially in the reduced velocity range of 27 to 60 and this reduction begins to decrease as the reduced velocity is increased, while the injection velocity of 40.4 m/s results in a reduction of about 50% in A/D at $U_r = 120$ (Fig. 7).

Fig. 8 shows the effect of variations in injeciton velocity U_i on the vibration amplitude for an injection location of S/D = 1. Comparing Figs. 7 and 8, for the cases U_i = 34.5, 40.4, and 31.9, one may conclude that the secondary injection has more pronounced effects on the cylinder induced vibration when the injection is placed at the vicinity of the cylinder.

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. It can

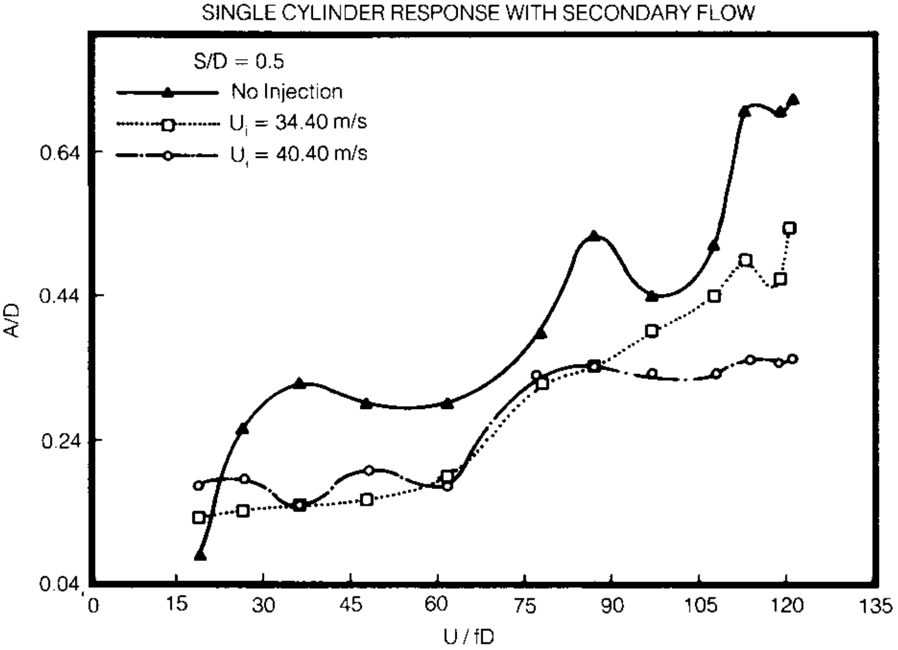

Fig. 7. The effect of injection on A/D at S/D = 0.5 for various U_i of 34.5 m/s and 40.40 m/s

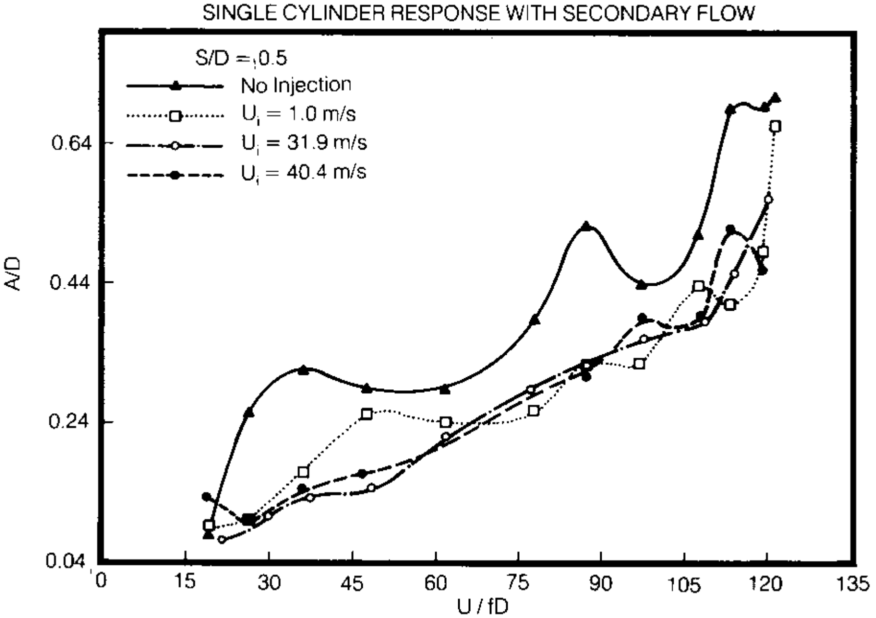

Fig. 8. The effect of injection on A/D at S/D = 0.5 for various U_i of 1 m/s, 31.9 m/s, and 40.4 m/s

be seen from Fig. 9 that the effect of blowing rate on the dimensionless vibration amplitude for different reduced velocities at the vicinity of the cylinder, S/D = 0.5, in the vortex shedding region may be classified according to two distinct ranges of low blowing rates and high blowing rates. At low blowing rates of $0.25 \leqslant M \leqslant 0.9$, increasing the blowing rate tends to reduce the dimensionless vibration amplitude, A/D for the reduced velocity values of 8.25, 12.5 and 16. The reduction of A/D is more pronounced at reduced velocity of 12.5 and almost negligible at reduced velocity of 8.25. Increasing the blowing rate to the range $0.9 \leqslant M \leqslant 1.75$ tends to increase the dimensionless amplitude as the blowing rates are increased for all values of reduced velocities, namely 8.25, 12.5 and 16. The effect in the fluid elastic region in the vicinity of the cylinder (Fig. 10) is different in that at reduced velocity of $U_r = 16$ the variation in the A/D with the bowing rates is almost negligible and at reduced velocity $U_r = 61.85$, increasing the blowing rate decreases the A/D. At very high reduced velocity of 108 and for blowing rate, $M > 0.3$ increasing the blowing rates reduce the A/D sharply.

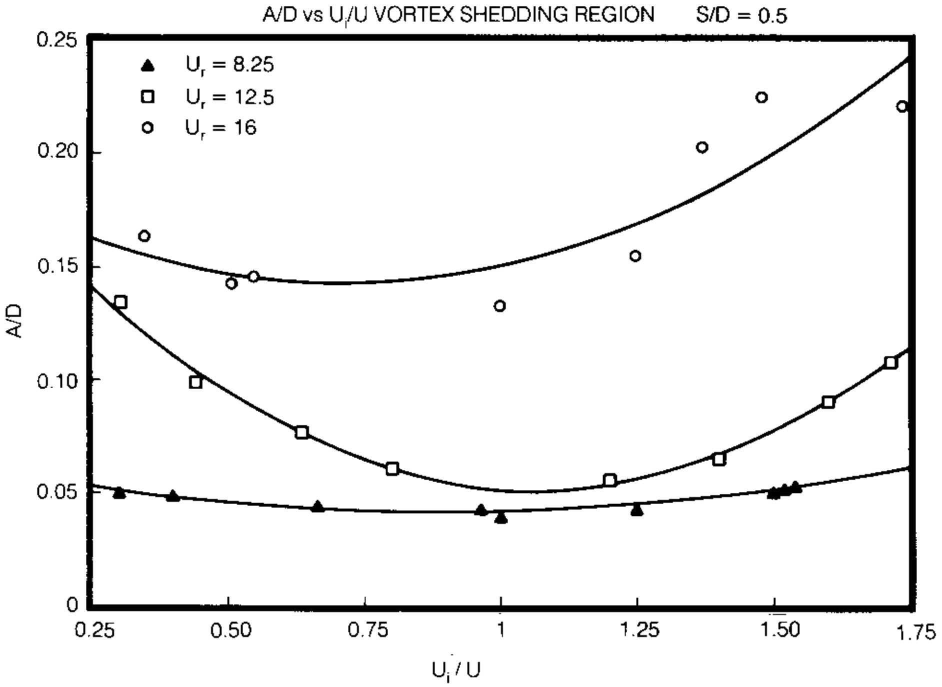

Fig. 9. The effect of injection on A/D at S/D = 0.5 for various U_r of 8.25, 12.5 and 16

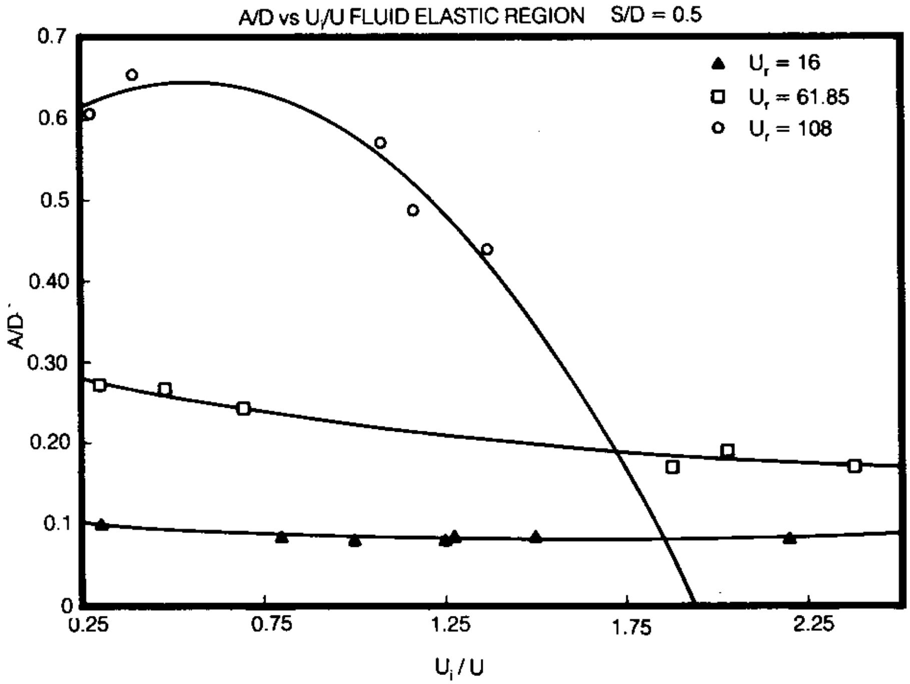

Fig. 10. The effect of injection on A/D at S/D = 0.5 for various U_r of 16, 61.85, and 108

The effect of the blowing rate on the dimenisonless amplitude for different reduced velocity at S/D = 1 is shown in Fig. 11 for the vortex region. The effect of injection on the dimensionless amplitude is very much dependent on the reduced velocity. At low blowing rates and a reduced velocity of 8.25 the effect of injection is almost negligible. Increasing the reduced velocity to 12.5 for blowing rates of 0.3 to 0.8 results in an increase in the value of A/D when $U_r = 12.5$. At higher blowing rates $0.8 \leq M \leq 1.8$ there is a decrease in A/D. Inreasing the reduced velocity to $U_r = 16$, two distinct effects are seen from Fig. 11; for the low blowing rates $0.25 \leq M \leq 0.8$ increasing the blowing rates tends to decrease A/D while for high blowing rates increasing the blowing rates tends to increase the dimensionless amplitude.

The effect of blowing rate on the dimensionless amplitude for different reduced velocities at S/D = 1 in the fluid elastic region is shown in Fig. 12. The most significant reduction occurs at a reduced velocity $U_r = 61.85$ with a sharp decrease in A/D as the blowing rates are increased. However, at $U_r = 108$, a slight reduction occurs at blowing rates less than 0.8 and then the dimensionless amplitude is increased again with the blowing rates.

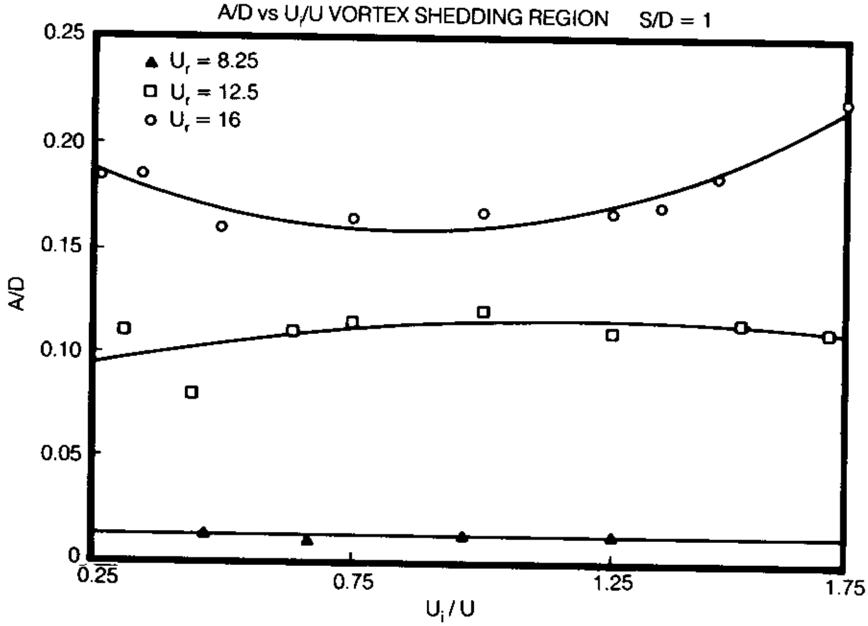

Fig. 11. The effect of injection on A/D at S/D = 1 for various U_r of 8.25, 12.5 and 16

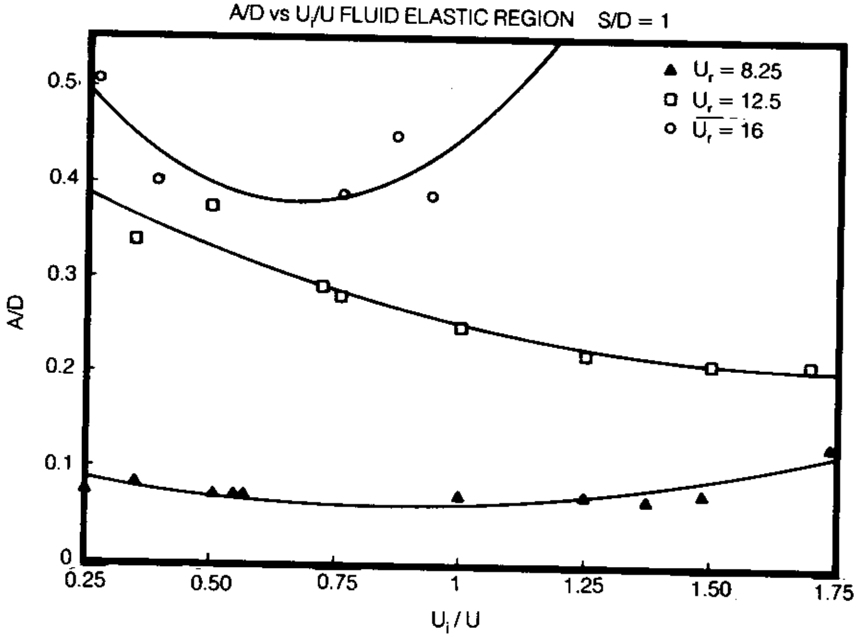

Fig. 12. The effect of injection on A/D at S/D = 1 for various U_r of 16, 61.85 and 108

Conclusions

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

1) The effect of the secondary injection on the flow induced vibration of a single cylinder is very much dependent on the location of injection, whether the flow induced vibration is in the vortex shedding region or in the fluid elastic region, and on the blowing rate ratio.

2) For most blowing rates considered the flow injection tends to reduce the fluctuations in the dimensionless amplitude A/D.

3) In the vortex shedding region for the reduced velocities of 8.25, 12.5 and 16 in the vicinity of the cylinder, $S/D = 0.5$, the injection tends to reduce the dimensionless amplitude for the low blowing rate range $0.25 \leqslant M \leqslant 0.8$. At high blowing rate range $0.8 \leqslant M \leqslant 1.75$ the blowing rates tends to increase the dimensionless amplitude.

4) In the vicinity of the cylinder for all blowing rates considered the secondary flow injection reduces the dimensionless amplitude in the fluid elastic region.

5) There is a strong evidence that the injection of a secondary flow may be used as a means of controlling the flow induced vibration of an elastically mounted cylinder. The reduction in the dimensionless amplitude could be as much as 50%

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تأثير الحقن الثانوي على الاهتزازات الحثّية الناتجة عن الجريان العارض لاسطوانة منفردة

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ملخص البحث. تقدم هذه الدراسة نتائج عملية لتأثير الحقن الثانوي بالقرب من أسطوانة ناعمة مرنة على الاهتزازات الحثية لهذه الأسطوانة مع دراسة احتمالية استخدام هذا الحقن كوسيلة للتحكم في الاهتزازات الحثية. لقد وجد أن هذا التأثير يعتمد على معدّل ومكان الحقن أمام الأسطوانة وكذلك على مقدار السرعة المقللة.

إن النتائج التي تمّ الحصول عليها تُشير إلى وجود مجموعة من سرعات ومكان الحقن ، والسرعة المقللة التي يمكن أن تؤدي إلى خفض في مقدار الاهتزازات غير البعدية بمقدار قد يصل إلى ٥٠٪. غير أنه يوجد هناك معدّلات حقن مثل معدّل الحقن الأكبر من ١ ، والذي يمكن أن يؤدي إلى زيادة في اهتزازات الأسطوانة.

إن نتائج هذه الدراسة تشير إلى أنه تحت ظروف جريان معينة يمكن استخدام طريقة الحقن الجانبي للتحكم في الاهتزازات الحثية للأسطوانة.