DYNAMIC RESPONSE OF THE FLOW INDUCED VIBRATION OF SMOOTH AND ROUGH SINGLE CANTILEVER CIRCULAR CYLINDERS

B. A. Jubran*, M. N. Hamdan
Department of Mechanical Engineering
University of Jordan
Amman, Jordan

and

M. S. Hijawi
Department of Mechanical Engineering
Wayne State University
Detroit, Michigan 48202, U.S.A.

الخلاصة :

يقدِّم هذا البحث نتائج عملية لتأثير شدة الاضطراب وخشونة السطح على الميزات الديناميكية للإهتزازات الحثية لإسطوانة مفردة ومثبتة من طرف واحد في جريان متعارض . تم قياس مدى الإهتزاز غير البُعدي في الاتجاه المستعرض (الرفع) وفي اتجاه جريان تيار هوائي (السحب) ووجد أنهما يعتمدان على شدة الاضطراب وخشونة السطح .

لقد وجُد وبشكل عام أن تأثير شدة الاضطراب تعمل على زيادة مقدار الاهتزازات في الاتجاه المستعرض وتقليلها في إتجاه الجريان . أما خشونة السطح فتقلل من مقدار الاهتزازات في الاتجاهين .

ABSTRACT

The effects of surface roughness and turbulence intensity on the dynamic characteristics of flow induced oscillation of a cantilever single circular cylinder in a cross air flow were experimentally investigated. Measurements of the dimensionless vibration amplitude in the transverse (lift) and streamwise (drag) directions were undertaken and found to be very much dependent on both freestream turbulence intensity and surface roughness.

It was found that, in general, increasing the turbulence intensity tends to increase the vibration amplitude in the transverse direction and to decrease it in the streamwise direction. The effect of surface roughness is to reduce the dimensional vibration amplitude in both directions.

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* To whom correspondence should be addressed.

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1. INTRODUCTION

Flow induced vibration is encountered in many engineering systems, such as tall towers, power transmission lines, bridges, and heat exchangers. It is generally known that as the flow separates from either side of cylinder, vortices are shed alternately resulting in an oscillating external force which causes the cylinder to oscillate.

An extensive bibliography of numerous experimental investigations on the flow induced vibration of a single elastically mounted circular cylinder have been presented by Blevins [1], Parkinson [2], and Blake [3]. Following the review of Blake [3] it seems that there is a lack of systematic investigation regarding the effect of turbulence intensity and surface roughness on the dynamic response of a single cylinder. The effects of various system parameters such as damping and natural frequency on the stability of induced oscillation have been reported in [1–7]. The results of these investigations agree with those presented by Blevins [1] in that they show the existence of a single resonance peak in the lock-in region. However, they disagree with regard to the width of the lock-in region and the value of the reduced velocity at which the peak may occur. Gerrard [8] conducted an experimental investigation to study the order of magnitude of the oscillating properties of the flow past a circular cylinder for Reynolds number in the range 2×10^3 to 5×10^4. It was found that in this range these properties are highly susceptible to small disturbance of the frequency of the transition waves which just precede turbulence in the shear layers just downstream of the cylinder and this susceptibility is responsible for the different coefficient values measured by other workers [8].

Chen and Jenderzejczyk [9] investigated the dynamic response of a single tube subjected to a liquid cross flow. It was found that the displacement of the response in the drag direction becomes significant for reduced velocity, U_γ, in the range 1.5–4.5. On the other hand the tube displacement response in the lift direction was significant for a reduced velocity larger than 4.5. Farell and Blessmann [10] investigated the characteristics of the flow around a smooth circular cylinder in the critical Reynolds-number range $1.5 \times 10^5 - 3.8 \times 10^5$. Two distinct pressure distribution regions were observed; the first is characterized by a symmetric pressure distribution and an intense vortex shedding, while the second is characterized by an intense flow oscillations associated with formation and bursting of laminar-separation bubbles on one or both sides of the tube.

Berger [11] studies the mechanism of vortex shedding oscillation of an elastically mounted rigid cylinder. It was concluded from his study that the amplitude dependence of the damping and coupling-ratio of the system is the most significant effect on the stability of the system. Humphries *et al.* [12] used a slender cylinder to study the nature of vortex shedding from flexible cylinder undergoing large amplitude vortex excited motions in sheared flow. The cylinder used in the experiments was either allowed to vibrate as a vertical cantilever or held rigidly. It was found that for a rigid cylinder in shear flow, the vortex shedding follows Strouhal relationship. For a flexible cantilever undergoing vortex induced vibration, the wake frequency was found to match the structural response frequency throughout lock-in. Al-Bedoor [13] studied the flow-induced vibrations of an elastically mounted cylinder in cross flow. It was found that the lock-in region starts at a reduced velocity of about 5 and ceases at reduced velocity of about 12.5.

Miyata and Miyazaki [14] studied the effect of turbulence scale on the drag and lift forces of rectangular bluff cylinders having oscillation and vortex shedding. They found that there is a significant dependency on the turbulence intensity and little or no effect of scale of turbulence on the drag forces of rectangular cylinders. It was also found that the unsteady lift forces are very much affected by both turbulence intensity and scale of turbulence. Kiya *et al.* [15] studied the effects of the free stream turbulence intensity on the flow past a circular cylinder and found a correlation between Reynolds number, drag coefficient and turbulence intensity. More recently Nakamura *et al.* [16] investigated the effects of free stream turbulence intensity on the mean flow past two and three dimensional bluff bodies. It was concluded that the turbulence intensity can significantly influence bluff body mean flow and found to be very much dependent on the value of scale of turbulence. Howell and Noval [17] studied experimentally the vortex shedding from vibrating circular cylinders in turbulent flows at subcritical Reynolds numbers. Pressure and their correlation, lift coefficient and dynamic response were studied.

Guven *et al.* [18] investigated the effect of surface roughness on the mean pressure distribution and boundary layer development over cylinders mounted vertically. They found that the drag coefficient, as well as the pressure distribution parameters, have a definite dependency on the relative roughness. Farell and Fedenick [19] used a rough cylinder to study the effect of end plates. It was found that for large roughness and narrow range of Reynolds numbers, the flow is essentially unsteady, with symmetric oscillating pressure distributions and broad-band pressure.

Jubran *et al.* [20] investigated the effects of freestream turbulence on the flow induced vibration of an elastically mounted smooth and rough cylinders. It was found that in the vortex shedding region, increasing the surface roughness results in a reduction of the amplitude of oscillation, while in the fluid elastic region, increasing the surface roughness tends to enhance the oscillations. It should be noted that the present problem deals with a dynamic system that is fundamentally different in many aspects from that investigated in [20]. For example the test cylinder in the present work is clamped-free in such a way that the natural frequency of vibration in both the transverse and the streamwise directions are basically about the same, while the test cylinder in [20] is elastically mounted at both ends and was allowed to deflect more freely (less rigid) in the transverse direction than in the streamwise direction. For this reason the vibration amplitude in [20] was measured only in the transverse directions whereas in the present investigation the flow induced vibrations were measured in the transverse and streamwise directions. Furthermore the turbulence intensity levels used in the present work is generally higher than that used in the early work.

It appears from the aforementioned investigations that most of the attention has been paid to the characteristics of the flow single cylinder elastically mounted at both ends. Furthermore there seems to be a lack of data on the effect of surface roughness and turbulence intensity on the flow induced vibration of a single clamped–free cylinder. It is known that many engineering structures such as mast antenna, and multistory buildings can be modeled as a cantilever beam which are often subjected to aerodynamic loadings.

The aim of the present work is to investigate the dynamic response of smooth and rough cantilever cylinders at different turbulence intensities.

2. 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 200 cm, Figure 1. The free stream velocity was varied from 5 to 35 m/s, with the free stream turbulence intensity level of 0.35%. 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 range of Reynolds number used were approximately $6.8 \times 10^3 < Re < 4.9 \times 10^4$, based on the outside diameter of the vibrating cylinder. In this range, the Strouhal number for a circular cylinder is 0.2.

The test cylinder was an aluminum tube with cross section of outer diameter $D = 21.5$ mm, wall thickness $t = 0.5$ mm, and length $L = 440$ mm. This combination yields an aspect ratio L/D of 20.5 and mass per unit length $\overline{m}$ of 0.1662 kg/m.

The cylinder was positioned in the wind tunnel horizontally; one end is rigidly clamped, while the other is free. The cylinder passed through two slots (28 mm by 28 mm) of the wind tunnel. Note that careful considerations were taken to ensure the two dimensionality of the vortex wake. This was achieved by making the height of the slots at the two sides of the wind tunnel much less than nearly four times the diameter of the test cylinder, as was recommended by Graham [21]. This was confirmed by preliminary tests.

Standard sand papers with known roughness were glued and wrapped firmly to obtain various values for the surface roughness of the test cylinder. Three grits of sand papers with equivalent roughness (k/D) of 0.0230, 0.0138, and 0.0118 were used.

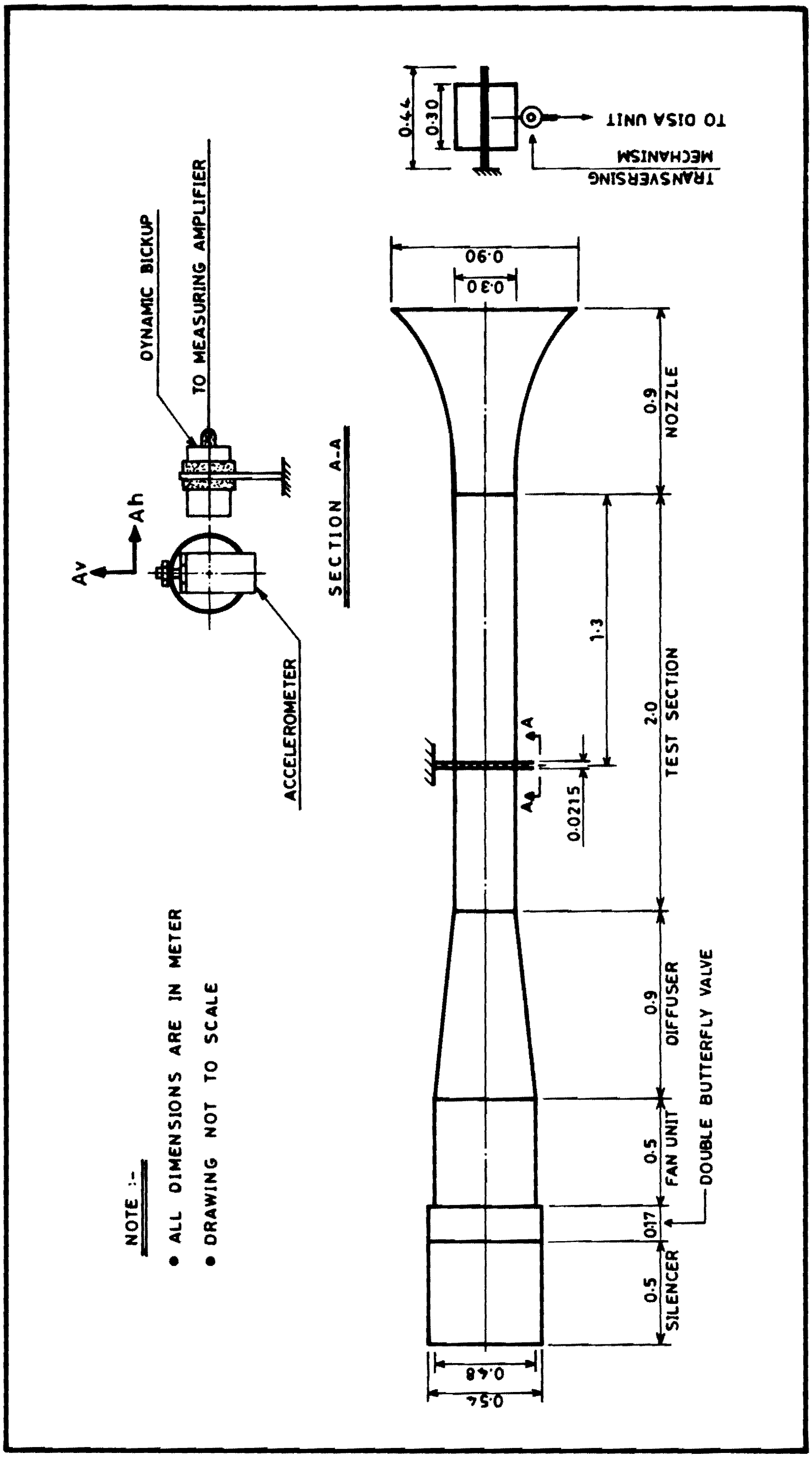

Figure 1(a). Schematic Diagram of the Different Parts of the Wind Tunnel and Experimental Rig.

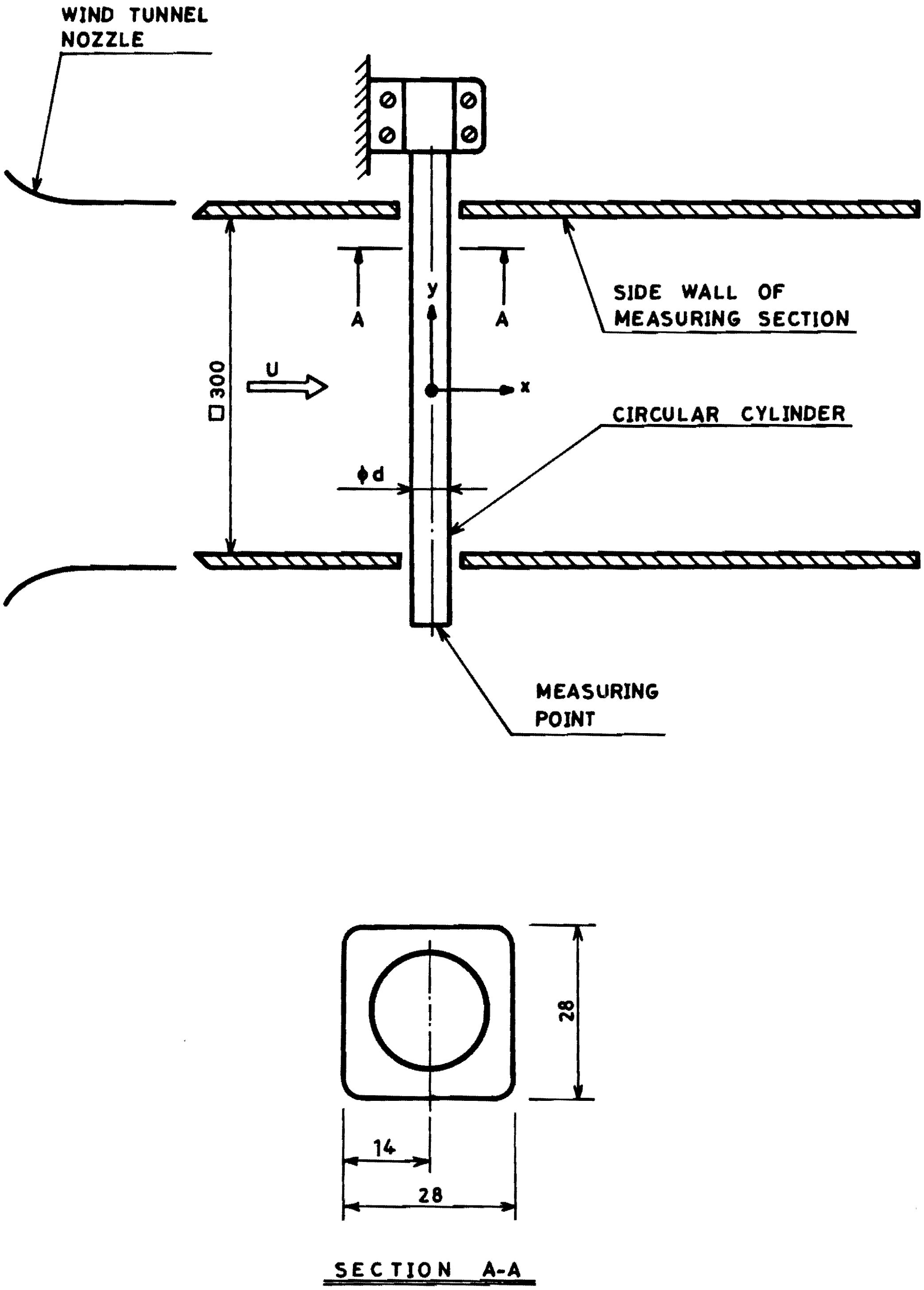

Figure 1(b). Cylinder Clamping in the Tunnel.

In order to investigate the effects of free stream turbulence intensity on the flow induced vibration of circular smooth and rough cylinders, five different "wood" turbulence generating grids were designed and used in the present experiments. The turbulence grid was located at 1 m upstream the test section. The specification of the grids as well as the turbulence intensity obtained at the position of the test cylinder are presented in Table 1. The location of the grids was found to produce a homogeneous turbulence at the position of the test cylinder by means of monitoring the turbulence signals in the test section by a digital frequency analyzer.

The amplitude of vibration in the transverse direction (lift force direction) was measured by mounting an accelerator (type B&K 4371) on the free end of the test cylinder. The output signal from the accelerator was simulataneously fed to a portable vibration meter (type B&K 2511) and to a frequency analyzer (type B&K 2131). The displacement vibration amplitude was obtained from the acceleration signal using a built-in integration network in the vibration meter. The output of the vibration meter was also fed to a storage oscilloscope type (OS 4100) where the time variation of the output displacement was monitored. The signal from the storage oscilloscope was recorded using an X–Y recorder (type WX 4402). On the other hand, the signal from the frequency analyzer was recorded by a level recorder (type B&K 2307).

The velocity of vibration in the streamwise direction (drag force direction) was measured by placing a contactless vibration up (B&K MM0002) underneath the free end of the cylinder at the same distance from the fixed end as the accelerometer. The output signal from the vibration signal was simultaneously fed to a digital frequency analyzer (B&K 2131) and to a tunable pass band filter (B&K 1621). The signal from the tunable filter was also simultaneously fed to a measuring amplifier (B&K 2636) and to a digital storage oscilloscope (OS 4100). The amplitude of displacement of the cylinder in the streamwise direction was assumed to be equal to the velocity divided by the natural frequency of the cylinder. This is justified by the fact that the dominant frequency of the response in both the transverse and streamwise directions is nearly equal to the natural frequency of the cylinder. Note that the natural frequency of the cylinder was found using simple impulsive tests to be about the same (56 Hz) in both directions.

Using the above arrangements it was possible to measure the RMS value and to monitor the signal on both frequency and time domain. A schematic diagram of this measuring arrangement is shown in Figure 2.

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 55M01). 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.

Table 1: Turbulence Grids Characteristics.

Grid No.	Rod Shape	Rod Size	Mesh Size	Turbulence Intensity
no				0.35%
1	Square	0.5 cm	2.7 cm	3.25%
2	Circular	1.0 cm	5.0 cm	3.76%
3	Square	0.5 cm	6.0 cm	4.0%
4	Circular	1.0 cm	6.0 cm	4.4%
5	Circular	1.0 cm	7.5 cm	4.68%

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 [22] was carried out. The error analysis indicated a ±4% 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. It was found that the repeatability is about ±5%. Reduced velocity within the vortex shedding was obtained by tuning the natural frequency of the test cylinder to about 56 Hz for which the logarithmic decrement was found to be about 0.083, obtained from a simple impulsive test as shown in Figure 3(*a–b*). The stability damping factor K_s is found to be 4.93.

It is worth noting that a very restricted comparison of results is outlined in the present discussion of results due to what appears to be lack of data regarding the free stream turbulence intensity and surface roughness on the dynamic response of a single cylinder on one hand, and on the other hand due to different experimental conditions and set-up. For instant Feng [4] used a damping ratio $\delta/\pi \approx 0.0026–0.007$ whereas in the present work $\delta/\pi \approx 0.026$, which is nearly an order of magnitude higher than in [4]. Consequently leading to a much lower amplitude ratio than in [4]. The mass ratio $u = \rho D^2/\overline{2m}$ and the eigenfrequency parameter $F_0 = f D^2/\nu$ are ≈ 0.0025 and 2400, respectively compared with 0.0017 and 1730 respectively in the present investigation. The clamping conditions are also different in Feng [4] and here which as will be seen later will affect the onset of the lock-in region.

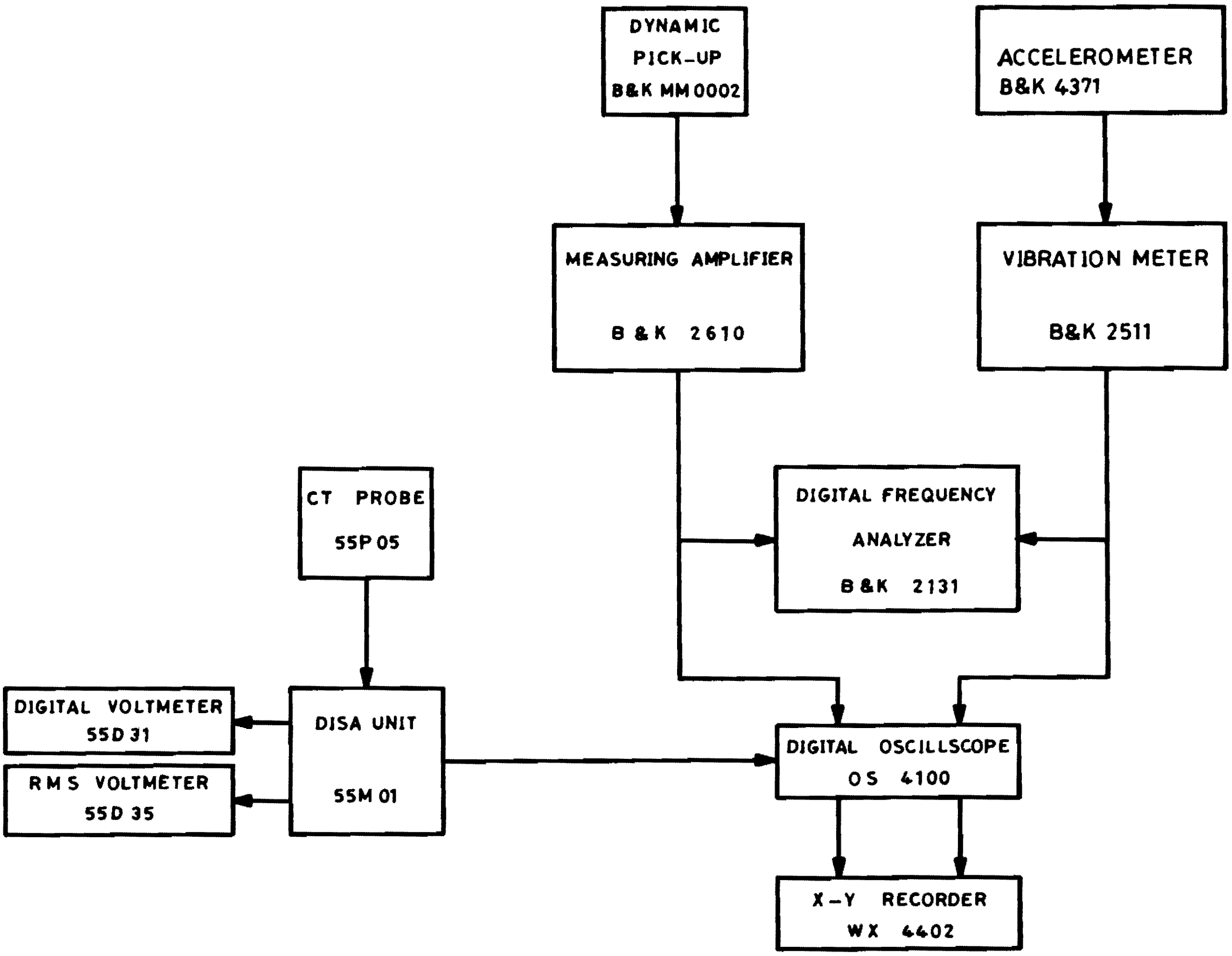

Figure 2. Signals Processing Diagram.

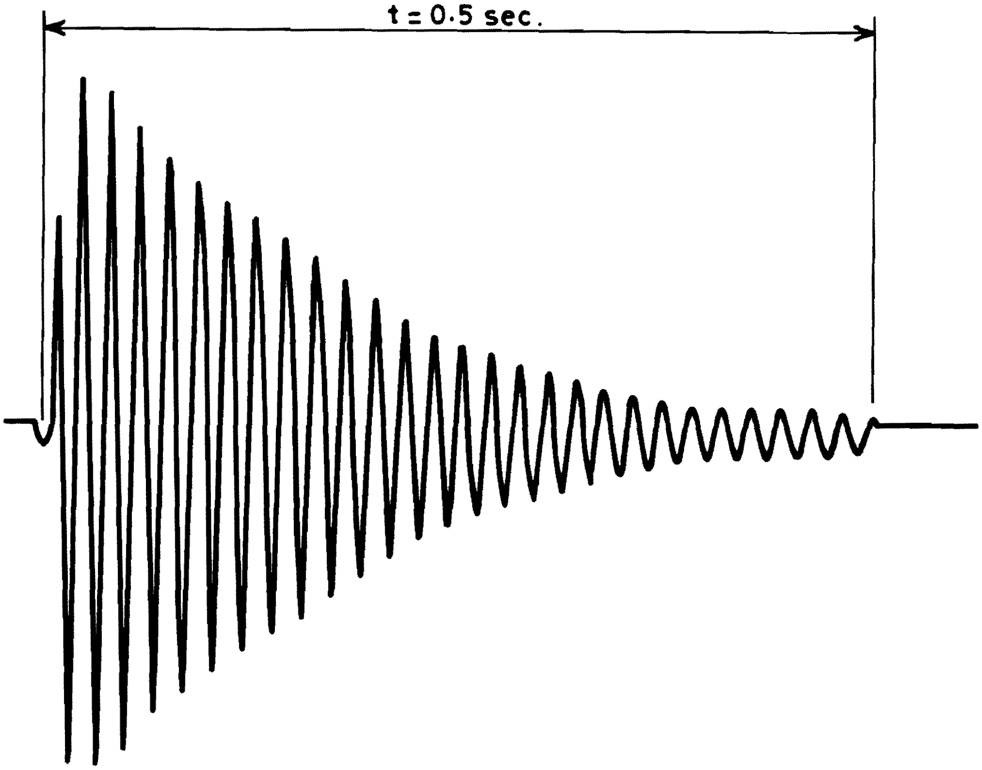

Figure 3(a). Signal Wave from the Impulse Test; f = *65 Hz,* δ = *0.090, and* k_s = *4.93.*

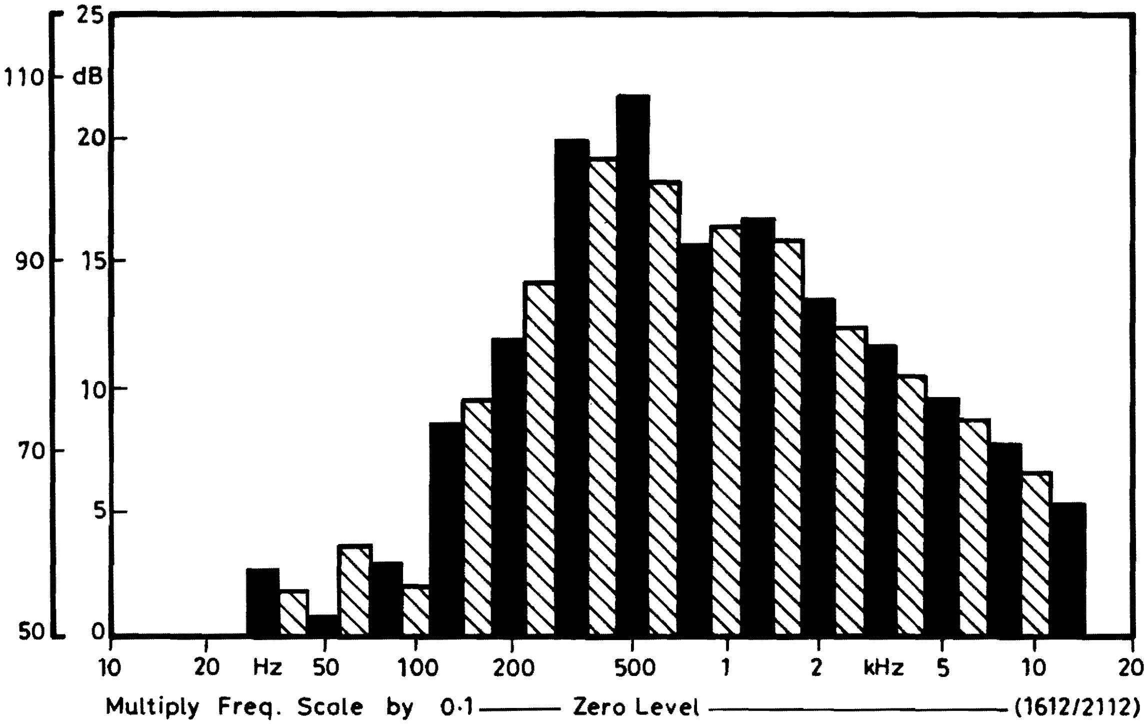

Figure 3(b). Frequency Spectrum of Impulse Test.

3.1. Smooth Cantilever Cylinder

The variation of the nondimensional RMS vibration displacement amplitude divided by the diameter of the test cylinder was measured in both the transverse direction, A_v/D and the streamwise direction, A_h/D. The dynamic response of the test cylinder is shown in Figure 4 for both the transverse and streamwise directions. It can be seen from this Figure that the dimensionless vibration amplitude is more significant in the transverse direction (lift direction) than that in the streamwise direction (drag direction). This agrees with the results of Chen and Jendrazejczyk [9] who reported that the drag force is lower than that of the lift force for air flow. It is also shown that the lock-in region (*i.e.* the range of reduced velocity over which the frequency of the vortex shedding approaches the frequency of the vibrating cylinder) starts at a reduced velocity of about 13.0. It is also shown that before this reduced velocity the cylinder is almost stationary due to a weak vortex shedding. The dynamic response curve exhibits only one distinct peak which agrees with that found for vertical cantilever cylinder by Blevins [1], Humpheries [12], Howel *et al.* [17], and Sviadosch *et al.* [23].

The largest amplitude of vibration, for both the transverse and streamwise directions, occurs at reduced velocity $U_\gamma = U/fD = 15.5$ in the lock-in region, Figure 4 where the cylinder vibrates harmonically at its fundamental natural frequency, (Figure 5). The lock-in region ceases for a reduced velocity around 21.0, after which the vibration amplitude of the cylinder shows little variation up to a reduced velocity of 30, (Figure 4).

Figure 4 shows that the lock-in region for the single smooth cylinder starts at $U_\gamma = 12.5$, which corresponds to Strouhal frequency ratio $\Omega = f_s/f \approx 2.5$, in contradiction to the findings of Feng [4], where it starts at $\Omega \approx 1.0$. This difference may be due to the difference in the mounting of the cylinders; in the present results the cylinder is rigidly mounted at one end with two degrees of freedom in the transverse and streamwise directions of the onflow, whereas in that of Feng [4], the cylinder is spring mounted with only one translatory degree of freedom in the transverse direction of the onflow since the lift force oscillates with f_s. On the other hand, the antisymmetric vortex formation causes the drag force to oscillates with $2f_s$ and consequently its resonance starts at $\Omega = 2$.

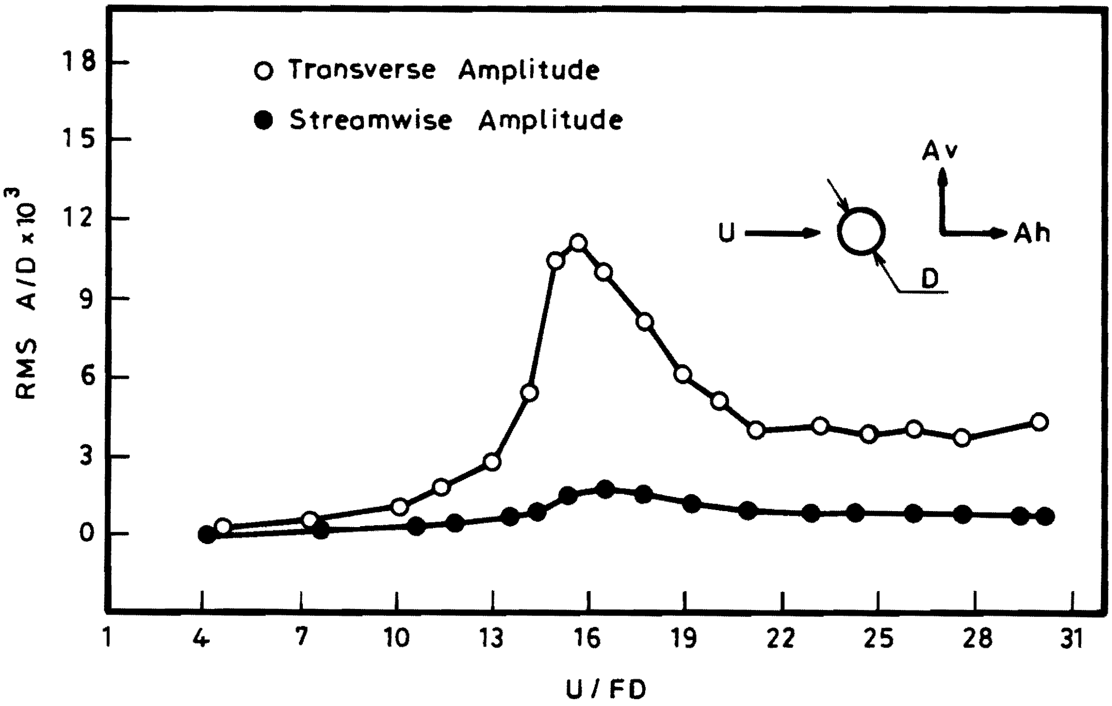

Figure 4. Dimensionless Vibration Amplitude in the Transverse and Streamwise Directions with Reduced Velocity of Single Cylinder.

It is interesting to note that the vibration signal wave form over the entire lock-in region was observed to be nearly harmonic at a frequency equal to the free vibration frequency of the test cylinder as shown in Figure 6. On the other hand the signal wave form outside the lock-in region shows nonlinear characteristics as shown in Figure 7. These features of the vibration signals are the same in both transverse and streamwise directions.

3.2. Effect of Turbulence Intensity

The results of the experimental investigation on the effect of variation of free stream turbulence intensity on the flow induced vibration of a test cylinder fixed only at one end are presented and discussed in this subsection. The free stream turbulence intensities used were, in addition to the low wind tunnel turbulence intensity (0.35%), 3.25%, 4.0%, 4.4%, and 4.68% at the position of the test cylinder. Figure 8(*a*) shows the distribution of the dimensionless amplitude A_v/D *versus* the reduced velocity for various turbulence intensities. It can be seen from

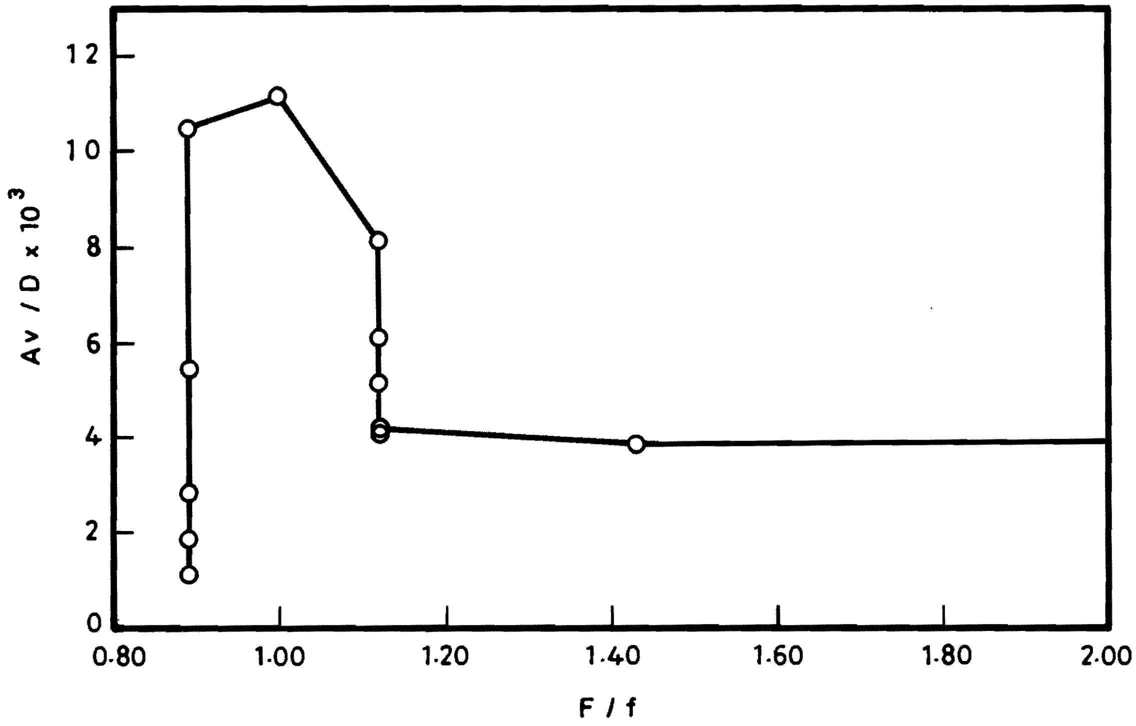

Figure 5. Dimensionless Vibration Amplitude in the Transverse Direction with Frequency of Single Cylinder Low Turbulence Intensity.

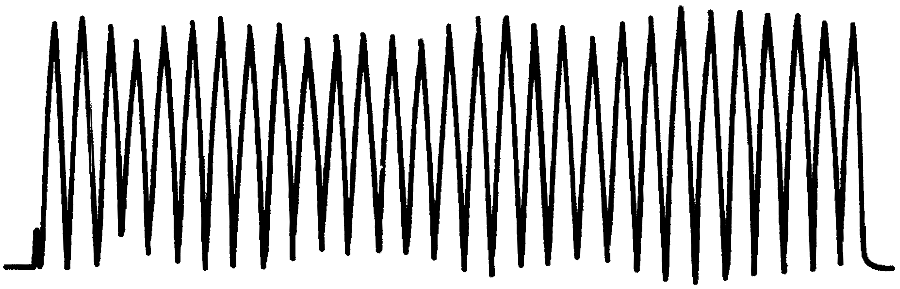

Figure 6. Signal Wave Form of the Vibrating Cylinder at Low Turbulence Intensity and in the Lock-in Region.

this Figure that the turbulence intensity has two main effects on the dynamic response of the test cylinder in the transverse direction:

1. Increasing the turbulence intensity was observed to delay the start of the lock-in region. For example in the absence of turbulence generating grids, the lock-in regions starts at $U_\gamma = 13$, while for $TU = 4.0\%$ the lock-in region was observed to start at $U_\gamma \approx 15$. Note that the start of the lock-in region was determined by observing the signal wave form, where in the lock-in region the signal wave form is nearly pure sinusoidal.
2. Increasing the turbulence intensity from $TU = 3.25\%$ to 4.0% resulted in an increase in the values of A_υ/D with response curve showing a continuous increase in A_υ/D with increasing the reduced velocity. On the other hand for $TU > 4.0$ the vibration amplitude increases with increasing the turbulence intensity where the response curve shows the same trend as the case of low turbulence where the vibration amplitude tends to fall to low value after reaching a peak in the lock-in region.

The difference in the dynamic response of the cylinder trends at $TU = 4.4\%$ and 4.68% (circular rods) on one hand and $TU = 3.25\%$ and 4.0% (square bars) on the other may be contributed to the type of the generating grids used. Hancock and Bradshaw [24] reported that grids made of parallel row of square bars tends to exhibit peculiar behavior of the *u*-component spectra which may leads to nonuniform unsteady flow due to the large size of the separated region behind the grids and this could produce the "quasi non resonant" response as shown in Figure 8(*a*) for $TU = 3.25\%$ and 4.0%. One other possible explanation for the "non resonant" response at $TU = 3.25\%$ and 4.0% is due to the high damping ration, $\delta/\pi = 0.026$, used in the present study which is very near to the critical threshold amplitude ratio for lock-in.

The increase in the turbulence intensity tends to modify the flow pattern around the cylinder and hence the flow induced forces on it. This in turn, changes the dynamic response of the test cylinder resulting in an increase in the dimensionless amplitude A_υ/D due to the increase in the growth rate of the shear layers as was reported by Miyata and Miyazaki [14].

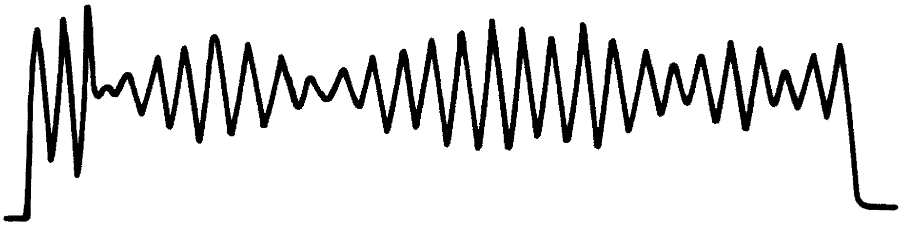

Figure 7(a). *Signal Wave Form of the Vibrating Cylinder at Low Turbulence Intensity and Outside the Lock-in Region at* $U_\gamma = 10$.

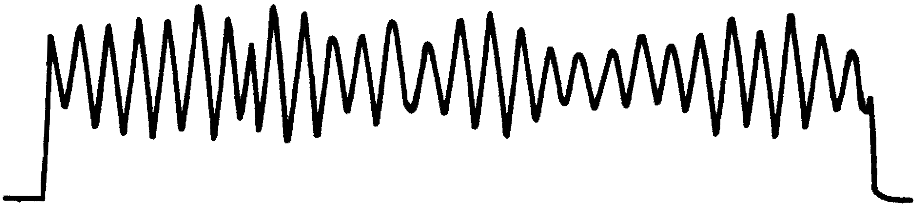

Figure 7(b). *Signal Wave Form of the Vibrating Cylinder at Low Turbulence Intensity and Outside the Lock-in Region at* $U_\gamma = 25$.

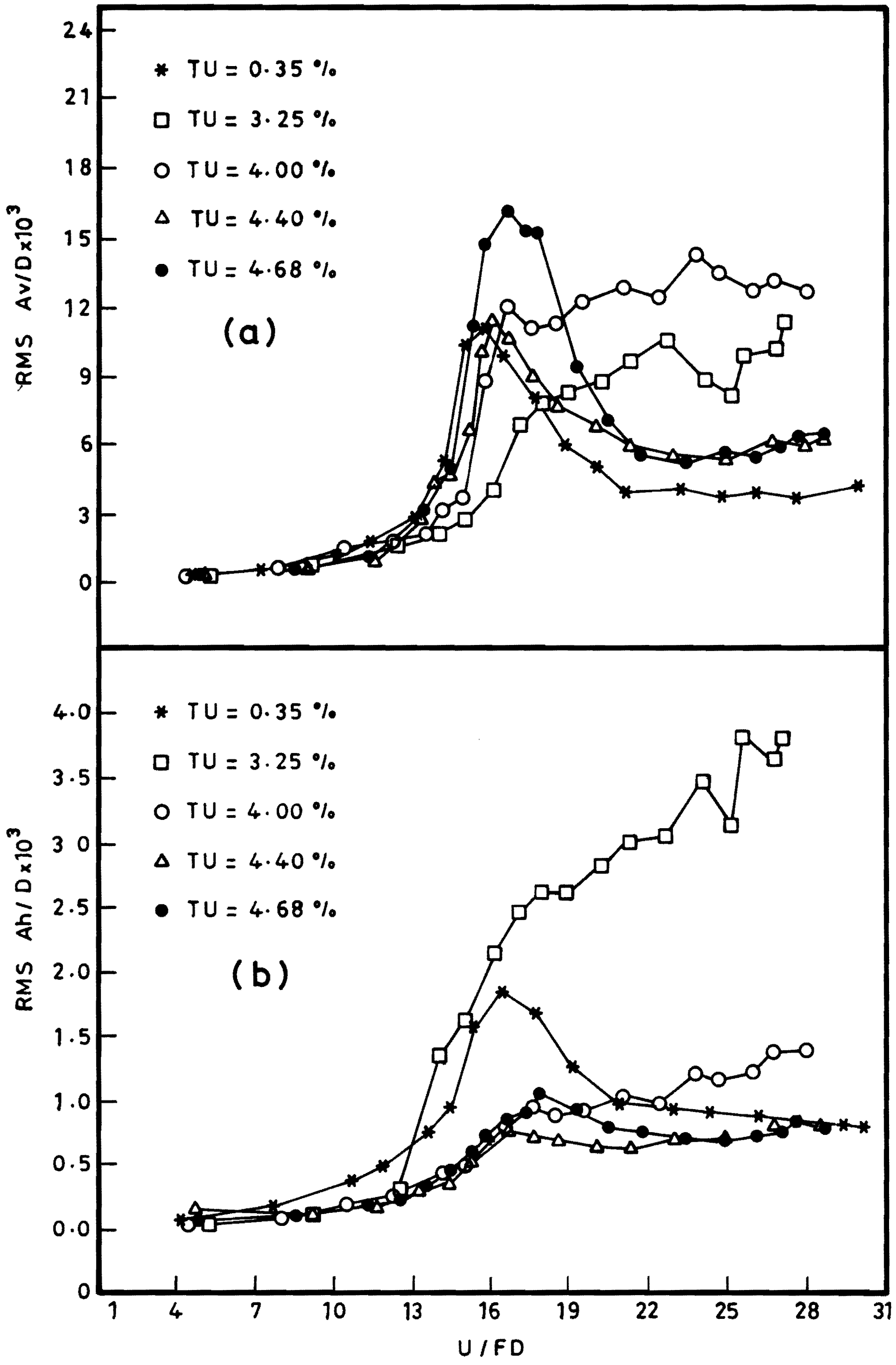

Figure 8. Effect of Turbulence Intensity on the Flow Induced Vibration of Single Cylinder; (a) Transverse Direction, (b) Streamwise Direction.

One interesting observation regarding the dynamic response in Figure 8(*a*) is that for *TU* = 4.4% and 4.68%: the dimensionless amplitude peak occurs almost at the same *U/fD* as for single cylinder. This implies that the frequency of vortex shedding from the cylinder remains unchanged, while the energy of pulsations induced by this shedding builds up. Similar results and conclusions were reported by Sviadosch *et al.* [23]. This may also be confirmed by the results displayed in Figure 9 which show that the maximum amplitude for *TU* = 4.68% is attained when the vibrating cylinder frequency approaches its natural frequency.

The variation of the RMS streamwise dimensionless vibration amplitude with the reduced velocity for different *TU* is shown in Figure 8(*b*). The main interesting finding is the sharp and continuous build up of the vibration amplitude when the turbulence intensity is *TU* = 3.25%. This implies that for this turbulence intensity, the drag forces increase at a larger rate than that for the lift forces. The general trend for the effect of turbulence intensity on the dynamic response of a cantilever cylinder in the streamwise direction is that increasing the turbulence intensity tends to reduce the dimensionless amplitude A_h/D in the streamwise direction. Except for turbulence intensity of *TU* = 3.25%, the dimensionless amplitude is lower than that of low turbulence.

3.3. Rough Cylinder

Surface roughness is known to affect the separation and to change the width of the wake behind an oscillating cylinder [25]. The variations of dimensionless vibration amplitude in the transverse and streamwise directions for cylinders of various surface roughness of *k/D* = 0.0118, 0.0138, and 0.023 together with those of smooth cylinder are shown in Figure 10. It can be seen from Figure 10(*a*) that for *k/D* = 0.0118 and *k/D* = 0.0138 the lock-in region disappeared and the dimensionless vibration amplitude in the transverse direction is significantly reduced by as much as 60% compared with that of a smooth cylinder lock-in region. The reduction of amplitude may be due to the retarded separation and narrowed wake which cause the suppression of the vortices and hence reducing the fluctuating components of the aerodynamic forces responsible for the cylinder excitation as found by Zdravkovich [25].

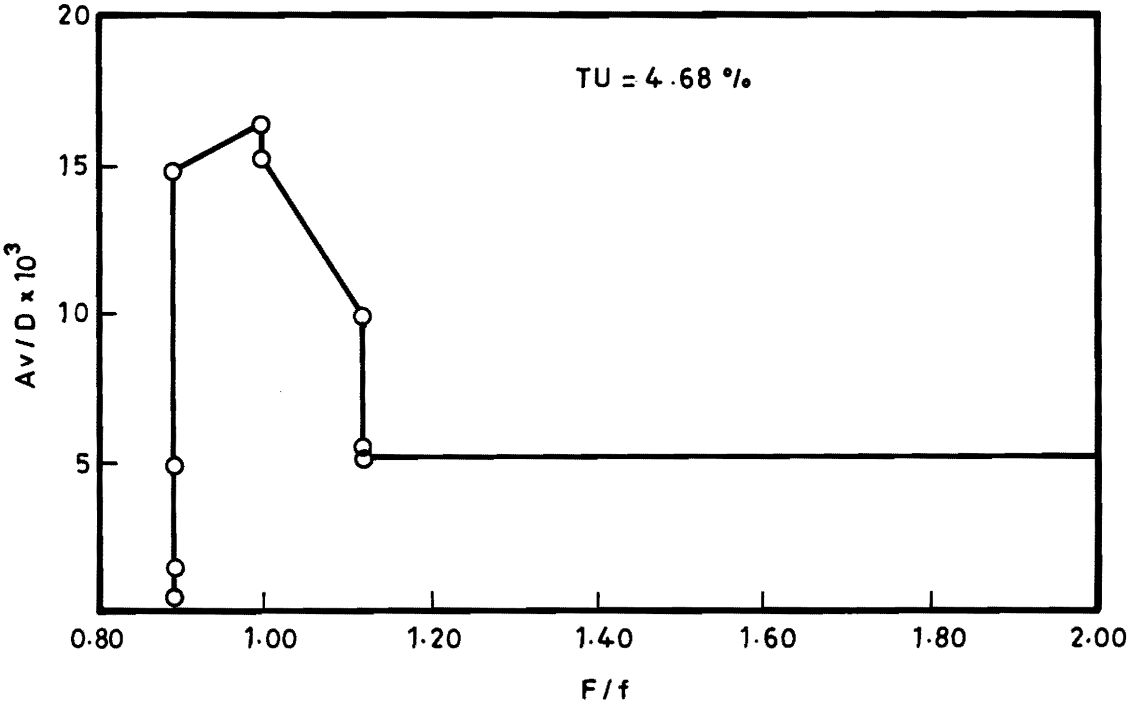

Figure 9. Dimensionless Vibration Amplitude in the Transverse Direction with Reduced Frequency of a Single Cylinder with Turbulence Intensity of TU = *4.68%.*

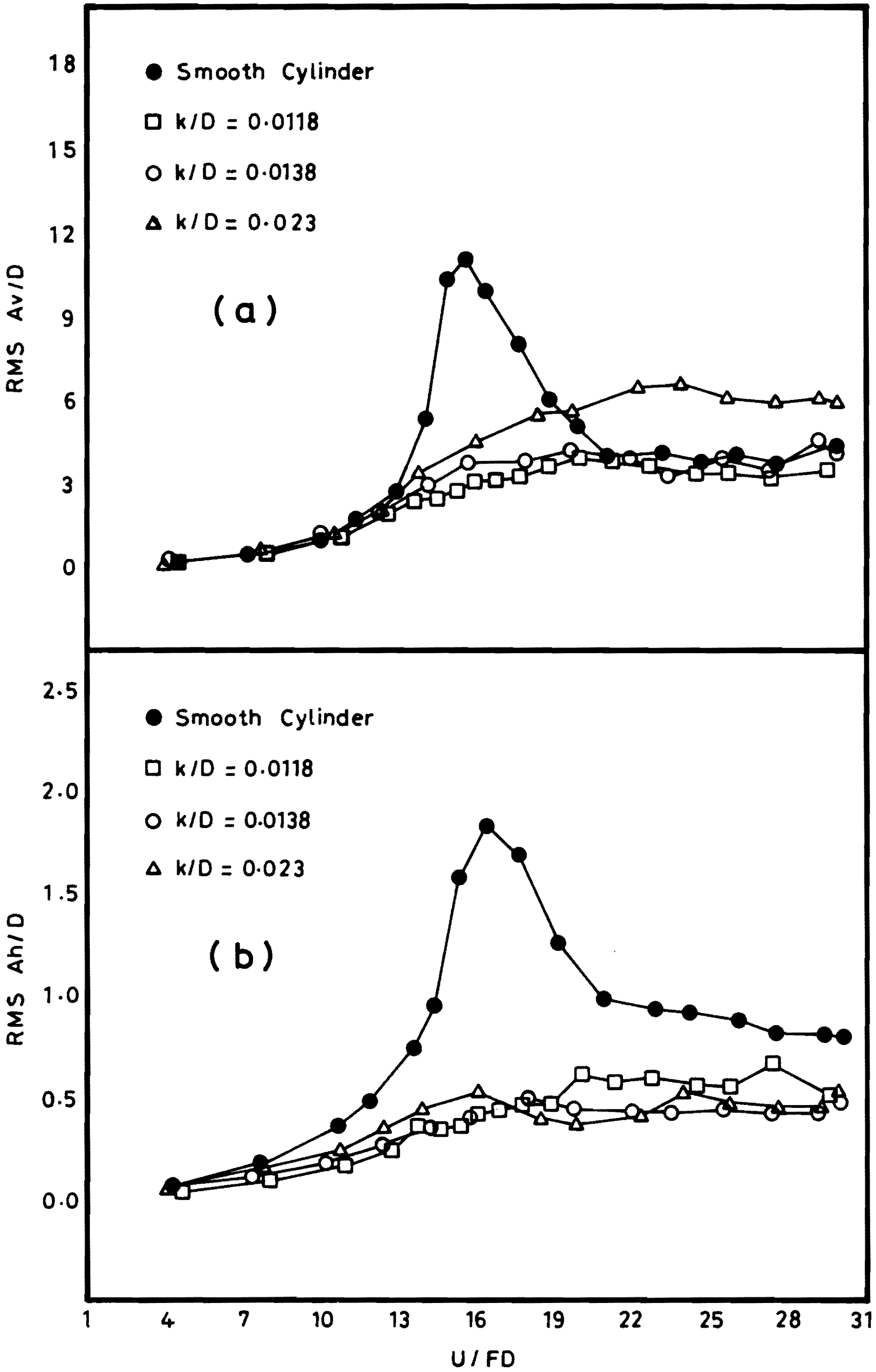

Figure 10. Effect of Surface Roughness on the Flow Induced Vibration of Single Cylinder; (a) *Transverse Direction,* (b) *Streamwise Direction.*

The vibration amplitude for the higher roughness (*i.e.* $k/D = 0.023$) is slightly larger than the other two values of the relative surface roughness. Note that for the above three values of k/D the values A_υ/D increases gradually and reach nearly constant values with increasing U_γ where the response curves do not show the usual lock-in region peak values observed for the smooth cylinder. This implies that the surface roughness tends to disturb the symmetry of vortex shedding resulting in the reduction of the induced oscillating lift force. The experiment for $k/D = 0.023$ was repeated several times to see if the increase in A_υ/D for this case was due to an experimental error but, all the time, the same results as shown in Figure 10(*a*) were obtained. This could be explained by the occurrence of a nonlinear induced negative aerodynamic damping which depends on the cylinder motion. This complex interaction with the nonlinear behavior is not yet understood. No comparison of the present results is established due to what appears to be a lack of data regarding the effect of free stream turbulence intensity and surface roughness on the dimensionless amplitude.

The effect of surface roughness on the dimensionless amplitude in the streamwise direction is shown in Figure 10(*b*). It can be seen that for the various surface roughness used, the dynamic response curves show the same behavior where A_h/D is significantly reduced with increasing surface roughness when compared with a smooth cylinder. The reduction in A_h/D may be attributed to the increase in the drag in the streamwise direction. No lock-in region peak is observed and the amplitude increases gradually to a nearly constant low value.

4. CONCLUSIONS

The main conclusions deduced from the present investigation are as follows:

1. For a single cantilever cylinder the flow induced oscillation in the transverse direction is much larger than that in the streamwise direction.
2. Three regions characterized the dynamic response of a smooth cantilever cylinder; (*i*) low vibration amplitude, $U/fD < 13.0$, (*ii*) large amplitude in the lock-in region, $13.0 < U/fD < 21.0$ and (*iii*) steady oscillatory response, $U/fD > 21.0$.
3. The dynamic response for a cantilever in air-flow is characterized by only one peak in the lock-in region.
4. The increase of turbulence intensity increases the vibration amplitude in the transverse direction and decreases it in the streamwise direction except for turbulence intensity of $TU = 3.25\%$.
5. In general, the effect of surface roughness is to reduce the transverse vibration amplitude in the vortex shedding region, with no apparent lock-in region.
6. The dimensionless amplitude in the transverse direction is larger than that obtained for smooth cylinder when high relative roughness of $k/D = 0.023$ is used.
7. The effect of surface roughness results in a reduction in the vibration amplitude in the streamwise direction.

NOTATION

A_υ	RMS vibration amplitude in the transverse direction.
A_h	RMS vibration amplitude in the streamwise direction.
D	Diameter of the test cylinder.
A_υ/D	Dimensionless vibration amplitude in the transverse direction.
A_h/D	Dimensionless vibration amplitude in the streamwise direction.
f	Natural frequency of the test cylinder.
f_s	Strouhal frequency.
F	Frequency of the vibrating cylinder.
k	Roughness height.
K_s	Stability Damping factor ($2\overline{m}\delta/\rho D^2$).
k/D	Relative roughness height.
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.
Ω	Strouhal frequency ratio.
ρ	Density of the fluid of the mainstream flow.
ν	Kinematic viscosity of air.
U	Mainstream velocity.
U_γ	Reduced velocity U/fD.
TU	Free stream turbulence intensity.

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