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An Investigation of the Criteria Controlling Sustained Self-Excited Oscillations of Cylinders in Flowing Water

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AN INVESTIGATION OF THE CRITERIA CONTROLLING SUSTAINED SELF-EXCITED OSCILLATIONS OF CYLINDERS IN FLOWING WATER.

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ABSTRACT

In this paper, water channel experimental data are discussed and compared with conventional wind-tunnel data. Stability criteria are proposed for the cross-flow and flow directions of oscillation. Fluctuating drag force coefficients are deduced from a linear mathematical representation of the cylinder located in flowing water and oscillating in the flow direction.

INTRODUCTION

Flow-excited oscillations of structures in wind are fairly well documented, and design criteria are correspondingly comprehensive. In flowing water (steady currents) such oscillations can be considerably more complex.

The purposes of this paper are to define stability criteria which, when developed can be applied to future designs of marine structures, and to quantify the fluctuating drag force coefficients on a single cylinder undergoing oscillations in the flow direction.

When a fluid flows about a stationary cylinder the flow separates, vortices are shed and a periodic wake is formed. The frequency of shedding of pairs of vortices primarily is a function of velocity (V) cylinder diameter (d) and Reynolds number (Re). The non-dimensional wake frequency S, the Strouhal number, is defined as $S = f_v d/V$, and over a wide range of Reynolds numbers $10^2 < Re < 10^5$, $S \simeq 0.2$. The overall relationship between S and Re is well documented, Morkovin (1964), and it is not proposed to quote details here, other than to point out that absolute values of S also depend upon cylinder surface roughness, length/diameter ratio and turbulence levels.

Each time a vortex is shed from the cylinder, it alters the local pressure distribution and the cylinder thus experiences periodic pressure-generated forces at frequencies f_v and $2f_v$ in the cross-flow and in-line directions respectively.

If the cylinder is flexible or flexibly mounted, interactions can arise between the vortex shedding mechanism and the cylinder deflections. Under certain conditions, sustained oscillations can be excited and the cylinder oscillates at a frequency close to or coincident with its natural frequency. Such oscillations are classed as self-excited.

In air flow, chimneys, telegraph wires and pipeline suspension bridges almost invariably oscillate in a direction normal to the flow of air. These are the so-called cross-flow oscillations. There have been rare exceptions when cylinders in air flow have oscillated in the direction of flow (i.e. in-line motion) but these have been due to features of their installation, Auger (1968), Walshe (1972).

In water, marine piles, submarine periscopes and braced members of offshore structures can be excited to oscillate in both the in-line and cross-flow directions, King (1974), and the in-line oscillations can be excited at flow velocities considerably lower than the critical velocities for cross-flow motion.

Aerodynamicists usually rank experimental data by relating non-dimensional oscillatory amplitudes (y/d) to the two non-dimensional groups, Reduced Velocity V/nd (n = cylinder natural frequency) and the Stability Parameter

$k_s = \frac{2 m_e \delta}{\rho d^2}$ (m_e is the equivalent mass/unit length, δ is the logarithmic decrement and ρ is the mass density of the fluid). This practice will be followed here.

It will be noted that Reduced Velocity and Strouhal number can be transposed; a Reduced Velocity of 5 is the inverse of the Strouhal number S for the condition $f_v = n$. For values of V/nd less than 5, f_v is less than n; conversely for V/nd greater than 5, f_v is greater than n. Similarly, k_s can be interpreted as an amalgamation of the mass ratio $m_e/\rho d^2$ and the logarithmic decrement δ. This grouping results from consideration of the energy balance at 'resonance', Scruton (1963). The Stability Parameter of a cylinder in water is discussed in the next section.

REVIEW OF RESEARCH AND DEFINITION OF CRITERIA

Cross-Flow Oscillations

The excitation range of cross-flow oscillations in air extends over $4.75 < V/nd < 8$, Wootton (1969), Vickery and Watkins (1962), and maximum amplitudes occur in the range $5.5 < V/nd < 6.5$.

In water, the excitation range of cross-flow oscillations can be increased to $4.5 < V/nd < 10$ with maximum amplitudes falling within the range $6.5 < V/nd < 8$, Glass (1970), King et al.(1973).

The differences between the performance in air and water probably are caused by differences in mass ratio and length/diameter ratio, although test facility details (i.e. damping and turbulence levels) could also influence the results, Wootton (1969).

The oscillations arise from interactions between the cylinders' flexibility and the vortex shedding mechanism, in which vortices are shed from alternate sides of the cylinder. Fig. 1 shows the wake of a cylinder oscillating in the cross-flow direction. The circulation in each vortex is augmented by the interactions referred to and this makes it possible to identify the individual vortices by the creation of dimples in the water surface, as seen in the photograph. The width of the vortex street is a function of the oscillatory amplitudes because a vortex is shed at each cross-flow reversal of direction, i.e. each half cycle. It should be noted that throughout the major part of the excitation range, the frequency of vortex shedding is no longer a function of velocity but is approximately constant and equal to the cylinder's natural frequency (in the case of a cylinder in water, the natural frequency measured in still water). This is termed synchronization or lock-in.

It will be remembered that the oscillatory amplitudes are dependent not only upon V/nd but also upon the Stability Parameter k_s. Fig. 2 is an assembly of wind tunnel and water channel experimental results and it will be seen that the results fall on a sensibly continuous curve of approximately hyperbolic form. The largest amplitudes are recorded for the smaller values of k_s and if k_s is sufficiently large (>18) then no significant amplitudes result. The amplitudes plotted on the graph are the maximum experienced mutually by the cylinder and fluid. These are defined fairly easily for cylinders in air flow but for the water channel tests with part-immersed cylinders the amplitudes are functions of mode shape. For the fundamental (sway) mode they are the amplitudes at the water surface whilst for higher normal modes they would be the maximum amplitudes of the immersed sections. It is not meaningful to quote amplitudes of sections of the cylinders not exposed to the fluid forces because the essentially non-linear and amplitude-dependent flow excitation phenomena are extant only over the common immersed length. The form of the Stability Parameter k_s also allows for the part-immersed effects by re-defining an equivalent mass/unit length, m_e, of the cylinder whose length is made equal to the water depth. King et al.(1973). King (1973) demonstrates the application of this Stability Parameter at the design stage by a worked example based on various modes of oscillation of a mooring dolphin. The justification for using this form of m_e for inclusion in k_s is that the in-phase component of fluid force is inertial and invariant with fluid velocity (i.e. regarding the added mass as constant and 'frozen' to the cylinder). Experimental results have confirmed this notion of added mass and its invariance with amplitude and frequency, King (1971). Darwin (1953) points out that in reality added mass cannot be regarded rigorously as a collar of fluid surrounding the cylinder as the system is actually a continuously changing process, involving changes in the 'drift mass' each half cycle.

The continuity of the common curve through the collected experimental points (Fig. 2) is regarded as confirmation of the validity of using this form of k_s and y/d for both part-immersed and wholly immersed cylinders.

From Fig. 2 it will be observed that the limiting cross-flow amplitudes are approximately 2 diameters. It is interesting to note that unlike mechanical oscillations, the amplitudes do not tend to infinity for zero damping, and this emphasizes the amplitude-dependence of the self-excited oscillations.

In-line oscillations

Oscillations in the in-line direction are contained within two adjacent but separate Instability Regions (see Fig. 3). The First Instability Region covers the range $1.25 < V/nd < 2.5$ and excitation in-line thus is initiated at velocities of only one quarter those necessary for cross-flow excitation (i.e. $V/nd = 1.25$ in-line, compared with $V/nd \simeq 5$ cross-flow). Maximum amplitudes coincide with $V/nd \simeq 2.1$. The Second Instability Region is $2.7 < V/nd < 3.8$ with maximum amplitudes at $V/nd \simeq 3.2$. These values are influenced by the magnitude of k_s, length/diameter ratio and other effects, King (1974). It will be seen that the amplitudes of oscillation in the two Instability Regions are approximately equal for low k_s, and whereas the crossflow motion was characterized by alternate vortex shedding, it will be seen that the two Instability Regions of in-line motion are associated with two types of vortex shedding, King (1973). The First Instability Region is identified by symmetric vortex shedding and the Second by alternate vortex shedding (see Figs. 4, 5). These results are applicable to at least the first three normal modes in-line and this allows a composite graph of families of Instability Regions of in-line and cross-flow motion to be drawn to a base of flow velocity.

Fig. 6 shows the oscillatory amplitude versus k_s graph for the first three normal modes of in-line motion. It is similar in shape to Fig. 2 and reveals that significant oscillations in-line will be initiated only if $k_s < 1.2$. Maximum amplitudes in-line are approximately 0.2 diameters, or about one tenth the corresponding maximum cross-flow amplitudes.

Although the graph of Fig. 6 was compiled from laboratory experiments, King (1973), the results of a full scale test, Wootton et al. (1972), are also included and these fall on the common curve. Hydroelastic model testing, King (1974), has previously established the validity of small scale testing of oscillating marine structures.

ANALYSIS OF THE FLUCTUATING FORCE COEFFICIENTS C'_d AND C'_L.

In this linear mathematical representation, the cylinder material properties (mass, geometry, elasticity and hysteretic damping), the added mass of water and the hydrodynamic damping were converted into matrix form for each element of the cylinder length. The vortex excitation was represented by a periodic forcing function dominated by C'_d or C'_L and uniformly distributed over the cylinder immersed length. King (1974), describes the detailed matrix manipulation and methods of solution.

First Instability Region of in-line oscillations:

Evaluation of C'_d. The hydrodynamic forces of excitation and damping exerted on a cylinder oscillating in-line are shown in Fig. 7. An analysis of the free shear layers in the vortex shedding of Fig. 4 shows that during the First Instability Region, identified by symmetric shedding, the fluctuating force coefficient C'_d should not exceed 0.86. The physical reasoning for this is based on the variation in the location of the separation points on the cylinder oscillating in-line as shown in Figs. 8a, 8b.

Fig. 8a shows the cylinder oscillating in the downstream direction; the free shear layers are similar to those separating from a very bluff body such as a flat plate, for which $C_d \simeq 2.1$. In Fig. 8b, the cylinder is oscillating in the upstream direction and the flow separation resembles that associated with Critical or Supercritical Reynolds numbers for which the steady drag coefficient $C_d \simeq 0.4$. When the cylinder is stationary with respect to the observer, at the ends of each half cycle of motion, the flow patterns are similar to those characterizing a stationary cylinder in flowing water. The steady drag coefficient C_d of the cylinder was measured as 1.26, King (1974): thus the instantaneous steady drag coefficient is $C_d = 1.26 \pm 0.86$ where the fluctuating force coefficient is defined as $C'_d = 0.86$.

Fig. 9 shows the results of the analysis of the experimental data for the fundamental and second normal modes in-line. For the analysis of the second normal mode, the hysteretic damping was increased by an amount determined from the logarithmic decrement of that mode. In general, the hysteretic damping constant (G) for the first two normal modes were approximately G and 1.2G respectively.

It can be seen that the maximum amplitudes of oscillations and the fluctuating force coefficients C'_d in Fig. 9 are related linearly, although there is some scatter in the computed values of C'_d for amplitudes less than the maxima. This could be an indication of the varying degrees of vortex shedding correlation along the cylinder's length, with the amplitudes of oscillation. The greatest departures from the straight line through the maxima were recorded at comparatively low amplitudes where the results were subject to the largest uncertainty.

The calculated C_d' values were deduced from the assumption that the excitation forces were distributed uniformly over the cylinder length; this was an approximation, as the force coefficients were almost certainly amplitude-dependent and this was demonstrated in a supplementary series of flow visualization studies. The vorticity associated with the larger amplitudes was considerably greater than that of the smaller amplitudes at the same Reduced Velocity, V/nd, and at different locations on the same oscillating cylinder. Furthermore, the point in the wake at which the alternate street was formed appeared to be a function of amplitude and Reduced Velocity, V/nd, and this is consistent with amplitude-dependent variations of exciting forces at various distances along the cylinder length. Thus, the calculated value of $C_d' = 0.69$ for $y/d = 0.15$ (the maximum amplitude recorded) represented the uniformly distributed equivalent of C_d' values ranging from 0.86 at the maximum amplitudes, to the pseudo-stationary C_d' near the base.

Hardwick & Wootton (1973), in their analysis of the vortex excitation process applied to the fundamental mode of in-line oscillations, predicted a limiting amplitude of $y/d \simeq 0.1$ corresponding to a maximum $C_d' = 0.8$ for the First Instability Region. The results of their laboratory tests with an elastically supported rigid cylinder, of $L/d = 5$, agreed with their theoretical reasoning although in previous full scale tests maximum amplitudes of up to $y/d = 0.13$ were recorded, Wootton et al (1972); in the author's tests, King (1974), amplitudes of up to $y/d = 0.16$ also were noted.

Second Instability Region in-line oscillations:

Evaluation of C_d'. The results from tests in the Second Instability Region were analyzed by a method similar to that employed in the preceding section. The relative magnitudes of the exciting and damping forces of this instability region were assumed to be of the same order of magnitude as those for the symmetric shedding region. However, the magnitude of C_d' determined in the preceding section from visual observation of the free shear layers obviously was of no relevance in this alternate shedding region.

The results of the mathematical analysis, shown in Fig. 10 reveal that the maximum amplitudes of the fundamental and second normal modes are related linearly to the fluctuating force coefficient C_d'. By extrapolating the y/d versus C_d' line towards the origin, a stationary cylinder value of $C_d' = 0.08$ was obtained. This is in agreement with the values recorded during wind tunnel tests with stationary cylinders, Wootton (1969), Vickery and Watkins (1962), Humphreys (1960). In the present tests, the Second Instability Region and the stationary cylinder (null) range immediately preceding this instability are both identified by alternate vortex shedding and the extrapolation therefore is considered justified. At the maximum recorded amplitude ($y/d = 0.14$) the fluctuating drag coefficient was calculated as $C_d' = 0.45$, compared with $C_d' = 0.65$ at a similar amplitude in the First Instability Region. In the First Instability Region, the oscillatory velocity (v) included in the hydrodynamic damping term, was comparable with the flow velocity (V), the damping was relatively large, and the fluctuating force coefficient, C_d', correspondingly high. In the Second Instability Region, the flow velocity was higher, although the oscillatory velocity remained approximately constant. The damping term (proportional to Vv) thus increased linearly with flow velocity whilst the excitation force increased as the square of the flow velocity. Hence, for equal amplitudes in the two Instability Regions, lower force coefficients were appropriate to the second of these. Photographs of vortex shedding in the Second Instability Region showed that the vortices separated from the cylinder at angles of approximately 130° to 160° from the forward stagnation point. The larger angle was observed at the maximum amplitude. An analysis of graphs of rms pressure distribution around a stationary circular cylinder, Surry (1969), gave $C_d' = 0.08$, at a separation angle of approximately 100°. By comparing the in-line components of the two separation angles recorded in the photographs, and making the elaborate assumption that in the cases considered, the vortex strengths were similar, the equivalent values of C_d' are $0.22 < C_d' < 0.43$. It will be noted that these two values of C_d' are close to those deduced from the matrix analysis of the oscillating cylinder. It is appreciated that these analogies with the stationary cylinder C_d' were approximate and that the results obtained thus, were of a qualitative nature only. However, the C_d' recorded in tests with stationary cylinders usually represented the average experimental reading at the instrumented section of the cylinders' length; in view of the generally low lengthwise correlation of such cylinders the average C_d' for the whole cylinder would be considerably less than the C_d' from the instrumented section. Thus, in the present tests, a calculated uniformly distributed C_d' equal to the stationary cylinder C_d' from Humphreys (1960), could denote well-correlated vortex shedding without necessarily implying a variation in vortex strength. Furthermore, although the vortex strengths appeared to be proportional to the oscillatory amplitudes of motion, increases in in-line force coefficients could also be caused by increases in separation angle, which in turn probably were functions of amplitude, V/nd and oscillatory velocity.

Cross-flow oscillations

Evaluation of C_L'. The analysis developed for the preceding sections was modified for application to the results from tests in the cross-flow direction; in the absence of a reasonable description of fluid damping in this direction, only the hysteretic damping was considered in the dissipative terms of the governing matrix. However, this analysis enabled the results to be compared directly with those of Vickery & Watkins (1962) who deduced values of C_L' from a simplified theory for which $h = L$; they assumed that the cross-flow fluid damping was negligible compared with the hysteretic damping.

The results of the present analysis, and those of Vickery & Watkins are shown in Fig. 11. It is seen that for amplitudes of $y/d < 0.4$, the figure resembles the graphs of Figs. 9, 10 in that the calculated force coefficients C_L' increase with increasing y/d.

For $y/d > 0.6$ the collected results demonstrated an inverse linear relationship between C_L' and y/d. The maximum amplitude possible is, from the graph, $y/d = 2$ and this is in agreement with the collected results of the graph of Fig. 2.

In Fig. 11, the one result from tests with the aluminium cylinder II.1, coincided with, and the results from tests with the stainless steel cylinder V.2 King (1974) were slightly below the calculated results of Vickery & Watkins (1962). The collected results of Fig. 11 showed an apparent dependence upon the types of material and, by inference, the magnitudes of hysteretic damping because there were no obvious mass ratio effects and the k_s values were comparable. Rather surprisingly, the most highly damped cylinder (the P.V.C. cylinder, King (1974)) oscillated consistently with the largest amplitudes; however, at the maximum amplitudes, the flow velocities and hence excitation forces on this cylinder were considerably larger than for the other cylinders considered. This observation indicates the possible need for considering not only k_s but also V/nd and δ when comparing amplitude response data from a variety of sources.

Extrapolation of the 'well-correlated' parts of the graph yielded $C_L' = 0.75$-0.8 for the stationary cylinder and this agrees with previous experimental studies, Humphreys (1960), Surry (1969).

Vickery & Watkins (1962) explanation of the increase, followed by the decrease, of calculated C_L' with y/d was that the total energy of the vortices in the wake was invariant with y/d and that at the smaller amplitudes, the graph demonstrated a lack of vortex shedding correlation in the presence of low damping. As y/d increased, the lengthwise correlation improved, the hydrodynamic damping increased, and the steady state limiting conditions, it was argued, were defined by $C_L' = 0$. The (constant) total energy of the wake was dissipated by the hysteretic and hydrodynamic damping. This explanation, which implies that complete correlation is achieved only at the larger amplitudes is considered plausible and on this basis the y/d versus C_L' graph (Fig. 11) may be analyzed in two parts. The lower part, in which the amplitudes are restricted by the poor lengthwise correlation (and the low damping) is followed by the upper part, in which the hydrodynamic damping energy increases more rapidly than the energy input from the exciting forces, until the limiting amplitude is established at $C_L' = 0$. Fig 11 indicates that complete lengthwise correlation is obtained when $y/d > 0.5$, and presumably persists up to the limiting amplitude $y/d = 2$. A comparison of Figs. 10, 11 shows that over a corresponding range of amplitudes ($y/d < 0.15$), the amplitudes and fluctuating force coefficients exhibit similar trends. Probably, the vortex shedding was not completely correlated in the cross-flow direction, and extrapolation of the lower part of Fig. 11 suggested that this was the case. Alternatively, the results from the in-line direction (Fig. 10) where considerably higher fluid damping was experienced, were consistent with well-correlated vortex shedding, and the maximum fluctuating force coefficient in-line exceeded by an order of magnitude the stationary cylinder C_d'.

CONCLUSIONS

Sustained self-excited oscillations will only be initiated for cylinders satisfying the Stability Parameter and Reduced Velocity criteria. The limiting amplitude of cross-flow oscillations is an order of magnitude larger than for the in-line direction. Similarly, the Stability Parameter necessary for suppressing the cross-flow oscillations is over ten times greater than for in-line motion.

In-line oscillations can be excited at flow velocities of only one quarter those for cross-flow motion.

The value of analyzing experimental results using a fairly crude linear mathematical analogue was illustrated. It was shown that the fluctuating drag coefficients varied linearly with amplitude and for the maximum amplitudes were equivalent to $C_d' = 0.69$ and $C_d' = 0.44$ in the First and Second Instability Regions respectively. These represent significant deviations from the stationary cylinder values of $0.02 < C_d' < 0.08$.

The calculated fluctuating lift coefficients were functions of amplitudes of oscillation; for amplitudes less than $y/d = 0.4$, C_L' increased approximately linearly with amplitude and for $y/d > 0.6$, C_L' decreased linearly with amplitude. The explanation of these features was based on the concept of varying degrees of vortex shedding correlation length and by extrapolating the 'well-correlated' part of the graph to zero amplitude, a mean value of $C_L' = 0.75-0.80$ was obtained. This is comparable with the experimental results of other authors.

In these calculations, the representation of exciting forces uniformly distributed along the cylinder's length is not compatible either with visual observations of the flow patterns or the notion of amplitude-dependent interactions. When the exciting forces were made linear functions of local amplitude the calculated results did not correlate well with recorded data, and it was concluded that more comprehensive expressions for the fluid-cylinder interactions should be developed. Many mathematical or heuristic models of flow-induced oscillations incorporate modified forms of the Van der Pol equation: recent publications by Griffin et al.(1973) and Skop and Griffin (1973), have demonstrated further modifications for specific application to cylinder oscillations, and it is suggested that these be used as the basis for extending the present method of calculations.

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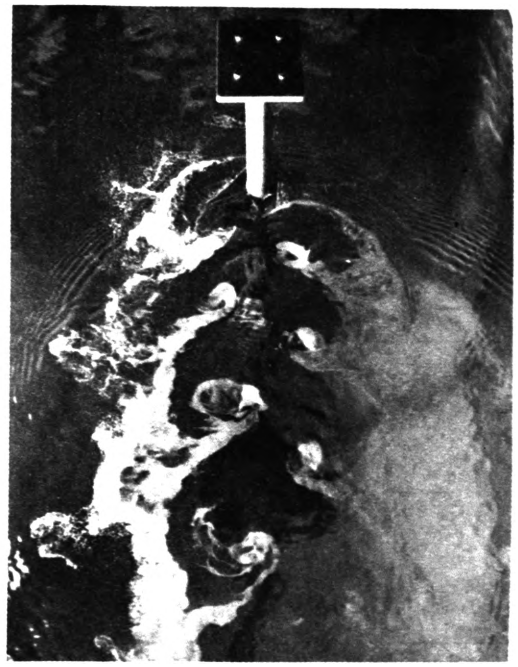

Fig. 1 SURFACE FLOW PATTERNS. CYLINDER OSCILLATING CROSS-FLOW. KING (1974).

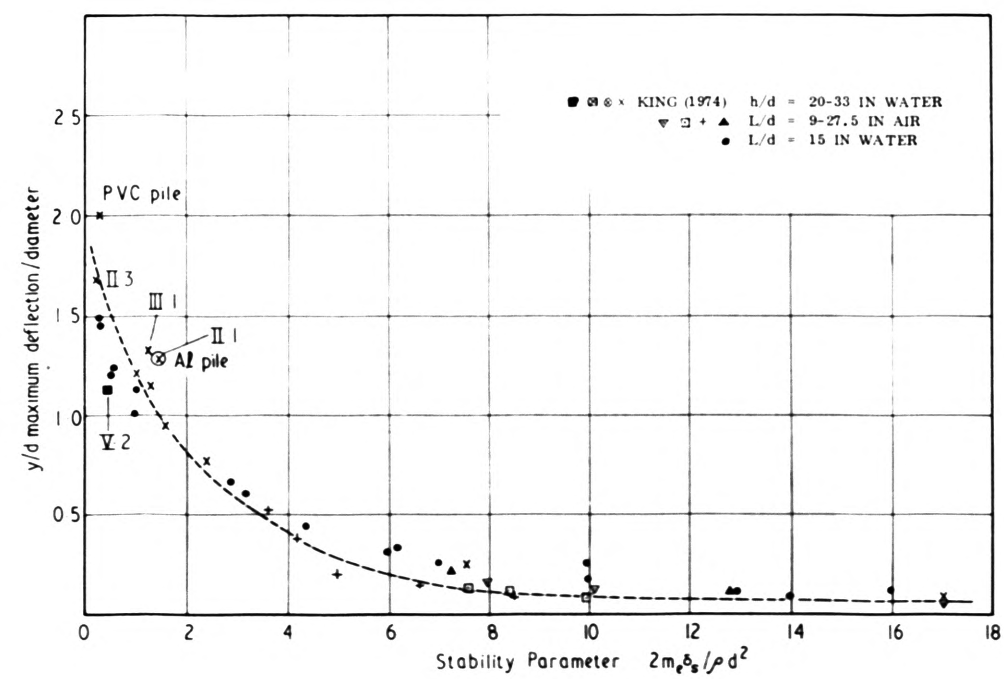

Fig. 2 COLLECTED RESULTS FOR CYLINDER OSCILLATIONS CROSS-FLOW. KING (1974).

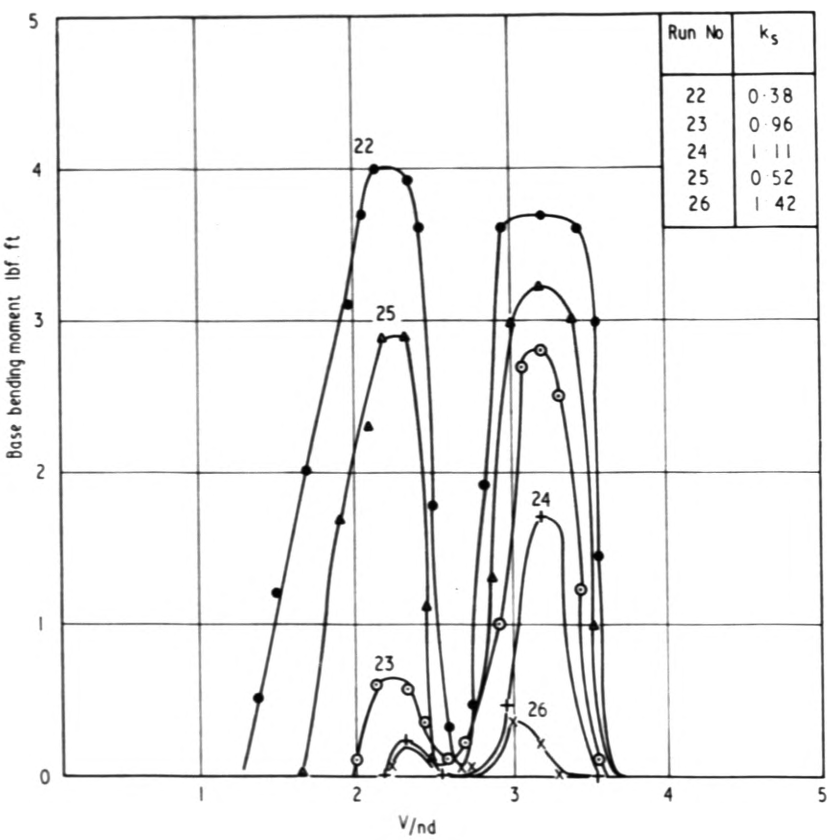

Fig.3 THE TWO INSTABILITY REGIONS OF IN-LINE MOTION. KING (1974).

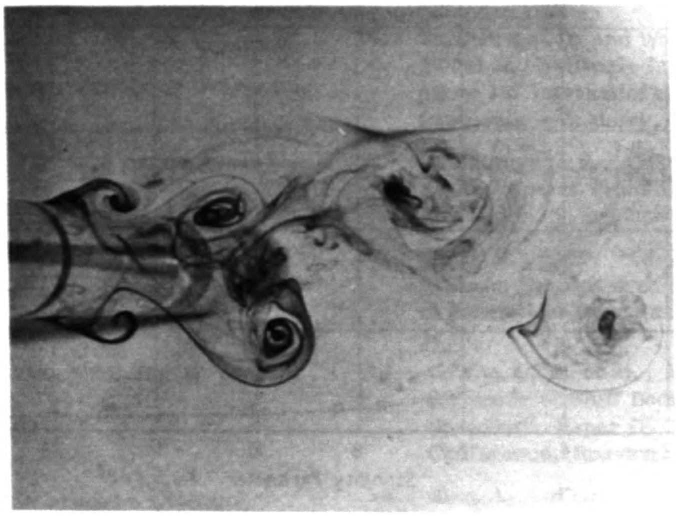

Fig.4 SYMMETRIC VORTEX SHEDDING FROM A CYLINDER OSCILLATING IN-LINE. FIRST INSTABILITY REGION. KING (1974)

Fig. 5 ALTERNATE VORTEX SHEDDING, CYLINDER OSCILLATING IN-LINE. SECOND INSTABILITY REGION. KING (1974)

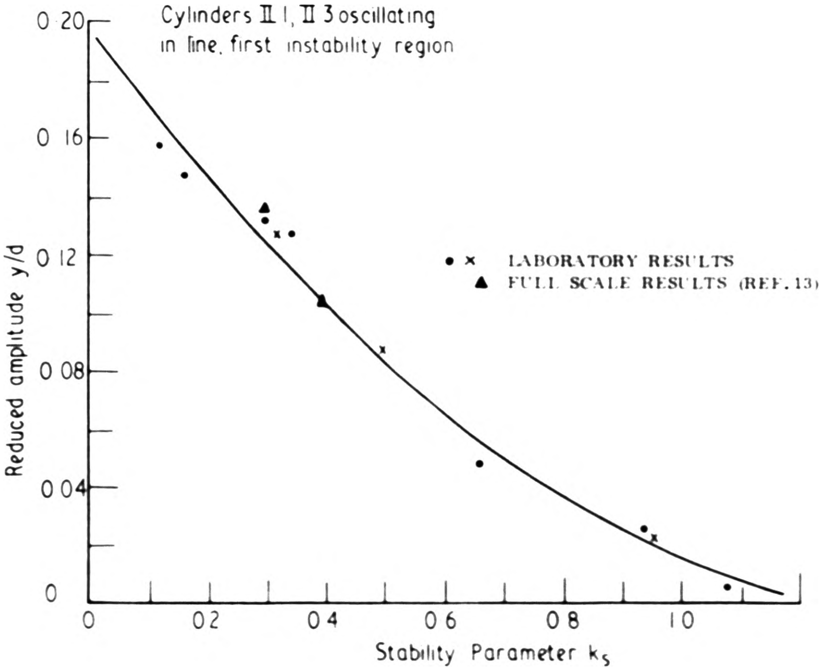

Fig. 6 COLLECTED RESULTS FOR CYLINDER OSCILLATIONS IN-LINE. KING (1974)

(a) CYLINDER OSCILLATING UPSTREAM

$$F - \Delta F = \tfrac{1}{2}\rho(C_d - C'_d)\,(V + v)^2 d.dx$$

(b) CYLINDER OSCILLATING DOWNSTREAM

$$F + \Delta F = \tfrac{1}{2}\rho(C_d + C'_d)\,(V - v)^2 d.dx$$

F = mean force/unit length

ΔF = fluctuating component of force F

v = oscillatory velocity = $2\pi ny$ = wy

from (a), (b) $F = \tfrac{1}{2}\,\rho\, V^2 d.C'_d\, dx - \rho V d\, w\, y\, C_d\, dx$

First term is **excitation** force $\tfrac{1}{2}\,\rho\, C'_d\, V^2 d.dx$

Second term is **damping** force $\rho\, d\, C_d\, V.v.dx$

Fig.7 FORCES ON CYLINDER OSCILLATING IN-LINE

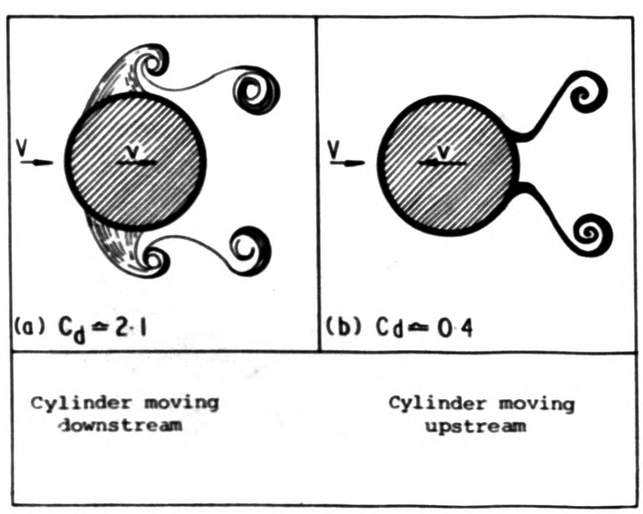

Fig.8 ANALYSIS OF FLOW PATTERNS. FIRST INSTABILITY REGION IN-LINE. KING (1974)

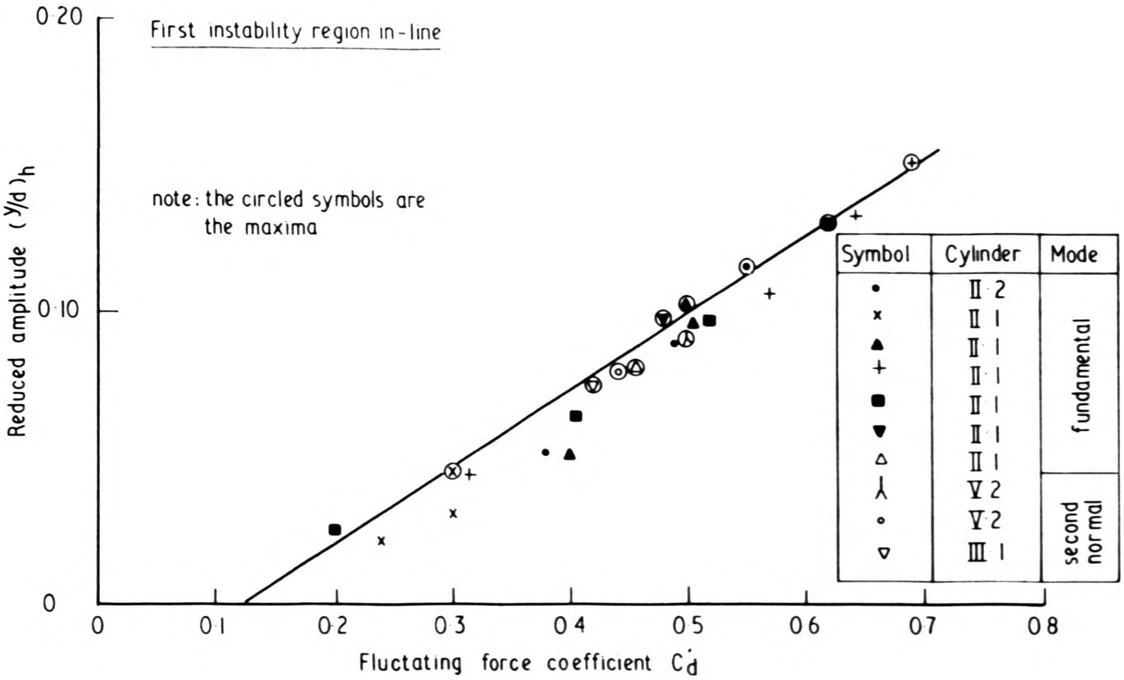

Fig. 9 FLUCTUATING FORCE COEFFICIENT C_d' VERSUS REDUCED AMPLITUDE. FIRST INSTABILITY REGION IN-LINE. KING (1974)

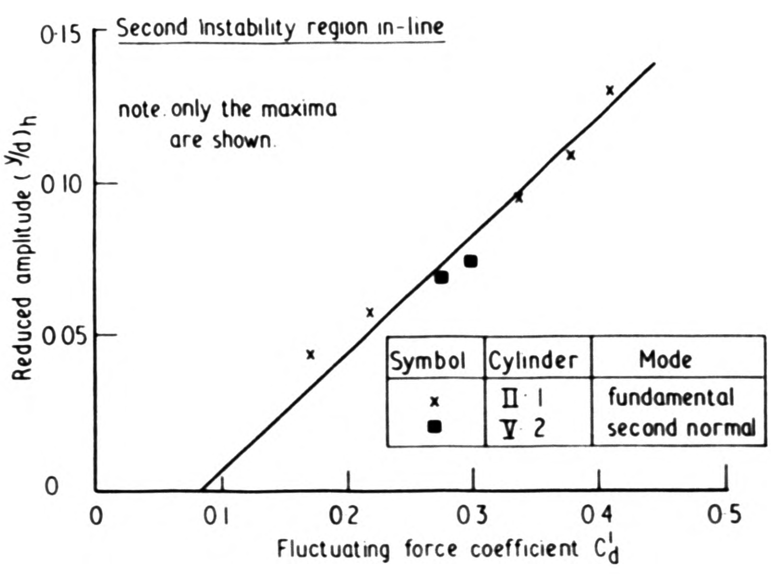

Fig. 10 FLUCTUATING FORCE COEFFICIENT C_d' VERSUS REDUCED AMPLITUDE. SECOND INSTABILITY REGION IN-LINE. KING (1974)

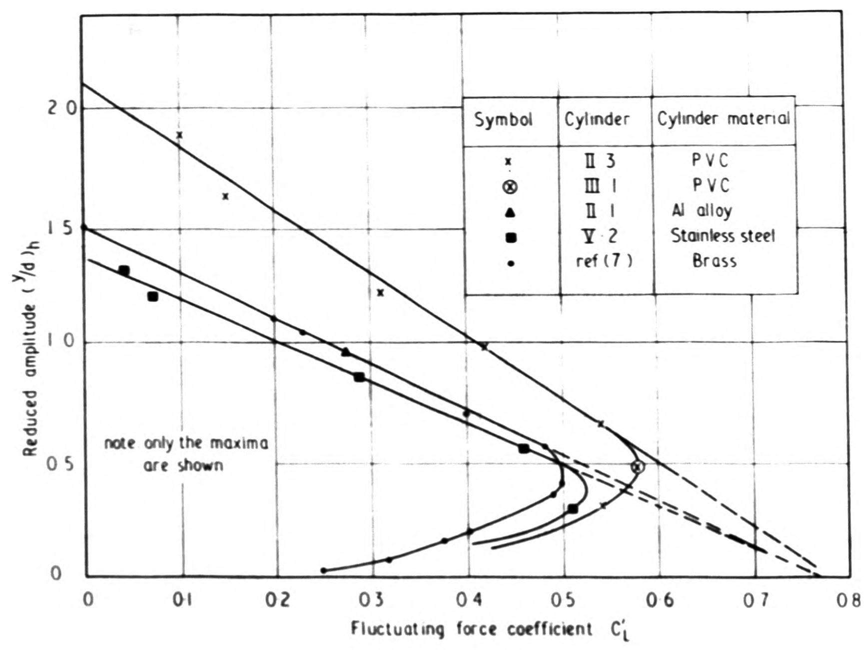

Fig. 11 CALCULATED FLUCTUATING FORCE COEFFICIENT C_L' VERSUS REDUCED AMPLITUDE. COLLECTED RESULTS KING (1974), VICKERY & WATKINS (1962)

DISCUSSION

Thomas Corke, IIT: At IIT we became involved with some work being done at Wood's Hole, Mass. dealing with cylindrical cables having hairy protrusions at one end. These cables were being used as moors and they didn't oscillate and had reduced drag. Our measurements using dyes and water indicate that these trailing strings prevent communication between vortices and our measurements tend to indicate a reduction in the drag on the cylinder. The question is: have you heard of this type of mooring cable?

King: The effect of a splitter plate in the near wake of a stationary cylinder was investigated by Roshko and from what I remember, his results were consistent with the behaviors mentioned by you.

W. K. Blake, Department of the Navy: Does the symmetric vortex shedding occur on rigit cylinders? Are you familiar with the stability calculations of Abernathy and Kronauer? Those calculations show "resonant modes" for shear layer motions and they predict the resonance wave-numbers for those motions. They ignored the symmetric mode on the assumption that it was stable.

King: Symmetric vortices, to my knowledge, have not been detected in the wake of stationary cylinders at Reynolds numbers greater than about 90. I had not realized that symmetric vortex shedding from oscillating cylinders had been recorded by researchers prior to about 1969-1970. However Laird (California) kindly sent me a film of just this, recorded by one of his students (Mandini) in 1964. This type of vortex shedding was not pursued or even taken seriously because it was thought unlikely to lead to sustained instability compared with the well known and exceptionally powerful crossflow forces. I believe a German researcher Rubach also noted inline oscillations in 1916.

A.K.M.Fazle Hussain, University of Houston: I am surprised to see no mention of Koopmann's (JFM 1969) work which is probably one of the earliest comprehensive investigations of the effect of transverse cylinder oscillation on vortex shedding; he also investigated the threshold amplitude necessary for synchronization or lock-in to occur. I also see no mention of Watanabe et al. (JFM, 1973) who reported the effect of imposed in-line oscillation on vortex shedding. The survey paper by Berger and Wille (Ann. Rev. of Fl. Mech. 1972) discussed the effect of self-excited as well as imposed cylinder oscillation. You may also be aware that Ian Currie (U. of Toronto) has done recent analytical studies on this same topic.

Have you studied the effect of imposed in-line cylinder oscillation on vortex shedding?

At the Univ. of Houston we have carried out the inverse problem viz., the effect of streamwise oscillations of controlled frequencies and amplitudes on vortex shedding from a circular cylinder. We have also studied the effect of free-stream turbulence, as well as mild favorable and adverse pressure gradients on vortex shedding. The effect of streamwise oscillations can be dramatic depending on amplitude and frequency.

King: I am aware of Koopman's work. No, I have never tried forcing the cylinder in-line.