CHAPTER 135

FORCES ON ROUGH-WALLED CIRCULAR CYLINDERS IN HARMONIC FLOW

by

Turgut Sarpkaya
Distinguished Professor of Mechanical Engineering
Naval Postgraduate School, Monterey, California

ABSTRACT

This paper presents the results of an extensive experimental investigation of the in-line and transverse forces acting on sand-roughened circular cylinders placed in oscillatory flow at Reynolds numbers up to 1,500,000, Keulegan-Carpenter numbers up to 100, and relative roughnesses from 1/800 to 1/50. The drag and inertia coefficients have been determined through the use of the Fourier analysis and the least squares method. The transverse force (lift) has been analysed in terms of its maximum and root-mean-square values. In addition, the frequency of vortex shedding and the Strouhal number have been determined.

The results have shown that all of the coefficients cited above are functions of the Reynolds number, Keulegan-Carpenter number, and the relative roughness height. The results have also shown that the effect of roughness is quite profound and that the drag coefficients obtained from tests in steady flow are not applicable to harmonic flows even when the loading is predominantly drag.

INTRODUCTION

The prediction of the forces generated by waves and currents remains as a basic problem in marine hydrodynamics. The complexity of the problem stems partly from the difficulty of accurately defining the kinematics of the flow field, partly from the difficulty of accounting properly for the effects of time-dependent separation and vortex shedding, and partly from the difficulty in extrapolating the laboratory findings to various conditions of the marine environment where three-dimensional effects and reduced spanwise coherence play important roles.

The methods based on diffraction theory and classical hydrodynamics are applicable only to relatively simple cases, irrespective of the size and shape of the structure, where separation does not play an appreciable

role. It is a well-known fact that the shear-layer instability and the non-linear interaction between the shear layers lead to vortex shedding in steady flow past bluff bodies. The general characteristics of this shedding mechanism are fairly well understood through measurements, flow visualization, and numerical experiments for various bluff bodies, in particular for a circular cylinder held normal to the ambient flow. Any effect, such as the periodicity of flow, which interfers with the production of vorticity, position of the separation points, shear-layer instability, and the feedback mechanism causes additional time and history dependent non-linear interactions. The net effect of these interactions is to change the vortex shedding and hence the vortex-induced oscillations in both the forces and structure in both the in-line and transverse directions. The problem is not yet amenable to mathematical analysis and requires experiments of high intrinsic quality for at least a partial understanding of its many perplexing aspects.

Much of the present knowledge on separated harmonic flows has been obtained by means of model tests at Reynolds numbers generally two to three orders of magnitude smaller than prototype Reynolds numbers. These model tests have relied heavily on the so-called Morison formula for expressing the force as the sum of a drag and inertia force. The values of the drag and inertia coefficients to be used in the Morison equation became the subject of many experimental studies in the last twenty years. The correlation of these coefficients with the relative amplitude of the waves (or the Keulegan-Carpenter number, hereafter referred to as K) has been generally inconclusive [1]. Furthermore, lift forces which are associated with vortex shedding have received relatively little attention. It thus became clear that much is to be gained by considering plane oscillatory flow about cylinders at high Reynolds numbers in order to isolate the influence of individual factors such as relative amplitude, Reynolds number, relative roughness, spanwise correlation, wall-proximity, etc. on vortex shedding and resistance. It is with this realization that a broad research program was undertaken to study the characteristics of periodic flow about bluff bodies.

The results obtained with smooth cylinders in two U-shaped water tunnels have been previously reported by Sarpkaya [2-6]. The preliminary results obtained with rough-walled cylinders for one particular value of K, (K = 50), through the use of various types of distributed roughness elements (sand, sand paper, and polystyrene beads) have also been reported in [3] and [4].

The present paper deals with in-line and transverse forces acting on sand-roughened circular cylinders in harmonic flow in the range of Reynolds numbers from 10,000 to 1,500,000; K values from about 4 to 100; and relative sand roughnesses from 1/800 to 1/50.

BACKGROUND ON THE EFFECTS OF ROUGHNESS

Of the scores of papers dealing with fluid loading on offshore structures (see the reviews by Grace [7] and Hogben [8]), none seems to have treated the effect of roughness on the force-transfer coefficients. Yet it is a fact that the structures in the marine environment become gradually covered with rigid as well as soft excrescences. Thus, the fluid loading due to identical ambient flow conditions may be significantly different from that experienced when the structure was clean partly because of the 'roughness effect' of the excrescences on the flow and partly because of the increase of the 'effective diameter' of the elements of the structure.

In the absence of any data appropriate to the harmonic or wavy flows, it has been assumed that "the drag coefficients obtained from tests in steady flow" over artificially - or marine-roughened cylinders "are applicable to wave flows at least when the loading is predominantly drag" [9].

It is not generally appreciated that the consequences of all "nearly steady flows" are not always identical to those of "steady flows." The case in point is the harmonic flow under consideration. Even for large amplitudes of oscillations, there is only a finite vortex street comprised of vortices of nearly equal strength due to the "nearly steady" nature of the flow. As the flow reverses, the situation is not that of a uniform flow (with or without free stream turbulence) approaching a roughnened cylinder but rather that of a finite vortex street approaching a rough-walled cylinder. Such a flow cannot be regarded identical to steady flow with some turbulence of fairly uniform intensity and scale as the present results show.

It is instructive to briefly review the salient features of the influence of roughness on the cross-flow around a cylinder in steady flow in order to delineate the differences between the steady and harmonic flow about rough-walled cylinders.

Among others, primarily the experiments of Fage and Warsap [10], Achenbach [11], Szechenyi [12], and Güven et al. [13] have shown that roughness in steady flow about a cylinder precipitates the occurrence of 'drag crisis' and gives rise to a minimum drag coefficient which is larger than that obtained with a smooth cylinder. This is partly because of the transition to turbulence of the free shear layers at relatively lower Reynolds numbers due to disturbances brought about by the roughness elements and partly because of the retardation of the boundary-layer flow by roughness (higher skin friction) and, hence, earlier separation. Evidently, the drag crisis in steady flow about a roughened cylinder is a state even more precarious than that for a smooth cylinder for the occurrence of a laminar-separation and turbulent reattachment bubble is hastened by the retardation of the flow by roughness. It is also evident that the Reynolds number must be sufficiently high for a given roughness to bring about a drag crisis.

The conditions leading to the occurrence of the drag crisis are therefore quite important. Not only the relative size of the roughness elements but also their shape and distribution may be quite important in addition to the parameters characterizing the ambient flow about an otherwise smooth bluff body. It is in fact partly for the difficulty of uniquely specifying the 'roughness' and partly for the differences in other test conditions (free stream turbulence, relative length of the cylinder, end gaps, etc.) that there are considerable differences between the data reported by various workers, particularly in the drag crisis region. For example, the effective surface roughness may be larger or smaller than the nominal relative roughness based on the geometric size of the roughness element depending on the shape and arrangement of the roughness elements [14]. Also, a higher turbulence level precipitates the drag crisis. Thus, the critical range is wider for higher free stream turbulence [13]. Attempts have been made [14] to experimentally determine an equivalent sand-grain roughness through the use of uniform flow in a channel. An equivalent roughness determined in this manner may not necessarily give a meaningful measure of the effect of roughness as far as the boundary layer flow over a circular cylinder is concerned.

In the supercritical and transcritical regions, the drag coefficient for a roughened cylinder is considerably larger than that for a smooth cylinder primarily because of the larger wake which is brought about by the earlier separation due to the retardation of the boundary layer. Several facts are worth noting. Firstly, the transcritical drag coefficient depends on both the character of the flow and the surface condition of the cylinder. In other words, the particular value of the transcritical drag coefficient in steady flow over a roughened cylinder is not necessarily identical to that for a time-dependent flow over the same cylinder. Experiments with steady flow over roughened cylinders show that the drag coefficient in the transcritical region returns more or less to its steady sub-critical value. Other flows may exhibit a similar behavior provided that the spanwise coherence is maintained. In other words, the subcritical value of the drag coefficient for a given flow may give an indication of its transcritical value for the same flow over a roughened cylinder. Evidently, what is specified here is the functional dependence of velocity on time and not the magnitude of the characteristic velocity.

Secondly, the larger the effective roughness, the larger is the retardation of the boundary layer. This leads to earlier separation and larger drag coefficient. Thirdly, the pressure distribution about the cylinder is affected not only by the location of the separation point but also by the development of the retarded boundary layer ahead of separation [13]. This in turn is affected not only by all the parameters characterizing the roughness but also by the character of the ambient flow (time-dependence, angle of attack, shear, turbulence, just to name a few of the parameters).

It seems from the foregoing that the disturbances generated by the roughness elements cause an incalculable change in the critical region of

the flow and that a more thorough examination of the one-parameter characterization of roughness, k/D, is required in order to understand the effect of roughness, because the packing, size distribution, and shape may be important. Although, wind- and water-tunnel experiments on flow past rough-walled cylinders have been made for about 50 years, there is still a lack of precision in the definition of even the roughness let alone the force and pressure coefficients. The purpose of this paper is not to study this question but rather to show, among other things, that different types of roughness elements (sand paper, polystyrene beads, sand) can give rise to different drag-coefficient curves in the critical region appropriate to the particular flow. It is in fact partly for this reason that it has been thought advisable to investigate afresh the effect of roughness on cylinders in harmonic flow using only sand of uniform size and packing rather than three different types of roughness [3].

IN-LINE AND TRANSVERSE FORCES AND GOVERNING PARAMETERS

The in-line force which consists of the drag force F_d and the inertia force F_i is assumed to be given by [15]

$$F = F_d + F_i = 0.5C_d LD\rho|U|U + 0.25C_m LD^2\pi\rho.dU/dt \tag{1}$$

in which C_d and C_m represent respectively the drag and inertia coefficients and U the instantaneous velocity of the ambient flow. For an oscillating flow represented by $U = -U_m\cos\theta$, with $\theta = 2\pi t/T$, the Fourier averages of C_d and C_m are given by Keulegan and Carpenter as [16]

$$C_d = -0.75\int_0^{2\pi}(F_m\cos\theta/\rho U_m^2 LD)d\theta \tag{2}$$

and

$$C_m = (2U_m T/\pi^3 D)\int_0^{2\pi}(F_m\sin\theta/\rho U_m^2 LD)d\theta \tag{3}$$

in which F_m represents the measured force.

The method of least squares consists of the minimization of the error between the measured and calculated forces. This procedure yields [5]

$$C_{dls} = -(8/3\pi)\int_0^{2\pi}(F_m|\cos\theta|\cos\theta/\rho DLU_m^2)d\theta \tag{4}$$

and $C_{mls} = C_m$. Evidently, the Fourier analysis and the method of least squares yield identical C_m values and that the C_d values differ only slightly.

The transverse force has been expressed in terms of the maximum lift coefficient defined by

$$C_L = (\text{maximum amplitude of the transverse force in a cycle})/(0.5\rho DLU_m^2) \tag{5}$$

In addition, the frequency of the oscillations of the transverse force and the Strouhal number have been evaluated.

It is recognized that the coefficients cited above are not constant throughout the cycle and are either time-invariant averages or peak values at a particular moment in the cycle. A simple dimensional analysis of the flow under consideration shows that the time-dependent coefficients may be written as

$$F/(0.5DL\rho U_m^2) = f(U_mT/D,\ U_mD/\nu,\ k/D,\ t/T) \tag{6}$$

in which F represents the in-line or the transverse force. Equation (6), combined with Eq. (1), assuming for now that the latter is indeed valid, yields

$$C_d = f_1(K\ ,\ Re,\ k/D,\ t/T) \tag{7}$$

$$C_m = f_2(K\ ,\ Re,\ k/D,\ t/T) \tag{8}$$

in which $K = U_mT/D$ and $Re = U_mD/\nu$, and k/D represents the relative roughness. Evidently, it is assumed that the effect of roughness may be characterized by the parameter k/D alone, with k defined as the average grain size. Experiments necessary to obtain an equivalent sand height or some other representative length are costly and time consuming and are not available for the oscillating flow data analysed here.

There is no simple way to deal with Eqs. (7) and (8) even for the most manageable time-dependent flows. Another and perhaps the only other alternative is to eliminate time as an independent variable and consider suitable time-invariant averages as given by Eqs. (2), (3), and (4). Thus, one has

$$[C_d,\ C_m,\ C_L,\ .\ .\ .\ .\ ] = f_i(K,\ Re,\ k/D) \tag{9}$$

It appears, for the purposes of Eq. (9), that the Reynolds number is not the most suitable parameter involving viscosity. The primary reasons for this are that the effect of viscosity is relatively small particularly for $Re < 20{,}000$ and that U_m appears in both K and Re. Thus, replacing Re by $\beta = Re/K \approx D^2/\nu T$ in Eq. (9), one has

$$C_i(\text{a coefficient}) = f_i(K,\ \beta,\ k/D) \tag{10}$$

in which $\beta = D^2/\nu T$ and shall be called the 'frequency parameter.'

From the standpoint of dimensional analysis, either the Reynolds number or β could be used as an independent variable. Evidently, β is constant for a series of experiments conducted with a cylinder of diameter D in water of uniform and constant temperature since T is kept constant in a U-shaped oscillating flow tunnel. Then the variation of a force coefficient with K may be plotted for constant values of β. Subsequently, one can easily recover the Reynolds number from $Re = \beta K$ and connect the points, on each β = constant curve, representing a given Reynolds number.

From the standpoint of the laminar boundary layer theory, β represents

the ratio of the rate of diffusion of vorticity through a distance δ (the boundary layer thickness) to the rate of diffusion through a distance D. This ratio is also equal to $(D/\delta)^2$ and, when it is large, gradients of velocity in the direction of flow are small compared with the gradients normal to the boundary, a situation to which the boundary layer theory is applicable. It should also be noted in passing that β is of special importance even for oscillations at very low Reynolds numbers. For example, for a cylinder or sphere undergoing harmonic oscillations without separation in a fluid otherwise at rest, the added mass and drag coefficients are uniquely determined in terms of β [17, 18].

A re-analysis of the data given by Keulegan and Carpenter [16] through the use of β, K, and Re in the manner just described clearly shows [3, 4] that (a) C_d depends on both K and Re and decreases with increasing Re for a given K; and that (b) C_m depends on both K and Re for K larger than approximately 15 and decreases with increasing Re. A similar analysis of Sarpkaya's data [2] also shows that C_d and C_m depend on both K and Re and that C_m increases with increasing Re. Notwithstanding this difference in the variation of C_m between the two sets of data, these results put to rest the long standing controversy regarding the dependence or lack of dependence of C_d and C_m on Re and show the importance of β as one of the governing parameters in interpreting the data, in interpolating the K values for a given Re, and in providing guide lines for further experiments as far as the ranges of K and β are concerned.

BRIEF DESCRIPTION OF THE EXPERIMENTAL ARRANGEMENT

The oscillating flow system consisted of a large U-shaped vertical water tunnel with a 3 ft by 3 ft test section. The cross-section of the two vertical legs is twice that of the test section. The two corners of the tunnel were carefully streamlined to prevent flow separation. The auxiliary components of the tunnel consisted of plumbing for hot and cold water, butterfly-valve system, and the air-supply system. Oscillations in the tunnel were obtained through the use of the butterfly valves (mounted on top of one of the legs of the tunnel) and a rack and pinion system actuated by an air-driven piston and a three-way control valve. The fluid oscillated smoothly with a period of T = 5.500 seconds. The elevation, acceleration, and the in-line and transverse forces were monitored continuously by means of appropriate transducers. The analogue traces were absolutely free from secondary oscillations so that no filters were used between the outputs of the transducers and the recording equipment (see sample trace in Fig. 1).

Circular cylinders with diameters ranging in size from 2 inches to 6.5 inches have been used in this study. The cylinders were turned on a lathe from aluminum pipes or plexiglass rods. The length of each cylinder was such that it allowed 1/32 inch gap between the tunnel wall and each end of the cylinder. A doubleball precision bearing was inserted at each end of the cylinder in aluminum housings which sealed the cylinder air tight.

In view of the discussion concerning the one-parameter characterization of the roughness in terms of k/D, it was decided to use only one type of roughness element. The possible use of sandpaper, glass beads, wire screens, etc. was disregarded for they would have exhibited different packing as well as different size distribution characteristics. Clean sand was sieved through the use of standard ASTM sieves in order to obtain a given grain size.

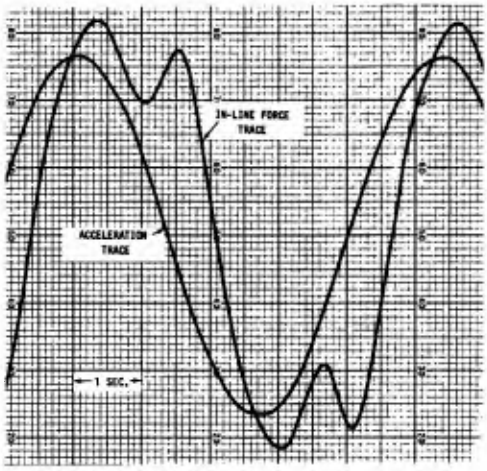

Fig. 1 Sample in-line force and acceleration traces.

Each cylinder was mounted horizontally on a specially constructed, manually operated, rotating apparatus and covered with a thin layer of air-drying epoxy resin using a brush. When the epoxy coating reached a certain degree of consistency, then the finely pre-sieved sand was transferred into a slightly larger sieve and sprinkled over the rotating cylinder. Within about 10 minutes, the epoxy hardened and the cylinder was left alone for the epoxy to cure. Then the cylinder surface was cleaned to remove excess sand and extra sand particles that at times attached to each other forming an easily breakable spike. This procedure has been followed for all cylinders and has invariably resulted in cylinders of roughness with perfect uniformity. A sample photograph of the rough surface, taken with a scanning electron microscope, is shown in Fig. 2.

In order to determine the variation of the force coefficients with Reynolds number for a given Keulegan-Carpenter number and relative roughness, all cylinders were tested at the same relative roughnesses (k/D = 1/800, 1/400, 1/200, 1/100, and 1/50), and the experiments were carried out at three or four water temperatures.

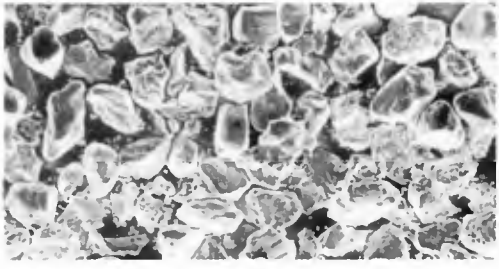

Fig. 2 Distribution of sand particles, (k = 0.0055 inch).

Two identical force transducers, one at each end of the cylinder, were used to measure the instantaneous in-line and transverse forces. The gages had a capacity of 500 Lbf with an overload capacity of 200 percent. The deflection of the gages under 500 Lbf load was 0.01 inch. For the largest cylinder and amplitude encountered in the experiments, the maximum load was less than 200 Lbf, and the deflection of the beam was less than 0.008 inches.

The in-line and transverse forces were simultaneously recorded with the instantaneous acceleration on two two-channel Honeywell recorders running at a speed of 10 divisions per second. The amplitude of the transverse force, instantaneous value of the in-line force, and the flow characteristics such as U_mT/D and Re were determined from these traces. The root-mean-square value of the lift force was determined for each cycle by reading the force at every division or 0.1 second intervals.

Three transducers were used to generate three independent d.c. signals, each proportional to the instantaneous value of the elevation, velocity, and acceleration. These transducers were calibrated and their linearity checked before each series of experiments. In addition, the velocity at the test section was directly measured with a magnetic velocity meter. Suffice it to say that all four methods gave nearly identical results and yielded the amplitude, velocity, or acceleration, to an accuracy of about two percent relative to each other. These comparisons, as well as the perfectly sinusoidal and noise-free character of all pressure and force traces, speak for the suitability of the unique test facility used in this study. The additional details of the apparatus and procedure are given in Ref. [3].

DISCUSSION OF THE RESULTS

The drag and the inertia coefficients, obtained through the use of equations (2) and (3) have been plotted for each cylinder and relative roughness as a function of K for various constant values of β. Then the Reynolds number for a particular value of K has been calculated simply through the use of $Re = K\beta$. As described earlier, such a procedure enables one to express C_d or C_m as a function of the Reynolds number for a given K and k/D. In view of the fact that each coefficient depends on at least three independent parameters (Re, K, and k/D), it is not possible to show on two-dimensional plots the variation of either C_d or C_m for all values of Re, K, and k/D. However, this difficulty is alleviated by the fact that the variation of a given force coefficient for a given Re and k/D is not very strong from one K to another. Thus it has been decided to choose five representative K values, namely K = 20, 30, 40, 60, and 100, to present the variation of C_d and C_m with Re.

Figures 3 through 12 show C_d and C_m for five values of K as a function of the Reynolds number. Each curve on each plot corresponds to a particular relative roughness. Also shown on each figure is the corresponding drag or inertia coefficient for the smooth cylinder at the corresponding K value.

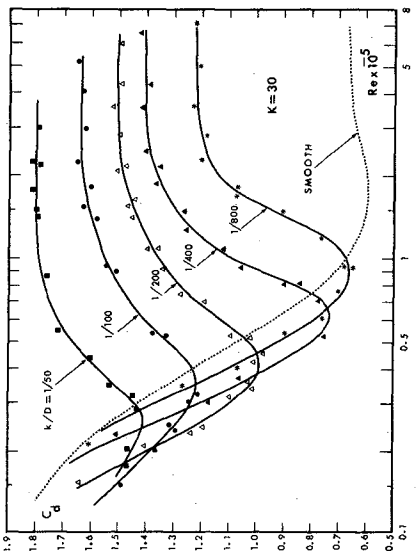

Fig. 5 C_d versus Re for K = 30.

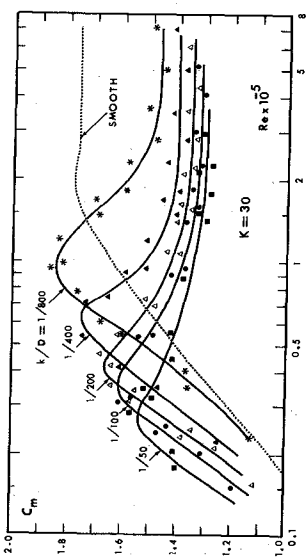

Fig. 6 C_m versus Re for K = 30.

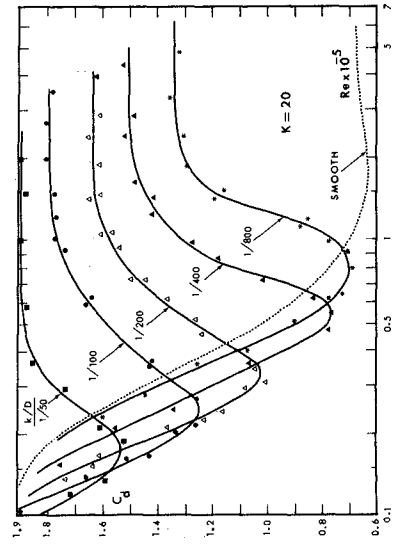

Fig. 3 C_d versus Re for K = 20.

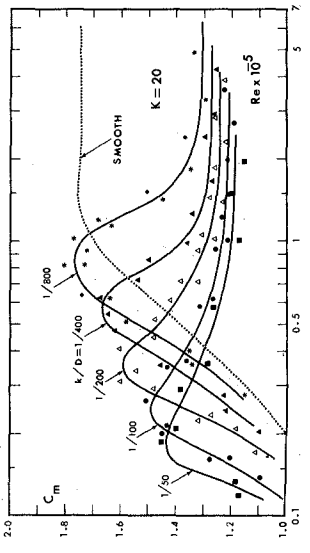

Fig. 4 C_m versus Re for K = 20.

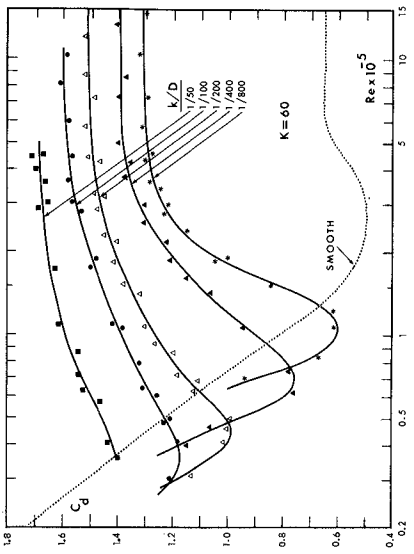

Fig. 9 C_d versus Re for K = 60.

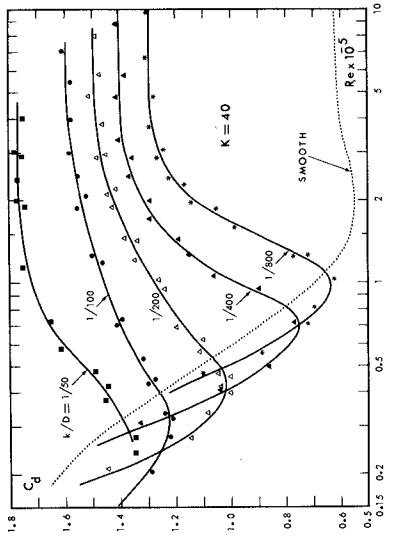

Fig. 7 C_d versus Re for K = 40.

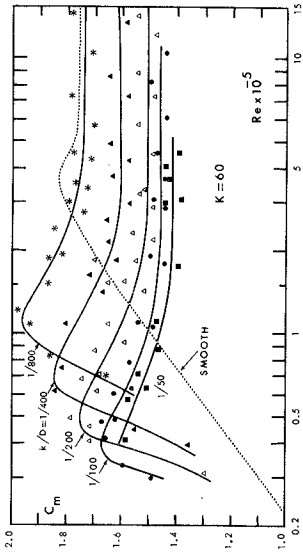

Fig. 10 C_m versus Re for K = 60.

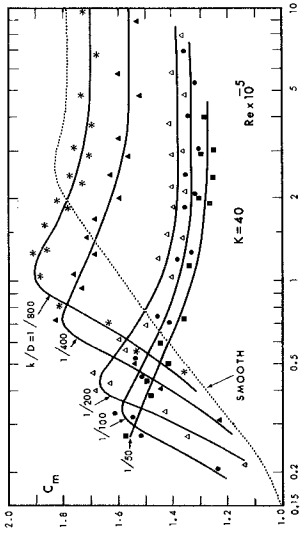

Fig. 8 C_m versus Re for K = 40.

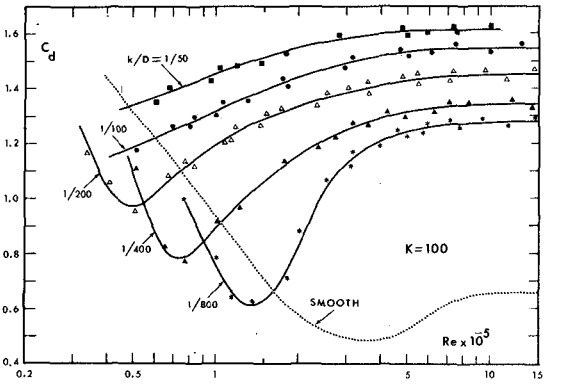

Fig. 11 C_d versus Re for K = 100.

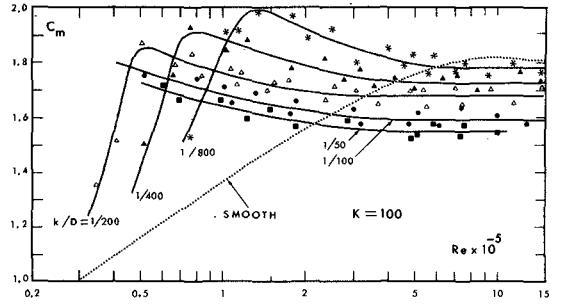

Fig. 12 C_m versus Re for K = 100.

The k/D = constant curves on each C_d plot are quite similar to those found for steady flow about rough cylinders [10-13]. For a given relative roughness, the drag coefficient does not significantly differ from its smooth cylinder value at very low Reynolds numbers. As the Reynolds number increases, C_d for the rough cylinder decreases rapidly, goes through the region of drag crisis at a Reynolds number considerably lower than that for the smooth cylinder and then rises sharply to a nearly constant transcritical value. The larger the relative roughness the larger is the magnitude of the minimum C_d and the smaller is the Reynolds number at which that minimum occurs. However, there appears to be a minimum Reynolds number below which the results for rough cylinders do not significantly differ from those corresponding to smooth cylinders. In other words, the Reynolds number must be sufficiently high for the roughness to play a role on the drag and

flow characteristics of the cylinder.

The figures for the drag coefficient also exhibit a few other interesting features. First, even a relative roughness as small as 1/800 can give rise to transcritical drag coefficients which are considerably higher than those for the smooth cylinder. Secondly, the asymptotic values of the drag coefficient for roughened cylinders (e.g., k/D = 1/100), within the range of Reynolds numbers encountered, can reach values which are considerably higher than those obtained with steady flows over cylinders of similar roughness ratios. In other words, it is not safe to assume that the transcritical drag coefficient in harmonic flows will be identical to those found in steady flows and will not exceed a value of about unity. On the basis of the present results it may be said that such a conjecture is not accurate even for K values as large as 100 (corresponding to a wave height-to-diameter ratio of about 30). It is therefore important to remember that the effect of roughness depends not only on the relative size of the roughness element but also on the characteristics of the ambient flow as well as on the body about which this flow takes place. The characteristics of the ambient flow determine to a large extent the state of the flow (subcritical, critical, and transcritical) during a given cycle of oscillation. The geometry of the body dictates, together with the flow, the variation with time of the separation points. It is therefore not easy to draw a parallel between the behavior of steady flow and that of harmonic flow over a smooth and rough cylinder. In fact, the steady as well as the oscillating flow results for rough cylinders show that, in either case, the transcritical drag coefficient nearly returns to its subcritical values.

The Reynolds number at which the drag crisis occurs gives rise to an 'inertia crisis.' In other words, for a given relative roughness, C_m rises rapidly to a maximum at a Reynolds number which corresponds to that at which C_d drops to a minimum. At relatively higher Reynolds numbers, C_m decreases somewhat and then attains nearly constant values which are lower than those corresponding to the smooth cylinders. It is also apparent from the inertia coefficient curves that the smaller the relative roughness the larger is the maximum inertia coefficient. For relatively smaller roughnesses such as k/D = 1/800, the terminal value of C_m is nearly equal to that of a smooth cylinder. The behavior of C_m is not entirely unexpected. It has long been noted [16] that whenever there is a rise in the drag coefficient, there also is a decrease in the inertia coefficient.

Before closing the discussion of the drag and inertia coefficients, it is necessary to point out the remarkably consistent behavior of the data points, particularly for C_d. Perhaps it would not have been too surprising had the data been obtained for one relative roughness through the use of only one cylinder. In the present investigation, the use of several cylinders and several temperatures for a given cylinder always provided data for nearly identical k/D, Re, and K values. For instance, the C_d and C_m values obtained at a given K, Re, and relative roughness k/D,

using a 5 inch cylinder at a low temperature corresponds to the C_d and C_m values using a 4-inch cylinder at a high temperature. Remembering the fact that not only the actual size of the cylinders but also the size of the sand grains differed in order to obtain the same k/D, and the fact that the experiments were carried out at different temperatures and times, one fully realizes that the correlation of the data and the relatively small scatter are indeed quite remarkable. This is due not only to the repeatability of the tests but also due to the vibration-free operation of the entire tunnel system.

The correlation length along the cylinders was not directly measured. However, one series of experiments was conducted with a 2.18-diameters (12 inches) long, centrally located, section of a 5.5 inch cylinder which 'floated' on the ends of the force transducers with small gaps (1/32 inch) between the section and the rest of the rigidly supported 12-inch long sections. The floating and the dummy sections were coated with sand for a relative roughness of k/D = 1/100. The comparison of the lift, drag, and inertia coefficients obtained with the short section with those obtained with the longer section spanning the entire test section has shown (at least for five Reynolds numbers, five K values, and one k/D) that the two sets of coefficients are nearly identical. Evidently, the force-cancelling effects of phase shifts which may have been brought about by three-dimensional effects were either insignificant or non-existent. Thus, it is concluded that both the three-dimensionality effects and the boundary-layer effects play very little or no role in the present exprimments. However, the comparison of the results shown in Figs. 3 through 12 with the previously reported [4, 6] preliminary results for K = 50 alone indicates the effect, particularly in the drag-crisis region, of the type of roughness element used on the variation of the force-transfer coefficients with the Reynolds number. Previously, sand paper, sand, and polystyrene beads were used as roughness elements for a given cylinder in order to achieve the desired relative roughness in a given Reynolds number range. A detailed study of the effective roughness of each type of roughness element and the discussions with the manufacturer have shown that the effective roughness of the sand paper is larger than the height of the mean sand particles applied on it. Furthermore, the gluing of the sand paper on the cylinder invariably resulted in a 'joint' along the cylinder which might have generated larger disturbances and promoted earlier transition. The polystyrene beads, on the other hand, present an effective-roughness height which is often smaller than their actual size [14]. In spite of these differences in the 'effective roughness' of various types of roughness elements, however, the terminal values of the drag coefficients in the transcritical region remained practically the same for a given actual effective relative roughness whether the data were obtained with sand alone or with a combination of other roughness elements. Evidently, it will be most interesting and desirable to carry out similar experiments with cylinders roughened in the ocean environment. The testing of such cylinders with steady uniform flow [9] is not sufficient for the purposes under consideration, namely the determination of the fluid loading on offshore structures.

APPLICABILITY OF MORISON'S EQUATION

Since its inception, questions have been raised regarding the applicability of Morison's equation to time-dependent flows in general and to wavy flows in particular. It has been known that the equation predicts quite accurately the in-line force for both very small values of K (K smaller than about 10) and for large values of K (K larger than about 20). For intermediate values of K, differences have been observed between the measured and calculated values. These differences have been attributed either to the imprecise measurement of the kinematics of the flow or to the shortcomings of the equation. It is now realized that not only these two factors (namely the heuristic nature of the equation and the difficulty of measuring the local velocities and accelerations) but also the three-dimensional nature of the wavy flows and decreased spanwise coherence must be partly responsible for the differences between the measured and calculated forces. In fact, it would have been extremely difficult to draw meaningful conclusions concerning the applicability of Morison's equation through the use of the field data. It is only through the use of carefully conducted two-dimensional harmonic flow experiments that one can ascertain the degree of applicability of Morison's equation.

Figure 13 shows the calculated and measured forces normalized by $0.5\rho DLU_m^2$ together with the normalized velocity and the difference between the measured and calculated forces for a relatively large value of K. It is evident that there is often a remarkable correspondence between the measured and predicted forces particularly for K values larger than about 20. This is also true for K values smaller than about 10. In the disturbance-sensitive region of vortex formation, the onset of asymmetry ($K \simeq 4.5$) and the subsequent growth and shedding of single or alternating vortices have profound effects not only on the measured in-line force but also on the coefficients calculated. Morison's equation assumes that the in-line force F is an odd harmonic function, i.e., $F(\theta) = -F(\theta+\pi)$, for a flow represented by $U = -U_m\cos\theta$. Thus, the drag and inertia coefficients calculated through the use of an in-line force for which $F(\theta) \neq -F(\theta+\pi)$ are not quite correct. Thus, it is clear that part of the reason for the larger differences between the measured and calculated forces even in two-dimensional harmonic flows is due to the use of the force-coefficient expressions [Eqs. (2) and (3)] which are derived by assuming the in-line force to be given by an odd harmonic function. In the range of K values from about 10 to 20, particularly for low values of Re, this assumption is not quite correct as evidenced by the present experiments [3, 4, 6].

The reason for the asymmetry in the magnitude of the in-line force and the differences between the measured and calculated forces is primarily the fractional shedding of vortices and vortex induced oscillations in the in-line force. It is a well-known fact that in steady flow the vortex shedding causes a gradient of fluctuating pressure across the body and gives rise to periodic force fluctuations in the in-line force. In harmonic flow, the fully grown vortices move back and forth about the cylinder and do not necessarily shed alternatingly. Thus, it is possible that the oscillations in the in-line force due to eddy shedding are relatively larger than those in steady flow. The effect of these oscillations may be incorporated into Eq. (1) as follows,

$$F/(0.5\rho DLU_m^2) = (\pi^2 D/U_m T)C_m \sin\theta - C_d|\cos\theta|\cos\theta - \eta C_L \cos(St.K.\theta - \phi) \quad (11)$$

in which η represents a coefficient, ηC_L the amplitude of the normalized difference between the measured and calculated forces, St the Strouhal number defined by $f_v D/U_m$ with f_v as the frequency of lift oscillations, and ϕ the phase angle. In the range of K values from 10 to about 15, St.K should be taken equal to 3. For larger values of K, St.K may be taken equal to 0.20K. Extensive calculations through the use of appropriate values of the parameters cited above with $\eta = 0.1$ have shown that the above equation considerably reduces the difference between the measured and calculated in-line forces. These calculations will not be reproduced here for their purpose was simply to demonstrate that the eddy-induced in-line oscillations can account for most of the error in the predictions of the Morison equation in the range of K values from 10 to about 20. For larger K values, the predictions of the Morison equation are indeed excellent as evidenced by Fig. 13.

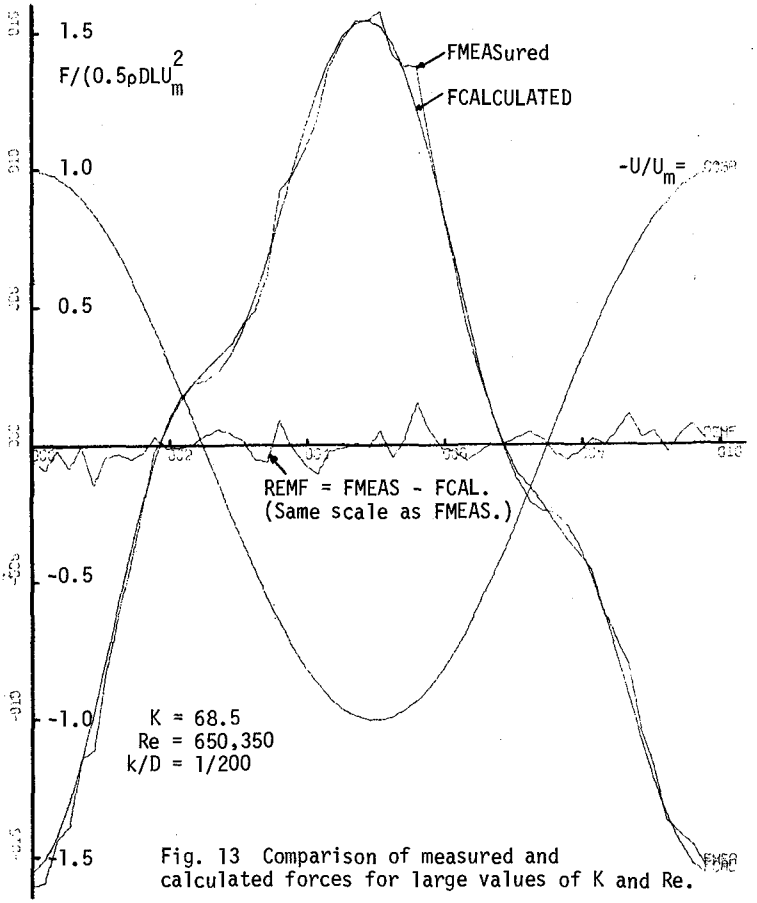

Fig. 13 Comparison of measured and calculated forces for large values of K and Re.

In considering the relevance of the coefficients presented herein and of the equation devised by Morison to wave induced loads on offshore structures, it is of course important to take into account the differences between uniform two-dimensional harmonic motion and the wave motion where the velocity vector both rotates with time at a point and decays in magnitude with depth. The spanwise variations of the flow in general lead to reduced spanwise coherence. It is safe to assume that both the three-dimensionality of the flow and the reduction of the correlation length along the cylinder, in an ocean environment, tend to increase the base pressure and thus give rise to transcritical drag coefficients which are smaller than those obtained with purely two-dimensional flows. The drag coefficients presented herein obviously represent their maximum possible values since they have resulted from a uniform, two-dimensional flow where the instantaneous wake of the cylinder has the highest possible degree of spanwise coherence. The similarity between the reduced drag coefficient due to lack of spanwise coherence in wavy flows and the drag coefficient in steady flows (both for roughened cylinders) is pure coincidence and certainly the wrong reason in arriving at the right value. It is rather unfortunate that even the experiments with wavy flows cannot be expected to isolate the effect of reduced spanwise coherence since such experiments surely bring in other factors whose influence is combined in a complex way with that of the reduced correlation. Thus, the value of the results presented herein lies in the fact that the designer now knows the maximum possible value of the coefficients under consideration, if not the values which might be more appropriate to the conditions under which the structure must survive and function. These conditions might include, among other things, currents and wave induced oscillations. Under these circumstances, the coefficients obtained either with two-dimensional harmonic flows or with waves without a current superimposed on them cannot be expected to apply to the design of the structures. Furthermore, the equation proposed by Morison needs major changes to accommodate the existence of the currents.

TRANSVERSE FORCE

The transverse force coefficients for smooth cylinders have been presented in Refs. [3, 4, 6]. The results for the rough cylinders are presented in Fig. 14 as a function of K for various values of β and one particular value of k/D. Additional details and data may be found in [19].

Evidently, C_L does not vary appreciably with either β or Re. The data presented in [19] for other values of k/D show that C_L does not vary with k/D also within the range of the parameters encountered. If there is some variation with these parameters (Re and β), it is certainly masked by the scatter in the data. The transverse force coefficient inevitably exhibits a larger scatter than that for the in-line force coefficients because of the somewhat random nature of the shedding of the vortices. Consequently, it is not too uncommon to obtain a variation of 20-25% for a given K value. This fact is of importance in discussing the effect of the Reynolds number on the lift coefficient.

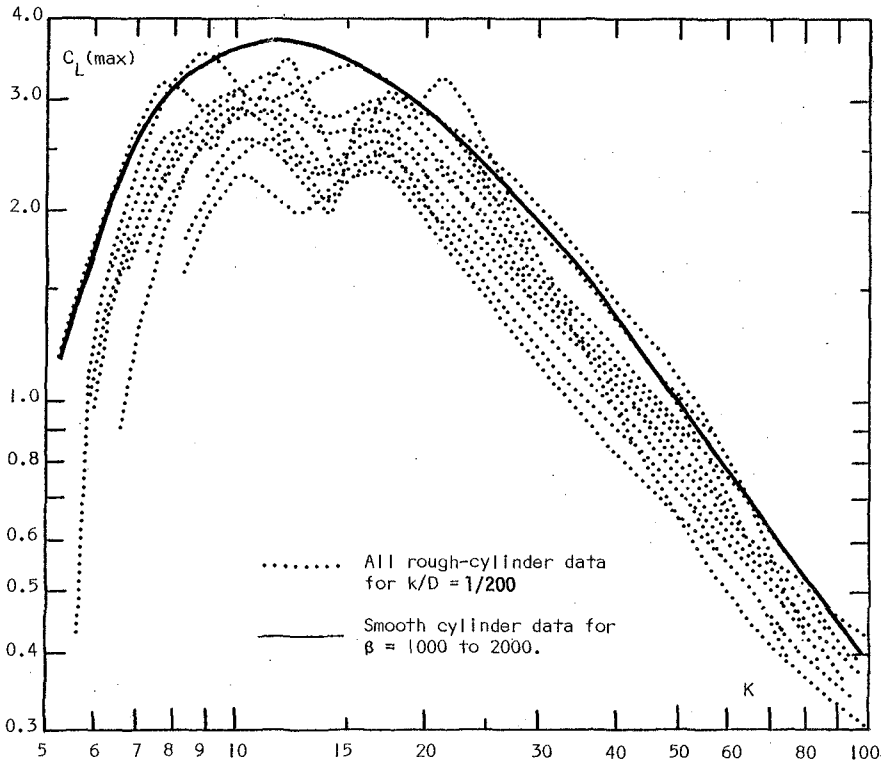

Fig. 14 Transverse force coefficient for various values of β for k/D = 1/200.

Also shown in Fig. 14 is the lift coefficient for smooth cylinders for β in the range 1000 to 2000. It is rather surprising that the smooth cylinder data at relatively low values of β form more or less the upper limit of the rough cylinder data. In other words, the lift coefficient for rough cylinders does not depend on Re and become almost identical with those for smooth cylinders at very low Reynolds numbers. The consequences of this observation for model testing purposes are rather obvious.

As noted earlier, the alternating nature of the transverse force is as important as its magnitude. It is for this reason that the frequency of the alternating force has also been calculated [14]. A close examination of the frequency ratios shows that f_r/K remains essentially constant at a value of about 0.22. To be sure, there are variations from one cylinder to another and from a given combination of Re and K to another one. Nevertheless, the Strouhal number ($St = f_v D/U_m = f_r/K$) is fairly constant for all roughnesses, relative amplitudes, and Reynolds numbers larger than about 20,000. This fact is of special importance in determining the in-line and transverse vibrational response of the elements of a structure to wave-induced transverse forces. Once again it should be kept in mind that the spanwise coherence along a vertical cylinder in the ocean environment is reduced by the variation of the velocity vector with time and depth and that the coefficients presented herein represent the maximum possible values of the transverse force.

CONCLUSIONS

The extensive investigation of the in-line and transverse forces on roughened circular cylinders in harmonic flow warrants the following conclusions:

1. The drag and inertia coefficients depend on Re, K, and k/D. The effect of size distribution and packing of the grains has been minimized by using only sand and applying it as uniformly as possible over the test cylinders;

2. The drag coefficient undergoes a 'drag crisis' depending on the relative roughness and rises to an asymptotic value within the range of Reynolds numbers tested. The asymptotic values of the transcritical drag coefficient are larger than those corresponding to the smooth cylinder case. Furthermore, the larger the relative roughness the larger is the asymptotic value of the drag coefficient;

3. The inertia coefficient also undergoes an 'inertia crisis' at Re values corresponding to the 'drag crisis' at which C_m reaches a maximum value and then asymptotically decreases. The terminal values of C_m depend, as in the case of C_d, on K and k/D;

4. The predictions of the Morison's equation through the use of the Fourier-averaged drag and inertia coefficients are in excellent agreement with the measured forces in the range of K values smaller than about 10 and larger than about 20;

5. Within the range of parameters tested, C_L does not depend on Re. Its distribution is, surprisingly enough, very close to that obtained with the smooth cylinders at very low Reynolds numbers. The Strouhal number for rough cylinders remains nearly constant for all Reynolds numbers at about 0.22 with the possible exception of those at very low Reynolds numbers.

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