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ABSTRACT

Experiments were conducted with two smooth and two sand-roughened cylinders in a harmonically oscillating flow with current to determine the drag and inertia coefficients and to examine the effect of current-induced wake biasing on the modified Morison equation. The various flow parameters such as the relative current velocity, Reynolds number, and the Keulegan-Carpenter number were varied systematically and the in-line force measured simultaneously. The principal results, equally valid for smooth and rough cylinders, are as follows: the drag coefficient decreases with increasing relative current for a given Reynolds number and Keulegan-Carpenter number; the effect of wake biasing on the drag and inertia coefficients is most pronounced in the drag/inertia dominated regime; and the two-term Morison equation with force coefficients obtained under no-current conditions is not applicable to the prediction of wave and current induced loads on circular cylinders.

INTRODUCTION

The analysis of the interaction of waves with pre-existing and/or wind-or wave-generated currents and the interaction of the modified wave-current combination with rigid or elastic structures and their components require different mathematical approaches, relevant observations, and experiments that are applicable to all or some of these physical circumstances.

Measurements of wave-current interaction phenomena are scarce. Among the first to perform substantial controlled experiments of this nature was Sarpkaya[1] in 1955. . Additional studies were conducted much later by Jonsson[2], Inman and Bowen[3], and Dalrymple and Dean[4]. A detailed discussion of the foregoing is given by Sarpkaya and Isaacson[5].

Little information exists on the effect of the co-existing flow field (wave plus current) on hydrodynamic loading of offshore structures. The complexity of the problem stems from several facts. Firstly, an analytical solution of the problem is not yet possible even for relatively idealized situations. Secondly, Morison's equation suffers from numerous uncertainties as discussed in detail by Sarpkaya[6]. Thirdly, waves and currents are omnidirectional. Even for a simple harmonic flow-current combination the wake and the vortex shedding are biased. Finally, a field study of the problem in the practically significant range of Reynolds number, Keulegan-Carpenter number, relative current velocity, and a suitably-defined current gradient is practically impossible. In fact, any experiment addressing this question faces rather difficult problems: how should the co-existing flow field be created and what measurements should be made in order to clarify the nature of the wake biasing? Measurements of the in-line and transverse forces, no matter how detailed and sophisticated, cannot lead to a unique picture concerning the nature of the particular time-dependent flow. One is forced therefore to make pressure measurements at numerous points on the cylinder (hopefully simultaneously) and to carry out extensive flow visualization studies. These, however, prove to be very difficult for a number of obvious reasons.

References and illustrations at end of paper.

RELATED INVESTIGATIONS

An extensive review of the previous investigations is given by Sarpkaya and Isaacson[5]. Here only the most recent and most relevant investigations will be described briefly.

Verley and Moe[7] evaluated the drag coefficient C_{dc} and the inertia coefficient C_{mc} (assuming that the two-term Morison equation applies to the co-existing flow field) through the measurement of the rate of damping of the amplitude of oscillations of a cylinder attached to a pendulum in a channel of uniform and constant velocity. These experiments were performed at very low Reynolds numbers (Re smaller than about 12,000 and Re/K = 300). Nevertheless, their data show that the current causes profound changes not only in C_{dc} but also in C_{mc} relative to the no-current case, at the corresponding K ($K = U_mT/D$) and Re (U_mD/ν) values. In general C_{dc} decreased and C_{mc} increased.

Iwagaki, Asano, and Nagai[8] carried out experiments with two relatively small vertical cylinders in a wave tank with recirculating flow. The cylinders were cantilevered at top. The force-coefficients were calculated by two approximate methods through the use of the total moment acting on the entire cantilever. They have expressed C_{dc} and C_{mc} in terms of various Keulegan-Carpenter numbers and claimed that a new Keulegan-Carpenter number based on the relative displacement of the fluid correlates the force coefficients quite well.

Kato, Abe, Tamiya, and Kumakiri[9] subjected a cylinder to a co-existing flow field by means of a carriage which oscillated in either the in-line or the transverse direction while moving forward at a presribed mean speed. They have evaluated only the drag coefficient, after subjecting the data to suitable filtering. They have concluded that the drag coefficient increases with increasing V_cT/D, hereinafter referred to as VK. This result is in contradiction to that obtained in the present study and by Verley and Moe[7] and by Iwagaki et al.[8] A closer examination of their data shows that the Reynolds number for a given K varies from one value of VK to another and the range of K decreases with decreasing VK, i.e., β = Re/K is not kept constant while varying K and VK. Thus, it is not possible to draw any conclusions regarding the dependence of the force-transfer coefficients on the governing parameters.

It is evident from the foregoing that much laboratory and field investigations remain to be carried out for a better understanding and quantification of the wave-current and wave-current-structure interactions. This need has long been recognized but it has not been possible to translate it into laboratory and field measurements. Test facilities in most laboratories consist of a long wave channel. However, the variation of the fluid velocity with depth (and hence of the Reynolds number, relative amplitude, relative-current velocity, vortex shedding, coherence length, pressure correlation, etc.) does not allow one to assess the effect of current on fluid loading. Field measurements are even more difficult for a number of reasons. It is necessary to make a number of simplifying assumptions to separate the effect of the current from that of the orbital motion, omnidirectionality of the waves and currents, random wake encounters, etc., in analyzing the data obtained in the ocean environment.

Measurements are needed with relatively more manageable flows where one can measure the oscillatory and mean velocity, vortex shedding frequency, pressure distribution, all components of the force, and the dynamic response of the body at relatively high Reynolds numbers and over a range of Keulegan-Carpenter numbers and relative current velocities. Such a manageable flow is the combination of a harmonically oscillating flow with a uniformly translating cylinder. The effect of the variation of the velocity with depth and of the orbital motion of the fluid particles are eliminated. However, there are certain limitations even to this type of flow: the constancy of the frequency of flow oscillation and the limitations imposed on the distance over which the cylinder may be moved tend to reduce the range of VK for a given K and Re. Nevertheles, it is easy to maintain β constant while varying K and VK. This enables one to asses the role of current (i.e., VK) on C_{dc} and C_{mc} for a given K and Re, even though Re for each K is different (Re = β.K).

It must be noted that similar co-existing flow fields can be created either by oscillating the cylinder in a uniform stream or by subjecting the cylinder to a constant mean velocity while oscillating it in the desired direction. The decision to oscillate the flow or the cylinder while moving the cylinder or the current at a constant speed depends on the ranges desired for the governing parameters, the availability of the equipment, and other considerations regarding vibration, signal noise, filtering, and the accuracy desired. In any case it is now quite clear that no single test facility can possibly cover all desired ranges of the governing parameters. Hopefully, complementary and overlapping data will emerge from various test facilities in order to understand the role of relative mean fluid motion superimposed on the oscillatory flow about a bluff body. This will enable one to assess the validity of the methods used in the determination of the so-called "hydrodynamic damping", (for small amplitude motions of the structures) , and of the effect of ocean currents on the loading and hydroelastic response of risers and other offshore structures.

The present investigation was undertaken to determine the forces acting on smooth and rough-walled cylinders, moving with a constant velocity, in a harmonically oscillating flow, (relative velocity $U = V_c - U_m \cos\theta$) and to examine in detail the applicability of the two-term Morison equation to the flow situation under consideration. Experiments have been conducted in a large U-shaped oscillating flow tunnel. The first phase of the investigation has shown that current significantly affects the drag and inertia coefficients, particularly in the drag-inertia dominated regime.

EXPERIMENTAL EQUIPMENT

The oscillating flow system used to generate the harmonically oscillating flow has been extensively used at this facility over the past ten years.[10,11] Only salient features, most recent modifications, as well as the adaptation for this investigation are briefly described in the following.

The length of the U-shaped water tunnel has been increased from 30 ft to 35 ft, the height from 16 ft to 22 ft, and the cross section of the test section from 36 inch by 36 inch to 36 inch by 56 inch. A small butterfly valve, placed in a special housing between the top of the tunnel and the supply line, oscillates harmonically at a frequency equal to the natural frequency of the flow oscillations in the tunnel, (f =1/5.3419 = 0.1872 Hz). The oscillation of the valve is perfectly synchronized with that of the flow through the use of a feedback control system. The output of a pressure transducer (sensing the instantaneous acceleration of the flow) is connected to an electronic speed-control unit coupled to a DC motor oscillating the valve. The circuit maintains the period of oscillations of the valve within 0.0001 seconds. The amplitude of oscillations is varied by constricting or enlarging an orifice at the exit of the fan. The flow oscillates at a given amplitude as long as desired.

In addition to the foregoing, three stainless steel guide rails have been mounted at mid height on each side of the inner side walls of the horizontal section. Two of the rails are fixed and one is free to move at a constant speed through the use of an electronically-controlled hydraulic system, actuated by a constant speed motor. The moving rails protrude outside the tunnel a distance of about 20 ft. Force transducers (one at each side) are mounted on a block which is attached to the moving rod and guided by the other two rails. The cylinders are attached to the force transducers with self-aligning ball bearings imbedded in the middle one-third of the cylinders. Electrical connections are made under water and the signals are transmitted to the amplifier-recorder system with cables going through the hollow moving rail. The cylinders may be mounted at any angle of inclination between the guide rails. The entire system operates quite smoothly and no electronic filters are used in recording the data either on charts or on tapes or on flexible discs.

The velocity of the ambient flow at the test section is determined by four independent means: A differential pressure transducer which yields the instantaneous acceleration and hence the velocity[10], a magnetic velocimeter, a capacitance wire which yields the instantaneous elevation , and a hot-film anemometer. These yield the velocity within $\pm 2\%$.

Circular cylinders with diameters ranging from 2.5 inches to 6 inches have been used. They yielded tunnel-height-to-cylinder-diameter ratios from $h/D = 56/2.5 = 22.5$ to $56/6 = 9.33$. The tunnel blockage is not expected to be important in this range of h/D ratios.

The data are electronically digitized and fed to a desk-top computer for the analysis of the force-transfer coefficients in terms of the governing parameters (K, Re/K, k/D, and VK).

GENERALIZATIONS OF MORISON'S EQUATION

It has been customary to express the in-line force per unit length either as

$$F = 0.5\rho D C_{dc}(V_c - U_m\cos\theta)|V_c - U_m\cos\theta| + (\pi\rho C_{mc}D^2/4)\, dU/dt \quad \cdots\cdots (1)$$

where V_c represents the current; $U = -U_m\cos\theta$, the oscillating flow; and, $\theta = 2\pi t/T$. In general one has

$$F = 0.5\rho D C_{dc}(V_c+U_w)|V_c+U_w| + (\pi\rho C_{mc}D^2/4)dU_w/dt \quad (2)$$

where U_w is the wave velocity, added vectorially to the current velocity (some designers use the projection of the current velocity on the wave velocity and assume the sum of the two to be in the direction of wave).

Equation (1) is certainly not the only means by which the time-dependent force may be decomposed into various components. It is possible to use a three term equation such as

$$F/(0.5\rho D U_m^2) = \overline{C}_d\, V_r^2 - C_d|\cos\theta|\cos\theta + C_m(\pi^2/K)\sin\theta \quad \cdots\cdots (3)$$

in which C_d and C_m are assumed to be given by their Fourier averages. Furthermore, neither C_d is assumed to be equal to the steady-state drag coefficient for a uniform flow at the constant velocity V_c, nor C_m and C_d are assumed to be identical to those obtained for a strictly sinusoidal oscillation. Extensive analysis of the present data in terms of this equation has shown that C_d exhibits unrealistically large values and that neither C_d nor C_m bear any resemblance to those obtained under no-current conditions. It is concluded on the basis of the foregoing that Eq. (3) is not very meaningful for the decomposition of the force exerted on a cylinder by the co-existing wave-current field. In what follows, only the results based on the modified version of Morison's equation [Eq. (1)] will be presented.

It is ordinarily assumed (as recommended by the Petroleum Institute) that Morison's equation applies equally well to periodic flow with a mean velocity and that C_{dc} and C_{mc} have constant, current-invariant, Fourier-or least-squares averaged values equal to those applicable to rigid, stationary cylinders in wave flows. This, in turn, implies that C_{dc} and C_{mc} are independent of the biased convection of vortices and its attendant consequences. The fact that this is not so is clearly evidenced by the results obtained in this investigation.

The Fourier averages of the drag and inertia coefficients have been calculated by multiplying both sides of Eq. (1) once with $\cos\theta$ and once with $\sin\theta$ and integrating between the limits $\theta = 0$ and $\theta = 2\pi$.

$$C_{dc} = \frac{\displaystyle\int_0^{2\pi} \frac{2\,F\cos\theta\, d\theta}{\rho D U_m^2}}{\displaystyle\int_0^{2\pi} (V_r-\cos\theta)\,|V_r-\cos\theta|\,\cos\theta\, d\theta} \quad \cdots\cdots (4)$$

and

$$C_{mc} = \frac{\displaystyle\int_0^{2\pi} \frac{2\,F\sin\theta\, d\theta}{\rho D U_m^2}}{\displaystyle\frac{\pi^2}{K}\int_0^{2\pi} \sin^2\theta\, d\theta} \quad \cdots\cdots (5)$$

where F represents the measured in-line force. Evidently, the above analysis assumes that the force coefficients are temporally invariant throughout the wave cycle. The validity of this assumption remains to be demonstrated through experiments over a wide range of the governing parameters. At present, this is not quite possible and Eq.(1) remains as a speculative generalization of Morison's equation.

Equation (4) may be integrated partially to yield

$$C_{dc} = -\int_0^{2\pi} (2\,F\cos\theta)d\theta/(\rho D U_m^2 \Sigma) \quad \cdots\cdots (6)$$

in which

$$\Sigma = 2\pi V_r\ , \text{ for } V_r = V_c/U_m > 1 \quad \cdots\cdots (7)$$

and

$$\Sigma = 4V_r^2 \sin\theta_o + 2V_r(\pi - 2\theta_o - \sin 2\theta_o) + (1/3)(\sin 3\theta_o + 9 \sin\theta_o) \quad , \text{ for } V_r < 1 \quad (8)$$

where

$$\theta_o = \cos^{-1} V_r \quad \cdots\cdots \quad (9)$$

Equation (5) may be reduced to

$$C_{mc} = (2K/\pi^3) \int_0^{2\pi} (2F \sin\theta) d\theta/(\rho D U_m)^2 \quad \cdots \quad (10)$$

in which V_r does not appear explicitly since V_c is assumed to be time invariant.

GOVERNING PARAMETERS

A simple dimensional analysis of the flow under consideration shows that the time-invariant force coefficients C_{dc} and C_{mc} are functions of a Keulegan-Carpenter number, a Reynolds number (or the ratio of the Reynolds number to the Keulegan-Carpenter number, i.e., $\beta = Re/K$), a parameter involving current velocity (e.g., V_cT/D or V_c/U_m), and the relative roughness k/D. There are numerous possibilities regarding the definitions of the Keulegan-Carpenter number and the Reynolds number. The purpose of the search for a more suitable Keulegan-Carpenter number and/or Reynolds number is to enhance the correlation of the data and to reduce the number of the governing parameters from four to three, possibly eliminating V_cT/D or V_c/U_m as an independent parameter.

A partial list of the possible Keulegan-Carpenter numbers and Reynolds numbers is given below.

a. $K = U_mT/D \quad , \quad Re = U_mD/\nu \quad \cdots\cdots \quad (11)$

b. $K^+ = K\,(1 + |V_r|) \quad , \quad Re^+ = Re\,(1 + |V_r|) \quad (12)$

c. $K_s = K \int_{\theta_o}^{\pi} |V_r - \cos\theta|\, d\theta \quad , \quad \text{for } Vr < 1 \quad (13a)$

$Re_s = K_s\,(D^2/\nu T) \quad \cdots\cdots \quad (13b)$

d. $K_m = K\,(1 + |V_r|)^2 \quad \cdots\cdots \quad (14a)$

$Re_m = Re\,(1 + |Vr|)^2 \quad \text{or} \quad Re = Re^+ \quad (14b)$

Equation (13a) expresses the Keulegan-Carpenter number in terms of the relative displacement of the fluid about the cylinder. Equation (14a) represents the ratio of the maximum convective acceleration to the maximum local acceleration.

For a limited range of the governing parameters, the data may appear to correlate well with one of the Keulegan-Carpenter numbers involving V_r [as in Eqs. (12-14)] thereby eliminating the need for an additional V_c-dependent parameter such as $VK = V_cT/D$ or V_r. The results of the present investigation have shown that there is no single Keulegan-Carpenter number with which the drag and inertia coefficients may be correlated without the need for an additional parameter involving V_r. Thus, the four governing parameters for the flow situation under consideration are taken as

$$\left.\begin{matrix} C_{dc} \\ C_{mc} \end{matrix}\right\} = f_i(K,\ VK,\ \beta,\ k/D) \quad \cdots\cdots \quad (15)$$

RESULTS

Figures 1 and 2 show that the drag coefficient for a smooth cylinder is strongly affected by the current, particularly in the drag-inertia dominated regime. For example, for K = 12, the drag coefficient for the co-existing flow (VK = 6.17, corresponding to V_r = 0.51) is approximately 40 percent smaller than that corresponding to the no-current case. A similar conclusion is reached regarding the drag coefficient shown in Fig. 2. Taken together, Figs. 1 and 2 show that C_{dc} is not equal to its no-current value and strongly depends on K, VK, and the Reynolds number (note that $Re = K\beta$ and β = 1594 for Fig. 1 and β = 2487 for Fig. 2).

Figures 3 and 4 show the inertia coefficient for two smooth cylinders for $\beta = 1594$ and $\beta = 2487$. These correspond to the drag coefficients shown in Figs. 1 and 2. It is clear that the inertia coefficient for the no-current case is about 50 percent smaller than that for the co-existing flow with K = 12 and VK = 6.17. Furthermore, the effect of the current spans over a large range of K values. Taken together, Figs. 3 and 4 show that the inertia coefficient is strongly affected by K, β, and VK (or by K, Re, and VK) and that there is a critical value of VK above which C_{mc} does not increase with VK.

Evidently, additional data are needed to cover a wider range of Re and VK values. The data shown here are sufficient to prove that the use of Eq. (1) with the drag and inertia coefficients obtained under no-current conditions is incorrect and may lead to large errors, particularly in the drag-inertia dominated regime. The data also show that the drag and inertia coefficients obtained from tests at sea (where there are always some currents) cannot be compared with those obtained under laboratory conditions with zero current. In fact, the present data with current substantiates the fact that the drag coefficients obtained from tests at sea will always be smaller, particularly in the drag-inertia dominated regime, than those obtained under laboratory conditions.[12] Orbital motion of the fluid particles in waves in the absence of current has a similar effect on the drag coefficient.[13] Thus, current and orbital motion may be regarded as the primary mitigating effects of the ocean environment as far as C_{dc} is concerned since the current and orbital-motion combination is not likely to reverse their individual effects.

The inverse is true for the inertia coefficient in the drag-inertia dominated regime. Outside this region, the inertia coefficient for the co-existing flow may be smaller than that for the no-current case (see Fig. 4 for K larger than about 20).

Figures 1 through 4 show conclusively that current has profound effects on both the drag and inertia coefficient. This effect (resulting from wake biasing) cannot be ignored, particularly in the drag-inertia dominated regime. For most offshore structures and piles this will correspond to the region below the free surface where the wave-induced velocities may be of the same order of magnitude as the local current velocity.

Figures 5 and 6 show the drag coefficient for two sand-roughened cylinders as a function of K for various values of VK. The most striking feature of these figures is that the wake biasing reduces the drag coefficient significantly in the drag-inertia dominated regime, in the range of Reynolds numbers encountered. For K larger than about 20, the effect of roughness is predominant and the wake biasing does not materially change the drag coefficient.

Figures 7 and 8 show the inertia coefficient for two rough cylinders for various values of VK. As in Figs. 3 and 4, the effect of the current is to increase the inertia coefficient in the drag-inertia dominated regime and to decrease it in the drag-dominated regime. Figure 8 also shows that the increase of the inertia coefficient with VK in the drag-inertia dominated regime depends on the Reynolds number, i.e., the larger the Reynolds number, the smaller is the dependence of the increase of C_{mc} on VK.

In summary of the foregoing, it is evident that current has profound effects on the variation of the drag and inertia coefficients with K and Re, particularly in the drag-inertia dominated regime. This effect cannot be ignored in the design of offshore structures. The results explain partly the reason as to why the ocean test data always yield smaller drag coefficients and larger inertia coefficients than those obtained under controlled laboratory conditions with no current. It is also evident that the use of various heuristic linearization methods in approximating the influence of current on the nonlinear hydrodynamic force must be based on a better understanding of the physics of the phenomenon.

MORISON'S EQUATION

As noted earlier, the use of Morison's equation for the combined wave and current loading is a speculative generalization of the original two-term Morison equation, devised for wave loading alone. It has been shown in the foregoing through the use of the data obtained under controlled laboratory conditions that the drag and inertia coefficients for the co-existing flow field are significantly different from those for the oscillating flow alone, particularly in the drag-inertia dominated regime. Thus, one may ask as to how well the measured force is represented by the modified Morison equation [Eq. (1)] even if one were to use the drag and inertia coefficients obtained through the use of Eqs. (4) and (5) rather than those obtained under no-current conditions (i.e., harmonic flow alone).

Numerous calculations have been carried out for both the smooth and rough cylinders for various values of K, VK, and β. The results of two sample calculations are shown in Figs. 9 and 10. Each figure shows the measured force, the force calculated through the use of Eq.(1) with the drag and inertia coefficients from Eqs. (4) and (5), and the force calculated through the use of Eq.(1) with the force coefficients for the harmonic flow alone, i.e., for the identical values of K, β, and k/D, but for VK = 0.

A careful examination of each figure shows that the two-term Morison equation, modified as in Eq. (1), represents the measured force in a co-existing flow field as adequately as the original Morison equation in a no-current field, provided that the force coefficients appropriate to each case are determined and used in Eq. (1). Figure 9 also shows that the use of Eq. (1) to represent the effect of the current in the drag-inertia dominated regime with the force coefficients obtained under no-current conditions is far from adequate. Figure 10 shows that for sufficiently large values of K (K larger than about 20), the use of Eq. (1) with the force coefficients obtained under no-current conditions yields an in-line force which is essentially identical to that obtained with the force coefficients calculated through the use of Eqs. (4) and (5). Evidently, additional experiments and analysis are needed to cover a wider range of Reynolds numbers, relative current velocities, relative roughness, and Keulegan-Carpenter numbers.

CONCLUSIONS

The results presented herein warrant the following conclusions:

(1) The drag and inertia coeficients for the no-current case are not identical with those obtained for the current-harmonic-flow case (co-existing flow field), particularly in the drag-inertia dominated regime. The wake biasing, resulting from the current, increases the inertia coefficient and decreases the drag coefficient. The variation of the force coefficients is governed by the Keulegan-Carpenter number ($K = U_mT/D$), Reynolds number ($Re = U_mD/\nu$), (or $\beta = D^2/\nu T$), relative-roughness (k/D), and the relative current displacement ($VK = V_cT/D$).

(2) The force coefficients obtained from tests at sea (where there are always some currents) are necessarily different from those obtained under no-current conditions. The comparison of the two sets of data are not warranted in the drag-inertia dominated regime. The results presented herein show that the drag coefficients resulting from the ocean tests must be smaller than those resulting from the strictly-harmonic-flow experiments with no current. The inverse is true for the inertia coefficient. However, the increase of the inertia coefficient does not compensate for the decrease of the drag coefficient as far as the maximum force and its phase relative to the maximum velocity are concerned. Thus, the use of the force coefficients obtained under no current conditions is not warranted in calculating the hydrodynamic loading of smooth and rough cylinders in wave-current environment.

(3) The two-term Morison equation, modified for the current [as in Eq. (1)], represents the measured force in a co-existing flow field with an accuracy almost identical to that of the original Morison equation for the no-current case, provided that force coefficients appropriate to each case are used. For Keulegan-Carpenter numbers larger than about 20, the effect of current on force-transfer coefficients and on the calculated in-line force is negligible, within the range of the parameters encountered in the present investigation. Additional experiments are needed to cover a wider range of the governing parameters, including the case where VK is larger than unity.

NOMENCLATURE

A	Amplitude of flow oscillations
C_d	Drag coefficient
C_m	Inertia coefficient
C_{dc}	Drag coefficient for $V_c \neq 0$
C_{mc}	Inertia coefficient for $V_c \neq 0$
D	Diameter of the test cylinder
F	In-line force
f	Frequency of flow oscillations, $f = 1/T$
K	Keulegan-Carpenter number, $K = U_mT/D$
k	Mean roughness height
Re	Reynolds number, $Re = U_mD/\nu$
T	Period of flow oscillations
t	Time
U	Instantaneous velocity of flow
U_m	Maximum velocity in a cycle of oscillating flow
V_c	Velocity of the steady current
VK	V_cT/D
V_r	V_c/U_m
β	frequency parameter, $\beta = D^2/\nu T = Re/K$
θ	$2\pi t/T$
ν	Kinematic viscosity of water
ρ	Density of water

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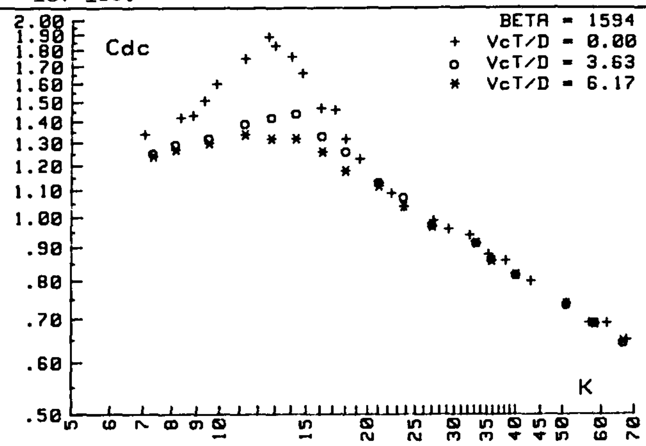

Fig. 1—C_{dc} vs. K for a smooth cylinder for beta = 1,594 and various values of VK.

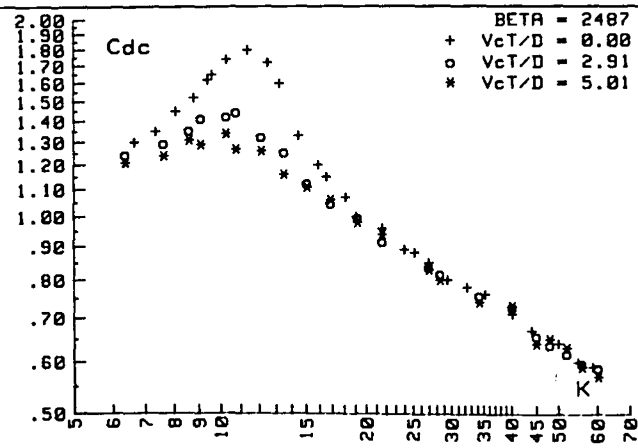

Fig. 2—C_{dc} vs. K for a smooth cylinder for beta = 2,487 and various values of VK.

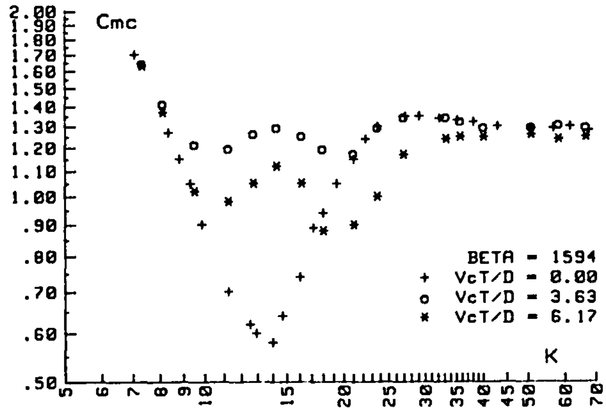

Fig. 3—C_{mc} vs. K for a smooth cylinder for beta = 1,594 and various values of VK.

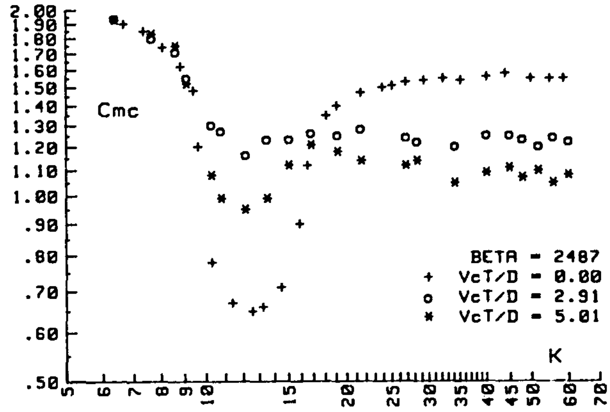

Fig. 4—C_{mc} vs. K for a smooth cylinder for beta = 2,487 and various values of VK.

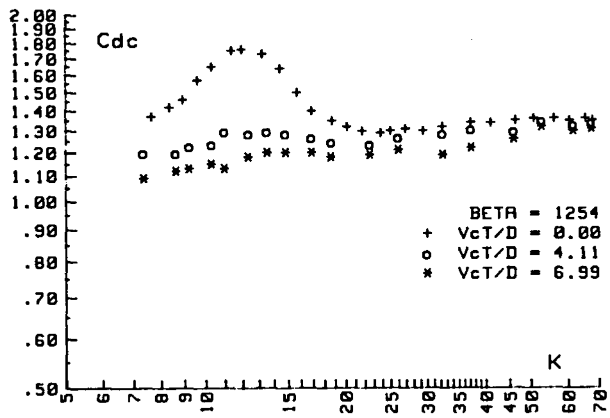

Fig. 5—C_{dc} vs. K for a rough cylinder for beta = 1,254 and various values of VK.

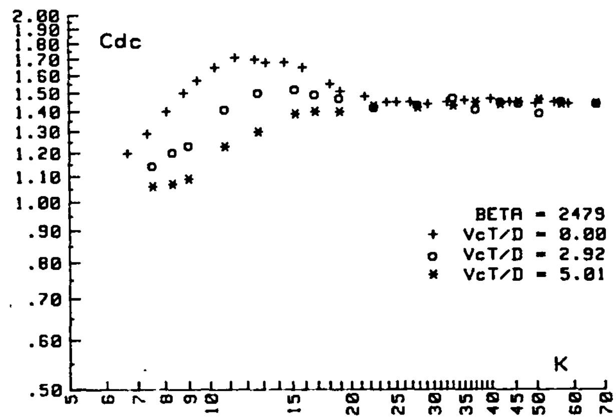

Fig. 6—C_{dc} vs. K for a rough cylinder for beta = 2,479 ana various values of VK.

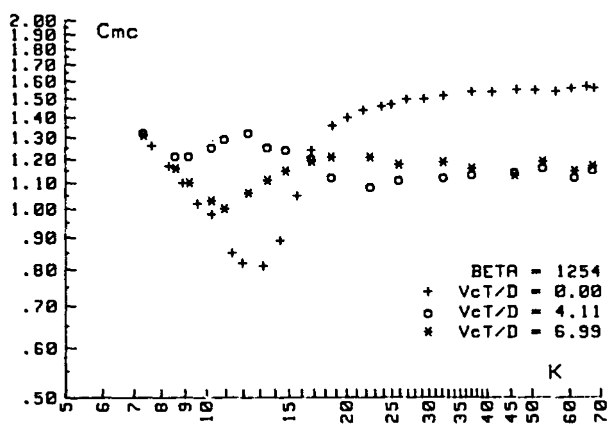

Fig. 7—C_{mc} vs. K for a rough cylinder for beta = 1,254 and various values of VK.

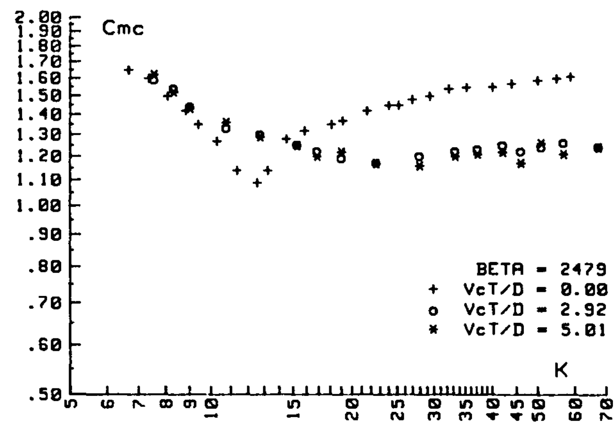

Fig. 8—C_{mc} vs. K for a rough cylinder for beta = 2,479 and various values of VK.

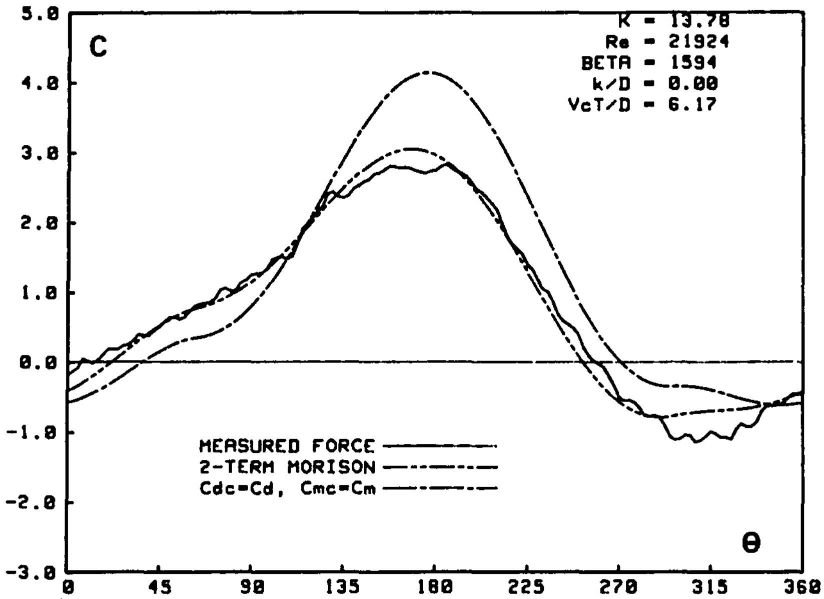

Fig. 9—Normalized in-line force vs. time for K = 13.78 (smooth cylinder).

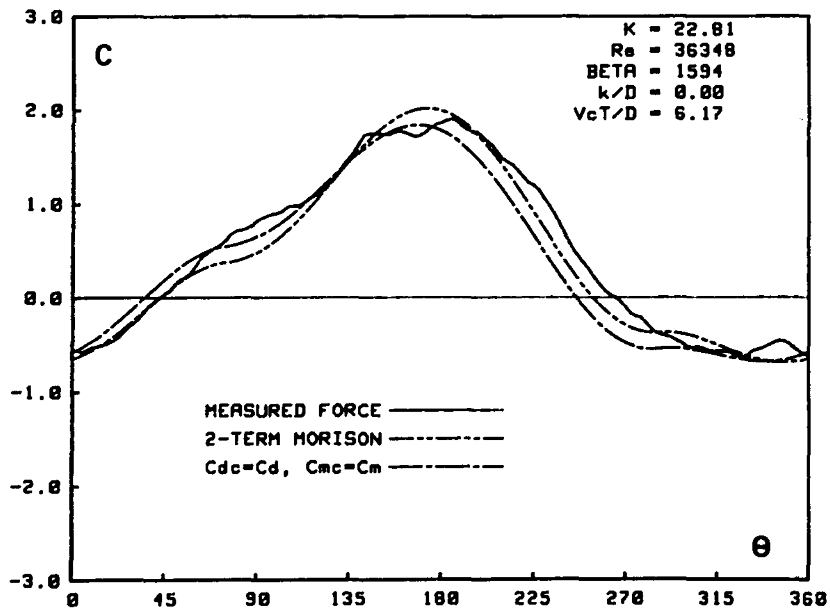

Fig. 10—Normalized in-line force vs. time for K = 22.81 (smooth cylinder).