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# Drag and Inertia coefficients of a Cylinder in Random Waves

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Laboratory experiments were carried out to research drag and inertia coefficients of a vertical circular cylinder in random waves. The results were compared with those of field experiments and numerical simulations to discuss the characteristics of the random wave force. This comprehensive study showed that the drag and inertia coefficients obtained from the least squares fit on a wave-by-wave basis scattered widely as a results of shedding vortices during the previous wave cycle, the so-called history effect. Coefficients determined by least squares fit of the complete force time series of a random wave record were well ordered as a function of Keulegan-Carpenter number defined by significant orbital displacement or significant wave height and showed good agreement with the values in regular waves.

This study enabled us to apply the results of extensive studies in regular waves or in harmonic flow to estimate wave forces acting on an ocean structure in random waves.

***Key words***: Drag coefficient, Random waves, Field experiment, Laboratory experiment, Numerical simulation

## 1. Introduction

The wave forces acting on an ocean structure in random waves have primarily been studied as a non-linear statistical problem[1]. This approach does not anticipate the existence of a serious hydrodynamic impact due to the irregularity of waves. The factor of whether or not the force coefficients for regular waves are valid for random waves is of great importance hydrodynamically. Many excellent studies have been done on hydrodynamic forces acting on a cylinder in regular waves[2] or in a harmonically oscillating flow[3]. The ultimate goal of all such studies should be the accurate estimate of wave forces acting on an ocean structure under actual sea conditions.

Everyone knows that "regular waves" never exist in the real sea, yet the

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applicability of the results of these studies to the random wave problem are unknown. This is admittedly strange because every designer of an ocean structure must estimate the wave forces acting on that structure in random waves; wave force research should therefore concentrate on this subject. The authors believe that the reason no clear conclusion has been reached is that the values of wave force coefficients obtained from experiments[4)-9)] in random waves varied greatly and no reasonable explanation for this scattering has been found. Comprehensive research is needed to reach a viable conclusion on the characteristics of random wave forces.

In this paper the hydrodynamic characteristics of random wave forces are discussed based on experiments conducted in both the field and the laboratory, and on numerical simulations.

## 2. Equations used for determining $C_D$, $C_M$ from the time series of wave force

Quite different methods are needed to get a time series of random waves for numerical, laboratory and field experiments, but after this time series is obtained the same procedure is used to determine the values of $C_D$ and $C_M$ from this time series. The procedure is shown here.

The time series of surface elevation, which is measured with a wave height meter in laboratory and field experiments but is generated numerically in numerical simulations, is represented as:

$$\zeta(t) = \sum_{i=1}^{M} a_i \sin(\omega_i t + \varepsilon_i) \tag{1}$$

where $\zeta$ is surface elevation, $a_i$ the amplitude of ith component of the wave, $\omega_i$ the circular frequency of waves and, $\varepsilon_i$ the phase.

The orbital velocity $u(z, t)$ and acceleration $u(z, t)$ are obtained by;

$$u(z, t) = \sum_{i=1}^{M} \left\{ -\frac{gk_i}{\omega_i} a_i \frac{\cosh k_i(h-z)}{\cosh k_i h} \sin(\omega_i t + \varepsilon_i) \right\} \tag{2}$$

$$\dot{u}(z, t) = \sum_{i=1}^{M} \left\{ -gk_i a_i \frac{\cosh k_i(h-z)}{\cosh k_i h} \cos(\omega_i t + \varepsilon_i) \right\} \tag{3}$$

$k_i$ is obtained from the equation

$$gk_i \tanh(k_i h) = \omega_i^2 \tag{4}$$

where g is gravity, $k_i$ the wave number, $h$ the water depth, and $z$ the vertical distance measured below the still water level.

The in-line force acting on a cylinder fixed in an oscillating flow is represented using Morison's formula as:

$$F = \frac{1}{2}\rho D C_D L u(t)|u(t)| + \frac{1}{4}\rho\pi D^2 L C_M \dot{u}(t) \tag{5}$$

In the case of a surface-piercing cylinder fixed in waves, the wave-making force $F_w$ should be taken into consideration and the value of $u$ changes with the depth $z$ ; then, the time series of wave force $F(t)$ can be written as,

$$F(t) = \frac{1}{2}\rho D\int_0^L C_D(z)u(z, t)|u(z, t)|dz+\frac{1}{4}\rho\pi D^2\int_0^L C_M(z)\dot{u}(z, t)dz+F_w(t) \qquad (6)$$

where $C_D$ is the drag coefficient, $C_M$ the inertia coefficient, $\rho$ the water density, $D$ the diameter of the test cylinder, L the length of the submerged part of the cylinder, and $F_w$ the wave-making force. $F_w$ is estimated from the linear potential theory, and is negligible compared with other forces except in the case of minimal wave height. If $F_w$ is neglected when wave height is very small, the value of $C_D$ becomes very large, especially in the case of a surface-piercing cylinder and high wave frequency.

The values of $C_D$ and $C_M$ are obtained by least squares fit on the time series of measured wave force $F_{exp}(t)$ in laboratory and field experiments or $F_{cal}(t)$ in numerical simulations of flow field, and the time series of orbital velocity and acceleration determined from the time series of measured or numerically generated waves. The data analysis method for obtaining these time series in experiments is given in the next section. The orbital velocity is variable with the distance from the water surface in experiments. It is therefore reasonable that the values of $C_D$ and $C_M$ vary along the axis of the vertical cylinder because they depend on $K_C$ number defined by the magnitude of the orbital velocity at a given section of the cylinder. In the present study, the wave length is usually much larger than the test cylinder length. We assume, therefore, that $C_D$ and $C_M$ are constant ; then their values can be obtained from the least squares fit[10] as follows :

$$Q = \sum_{j=1}^{N}\left\{F_{expj}-\frac{1}{2}\rho DC_D\int_0^L u(z, t)|u(z, t)|dz-\frac{1}{4}\rho\pi D^2C_M\int_0^L \dot{u}(z, t)dz-F_w(t)\right\}^2 \qquad (7)$$

$$\frac{\partial Q}{\partial C_D} = 0, \ \frac{\partial Q}{\partial C_M} = 0 \qquad (8)$$

where $j$ and $N$ are the order and number of the data. The $K_C$ number is defined as :

$$(K_C)_{max} = \pi H_{max}/D$$
$$(K_C)_{1/3} = \pi H_{1/3}/D \qquad (9)$$

where $H_{max}$ is the maximum horizontal orbital displacement between successive zero-up-crossings in least squares fit employing a wave-by-wave method, and $H_{1/3}$ is the significant horizontal orbital displacement for a random wave record in least squares fit in the complete time series method. The value of $H_{1/3}$ is equal to significant wave height $H_w 1/3$ in deep water and in most cases in this study these values were nearly equal.

## 3. Methods to obtain the force time series

### 3.1. Laboratory experiments

The laboratory experiments conducted at the Experimental Tank for Sea Disaster ($L \times B \times D = 80m \times 8m \times 3m$) of the Research Institute for Applied Mechanics used a 1/20 scale model of the test cylinder in the field. Length of

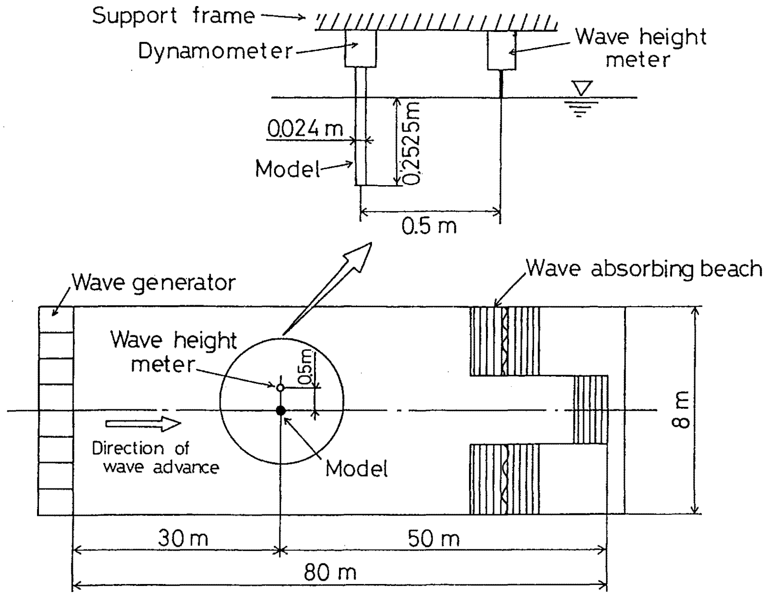



Fig. 1 Experimental setup for laboratory experiments.

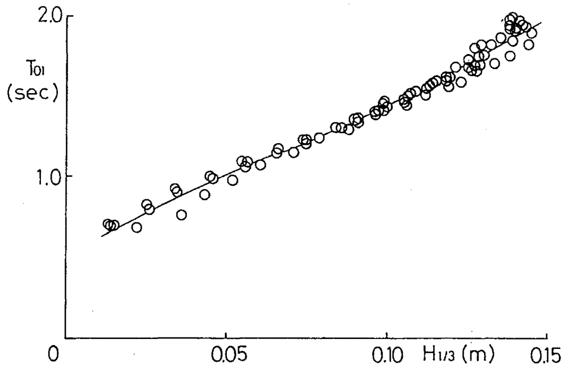



Fig. 2 Relation of average period to significant wave height of irregular waves used in laboratory experiments.

the submerged portion is 264mm and the diameter is 24mm. Experimental set up is shown in Fig. 1. Two-dimensional random waves are generated using wavemaker located at the end of the experimental tank. A servo-type wave height meter measures wave height and the forces acting on the model are recorded by a multi-component dynamometer fixed at the upper end of the model.

The power spectrum of random waves generated in the experiments is based on the Pierson-Moskowitz type spectrum and the relation of average period to significant wave height (Fig. 2) is linear ; these were based on data of waves observed at the ocean research platform.

### 3.2. Field experiments

A test cylinder is fixed to an ocean research platform set 2km off the coast, where the water depth is about 15m. The diameter $D$ and the length L of the test cylinder are 0.5m and 9m, respectively, and the mean length of the submerged portion is 5.5m, varying slightly with the tide. The details of the experiment can be found in reference[11].

Data obtained are analyzed as follows. The principal direction of waves is first determined from a random wave record measured with three wave height meters. Next, from the time series of waves measured with the wave height meter located on the weather side of the test cylinder, the time series of orbital velocity and acceleration are determined using Eqs. 2 and 3. Orbital velocity is also measured directly with an electromagnetic current meter. The principal direction of waves obtained from the data of these three meters coincides with that of the current meter perfectly[12]. The accuracy of the principal direction is of prime importance in calculating $C_D$ and $C_M$. After determining the principal direction of incident waves from the data of the three wave height meters, the time series of orbital velocity at the test cylinder is calculated using the data of one meter. The incident waves are thereafter regarded as the long crest waves, and $C_D$ and $C_M$ are determined using Eqs. 7 and 8. For this procedure the principal direction of waves is a key factor in determining the phase difference between the orbital velocity and measured force.

### 3.3 Numerical simulation

In order to gain a deeper understanding of the nature of the random force a numerical simulation of the flow field around a circular cylinder was also made. The simulation in the present study is two-dimensional on the consideration that the cylinder is long enough to be treated on a sectional basis.

In the simulations, the random waves are chosen from laboratory experiments explained in the previous section, and the Morison force coefficients are obtained by the least squares fit of the total time series and the wave-by-wave method which are the same as used in field and laboratory experiments.

A brief introduction of the numerical method is as follows.

The equations of a two-dimensional incompressible viscous flow are continuity and Navier-Stokes equations. These can be expressed in non-dimensional form as:

$$\nabla\cdot \mathrm{u} = 0 \tag{10}$$

$$\frac{\partial \mathrm{u}}{\partial t}+\mathrm{u}\cdot\nabla\mathrm{u} = -\nabla p+\frac{1}{R_e}\nabla^2\mathrm{u} \tag{11}$$

where u stands for the velocity vector, and $p$, the pressure. The velocity is normalized by a reference velocity $U$ (such as the velocity of a uniform flow), the pressure by $\rho U^2$, the length by the cylinder diameter $D$, and the time by $D/U$. Here $\rho$ denotes the density of the fluid. The equations in this paper are normalized in such a way.

The Poisson equation for pressure $p$ is[13]:

$$\nabla^2 p = -\nabla\cdot(\mathrm{u}\cdot\nabla)\mathrm{u}+R \tag{12}$$

where:

$$R = -\frac{\partial\Phi}{\partial t}+\frac{1}{R_e}\nabla^2\Phi, \qquad \Phi\equiv\nabla\cdot\mathrm{u}$$

To obtain finite-difference expressions of the equations, a third-order upwind scheme is employed for the convective term of Eq. (11), and a central difference for the other spatial derivatives of (11) and (12). The Euler backward scheme is used for the time-difference of Eq. (11), except that the nonlinear convection term is approximated by:

$$\mathrm{u}\cdot\nabla u\approx\mathrm{u}^n\cdot\nabla\mathrm{u}^{n+1}$$

Equations (10–12) are then transformed to a time-dependent generalized coordinate system[15] in order to conveniently obtain an accurate numerical representation of boundary conditions for a cylinder.

## 4. Results and discussion

### 4.1. $C_D$ and $C_M$ from wave-by-wave method

Figure 3 shows $C_D$ and $C_M$ determined by the least squares fit on a wave-by-wave basis for the laboratry experiments (a) and field experiments (b). In this paper the values of $C_D$ and $C_M$ are assumed to be constant along the vertical axis of the test cylinder, because the ratio of cylinder length to wave length is comparatively small for most of the experiments. The wave-by-wave fit method is most popular for analyses of random wave forces because its physical meaning is intuitive. Each figure is obtained from a single random wave force record and all results in Fig. 3 are obtained from one experiment. As seen, the values of $C_D$ and $C_M$ are widely scattered, especially in the range of small $(K_C)_{max}$ which is defined by the maximum horizontal orbital displacement $H_{max}$ between successive zero-upcrosses $(K_C)_{max} = \pi H_{max}/D$. In deep water $H_{max}$ coincides with the wave height $H_w$.

Similar results are shown by Heideman et al.[7] in which drag amd inertia coefficients from OTS data also exhibit large scatter especially in low $K_C$ range.

There are two possible explanations of the scatters: one is that it is difficult to measure small wave force accurately with a large capacity dynamometer, and the other involves the hydrodynamic alone. The former reason is the more plausible for the field experiments, because it is very difficult to maintain high accuracy of the measurement system throughout the experimental term; but for laboratory experiments this is not reasonable because experiments in regular waves carried out using the same model confirmed the accuracy of the measurement system (Fig. 3(a)). The results of experiments in regular waves concentrate around the mean line for the results of irregular waves in the range of large $(K_C)_{max}$, but in the small $(K_C)_{max}$ range the irregular wave results are too widely scattered to be compared with those of regular waves. The latter reason is therefore stronger. The hydrodynamic force acting on a body in an unsteady flow depends not only on the present flow field but also

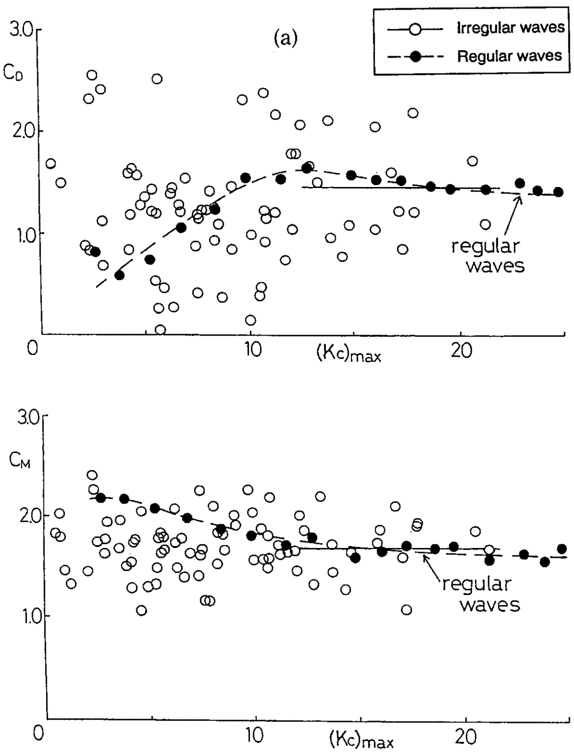



Fig. 3-(a) $C_D$ and $C_M$ obtained from least squares fit on wave-by-wave method versus $(K_C)_{max}$. (laboratory experiments.)

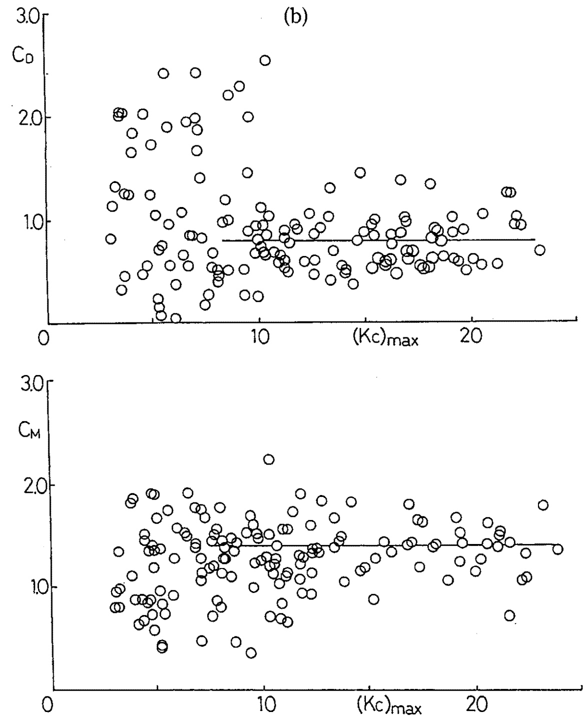
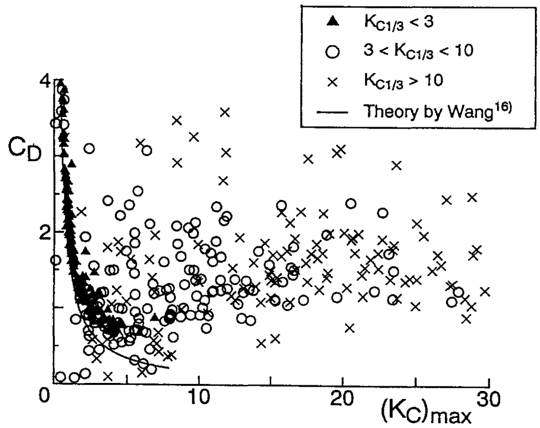



Fig. 3-(b) $C_D$ and $C_M$ obtained from least squares fit on wave-by-wave method versus $(Kc)_{max}$. (field experiments.)

on the past, this is the so-called history effect. In a regularly oscillating flow such as regular waves or sinusoidally oscillating flow, the parameters which characterize the past flow field are the same as those of the present flow field. When the Reynolds number can be viewed as constant, the wave force coefficients $C_D$ and $C_M$ in regular waves depend, therefore, on only one parameter $(Kc)_{max}$, which is defined by the present wave motions and the dimensions of the test body. In irregular waves, the parameters characterizing the past flow field are different from those of the present flow. This means that parameter $(Kc)_{max}$ is not appropriate to represent the random wave force.

In order to research this matter in depth we now turn to use of the wave-by-wave method for numerical simulation, and the results of one calculation are presented in Fig. 4, where $C_D$ and $C_M$ versus $(Kc)_{max}$ are shown for all calculations. Serious scatters are clearly visible, the tendencies are very similar to the experimental results in Fig. 3 except for an extremely small $(Kc)_{max}$ region. As mentioned earlier there are two possible explanations for the scatter : one is the accuracy of the force measurement, and the other is the so-called history effect in random wave forces. In the calculation only the



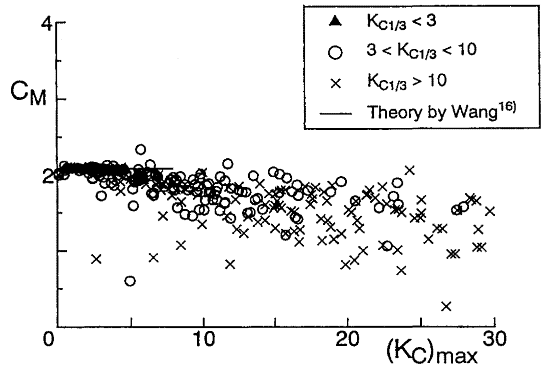




Fig. 4 $C_D$ and $C_M$ obtained from numerical simulations using least squares fit on wave-by-wave method versus $(K_C)_{max}$.

second reason is plausible and the first one is absolutely impossible here contrary to general belief. Thus the history effect in random wave forces is considered to be essential for the scatters. We discuss this effect in detail using the result of numerical simulation.

A viscous oscillatory flow around a cylinder is known to be very complicated, as it includes flow separation, vortex development, shedding and moving. Especially, the growth and motion of vortices in the neighborhood of a cylinder may strongly affect the force coefficients. Although no appropriate parameter is found to associate with this effect, for a regular wave the repetition of flow makes the vortex shedding appear periodic, therefore the force coefficients can be well conditioned by the $K_C$ number. For a random wave, however, there is no such repetition, so it is not surprising that the force coefficients appear scattered when they are expressed as a function of this $K_C$ number.

It should be emphasized here that such scatters are the consequence of vortex shedding. If no large vortex is shed through a complete time series of an irregular wave, it can be expected that the scatter will disappear and that the Morison equation will still be applicable to the wave-by-wave method. In Fig. 4, $C_D$ and $C_M$ for $K_{C1/3} < 3$ are plotted as black triangles, and compared with an analytical solution[16]. $K_{C1/3}$ is Keulegan-Carpenter number defined by the significant orbital displacement of fluid particles and cylinder diameter. Small $K_{C1/3}$ means that vortex shedding does not occure throughout the complete time series of an irregular wave. The results in such small $K_{C1/3}$ range show no scatter because all waves included in the random wave record in this case are so small that there is no vortex shedding throughout the random wave record.

Fig. 5 displays time series of $K_{Cmax}$, $C_D$ and $C_M$ for a random wave force record from the numerical simulation, where it can be seen that the serious scatters of drag coefficient tend to appear at the time when a small wave occurs following large waves. This means that the vortices and the viscous wake generated by large waves can exert a strong effect on the value of $C_D$ and $C_M$ for subsequent small waves. Then, we can conclude that the scatters of $C_D$ and $C_M$ values in the range of small $K_{Cmax}$ obtained from wave-by-wave analyses of an irregular wave are caused by the vortex shedding during large waves.

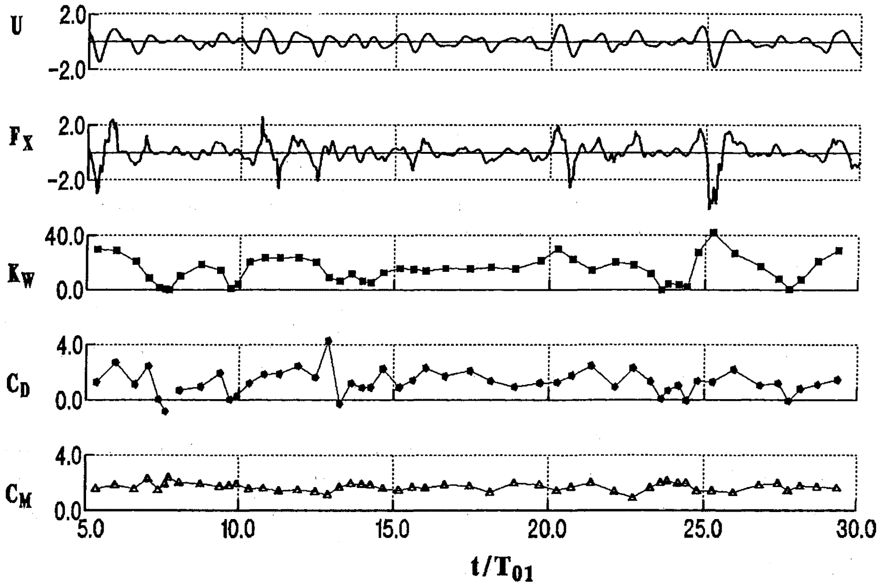



Fig. 5 An example of time series of $C_D$, $C_M$ obtained from numerical simulations using least squares fit on wave-by-wave basis in the case of $(K_C)_{1/3}=13.56$.

A visualized explanation using numerical simulated flow patterns was also made in reference [14] to confirm the above mentioned opinion.

### 4.2. $C_D$ and $C_M$ from least squares fit of a complete force record

The wave-by-wave method is simple and it is easy to understand its physical meaning, making it very popular. Its only lack is that it does not take in account the history effect. We proved that the scatter of values of $C_D$, $C_M$ of a cylinder in random waves is the result of this lack, especially serious being the effect of a large previous wave on a small following wave. Some parameters for the history effects might be found, but they should not be simple and would complicate the problem.

Is it so important to know the accurate values $C_D$, $C_M$ for small waves in random waves for practical use? A designer wants to know the maximum wave force caused by a random wave train and the power spectrum of wave forces in order to plan appropriately the dimensions of strength members or to estimate the motions of the structure being designed in random waves. Wave forces or motions caused by large waves are larger than those by small waves even if the values of $C_D$, $C_M$ for small waves are greater than those for large waves, and the power spectrum of random wave forces are not greatly affected by the small wave forces. The figure of the power spectrum for ocean waves existing in the real sea is determined by the significant wave height $H_{w1/3}$ and period $T_{01}$. If we can succeed in putting $C_D$, $C_M$ in order by the $K_C$ number defined by $H_{w1/3}$ and $T_{01}$, we obtain one to one correspondence between random waves and forces. To adopt this idea, we have to give up obtaining accurate wave force coefficients for small waves included in a random wave train, in any event it seems impossible to determine accurate values for small waves in a random wave train.

The significant wave height is based on comparatively large waves and the entire wave train, not each individual wave. This idea fits our problem well.

The drag coefficient $C_D$ and the inertia coefficient $C_M$ determined from the least squares fit on the complete time series of wave forces are shown in Fig. 6(a) for laboratory experiments, 6(b) for field experiments, and 6(c) for numerical simulations versus the Keulegan-Carpenter number $K_{C1/3}$, as defined by the diameter D of the test cylinder and the significant horizontal orbital displacement $H_{1/3}$ of that at the still water surface; where $H_{1/3}$ is obtained from the data of wave height and Eq. 2. The values of $C_D$ and $C_M$ are assumed to be constant along the vertical axis of the test cylinder in these analyses. The significant horizontal orbital displacement $H_{1/3}$ is equal to significant wave height $H_{w1/3}$ in deep water and in most of our cases $H_{1/3}$ coincided with $H_{w1/3}$.

Before adopting this method, we tried two approaches based on the viewpoint that the comparatively large waves in a wave train should be regarded as important and that random waves should be considered as a continuous wave group and should not be divided into individual waves. We first carried out the least squares fit on only the large waves and neglected the small waves. We then applied the least squares fit on several continuous wave groups. Using the first method we obtained a well-ordered figure, while with the second we had to analyze more than ten waves as a single group. Both methods gave us figures similar to those in Fig. 6.

The method of least squares fit on the complete time series was ultimately adopted because it is the simplest and the easiest in which to find the physical meaning. The physical meaning of this method is explained as : a random wave is characterized by the significant wave height $H_{w1/3}$ and period $T_{01}$. $H_{w1/3}$ represents the comparatively large waves among random waves. Comparatively large waves characterize the random wave train, and the flow field around the cylinder in the random waves. The wave forces in random waves are

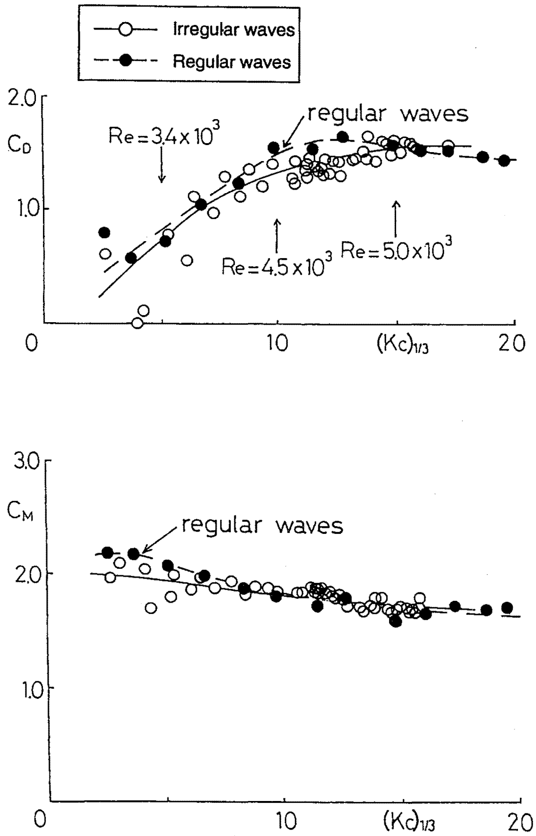



Fig. 6-(a) $C_D$, $C_M$ obtained from least squares fit on the complete time series of wave forces. (Laboratory experiments.)

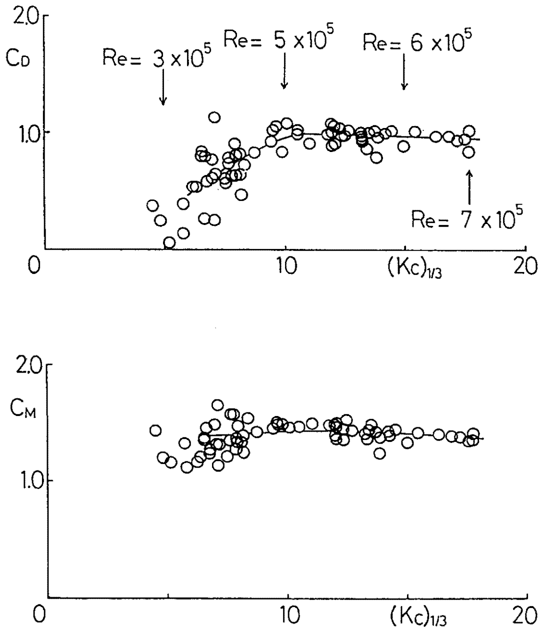



Fig. 6-(b) $C_D$, $C_M$ obtained from least squares fit on the complete time series of wave forces. (Field experiments.)

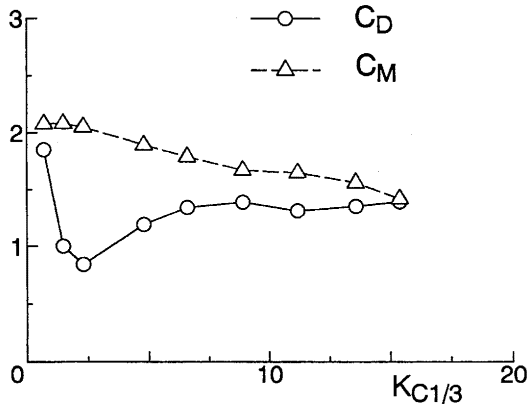


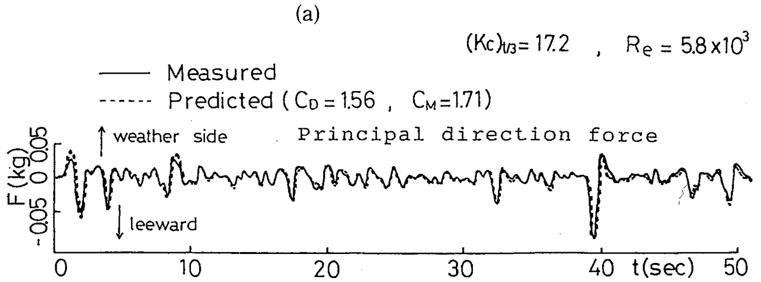

Fig. 6-(c) $C_D$, $C_M$ obtained from least squares fit on the complete time series of wave forces. (Numerical simulations.)

therefore expressed as a function of $H_{w1/3}$.

The wave force coefficients from the least squares fit on complete time series thus become the values fitting large waves, and they should be a function of a parameter containing $H_{w1/3}$ and $T_{01}$, which is exactly $K_{C1/3}$.

The scatters are very small in Fig. 6 as compared with the results from other field experiments, most of which were obtained by the wave-by-wave method, indicating good measurement accuracy and the validity of this analytical method. Reynolds numbers are indicated for information in this figure.

The values of $C_D$, $C_M$ obtained from laboratory experiments in regular waves are also shown in Fig. 6(a). The same model was used for these experiments as used for irregular waves, the Reynolds number is therefore the same. The figure shows that the results in regular waves are in good agreements with those in irregular waves, except that for $C_D$, in the region of about $K_C = 12$ where a peak values is found for regular waves but not for random waves. This is because for regular waves, the interaction between the newly and previously shed vortex becomes violent and a transverse vortex street may appear in this $K_C$ range. However, such peak of $C_D$ will disappear in high Reynolds number



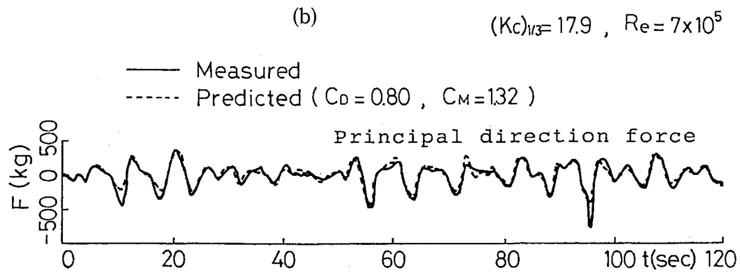




Fig. 7 Comparisons of measured time series and predicted one. (a) Laboratory experiment. (b) Field experiments.

region ($R_e \geq 4\times10^4$, see Sarpkaya and Isaacson[17)]). This result indicates that in high Reynolds number range, the extensive experimental results obtained in the past in regular waves can be applied to estimate the random wave forces by adoption of the method proposed here. In the case of low Reynolds number range ($R_e < 4\times10^4$), it can not be in the region of $K_C$ number about 12.

Figure 7 shows an example of the comparison of the wave forces predicted by Morison's formula using $C_D$ and $C_M$ in Fig. 6 and those measured directly. In laboratory experiments the predicted time series of wave forces perfectly simulate the measured series. In the field experiments, on the whole, the predicted wave force time series coincides with those measured directly, verifying the validity of the proposed method here. The large leeward forces sometimes found in directly measured forces in the field experiments are not represented with fidelity in the predicted time series. These large leeward forces are supposed to be caused by breaking waves, because small scale breaking waves are often observed among actual ocean wind waves.

Nonlinear forces like the breaking wave forces cannot be accommodated by Morison's formula. We analyzed these forces using the current meter data and obtained the same results; therefore, this discrepancy should not be attributed to the linear wave theory used to obtain the orbital velocity from the data of a wave height meter. A discussion on the effect of breaking wave can be found in reference [12].

## 5. Conclusions

Wave forces acting on a vertical cylinder in random waves were studied in field and laboratory experiments and numerical simulation. The main conclusions obtained were:

(a) The values of $C_D$ and $C_M$ obtained from least squares fit of a complete force time series of a random wave record are well-arranged as a function of significant values of Keulegan-Carpenter number $(K_C)_{1/3}(=H_{1/3}/D)$ defined by the significant horizontal orbital displacement $H_{1/3}$ at the water surface and the diameter $D$ of the cylinder, but those determined by the least squares fit on a wave-by-wave basis scater widely, especially in the small $(K_C)_{max}$ range, where $(K_C)_{max}$ is defined by the maximum horizontal orbital displacement $H_{max}$ between successive zero-up-crosses and the diameter of the test cylinder. The scatter is due to the history effects mainly created by the shedding vortices.

(b) The laboratory experiments showed that the values of $C_D$, $C_M$ obtained from experiments in regular waves or harmonic flow in high Reynolds number ($R_e \geq 4\times10^4$) can be applied to estimate random wave forces using the analysis method proposed in this paper.

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