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THE STRUCTURE OF TURBULENT AIR FLOW OVER WAVY WALL. PART 3

By Toshiyuki BANDOU* and Hisashi MITSUYASU†

Effects of surface roughness on the pressure distribution along a wavy surface are studied by putting various artificial roughness (trip wires) on a solid Stokes wave with a height-to-length ratio $H/L = 0.1$. When a single trip wire is mounted on the Stokes wave, the pressure drag coefficient Cd of the wave shows various values depending on the position (phase) of the trip wire. That is, when a single trip wire is mounted on the wave surface below the mean level of the Stokes wave, the value of the pressure drag coefficient, Cd is equal to or smaller than that of the wave without trip wires, Cd_0. On the other hand, when the single trip wire is mounted on the wave crest, the value of Cd is larger than Cd_0. Moreover this value of Cd has shown nearly constant value of 1.0×10^{-2} in the present range of the Reynolds number, $170 < Re_2 < 2200$, where Re_2 is the Reynolds number based on the velocity of the free stream U_0 and the diameter of the trip wire, φ. When a train of trip wires covers the wave crest, the pressure drag coefficient Cd does not depend much on the number of the trip wries and shows nearly constant value of 1.0×10^{-2} in the above range of the Reynolds number.

Key words : wind-wave interaction, turbulent flow over wave surface, roughness of wave surface, pressure drag coefficient, air flow separation

1. Introduction

The pressure drag coefficient Cd of the solid Stokes wave with a surface roughness is considered to be a function of the wave steepness, H/L, the

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Reynolds number based on the form parameter of the Stokes wave, Re_1 ($\equiv U_0H/\nu$), and the dimensionless parameter relating to the surface roughness on the Stokes wave, $\tilde{D}$. That is,

$$Cd = F(H/L, Re_1, \tilde{D}) \ .$$

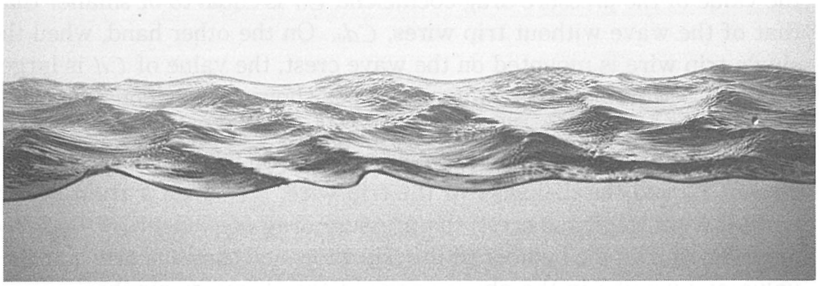
Here H is the wave height, L the wave length, U_0 the free stream velocity and ν the kinematic viscosity of the air.

For the Stokes wave with smooth surface, $\tilde{D} \simeq 0$, we have obtained, in a previous study (Bandoù et al., 1988)[1] the following empirical relation

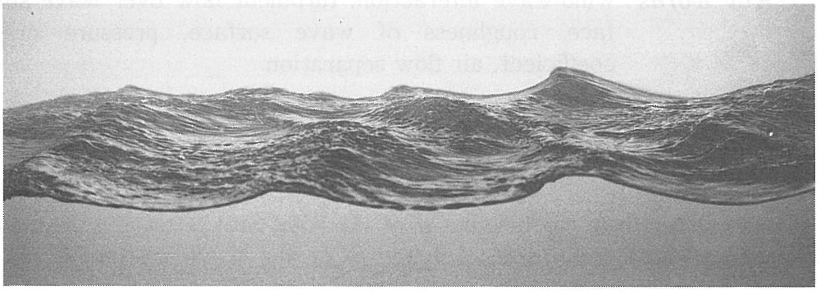
$$Cd/RH = 0.634(U_0H/\nu)^{-0.379} \ ,$$

where R is the curvature at the wave crest. It should be noted that RH is a function of H/L.

In the water waves under wind action, ripples cover the surface of the water waves as shown in Fig. 1. It is pointed out by many authors that the ripples overlapping on the water waves have an important role in momentum transfer



(a)



(b)

Fig. 1 Typical water waves under wind action.
(a) Reference wind speed $U_r = 7.5$ m/s.
(b) Reference wind speed $U_r = 10.0$ m/s.
It should be noted that the wind is blowing from the right to the left.

from wind to waves[2)3)4)].

In the present study, we investigate the effect of the surface roughness on the pressure drag coefficient Cd of the solid Stokes wave when a train of trip wires is mounted on the waves.

2. Experiments

Experiments are conducted in the same facility used in our earlier study of the same title, part 1[1)]. The arrangement of the facility is shown in Figs. 1 and 2 in part 1. The solid Stokes waves which are composed of twenty successive waves with the height-to-length ratio $H/L = 0.1$, are installed in a wind-wave facility. The pressure distribution on the wave surface have been measured at the thirteenth wave from leading edge of the successive waves.

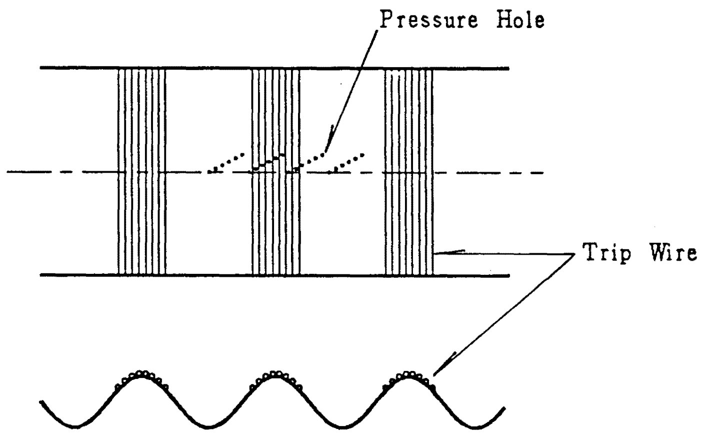


Fig. 2 Configuration of the solid waves with a train of trip wires at the measuring station. The upper part shows the top view of the measuring station. The lower part shows its side view.

In order to simulate ripples overlapping on the water waves under wind action, we installed trip wires on the wave surface as shown in Fig. 2. The trip wires are fixed laterally on the wave surface between adjacent pressure holes. The smallest separation distance between adjacent trip wires is $(X_j - X_{j-1})/L = 0.05$, where X_j is the distance from the windward trough. Generally the trip wires are mounted on the fourteen successive waves from the leading edge. However, in some experiment, the number of waves with trip wires is changed to see the effects of the number of the waves with a roughness.

The effects of the following dimensionless parameters on the pressure drag coefficient of the solid Stokes wave are studied;

$$Re_2, M, N, X_j/L \quad (j = 1, 2, \cdots, N) \ ,$$

where Re_2 is the roughness Reynolds number based on the parameter for the artificial roughness (trip wires with a diameter φ), e. g., $U_0\varphi/\nu$, M the number of the waves with trip wires, which is counted from the wave one after the measurig station to the windward side, N the number of trip wires per one wave and X_j/L the position of the trip wire on each wave.

In order to clarify the effects of these parameters on the static pressure, the following six experiments are done for the reference wind velocity $U_0 \simeq 3$, 10(m/s) where U_0 is the maximum wind velocity at the measuring station which corresponds roughly to the free stream velocity of the wind.

Experiment 1 (*Ex. 1*)

The effect of the position of a trip wire, X/L is investigated, when a single trip wire ($N = 1$) with the diameter of $\varphi = 3.5$ mm is mounted on each wave of fourteen successive waves ($M = 14$), including the wave at the measuring station (see Fig. 3-(a)).

The position X/L is changed in turn as

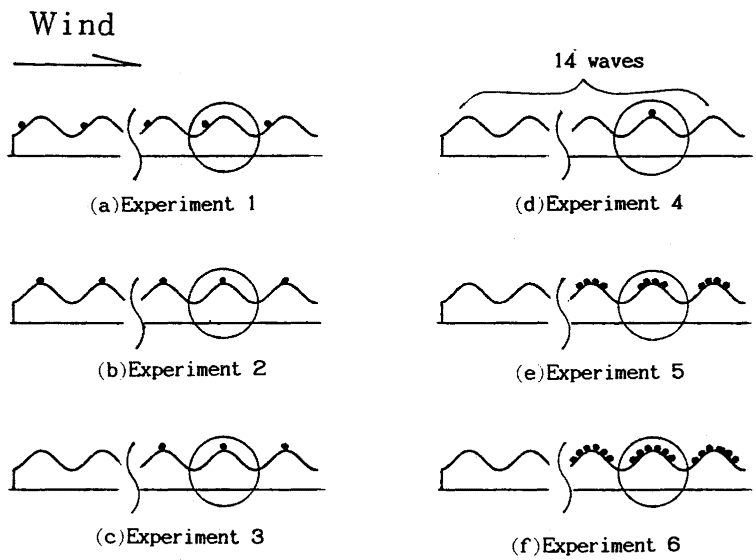


Fig. 3 Schematic representations of the arrangement of the trip wires on the waves in each experiments. Total number of the successive waves is twenty. The pressure measurement is done at the thirteenth wave which is marked with a circle in the figure.

$X/L = 0.025, 0.125, 0.225, 0.325, 0.425, 0.475, 0.525, 0.625, 0.725, 0.825, 0.925$.

Two roughness Reynolds numbers $Re_2 \simeq 670$ and 2200 are used for the experiment.

Experiment 2 (*Ex. 2*)

The effect of the roughness Reynolds number $Re_2(= U_0\varphi/\nu)$ is investigated when a single trip wire ($N = 1$) is mounted on the phase close to each wave crest, $X/L = 0.525$, of fourteen successive Stokes waves ($M = 14$) (see Fig. 3 -(b)).

The diameter of each trip wire is changed in turn as

$$\varphi = 0.9, 1.8, 3.5 \text{ mm}$$

Experiment 3 (*Ex. 3*)

The effect of the roughness Reynolds number Re_2 is investigated when a single trip wire ($N = 1$) is mounted on the phase close to the each wave crest, $X/L = 0.525$, for only successive three waves ($M = 3$) (see Fig. 3-(c)).

The diameter of each trip wire is changed in turn as

$$\varphi = 0.9, 1.8, 3.0, 5.0 \text{ mm}$$

Experiment 4 (*Ex. 4*)

The effect of the roughness Reynolds number Re_2 is investigated when a single trip wire ($N = 1$) is mounted on the phase close to the wave crest, $X/L = 0.525$, for only one wave at the measuring station (see Fig. 3-(d)).

The diameter of each trip wire is changed in turn as

$$\varphi = 0.9, 1.8, 3.5, 5.0 \text{ mm}$$

Experiment 5(*Ex. 5*)

The effect of the roughness Reynolds number Re_2 is investigated when four trip wires ($N = 4$) per one wave are mounted on the phases $X/L = 0.425, 0.475, 0.525, 0.575$ of each wave of successive three waves ($M = 3$) (see Fig. 3-(e)).

The diameter of each trip wire is changed in turn as

$$\varphi = 0.9, 1.8, 3.5, 5.0 \text{ mm}$$

Experiment 6 (*Ex. 6*)

The effect of the number of trip wires per one wave, N is investigated by changing the number of trip wires mounted on the phases, $X/L = 0.5 \pm 0.05j (j = 1, 2, \cdots, N/2)$, of successive three waves ($M = 3$) (see Fig. 3-(f)). The diameter of the trip wire is fixed to $\varphi = 0.9$ mm.

The number of the trip wire is changed in turn as

$$N = 4, 10, 20 \ .$$

Two roughness Reynolds numbers $Re_2 \simeq 170$ and 560 are used for the experiment. The trip wires of $N = 20$ covers homogeneously the surface of successive three waves.

Table 1 shows the prameters of artificial roughness for each experiment.

Table 1 Dimensionless parameters for the artificial roughness. Re_2 is the roughness Reynolds number defined by $U_0\varphi/\nu$, M the number of the waves with trip wires, N the number of trip wires per one wave, and X/L the positions of the trip wires on each wave.

No.	Re_2	M	N	X/L
Ex. 1	670, 2200	14	1	0.025~0.925
Ex. 2	170~2200	14	1	0.525
Ex. 3	170~3100	3	1	0.525
Ex. 4	170~3100	1	1	0.525
Ex. 5	170~3100	3	4	0.425~0.575
Ex. 6	170, 560	3	4~20	$0.5 \pm 0.05\,j$ ($j = 1, 2, \ldots, N/2$)

3. Analysis of the pressure data

In each experiment, the pressure drag coefficient Cd is calculated from the measured pressure distribution along the wave surface and its depnedence on various parameters is studied. The procedure of the analysis is as follows.

Calculation of the pressure drag coefficient

The pressure drag coefficient Cd is calculated from the Fourier components of both the pressure distribution $P(x)$ and the profile of the wave surface $\eta(x)$, as

$$Cd = \frac{1}{L}\int_0^L \left(P(x)\,\frac{\partial\eta(x)}{\partial x}\Big/\frac{1}{2}\rho U_0^2\right)dx = \sum_{i=1}^{4}\frac{a_i k_i}{2}Cp_i(-\sin\theta_i)$$
$$= \sum_{i=1}^{4} Cd_i \ ,$$

where

$$P(x) = \sum_{i=1}^{4} A_{pi}\cos(k_i x - \theta_i) \ , \quad \eta(x) = \sum_{i=1}^{4} a_i\cos(k_i x) \ ,$$

$$Cp_i = A_{pi}\Big/\frac{1}{2}\rho U_0^2 \ , \qquad Cd_i = \frac{a_i k_i}{2}\,Cp_i(-\sin\theta_i).$$

Here Cd_i, Cp_i and θ_i are called respectively as the pressure drag coefficient, the amplitude coefficient and the phase angle of the pressure distribution for each Fourier component.

Parameterization of the pressure drag coefficient

When a train of trip wires, each of which has the same diameter φ, is mounted on the successive waves in the same configuration, the pressure drag coefficient Cd of the waves is considered to be a function of the form

$$Cd = F(H/L, Re_1 ; Re_2, M, N, X_j/L) \quad (j = 1, 2, \cdots) ,$$

where H/L is the wave height-to-length ratio of the waves, Re_1 the Reynolds number based on the wind speed of the free stream and the wave height, i. e, U_0H/ν, Re_2 the roughness Reynolds number based on the wind speed of the free stream and the diameter of the trip wires, i. e, $U_0\varphi/\nu$, M the number of the waves with trip wires in the arrangement shown in Fig. 3, N the number of trip wires per one wave, and X_j/L the position of the trip wires in each wave.

From the six experiments described in the previous section, we will study the functional form of F for the Stokes wave with surface roughness. The Reynolds numbers $Re_1(\equiv HU_0/\nu)$ and $Re_2(\equiv \varphi U_0/\nu)$ in the present experiment cover respectively the ranges of 4000~14000 and 170~3100.

4. Experimental results

We investigate firstly the effect of a single trip wire on the pressure drag coefficient. Next we investigate the relation between a train of trip wires covering the wave crest and the pressure drag coefficient.

4.1. Pressure drag coefficient of the wave with a single trip wire

In Ex. 1~Ex. 4, we investigate the effects of such dimensionless parameters as X/L, $Re_2(\equiv U_0\varphi/\nu)$ and M, on the pressure drag coefficient, Cd, when the number of trip wires on each wave is fixed to $N = 1$.

Effect of the position of a single trip wire

Effect of the position of a single trip wire, X/L on the pressure drag coefficient, Cd is investigated by using the data of the Ex. 1 where the other parameters for artificial roughness are fixed to $M = 14$, $N = 1$, and $Re_2 \simeq 670$ and 2200.

Figure 4 shows the pressure distribution along the wave with a single trip wire when the position of the trip wire is changed from the windward trough, $X/L \simeq 0.0$, to the leeward trough, $X/L \simeq 1.0$ for $Re_2 \simeq 2200$. The open circles, the solid curves and the broken curves represent respectively the measured pressure profiles, the Fourier composition of four terms calculated from measured pressure profiles and the pressure profiles along the wave without the trip wires. We can see from the figure that the Fourier composition of four terms

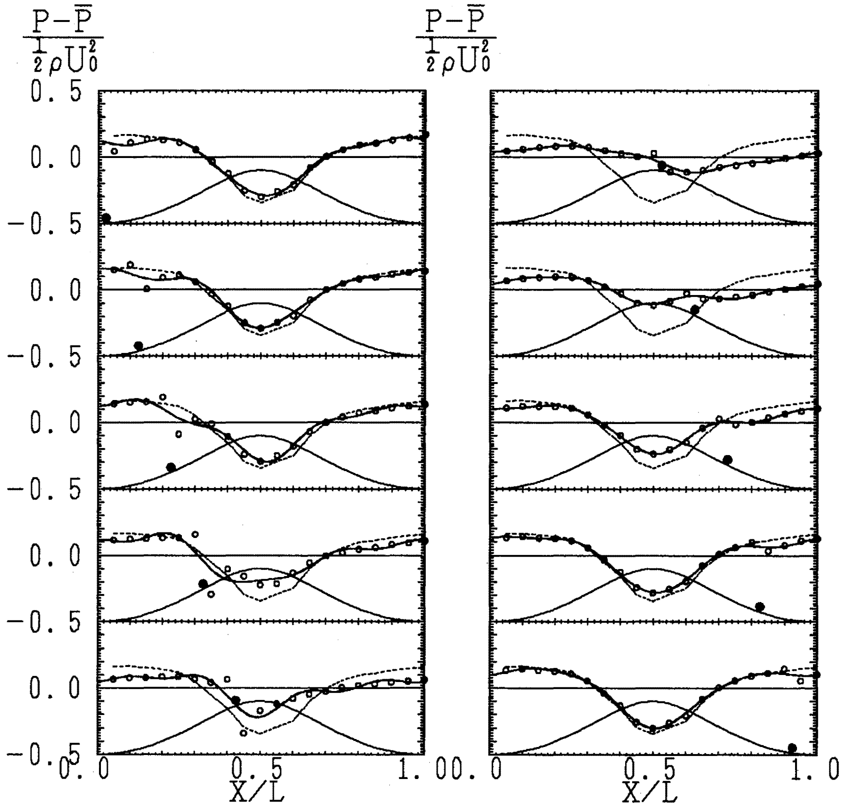


Fig. 4 The pressure distributions along the wave with a trip wire ($Re_2 \simeq 2200$) when the position of the trip wire is changed from the windward trough to the leeward trough. ●, the position of a trip wire; ○, the measured pressure profiles; —, the Fourier composition of four terms calculated from measured pressure distributions; ---, the measured pressure profiles along the wave without the trip wires; —, the profiles of the wave surface. (X is the longitudinal distance from the windward trough at the measuring station, L the wavelength of the solid wave, P the static pressure distribution along the wave, $\bar{P}$ the static pressure averaged over one-wavelength, ρ the density of the air and U_0 the mean velocity of the free stream.)

(solid curve) represents the measured pressure profile (open circle) very well except for the pressure profile (spike-form) near the trip wire. From the comparison of the pressure profile with the trip wire (solid curve) with the profile without the trip wires (broken curve), following feature can be seen. When the trip wire is mounted near each wave trough, the pressure profiles are not much different from the profiles along the Stokes wave without trip wires. On the

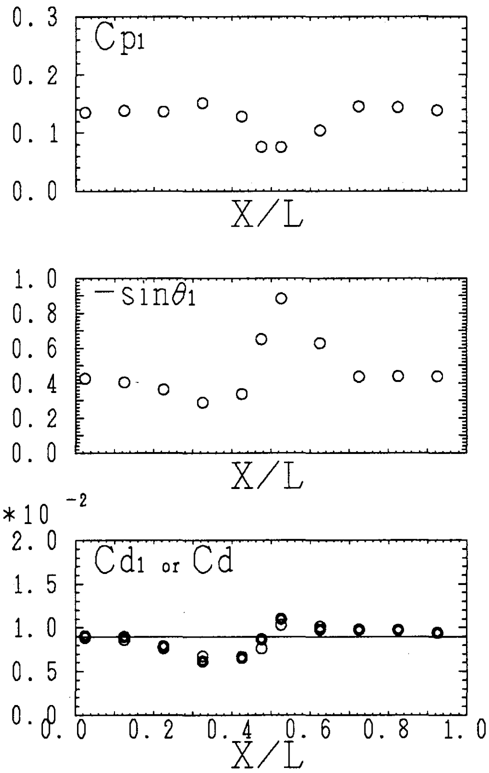


Fig. 5-(a) The change of $Cp_1\left(\equiv A_{p1}\Big/\frac{1}{2}\rho U_0^2\right)$, $-\sin\theta_1$, $Cd_1\left(\equiv \frac{a_1k_1}{2}Cp_1(-\sin\theta_1)\right)$ and $Cd(\equiv \sum_{i=1}^{4} Cd_i)$ with the normarlized position of the trip wire, X/L. The dimensionless parameters for artificial roughness are $Re_2 \simeq 750$, $M = 14$ and $N = 1$ (Ex. 1). ◎ corresponds to Cd and ○ to Cp_1, $-\sin\theta_1$ or Cd_1. —, the pressure drag coefficient without trip wires.

other hand, when the trip wire is mounted near the wave crest, the pressure profiles shows a remarkble asymmetric form. Therefore the pressure drag coefficient Cd is considered to be affected greatly by the position of the trip wire. These characteristics can be also seen for $Re_2 \simeq 670$.

Figure 5 shows the changes of the amplitude coefficient Cp_1, the phase shift θ_1, the pressure drag coefficient $Cd_1(\equiv \frac{a_1k_1}{2}Cp_1(-\sin\theta_1))$ for the fundamental mode of the pressure distribution and the total pressure drag coefficient $Cd(\equiv \sum_{i=1}^{4} Cd_i)$ with the position of the trip wire X/L. Figure 5-(a) corresponds

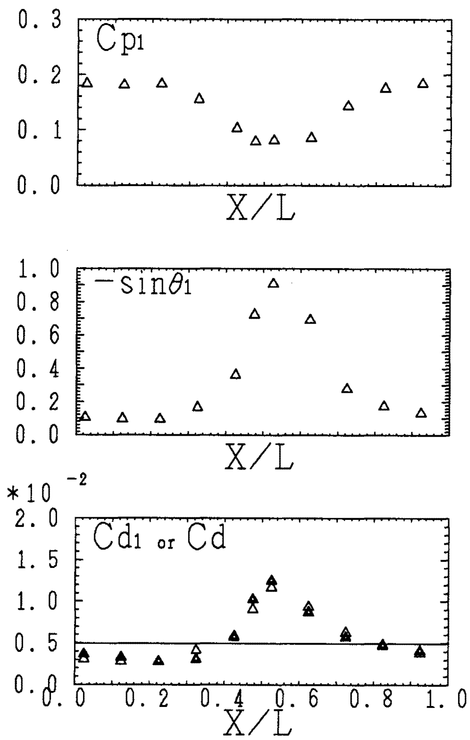


Fig. 5-(b) The same as Fig. 5-(a) except for $Re_2 \simeq 2200$. ▲ corresponds to Cd and △ to Cp_1, $-\sin\theta_1$ or Cd_1. —, the pressure drag coefficient without trip wires.

to the results for $Re_2 \simeq 670$ and Figure 5-(b) to the results for $Re_2 \simeq 2200$. As can be seen from Fig. 5, the profile of the pressure drag coefficient Cd_1 for fundamental mode of pressure distribution is mainly affected by the phase of the fundamental mode, $-\sin\theta_1$ but not much by the amplitude coefficient of the fundamental mode, Cp_1. Furthermore the pressure drag coefficient Cd is approximated by that for the fundamental mode of the pressure distribution, Cd_1, namely,

$$Cd \simeq Cd_1 = \frac{a_1 k_1}{2} Cp_1(-\sin\theta_1) \ .$$

Characteristic feature of the pressure drag coefficient Cd can be seen in the following three regions where the trip wire is mounted; (1) When a single trip wire is mounted on the phase $X/L = 0.0 \sim 0.3$, which corresponds to the windward side below the mean level of the Stokes wave, the value of the pressure drag coefficient Cd is equal to or smaller than that of the Stokes wave without trip wires. Furthermore, this value gradually decrease with increasing position (phase) of the trip wire X/L, until it has the minimum value near the mean level of the Stokes wave, $X/L \simeq 0.3$. (2) When the trip wire is mounted near the wave crest, $X/L \simeq 0.5$, the pressure drag coefficient Cd increase greatly and its value is larger than that of the wave without trip wires. Furthermore, it seems that the coefficient for this case does not much depend on the roughness Reynolds number Re_2. (3) When the trip wire is mounted on the phase, $X/L = 0.7 \sim 1.0$, which corresponds to the phase at the leeward side below the mean level of the Stokes wave, the pressure drag coefficient Cd is gradually decrease with increasing position (phase) of the trip wire X/L. This trend is remarkable for $Re_2 \simeq 2200$. Moreover the value of Cd is nearly equal to that over the Stokes wave without trip wires. This fact shows that the pressure drag coefficient Cd is not much affected by the roughness of the surface in the leeward side below the mean level.

Effect of the roughness Reynolds number

Effect of the roughness Reynolds number Re_2 on the pressure drag coefficient Cd is investigated in Ex. 2 by fixing the other parameters for the artificial roughness as $M = 14$, $N = 1$, and $X/L = 0.525$.

Figure 6 shows the change of Cp_1, $-\sin\theta_1$, $Cd_1(\equiv \frac{a_1 k_1}{2} Cp_1(-\sin\theta_1))$ and $Cd(\equiv \sum_{i=1}^{4} Cd_i)$ with the roughness Reynolds number Re_2. The value of $-\sin\theta_1$ increases with increasing the roughness Reynolds number Re_2, whereas the value of Cp_1 decreases with increasing the roughness Reynolds number Re_2 for the fixed Reynolds number $Re_1(\equiv U_0 H/\nu)$. Hence the pressure drag coefficient Cd_1 for the fundamental mode of the pressure distribution has nearly constant value of 1.0×10^{-2} in the range of the roughness Reynolds number, $170 < Re_2 < 2200$, though it increases slightly with increasing the roughness Reynolds number Re_2 for fixed Reynolds number Re_1. Moreover Cd_1 is found to be approximated by Cd.

Therefore the pressure drag coefficient Cd is given approximately by

$$Cd \simeq 1.0\times10^{-2} \quad (1)$$

for $M = 14$, $N = 1$, $X/L = 0.525$ and any Re_2 in a range $170 < Re_2 < 2200$.

This fact suggests that the trip wire near the wave crest generates the stationary flow separtion in this range of the roughness Reynolds number.

Effect of the number of the waves with a trip wire

Effect of the number of the preceding waves with a trip wire on the pressure drag coefficient of a particular wave is investigated by comparing the results of Ex. 2, Ex. 3 and Ex. 4. In these experiments, the static pressure is measured

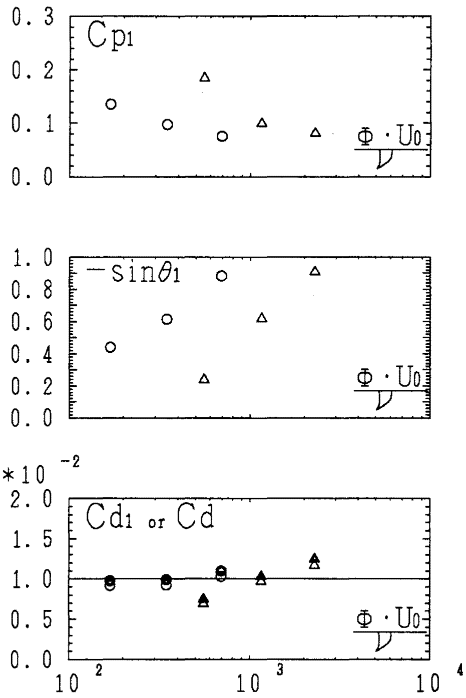


Fig. 6 The change of Cp_1, $-\sin\theta_1$, Cd_1 and Cd with $Re_2(\equiv \varphi U_0/\nu)$. The dimensionless parameters for artificial roughness are $M = 14$, $N = 1$ and $X/L = 0.525$ (Ex. 2). Solid line shows the value of 1.0×10^{-2}. ○, ◎ : the profile for $Re_1 \simeq 4000$; △, ▲ ; the profiles for $Re_1 \simeq 14000$; ◎, ▲ correspond to Cd and ○, △ to Cp_1, $-\sin\theta_1$ or Cd_1.

along the thirteenth wave when a single trip wire is mounted on the phase close to each wave crest, $X/L = 0.525$ of successive fourteen waves (in Ex. 2), successive three waves (in Ex. 3) or a single wave at measuring station (in Ex. 4).

The results are shown in Figs. 6, 7 and 8. As shown in Fig. 7, when the successive three waves have the trip wire at each wave crest, the trends of $-\sin\theta_1$ and Cp_1 are similar to those in Fig. 6. Hence the pressure drag coefficient $Cd(\simeq Ca_1)$ has nearly constant value of 1.0×10^{-2} except for the pressure drag coefficient for the roughness Reynolds number $Re_2 \simeq 3100$ in Fig. 7, which shows very peculiar property*).

*) The pressure drag coefficient for this case is nearly equal to zero. This is attributed to the following reason; The pressure drag in this case is mainly supported by the drag of the trip wire itself which is not counted in the present calculation of the pressure drag coefficient.

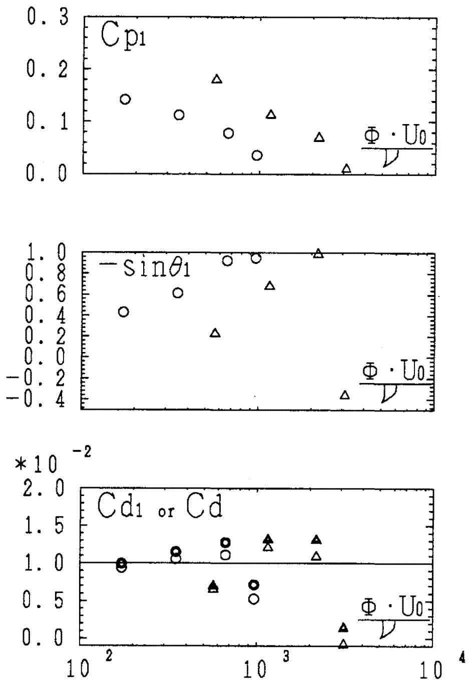


Fig. 7 The same as Fig. 6 except for the number of waves with the trip wire, M = 3 (Ex. 3).

Thus when a single trip wire is mounted at each crest of the Stokes waves, the pressure drag coefficient is mainly affected by just preceding wave of the measuring station, not much by the waves beyond the preceding wave.

Therefore the pressure drag coefficient Cd is given roughly by

$$Cd \simeq 1.0 \times 10^{-2} \tag{2}$$

for any $M \geqq 3$, $N = 1$, $X/L = 0.525$ and any roughness Reynolds number Re_2 in the range $170 < Re_2 < 2200$.

On the other hand, when only a single wave at the measuring station has a single trip wire on the wave crest, appreciable difference can be seen. As shown in Fig. 8, the value of $-\sin\theta_1$ increases with increasing the roughness Reynolds number Re_2, whereas the value of Cp_1 in not much different in each others. Hence the pressure drag coefficient $Cd(\simeq Cd_1)$ increases with increasing the roughness Reynolds number Re_2. It should be also pointed out that the pressure drag coefficient in this case is very large. It is thought that this is attributed to the gradual increase of the separation region of the air flow with increasing the roughness Reynolds number Re_2.

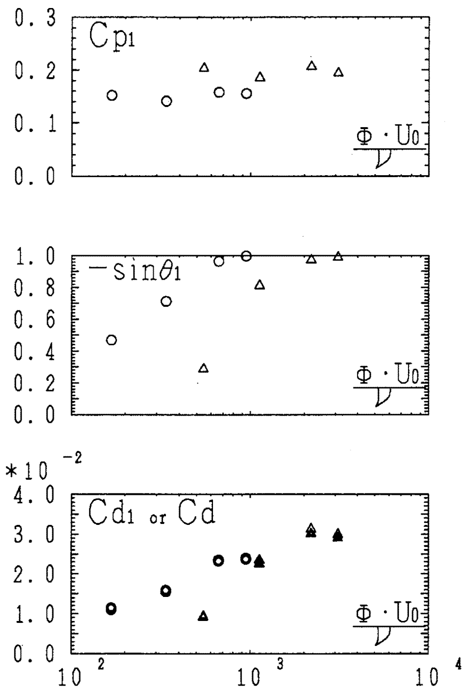


Fig. 8 The same as Fig. 6 except for the number of waves with the trip wire, $M = 1$ (Ex. 4).

4.2. Pressure drag coefficient of the wave with a train of trip wires

In Ex. 5 and Ex. 6, we investigate the effect of each parameter for the artificial roughness, i. e., Re_2 and N on the pressure drag coefficient, Cd, when a train of trip wires covers the wave crest.

Effect of the roughness Reynolds number

Effect of the roughness Reynolds number Re_2 of the multiple (four) trip wires on the pressure drag coefficient Cd is investigated in Ex. 5. In this experiment, the static pressure is measured along the Stokes wave when four trip wires ($N = 4$) are mounted on the phases, $X/L = 0.425, 0.475, 0.525, 0.575$, respectively of the each wave of successive three waves ($M = 3$) including the central wave at which the pressure measurements are done.

The results are shown in Fig. 9. The value of $-\sin\theta_1$ increases with increasing the roughness Reynolds number Re_2, whereas the value of Cp_1 shows nearly constant value or slightly decreases with increasing the roughness Reynolds number Re_2 for fixed Reynolds number Re_1. Hence the pressure drag

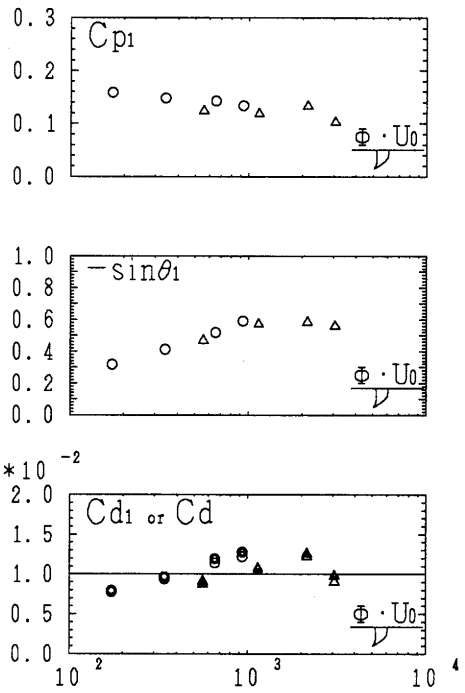


Fig. 9 The same as Fig. 6 except for the number of the trip wires per one wave, $N = 4$ (Ex. 5). The position of the trip wires are $X/L = 0.425, 0.475, 0.525, 0.575$.

coefficient $Cd(\simeq Cd_1)$ increases slowly with increasing the roughness Reynolds number Re_2. In a rough sense, however, the pressure drag coefficient is not much different from the value of 1.0×10^{-2}.

Therefore the pressure drag coefficient Cd is given approumatedly by

$$Cd \simeq 1.0\times10^{-2} \tag{3}$$

for $M = 3$, $N = 4$, and any roughness Reynolds number Re_2 in the range $170 < Re_2 < 2200$.

Effect of the number of trip wires

Effect of the number of trip wires N on the pressure drag coefficient Cd is investigated in Ex. 6. In this experiment, the static pressure is measured along the Stokes wave when the multiple trip wires are mounted on the phases, $X/L = 0.5\pm0.05j (j = 1, 2, \cdots, N/2)$ respectively of the of successive three waves ($M = 3$) including the central wave for the pressure measurement.

Figure 10 shows the changes of Cp_1, $-\sin\theta_1$, $Cd_1\left(\equiv \frac{a_1k_1}{2}Cp_1(-\sin\theta_1)\right)$ and

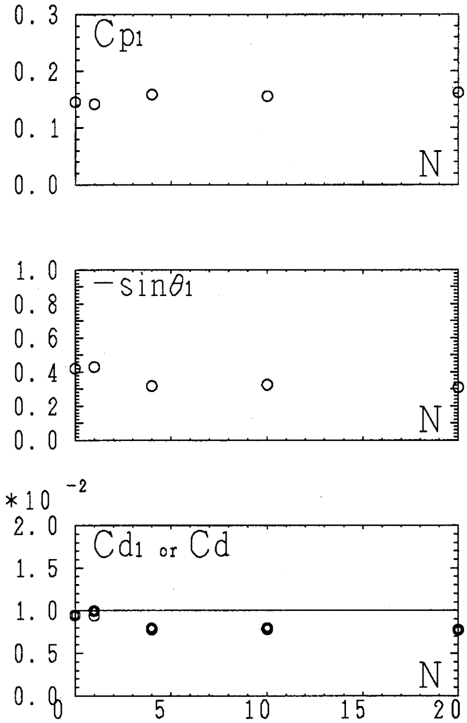


Fig. 10-(a) The change of Cp_1, $-\sin\theta_1$, Cd_1 and Cd with the number of the trip wires per one wave, N. The dimensionless parameters for artificial roughness are $Re_2 \simeq 170$ and $M = 3$ (Ex. 6). The position of trip wires is $X/L = 0.5 \pm 0.05j (j = 1, 2, \cdots, N/2)$. Solid line shows the value of 1.0×10^{-2}. ◎ corresponds to Cd and ○ to Cp_1, $-\sin\theta_1$ or Cd_1.

$Cd(\equiv \sum_{i=1}^{4} Cd_i)$ with the number of trip wires N. Figure 10-(a) corresponds to the results for $Re_2 \simeq 170$ and Figure 10-(b) to the results for $Re_2 \simeq 560$. The values of Cp_1 and $-\sin\theta_1$ do not much depend on the number of the trip wires. The pressure drag coefficient $Cd(\simeq Cd_1)$ shows nearly constant value which is slightly smaller than 1.0×10^{-2} except for the cases of $N = 0$ and 1.

From Ex. 5 and Ex. 6 where a train of trip wires is mounted near the crest of the successive three waves, following conclusions can be obtained; The pressure drag coefficient Cd can be approximated by Cd_1 and the coefficient shows nearly constant value in the range of the roughness Reynolds number, $170 < Re_2 < 2200$, irrespective of the number of the trip wires on each wave, N.

Refering to the result on the effect of the number of waves with a single trip wire (see Eq. (2)), we expect that the pressure drag coefficient Cd of the Stokes

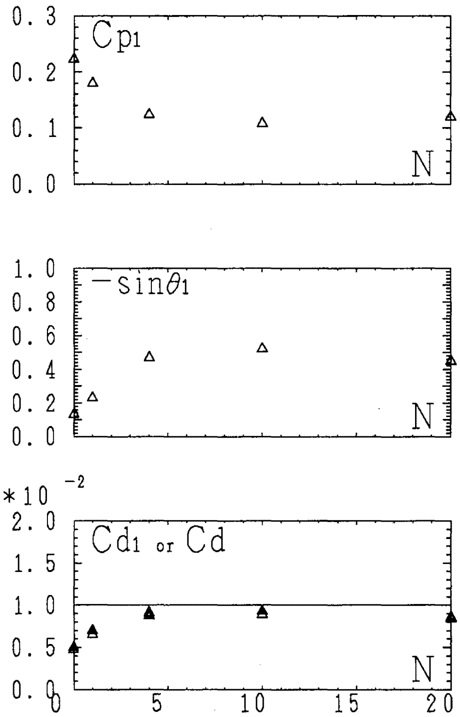


Fig. 10-(b) The same as Fig. 10-(a) except for $Re_2 \simeq 560$. ▲ corresponds to Cd and △ to Cp_1, $-\sin\theta_1$ or Cd_1.

wave with a train of trip wires also shows a constant value of 1.0×10^{-2} for any $M \geqq 3$.

Then we can obtain the following relation

$$Cd \simeq 1.0\times10^{-2} \tag{4}$$

for the Stokes wave with the trip wires near the wave crest. The dependence of Cd on M, N and Re_2 are relatively small for $M \geqq 3$, $N > 1$ and $170 < Re_2 < 2200$.

5. Summary and conclusion

The effects of surface roughness on the pressure drag coefficient of a solid wave surface have been investigated by measuring the pressure distribution on the solid Stokes wave on which trip wires of various sizes and configurations are mounted. Important results are summarized as follows;

(i) The pressure drag coefficient Cd of the solid wave with the trip wires is nearly equal to that calculated from the fundamental mode of the pressure distribution along the wave, namely $Cd \simeq Cd_1 = \frac{a_1 k_1}{2} Cp_1(-\sin\theta_1)$.

(ii) When a single trip wire is mounted on the wave surface, the pressure drag coefficient Cd shows various values depending on the position of a trip wire. That is, when the single trip wire is mounted below the mean level of the waves, the pressure drag coefficient Cd is equal to or smaller than that of the waves without trip wires Cd_0. On the other hand, when the trip wire is mounted near on the wave crest, Cd is larger than Cd_0. Moreover Cd has nearly constant value of 1.0×10^{-2} in the range of the Reynolds number, $170 < Re_2 < 2200$. This fact suggests that the trip wire near the wave crest generates the stationary flow separation.

(iii) The pressure drag coefficient of a particular wave in a wave train is affected mainly by a just preceding wave with a trip wire, and it does not depend much on the number of the preceding waves with the trip wire as shown in the results of Ex. 2, Ex. 3 and Ex. 4.

(iv) When only one wave in the successive waves has a single trip wire near on the wave crest, the pressure drag coefficient Cd of that wave increases with increasing the roughness Reynolds number Re_2. It is thought that this is attributed to the gradual increase of the separation region of the air flow with increasing the roughness Reynolds number Re_2.

(v) When each wave of successive three waves has a train of trip wires near the wave crest, the pressure drag coefficient of the middle wave shows nearly constant value of 1.0×10^{-2} in the range of the Reynolds number, $170 < Re_2 < 2200$. Furthermore it does not depend much on the number of the trip wires per one wave including the case of a single trip wire.

The following conclusion may be drawn from the results summarized above; the pressure drag coefficient of a solid Stokes wave with artificial roughness near the wave crest shows nearly constant value, $Cd \simeq 1.0\times10^{-2}$ irrespective of the number of the trip wires, the number of the windward waves with the trip wires and the values of the roughness Reynolds number Re_2 within a range $170 < Re_2 < 2200$. When only one wave in the successive solid Stokes waves has a single trip wire near the wave crest, the pressure drag coefficient of that wave shows slightly different properties; the drag coefficient increases with the roughness Reynolds number, and it attains to the values larger than 1.0×10^{-2}.

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