CHAPTER 42

EXPERIMENTAL STUDY OF WIND WAVES GENERATED ON CURRENTS

by

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ABSTRACT

This paper presents some experimental results of wind waves generated on currents in a wind-wave channel with a water circulation pump system. The waves were measured at fetches less than 27.8 m by using resistance-type wave gauges. Surface velocities as well as velocity profiles in water were also measured elaborately and true frequency wave spectra were obtained from observed apparent spectra which were modified by the doppler effect of current.

Significant wave heights $H_{1/3}$ computed from $\overline{\eta^2}$ and peak frequencies of true specyra f_{0m} were examined with emphasis. It was inferred from the variation of true spectra that the most prominent effect of water current is to change the effective fetch length. Then an idea of equivalent fetch length was proposed to express the current effect on the development of total wave energy.

By using the equivalent fetch F' in place of the natural fetch it is shown that $H_{1/3}$ and f_{0m} measured under various current conditions can be represented by the non-dimensional fetch relations, respectively, which were originally obtained in the case of no current.

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1. Introduction

It seems to have been known since old times that in the sea where a tidal current exists the wind-generated waves are greatly changed with the direction of current. There was a remark by Lord Rayleigh (1911) in this connection. Francis and Dudgeon (1967) conducted experiments of pilot nature and demonstrated that the water currents actually have an intense effect on the generation of wind waves. Such an effect of current is considered not negligible in the prediction of wind waves in the sea area where a tidal or ocean current exists. However, the effect of current upon the development of wind waves has not been made clear so much quantitatively, and to our knowledge no method is known to evaluate the current effect in the prediction of wind waves.

In order to shed some light on the effect of current and to find some clues to the prediction of waves in the current field we have investigated wind-generated waves on currents in a wind-wave channel which is equipped with a water circulation pump system. A difficult problem in this kind of experiment is the measurement of the waves. In the experiments of Francis and Dudgeon (1967) the waves were measured photographically and crudely averaged. They state that a more sophisticated method of determining the wave characteristics might be justified in the further work.

In our experiments the waves were measured by means of wave gauges. Therefore what are directly computed from the wave records are the apparent spectra with respect to the apparent frequency modified by the doppler effect of current. For exploring intrinsic wave properties, especially the growth rates of component waves, we calculate (as substitutes for the wavenumber spectra) the true spectra defined with respect to the true frequency by making use of the dispersion relation corresponding to the actual current conditions.

In this paper we mainly discuss the non-dimensional representation of significant wave heights $H_{1/3}$ computed from the total wave powers and peak frequencies of true spectra f_{0m} measured under various current conditions. For this purpose we introduce an idea of the equivalent fetch length and show that it is effective for expressing the current effect on the development of wind waves.

2. Experimental procedures

2.1 General description

Rough sketches of the wind-wave channel used for the experiments are shown in Figs. 1 and 2. The uniform test section is 1.5 m wide, 1.3 m high and 28.5 m long. The side walls and most of the ceiling consist of glass plates. On the windward (right hand) side of the test section over the waterway is a wind blower, where wind is generated by an axial fan driven by 50 KW variable-speed motor. Passing through guide vanes, a fine mesh screen and honeycombs the wind is

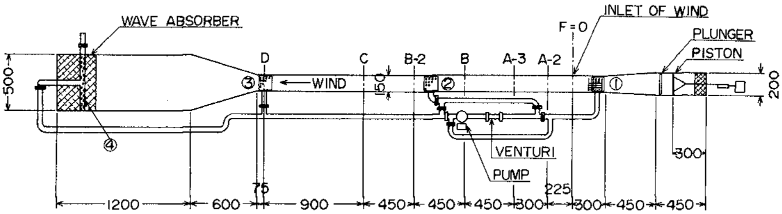

Fig. 1. A plan of the wind-wave channel

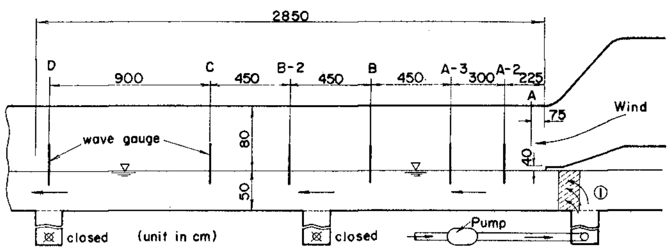

Fig. 2. A side view of the test section

Table 1. Current conditions in the experiments

	Δh (cm)	Q (ℓ/sec)	$\overline{U}$ (cm/sec)
Favorable current	130	224	+29.9
	60.0	152	+20.3
	15.0	76	+10.1
No current	0	0	0
Adverse current	15.0	76	-10.1
	30.0	108	-14.4
	60.0	152	-20.3

allowed to flow onto water of 50 cm depth by means of an adjustable-height guide plate at the inlet section (see Fig. 2), where the wind velocity profile is quite uniform. The wind speed was set up by regulating the speed of fan (rpm). In the experiments the winds at rpm 200, 300 and 400 were used, and the corresponding cross-sectional average wind speeds $\bar{U}_a$ at the inlet section were nearly 5.6, 8.2 and 11.0 m/sec, respectively.

The water currents were generated by a pump between (1) and (4) shown in Figs. 1 and 2. The current condition in each run was controlled by adjusting the flow rate Q accurately by means of a venturi-meter. The experimental current conditions are listed in Table 1, where Δh is the differential pressure head of venturi and $\bar{U}$ is the average cross-sectional velocity. The measurements of waves and currents were made at six stations A-2, A-3, B, B-2, C and D shown in Figs. 1 and 2, and the fetches were 2.25 to 27.75 m. Wind velocities were measured at A-2, B, C and D stations.

2.2 Methods of measurement

The waves were measured by means of resistance-type wave gauges. The sensors were made of two parallel platinum wires 0.1 mm in diameter with 2 mm spacing. Wind velocity profiles over the water surface were measured by using a pitot static tube and a differential pressure transducer. A digital data recorder (DATAC-2000B) was used for recording the output voltages of wind and waves on line, and the later data processing was performed by using a computer. A sampling interval for the wave data was taken as $\Delta t = 1/51.2$ second considering the convenience in the computations of wave spectra by FFT.

Current velocities were measured by means of a small propeller-type current meter both with and without wind. The surface current velocities u_0 were measured by using paraffin flakes in the shape of disk about 6 mm in diameter. In order to check the drift current profile near the water surface a hot-film anemometer was also used in several cases with small amounts of detergent mixed in water to suppress wind waves, for otherwise the hot-film could not detect the horizontal velocity component correctly.

2.3 Method of analysis

As mentioned earlier, what are directly obtained from the wave data are the apparent spectra with respect to the apparent frequency f_A which is expressed as

$$f_A = c / L \tag{1}$$

where c is the wave speed for the wavelength L in the actual current field. From the apparent spectra we calculate the true spectra with respect to the true frequency f_0 given by

$$f_0 = \frac{c_0}{L} = \frac{k}{2\pi}\left[\left(\frac{g}{k} + \frac{T_1 k}{\rho}\right) \tanh kd\right]^{1/2} \tag{2}$$

where c_0 is the wave speed under no current for wavelength L, k the wavenumber ($=2\pi/L$), T_1 the surface tension, ρ the density of water, g the acceleration due to gravity, and d the depth of water. If the wave speed c is expressed as a function of wavelength L for a particular current condition, then f_A and f_0 are related by (1) and (2).

In the calculation of c the effect of drift current must be taken into account in addition to various general currents. For this purpose we used the wave speed solution for a logarithmic drift current obtained by Kato (1974). That is, the drift current profile was assumed to be represented by the logarithmic distribution

$$U(y) = u_0 - U_r \ln[(z_{0W} - y)/z_{0W}] - by \tag{3}$$

where y is the vertical position measured upward from the water surface, u_0 is the surface drift current, and U_r, z_{0W} and b are arbitrary constants which are to be determined corresponding to the actual drift current profile. In practice z_{0W} was taken to be 0.01 cm for all cases (cf. Kato (1974) and Duncan et al (1974) for the measured values in the wind-wave channel), and U_r and b were determined by using the observed current velocity profiles.

Since the wind waves have the angular spreading the actual relation between f_A and f_0 is considerably complicated as discussed by Cartwright (1963) and Barnett and Wilkerson (1967) for somewhat different cases where the wave sensor was transferred with a uniform speed. However, the angular spreading is relatively small for the waves in the wind-wave channel, especially for the dominant wave components which are mainly concerned in this paper. If we neglect the angular spreading, then the relation between the true spectrum ϕ_0 and the apparent spectrum ϕ_A is expressed as

$$\sum \phi_0(f_0)\,|\partial f_0/\partial f_A| = \phi_A(f_A) \tag{4}$$

where the summation is taken for all possible combinations of f_0 and f_A. In our experiments f_0 and f_A were uniquely related in all cases and the relation (4) can be simplified to

$$\phi_0(f_0)\cdot\Delta f_0 = \phi_A(f_A)\cdot\Delta f_A \tag{5}$$

By using the relation (5) we calculated the true spectra from the apparent spectra.

3. Experimental results

3.1 Data of winds and currents

The values of wind friction velocity u_{*a} which were determined from the wind velocity profiles are shown in Table 2. In general u_{*a} are larger in the cases of adverse current than in the cases of favorable current reflecting the water surface conditions.

Table 2. Values of u_{*a} (cm/sec).

Wind	Station	Currents			
		+29.9	+20.3	$\bar{U}$ = 0	-20.3
5.6 (m/sec)	A - 2	19.8	20.7	23.3	30.6
	B	23.5	24.2	26.1	30.8
	C	21.4	21.7	25.7	27.8
	D	19.0	21.2	26.6	22.3
8.2	A - 2	34.8	34.3	40.0	49.2
	B	31.5	35.3	46.1	47.9
	C	29.9	31.3	41.2	48.7
	D	27.5	30.4	44.6	43.1
11.0	A - 2	59.1	68.2	71.1	
	B	55.7	64.3	72.3	
	C	54.4	67.3	78.1	
	D	61.7	76.2	89.9	

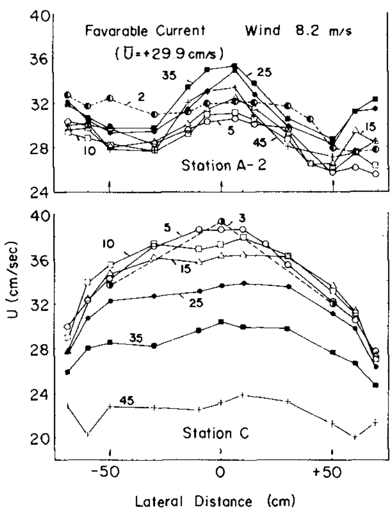

Fig. 3 Lateral current distribution in a case of favorable current.

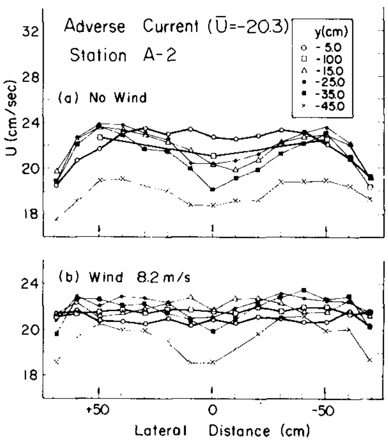

Fig. 4 Lateral current distribution in a case of adverse current.

The lateral distributions of current velocity at A - 2 and C stations in the case of favorable current $\overline{U}$ = +29.9 cm/sec at wind 8.2 m/sec are shown in Fig. 3. As seen from this figure, in the cases of relatively large favorable currents ($\overline{U}$ = +20.3 and +29.9 cm/sec) the velocities near the water surface at C and D stations became somewhat larger at the central part than those at the both sides. On the other hand, in the cases of adverse current the lateral velocity distributions were almost uniform at every station. The distributions with and without wind at A - 2 station in the case of $\overline{U}$ = -20.3 cm/sec are shown in Fig. 4. Obviously the distributions near the surface were made more uniform by the action of wind.

The values of surface current velocity u_0 under various current conditions at wind 8.2 m/sec are shown in Fig. 5. The measurement of u_0 was so difficult in the case of adverse current $\overline{U}$ = -20.3 cm/sec that it was performed in that case by suppressing the waves with detergent mixed in water.

3.2 Variation of wave heights

The measurements of waves at each station were conducted at three lateral positions; at the center of channel width and 50 cm apart from it to both sides. As a parameter to represent the total wave energy we use the significant wave height $H_{1/3}$ evaluated from $\overline{\eta^2}$, the average of the three lateral values, where η is the water surface displacement. Fig. 6 shows the variation of $H_{1/3}$ with fetch under various current conditions at wind 8.2 m/sec.

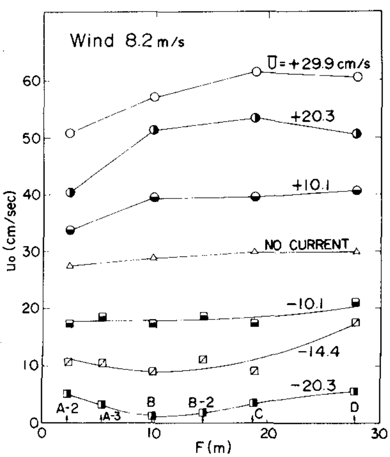

Fig.5 Values of surface current velocity u_0.

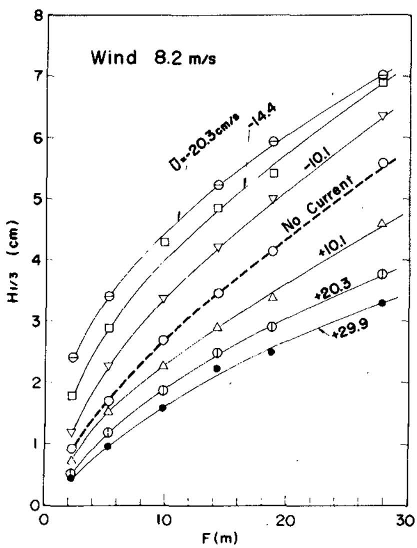

Fig.6 Variation of $H_{1/3}$.

In the cases of large adverse current the peculiar waves propagating obliquely grew with time at short fetches and the total power there became unusually large. The frequencies of such waves were smaller than those of usual wind waves, and the powers (spectral densities) of such oblique waves were excluded approximately in the computation of $H_{1/3}$. As seen from Fig. 6 the wave heights $H_{1/3}$ change systematically with currents, being small for favorable currents and large for adverse currents.

3.3 True spectra and the peak frequencies f_{0m}

As some examples of the obtained true spectra the results in the cases of $\overline{U}$ = +29.9 and -14.4 cm/sec at wind 8.2 m/sec are shown in Figs. 7 and 8. From Fig. 7 it is seen that the low frequency wave components develop remarkably from A - 2 to B stations. In Fig. 8 the spectra at short fetches such as A - 2 and A - 3 have two peaks, respectively. The right peaks of them correspond to the usual wind waves. Concerning the left peaks the obtained spectral densities may not be correct so much, but they correspond to the obliquely propagating waves mentioned above.

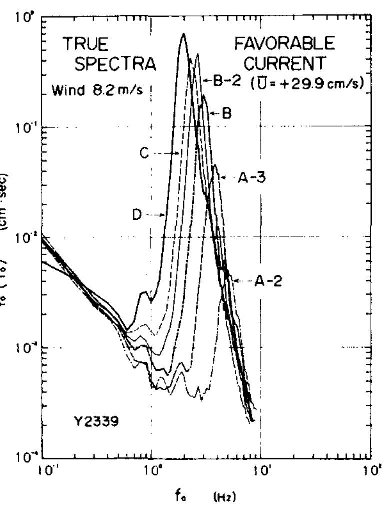

Fig.7 True spectra ; $\overline{U}$ = +29.9 cm/sec, Wind = 8.2 m/sec.

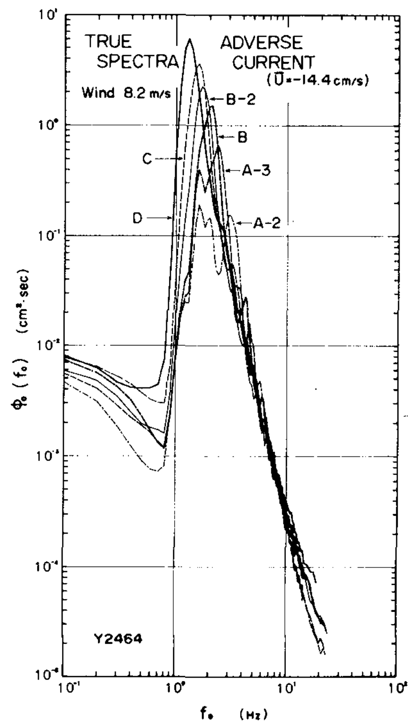

Fig.8 True spectra ; $\overline{U}$ = -14.4 cm/sec, Wind = 8.2 m/sec.

We define a dominant wave at each fetch corresponding to the peak frequency of true spectrum f_{0m}. Then the dominant wave length L_m can be calculated from f_{0m} by using the relation (2). Fig. 9 shows the obtained values of L_m under various current conditions at wind 8.2 m/sec. As seen from this figure the dominant wave lengths L_m are just like $H_{1/3}$ small for favorable currents and large for adverse currents. This variation of wavelength with current is quite contrary to the behavior of the waves moving from still water to a region of current. Huang et al (1972) calculated the wave spectra on currents by considering the kinematic and dynamic interaction between a component wave and current and also using the Pierson-Moskowitz spectrum. However, we must be aware of the distinct difference between the waves generated on a current and the waves propagated into the current from still water.

The values of L_m in each case could be represented as a function of fetch F in the form

$$L_m = \alpha F^n + L_0 \tag{6}$$

where α, n and L_0 are constants. The curves in Fig. 9 show the relation (6) applied to the data in each case, where at short fetches in the cases of adverse current the values of L_m measured photographically (but not shown in Fig. 9) were taken into consideration in order to exclude the influence of the oblique waves mentioned earlier.

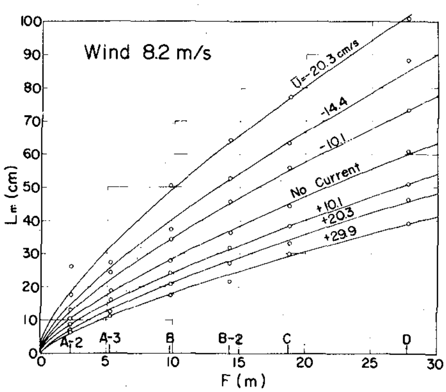

Fig. 9 Variation of dominant wave-lengths L_m with fetch.

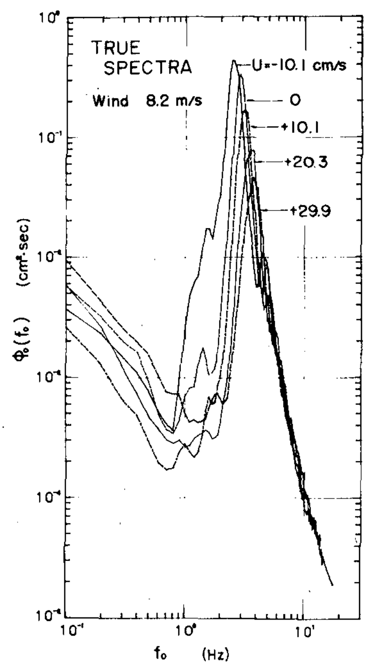

Fig. 10 True spectra under different current conditions.

3.4 Equivalent fetch length

Fig. 10 shows the true spectra obtained under different current conditions at the station A - 3 (fetch = 5.25 m) at wind 8.2 m/sec. The high frequency parts of these spectra almost coincide in a curve and the variation of these spectra with currents resemble closely the variation of the spectra with fetch under no current. This fact suggests that the most prominent effect of water current on the development of wind waves is to change the effective fetch length. This effect must be caused by the change of the wave energy transfer velocity due to the current.

Concerning the development of a particular wave component, a fetch length F_1 and a wind duration time t_1 related by

$$t_1 = F_1 / c_g \tag{7}$$

are regarded as equivalent dynamically (Phillips and Katz, 1961), where c_g is the group velocity of the component wave. t_1 of eq. (7) represents the time required for the energy of the component wave to propagate over the distance F_1. In the sense similar to (7) we assume that the wind duration time which substantially controls the total wave energy at fetch F under a particular current condition is directly proportional to the time $\hat{t}$ given by

$$\hat{t} = \int_0^F \frac{1}{c_{gm}(x)}\, dx \tag{8}$$

where c_{gm} is the group velocity of the dominant wave at each fetch; $\hat{t}$ of (8) is the time required for the energy of dominant wave to arrive at the measuring spot concerned. Then we can define the effective fetch length F' which is equivalent to fetch F under no current in respect of the development of total wave energy as follows:

$$F' = F \cdot [\hat{t} / \hat{t}_0] \tag{9}$$

where $\hat{t}_0$ is the value of $\hat{t}$ under no current. In our experiments the values of $\hat{t}$ were calculated numerically by using the empirical relation (6) as well as the current data measured at six stations.

3.5 Non-dimensional representation of $H_{1/3}$ and f_{0m}

Concerning the growth of wave spectra under no current it has been found by Mitsuyasu (1968) that the total wave energy E ($=\overline{\eta^2}$) and the spectral peak frequency f_m are represented in the non-dimensional forms such as

$$g\sqrt{E} / u_{*a}^2 = 1.31 \times 10^{-2} \, (gF/u_{*a}^2)^{0.504} \tag{10}$$

$$u_{*a}\, f_m / g = 1.00 \, (gF/u_{*a}^2)^{-0.330} \tag{11}$$

These fetch relations were obtained using the wind and wave data in a bay as well as in a wave tank and the similar relations were also obtained from the wave data of JONSWAP (Hasselmann et al, 1973). Recently it was found by Mitsuyasu and Rikiishi (1975) that the wave data in a wind-wave channel only are more fitted to the following relations:

$$g\sqrt{E} / u_{*a}^2 = 6.70 \times 10^{-3} (gF/u_{*a}^2)^{0.641} \tag{12}$$

$$u_{*a} fm / g = 1.19 (gF/u_{*a}^2)^{-0.357} \tag{13}$$

By replacing $\sqrt{E}$ with $H_{1/3}$ the relation (12) can be rewritten as

$$\frac{g H_{1/3}}{u_{*a}^2} = 0.0268 \left(\frac{g F}{u_{*a}^2} \right)^{0.641} \tag{14}$$

Using the equivalent fetch F' of eq. (9) in place of the natural fetch F together with the wind friction velocity u_{*a}, experimental data of $H_{1/3}$ and f_{0m} were plotted in the non-dimensional forms stated above, respectively. Fig. 11 shows the results for $H_{1/3}$. In this figure, at the higher wind speeds (8.2 and 11.0 m/sec) the data from different current conditions are consistent very well in a line and this indicates that the non-dimensional representation by the equivalent fetch F' is adequate. On the other hand, the data at the lowest wind speed (5.6 m/sec) deviate from the points at the higher wind speeds. Such inconsistency, however, has already been reported in the case of no current by Mitsuyasu and Honda (1975), and it is supposed to be due to the undeveloped wave condition. A straight line in Fig. 11, which was determined for the data at the higher winds, is represented by

$$\frac{g H_{1/3}}{u_{*a}^2} = 0.0222 \left(\frac{g F'}{u_{*a}^2} \right)^{0.669} \tag{15}$$

The dotted line in Fig. 11 shows the relation obtained by Mitsuyasu and Rikiishi (1975), eq. (14), and the two relations coincide very well.

Fig. 12 shows the results for the peak frequency f_{0m}. Also in this figure the data at the higher two wind speeds are represented pretty well by a straight line in the figure which is given by

$$\frac{u_{*a} f_{0m}}{g} = 0.939 \left(\frac{g F'}{u_{*a}^2} \right)^{-0.354} \tag{16}$$

The relation (13) by Mitsuyasu and Rikiishi (1975) is also shown in Fig. 12 by the dotted line. Although there is some difference between our result and (13), it is mostly attributed to the effect of drift

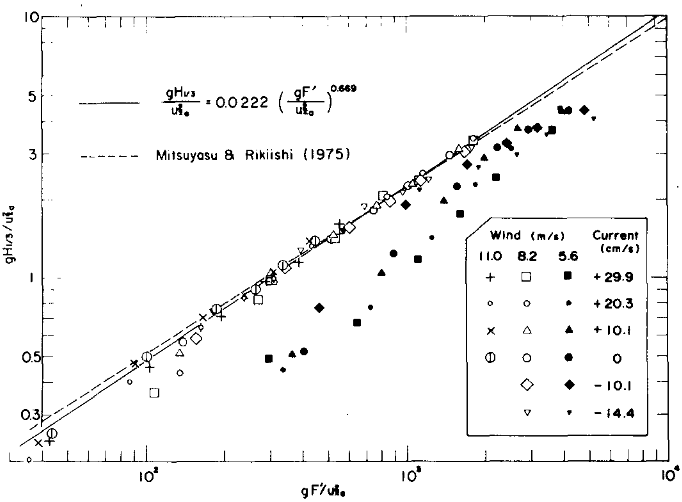

Fig. 11 Experimental results of $H_{1/3}$ represented in the non-dimensional form.

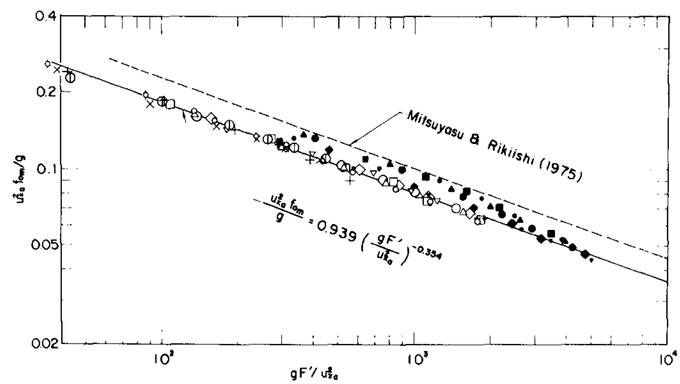

Fig. 12 Experimental results of the peak frequency f_{0m} represented in the non-dimensional form.

current; in our experiments the effect of drift current was completely corrected, while no correction was made for the data of Mitsuyasu and Rikiishi (1975). Since, however, it is rather customary under no current to use the frequency data including the effect of drift current, we must notice it in case of extrapolating the present relation (16) up to a field scale.

4. Conclusions

We have described the experiments conducted in a wind-wave channel to investigate the effect of water current upon the development of wind waves.

From the experimental results it was inferred at first that a water current has an effect to change the substantial (effective) fetch length; an adverse current increases the effective fetch and a favorable current decreases it. Considering the change of energy transfer velocity due to the current, we proposed an idea of equivalent fetch length to express the current effect on the development of wind waves.

It was shown that the non-dimensional fetch relations, which were originally obtained for the wind waves under no current, can equally be applied to the wave data, $H_{1/3}$ and f_{0m}, under various current conditions if the equivalent fetch length is used in place of the natural fetch.

The idea of equivalent fetch length is expected to be of use in the prediction of wind waves in the sea when there is a current, although some assumptions will be necessary in the case of adverse current.

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