INTERACTIONS BETWEEN WATER WAVES AND WINDS (I): co-existent system of wind wave and regular oscillatory wave

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INTERACTIONS BETWEEN WATER WAVES AND WINDS (I)

—co-existent system of wind wave and regular oscillatory wave—

By Hisashi MITSUYASU

Abstract: A series of laboratory experiments was made on the co-existent system of wind wave and regular oscillatory wave. The co-existent system described here was realized when the mechanically-generated wave passed through the local wind-generated wave field where the steady wind was blowing in the direction of the insident wave.

It was shown that the wind wave overlapped on the regular oscillatory wave without appreciable changes in its spectrum, so long as the steepness of the passing wave was very small. However, when the regular wave of large steepness passed through the wind area the wind wave attenuated very quickly and the energy of the wind wave, especially the energy near the dominant peak of the spectrum, was attenuated remarkably. In this way, a close relation was found between the attenuation of the wind wave energy and the steepness of the passing wave.

It was also shown that the regular wave of long period slightly attenuated when it passed through the wind area. Up to the present, however, the definite conclusions have not been obtained on the change of regular oscillatory wave in the wind area.[1)]

1. Introduction

In the present state of our knowledge it is not so easy to answer either of the following questions: what happens when the regular oscillatory wave passes through the local wind-generated wave field where the steady wind is blowing, or what is the consequence if the wind continues to blow over the water surface where the definite wave already exists? Concerning the first question, Phillips (1963) proposed theoretically the attenuation mechanism of swell by the local wind-generated wave field, and the field observations by Munk et al. (1963) and by Snodgrass et al. provided some informations. For the second question, we can secure a theoretical solution based on the modern theories of wind wave generation such as Miles' theory (1957, 1960) or Phillips' theory (1966), if we are mainly concerned with the change of the wave previously given. However, in both cases, the available informations are mainly concerned with the behaviours

1) This is mainly due to the shortness of propagation distance of regular wave. Further experiments, in which the fetch was extended from 5.2 m to 10 m, 15 m and 18.6 m successively, showed that the regular wave of long period was attenuated and the regular wave of short period was amplified when they propagated through the wind area. The results will be published in near future.

of long period wave rather than those of the wind wave or of the co-existent system. Moreover, we know little about the actual phenomena and their physical processes.[2)]

The present studies were designed first to secure the fundamental data about those physical processes experimentally, and furthermore, to clarify the mechanism of interaction between wind and wave.

In the preliminary study, the following two cases, which correspond respectively to the previous two questions, were tested; in the first case, the regular oscillatory wave was generated at one end of the wave tank and made pass through the local wind-generated wave field in the middle part of the tank where the steady wind was blowing, and in the second case, the regular oscillatory wave was first generated and then wind blower was started in the same experimental arrangement with that in the first case. It was found that final steady states of co-existent system were almost the same in both cases when the sufficient time was elapsed. Therefore, the two problems previously proposed came into one (at least within a limit of our experimental condition). Throughout the present experiment the first way was adopted as the experimental procedure, since the new steady state was attained very quickly in this case as will be discussed later.

A series of experiment was conducted by changing the experimental conditions, i.e. the fetch length and properties of regular wave passing through the wind area. In the present paper the experiments of first two series, in which the fetch is limited to 5.2 m, are discussed in particular.

2. Experimental apparatus and procedure

The experiment was conducted in a large scale wave tank which is 70 m long by 8 m wide, with a water depth of 2.9 m. Fig. 1 shows the general layout of the experimental arrangement. As shown in Fig. 1, a local wind-generated wave field was caused at the middle part of the tank by using the wind blower, the outlet mouth of which is 20 m from the wave generator[3)]. The regular oscillatory wave was generated at one end of the tank by the plunger type wave generator[4)] and made pass through the local wind area to simulate the co-existent system of wind wave and regular oscillatory wave under the action of wind.

Throughout the present experiment wind speed was kept at 20 m/sec at the

2) Since this study went on, several papers were published in which the laboratory experiments similar to ours were described (Wiegel et al 1966, Shemdin et al 1966). In both the cases, however, attentions were mainly paid for verifying Miles' theory of wave generation (Miles 1957, 1960), and central discussions were concerned with the wind structures over mechanically-generated waves.

3) The wind blower can be moved at any places along the tracks on the side wall of the tank.

4) The plunger of wave generator is composed from eight parts so as to generate short-crested waves as well as long-crested waves. Only long-crested waves were used in the present experiment for simplifying the experimental condition.

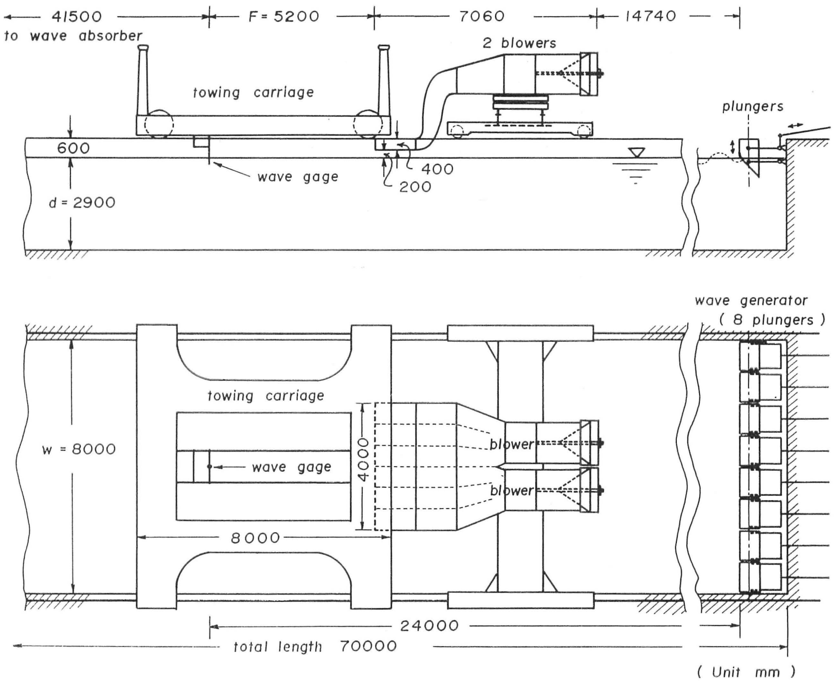

Fig. 1 Experimental tank

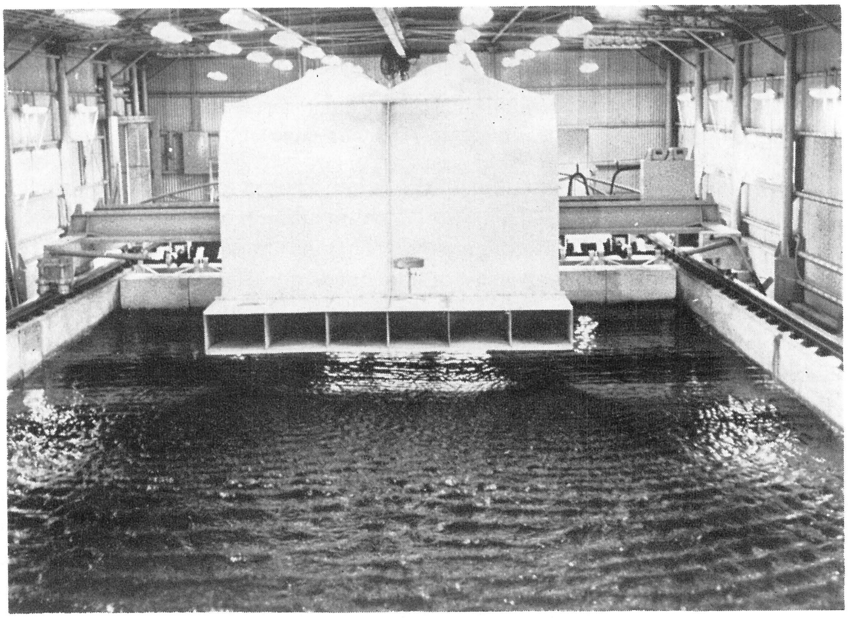

Photo. 1. Experimental tank
In the present series of experiments, wind blower (at the center of this Photo) was connected to the towing carriage which is in this side and out of this photo.

outlet mouth of wind blower by adjusting the damper of the blower intake. The cross section of the outlet of the blower's duct was 4 m in width and 0.4 m in height. The bottom of the duct is 0.2 m above the still water level so that the regular wave may pass through the gap (Fig. 1). Therefore, the wind near the outlet of the duct can be considered as a rectangular jet. As it diverges the wind touches to the water surface at some location (approximately 1.2 m downstreem from the duct, in our present case), and then the boundary layer affected by the water surface develops. As a result, the effective fetch in our present experiment is shorter approximately by 1.2 m than the geometrical fetch. Fig. 2 shows

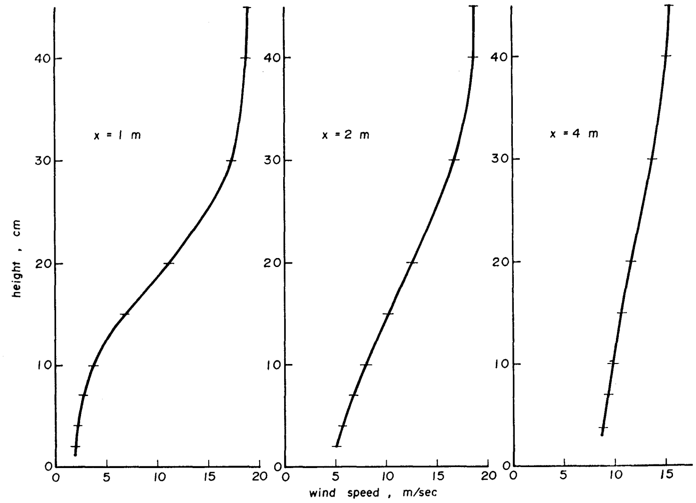

Fig. 2 Wind-profiles over water surface.
X: distance from the edge of the blower.

the examples of vertical distribution of the wind at several locations along the center line of the wave tank. The special configulation of the wind blower has several advantages and also disadvantages. That is, unlike usual wind-wave tunnels the effects of the top and sides of the flume on the wind are practically neglisible, and in this respect, the wind is similar to the natural wind. However, since there are no boundaries which restrict the air flow within some definite cross section, the wind diverges as a rectangular jet bounded only at the bottom, and therefore, wind speed changes toward the downstream. The similar things can be said about the wind-generated waves in the present tank. That is, as the width of wind area is approximately half of that of the wave tank, wind waves can spread through the boundaries in both sides of the wind area. The effects of the special shape of our experimental tank on the wind structures and also on the wind-generated waves are now being examined in some detail. However, as far as the present studies are concerned, such problems will not be so serious because we are mainly concerned here with a comparison between wind wave properties in the presence and in the absence of the regular wave.

Waves were measured by the capacitance type wave gauge [Ohji et al(1964)] fixed on the towing carriage (Fig. 1), and recorded on the visigraph. The properties of regular oscillatory waves used in the present experiment are listed in

indeex of wave	2—6		2—12		0.8—4		0.8—6		wind wave
	wa	wa+wi	wa	wa+wi	wa	wa+wi	wa	wa+wi	
T sec	1.99	1.97	2.05	1.97	0.86	0.84	0.82	0.82	0.36
σ_T sec	0.03	0.10	0.02	0.09	0.01	0.04	0.01	—	—
H cm	4.0	6.5	7.5	9.2	4.6	5.3	7.8	9.4	2.3
σ_H cm	0.1	0.6	0.2	0.5	0.2	0.6	0.1	1.7	—
H/L	0.0065	0.011	0.011	0.015	0.040	0.048	0.075	0.090	0.11
E cm^2	[2.02]*	2.78	[7.00]	7.27	[2.64]	2.53	[7.64]	8.15	1.02
E_1 cm^2	[2.02]	1.75	[7.00]	6.50	[2.64]	2.28	[7.64]	7.34	—
E_2 cm^2	—	1.03	—	0.77	—	0.25	—	0.81	1.02
H' cm	—	6.1	—	9.2	—	5.5	—	9.8	2.3
H_1 cm	—	3.7 (3.7)**	—	7.2	—	4.3	—	7.7	—
H_2 cm	—	2.4	—	2.0	—	1.2	—	2.1	2.3

Table 1 Results of the first seriest of experiment.
(air temperature T_a=25°C, water temperature T_w=18.5°C)
T : mean wave period, σ_T : standard deviation of wave period
H : mean wave heght, σ_H : standard deviation of wave height
H/L : wave steepness, $E=E_1+E_2$, E_1 : energy of regular wave,
E_2 : energy of wind wave, $H_1=H_1+H_2$, $H_1=\sqrt{8E_1}$, $H_2=2.32\sqrt{E_1}$
*) The values with [ ]were obtained from H by using $E=H^2/8$.
**) The value with ( ) was obtained by filtering out the wind wave from the record of co-existent system.

index of wave	1.4—10		1.4—7.5		1.4—5		1.4—2.5		Wind wave
	wa	wa+wi	wa	wa+wi	wa	wa+wi	wa	wa+wi	
T sec	1.40	1.40	1.44	1.39	1.39	1.38	1.39	1.39	0.38
σ_T sec	0.02	0.06	0.01	0.09	0.01	0.12	0.03	0.10	—
H cm	10.0	10.3	7.1	8.8	5.0	6.8	2.4	5.5	3.0
σ_H cm	0.4	0.7	0.2	0.6	0.1	0.9	0.1	0.9	—
H/L	0.033	0.034	0.022	0.029	0.016	0.023	0.0082	0.018	0.13
E cm^2	[12.42]	12.20	[6.37]	8.07	[3.08]	4.08	[0.74]	2.19	1.70
E_1 cm^2	[12.42]	11.58	[6.37]	7.22	[3.08]	3.01	[0.74]	0.83	—
E_2 cm^2	—	0.62	—	0.85	—	1.07	—	1.36	1.70
H' cm	—	11.8	—	9.7	—	7.3	—	5.3	3.0
H^1 cm	—	10.0	—	7.6	—	4.9	—	2.6	—
H_2 cm	—	1.8	—	2.1	—	2.4	—	2.7	3.0

Table 2. Results of the second series of experiment.
(air temperaturature T_a=15°C, water temperature T_w=10.5°C)

Table 1 and Table 2 (columns: wa), in which the properties of the same kinds of waves under the action of wind are also shown, (columns: wa+wi).

The measurements were classified tentatively into ten series according as the experimental conditions, i. e., fetch length, properties of passing regular waves and wind speed. In the first two series of experiments, the measurements were conducted at the location shown in Fig. 1 (fetch $F=5.2$ m). In the later series of experiments, from third to ten series, fetch was changed from 5 cm to 10 m, 15 m and 18.6 m successively by moving the towing carriage to the corresponding locations. In the present paper, only the results of the first two series of experiments are presented. However, it has been checked that many of the findings of this paper are not so largely altered even when the experimental results of later series are included.

3. Experimental results

3-1. *Results of the preliminary test.*

In the preliminary study, the following two cases were tested: i) an almost saturated wind wave field (Philips 1958a) was generated first, and then the mechanically-generated wave was sent into that field, ii) the uniform train of regular wave was generated first, and wind was sent over it. Fig. 3 shows examples of wave records of those tests. In Fig. 3, (a) is the record of mechanically-

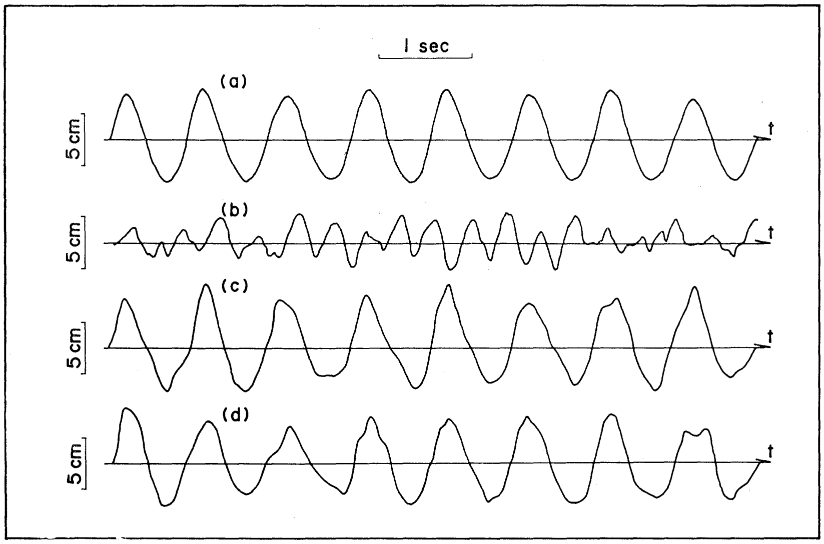

Fig. 3 Samples of wave records showing
(a) regular oscillatory wave, (b) original wind wave,
(c) co-existent system generated when the regular oscillatory wave came into the wind field,
(d) co-existent system generated when the wind was sent over the regular oscillatory wave. ($F=5.2$ m, $U_0=20$m/s, regular wave: 0.8–6)

generated wave (wave: 0.8-6) which is unaffected by the wind, (b) is the record of wind wave unaffected by the mechanically-generated wave, (c) and (d) are the records of co-existent systems in the cases i) and ii) respectively. In both the cases, wave records were taken when the sufficient time was elapsed after the generation of each co-existent system. It can be seen from Fig. 3 that almost the same steady states of the co-existent systems were attained in both the cases.

Fig. 4 shows the wave records including the transition stage of the co-existent system which is caused when the front of the mechanically-generated wave (wave : 14-10) comes into the local wind generated wave field. Note that the new steady state is attained very quickly when the regular wave train comes into the wind wave field.[5)]

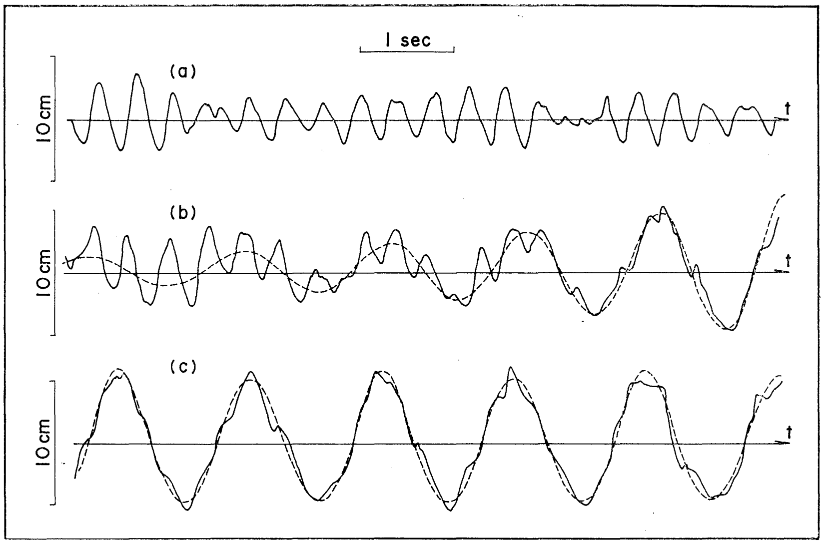

Fig. 4 Samples of wave records showing
(a) wind wave unaffecte by the regular oscillatory wave,
(b) transition state of co-existent system of wind wave and regular oscillatory wave,
(c) Steady state of the co-existent system. The broken curve shows the record of the regular wave unaffected by the wind.
(F=5.2 m, U_0=20 m/s, regular wave: 1.4-10)

5) The gradual change of the amplitude of the regular wave in the record (b) is not due to the transition of the co-existent system, but due to the characteristics of the original wave train. Because, the similar transition can be found in the record of regular wave unaffected by the wind, which is shown by the dotted curve overlapped on the record of the co-existent system. In the case of wave which is propagating into the water initially at rest, the first wave, travelling at the phase speed, is very small and wave hight increases sharply near the center wave which travels at the group speed. Therefore, some transition stage exist between the first wave and the center wave. Detailed discussions were given by Sverdrup & Munk (1947).

3-2. *General aspects of the co-existent system.*

When the regular wave came into the local wind-generated wave field the distinct difference in the final steady state of the co-existent system was found depending on the steepness of the passing regular wave. That is, when the regular wave of very small steepness passed through the wind-generated wave field, the wind wave was little affected by the passing wave and it overlapped on the regular wave. This is

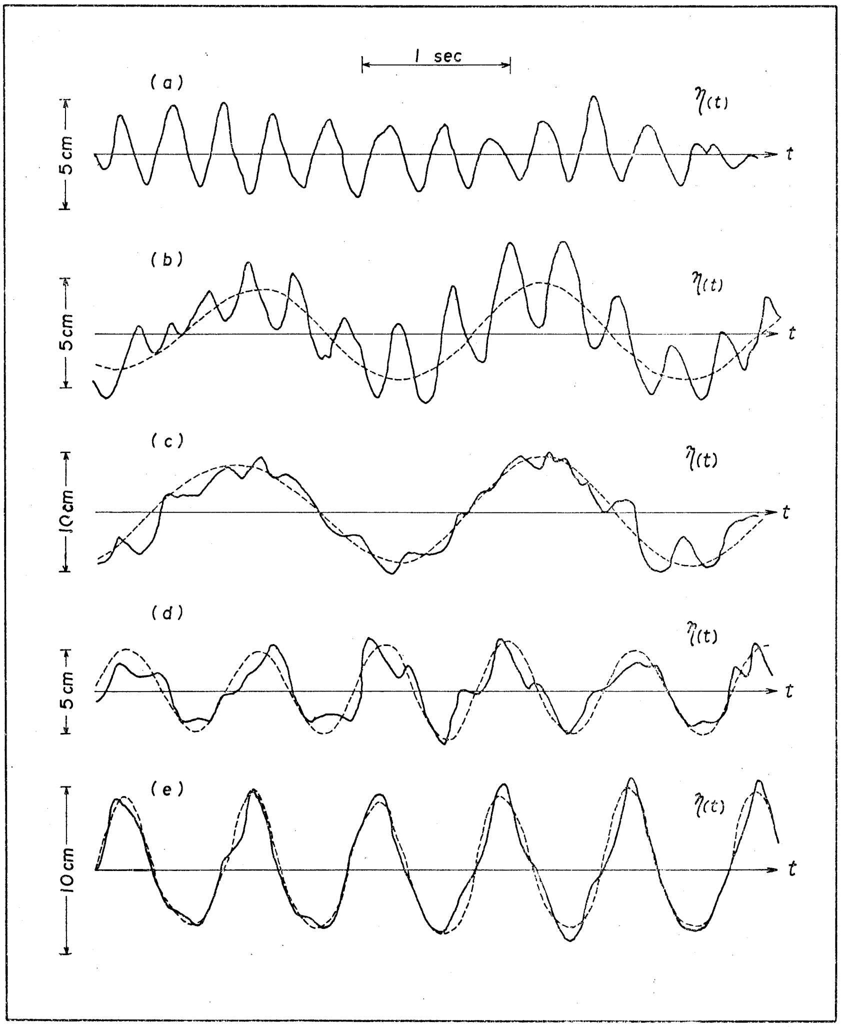

Fig. 5. Samples of wave records of the first series of experiments showing the wind wave (a) and the co-existent systems of wind wave and regular wave (b), (c), (d) and (e). The records (b), (c), (d) and (e) correspond, to the insident regular waves 2-6, 2-12, 0.8-4, and 0.8-6 respectively. The broken curve shows the record of the regular wave unaffected by the wind. (F=5.2 m U_0=20 m/s)

cleary seen in the wave record (b) shown in Fig. 5. On the other hand, when the regular wave of large steepness passed through that field, the wind wave attenuated very quickly and only the short ripples were visually observed (Photo 4).

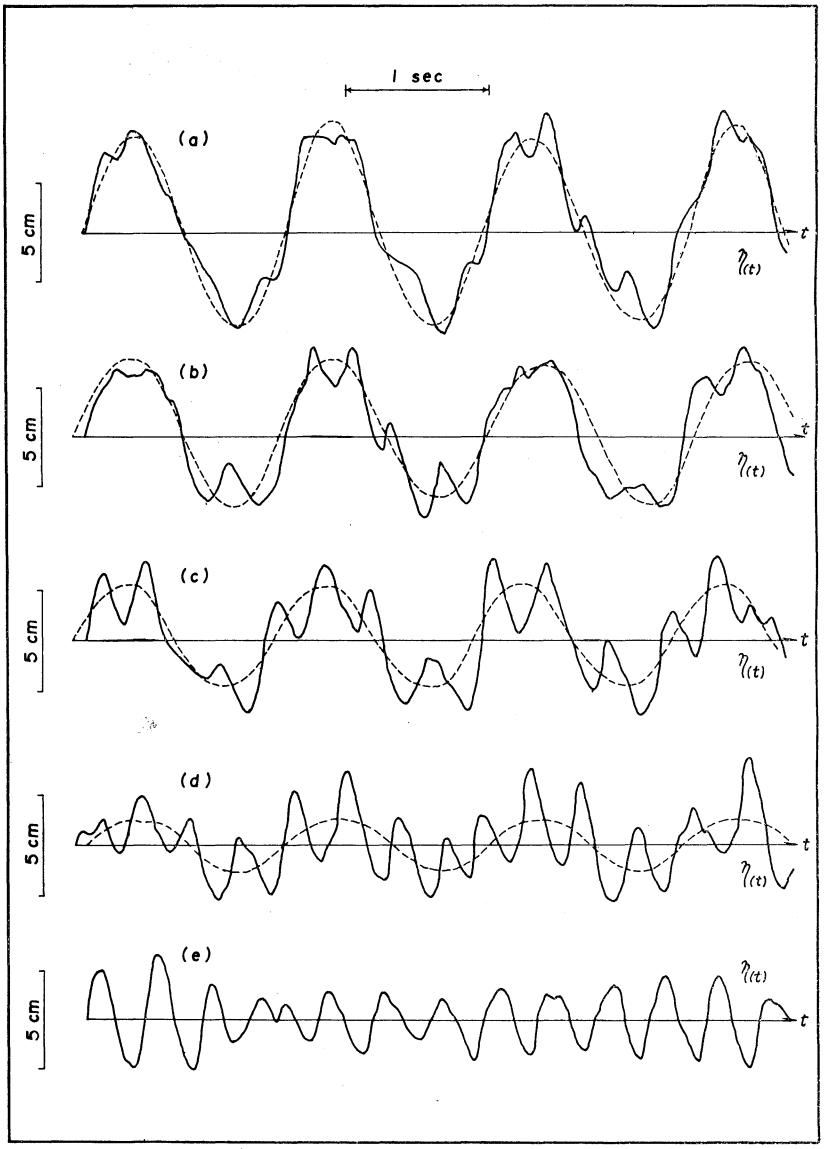

Fig. 6. Samples of wave records of second series of experiments showing the co-existent systems of wave and regular wave (a), (b), (c) and (d), and original wind wave (e). The records (a) (b), (c) and (d) correspond to the insident regular waves 1.4–10, 1.4–7.5, 1.5–5, and 1.4–2.5 respectively. The broken curve shows the record of regular wave unaffected by the wind. (F=5.2 m, U_0=20 m/s)

However, carefully observation of the wave record (e) in Fig. 5 shows that dominant wind waves are still existing even in this case although their amplitudes were very small. This fact can be clearly seen in the wave spectrum of the co-existent system of wind wave and regular wave, which will be discussed later. Wave records (c) and (d) in Fig. 5 show the intermediate cases. Fig. 6 shows the wave records of the second series of experiment in which the regular waves with the same period but different heights were used for the measurements. Fig. 6 clearly shows that the wind wave attenuates gradually with increasing the steepness of the passing regular wave.

According to the theory of non-linear interaction between waves, it is shown that in the absence of growth or decay of the short wave, the amplitude a_2 of the short wave overlapped on the long wave is given approximately by

$$a_2=(a_2)_0[1+a_1k_1\cos(k_1x-n_1t)] \tag{1}$$

where $(a_2)_0$ is the amplitude of the short wave, unaffected by the long wave, a_1 the amplitude of the long wave, $k_1(=2\pi/L_1)$ the wave number of the long wave, and $n_1(=2\pi/T_1)$ the angular frequency of the long wave (Longuet-Higgins & Stewart 1964).[6] However, as will be seen from the wave record (b) in Fig. 5, the dependence of the wind wave properties on its position on the regular wave is not so clear. This means that in this case the non-linear interaction between the wind wave and the regular wave is very weak because of the small steepness of the regular wave[7], although the exact examination of its dependence is difficult owing to the statistical variation of the wind wave. In the case of very steep wave (wave record (e) in Fig. 5), here again the change of wind wave is not so clear on account of its great attenuation by the effects of the long wave.

The properties of co-existent systems obtained directly from the wave records are summerized in the upper parts of the Table 1 and Table 2 (columns: wa+wi). In obtaining those data, the co-existent systems were considered to be equivalent to the regular wave systems affected by the wind. That is, wave heigh H here means the overall wave height which is defined as the difference between the maximum in any crest of the regular wave and the minimum in the succeeding trough of the regular wave. Similarly, overall wave period is defined. From the results shown in Tables 1 and 2, it can be seen that the overall wave height increases under the action of wind and that the standard deviations of both wave height and wave period increase remarkably even when the development of the wind wave is greatly suppressed. The latter is considered to be reflecting the irregular deformation of the regular oscillatory wave.

The properties of the wind wave representing the original wind-generated wave field are shown in the last column of each table. On the other hand, according to the rough estimations of wind wave characteristics by means of the

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6) The assumptions were made that i) the short wave is much shorter than long wave, and ii) the long wave is also effectively in deep water.

7) In fact, in the case of wave record (b), $a_1k_1(=\pi H/L)=0.020$ from Table 1. Therefore, the interaction of this type must be very weak.

fetch graph (Wiegel 1964), the following values of wave height and of wave period can be obtained for our present case[8];

$H_{1/3}=3.9$ cm, $\bar{H}(\doteqdot H_{1/3}/1.6)=2.4$ cm

$T_{1/3}=0.39$sec, $\bar{T}(\doteqdot T_{1/3})=0.39$ sec

These are fairly close to our measured values.

3–3. *The spectrum of the co-existent system*

To clarify the detailed properties of co-existent system of wind wave and regular wave more quantitatively spectral analysis of wave records were conducted, Each wave record of two minutes in lenth was digitized on a commercial semi-automatic analog-to-digital converter (AUTOPROCESS, Type CR 2050). The sampling rate was 50 samples per 3sec. The computation of the wave spectrum $\phi_{(f)}$ was done by the OKITAC 5090 H digital computer in the Kyushu University Computation Center. The adopted program was based essentially on the analysis system by Blackman and Tukey (1958) : sample size $N=2000$, maximum lag $M=42$, Niquist frequency fn=8.4c/s, resolution $\Delta f=0.2$c/s, degree of freedom d. f.=95 and corresponding 90% confidence band of 0.8 $\phi_{(f)}$ to 1.3 $\phi_{(f)}$.

Fig. 7 shows the spectrum of the wind wave representing the wind-generated wave field unaffected by the passing regular wave. From Fig. 7 it can be seen that the high frequency part of the wind wave spectrum is steeper than f^{-5} and that energy is overconcentrated near the peak of wave spectrum as compared the equilibrium spectrum of wind wave (Phillips 1958a). Those properties are usually observed in the wind wave spectra measured in laboratories (Hamada 1964, Mitsuyasu 1964), and are not necessarily attributed to the special shape of our experimental tank.

a) *The spectrum of the co-existent system.*

Measured spectra of the co-existent systems are shown in Figs. 8–1, 8–2, 8–3, 8–4 and 9. In some of the figures, the scale of ordinate is changed in the high frequency range to see more closely the characteristics of wind wave spectrum (the second peak). Fig. 8–1 shows the spectrum of co-existent system of wind wave and regular oscillatory wave of small steepness, which corresponds to the wave record (b) in Fig. 5. In this case, the spectrum of regular wave (the first peak) and the spectrum of wind wave (the second peak) are clearly separated. This makes it possible to treat separately and quantitatively the energy of the regular wave and that of wind wave. By comparing the latter with the spectrum of original wind wave (dotted curve) which is generated on the water surface without regular oscillatory wave, it can be seen that both spectra are quite

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8) In the calculations the following values were used respectively for fetch F and wind speed U;

$F=4$m $(=5.2\text{ m}-1.2\text{ m})$

$U=17.3$ m/s $(=[20\text{ m/s}+14.5\text{ m/s}]/2)$

where the correction (−1.2 m) was made for the fetch length, and the mean value of wind speeds measured at $F=0$ and $F=5.2$ m was taken.

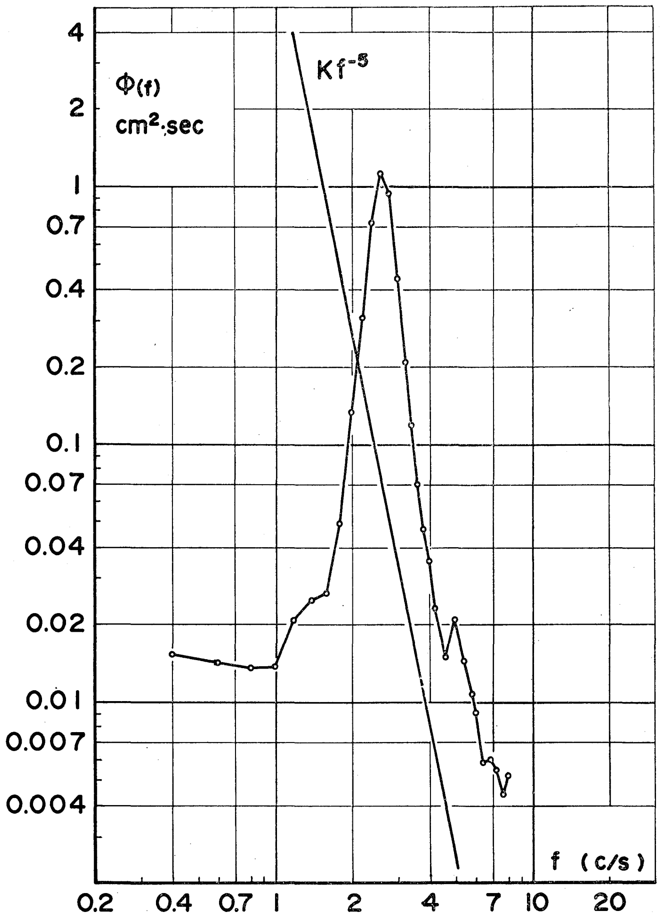


Fig. 7. Spectrum of wind wave. $K=\beta g^2(2\pi)^{-4}$ and $\beta=1.48\times10^{-2}$ (Burling 1959)

similar except for the slight difference in the energy concentration. In the case of moderately steep regular wave (wave record (c) in Fig. 5), the spectrum of wind wave is considerably attenuated as shown in Fig. 8-2. In Figs. 8-1 and 8-2, the small peak between the first peak and the second peak in the spectrum is due to the second harmonics of the regular oscillatory wave. In some cases (Figs. 8-3 and 8-4), such higher harmonics of the regular oscillatory wave overlapped on the spectrum of wind wave, and some difficulties were encountered in the analysis of the data. Fig. 8-3, which corresponds to the wave record (d) in Fig. 5, shows that spectrum of wind wave is greatly attenuated when steep regular oscillatory wave passed through the local wind-generated wave field. Contrary to our expectations, in Fig. 8-4, which shows the spectrum of the steepest wave of our present experiment and corresponds to the wave record (e) in Fig. 5, there can be seen a considerable wave energy in the frequency range of wind wave. However, this is not the true en-

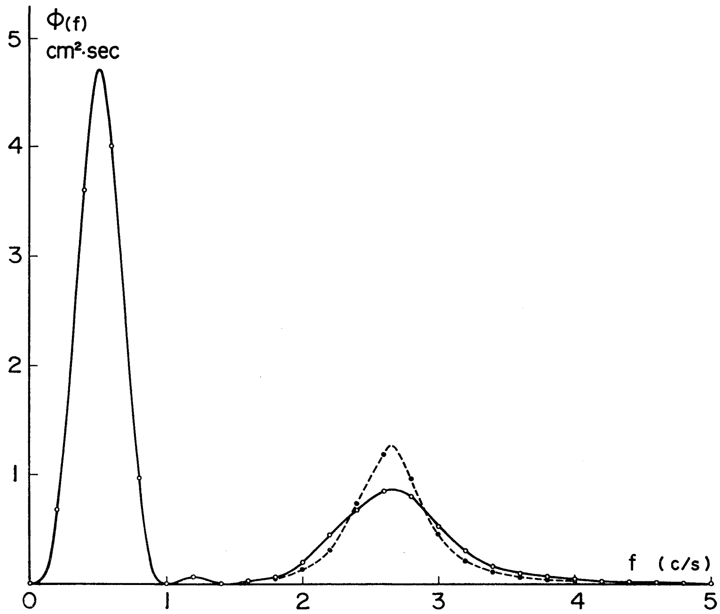


Fig. 8-1. Spectrum of co-existent system of wind wave and regular oscillatory wave (wave: 2-6). ······· shows the spectrum of wind wave unaffected by the regular oscillatory wave.

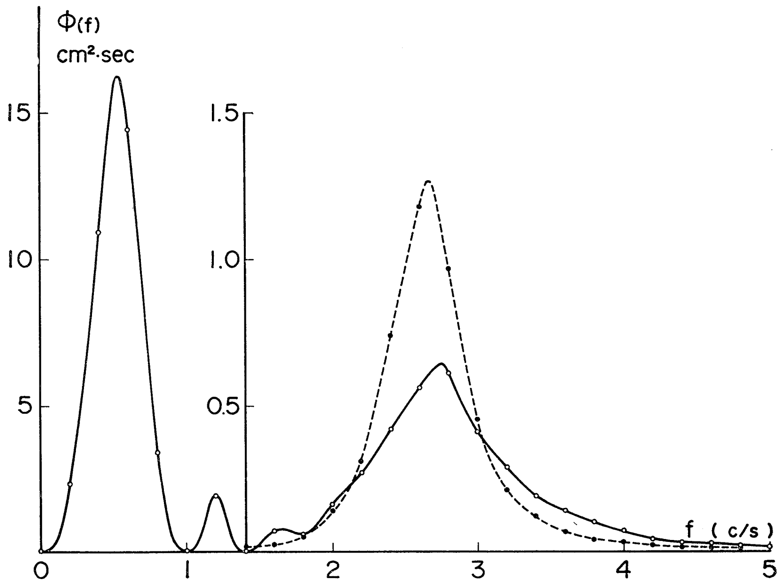


Fig. 8-2. Spectrum of co-existent system of wind wave and regular oscillatory wave (wave: 2-12). ··· · ··· shows the spectrum of wind wave unaffected by the regular oscillatory wave.

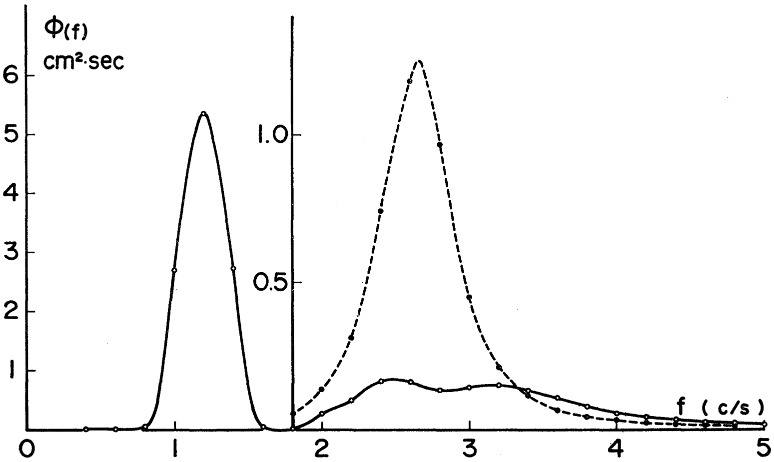


Fig. 8–3. Spectaum of co-existent system of wind wave and regular oscillatory wave (wave: 0.8–4). ···· • ···· shows the spectrum of wind wave unaffected by the regular oscillatory wave.

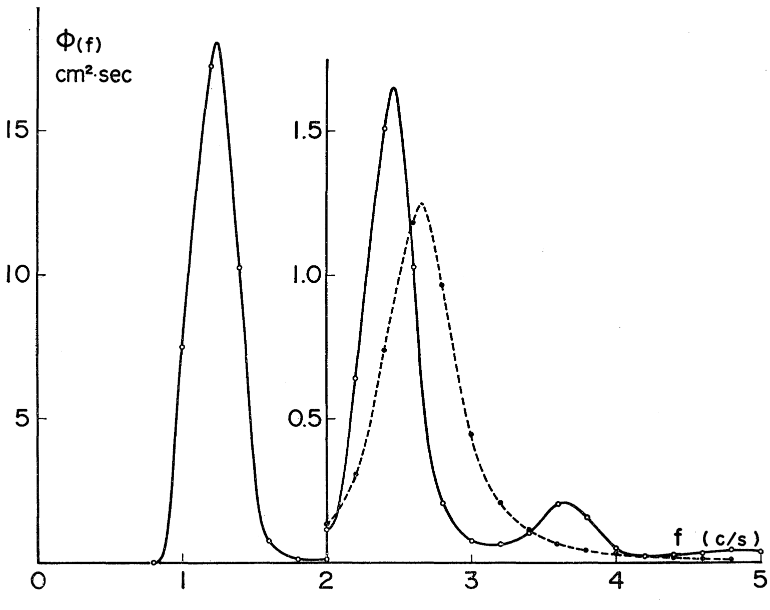


Fig. 8–4. Spectrum of co-existent system of wind wave and regular oscillatory wave (wave: 0.8–6). ···· • ···· shows the spectrum of wing wave unaffected by the regular oscillatory wave.

ergy of wind wave but largely attributed to the higher harmonics of the regular wave. Moreover, the magnitudes of the higher harmonics in this case seemed to be much larger than what were expected from the higher order theory of water

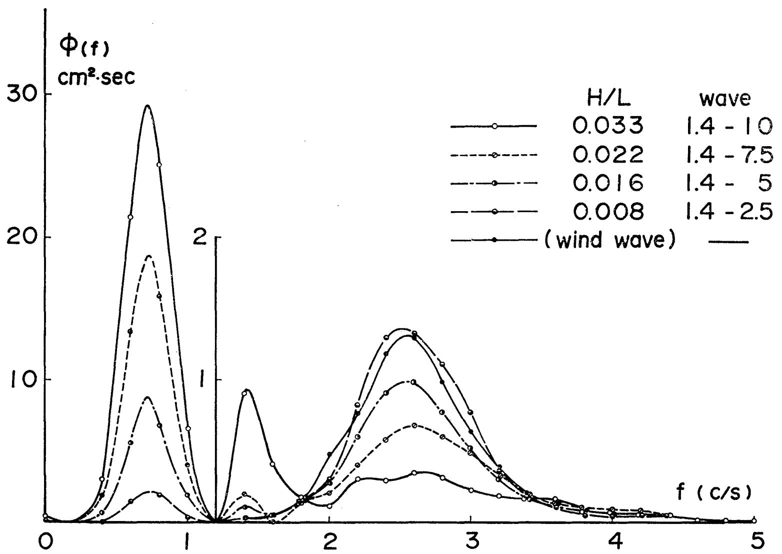


Fig. 9. Spectra of co-existent systems of wind wave and regullar oscillatory wave.

wave[9]. Therefore there are no ways to estimate the accurate wind wave energy in this case.

In Figs. 8-2 and 8-3, it should be noticed that the attenuations of wind wave spectra are conspicuous especially near the peak of each spectrum. Such characteristics of the attenuation of wind wave spectrum can be seen more clearly in Fig. 9. In Fig. 9, five different spectra are shown, each of which corresponds to the wave record in Fig. 6. Fig. 9 clearly shows that the wind wave spectrum is attenuated gradually with increasing the steepness of regular oscillatory wave, and that the attenuations are remarkable near the peak of each wind wave spectrum and frequency range of each wind wave spectrum is not so altered.

b) The wave energies and the overall wave height.

To examine the energy distribution in the co-existent system quantitatively, total energy E_1 contained in the regular oscillatory wave and the total energy E_2 contained in the wind wave were obtained by the numerical integration of each wave spectrum. Such obtained wave energies E_1 and E_2, and the total wave energy of the co-existent system $E(=E_1+E_2)$ are summerized in the lower parts of Tables. 1 and 2. In the case of short regular wave of large steepness, its higher harmonics was considered to be overlapped on the spectrum of wind wave which is co-existing with the short regular wave. Since there are no way to separate them directly,

9) This fact will be considered that the higher harmonics of the regular wave were much amplified by the action of wind. More detailed data and their discussions will be given in the next paper of this series.

approximate corrections were made in the computations of E_1 and E_2 by using the higher-order theory of surface wave. That is, the higher harmonics of the regular wave were estimated by using the third-order solution of Stokes wave, and the corresponding wave energies were substracted from E_2 and added to E_1. However, as disussed previously, such corrections are not satisactory for the case of the wave spectrum shown in Fig. 8-4.

The characteristic wave heights H_1 and H_2 were determined respectively from the wave energies E_1 and E_2 by the following relations;

$$H_1=\sqrt{8E_1} \tag{2}$$

$$H=2.32\sqrt{E_2} \tag{3}$$

The first relation was obtained from the first-order theory of surface wave, and the second relation was determined experimentally from the obseved values of wave energy and of mean wave height of the wind wave which is unaffected by the regulary wave[10]. Obtained results are shown in Tables 1 and 2. To check the accuracy of the spectrum computation and also the relation (2), the wave height of the regular wave was obtained directly from the wave record of co-existent system by filtering out the overlapping wind wave, and such obtained value (the value with ( )** in Table-1) was compared with the wave height H_1 which was determined from E_1 by using the relation (2). Agreement is quite good as shown in Table-1.

The overall wave height H' of the co-existent system was determined as the sum of H_1 and H_2, i. e., by

$$H'=H_1+H_2 \tag{4}$$

As show in Tables 1 and 2, the wave height H' obtained in such a way agrees fairly well with the overall wave height H obtained directly from the wave record of co-existent system by the method described in 3-2.

3-4. *The attenuation of wind wave energy by the co-existing regular wave*

Fig. 10 shows the relation between the total energy contained only in the wind wave and the steepness of the co-existing regular wave[11]. In the ordinate of Fig. 10 the dimensionless wind wave energy $E_2/(E_2)_0$ is taken, where $(E_2)_0$ is the energy of the wind wave which is generated on the water surface without the regular wave. As it was expected from Fig. 6 or Fig. 9 close relation can be seen between the wind wave energy and the steepness of the co-existing regular wave. Fig. 10 shows that the energy of wind wave attenuates greatly with increaseing the steepness of the co-existing regular wave and that the energy of wind wave becomes almost neglisibe beyond the steepness say $H/L=0.06$ if we extrapolate the present result. Although the present result was obtained only from

10) Accordihg to the theory of wind wave the constant in Eq. (3) is 1.772 (Longuet-Higgins 1952). The difference must be mainly due to our neglect of very small wave in the determination of mean wave height.

11) In Fig. 10, datum on the wave spectrum of Fig. 8-4 was not used for the reasons previously stated.

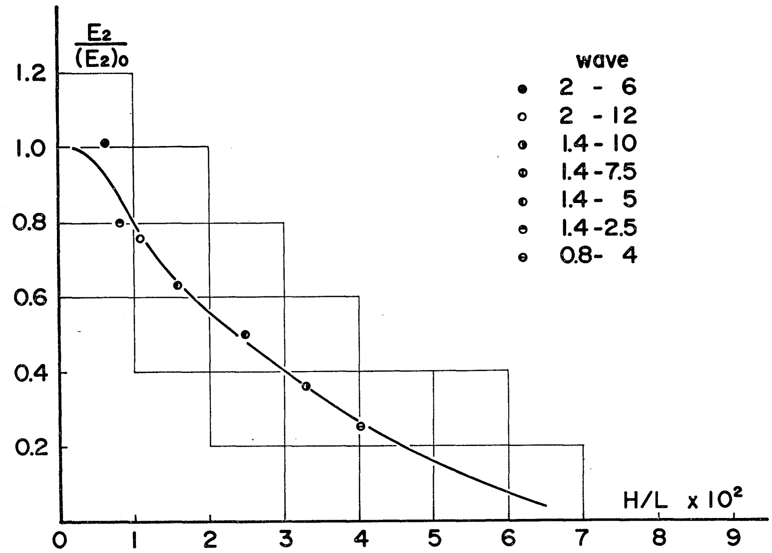


Fig 10. Relation between the wind wave energy and the steepness of regular oscillatory wave co-existing with the wind wave.
(F_1=5.2 m, U_0=20 m/s)

the measurements at the fetch F=5.2 m, such characteristics seemed to be not so altered even when the data of longer fetches (F=10 m, 15 m and 18.6 m) were included. The attenuation of the wind wave must be due to the various effects, among which the following two will be particularly effective: i) the mechanism proposed by Longuet-Higgins & Stewart (1964), i. e., the breaking of the wind wave near the crest of the long wave (passing regular wave) and the non-linear interaction between the wind wave and the long wave, ii) the change of wind field originally due to the perturbing effect of the passing regular wave. Both effects are closely related with the steepness of the passing regular wave (Longuet-Higgins & Stewart 1964, Phillips 1966). This must be the reason why the attenuation of the wind wave was closely related with the steepness of the passing regular wave.

3-5. *The change of regular oscillatory wave in the wind-generated wave field*

Another point of interest is the change of the regular oscillatory wave passing through the local wind-generated wave field. It is quite probable that the passing wave is greatly affected by the local wind-generated wave field on account of such various mechanisms as i) the interaction between the passing wave and the wind field, ii) the interaction between the passing wave and the short wind wave, and iii) the interactions between the passing wave and the various modes of motions other than wave motion, such as turbulence and drift current. As shown in Tables 1 and 2, the present results show that the energies of the regular oscillatory waves in the wind field are slightly attenuated in almost every cases as compared with the energies of the corresponding original waves which are unaffected by the wind field. However, no definite characteristics are observed as far as the present results are concerned. This is mainly due to the short propagation distance of regular wave in the wind-generated wave field. That is, owing to the short interaction time the change of the passing regular wave could not grow sufficiently. According to the further studies, in which the fetch was extended from 5.2 m to 10 m, 15 m and 18.6 m, the change of the passing regular was observed to depend distinctly on the wave speed relative to the wind speed. That is, short regular waves were amplified and the long regular waves were attenuated respectively in the wind field. The results and their dissussions will be given in the next paper of this series.

4. Discussion and further remarks

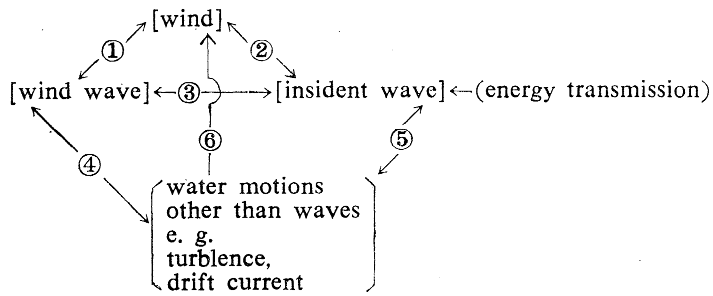
The experimental result shown in Fig. 10 is perhaps the most interesting finding of the present study, and it will reveal an essential property of the co-existent system of wind wave and the regular oscillatory wave. However, we are still not in a position to draw the definite conclusions about this problem and further studies are needed, because the phenomena seems to be extremely complicated.

In addition, it should be mentioned here that, in our present experiment, the frequecy of the passing regular wave is much lower than that of wind wave locally generated. Therefore, further studies are need for such cases that the frequency ranges of both wave systems are very close.

Before concluding, the following remarks should be made on the dynamical process of our present problem:

a) The dynamical process of the co-existent system which we have dealt here can be conjectured as follows: i) Initially, the equilibrium state has been attained in the wind-generated wave field, that is, the energy transfered from wind to wind wave is balanced by the energy dessipated from the wind wave (Phillips 1958a). ii) When the mechaniclly-generrted wave comes into that field the insident wave changes affected by the wind action and also by the interactions with the wind wave and other modes of water motions (Miles 1957, Phillips 1959, 1963, 1966,). iii) The wind field is also changed by the perturbing effect of the insident wave (Stewart 1961, Miles 1965, Phillips 1966, Shemdin 1966), and therefore, the energy transfered from wind to wave will be altered. iv) This inevitably causes the change of the wind wave field in cooperation with the non-linear interaction between the wind wave and the insident wave. v) Finally, a new equilibrium state is attained among the wind field, the wind wave, the insident wave and the water motions other than waves such as drift current and turbulence in water.

b) The dynamical model of the newly attained equilibrium state of the co-existent system will be schematically shown as



Here, ① and ② represent the typical wind-wave interations, ③ the non-linear interaction between waves, ④ and ⑤, the interactions between wave motions and the water motions other than waves. In ④, breaking of wind wave will take the important part. The interaction between the wind and the water motions other than waves will be caused partly directy (⑥, e. g., drift current due to wind shear), and partly through the medium of wave motion (①→④ e. g., the turbulence and drift current due to the breaking of wind wave). Among those various types of interations the important interactions in our present problem of interest will be ①, ② and ③, althohgh the various interactions are connected with one another.

Further work. It is evident that the present paper is, to some extent, a progress report. New data are being collected, and they are being subjected to more detailed analysis. In particular, we expect soon to be able to report the results on the properties of the regular waves passing through the wind-generated wave field and on the wind field over the water surface. Also, efforts are continuing to analyse the experimental results in the light of the recent theories on wind-wave interaction and on non-linear interactions among various modes of water motions.

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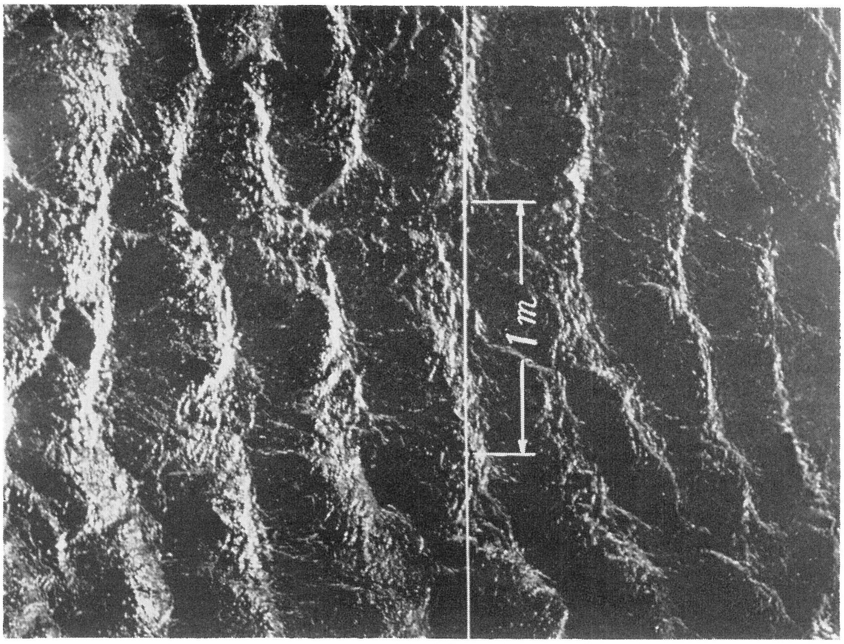


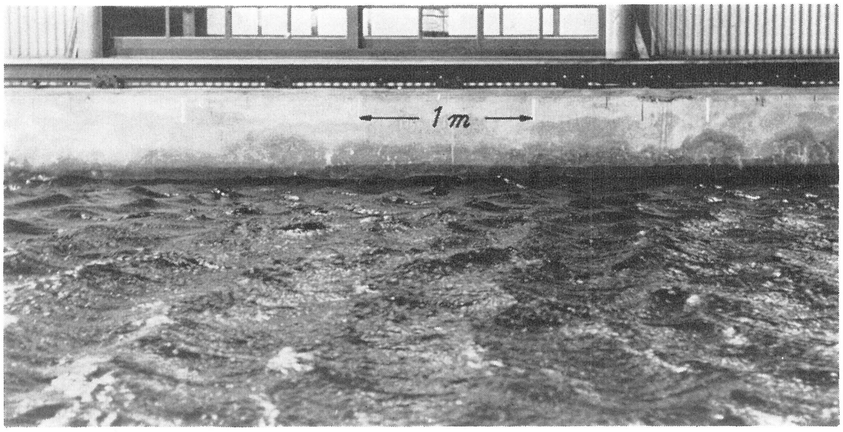


Photo 2. Wind wave.
The upper photo was taken from 4.2 m above the water surface. Wind is blowing from right to left. The lower photo shows the side view of wind wave. (U_0=20 m/s, the center of the photo is approximately 10 m from the wind blower)

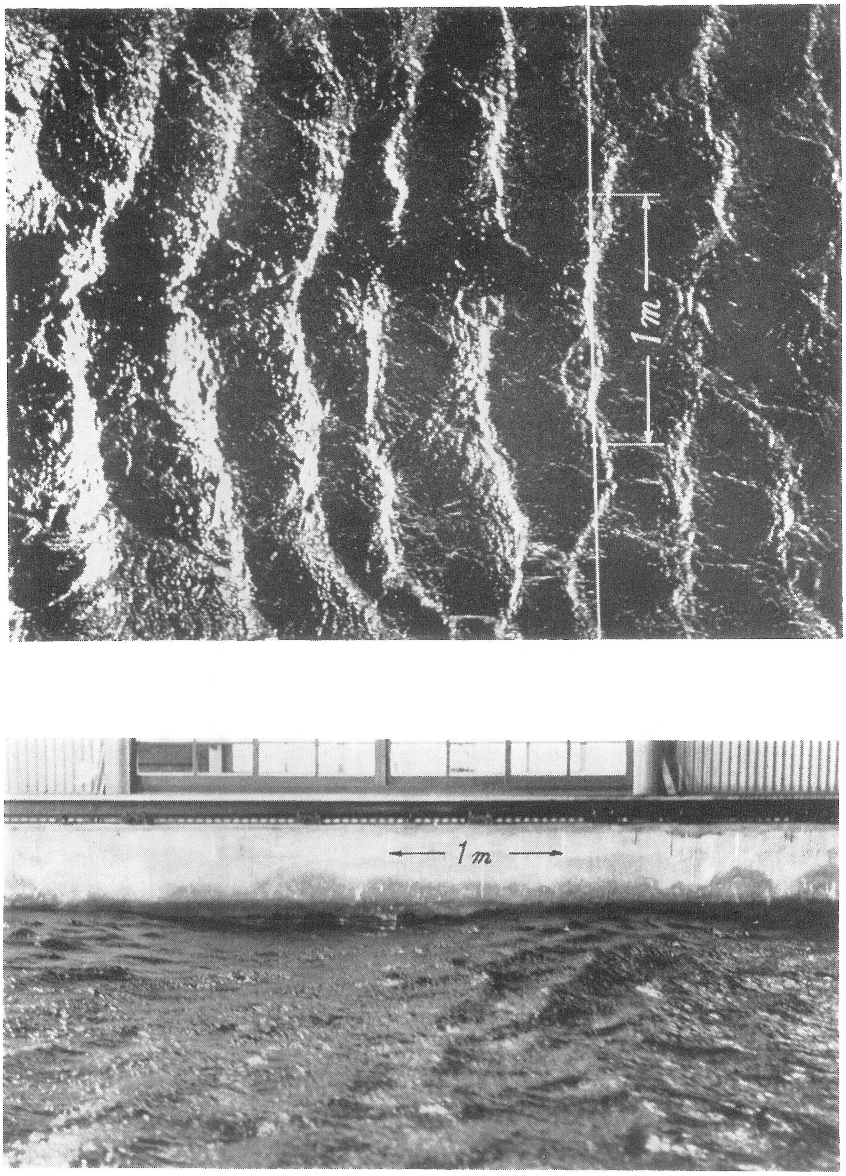
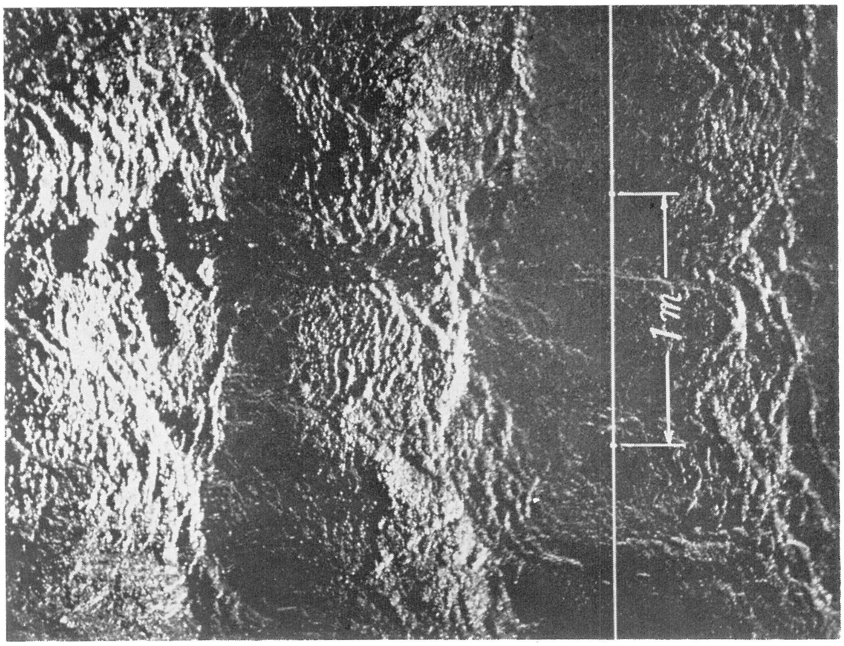


Photo 3. Co-existen system of wind ware and regular oscillatory wave of moderate steepness(wave: 1.4–10). In the upper photo, the crest lime of the regular oscillatory wave cannot be recognized, although it is in the range of this photo. The comparison of this photo with Photo-2 shows that the wave length of wind wave is not so altered by the co-existing regular oscillatory wave.



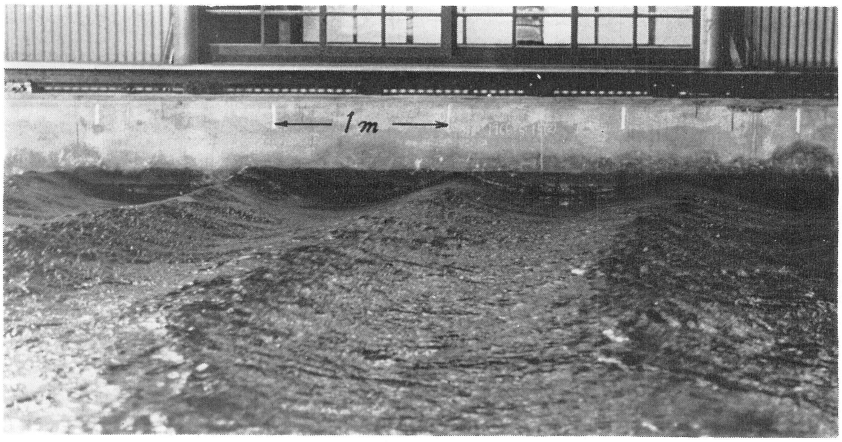


Photo 4. Co-existent system of wind wave and regular oscillatory wave of large steepness (wave: 0.8–6). The crest lines of regular oscillatary wave can be clearly shown in the upper photo. Note that wind wave is greatly attenuated in this case.