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Experimental Study on Strong Interaction between Regular Waves and Wind Waves—I*

Mitsuhiko HATORI**, Masayuki TOKUDA**† and Yoshiaki TOBA**

Abstract: The interaction between mechanically generated regular waves and wind waves is experimentally investigated in a wind-wave tunnel. It is shown that the growth process of regular waves is divided into the four distinct stages as follows: (1) almost independent coexistence of wind waves and regular waves, (2) attenuation of wind waves with simultaneous growth of regular waves, (3) rapid growth of regular waves after disappearance of wind waves, and (4) transition of regular waves to wind waves after the wave breaking. At the second stage there is an apparent relation between the attenuation of wind waves and the growth of regular waves. This fact suggests that there is some strong nonlinear interactions which transfers energy effectively from wind waves to regular waves.

1. Introduction

Experimental studies on the evolution of regular waves under the action of the wind were at first attempted mainly for the examination of Miles' linear instability theory (MILES, 1957) for wind-wave generation. For example, SHEMDIN and HSU (1967) and LAI and SHEMDIN (1971) obtained a qualitative agreement with the theory, in the observation of the air flow and the pressure distribution, but BOLE and HSU (1969) and MIZUNO (1975) reported that the Miles' theory underpredicts the real wave growth from the measurements of the spatial growth rate of regular waves. On the other hand, MITSUYASU (1966) reported a peculiar nonlinear phenomenon, i.e., wind waves riding on regular waves attenuate with increase of the steepness of regular waves, and very little is known about this interaction.

As to the wind waves, several nonlinear characteristics have been intensively studied in recent years. The first is the weakly nonlinear interaction among component waves as studied by PHILLIPS (1960), HASSELMANN (1962) and others. The second is related with the peculiar behavior of the phase speed of component waves. This problem was discussed by RAMAMONJIARISOA (1974), RIKIISHI (1978) and others; and MASUDA *et al.* (1979), MITSUYASU *et al.* (1979), and also TOKUDA and TOBA (1981), have shown that it is essentially due to the forced waves, or to the effect of the non-sinusoidal shape of dominant waves. The third is the nonlinear modulation and the low-frequency shift by an instability of the wave train, as studied by LAKE *et al.* (1977) and LAKE and YUEN (1978). The fourth is the strong nonlinearity associated with the local wind drift on individual waves or by wave breaking, as studied by BANNER and PHILLIPS (1974), TOBA *et al.* (1975), OKUDA *et al.* (1976, 1977), KAWAI (1979) and OKUDA (1981).

In view of these variety of processes occuring in the system of wind and wave, the evolution of regular waves under the action of the wind is reexamined in the present study. The experiment includes a wide range of conditions from the generation of high frequency wind waves superimposed on swell like regular waves to transform of regular waves into random waves. A new phase of interaction is pointed out to occur between the regular waves and the wind waves, when the frequency of both the components become close to each other. It is a phenomenon which may not be understood by the existing theory of weakly wave-wave interactions. This is the reason that we use

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** Geophysical Institute, Faculty of Science, Tohoku University, Sendai 980, Japan
† Present address: Institute of Coastal Oceanography, National Research Center for Disaster Prevention, Hiratsuka 256, Japan

the term of strong interaction.

The extension of these experiments must be useful not only for further elucidation of the mechanisms of wind wave generation, but also for the improvement of wave prediction models, especially when wind waves and swells are coexistent.

In the present paper, to avoid confusion, regular waves and local wind waves are termed as the regular wave components (expressed by the suffix R) and the wind wave components (by W), respectively.

2. Experiments and analyses

The experiments were performed in a wind wave tunnel of 0.6 m wide, 1.2 m high and 20 m long with a water depth of 0.6 m. A schematic picture of the air intake portion of it is shown in Fig. 1. Regular waves were generated by a flap-type wave generator located at 2.15 m upstream of the air inlet, and introduced through mesh filters located under the transition plate to obtain smooth sinusoidal water surface before being subject to the wind action. The transition plate 1.05 m long with a slope of 55/1,050 is fixed at 4.5 cm above the mean water surface at the air inlet to allow the passage of the regular waves under it. The fetch was measured from the end of the transition plate. Two permeable wave absorbers were installed at the upstream of the wave generator and the downstream end of the tank.

Measurements of the surface displacement were made with capacitance type wave gauges. The experimental conditions are summarized in Table 1. Seven types of regular waves and two kinds of wind speeds were used, where the reference wind speeds $U_r=7.5$ and $10\ \mathrm{ms}^{-1}$ were measured at the center of the entrance of the tunnel. The wave height H_0 in the table represents values at Stn. 0. Experiments of pure wind waves were also carried out for the two wind conditions in order to clarify the effects of regular waves. Waves were measured at seven stations listed in Table 1(a) for all combination of regular wave and wind conditions. Wave records at the Stns. 1 to 6 were successively taken with a single wave gauge. In order to check the stability of regular waves, the surface elevation at Stn. 0 was measured by another wave gauge during the whole period of the measurements at the six stations. The range of variation of the regular wave height H_0 during the experiments is shown in the right end column of Table 1(b). The ranges of variation were smaller than 0.2 cm for all cases or smaller than 10 % of the mean values except for the case T1H1.

For each wave data, a record with 40.96 s length was digitized at every 0.02 s, and power spectra were calculated by the fast Fourier transform (FFT) method. The raw spectra were smoothed by a triangular filter function.

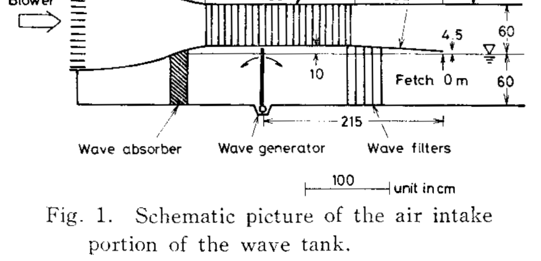

Fig. 1. Schematic picture of the air intake portion of the wave tank.

Table 1. Experimental conditions. (a) Seven stations at which wave records are taken. (b) Characteristics of regular wave: period T, wave height H_0 at Stn. 0, steepness H_0/L_R and the deviation range of H_0 during the experiment. (c) Wind conditions. The U_r represents the reference wind speed near the entrance of the tunnel.

(a)

Stn. No.	0	1	2	3	4	5	6
Fetch (m)	0.05	1.80	3.80	5.80	7.80	10.80	13.80

(b)

Regular wave symbol	Period T (s)	Wave height H_0 (cm)	Steepness	Wave height range (cm)
T1H1	0.55	0.55	0.012	0.44～0.59
2		1.29	25	1.26～1.33
3		2.20	43	2.15～2.30
T2H1	0.70	1.30	0.017	1.21～1.33
2		2.20	29	2.15～2.31
3		3.50	45	3.43～3.65
T3H1	0.45	1.45	0.046	1.36～1.51

(c)

U_r(m s^{-1})	7.5	10.0
u_*(m s^{-1})	0.39	0.55

The smoothed spectra used hereafter have a resolution band of width of 25/128 Hz. Since the filter leaks the energy of regular wave component, which have a discrete line spectrum, into four points near the frequency of regular wave component f_R, the energy of regular wave component E_R is defined as the sum of spectral densities at these four points. Other errors of regular wave energy may be mainly due to the exclusion of the regular wave harmonics. For the case of no wind, the error was about 2%. The reference wave heights of the regular wave component H_R were calculated from the relation $H_R=\sqrt{8E_R}$ where a sinusoidal form was assumed for the real wave train. The steepness of regular wave component δ_R is defined as H_R/L_R, where the wave length L_R is estimated from the frequency of regular wave component f_R following the linear theory.

The mean wind profiles were taken with a pitot-static tube at Stns. 1, 4 and 6 for the conditions of no regular waves and of the regular wave T1H2. The friction velocities u_* were estimated from these velocity profiles by assuming the logarithmic velocity profiles. The results indicate that the regular waves tend to reduce u_* slightly, say, 5%. On the contrary, MIZUNO (1975) reported an increase of u_* in the case associated with the breaking of regular waves. Though a detailed investigation of the wind field will further be necessary, an average value of u_* at three stations for the case of pure wind waves is used as a reference friction velocity for simplicity in the present paper. The reference friction velocity are listed in Table 1(c).

3. Results

3.1. Description of four stages in the growth process

We start with a description of the growth process for two typical examples. Fig. 2 shows (a) wave records and (b) power spectra at several fetches for the regular wave T1H1 ($T=0.55$ s and $H_0=0.55$ cm), and $U_r=10$ m s^{-1}. The wave records indicate that the regular waves are unaffected by the wind at Stn. 0, but the wind waves become conspicuous at Stns. 1 and 2. At Stn. 3, however, the regular waves dominate again over the wind waves. At Stns. 5 and 6, the wind wave component disappears and a

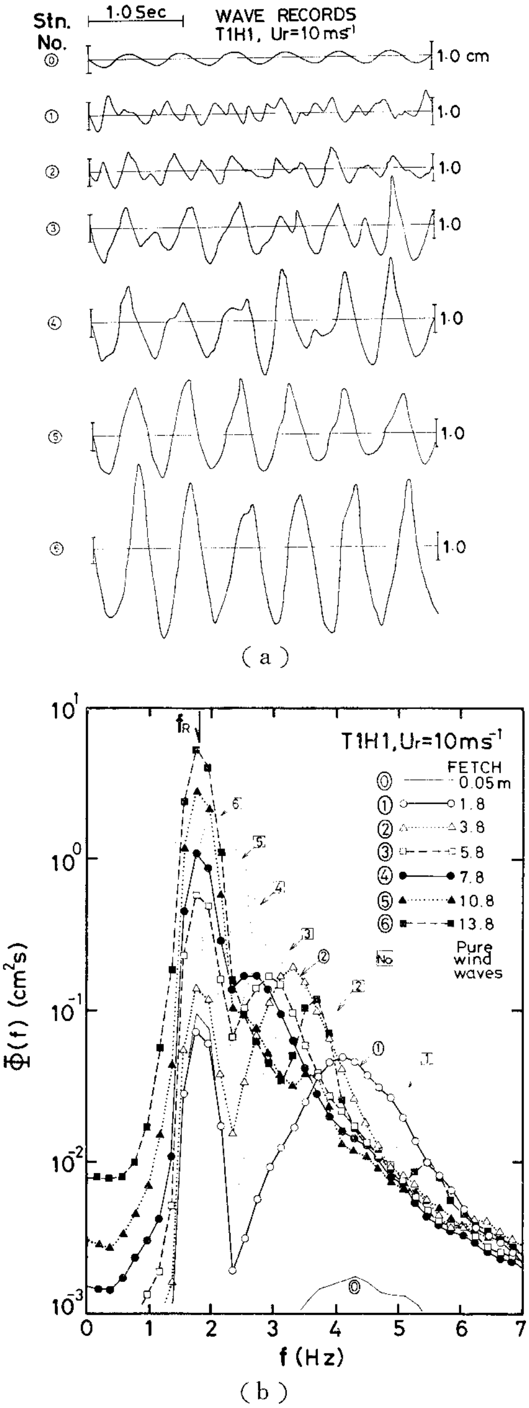

Fig. 2. An evolution of wave records (a) and power spectra (b) with the fetch for the case T1H1 ($T=0.55$ s, $H_0=0.55$ cm) for $U_r=10$ m s^{-1}. Thin dotted lines in (b) show the growth of power spectra with fetch for pure wind waves for the same wind condition.

considerable increase is observed in the height of the regular wave component.

These evolutions are more clearly seen in the power spectra in Fig. 2(b). The power spectra of pure wind waves are shown by thin dotted lines for comparison. The development of wind wave component from Stn. 1 to 2 is similar to that of the pure wind wave, although the spectral peak frequency is slightly lower than that of the pure wind waves for the same fetch and wind. The energy of the regular wave component does not change significantly at these two stations. From Stn. 3 onwards the energy of wind wave component decreases compared with that of pure wind waves for the same fetch and wind, although the spectral peak frequency shifts to lower ones in the same way as in the pure wind waves. At the same time the energy of regular wave component seems to increase rapidly from Stn. 2. At Stns. 5 and 6 the wind wave component is not distinguishable from the spectral peak of the regular wave component. In the above state, we consider the wind wave component to be none.

In order to investigate the evolution that will succeed the last state of the previous example, another case T3H1 ($T=0.45$ s, $H_0=1.45$ cm) is shown in Fig. 3. The regular wave is shorter than that of Fig. 2, and the wind conditions are the same. The last state of Fig. 2 is found at Stn. 2 or 3 in this case. Then, the energy of the regular wave component once decreases slightly, and the component evolves into random waves with a spectral peak frequency lower than that of the original regular waves f_R. The power spectrum at Stn. 6 has a structure similar to and a magnitude smaller than that of pure wind waves having the same spectral peak frequency under the same wind condition. From visual observations, it seems that the under-shooting of the energy level of wind waves from Stn. 4 onwards is associated with the wave breaking. Though the wave data at the stage next to Stn. 6 was not obtained because of the experimental limits, it can be expected that the random waves may evolve to have a spectral structure similar to pure wind waves. The transition from regular waves to lower frequency random waves after breaking has already been reported by MIZUNO (1975).

The above two typical examples indicate that there are four distinct stages in the development of the regular wave under the influence of the wind. Fig. 4 shows schematically the four growth stages of the power spectrum.

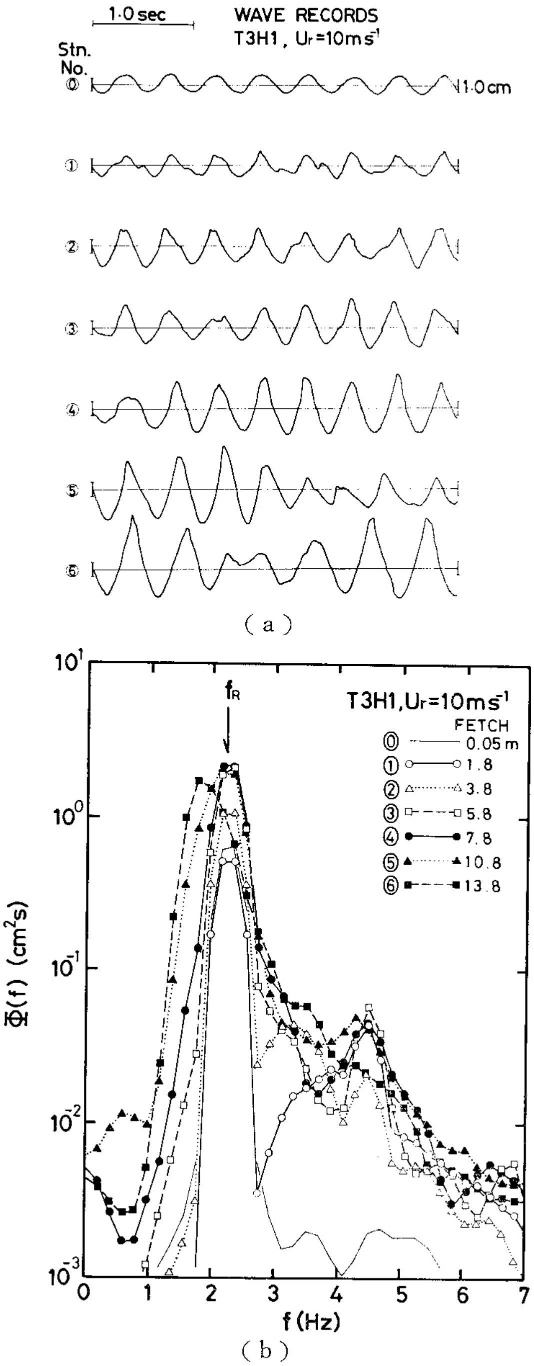

Fig. 3. Same as in Fig. 2 for the case T3H1 ($T=0.45$ s, $H_0=1.45$ cm) for $U_r=10$ m s^{-1}.

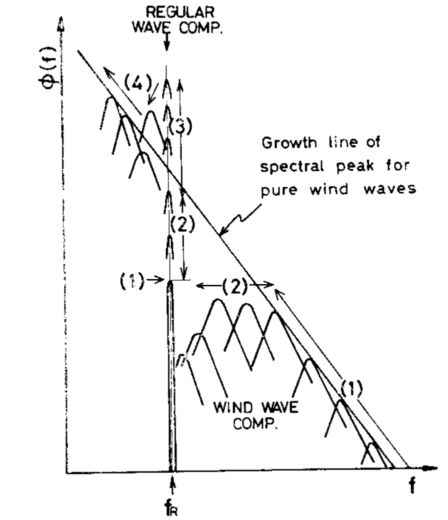

Fig. 4. Schematic representation of the evolution of power spectra with the fetch. Number in parentheses and lines with an arrow head indicate four stages of the evolution and their regions, respectively.

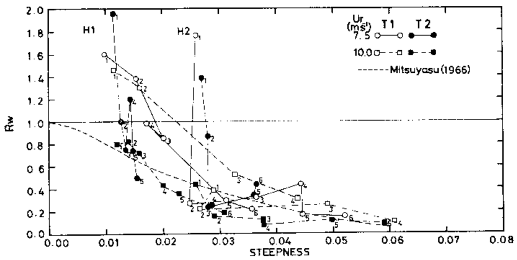

Fig. 5. The relative attenuation rate R_W as a function of the steepness of regular wave component δ_R. The suffixes represent the station numbers.

Stage (1): The way of growth of the wind wave component is almost the same as that of pure wind waves, and the variation in the regular wave component is substantially negligible.

Stage (2): The energy of the wind wave component decreases in comparison with the case of pure wind waves and simultaneously the regular wave component grows rapidly.

Stage (3): The regular wave component develops fast after the wind wave component becomes indistinguishably small.

Stage (4): After the occurrence of wave breakings, the regular wave component evolves into low frequency random waves which have a spectral structure similar to the pure wind waves. Associated with this transition, the spectral peak decreases once, and then the wave field will develop as that of the pure wind waves.

The growth process shows that the coexisting system of the regular wave component and the wind wave component is far from a linear superposition. Some nonlinear interaction between the wind wave component and the regular wave component must play an important role at stage (2), where regular wave component seems to develop at the expense of the wind wave component.

In the fourth stage, it seems that the transition of the regular wave component to the low frequency random waves in this experiment is associated with the wave breaking. However, the fourth stage is not discussed hereafter, since the main purpose of the present study is to point out the strong nonlinear interaction between the regular wave component and the wind wave component.

3.2. *Interaction between wind wave and regular wave components*

To investigate the interaction further, we introduce two quantities. The first is the ratio of wind wave components to pure wind waves, which is defined by

$$R_W \equiv \Phi(f_W)/\Phi(f_{WO}) \qquad (1)$$

where $\Phi(f_W)$ is the spectral density at the peak frequency of the wind wave component f_W, and $\Phi(f_{WO})$ that of pure wind waves for the same fetch and wind velocity. As a representative value of the wave energy, the spectral peak density is adopted instead of the total energy of the wind wave component, since the latter defined by the summation of spectral densities for frequencies higher than f_R includes the energy of the regular wave harmonics. The spectral peak frequency of the wind wave component shifts in a similar way as that of the pure wind waves. The ratio R_W is regarded as an index of the integrated strength of the interaction and takes values $R_W \sim 1$ in stage (1), $R_W < 1$ in (2) and $R_W \sim 0$ in (3) and (4).

It has been reported by MITSUYASU (1966) that the energy of the wind wave component in the presence of regular waves is less than that of pure wind waves, and that a ratio similar to R_W decreases with increase of the steepness of regular waves. Fig. 5 shows R_W as a function of the regular wave steepness δ_R. The dashed line represents the results by MITSUYASU (1966). Although the data are rather scattered, there is a general trend that, following the line of each regular wave case in Fig. 5, R_W decreases with the fetch, keeping steepness δ_R more or less constant, and after it reaches the Mitsuyasu's line, it moves along the Mitsuyasu's line. This result and the existence of the already mentioned four stages in the growth process, suggest that R_W depends not only on the steepness δ_R but also on the scale ratio of the wind wave component and regular wave component, that is, the ratio of frequency of the regular wave component f_R to that of the wind wave component f_W. Here, however, f_R/f_{WO} is used instead of f_R/f_W, and we use this parameter also when the wind wave component is absent, for example in the third stage. The scale parameter f_R/f_{WO} increases with the fetch, since f_{WO} decreases with the fetch and f_R is constant.

Fig. 6 shows the distribution of R_W as a function of δ_R and f_R/f_{WO}. The value of R_W is represented by the size of circles. The solid line in the figure indicates the contour of $R_W=0.5$, whose neighborhood corresponds to the second stage. The figure shows that R_W decreases with increase of δ_R and f_R/f_{WO}. In other words,the attenuation of the wind-wave component relative to the pure wind wave becomes larger as the regular wave component steepens and the peak frequency of the wind wave component approaches to that of the regular wave component. The border value of f_R/f_{WO} which discriminates stage (1) and (2) is approximately 0.5 for the case of δ_R of about 0.02, and it decreases with the increasing δ_R. After this transition, the wind wave component attenuates rapidly by some stronger interaction in the region near the contour of $R_W=0.5$. For the region of the steepness δ_R above 0.05, the values of R_W are lesser than 0.2 and become almost independent of the parameter f_R/f_{WO}.

The second quantity we examine is the momentum retention rate G_R, or the part of momentum which is retained as the momentum of the regular wave component M_R to the total momentum transferred from the wind to the water, defined, in a similar manner as in TOBA (1978), by:

$$G_R \equiv \frac{1}{\tau}\frac{\partial M_R}{\partial t}, \quad \tau=\rho_a u_*^2$$

where τ is the wind stress, ρ_a is the density of the air and t is the time. Since we are

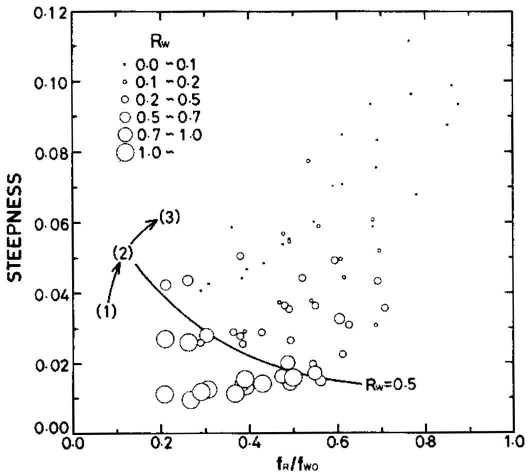

Fig. 6. Distribution of the relative attenuation rate R_W as a function of the steepness of regular wave component δ_R and the scale parameter f_R/f_{WO}. The value of R_W is represented by the size of circles. The solid line represents the contour of $R_W=0.5$ and inserted numbers represent the stage of development.

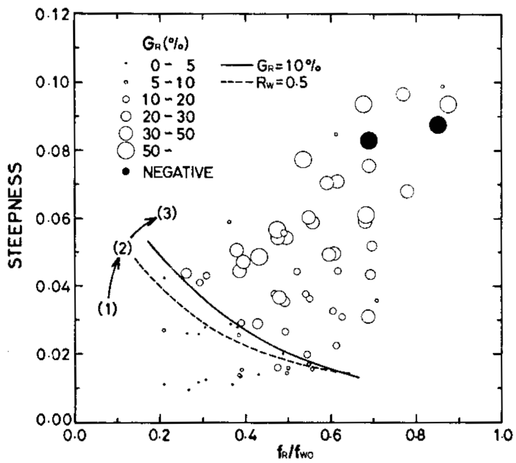

Fig. 7. Distribution of G_R as a function of δ_R and f_R/f_{WO}. The thin dotted line is the contour of $R_W=0.5$ and the solid line that of $G_R=10\,\%$.

investigating the change of the energy E_R with the fetch F, the time t is approximately converted to the fetch F, and the momentum M_R to the energy E_R by the relations of the linear theory, $F=\frac{1}{2}Ct$ and $M_R=E_R/C$, where C is the phase speed of the regular wave component. The derivative of E_R with respect to F is approximated by the central difference scheme.

Fig. 7 shows G_R as a function of δ_R and f_R/f_{WO}. To make a comparison with R_W, G_R is plotted against the same abscissa and ordinate as in Fig. 6. The solid line represents the contour of $G_R=10\%$ and the broken line that of $R_W=0.5$; the two lines approximately coincide with each other. The value of G_R increases with increasing δ_R and f_R/f_{WO}. The tendency is the reverse of the case of R_W in Fig. 6. This indicates that there is an apparent relation between R_W and G_R. At stage (1), where $R_W\sim 1$ and $G_R\sim 0$, the regular wave and wind wave components do not interact appreciably and only the wind wave component mainly gains the wave momentum from the wind. At stage (2), where $R_W<1$ and $G_R>0$, the regular wave component gains the energy while the energy of wind wave component decreases gradually, At stage (3), especially for the steepness above 0.05, the wind wave component disappears ($R_W \sim 0$) and a fair amount of the total momentum transferred from the wind (about 50 %) is absorbed by the regular waves. A few negative values of G_R at this stage can be attributed to the wave breaking, as suggested by the visual observation.

Finally, we refer briefly to the exponential growth rate of the regular wave component which has been a main subject of the previous similar works. The exponential growth rate in this experiment depends on the stage. The rate is small at stage (1), increases at stage (2), and then decreases with further increase of wave height in stage (3). The mean rate from Stns. 0 to 6 is two times greater than that of the Miles' linear instability theory. Further, the maximum value of G_R in excess of 50 %, which occurs at stage (3), is far larger than that expected from the linear theory.

4. Discussion

The results in the last section are summarized as follows. Both the values of the attenuation of wind wave component R_W and the growth of regular wave component G_R are related to the two parameters, δ_R and f_R/f_{WO}, and further R_W and G_R are apparently connected with each other at stage (2). These results suggest the existence of some stronger nonlinear process which transfer energy from the wind wave component to the regular wave component in that stage. The value of G_R is much larger than that expected from the linear theory especially at Stage (3). This suggests also the existence of an effective mechanism of momentum transfer from the wind to the regular wave, the values being much larger than the maximum value of momentum retention rate (G_0) of 6 % which was estimated by TOBA (1978) for the case of pure wind waves.

HASSELMANN (1963) calculated the nonlinear energy transfer in a spectrum of the coexisting system of wind waves and swell. His results showed that the energy of swell decreases by the weak interaction among wind waves and swell, and that the interaction becomes weaker as the frequency of wind waves approaches that of the swell. These tendencies are opposite to the above described experimental results. PHILIPS and BANNER (1974) proposed a breaking mechanism of wind waves superposed on longer waves, which is closely related to the decrease of the wind-wave energy. However, their theory cannot be applied directly to the present situation, since the theory assumes the condition of $f_R/f_W \ll 1$ and the presence of wave breakings, while in the present experiment the above assumptions are not always satisfied.

As to Stages (2) and (3), it is expected that studies from the view point of individual waves initiated by TOKUDA and TOBA (1981) is useful, and vorticity concentrated region near the crest studied by OKUDA (1981) or such a kind of processes may be related to the phenomenon. Here there should be some strong nonlinear interaction where the elements other than the irrotational waves may be of crucial importance. Also, there might be an interaction of the wind wave component and the regular wave component through the harmonics or forced waves of the regular waves. As to Stage (4), there is a possibility that the strongly nonlinear effect studied by LAKE *et al.* (1977) and LAKE and YUEN (1978) is partially relevant. A study using the individual wave analysis technique will be reported by IMAI *et al.* (1981).

In any case, the phenomena observed in this experiment are not fully investigated yet. Further studies will be required to understand the generation mechanisms of wind waves, and also to develop wave prediction models applicable to the coexisting field of wind waves and swell.

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規則波と風波との強い相互作用に関する実験的研究—I

羽 鳥 光 彦*, 徳 田 正 幸*†, 鳥 羽 良 明*

要旨: 風洞水槽において，機械的におこした規則波と風波との相互作用を調べた．その結果，規則波の発達過程は，次の4つの明瞭な段階にわけられることがわかった．(1)風波と規則波の殆ど独立な共存，(2)風波の減衰並びに規則波の発達，(3)風波消失後の規則波の急激な発達，(4)砕波後の規則波の風波への遷移．(2)の段階で風波の減衰と規則波の発達との間には明瞭な関係があり，風波から規則波へ効率良くエネルギーを輸送する強い非線形相互作用が存在すると推察される．

* 東北大学理学部地球物理学教室
〒980 仙台市荒巻字青葉
† 現住所: 国立防災科学技術センター平塚支所
〒254 神奈川県平塚市虹ケ浜 9-2