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On the Contribution of Swell to Sea Surface Phenomena (2)

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ABSTRACT On the basis of recent studies, contributions of swell to sea surface phenomena are discussed. It is shown that the attenuation of wind waves by swell depends not only on swell steepness but also on the ratio of the frequency of the swell to the spectral peak frequency of wind waves. It is also shown that the measured growth rate of swell in a wind area agrees well with the empirical formula of Hsiao and Shemdin (1983) in a region of small inverse wave age, while it approaches to the empirical formula of Mitsuyasu and Honda (1982) in a region of large inverse wave age. Finally, short discussion is given on the increase of surface drift current by opposing swell by using the result of recent study on Langmuir circulation (Mizuno, 2002).

KEY WORDS: ocean waves; wind waves; swell; growth of swell; interactions between swell and wind waves; interaction between swell and surface drift current.

INTRODUCTION

Recently the effect of swell on air-sea interaction phenomena is controversial; there are many discussions which are concerned with the attenuation of wind waves by swell, the growth or decay of swell by wind, and the effect of swell on sea surface roughness (Donelan, 1987; Mitsuyasu and Yoshida, 1991; Mason, 1993; Donelan, 1999; Drennan et al., 1999; Donelan and Dobson, 2001). The problem is important not only as dynamical processes at air-sea boundary but also for practical application such as wave forecasting. On the attenuation of wind waves by swell, the phenomenon itself was found many years ago (Mitsuyasu, 1966) and the famous theory to explain the phenomenon was presented by Phillips and Banner (1974). However, several studies done later (e.g., Wright, 1976; Hatori et al., 1981; Sakai et al., 1994) presented the results that did not support the theory of Phillips and Banner (1974). Recently we also found a curious phenomenon where the wind waves were not attenuated by opposing swell (Mitsuyasu and Yoshida, 1991), while the theory of Phillips and Banner (1974) predict the attenuation of wind waves. On the other hand, Masson (1993) made numerical computation of nonlinear coupling between swell and wind waves and showed that the coupling is negligible unless the frequencies of swell and wind waves are very close. In order to make clear the controversial problem, in the present study, we firstly test the Phillips and Banner's theory by using reliable laboratory data of Maeda (1990) for the case of following wind.

Secondly we study the growth of swell by following wind. In a sense this problem is nothing but the problem of wind-induced growth of water waves, for example, which has been studied by Mitsuyasu and Honda (1982) and recently by Kato et al. (2000). In these studies, however, the measurements were limited to the growth of relatively short waves (waves of large inverse wave-ages) due to the small wind-wave tanks. On the other hand, Maeda (1990) measured the growth rate of longer waves by using a much larger wave tank, and his data contains the growth rate of waves in relatively small inverse wave ages. Therefore, in the present study an attention is paid on the growth rate of water waves for relatively small or moderate inverse wave age as well as that for large inverse wave age.

Finally we will make a short discussion on the increase of surface drift current by opposing swell. In a laboratory experiment, Cheng and Mitsuyasu (1992) found a very interesting phenomenon that the surface drift current was strongly intensified by steep opposing swell, while the surface drift current was not much affected by the following swell. Quite recently Mizuno (2002) made a series of laboratory experiments on the Langmuir circulation in a wind-wave tank. He found that the Langmuir circulation, a kind of secondary flow is generated by wind in a wind-wave tank and it suppresses the surface drift current in ordinary conditions, but opposing swell suppresses the Langmuir circulation considerably and this process is the cause of the increase of the surface drift.

WIND AND WAVE DATA

In the present study, we mainly use the wind and wave data presented by Maeda (1990). This paper is the author's master's thesis of Kyushu University, which concerns dynamical process in the water surface where wind waves co-exist with swell propagating in the direction of the wind. Since the paper is not commonly available, some detailed descriptions of the experimental conditions are given below.

The experiment was carried out in a large wind-wave flume 2m high (water depth; 1.2m), 1.5m wide and 54m long. Detailed description of the flume is given by Kusaba and Masuda (1988). Waves were measured at fetches 1m, 5m, 10m, 20m, 25m, 30m, 35m by using capacitance wave gages. Vertical wind profiles over the water surface U(z) were measured at fetches 10m, 20m, 30m. The measurements of waves were conducted under the following three different conditions;

pure wind waves without swell, swell without wind, and swell under the action of the wind, where the swell co-exists with wind waves. Various fundamental parameters in the experiment are as follows; reference wind speed Ur (m/s): 2.0, 5.0, 7.5, 10.0; swell period T(sec): 0.8, 1.1, 1.4; initial steepness of each swell H_0/L_0: 0.1, 0.2, 0.4.

Friction velocity of the wind was determined by applying the logarithmic distribution to the wind profile near the water surface. Through the computation of power spectrum of the co-existent system of wind waves and swell, swell energy and wind wave energy were separated as were done by Mitsuyasu and Yoshida (1991). Parameters in the spectral analysis are as follows; sampling frequency of the wave data: 200Hz, data length for one sample: 40.96sec, number of samples: 58. By using the swell energy and period, the swell steepness H/L under the action of the wind was determined. The growth rate of the swell by wind was determined by using data of the fundamental frequency component of the swell under the action of wind, which showed the exponential growth with fetches. The spatial growth rate was converted into temporal growth rate by using each group velocity of the swell.

THE SUPPRESSION OF WIND WAVES BY SWELL

Fig.1 shows typical examples of wave spectra obtained by Maeda (1990) for the case of the wind speed Ur=10m/s. From the left to the right the figure shows pure wind wave spectra and spectra of co-existent system of wind waves and swell with the same period of T=1.1sec but different steepness (H/L: 0.01, 0.02, 0.04). In the latter spectra corresponding spectrum of pure wind waves shown in the leftmost side is superimposed for comparison.

From the top to the bottom the spectra measured in different fetches (X: 10m, 20m, 30m) are shown. In the spectra of the co-existent system, higher harmonics eliminated, following Sakai et al. (1994).

From Fig.1 we can see general features of the phenomenon that the attenuation of wind waves increases with the increase of swell steepness, high frequency region of the wind wave spectrum is not much affected by swell and the effect of fetch on the phenomena is weak.

In order to make more quantitative discussion, the ratio of the energy of wind waves co-existing with swell E_w to the energy of wind waves in the absence of swell $(E_w)_0$ was obtained from the measured spectra and plotted against the steepness of the swell under the action of wind. The result is shown in Fig. 2, which shows a quite similar property to the results of Mitsuyasu (1966) and Kato et al. (2000).

According to Phillips and Banner (1974), the suppression rate of wind wave energy, the ratio of the maximum wind wave energy co-existing with swell to the energy of wind waves in the absence of swell is given by

$$r^2 = E_w/(E_w)_0 = \left[\frac{g}{g'}\right]^2 \left[\frac{c_c - q_{max}}{c_0 - q_0}\right]^4, \tag{1}$$

where g is gravitational acceleration, g' apparent gravitational acceleration at the crest of swell, c_c the phase speed of wind waves at the crest of swell, c_0 the phase speed of wind waves at still water level, q_{max} the drift current at the crest of swell, and q_0 the drift current at still water level. The drift current at the crest of swell q_{max} which is augmented by the swell is given by Phillips and Banner (1974) as,

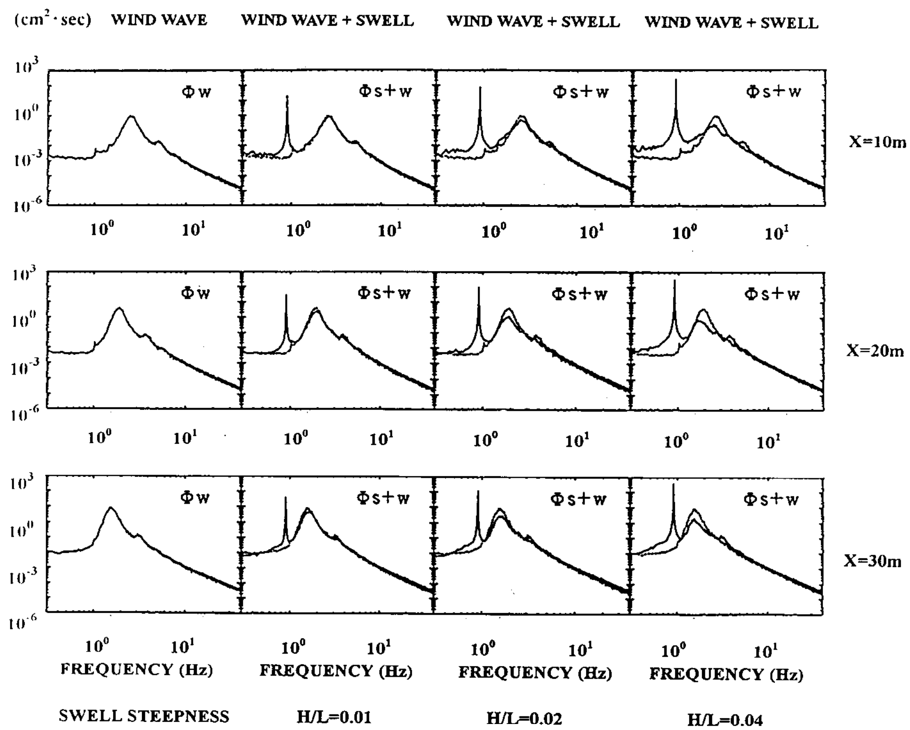

Fig.1 Spectra of wind waves and co-existent system of swell and wind waves. Wind speed Ur=10m/s. Swell period T=1.1sec. From the left to the right the figure shows pure wind wave spectra and spectra of co-existent system of wind waves and swell of different steepness (H/L: 0.01, 0.02, 0.04). From the top to the bottom the figure shows the spectra at different fetches (X: 10m, 20m, 30m).

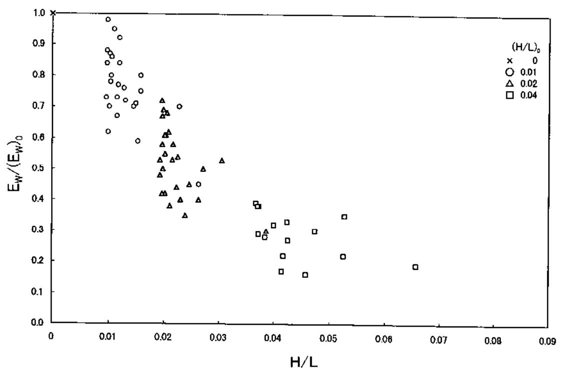

Fig.2 Measured energy ratio $E_w/(E_w)_0$ versus swell steepness H/L

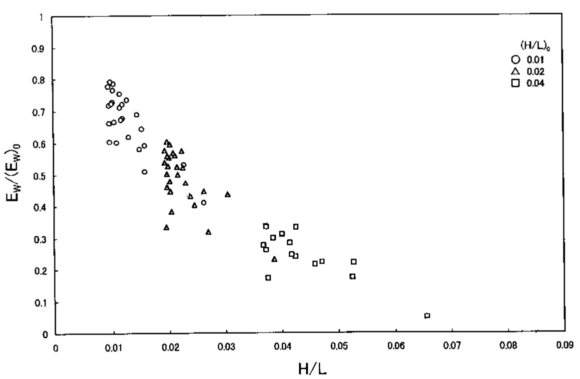

Fig.3 Calculated energy ratio $E_w/(E_w)_0$ versus swell steepness H/L

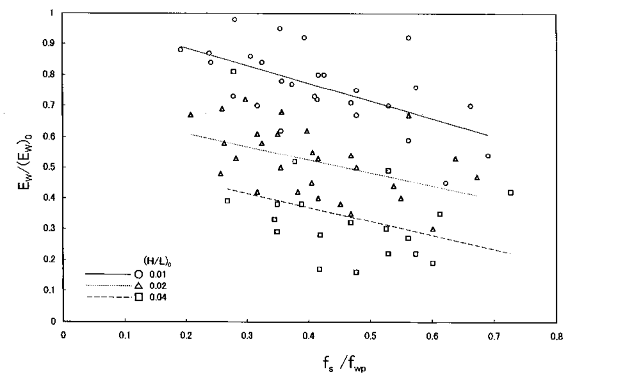

Fig.4 Measured energy ratio $E_w/(E_w)_0$ versus the frequency ratio f_s/f_{wp}

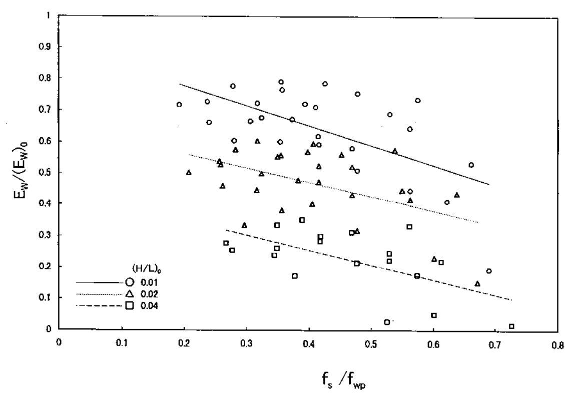

Fig.5 Calculated energy ratio $E_w/(E_w)_0$ versus the frequency ratio f_s/f_{wp}.

$$q_{\max} = (C - u_0) + \left\{(C - u_0)^2 - q_0(2C - q_0)\right\}^{1/2}, \qquad (2)$$

where C is the phase speed of the swell and u_0 is the orbital velocity of the swell at the crest of the swell.

Following the formulation of Phillips and Banner (1974) and using the relation $q_0=0.52u_*$ obtained by Cheng and Mitsuyasu (1992), we can transform Eq.1 to the following form,

$$r^2 = E_w/(E_w)_0$$

$$= [1 - \pi H/L]^2 \left[\frac{(f_s/f_{wp})(1 - \pi H/L) - q_{\max}/C}{f_s/f_{wp} - 0.52u_*/C} \right]^4, \qquad (3)$$

where u_* is the friction velocity of the wind, H/L the swell steepness, f_s the frequency of swell and f_{wp} spectral peak frequency of wind waves.

In order to compare the measured result with the theoretical prediction of Phillips and Banner (1974), we computed the suppression rate of wind wave energy $E_w/(E_w)_0$ by putting the measured values into the variables in the right side of Eq.3, and plotted it against the swell steepness H/L in Fig.3. From the comparison of Fig.2 and Fig.3 we can see that the theory predict fairly well the measured trend, though the theory gives a little underestimation. If we use the other formulas for the surface drift current, e.g., $q_0=0.55u_*$ obtained by Wu (1973), the value of r^2 increases by up to 30% for special but possible combinations of the parameters in Eq.3. Certainly scatters of the data are large in the both figures. These are due to the fact that the swell steepness is not the only variable controlling the energy ratio as can be seen in Eq.3.

According to Masson (1993), nonlinear energy transfer between swell and wind waves is strongly affected by the ratio of frequencies of swell and wind waves and it is negligible unless the both frequencies are very close. However the mechanism proposed by Phillips and Banner (1974) also include the frequency ratio as a controlling parameter. As shown in Eq.3, the suppression rate of wind wave energy $E_w/(E_w)_0$ depends not only on swell steepness H/L but also on the ratio of frequencies of swell and wind waves f_s/f_{wp}.

The relation between the suppression rate of wind wave energy $E_w/(E_w)_0$ and the frequency ratio f_s/f_{wp} was determined from the measured data of Maeda (1990) and shown in Fig.4, where an initial wave steepness $(H/L)_0$ is taken as a parameter. As shown in Fig.4, the suppression rate $E_w/(E_w)_0$ decreases with increasing the frequency ratio f_s/f_{wp}, though the scatter of the data is again considerable. The scatter of the data is mainly due to the effect of the swell steepness, because the data are classified by the initial wave steepness, while the wave steepness changes with wind speeds and fetches even if the initial wave steepness is the same. Fig.5 shows the same relation derived from Eq.3 corresponding to the measured data. As can be seen from the comparison of Fig.4 and Fig.5 the theoretical prediction gives a similar trend to the measured relation, though the computed values are slightly smaller than the measured one. That is, Eq.3 obtained by Phillips and Banner (1974) predicts fairly well the effect of the frequency ratio of swell and wind waves for the attenuation of wind waves by swell.

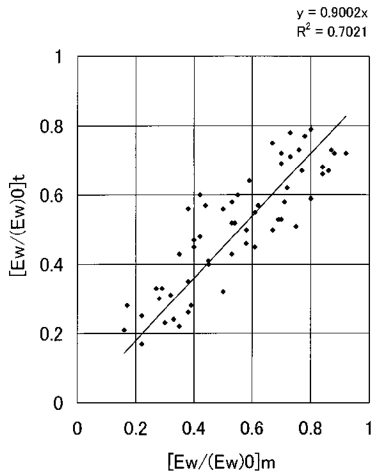

Fig.6 The theoretical energy ratio $[E_w/(E_w)_0]_t$ versus the measured energy ratio $[E_w/(E_w)_0]_m$

In the above discussions, we concerned with the effects of swell steepness and the frequency ratio of swell and wind waves separately. Here more direct comparison is made in Fig.6 by taking the measured suppression rate $[E_w/(E_w)_0]_m$ in the abscissa and the theoretical one $[E_w/(E_w)_0]_t$ in the ordinate. The theoretical values are calculated from Eq.3 by using the values of f_s/f_{wp}, H/L and u_*/C corresponding to each datum. The agreement is good, which is better than expectation, though the theory gives the values slightly smaller than the measured values. If we consider the scatter of the data in Fig.6 and the results of similar experiment done by Kato et al. (2000) which show an opposite trend that measured values are slightly smaller than the theoretical predictions, we can say that Eq.3 presented by Phillips and Banner (1974) predict fairly well the attenuation of wind waves by the following swell. However a fundamental question still remains; why the theory cannot predict the phenomena that happen when the swell is propagating against wind waves (Mitsuyasu and Yoshida, 1991)? Therefore, at present stage, we can say that the Eq.1 or Eq.3 derived by Phillips and Banner (1974) predicts fairly well the attenuation of wind waves by following swell formally, while fundamental problems still remain on the underlining mechanism of the attenuation. This is a difficult but interesting problem in the future. New approaches to the problem will be needed.

THE GROWTH OF SWELL BY FOLLOWING WIND

When swell comes into an area of following wind the swell develops by momentum input from the wind depending on its wave age. This problem is nothing but a wind-induced growth of water waves by wind, which has been studied many years ago by Mitsuyasu and Honda (1982) and recently by Kato et al. (2000). However, they used relatively short waves (waves of large inverse wave-age) due to their small wind-wave tanks. On the other hand, Maeda (1989) measured the growth rate of waves by using a much larger wave tank. Therefore, his data include the data of the growth rate for relatively small inverse wave age as well as those for the large inverse wave age.

The dimensionless growth rates of water waves β/f measured by Maeda (1990) are shown in Fig.7 as a function of the inverse wave age u_*/C, where β is an exponential growth rate of swell by wind and f is the frequency of the swell. The curves in the figure show the following typical empirical formulas for the growth rate of water waves by wind:

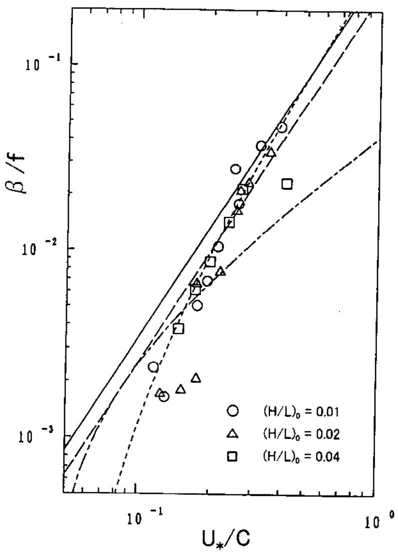

Fig.7 The dimensionless growth rate β/f versus the inverse wave age u_*/C. Curves in the figure show the various empirical formulas; dot-dash line: Eq.4, dash line: Eq.5, solid line: Eq.6, dot line: Eq.7.

$\beta/f = 0.043(u_*/C - 0.043)$; dot-dash line, (Snyder et al., 1981), (4)

$\beta/f = 0.25(u_*/C)^2$; dash line, (Plant, 1982), (5)

$\beta/f = 0.34(u_*/C)^2$; solid line, (Mitsuyasu and Honda, 1982), (6)

$\beta/f = 0.41(u_*/C - 0.047)^2$; dot line, (Hsiao and Shemdin, 1983). (7)

In a region of relatively small inverse wave age, the present data support the formula of Hsiao and Shemdin (1983), while they approach to the formula of Mitsuyasu and Honda (1982) with the increase of the inverse wave age. The empirical relation of the growth rate obtained recently by Kato et al. (2000) for neutral stratification is quite similar to that of Mitsuyasu and Honda (1982) and also to that of Maeda (1990) in a region of large inverse wave age.

The result of Kato et al. (2000) also shows an interesting property that the wind-induced growth rate of water waves follows to almost the same formula even for the stratified air flow, if we use the friction velocity of the wind measured in each condition. This is an extension of "the u_*-similarity" obtained by Mitsuyasu and Honda (1982) for the neutral stability of the air flow to the case of stratified air flow. That is, Mitsuyasu and Honda (1982) studied the growth rate of water waves for different water surface conditions (smooth and rough) by using a surfactant, but for the neutral stability, and they found that the growth rate of waves follows to almost the same formula, if we use the friction velocity of the wind u_* measured for each surface condition.

Al-Zanaidi and Hui (1984) studied turbulent airflow over water waves numerically based on the two-equation closure model for the boundary layer turbulence. From systematic computations they obtained an approximate formula for the growth rate of water waves by wind. After slight modification (Mitsuyasu and Kusaba, 1988), their formula is given by

$$\beta/f = 4.7\times10^{-4}\,(U_\lambda/C-1)^2 \ \text{(for rough flow)}, \quad (8)$$

where U_λ is the wind speed at the height of one wavelength λ.

By using the measured data for the growth rate, which included the data of Mitsuyasu and Honda (1982), Mitsuyasu and Kusaba (1988) derived the following empirical formula that corresponds to Eq.8;

$$\beta/f = 8.2\times10^{-4}\,(U_\lambda/C-1)^2 \ \text{(for rough flow)}. \quad (9)$$

The comparison of these two formulas Eq.8 and Eq.9 shows that the measured growth rate is about 1.7 times the theoretical prediction of the formula by Al-Zanaidi and Hui (1984). The present data of Maeda (1990) also support this conclusion, because, as shown in Fig.7, the data of Maeda (1990) agree well to the empirical formula of Mitsuyasu and Honda (1982) in a region of large inverse wave age.

Quite recently Donelan (1999) made a laboratory measurement of the wind-induced growth and attenuation of water waves. He reported that the measured growth rates are a factor of three or four larger than those obtained by the formula of Al-Zanaidi and Hui (1984). This means that his measured growth rate is about one and half or two times greater than ours. Donelan (1999) determined the growth rate by measuring the pressure fluctuations above water waves simultaneously with the surface elevation of waves and computing momentum flux from the wind to water waves, while Mitsuyasu and Honda (1982), Maeda (1990) and Kato et al. (2000) determined the growth rate of waves by measuring directly the wind-induced growth of paddle-generated water waves. Presently it is not clear, however, whether or not the different results are due to the difference in the measuring techniques of the growth rate. Because the empirical formulas of Snyder et al. (1981) and Hsiao and Shemdin (1983) were also determined from the data of momentum fluxes from the wind to water waves measure in the ocean by using similar techniques with that of Donelan (1999), while these formulas do not give s made a uch large values as that given by Donelan (1999).

EFFECT OF SWELL ON SURFACE DRIFT CURRENT

Ten years ago, Cheng and Mitsuyasu (1992) studied the effects of swell to surface drift current in their laboratory tank. They found an interesting phenomenon that surface drift current is much intensified by opposing swell of large steepness, while the drift current is not much affected by following swell. This has been a difficult problem to answer for a long time. Quite recently, however, Mizuno (2002) has presented a clear explanation of this phenomenon by using the results of his laboratory experiment and its theoretical analysis. As well known wind over water surface in a wind-wave tank generates a (dominant) circulation of the surface drift current and its return flow. However, according to Mizuno (2001), the wind also generates a cross-sectional secondary flow (a kind of the Langmuir circulation) simultaneously with the generation of the dominant circulation. The secondary flow shows downwelling near the both sides walls in the tank and upwelling at the center of the tank. Under this condition, the surface drift current near the center of the tank becomes weak due to the upwelling, because the upwelling transfers a smaller horizontal momentum from lower side to the water surface. He also found that the secondary flow becomes much weaker than usual by the co-existence of opposing swell, while it is not much affected by following swell. He explained these phenomena by using the theory of Langmuir circulation, particularly by using CL2 mechanism presented by Craik (1977) and Leibovich (1977). His prediction on the changes of surface drift current by the both swells agreed fairly well with the observations of himself and ours.

However the following question still remains; if the surface drift current generated in a wind-wave tank without swell is affected originally by the secondary flow due to the boundary condition of the tank, how can we simulate in our laboratory tank the drift current in the ocean, or can we apply the results of laboratory experiments to estimate the drift current in the ocean.

CONCLUDING REMARKS

It is clear that the swell propagating in the direction of the wind suppresses the wind waves with the increase of its steepness. The suppression depends not only on the swell steepness but also on the frequency ratio the swell and the wind waves and further on the inverse wave age. Such properties can be predicted fairly well by the formula presented by Phillips and Banner (1974) formally. However problems still remain, because the mechanism proposed to derive the formulae of Phillips and Banner (1974) contains some questions and the formula can't be applied to the case of opposing swell (Mitsuyasu and Yoshida, 1989, 1991).

In a region of small or moderate inverse wave age, the growth of swell by the following wind can be predicted fairly well by the empirical formula of Hsiao and Shemdin (1983), while the relation is not much different from that of Mitsuyasu and Honda (1982) in a region of large inverse wave age. The theoretical formula of the growth rate by Al-Zanaidi and Hui (1984) gives the values of underestimation as compared to those given by Mitsuyasu and Honda (1982) and Maeda (1990). Although Donelan (1999) reported recently a very large growth rate, we need more detailed information on his study to discuss the problem.

An interesting phenomenon of large increase of surface drift current in a laboratory tank by opposing swell (Cheng and Mitsuyasu, 1992) can be clearly explained by the recent study of Mizuno (2002). He has shown that the opposing swell suppresses the secondary flow in the tank, which was generated in the tank by wind and contributed to decrease the surface drift current. However some problem still remains to estimate the surface drift current in the ocean by using laboratory data.

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