Two-Dimensional Surface Wave on the Shearing Current

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雑誌名	国立防災科学技術センター 研究報告
巻	13
ページ	75-87
発行年	1976-03
URL	http://doi.org/10.24732/nied.00000716

Report of the National Research Center for Disaster Prevention, No. 13, March 1976

551. 466. 4:551. 465:551. 556. 8(265. 5)

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Abstract

Results of the field observations of surface waves in the Kuroshio current were obtained by making use of the holographic method. The directional dispersion of the surface wave spectrum was recognized in the Kuroshio, and the propagating direction of longer waves was found to run parallel with the averaged stream of the Kuroshio, while the wave direction is closely related to the direction of local wind outside the Kuroshio area.

A tentative interpretation of the difference in directional spectrum between outside and inside the Kuroshio was done by two dynamical processes. One of the processes utilizes the non-linear interaction between a shearing current and incident waves, which is computed numerically by using the two-dimensional Pierson-Moskowitz spectrum including the radiation stress effect, and the other deals with a wind-generated wave on a shearing current on the basis of Phillips' theory.

Only the resonance mechanism of generating the waves on a shearing current as proposed by Phillips (1957) can be considered as one of the possible processes which yields the dispersion of directional spectrum.

1. Introduction

When gravity waves propagate into a current, the wave length and direction are changed. Several papers deal with this problem (Evans, 1955; Johnson, 1947; Unna, 1942; Ursell, 1960). All of these studies indicate that no coupling takes place between the waves and the current and that the wave energy travels at the velocity $(V+C_g)$, where C_g is the group velocity, and V the local current velocity. The coupling is, however, of importance. Longuet-Higgins and Stewart (1960a, b; 1962) considered that short waves riding on the backs of longer waves are substantially modified to an extent much greater than if there were no interchange of energy between the waves and the current. The amplitude of surface waves on currents is affected by a non-linear interaction between the waves and the components of the currents; the coupling terms are proportional to the radiation stress.

Waves entering on a shearing current that varies in the direction of wave propagation undergo an amplification that is greater than the previous one and is dependent on whether the variation in current is made up by a small vertical upwelling from below or by a small horizontal inflow from all the sides. Longuet-Higgins and Stewart (1960a, b; 1962) calculated the amplification of waves on a transverse shearing current. The interaction between waves and a current produces an amplification which is different from that obtained by neglecting the interaction terms.

Recently the dispersion of the directional spectrum of short gravity waves was obtained from air photographs of the Kuroshio using the holographic method (Sugimori, 1973, 1975). Low-frequency components in the direction of the averaged stream of the Kuroshio can be clearly seen. On the contrary, the directional spectrum of waves outside the Kuroshio current is closely related to the direction of local winds.

In order to explain the difference in wave spectra characteristics inside the Kuroshio, two dynamic processes might be considered. The first process deals with the non-linear interaction between the Kuroshio current and incident waves which are generated outside the Kuroshio as mentioned above and include the radiation stress effect. The second process can be narrowed down to a process of generation of wind waves in general. Recent theories on this process can be included in the resonance mechanism (Phillips, 1957). The resonance theory of wave generation predicts that, when a scalar wave-number K is given in the two-dimensional instantaneous wave spectrum, the resonance maxima should occur at angles α_c such that $KU \cos \alpha_c = (gK)^{1/2}$, where U is the wind speed at a height of approximately K^{-1} above the surface. This means that waves grow most rapidly by means of a selective resonance between the Fourier components of the fluctuating pressure distribution convecting across the water surface by the mean wind and such components of the wave field that have both the same wave number and the same velocity. In spite of the wind wave theory in still water, resonance mechanism on a shearing current is also variable in this case, because the observed result on both sides of resonance maxima in higher wave number range of the wave spectrum can be explained simply by this model. The angle increasing of wave spectrum near the resonance maxima might become broad as the coupling effect between wave and current becomes stronger.

These processes are to be successively referred to, in order to examine which of them will most reasonably interpret the observed result. However, it should be remarked that the estimate of each effect should be done with some reserve, because no meaningful estimate can be done for individual effects if these are correlated with each other by a non-linear coupling.

2. Measurement

Areal distribution of surface temperature was measured for defining the meander of the Kuroshio by an infrared radiation thermometer, and also air photographs of sea surface were taken by aircraft of the Maritime Safety Agency of Japan on August 17th, 1971. The directional slope spectra obtained from the aerial photographs using

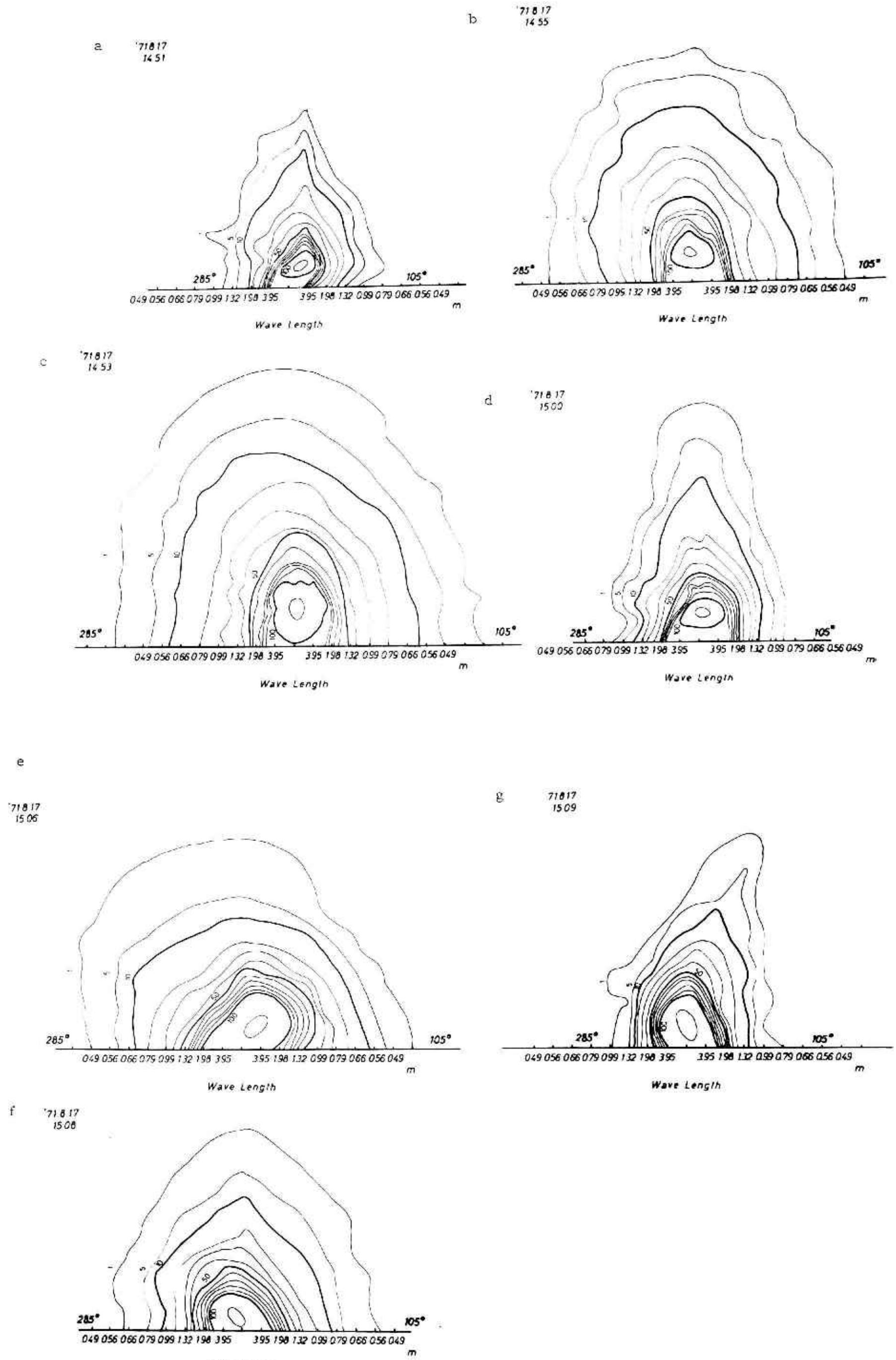

Fig. 1. Contours of directional power spectra of the waves from Bayonnaise Rocks to Tokyo Bay. "a" is a contour map of directional power spectrum outside the Kuroshio. "b" through "f" are those inside the Kuroshio. "d" is that near Miyake Island.

the holographic method are shown in Fig. 1, a to g. These figures are for 7 points on a course which is from Bayonnaise Rocks to Tokyo Bay and passes across the Kuroshio. However, the flight altitude chosen was about 450 m because it is an optimum altitude for observation with an infrared radiation thermometer. Hence, the spectra of observed surface waves were limited for a range of shorter gravity waves.

It is clearly seen in these 7 figures that surface waves are uniformly developed in all directions, irrespective of the wind (SSW wind) and current direction (NE flow), especially inside the Kuroshio if the wave length is shorter than 1 m; but a directional distribution is revealed for longer waves, as shown in Fig. 1, b to f. On the other hand, the direction of the waves longer than 1 m coincides with that of the averaged stream of the Kuroshio, whereas it coincides with the local wind direction outside the Kuroshio. Most of the energy is concentrated in the local wind direction outside the Kuroshio (Fig. 1, a and g).

In order to study the change in directional dispersion of wave spectra between inside and outside the Kuroshio, the average is determined for an interval of 10 degrees from the direction of the wind, for example Fig. 2. Figure 3, a and b, indicates the distribution of the power about the angles at a constant wave length for the spectra of Fig. 1, c nad g, respectively. The drop of power spectrum except for the direction of local wind in the range of wave lengths shorter than 1 m outside the Kuroshio is well seen. In other words, the power spectrum in such a wave-length range is conserved quite uniformly in every direction inside the Kuroshio.

3. Interpretation by the radiation stress

3.1 Single wave on a shearing current

Waves propagating in the opposite direction in a current with horizontal shearing

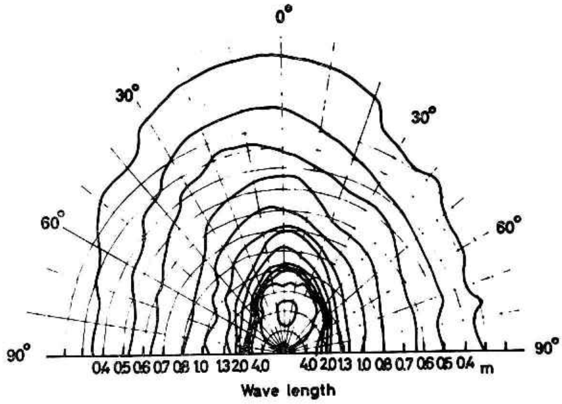

Fig. 2. Processing example of the power spectrum (Fig. 1, b through g) at each fixed wave length picked up by angular interval of 10 degrees.

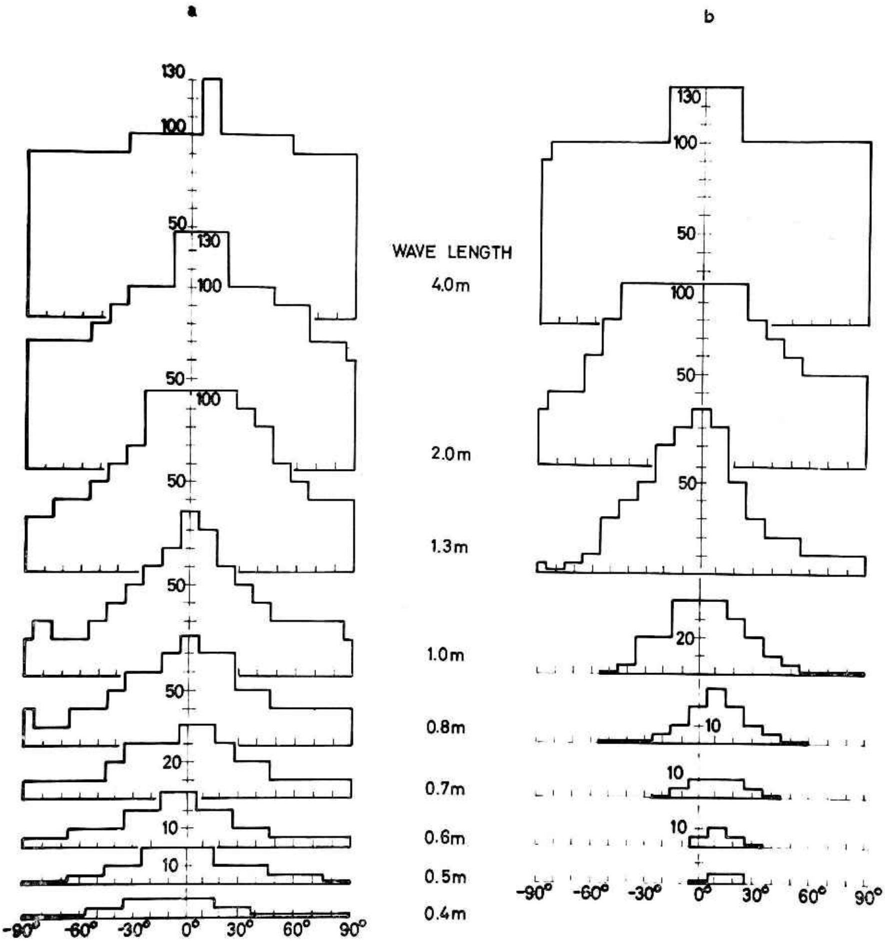

Fig. 3. An angular variation for a constant wave length in the directional spectra: "a" on the inside (Fig. 1, b) and "b": on the outside (Fig. 1, g) of the Kuroshio.

have their amplitudes greater than those of still water waves. Longuet-Higgins and Stewart (1960) showed that the effect of a shearing current on the wave amplitude is proportional to the so-called radiation stress, and that the current does work on the waves at a rate $1/2S_{ij}(\partial V_i/\partial x_j+\partial V_j/\partial x_i)$ per unit distance where the suffixes i and j $(i, j=1, 2)$ refer to rectangular coordinates arbitrarily chosen, S_{ij} being the radiation stress.

The energy equation is generally written as

$$\frac{\partial \boldsymbol{E}}{\partial t}+\nabla\cdot[\boldsymbol{E}(\boldsymbol{c}_g+\boldsymbol{V})]+\frac{1}{2}\cdot S_{ij}\left(\frac{\partial V_i}{\partial x_j}+\frac{\partial V_j}{\partial x_i}\right)=0 \qquad (1)$$

on the assumptions that the current velocity has only the y-compounent V, that y-component V is not variable with y and the depth, and that the apparent angular frequency is constant outside and inside the current, the above-mentioned authors obtained

$$E \cos\theta \sin\theta = \text{const} \tag{2}$$

and

$$\frac{a}{a_0} = \left(\frac{E}{E_0}\right)^{1/2} = \left(\frac{\sin 2\theta_0}{\sin 2\theta}\right)^{1/2} \tag{3}$$

where θ and θ_0 denote the angles between the directions of current and wave inside and outside the current, respectively. Obtained results hold good for a single wave. Since waves in nature are for from being a single wave, it is now tried to generalize the above theory for application to the waves of various frequencies and directions and to interpretation of the directional power spectrum observed.

3.2 Random spectrum of the waves on a shearing current

If the wave frequency is actually observed on a shearing current, it is denoted by ω in the frequency relation:

$$\tilde{\omega}^2 = gK = (\omega - \boldsymbol{K}\cdot\boldsymbol{V}) \tag{4}$$

where ω is a frequency on a still water. Now we reconfirm Eq. (2), starting from the following wave action conservation law:

$$\frac{\partial}{\partial t}\left(\frac{a^2}{\tilde{\omega}}\right) + \nabla\cdot\left[\frac{a^2}{\tilde{\omega}}(\boldsymbol{c}_g + \boldsymbol{V})\right] = 0 \tag{5}$$

where $\tilde{\boldsymbol{c}}_g$ is the group velocity in the current. Since the phenomenon is assumed to be conserved with y and the time, the above equation is reduced to

$$\frac{\partial}{\partial x}\left[\frac{a^2}{\tilde{\omega}} C_g \cos\theta\right] = 0 \tag{6}$$

Using the relation $\tilde{C}_g = (1/2)\tilde{C} = (1/2)g/\tilde{\omega}$ in deep water and substituting Eq. (4) into Eq. (6), we obtain

$$\frac{\partial}{\partial x}\left[\frac{a^2}{K}\cos\theta\right] = 0 \tag{7}$$

K being the wave number in the current.

Since the wave number conservation law reduces $\nabla\times\boldsymbol{K}=0$ or $\partial(K\sin\theta)/\partial x=0$ with the above-mentioned assumption, Eq. (7) is simplified as

$$\frac{\partial}{\partial x}[a^2 \sin 2\theta] = 0 \tag{8}$$

which is identical with Eq. (2).

In case of a random field the following relation is obtained:

$$a^2 = E(\boldsymbol{K})\mathrm{d}\boldsymbol{K} = E(K, \theta)\, K\mathrm{d}K\mathrm{d}\theta \tag{9}$$

and Eq. (7) becomes $\partial[E(K, \theta)\cos\theta \mathrm{d}K\mathrm{d}\theta]/\partial x=0$. Then, energy conservation equation can be expressed as follows:

$$E(K, \theta) \cos \theta \mathrm{d}K\mathrm{d}\theta = E_0(K_0, \theta_0) \cos \theta_0 \mathrm{d}K_0\mathrm{d}\theta_0 \tag{10}$$

K_0 being the wave number in a still water. The equation of the wave number conservation is $(\partial K/\partial t)+(\partial\omega/\partial x)=0$. Since only the steady state is here dealt with, the angular frequency ω does not vary with x. In a still water, Eq. (4) is written as

$$\tilde{\omega} + KV \sin \theta = \sigma_0 \tag{11}$$

With the relations:

$$\sigma_0^2 = (K_0C_0)^2 = gK_0$$
$$\tilde{\omega}^2 = (KC)^2 = gK, \ (\tilde{\boldsymbol{C}} = C - V \sin \theta)$$
$$\omega^2 = (KC)^2 = gK_0$$

Eq. (11) becomes

$$\sqrt{K_0} = \sqrt{K}\left[1+\sqrt{\frac{K}{g}}V \sin \theta\right] > 0 \tag{12}$$

Or substitution of the relation $K \sin \theta = K_0 \sin \theta_0$ into Eq. (11) gives

$$\sqrt{K} = \sqrt{K_0}\left[1-\sqrt{\frac{K_0}{g}}V \sin \theta_0\right] \tag{13}$$

Then, Eq. (13) is substituted into the relation $\partial K_0/\partial K = (K_0/K)^{1/2} + 2\sqrt{K_0/g}\, V \sin \theta$, which is derived from Eq. (12), and the following equation is yielded:

$$\frac{\partial K_0}{\partial K} = \frac{1+\sqrt{\frac{K_0}{g}}V \sin \theta_0}{1-\sqrt{\frac{K_0}{g}}V \sin \theta_0}\left(\frac{K_0}{K}\right)^{1/2} \tag{14}$$

From the wave number conservation relation the following equation is obtained:

$$\sin \theta = \frac{\sin \theta_0}{\left(1-\sqrt{\frac{K_0}{g}}V \sin \theta_0\right)^2}\left(1+\sqrt{\frac{K}{g}}V \sin \theta\right)^2 \sin \theta_0 \tag{15}$$

Therefore, Eqs. (14), (15) and (10) give

$$\frac{\cos \theta}{\cos \theta_0}\cdot\frac{\partial \theta}{\partial \theta_0} = \frac{1+\sqrt{\frac{K_0}{g}}V \sin \theta_0}{\left(1-\sqrt{\frac{K_0}{g}}V \sin \theta_0\right)^3} \tag{16}$$

Finally we have

$$\frac{E(K, \theta)}{E(K_0, \theta_0)} = \frac{1}{1+\sqrt{\frac{K}{g}}V \sin \theta} = 1 - \sqrt{\frac{K_0}{g}}V \sin \theta_0 \tag{17}$$

Eq. (17) defines the spectrum growth rat eon a shearing current which is $(1-\sqrt{K_0/g}\, V \sin \theta_0)$. The wave energy is decreased at this rate when the incident waves turn in the direction of the shearing current, and is increased at the same rate when the waves and the shearing current are in the opposite direction. A numerical example is given below to show the change of the wave number spectrum in the current, by using the Pierson-Moskowitz spectrum. The Pierson-Moskowitz type spectrum for ocean wave is as follows:

$$E_0(K_0,\ \theta_0)=\frac{\alpha}{2}K_0^{-4}\exp\left[-\beta\left(\frac{g}{K_0U_a^2}\right)^2\right]\cos^4(\psi-\theta_0) \tag{18}$$

where α, β: constants,

K_0: wave number in a still water,

U_a: wind velocity over the incident waves,

ψ: main direction of incident waves,

θ_0: direction of each wave number component of the incident waves.

If the peak wave number of $E_0(K_0,\ \theta_0)$ is denoted with K_m, then the following relation is obtained:

$$\left(\frac{g}{K_mU_a^2}\right)^2=\frac{2}{\beta}$$

Hence, Eq. (18) becomes

$$E_0(K_0,\ \theta_0)=\frac{\alpha}{2}K_0^{-4}\exp\left[-2\left(\frac{K_m}{K_0}\right)\right]\cos^4(\psi-\theta_0) \tag{19}$$

For the wave number spectrum, Eqs. (12) and (19) give

$$\begin{aligned}E_0(K_0,\ \theta_0)=&\frac{\alpha}{2}\cdot K^{-4}\left(1+\sqrt{\frac{K}{g}}V\sin\theta\right)^{-8}\\&\times\exp\left[-2\left(\frac{K_m}{K}\right)^2\left(1+\sqrt{\frac{K}{g}}V\sin\theta\right)^{-4}\right]\\&\times\cos^4\left[\frac{1}{2}\psi-\frac{1}{2}\sin^{-1}\left\{\sin\theta\left(1+\sqrt{\frac{K}{g}}V\sin\theta\right)^{-2}\right\}\right]\end{aligned} \tag{20}$$

Therefore, the Pierson-Moskowitz spectrum of surface waves on a shearing current is found by substituting Eq. (20) into Eq. (17):

$$\begin{aligned}E(K,\ \theta)=&\frac{\alpha}{2}K^{-4}\exp\left\{-2\left(\frac{K_m}{K}\right)^2\right\}\cos^4\left(\frac{\psi}{2}-\frac{\theta}{2}\right)\\&\times\left[\left(1+\sqrt{\frac{K}{g}}V\sin\theta\right)^{-9}\right.\\&\times\exp\left\{2\left(\frac{K_m}{K}\right)^2\left\langle1-\left(1+\sqrt{\frac{K}{g}}V\sin\theta\right)\right\rangle^{-4}\right\}\Bigg]\\&\times\frac{\cos^4\left[\frac{\psi}{2}-\frac{1}{2}\sin^{-1}\left\{\sin\theta\left(1+\sqrt{\frac{K}{g}}V\sin\theta\right)^{-2}\right\}\right]}{\cos^4\left(\frac{\psi}{2}-\frac{\theta}{2}\right)}\end{aligned} \tag{21}$$

Energy spectrum computed by Eq. (21) and Eq. (17) is illustrated in Fig. 4 as a function of K/K_m. In this computation the shear structure of the current is given by the following relation:

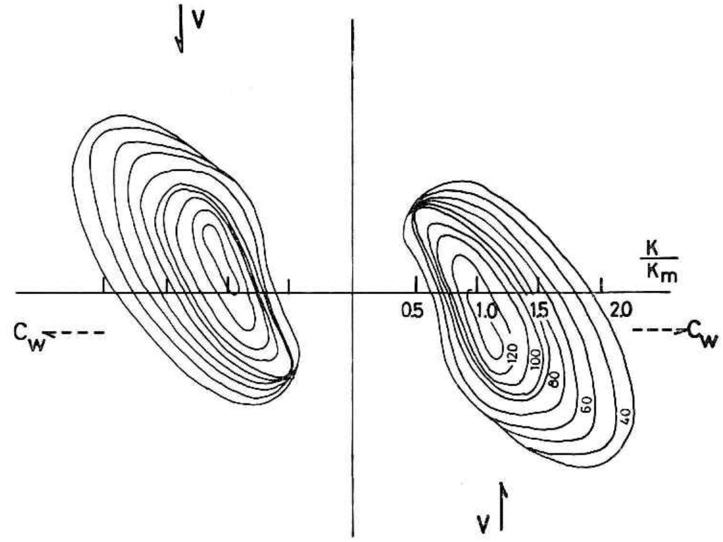

Fig. 4. Modulated slope spectrum of the surface waves in a shearing current.

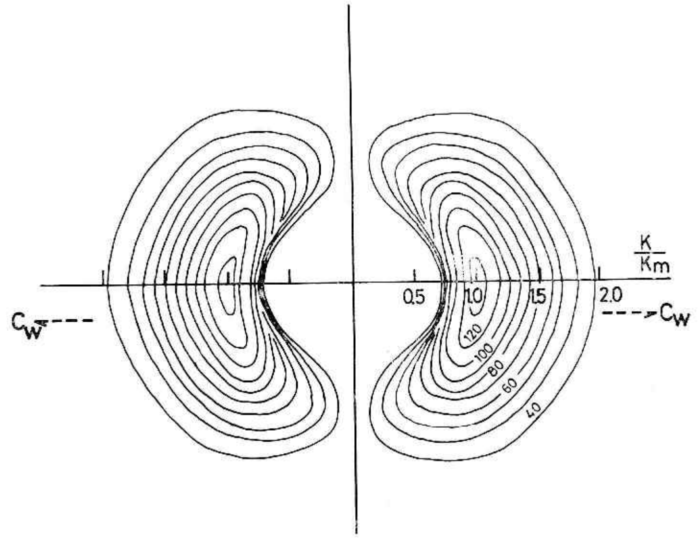

Fig. 5. *A priori* given slope spectrum of the surface waves in a still water.

$$\left(\frac{K_m}{g}\right)^{1/2} \cdot V = 0.2$$

where K_m is the peak wave number of $E_0(K_0, \theta_0)$, and V the current velocity. Figure 5 is the energy spectrum of the surface waves in a still water given for this numerical example. After the waves of this directional spectrum have entered into the current with the same velocity as the Kuroshio (the x-axis is taken as the main direction of the spectrum), the shape of the directional spectrum is modified by the radiation stress. Figure 4 shows the resultant spectrum, which spreads with the angular distribution of $\cos^4\psi$ on both sides of the dominant direction. Large wave number components have disappeared.

It is noteworthy that the shape of the directional spectrum can never be dispersed by the radiation stress effect, and the direction of dominant wave in directional spectrum becomes opposite to the stream of the Kuroshio by the radiation stress as seen in Fig. 4.

4. Wind-generated wave on a shearing current

The resonance theory (Phillips, 1957) were proposed for the generation of waves by wind. This theory is a random excitation by atmospheric pressure fluctuations, and the ocean is viewed as a resonant system excited by incoherent turbulent atmospheric pressure fluctuations. However, the resonance theory was based on an assumption of no current in the ocean, and here the model is modified into a case with a current. Phillips predicts that, for a given scalar wave number K in the two-dimensional wave spectrum, resonance maxima should occur at the angle ϕ_1 such that

$$U \cos \phi_1 = C(K) = \left(\frac{g}{K}\right)^{1/2} \tag{22}$$

where ϕ_1 is defined by an angle between the direction of dominant wind and the direction of resonance wave, and U the velocity of dominant wind. Condition (22) is well-known as the resonance condition, and waves, whose wave numbers and directions of propagation under a given wind field satisfy Eq. (22), will be called resonance waves. This theory, then, makes the simple prediction in a still water that, for a given scalar wave number of the spectrum, there will be resonance peak in the wave number spectrum at each of the angles $\pm\phi_1$.

The apparent phase velocity of waves on the current, for a given scalar wave number, will consist of the phase velocity of the resonance wave and the component of current velocity in the direction of wave propagation. Therefore, the Eq. (22) is modified into

$$U \cos \phi_1 = V \cos \phi_2 + C(K) = V \cos \phi_2 + \left(\frac{g}{K}\right)^{1/2} \tag{23}$$

where V is the current velocity and ϕ_2 is defined by the angle between the wave and current. (See Fig. 6).

The phase velocity of resonance waves seems to ride apparently on the current, and velocity becomes $(\tilde{C}+V \cos \phi_2)$ as in Eq. (23). It is, however, reasonable to consider that the inherent phase velocity of resonance waves C in the current may be smaller than that of apparent one by $V \cos \phi_2$, because $(\tilde{C}+V \cos \phi_2)$ keeps a balance with $U \cos \phi_1$ in Eq. (23). Therefore, the inherent wave number K for small $\tilde{C}$ will become larger as in the following equation:

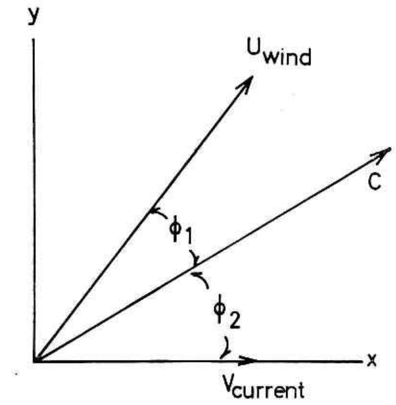

Fig. 6. The resonance mechanism (Phillips, 1957) on the following current.

$$K=\frac{g}{C_2}$$

The direction if U_{wind} shows not only a dominant one of local wind, but also direction of surface waves generated by the local wind. As angle ϕ_1 becomes larger, the resonance waves on both sides of the dominant wave will get a higher wave number than that of dominant wave, since angle ϕ_2 decreases as angle ϕ_1 ($\phi_1+\phi_2=$constant) increases and $V\cos\phi_2$ in Eq. (23) consequently increases, or K in the second term of Eq. (23) should also become larger in order to keep an equilibrium state with left side of this equation $U\cos\phi_1$. In other words, the resonance waves on the current with high wave number K may be generated on both sides of the direction of dominant waves (Fig. 7), and the angle spreading of wave spectrum becomes broader.

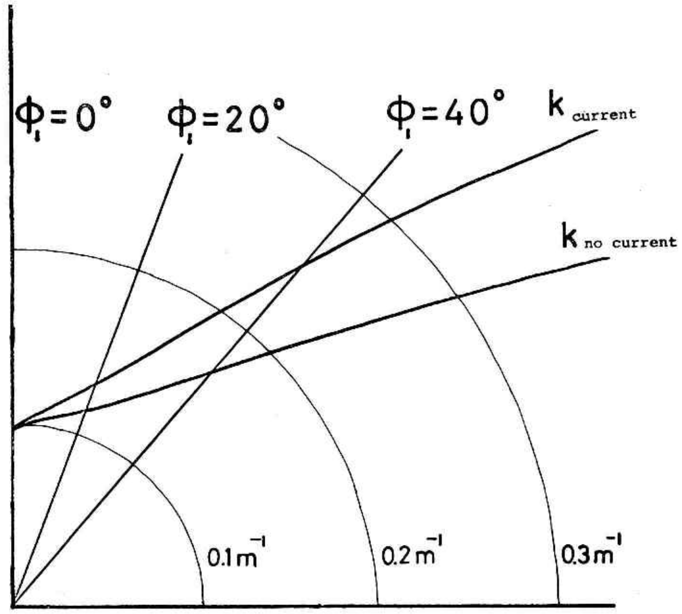

Fig. 7. Angular spreading of the surface waves on the following current in wave-number domain.

5. Conclusion

A tentative interpretation of the difference of the directional spectrum between outside and inside the Kuroshio was made in the present paper. Two kinds of dynamical processes were taken into account. In one of the processes, the non-linear interaction between shearing current and incident waves is computed numerically by using the two-dimensional Pierson-Moskowitz spectrum modulated with radiation stress effect, and in the other wind-generated waves on the shearing current are dealt with on the basis of resonance mechanism. The former process is interpreted by the point of view that the incident waves generated outside the current would interact with the shearing current oncoming from the outside. The latter process is used for an interpretation of wind-generated waves on a shearing current because the results of observation show the range of shorter gravity waves.

Only the resonance mechanism of generation of waves on a shearing current, as proposed by Phillips (1957), might be considered as one of the possible processes which will yield the dispersion of directional spectrum, and Pierson-Moskowitz spectrum due to the radiation stress effect shows the propagating direction of the wave opposing the current. It can explain the observation result about the direction of waves parallel with the meander of Kuroshio, since the holographic method has an ambiguity of 180 degrees in direction.

It is, moreover, noteworthy that from an analytical derivation on the basis of radiation stress effect, the wave energy will be decreased by the rate of $(1-\sqrt{K_0/g}\ V \sin \theta_0)$ when the incident waves turn in the direction of a shearing current, and will be increased at the same rate when the waves and the current are in opposite directions.

Another possible process is the effect of current of vertical shear on waves. However, our knowledge of the process is still too poor to estimate how it comes into play, though it was discussed by Hunt (1955), Benjamin (1957, 1959), Velthuizen *et al.* (1969) and Chia-Shun Yih (1972). This problem should be more extensively studied in the near future. No definite conclusion is drawn, unless the measurements of both horizontal and vertical shears in the fluctuations of the Kuroshio and the air over the current are conducted with sufficient accuracy, simultaneously with the wave observation. These measurements, even though they are particularly difficult in such a strong current as the Kuroshio, are very helpful to have insight into dispersion of the surface waves inside the Kuroshio.

Acknowledgements:——The author wishes to express thanks to Professor Hideaki Kunishi, Geophysical Institute of Kyoto University, to Professor R. O. Reid, Department of Oceanography of Texas A & M University, to Professor Toshihiko Teramoto, Ocean Research Institute of Tokyo University, to Dr. Noriyuki Iwata, National Research Center for Disaster Prevention, for their fervent discussions about the interpretation of observational results, and for their critiques of the author's original manuscript. The writing of the text was completed with the support of the National Science Foundation under Grant GA-26498 and ONR contract NO0014-68-A-0308-0002 to Texas A & M University.

References

1) Benjamin, T. B. (1957): Wave formation in the laminar flow down an inclined plane. *J. Fluid Mech.*, **2**, 554—574.
2) Benjamin, T. B. (1959): Shearing flow over a way boundary. *J. Fluid Mech.*, **5**, 161—205.
3) Evans, J. T. (1955): Pneumatic and similar breakwaters. *Proc. R. Soc. A*, **231**, 457—466.
4) Hunt, J. N. (1955): Gravity waves in flowing water. *Proc. R. Soc. A*, **231**, 496—504.
5) Johnson, J. W. (1947): The refraction of surface waves by current. *Trans. Am. geophys. Union*, **28**, 867—874.
6) Kinsman, B. (1965): *Wind Waves*, Prentice-Hall, Inc., 336—342.
7) Longuet-Higgins, M. S. and R. W. Stewart (1960): Changes in the form of short gravity waves on long waves and tidal currents. *J. Fluid Mech.*, **8**, 565—583.
8) Longuet-Higgins, M. S. and R. W. Stewart (1960): The changes in amplitude of short gravity waves on steady non-uniform currents. *J. Fluid Mech.*, **10**, 529—549.
9) Longuet-Higgins, M. S. and R. W. Stewart (1962): Radiation stress and mass transport in gravity waves, with application to "surf-beats". *J. Fluid Mech.*, **13**, 481—504.
10) Phillips, O. M. (1957): On the generation of waves by turbulent wind. *J. Fluid Mech.*, **2**, 417—445.
11) Sugimori, Y. (1973): Dispersion of the directional spectrum of short gravity waves in the Kuroshio current. *Deep-Sea Res.*, **20**(8), 747—756.
12) Sugimori, Y. (1975): A study of the application of the holographic method to the determination of the directional spectrum of ocean waves. *Deep-Sea Res.*, **22**, 339—350.
13) Unna, P. J. H. (1960): Waves and tidal streams. *Nature, Lond.*, **149**, 219—220.
14) Ursell, F. (1960): Steady wave patterns on a non-uniform steady fluid flow. *J. Fluid Mech.*, **9**, 333—346.
15) Velthuizen, H. G. M. and van Wijngaarden, L. (1969): Gravity waves over a non-uniform flow. *J. Fluid Mech.*, **39**, 817—829.
16) Yih, C.-S. (1972): Surface waves in flowing water. *J. Fluid Mech.*, **51**(2), 209—220.

(Manuscript received 9 June 1975)

乱れた流れの上の波浪の方向特性について

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黒潮流域における波浪の観測がホログラム法を用いて行なわれた (杉森, 1973, 1975). この観測結果として黒潮流上の波浪の方向スペクトルが, 短周期重力波の波長の短い成分で著しく分散特性を示し, また長い波長成分は黒潮流の流れの方向に沿って伝搬していることが分かった. 黒潮流域外での波長の長い成分は局地風に応答し, その方向とよく一致し黒潮流域上とは異なる特性を示した.

この論文では, 以上の観測結果に基づき黒潮流内外での波浪の方向スペクトルの特性の差異について解析が試みられ, 理論的に二つの発生機構が考えられた. その一つの機構は乱れた流れの中に入って来る波と流れの非線形の干渉であり, この機構についてラジエーションストレス (radiation stress) を含んだ二次元の Pierson-Moskovitz スペクトルのモデルを作り数値解析が行なわれた. 結果はホログラム法による観測結果の短い波長成分の分散結果とは反対に波のエネルギーがスペクトルのピーク域に収れんした. 他の機構は Phillips の共鳴機構 (resonance mechanism) を基礎とし, この機構に流れを加えて波浪の方向スペクトルの分散過程を検討するものである. 解析の結果波浪の方向スペクトルの分散が, この機構によって生じる可能性のあることが示された.