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A NOTE ON THE ENERGY TRANSFER FROM WIND TO WAVES

By

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Abstract

The amount of the energy transfered from wind to waves is estimated from our previous experimental data. This was carried out by assuming that the wind waves dissipate the energy only due to molecular viscosity, and by estimating $\frac{\partial}{\partial x}\left(C\cdot\frac{E}{2}\right)$ from the distributions of mean wave height in the wind tunnel. It is considered from this estimation that the energy transfer from wind to waves is about 15% of that at the critical layer in the wind field $C\cdot\tau$, where τ is the total stress of wind, and C the phase velocity of waves. The "wave drag coefficient" $\gamma_w{}^2$ which relates with the "effective stress" for wave growth is also shown as a function of wind speed.

1. Introduction

Much investigation on wind waves has been done theoretically, experimentally and observationally over a long period of time. The investigators have given many interesting results and clarified the mechanism of the generation and growth of wind waves (Ocean Wave Spectra [1963]). There are, however, many questions which remain to be solved. One of the authors, Kunishi [1963] carried out a wind tunnel experiment and indicated that the process of the wave generation and growth can be classified in three or four regimes, that is the initial tremor, the earlier and later stage of initial wavelet, and the sea wave, and the transition points between them are given as $u_*H/\nu_a \approx 0.3$, 6 and 200, where u_* is the friction velocity, H the mean wave height, and ν_a the kinematic viscosity of air. He also indicated that the waves in the regime of the initial wavelet have a similar character as a natural roughness on a solid wall, and that the friction factor or the total drag coefficient γ^2 is a function of the wind speed. We carried out another experiment (Kunishi and Imasato [1966]) under the high wind speed of 8～34 m/sec at the center of the air passage in the wind tunnel, and indicated that γ^2 is a function of the wind speed and the fetch.

The friction factor γ^2 is usually deduced from the mean wind profile over the wind waves by the equations (1) and (2),

$$\gamma^2 = \tau/(\rho_a W^2), \tag{1}$$

$$\left.\begin{array}{l} W = \dfrac{u_*}{\kappa} l_n \dfrac{z}{z_0} \\ u_* = (\tau/\rho_a)^{1/2} \end{array}\right\}, \tag{2}$$

where ρ_a is the density of air, W the wind speed at the anemometer height z over a water surface, z_0 the roughness parameter, and κ the Kármann constant. According to this treatment, momentum flux of the air passing towards the boundary is expressed as the wind stress τ, and energy going into waves of phase velocity C is evaluated by $C \cdot \tau$. It is doubtful that water receives all the energy flux $C \cdot \tau$ at the critical layer of the wind profile over the waves in the form of the wave motion of phase velocity C. Some might be used to make wind-driven currents and turbulences in air and water. An estimation of effective energy transfer from wind to wave motion may be helpful to understand what the mechanism of the generation and growth of wind waves is. We have already begun to approach to this problem through an experiment in a wind tunnel and the observations in Lake Biwa.

The purpose of this paper is to examine the process of the generation and growth of wind waves from the point of view mentioned above by using the data of our previous experiments (Kunishi [1963], and Kunishi and Imasato [1966]).

2. Energy equation

Energy equation of the wind waves is given, as is well known, by the equation

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x}\left(C \cdot \frac{E}{2}\right) = R_N - D, \tag{3}$$

where E is the mean total energy of waves per unit area calculated from the mean wave height H, R_N the mean rate of energy transfer to waves, and D the mean rate of dissipation of wave energy. Assuming that wind waves lose energy only due to the molecular viscosity, we may put D as follows,

$$D \equiv R_\mu = 4\nu_w k^2 E, \tag{4}$$

where ν_w is the kinematic viscosity of water, and k the mean wave number. The time change of wave energy is zero in the case of the experiments in the wind tunnel. Therefore R_N may be evaluated by the equation

$$R_N = R_I + R_\mu , \tag{5}$$

where

$$R_I = \frac{\partial}{\partial x}\left(C \cdot \frac{E}{2}\right). \tag{6}$$

3. Data process and discussion

Wind waves have been measured simultaneously at three points in the wind tunnel. Therefore $\frac{\partial}{\partial x}\left(C \cdot \frac{E}{2}\right)$ can be estimated from the distributions of the mean total energy of waves. The results of $R_{\rm I}$ and R_μ are summarized against $u_* H/\nu_a$ in Fig. 1. Till $u_* H/\nu_a$ reaches to about 10, R_μ is larger than $R_{\rm I}$ and both increase

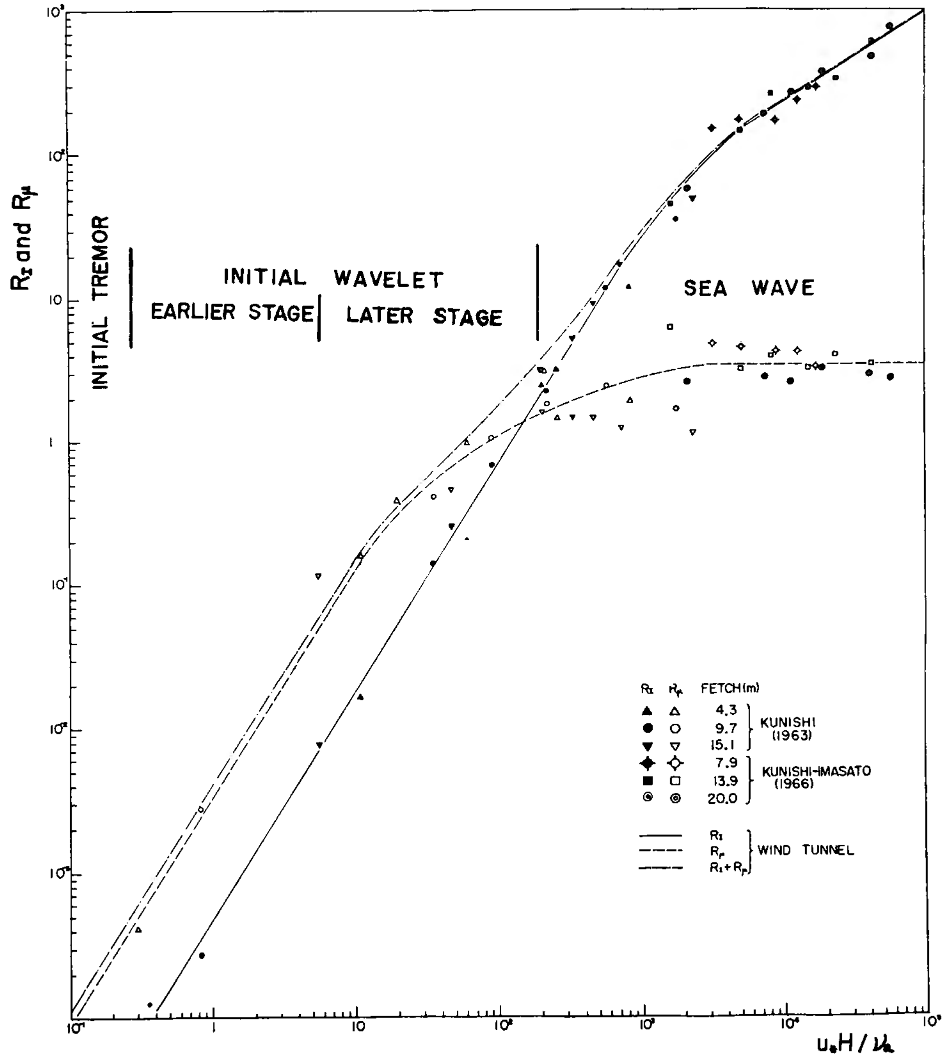

Fig. 1. Energy increase $R_{\rm I}$ and energy dissipation R_μ of wind waves versus the nondimensional quantity $u_* H/\nu_a$ of the mean wave height. Regimes in the process of the growth of wind waves are also shown after Kunishi [1963].

with u_*H/ν_a at the same rate. After that, the rate of increase of R_μ decreases gradually, but R_I increases at the same rate until u_*H/ν_a becomes about 10^3. When u_*H/ν_a is about 150, R_μ becomes to be equal to R_I, and then R_μ is less than R_I and approaches to a constant value. It can be clearly seen from this figure that the transitions in the relation between R_I and R_μ agree well with those in the relation given by Kunishi [1963]. Therefore, the following definition may be made concerning these regions in the generation and growth of wind waves as follows;

(i) the initial tremor and the earlier stage of initial wavelet are the regions where $R_I<R_\mu$. Although the waves develop quite rapidly, the greater amounts of energy transferred from the wind are dissipated by the molecular viscosity;

(ii) the sea wave is the region where $R_I>R_\mu$ and the large amounts of the energy transferred from the wind is used to maintain and develop the wave motion;

(iii) the later stage of initial wavelet is the transitional region from the earlier stage of initial wavelet to the sea wave.

R_I increases at another rate in the range of $u_*H/\nu_a>10^3$, and the reason of this change may be that the wave crests are torn by a strong wind.

Energy transfer to the waves of phase velocity C estimated from the total stress τ in the equation (1) is given by $C \cdot \tau$. On the other hand, the energy transfer estimated from the energy contained in the form of wave motion is R_N, which may be called the "effective energy transfer" to the waves of the phase velocity C. The ratio $R_N/C\cdot\tau$ of these two quantities is summarized in Fig. 2.

It can be seen from the figure that this ratio increases with wind speed W depending on fetch, and begins to decrease gradually after W becomes to be larger than 12 m/sec, and that the water takes at most 15% of the enrgy flux of the wind at the critical layer ($W=C$) in the form of the wave motion. This value does not contain the energy received by the water in other forms of motion such as the current and the turbulence passing through the wave motion. Wind waves might be considered to get the much more energy from the wind than the results in Fig. 2. It is very important question open to the future investigation.

R_N/C has the nature of a stress, and a quantity $\gamma_w{}^2$ defined by

$$\gamma_w{}^2 = R_N/C\rho_a W^2, \tag{7}$$

has the nature of a drag coefficient. The quantity R_N/C may be called the "effective wind stress" for waves or the "wave drag", and then the coefficient $\gamma_w{}^2$ may be called the "wave drag coefficient". It should be noted here that R_N/C in Fig. 2 expresses the ratio of the "effective wind stress" to the total stress.

The coefficients $\gamma_w{}^2$ and γ^2 deduced from our experiments are summarized in Fig. 3 as a function of the wind speed W. In the range of 10~40 m/sec of W, $\gamma_w{}^2$ is about 1.5×10^{-4}, and is about 0.7×10^{-4} in the higher wind speed. If waves don't break, the coefficient $\gamma_w{}^2$ may be constant in the region of the sea wave.

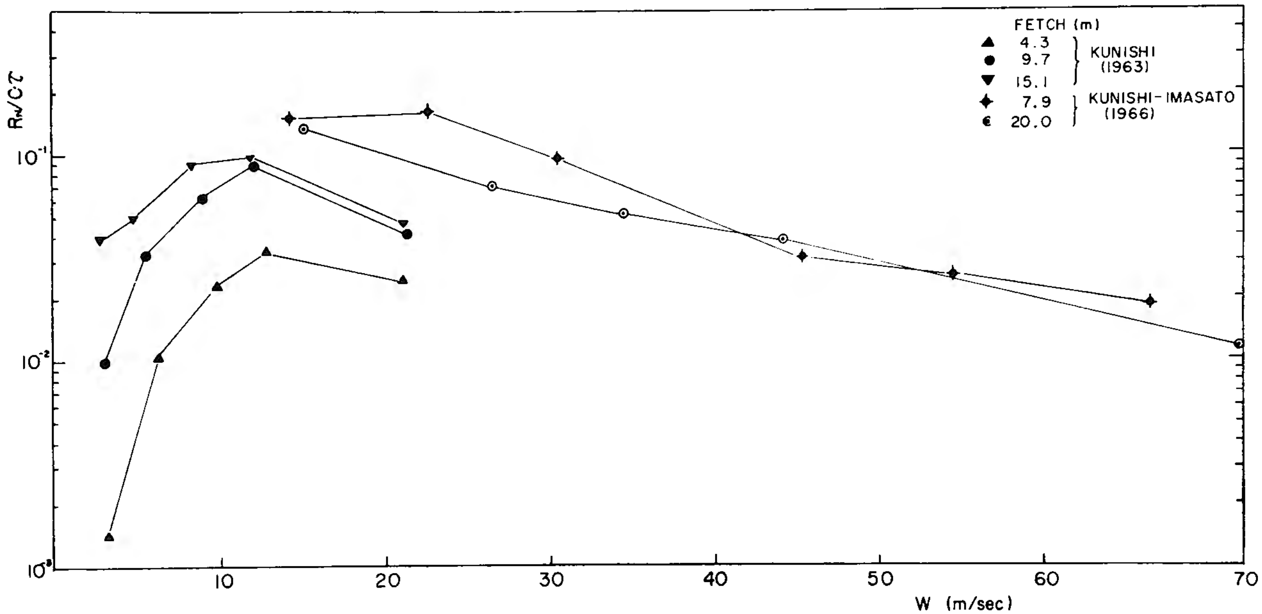

Fig. 2. The ratio of the "effective wind stress" γ_w^2 to the "total wind stress" γ^2 versus the wind speed W.

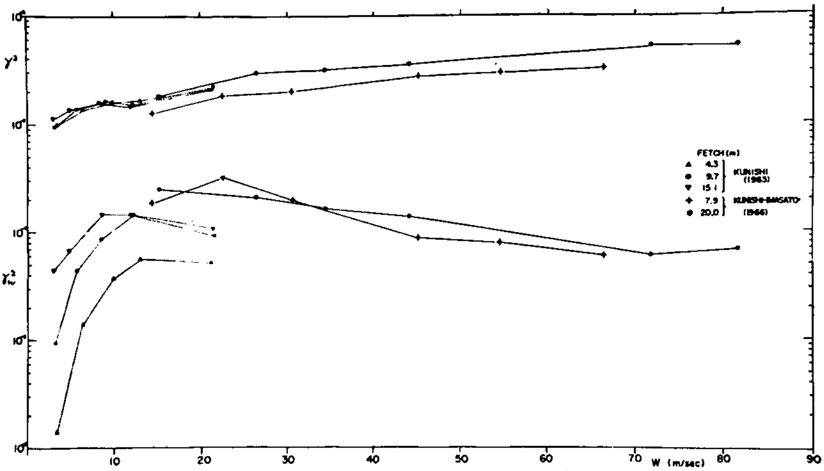

Fig. 3. The "total drag coefficient" γ^2 (upper) and the "wave drag coefficient" γ_w^2 (lower) versus the wind speed W.

Stewart [1961] has also reported the amount of this rate to be about 20% by estimating R_1 from $\partial E/\partial t$. His estimation is a little larger than ours, but agrees in the order. These results suggest that water takes quite a little amount of energy from the wind in the form of the wave motion, and it is absolutely necessary to estimate the energy transfer to the current and the turbulence. Such an investigation will help to understand the wind profile to the wave field. A part of this study was supported by scientific research fund from the Ministry of Education.

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