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MITSUYASU, Hisashi
Research Institute for Applied Mechanics, Kyushu University : Professor

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ON THE GROWTH OF THE SPECTRUM OF WIND-GENERATED WAVES (II)

-Note on the equilibrium spectrum and the overshoot phenomena-

By Hisashi MITSUYASU*

Two interesting characteristics of the spectrum of wind-generated waves, (i) the equilibrium spectrum and (ii) the overshoot phenomena, are studied. In part I, it is shown that the observed results of the equilibrium spectrum in various conditions support the theoretical inference proposed recently by Longuet-Higgins, and the definite relation exists between the constant β in the equilibrium spectrum and a dimensionless fetch. In part II, detailed discussions are conducted on the relations between the the peculiar characteristics of wind-wave spectra observed in our previous studies, and the overshoot effect in wind-generated waves observed by Barnett & Wilkerson and by Sutherland. It is shown that the overshoot effect in a spectral component of wind waves occurs when the frequency of that component is very close to, but slightly larger than, the frequency of the dominant peak of the spectrum of wind-generated waves. That evidence is verified by showing that the fetch equation for the frequency of spectral peak is very close to the relation between the dimensionless frequency of the spectral component of wind waves and the dimensionless fetch where the overshoot effect in that spectral component is observed. The discussions on the possible mechanism of the growth of wave spectra are included.

Introduction

This paper is a sequel to an earlier paper of the same title (Mitsuyasu[1], hereinafter denoted by I). In I the growth of the spectrum of wind-generated waves at short fetch was investigated experimentally. On the basis of the similarity hypothesis proposed by Kitaigorodskii,[2] the form of the wave spectrum in a low frequency part (steep forward face) was determined by using the data of accurately measured wave spectra in our laboratory and in a bay. A new spectral form was proposed for the wind waves at short fetch by utilizing the newly determined spectral form in a low frequency part, together with the equilibrium spectrum in a high frequency part proposed by Phillips[3]

$$\phi(\omega)=\beta g^2\omega^{-5}, \tag{1}$$

* Professor, Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan.

$$\text{or} \quad \phi(f) = \beta' g^2 f^{-5} \tag{1'}$$

$$\beta' = (2\pi)^{-4}\beta, \tag{2}$$

where β denotes a dimensionless constant, g the acceleration of gravity, ω the angular frequency, and f the frequency (in cycle per second). Although the constant β in the equilibrium spectrum (1) was tentatively assumed as $\beta = 1.48 \times 10^{-2}$ for obtaining a fetch equation (graph), it was shown that the constant β was not a universal constant but it decreased with an increas of the dimensionless fetch gF/u_*^2, where F denotes the fetch and u_* the friction velocity of the wind. However, the previous derivation of the relation between β and gF/u_*^2 was not so straightforward. In part I of this paper, therefore, the previous experimental data are analyzed for obtaining that relation directly. In the analysis, the theoretical model on the equilibrium spectrum, which has been proposed recently by Longuet-Higgins[4], is effectively used.

Part II of this paper describes the fine structures of the spectrum of wind-generated waves, which are observed from near the dominant peak of the spectrum to its high frequency side, and also in a growth curve of a spectral component (spectral density as a function of fetch). The unified discussions are conducted on the following peculiar phenomena in the spectrum of wind-generated waves; the excess energy concentration near the dominant peak of the wave spectrum[1),5)], a large amount of energy loss from near that spectral speak,[1),5),6)] and the overshoot effect in a spectral component of wind waves.[7),8)]

Part I. The equilibrium spectrum

I-1. Brief summary of theoretical results

With reference to the high frequency part of the wave spectrum, Phillips,[3)] from the consideration of limiting configuration of surface waves, showed that an equilibrium range may exist, and by similarity considerations he derived the equation (1) as its spectral form. He also determined the value of β as 1.48×10^{-2} by using the Burling's data.[9)] The frequency-dependence of the spectrum (1) has been approximately verified by various observations over a wide range of frequencies.[1),10),11)]

The basic idea underlying Phillips's derivation of the equilibrium spectrum is that over this range of frequencies the spectrum is limited by wave breaking*). Longuet-Higgins[4)] made a theoretical calculation on the loss of energy by wave breaking in a random sea state in terms of the spectral density function. In the spectral form of the equilibrium spectrum

$$\phi(\omega) = \beta g^2 \omega^{-5} \times \begin{Bmatrix} 0 & \omega < \omega_m \\ 1 & \omega > \omega_m \end{Bmatrix}, \tag{3}$$

the proportion $\tilde{w}$ of energy lost per mean wave cycle was found to be given by

*) Hamada[12),13)] proposed a different instability mechanism for the explanation of the equilibrium spectrum.

$$\tilde{w} \doteqdot \exp\{-1/8\beta\} \tag{4}$$

irrespective of the low-frequency cut-off in the spectrum. Further, by assuming that in the equilibrium state the loss of energy by breaking is comparable with the total energy supplied by wind, he derived the following relation

$$\tilde{w}E/T \sim W\ , \tag{5}$$

where E denotes the total wave energy density per unit area, T the mean period of waves and W the mean rate of work done by the wind. The rate of working W of the wind was roughly assumed that

$$W \sim \tau u_*\ , \tag{6}$$

where τ denotes the wind-stress and u_* the friction-velocity defined by

$$\tau = \rho_{\rm air}\ u_*^2. \tag{7}$$

Further, he conjectured that $\tilde{w}$, which is proportional to T/E from (5), might be expected to decrease with an increase in gF/u_*^2, and so β, by (4), would also decrease with an increase in gF/u_*^2.

1-2. Comparison of the theory and observations

Figs. 1, 2 and 3 show examples of wave spectra in a dimensionless form which have been observed in I. As will be seen from those figures, the equilibrium spectrum of the form (1) seems to be applied, as a first approximation,

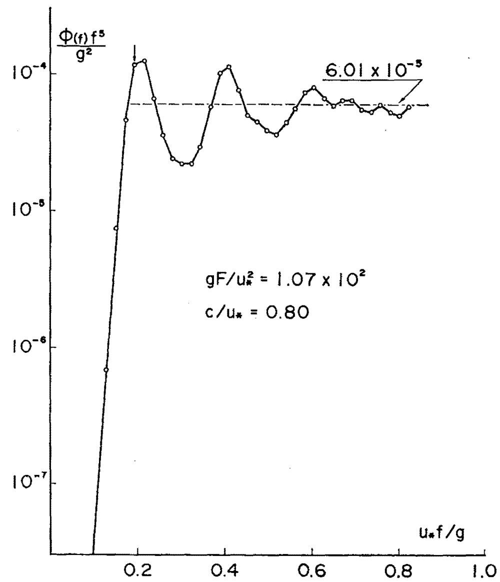


Fig. 1. Normalized spectrum of wind-generated waves (F=13m, u_*=109 cm/sec)

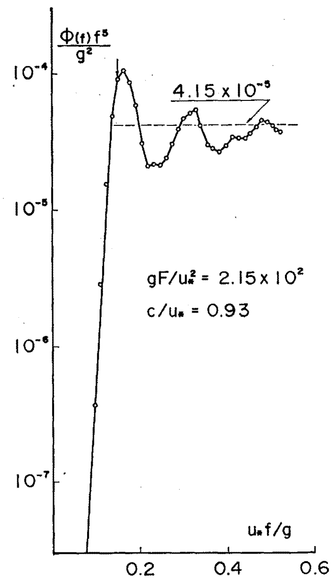


Fig. 2. Normalized spectrum of wind-generated waves (F=13m, u_*=77 cm/sec)

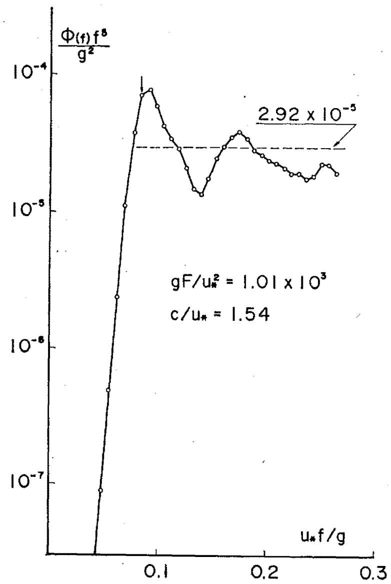


Fig. 3. Normalized spectrum of wind-generated waves (F=18m, u_*=41.8 cm/sec)

for a high frequency part of the observed spectra, though some definite deviations from that form are clearly observed; the detailed discussions on these deviation will be made in part II of this paper. The value of constant β' in each spectrum has been determined as the mean value of $\phi f^5/g^2$ in the frequency range $f > f_m$ where f_m is the frequency of the maximum spectral density. The values of β' thus obtained and β converted from β' by (2) are shown in Table 1 together with the data quoted by Longuet-Higgins.[4] As the dimensionless fetch gF/u_*^2 has been used in our previous paper I, gF/U^2 in Longuet-Higgins's data has been converted by assuming the following relation;[1]

$$U = U_{10} \doteqdot 25 u_* . \tag{8}$$

The values of the constant β' may be determined in different ways; for examples, $\beta_1' = \int_{fm}^{\infty} \phi(f) df \Big/ \int_{fm}^{\infty} f^{-5}\, df$ or by the method of least squares in which the obtained value is denoted by β_2'. Those values are also included in Table 1, although the use is made of the β' and the corresponding β in most of the following discussions.

According to the previous study (I, equations (10), (12) and (13)), the wave period T is given by

$$T \doteqdot T_{1/3} = \frac{u_*}{1.05\, g} \left(\frac{gF}{u_*^2} \right)^{0.330} . \tag{9}$$

Table 1. Observed values of the equilibrium range constants

Author	F (m)	u_* (cm/sec)	gF/u_*^2	β	β' $(=(2\pi)^{-4}\beta)$	β_1'	β_2'	method	Place
Mitsuyasu (1968)	8	49.2	3.24×10^{2}	4.02×10^{-2}	2.58×10^{-5}	4.68×10^{-5}	6.00×10^{-5}	capacitance wire	laboratory index (D-F) (15-8)
〃	13	44.4	6.46×10^{2}	5.02×10^{-2}	3.22×10^{-5}	7.08×10^{-5}	9.09×10^{-5}	〃	(15-13)
〃	18	41.8	1.01×10^{3}	4.55×10^{-2}	2.92×10^{-5}	5.42×10^{-5}	6.66×10^{-5}	〃	(15-18)
〃	8	82.0	1.17×10^{2}	8.14×10^{-2}	5.23×10^{-5}	8.43×10^{-5}	1.06×10^{-4}	〃	(25-8)
〃	13	77.0	2.15×10^{2}	6.46×10^{-2}	4.15×10^{-5}	7.30×10^{-5}	8.86×10^{-5}	〃	(25-13)
〃	18	77.2	3.40×10^{2}	9.35×10^{-2}	6.01×10^{-5}	9.01×10^{-5}	1.10×10^{-4}	〃	(25-18)
〃	8	111	6.40×10	1.02×10^{-1}	6.58×10^{-5}	8.16×10^{-5}	8.45×10^{-5}	〃	(85-8)
〃	13	109	1.07×10^{2}	9.35×10^{-2}	6.01×10^{-5}	8.74×10^{-5}	1.07×10^{-4}	〃	(85-13)
〃	18	110	1.46×10^{2}	1.38×10^{-1}	8.86×10^{-5}	7.70×10^{-5}	8.18×10^{-5}	〃	(85-18)
Mitsuyasu (1968)	4.5×10^{3}	22.0	6.05×10^{5}	1.22×10^{-2}	7.83×10^{-6}	5.75×10^{-6}	5.78×10^{-5}	capacitance wire	Hakata Bay
〃	4.5×10^{3}	27.0	9.17×10^{5}	$1,20\times10^{-2}$	7.68×10^{-6}	6.14×10^{-6}	6.29×10^{-5}	〃	〃
Burling (1959)	70	15.6	1.12×10^{5}	1.48×10^{-2}	9.53×10^{-6}	—	—	capacitance wire	out door reservoir
Hicks (1960)	55	4.8	2.38×10^{5}	1.21×10^{-2}	7.79×10^{-6}	—	—	〃	inland lake
Kinsman (1960)	2.5×10^{3}	22.4	5.00×10^{5}	1.04×10^{-2}	6.69×10^{-6}	—	—	〃	Chesapeake Bay
Longuet-Higgins, Cartwright & Smith (1963)	5×10^{5}	40.0	3.12×10^{7}	8.00×10^{-3}	5.15×10^{-6}	—	—	accelerometer buoy	open sea

From the observed relation between a dimensionless wave height $g\sqrt{E}/u_*^2$ and a dimensionless fetch gF/u_*^2 (I, Fig. 12) the wave energy E is given by

$$E=\rho_{\text{water}}\, g(1.31)^2\times 10^{-4}\frac{u_*^4}{g^2}\left(\frac{gF}{u_*^2}\right)^{1.008}. \tag{10}$$

According to the inferene in the previous section, from (5), (6) and (7), the proportion $\tilde{w}$ of wave energy loss per mean wave cycle is given by

$$\tilde{w}=A\frac{T\rho_{\text{air}}u_*^3}{E}\ , \tag{11}$$

where A is an undetermined dimensionless constant.

On substituting (9) and (10) into (11) we can easily show that the term in u_* and g cancel each other identically, giving

$$\tilde{w}=B\left(\frac{gF}{u_*^2}\right)^{-0.678}, \tag{12}$$

$$\text{where}\qquad B=5.56\times 10^3\cdot A\cdot\left(\frac{\rho_{\text{air}}}{\rho_{\text{water}}}\right). \tag{13}$$

On the other hand, from (4), β is given by

$$\beta\sim\frac{-1}{8\ \ln\ \tilde{w}}=\frac{-1}{18.4\ \log_{10}\tilde{w}}\ , \tag{14}$$

or, more generally, for the spectral form which is slightly different from (3), by

$$\beta=\frac{-1}{C\log\tilde{w}}\ , \tag{15}$$

where C is an undetermined constant of the order of $20\sim30$.*)

Now, substituting (12) in (15), the relation between β and the dimensionless fetch gF/u_*^2 can be writen as

$$\frac{1}{\beta}=D\ \log\left(\frac{gF}{u_*^2}\right)-G\ , \tag{16}$$

$$\text{where}\qquad D=0.678\,C,\qquad G=C\ \log\ B\ . \tag{17}$$

The observed values of β and gF/u_*^2, which are shown in Table 1, can be used for determining, by the method of least squares, the constants D and G in (16). Now, we obtain

$$\frac{1}{\beta}=21.0\ \log\left(\frac{gF}{u_*^2}\right)-34.5\ . \tag{18}$$

As will be seen from Fig. 4, the relation (18) fits quite well to the observed

*) It is not so difficult to show approximately that C is greater than 18.4 when the overshoot effect in the wave spectrum exists.

results. Furthermore, from (13), (17) and (18), the constant A in (11) and C in (15) are given respectively by

$$A=1.93, \quad C=31.0 \ . \tag{19}$$

Part II. The overshoot phenomena in wind-generated waves

2-1. The high frequency part of the wave spectrum

Excess energy concentration The high frequency part of the wave spectrum observed in I has shown several interesitng characteristics as seen in Figs. 1, 2 and 3. That is:

(i) There is an excess energy concentration near the dominant peak of the wave spectrum as compared with the equilibrium spectrum. (The small arrow in those figures shows the position of the maximum spectral density.)

(ii) Then, the dimensionless spectral density $\phi f^5/g^2$ seems to approach in an oscillatory mode to some equilibrium value, showing the pattern similar to that of a damped oscillation.

(iii) The location of the second peak is very close to $2f_m$, the twice the frequency of the dominant peak, and third peak locates at around $3f_m$, and so on. These characteristics are thought to be explained by the nonlinear models of waves proposed by Tick[14] and Phillips.[15]

Cox,[16] as far as we know, should be the first to present the experimental evidence of the excess energy concentration, showing that $S_x f$, the slope spectrum S_x multiplied by frequency f, is not constant.*) Several years later Mi-

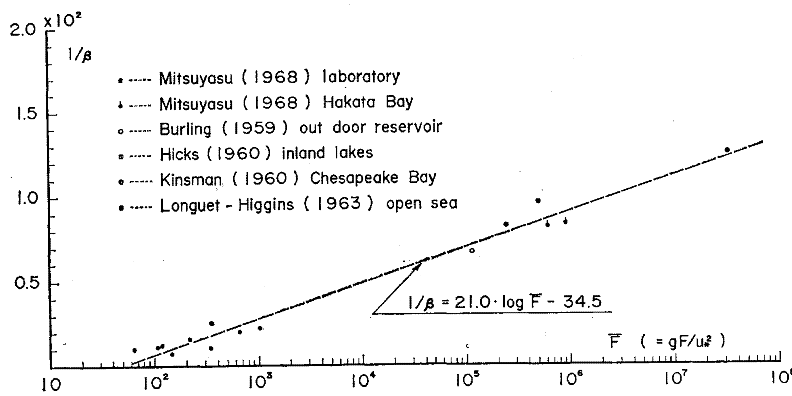
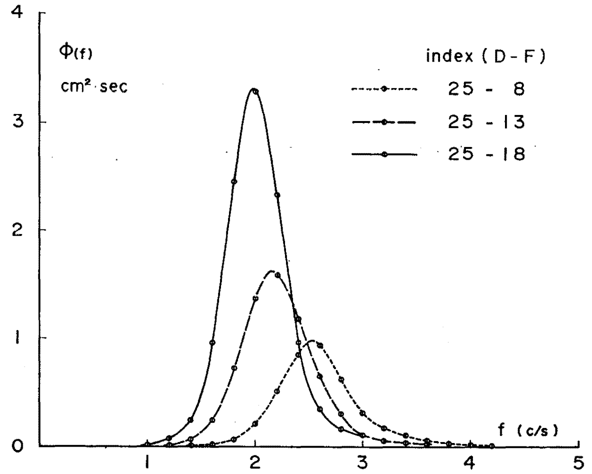


Fig. 4. The relation between the constant β and the dimensionless fetch gF/u_*^2.

*) The slope spectrum is given by
$$(S_x+S_y)=k^2\phi_{(f)}=(2\pi)^4 f^4 \phi_{(f)}/g^2.$$
Therefore, if the equilibrium spectrum of Phillips is satisfied, it follows
$$S_x f \doteqdot (S_x+S_y)f=(2\pi)^4 f^5 \phi_{(f)}/g^2=\omega^5\phi_{(\omega)}/g^2=\beta$$



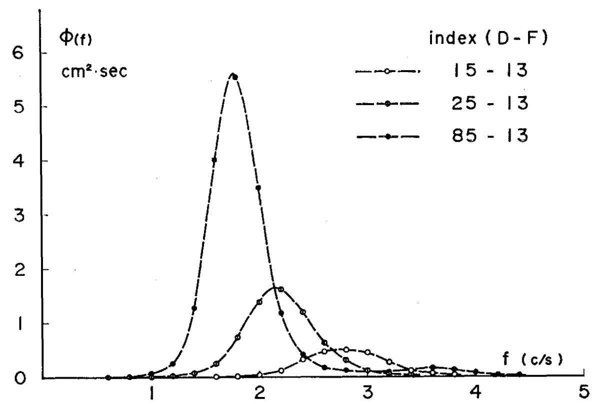


Fig. 5. The growth of the spectra of wind-generated waves. The upper curves show the growth of the spectrum with fetch. The lower curves show the growth of the spectrum with wind speed. Some of the parameters relating to these spectra are shown in Table-1.

tsuyasu observed the similar phenomena in the measurement of laboratory wind waves.[5] In contrast with such evidences in the laboratory wind waves, those characteristics were never observed in the bay or in the open seas before the observation by Barnett & Wilkerson.[7]

Dissipation of wave energy In a laboratory measurement of wind waves in a calm area where the wind was not blowing, the following interesting phenomena were observed by Mitsuyasu[5]: When the wind-generated waves propagated into the area where the wind was not blowing, the dissipation of wave energy much greater than that due to viscous dissipation was observed in the frequency range of the spectrum where the excess energy was found. Later, Mitsuyasu[6] presented some possible explanation for such energy dissipation by taking the nonlinear wave-wave interactions (Hasselmann,[16],[17] Barnett[18]) into account. In the previous study I, such energy dissipations near the dominant peak of the wave spectrum were observed even in the spectra of growth stage. As will be seen from Fig. 5, (I, Figs. 5a and 5b), the excess wave energy near the dominant peak of the fetch-limited spectrum at some equilibrium condition is dissipated very rapidly even when the conditions are changed to increase the gross wave energy in the spectrum, i.e., when the wind speed or the fetch is increased. From those evidences, it seems that there is some optimum condition in which the maximum wave energy can be contained in the particular spectral component of wind-generated waves and an equilibrium state of high energy level can be maintained compensating for a large amount of energy loss from that frequency range by some supply. According to Fig. 5, the optimum condition will be the case where the frequency of that spectral component is very close to, but slightly larger than, the frequency of the dominant peak of a wave spectrum. In other words, there must be special mechanisms which transfer the energy from the wind selectively to the spectral component near the dominant peak of the wave spectrum. The sheltering mechanism[19] and a non-linear mechanism proposed recently by Longuet-Higgins[20] are thought to be responsible for them. At this time, however, we will not enter into the detailed discussions of this problem.

2–2. The overshoot effect in wind-generated waves

The overshoot effect Barnett & Wilkerson[7] observed a peculiar phenomena in their measurments of fetch-limited spectra, and they termed it 'overshoot effect'. The phenomenon is characterized by a growth curve (spectral density as a function of fetch), which has a shape similar to that shown in Fig. 6. That is, when the growth of some particular spectral component of waves generated by steady wind is traced along the fetch, the energy of the spectral component increases linearly first, then exponentially with fetch, and reaches a maximum value ϕ_m at some fetch overshooting the equilibrium value. Then, the curve drops sharply, and undershoots to a minimum spectral density ϕ_u before reaching a final equilibrium value of ϕ_e. The laboratory data obtained by Sutherland[8] have shown clealry the same features as those of Fig. 6. The similar overshoot effect has been observed recently in the growth curve of a spectral component of local wind waves at the sea, where the duraton t of the wind is used as a variable instead of the fetch F.[21] Such evidence is quite understandable if we consider the following relation between the two variables

$$t=F/Cg\ , \tag{20}$$

where Cg denotes the group velocity of the spectral component of waves,

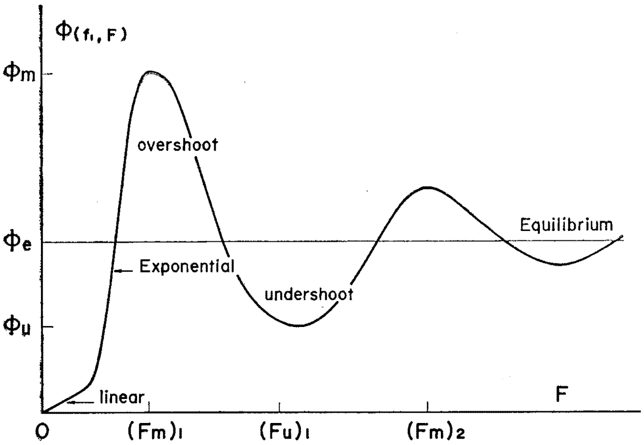


Fig. 6. A schematic growth curve of a spectral component with fetch

The overshoot effect and wave spectrum If we recall the peculiar characteristics in the growth of the wave spectrum shown in Fig. 5, we can easily understand the correspondence between the phenomena shown in Fig. 5 and those shown in Fig. 6. That is, the growth curve of a spectral component shown in Fig. 6 can be obtained when the energy densities of spectra shown in Fig. 5 are traced at a fixed frequency. More generally speaking, the spectral density of wind waves can be represented as

$$\phi\ (f, F,\ u_*, t) \tag{21}$$

within a range of gravity wave in deep water. The growth pattern of wave spectrum shown in Fig. 5 corresponds to a group of frequency spectra $\phi(f)$ in a steady state, in which u_* or F is used as a parameter by fixing the other. On the other hand, the growth curve of Fig. 6 corresponds to $\phi\ (F; f_1, u_{*1})$, i.e., the spectral density at a fixed frequency of waves as a function of the fetch under the action of steady wind.

From those correspondence and from the peculiar characteristics of the wave spectrum shown in Figs. 1, 2 and 3, the following important results can be obtained.

The conditions for the overshoot effect According to the previous discussions, the condition for the overshoot effect is thought to be relating to a fetch graph, i.e., the relation between a dimensionless frequency $u_* f_m/g$ and a dimensionless fetch gF/u_*^2, where f_m denotes the frequency of the maximum spectral density. Fig. 7 shows the comparison of the following fetch equation obtained in the previous study I,

$$\frac{u_* f_m}{g} = 1.00 \left(\frac{gF}{u_*^2}\right)^{-0.330}, \tag{22}$$

and the relation between the similar dimensionless parameters calculated from the data on the overshoot effect reported both by Sutherland and by Barnett & Sutherland [Sutherland,[8] Table 2 and Barnett & Sutherland,[22] Table 2 (ocean data)*)]. As it has been expected, Fig. 7 shows that the relation corresponding to the condition for the overshoot effect is quite similar to the fetch equation for the frequency of the maximum spectral density. When we recall again Figs. 1, 2 and 3 showing that the overshooting frequency is slightly larger than the the frequency of the maximum spectral density, we can easily understand why values of $u_* f_m/g$ obtained from the data of overshoot effect are slightly larger than those of fetch graph.

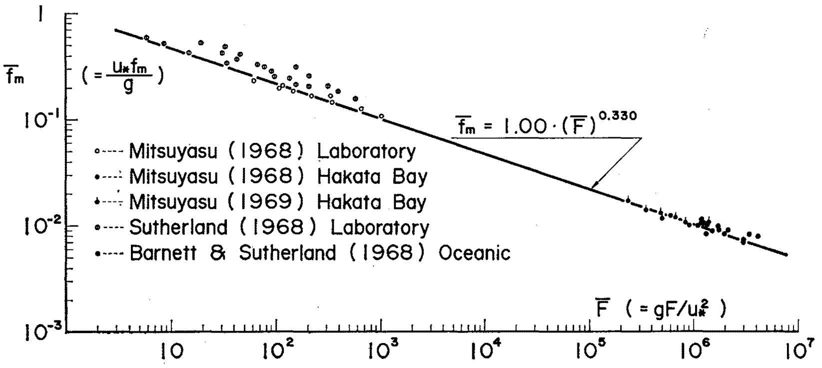


Fig. 7. A comparison of the fetch graph for the frequency of spectral peak and that for the frequency of overshooting wave component

The overshoot and the undershoot When we remember the evidences that the frequency of the second peak in a dimensionless wave spectrum locates at around $2f_m$, and the third peak at around $3f_m$, we can conjecture that, in the growth curve of the wave component of some particular frequency f_1, the second overshoot may happen at the fetch where the spectrum with dominant peak near $f_1/2$ has been generated. On the basis of similar reasoning we can also conjecture that the first undershoot of that wave component may happen at the fetch where the wave spectrum with dominant peak near $f_1/1.5$ has been generated. The existence of the third overshoot may be also expected corresponding to the third perk in a dimensionless wave spectrum.

If we denotes the fetch corresponding to the first overshoot as $(F_m)_1$ and the fetch corresponding to the second overshoot as $(F_m)_2$, the following relation can be obtained from (22)

$$\frac{(F_m)_2}{(F_m)_1} = \left[\frac{(f_m)_1}{(f_m)_2}\right]^{1/0.330} = \left[\frac{(f_m)_1}{\frac{1}{2}(f_m)_1}\right]^{1/0.330} \doteqdot 2^3 = 8 \ . \tag{23}$$

*) For obtaining gF/u_*^2 from oceanic data in Table 2[22] the following relation is assumed $F \doteqdot 2X$,
where X denotes the spatial distance required for a selected component to decay from its peak energy to its minimum energy.

In the same way, if we denotes the fetch corresponding to the first undershoot as $(F_u)_1$, we obtain

$$\frac{(F_u)_1}{(F_m)_1}=\left[\frac{(f_m)_1}{\frac{1}{1.5}(f_m)_1}\right]^{1/0.330}\doteqdot 1.5^3=3.4\ . \tag{24}$$

The experimental data presented by Sutherland (Sutherland[8] Fig. 3) seems to support those inferences.

Ocean waves and laboratory wind waves The oceanic wind waves are quite seldom to show distinctly the overshoot effects either of the type discssed in 2-1 or of the type discussed in 2-2. For example, the phenomenon was not conspicuous in the wave spectrum measured at a bay, although the weak trend of the overshoot effects of the wave spectrum could be seen (I, Fig.9). On the other hand, laboratory wind waves show, in almost every case, the overshoot effects of the either type. What is the reason why such differences are happened? In the previous study, Mitsuyasu attributed the causes for such difference to the special conditions for generating the laboraotry wind-waves, i.e., short fetch, limited width of wave tank, unidirectional and steady wind, etc.[5] However, oceanic measurements of the conspicuous overshoot effects by Barnett & Wilkerson[7] suggest that the difference seems rather to be attributed to the oceanic phenomena. That is, we are considered to have had a few chance to observe the oceanic wind-waves in a uniform wind area corresponding strictly to those wind waves. If we observe the ocean waves at the outside of the generating area, where the wind speed is relatively small, a part of the wave energy concentrated near the dominant peak of the spectrum will be transfered to the othere frequency range by the effect of nonlinear wave-wave interactions.[6] Therefore, the overshoot effect will be difficult to observe in this case. Another cause may be attributed to the relatively short duration of the wind or rather to the unsteadiness of wind speed. Our laboratory measurements are now in progress in order to find the effects of the unsteadiness of wind speed on the wave spectrum.

Concluding remarks

The author's intention in this paper has been to discuss the following peculiar phenomena in the spectrum of wind-generated waves observed in the previous study I; (i) the dependence of the equilibrum spectrum on the dimensionless fetch, and (ii) the overshoot phenomenon in the spectrum of wind-generated waves, and its correspondence to the overshoot phenomenon in the growth curve of a spectral component.

On the basis of the results of the discussions in this paper, the following inferences will be possible on the dynamical models of the wave spectrum:

(i) In the wave spectrum in some equilibrium condition the energy transfered from the wind to a spectral component of waves must be comparable with the sum of the energies lost from that component to the other spectral components by nonlinear wave-wave interactoins, to the other modes of motions mainly by breaking of waves, and the heat through the effect of viscosity.

(ii) Concerning a particular frequency component of wind-generated waves, there is an optimum condition under which the maximum spectral density can be obtained, and its energy is much greater than that of the equilibrium spectrum finally attained. The optimum condition is satisfied when the frequency of that component is very close to, but slightly higher than, the frequency of the dominant peak of the spectrum of wind-generated waves.

(iii) If the condition changes, there is a rapid dissipation of wave energy from that spectral component, even when the wind speed or the fetch is increased, and thus, the growth of the spectrum (i.e. the increase of the total energy and a downward shift of the spectral peak) can be seen. The energy density of that spectral component approaches gradually, in an oscillatory mode, to a final equilibrium value which has been a function of the dimensionless fetch according to the result of part I of this paper.

(iv) The rapid dissipation of wave energy from near the dominant peak of the wave spectrum is largely attributed to the nonlinear wave-wave interaction.

(v) The phenomena described in (ii) and (iii) suggest the existence of special mechanisms which transfer the energy from the wind selectively to the spectral components near the dominant peak of the spectrum, and which keep the equilibrium state of spectral components at high energy level, compensating a large amount of energy loss. The sheltering mechanism and the maser mechanism seem to be responsible for them, because both of them are thought to transfer the energy from the wind selectively to the dominant waves.

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