CHAPTER 13

THE ONE-DIMENSIONAL WAVE SPECTRA AT LIMITED FETCH

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ABSTRACT

The data for the spectra of wind-generated waves measured in a laboratory tank and in a bay are analyzed using the similarity theory of Kitaigorodski, and the one-dimensional spectra of fetch-limited wind waves are determined from the data. The combined field and laboratory data cover such a wide range of dimensionless fetch $\hat{F}$ (= gF/u_*^2) as $\hat{F}$: $10^2 \sim 10^6$. The fetch relations for the growthes of spectral peak frequency ω_m and of total energy E of the spectrum are derived from the proposed spectra, which are consistent with those derived directly from the measured spectra.

INTRODUCTION

In a series of recent papers (Mitsuyasu 1968, 1969 and 1970, hereinafter denoted by I, II and III) the author attempted to uncover the growth characteristics of the spectrum of wind-generated waves at short fetch. In I the low frequency part of the wave spectrum was mainly studied by using the wind and wave data measured in a laboratory tank and in a bay. The low frequency parts of the measured spectra were analyzed using the similarity theory of Kitaigorodski (1961), and the dependence on dimensionless fetch $\hat{F}$ of the constants " a " and " b " in the expression

$$\log_{10}\hat{\Phi} = a + b\,\hat{\omega}\ , \qquad (1)$$

where $\hat{\Phi} = \phi(\omega)\,\omega^5/g^2$,

was determined from the data, where g is the acceleration of gravity, F the fetch, u_* the friction velocity of the wind, $\phi(\omega)$ the frequency spectrum of the wind waves, ω the angular frequency and $\hat{\omega}$ the dimensionless frequency defined by $\hat{\omega} = u_*\omega/g$. Patching together the spectral form for low frequency part and the equilibrium spectrum proposed by Phillips (1958), the author proposed the form of the wave spectrum at limited fetches. The fetch relation for the growth of the dimensionless spectral peak frequency $\hat{\omega}_m$ was determined from the proposed spectrum but the fetch relation for the growth of the dimensionless wave height $\sqrt{\hat{E}}$ (= $g\sqrt{E}/u_*^2$) was not determined due mainly to the difficulties of the mathematical integration of the proposed spectrum, where E is total energy of the wave spectrum defined by

$$E = \int_0^\infty \phi(\omega)\, d\omega \left(= \overline{\eta^2},\ \eta : \text{surface elevation}\right) . \quad (2)$$

In II a high frequency part of the measured wave spectrum was carefully analyzed by using the recent theory of Longuet-Higgins (1969) . It was shown that, as had been predicted by Longuet-Higgins, the equilibrium range constant β was not a universal constant but that β decreased with increasing the dimensionless fetch $\hat{F}$. A tentative empirical relation between β and $\hat{F}$ was determined from the various data of measured wave spectra. Detailed discussions were also made in II on the " overshooting and undershooting effects " of the spectra of wind-generated waves. The excess energy concentration of the wave spectrum near the spectral peak frequency was related to the overshooting effect of the spectral component in the stage of its growth with fetches.

In III the results of the earlier two studies I and II were summed up for obtainning the dimensionless spectral form $\hat{\phi}$ ($= \phi(\omega)\,\omega^5/g^2$) of fetch-limited wind waves. That is, the following spectral form determined in I was used as the spectrum for low frequency part ;

$$\hat{\phi} = 1.66 \times 10^{-9} \exp\left[\, 3.94\, (\hat{F})^{0.283} \hat{\omega} \,\right], \quad \text{for } \omega < \omega_m . \quad (3)$$

The spectral form for high frequency part was determined from the results of study II as

$$\hat{\phi} = \left[\, 21.0 \log_{10} \hat{F} - 34.5 \,\right]^{-1} \text{ for } \omega > \omega_m . \quad (4)$$

The fetch relation for the growth of the dimensionless spectral peak frequency $\hat{\omega}_m$ could be obtained from the proposed spectrum (3) and (4), though the fetch relation for the dimensionless wave height $\sqrt{\hat{E}}$ could not be obtained from the proposed spectrum.

Recently, however, closed comparisons of the proposed spectrum (3) and (4) with the measured spectra have shown that the agreement between them is not so good in some cases. Furthermore, the agreement between the fetch relation for the growth of the dimensionless wave heicht $\sqrt{\hat{E}}$ directly measured and that obtained from the proposed spectrum by numerical integration of the spectrum has been shown to be not so good . Therefore, the author attempt in this paper to revise the spectral forms proposed in III in order to obtain the spectral forms which fit to the measured spectra more closely than the previous one. In the courses of the present study, reanalysis is done on the previous data, some new data have been added, and only the data carefully checked are used for determinning the spectral forms. Patching together the new results for high and low frequencies, the author proposes the revised form of the wave spectrum which can be useful for practical forcasting. The fetch relation for the growth of the dimensionless spectral peak frequency is determined from the revised form of the wave spectrum. The fetch relation for the dimensionless wave hight $\sqrt{\hat{E}}$ is also determined from the revised form of the wave spectrum by the numerical integration of the present spectrum. The both fetch relations agree quite well to those determined directly from the measured spectra.

WIND AND WAVE DATA

The wind and wave data used in the present study are almost the same to those used in our previous study I and II except that two new data measured in Hakata Bay are added. That is, the data obtained in a laboratory tank (Fig. 1) and in Hakata Bay (Fig. 2) are used. As shown in Fig. 1, the wave tank has been divided tentatively by the dividing wall and the ceiling connecting to the wind blower so as to form the ordinary wind-wave channel. In both measurements waves have been measured by capacitance-type wave gages and the vertical wind profiles over the water surface have been measured respectively by traversing a pitot-tube in the laboratory tank and by cup-anemometers at different heights of the observation tower (Fig. 3) in Hakata Bay. The friction velocity u_* of the wind has been determined by the application of the logarithmic law to the measured wind profiles. Many of the wind and wave data in Hakata Bay have been measured when the wind is blowing from the north, and corresponding fetch length is approximately 4.5 km. The spectral analysis of the wave data has been done in the ordinary Blackman-Tukey's method. The degrees of freedom of the measured spectra are approximately 90. The ranges of the dimensionless fetch $\hat{F}$ covered by the present data are $10^2 \sim 10^3$ for the laboratory data and $10^5 \sim 10^6$ for the field data.

SIMILARITY CONSIDEREATION OF THE WAVE SPECTRUM

Kitaigorodski (1961) extensively applied the similarity theory to the description of wave spectra. By a close analogy to the spectrum of turbulence, he has shown that the wave spectrum can be devided into various frequency ranges which respectively have different main controlling factors as schematically shown in Fig. 4. Furthermore, from considerations of similarity theory, he obtained the following general forms of the wave spectrum for each frequency range :

(1) linear [I] and intermediate [II] intervals, $\omega < \omega_0$,

$$\hat{\Phi} = F_1 (\hat{\omega} , \hat{F}), \qquad (5a)$$

$$F_1 = 10^{a + b\hat{\omega}} , \qquad (5b)$$

where " a " and " b " are the dimensionless constants which, in a general case, are the functions of $\hat{F}$.

(2) interval of small scale turbulence [III], $\omega_0 < \omega < \omega_1$,

$$\hat{\Phi} = \overline{\Psi}_1 (\varepsilon_m \omega / g^2) , \qquad (6)$$

where ε_m is the rate of energy dissipation from the frequency range with the maximum value of $\Phi(\omega)$ to the range of high frequencies corresponding to small-scale turbulence. By introducing the relation

$$\varepsilon_m = \alpha \; u_* g \qquad (7)$$

(6) becomes

$$\hat{\Phi} = \bar{\Psi}_1 (\alpha \hat{\omega}) \quad , \qquad (8)$$

where α is a dimensionless constant which, in a general case, is a function of dimensionless fetch $\hat{F}$.

(3) equilibrium interval (Phillips 1958) [IV], $\omega_1 < \omega < \omega_2$ and $\omega \ll \omega_\gamma = (4g^3/ \gamma)^{1/4}$,

$$\hat{\Phi} = \beta \quad , \qquad (9)$$

where γ is the ratio of surface tension σ to water density ρ_w , and β is a dimensionless constant (equilibrium range constant).

(4) interval of small-scale isotropic turbulence [V], $\omega_2 < \omega < \omega_4$,

$$\Phi(\omega) \sim \varepsilon_m \omega^{-4} = \alpha u_* g \, \omega^{-4} \quad , \qquad (10a)$$

or

$$\hat{\Phi} \sim \alpha \hat{\omega} \qquad (10b)$$

(5) capillary-turbulence interval [VI], $\omega_4 < \omega < \omega_5$,

$$\Phi(\omega) \sim \varepsilon_m \omega^{-4} \bar{\Psi}_2 (\gamma^{2/3} \omega^{5/3} / \varepsilon_m)$$

$$\sim \alpha u_* g \omega^{-4} \bar{\Psi}_2 (\gamma^{2/3} \omega^{5/3} / \alpha u_* g) , \qquad (11a)$$

or

$$\hat{\Phi} \sim \alpha \hat{\omega} \bar{\Psi}_2 (\gamma^{2/3} \omega^{5/3} / \alpha u_* g) . \qquad (11b)$$

In addition to these spectra, he also proposed the following spectra ; gravity-capillary interval

$$\hat{\Phi}(\omega) \sim \psi (\gamma \omega^4 / g^3), \qquad (12)$$

and pure capillary interval

$$\Phi(\omega) \sim \gamma^{2/3} \omega^{-7/3} . \qquad (13)$$

(12) can be considered as a more general formula of the equilibrium spectrum (9), where the frequency range is extended to higher frequency side and the capillary effect is included. (13) can be obtained when the effect of molecular viscosity is neglected in a pure capillary interval where the condition $\omega \gg \omega_\gamma$ is satisfied and $\Phi(\omega)$ does not explicitly depend on g.

In our present study, the discussions of the wave spectrum will be confined only to the gravity wave range in which the influences of the surface tension and molecular viscosity are neglisible, because the highest frequency of our measured spectra is at most 7 Hz which is smaller than f_γ $(= 1/2\pi \cdot [4g^3/ \gamma]^{1/4}) \doteqdot 14$ Hz. The interval of small scale isotropic turbulence is tentatively neglected because, as will be shown later, the frequency dependence " ω^{-4} " of the measured spectra can not be found in our measured spectrum. Therefore, the frequency ranges of our measured spectra extend from the linear interval [I] to the equilibrium interval [IV] in the classification by Kitaigorodski. According to the above discussions the spectral form (8) can be modified into

$$\hat{\Phi} = \Psi_3 (\hat{\omega}, \hat{F}) . \qquad (14)$$

because α in (8) is assumed to be a function of $\hat{F}$. On the other hand, according to our previous study II equilibrium spectrum (9) can be shown, in a more general form, as

$$\hat{\Phi} = \beta (\hat{F}) , \qquad (15)$$

because β has been shown to be a function of $\hat{F}$. Comparing (5a), (14) and (15), it will be natural to assume that the general form of our measured spectrum which is in a frequency range $0 < \omega < \omega_2$ can be shown, in a general expression, as

$$\hat{\Phi} = \Phi (\hat{\omega} , \hat{F}) . \qquad (16)$$

LOW FREQUENCY PART OF THE WAVE SPECTRUM

Fig. 5 shows our measured spectra which are normalized according to (16). It will be seen from Fig. 5 that the functional form of (16) for the low frequency part $\omega < \omega_m$ can well be approximated by (1). In our previous study I, the dependence on the dimensionless fetch $\hat{F}$ of the constants " a " and " b " in (1) have been determined from three groups of data, i.e., the data obtained in our laboratory tank, the data obtained in Hakata Bay and Burling's data analyzed by Kitaigorodski (1961). In the present determinations of the constants, however, we will not use Burling's data, because the spectral form (1) is very sensitive to the value of " b " and Burling's data on " b " seem to deviate slightly but systematically from our data as shown in Fig. 6. Furthermore, some of our previous data are reanalyzed in order to obtain more reliable results.

Fig. 6 shows the revised relations between the dimensionless fetch $\hat{F}$ and the constants " a " and " b ", which have been obtained by using the reanalyzed data. Other data obtained by Burling (1959), Moskowitz (1964) and Stevens (1965) are shown for the comparison. The following simple relations can be obtained by the method of least squares :

$$a = -9.04 , \qquad (17)$$

$$b = 1.53 \hat{F}^{0.312} . \qquad (18)$$

On substituting (17) and (18) into (1) we can determine the functional form of the wave spectrum as

$$\hat{\Phi} = 9.12 \times 10^{-10} \exp 3.55 \hat{F}^{0.312} \hat{\omega} . \qquad (19)$$

(19) can be considered as the spectral form in a frequency range lower than the spectral peak frequency ω_m . It should be mentioned here that the spectrum $\Phi(\omega)$ derived from (19) has the minimum value at some frequency near $\omega_c = 0.3\ \omega_m$, the values of which depend weakly on the dimensionless fetch $\hat{F}$, and for $\omega < \omega_c$ $\Phi(\omega)$ increases with decreasing ω approaching finally to ∞ for $\omega \rightarrow 0$. Therefore, strictly speaking, (19) should be used for the frequency range greater than a cut-off frequency ω_c ($\fallingdotseq 0.3\ \omega_m$). This restriction for the spectral form introduces no problems for the practical applications of the spectrum, because the spectral energy at near the cut-off frequency ω_c is neglisiblly small.

HIGH FREQUENCY PART OF THE WAVE SPECTRUM

The following equilibrium form proposed first by Phillips (1958) is used tentatively as the functional form of (16) for the high frequency part

$$\hat{\Phi} = \beta (\hat{F}) \qquad \text{for} \quad \omega > \omega_m , \qquad (20)$$

Although Phillips (1958) had conjectured β being universal constant, it was shown in our previous study II that β depend on the dimensionless fetch $\hat{F}$ as had been predicted by Longuet-Higgins (1969). It was also shown in II that high frequency part of the measured wave spectrum showed, in some cases, the oscillatory deviation from the spectral form given by (20)*) In other words, the " overshooting " and " undershooting " were seen in some of the measured spectra. These facts mean that β depend not only on dimensionless fetch $\hat{F}$ but also on dimensionless frequency $\hat{\omega}$. These results may be partly attributed to the facts that the equilibrium form (20) has been originally proposed only for the spectrum in some narrow frequency range

$$\omega_m \ll \omega \ll \omega_\gamma , \qquad (21)$$

but we have applied it to the spectrum in such a wide frequency range as $\omega > \omega_m$. Therefore, the interval of small-scale turbulence, which is a function of $\hat{\omega}$ and $\hat{F}$ as shown in (8), is included in (20). However, if we take some kind of average of $\Phi (\hat{\omega} , \hat{F})$ with respect to $\hat{\omega}$ we can derive a functional form which is only a function of $\hat{F}$. The assumption of (20) for the spectral form for high frequency part corresponds to such procedure.

In II, β has been determined in three different ways, i.e., (i) β which is the mean value of $\hat{\Phi}$ with respect to $\hat{\omega}$ in a frequency range $\hat{\omega} > \hat{\omega}_m$, (ii) β_1 which is determined by

$$\beta_1 = \int_{\omega_m}^{\infty} \Phi(\omega)\, d\omega \Big/ \int_{\omega_m}^{\infty} g^2 \omega^{-5}\, d\omega , \qquad (22)$$

(iii) β_2 which is determined by the method of least squares, under the assumption that the spectral form is $\Phi(\omega) = \beta_2\, g^2\, \omega^{-5}$. The dependence of β defined by (i) on $\hat{F}$ has been mainly studied in II.

*) Such a characteristic can be seen in the laboratory spectra shown in Fig. 5.

However, we will use β_1 for the present study, because it is more reasonable to use β_1 for the discussion of the total energy of the wave spectrum. In the previous study II, the following relation has been determined by using the theory of Longuet-Higgins (1969) ;

$$\beta = [D \log_{10} \hat{F} - G]^{-1} \tag{23}$$

D and G are dimensionless constants, and they have been determined from the measured values of β and $\hat{F}$. In the present study, however, the measured values of β_1 and $\hat{F}$, which has been also shown in II (Table 1)*), are used for determining, by the method of least squares, the constant D and G in (23). The relation finally obtained in the present analysis is given by

$$\beta_1 = [\, 24.3 \log_{10} \hat{F} - 47.1 \,]^{-1} . \tag{24}$$

In addition to this relation, the following empirical relation is obtained from the same data ;

$$\beta_1 = 0.589\, \hat{F}^{-0.308} . \tag{25}$$

As can be seen from Fig. 7 the relation (25) fits quite well to the observed results and it is better than the relation (24) within a range of $\hat{F}$: $10^2 \sim 10^6$. Therefore, the relation (25) will be used for the present study. Now, substituting (25) into (20), the high frequency part of the wave spectrum can be determined as

$$\hat{\Phi} = 0.589\, \hat{F}^{-0.308} . \tag{26}$$

(26) can be considered as a kind of equilibrium spectrum of fetch-limited wind waves.

A. PROPOSED SPECTRUM OF WIND WAVES AT LIMITED FETCH

In the preceding sections, on the basis of the accurately measured wave spectra, we have experimentally determined the forms of the spectrum of wind waves at short fetches. Applying (19) to the spectrum in the low frequency range $\omega_c < \omega \leqslant \omega_m$, and (26) to that in the high frequency range $\omega \geqslant \omega_m$, and defining conventionally the spectral peak frequency ω_m as the intersection of the both spectral forms one can get the spectral form of wind waves at limited fetch, which is schematically shown in Fig. 8. When the frequency is measured in cycles instead of radian, the proposed spectral form can be writen as

$$\hat{\Phi} = 5.86 \times 10^{-13} \exp [\, 22.1\, \hat{F}^{0.312}\, \hat{f} \,], \qquad \hat{f}_c < \hat{f} \leqslant \hat{f}_m , \tag{27}$$

$$\hat{\Phi} = 3.79 \times 10^{-4}\, \hat{F}^{-0.308}, \qquad \hat{f} \geqslant \hat{f}_m , \tag{28}$$

where $\hat{f}$ is the dimensionless frequency defined by

$$\hat{f} = \hat{\omega} / 2\pi \quad (= u_* f / g) . \tag{29}$$

*) In Table 1 β_1' is shown instead of β_1, but β_1 can be obtained from β_1' by using the relation $\beta_1 = (2\pi)^4 \beta_1'$.

Figs. 9a, 9b and 9c show some examples of the comparison of the measured spectra with the proposed spectrum. As can be seen from these figures, the proposed spectra fit quite well to the measured spectra.

At the intersection of the spectral forms (19) and (26) or (27) and (28), which corresponds to the spectral peak, the following relations are satisfied :

$$\hat{\omega}_m = (5.76 - 0.201 \log_{10} \hat{F}) \hat{F}^{-0.312}, \qquad (30)$$

$$\hat{f}_m = (9.17 - 0.320 \log_{10} \hat{F}) \times 10^{-1} \hat{F}^{-0.312}. \qquad (31)$$

(30) or (31) represents the fetch relation by which the dimensionless frequency of spectral peak can be determined as a function of the dimensionless fetch $\hat{F}$. (31) can be simplified, with sufficient accuracy, to the following equation*);

$$\hat{f}_m = 0.917 \hat{F}^{-0.327} \quad . \qquad (32)$$

(32) is very close to the following fetch relation which is determined directly from the measured spectra ;

$$\hat{f}_m = 1.00 \hat{F}^{-0.330} \quad . \qquad (33)$$

On the other hand, it is difficult to determine the fetch relation for the total energy of our proposed spectrum, because the integration of (19) or (27) is analytically difficult. That is, in order to obtain the fetch relation for the total energy of the proposed spectrum it is necessary to perform the following integrations ;

$$\begin{aligned} E = E_1 + E_2 &= \int_{\hat{f}_c}^{\hat{f}_m} \Phi \, d\hat{f} + \int_{\hat{f}_m}^{\hat{f}_N} \Phi \, d\hat{f} \\ &= 5.86 \times 10^{-13} \int_{\hat{f}_c}^{\hat{f}_m} (\hat{f})^{-5} \exp [22.1 \hat{F}^{0.312} \hat{f}] \, d\hat{f} \\ &\quad + 3.79 \times 10^{-4} \int_{\hat{f}_m}^{\hat{f}_N} (\hat{f})^{-5} \hat{F}^{-0.308} \, d\hat{f} \; , \end{aligned} \qquad (34)$$

where $\hat{f}_c$ is the dimensionless cut-off frequency and $\hat{f}_N$ the dimensionless Nyquist frequency. The second integration can be easily done reducing to

$$E_2 = 9.48 \times 10^{-5} \hat{F}^{-0.308} [(\hat{f}_m)^{-4} - (\hat{f}_N)^{-4}], \qquad (35)$$

but the first integration is difficult. Therefore, the first integration has been done numerically for some typical values of $\hat{F}$ which are within the range $\hat{F}$: $10^2 \sim 10^7$. The results have been then added to E_2 obtaining finally the total energy E . By using the values of the total energy E thus obtained corresponding to the dimensionless fetch $\hat{F}$, the following fetch relation has been determined by the method of least squares

$$\sqrt{\hat{E}} \; (= g\sqrt{E} \, / \, u_*^2) = 1.22 \times 10^{-2} \hat{F}^{0.514} \quad . \qquad (36)$$

*) This is performed by taking the logarithm of the both sides of (31) and taking the first term in the expansion of the type of $\ln (1 - x) = -x - x^2/2 - \cdots\cdots$

(36) is very close to the following fetch relation obtained directly from the measured spectra ;

$$\sqrt{\hat{E}} = 1.13 \times 10^{-2} \hat{F}^{0.504} \quad . \qquad (37)$$

Fig. 10 shows the fetch relations for the growth of dimensionless spectral peak frequency $\hat{f}_m$ and for the growth of dimensionless wave height $\sqrt{\hat{E}}$, which have been determined directly from the measured spectra. Fig. 10 also includes the following fetch relations ;

$$\hat{f}_m = 9.46 \times 10^{-1} \hat{F}^{-1/3} \ , \qquad (38)$$

$$\sqrt{\hat{E}} = 1.5 \times 10^{-2} \hat{F}^{1/2} \ , \qquad (39)$$

which are determined from Wilson's formulas IV (Wilson 1965) under the present assumptions ;

$$U_{10} = 25\, u_* \ , \qquad H_{1/3} = 4\sqrt{E} \ , \qquad T_{1/3} = 1/1.05\, f_m \qquad (40)$$

Although the fetch relation (32) and (36) which have been determined from our proposed spectra are not shown in Fig. 10 to avoid the congestion of the figure, they are very close to our directly measured one and Wilson's one. Therefore, it can be said that the proposed spectrum not only fits quite well to the measured spectra but also gives quite accurate fetch relations both for f_m and for E . For convenience, the present spectral form will be called as Formula I (revised).

DISCUSSIONS AND CONCLUSION

In a previous paper (Mitsuyasu 1971), starting from a simple assumption that the general form of the wave spectrum can be given by

$$\phi(f) = k_1 f^{-5} \exp[-k_2 f^{-4}] \ , \qquad (41)$$

where k_1 and k_2 are undetermined constants, and using the empirical fetch relations (33) and (37) for determining the constants k_1 and k_2, the author has derived the following spectral form of fetch-limited wind waves (Formula II).

$$\hat{\phi} = 8.58 \times 10^{-4} \hat{F}^{-0.312} \exp[-1.25 \hat{F}^{-1.32} \hat{f}^{-4}] \ . \qquad (42)$$

It was also shown that (42) is almost the same to the simplified spectral form of Bretschneider (1968) and (42) approaches to the spectral form of Pierson-Moskowitz (1964) at near $\hat{F} = 10^7$.

Obviously, Formula II gives quite consistent results for the growthes of the spectral peak frequency f_m and of the total energy E of the wave spectrum, because the empirical fetch relations for f_m and E have been used in its derivation. However, slight differences exist between its spectral form and measured spectra particularly at a low frequency part and at near the spectral peak. In this respect, present spectral form [Formula I (revised)] gives much better agreement to the measured spectra, though its spectral form is not so simple as Formula II. Therefore, the selection of either spectra will depend on the application purpose of the wave spectrum.

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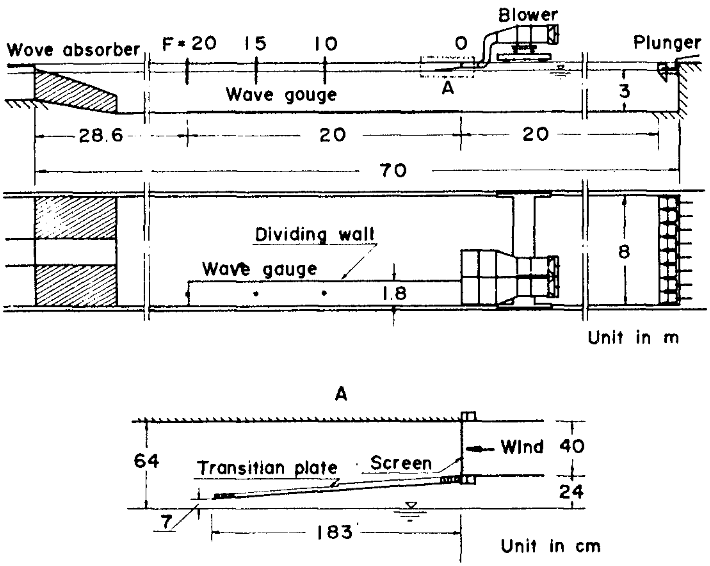


Fig. 1. WIND-WAVE FACILITY

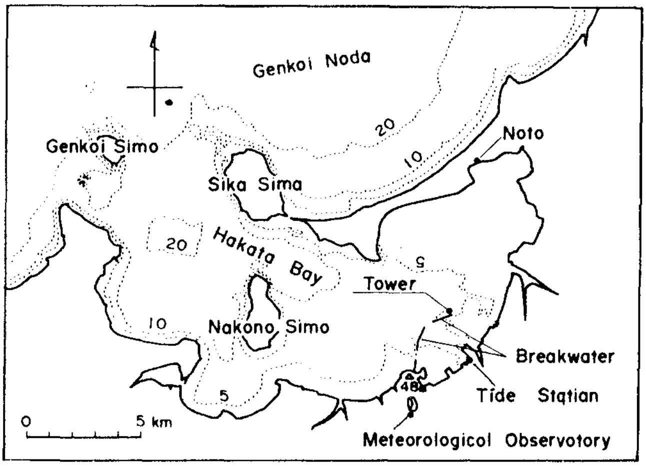


Fig. 2 SITE OF THE FIELD OBSERVATION
(HAKATA BAY)

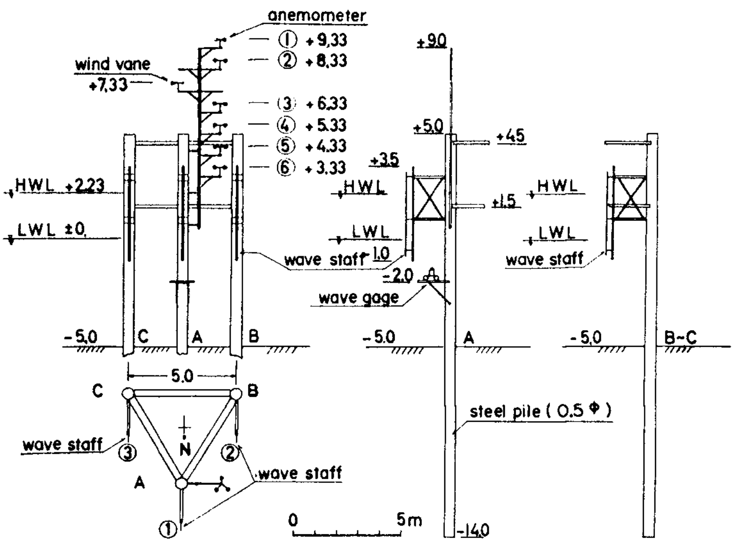
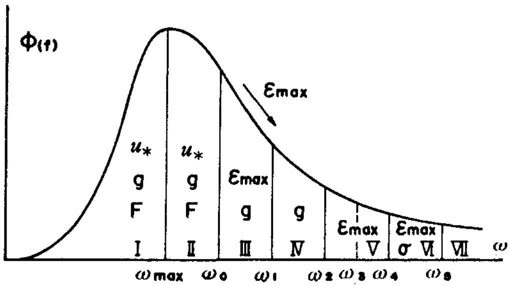


Fig. 3 OBSERVATION TOWER, UNIT IN M



I linear interval
II intermediate interval
III interval of small scale turbulence
IV equilibrium interval (breaking)
V interval of small scale isotropic turbulence
VI capillary turbulence interval
VII dissipation interval

Fig. 4 SCHEMATIC REPRESENTATION OF WIND-WAVE SPECTRUM (KITAIGORODSKI, 1961)

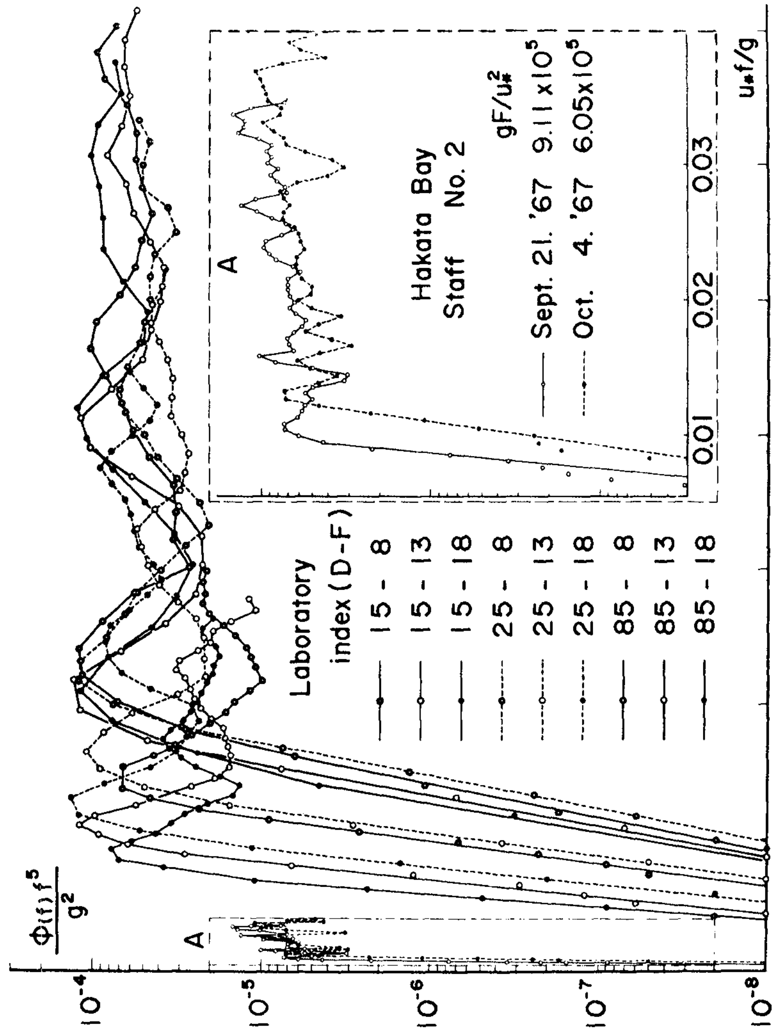


Fig. 5 NORMALIZED WAVE SPECTRUM

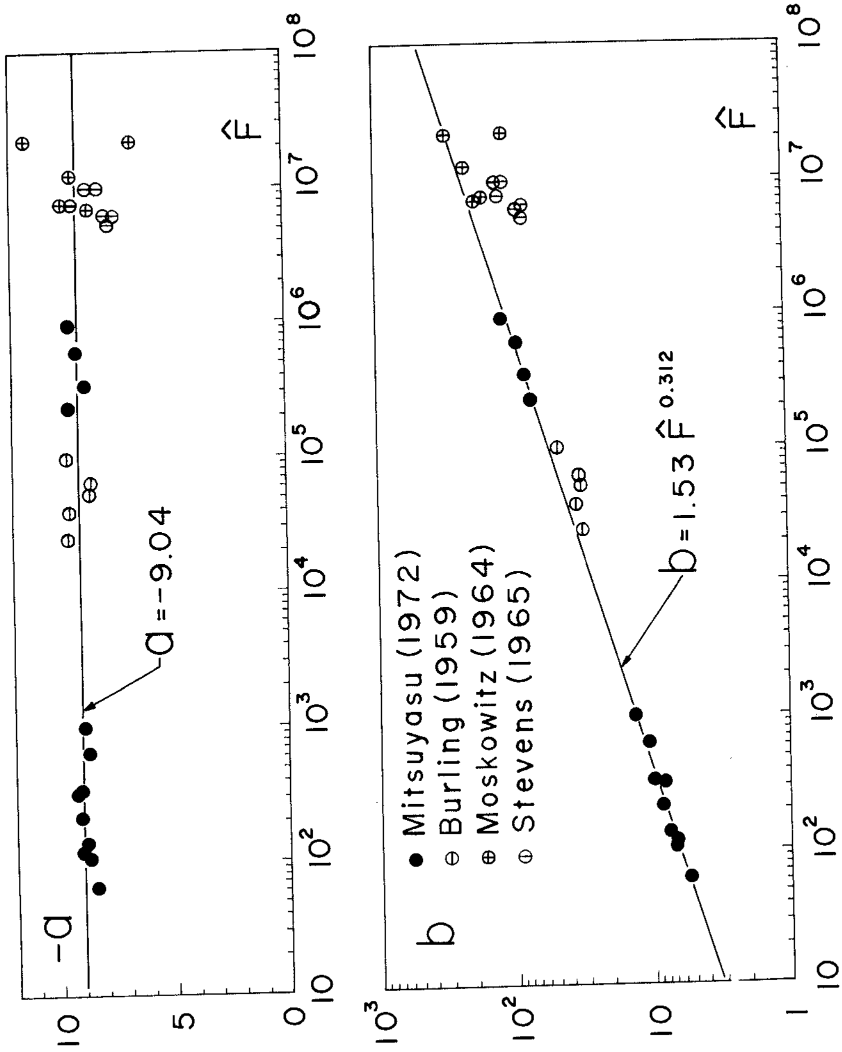


Fig. 6 THE RELATION BETWEEN DIMENSIONLESS CONSTANTS a AND b AND THE DIMENSIONLESS FETCH $\hat{F}$

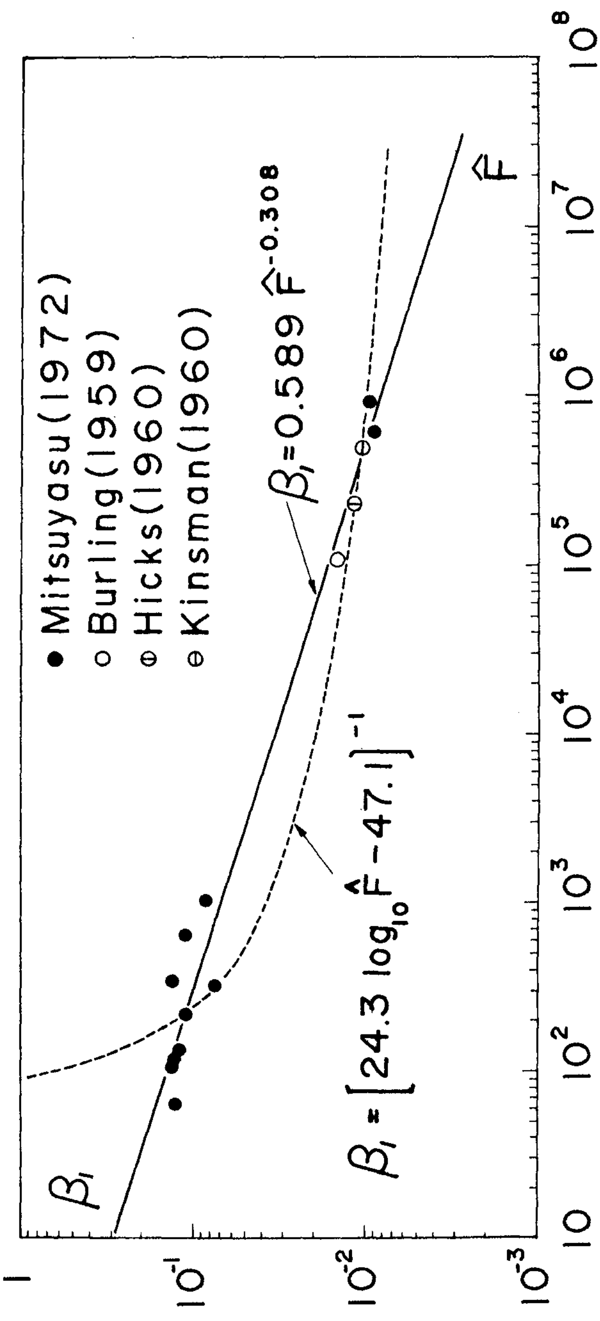


Fig. 7 THE RELATION BETWEEN EQUILIBRIUM RANGE CONSTANT β_1 AND THE DIMENSIONLESS FETCH $\hat{F}$.

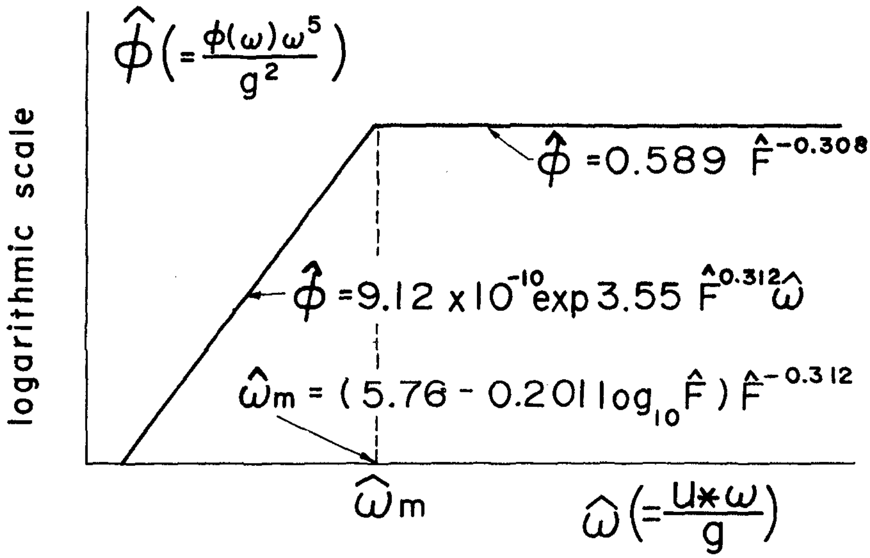


Fig. 8 PROPOSED FORM OF WIND-WAVE SPECTRUM

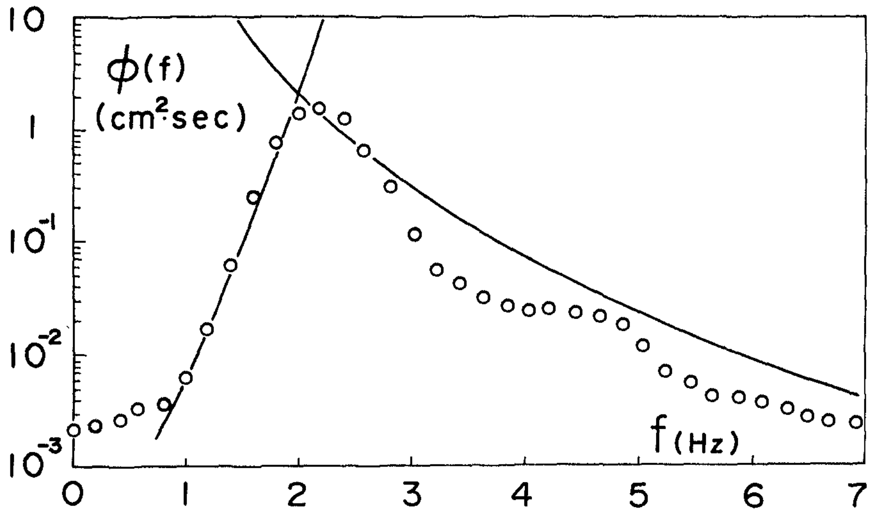


Fig. 9a COMPARISON OF THE PROPOSED SPECTRUM WITH THE MEASURED ONE.
(LABORATORY, $\hat{F} = 2.15 \times 10^2$)

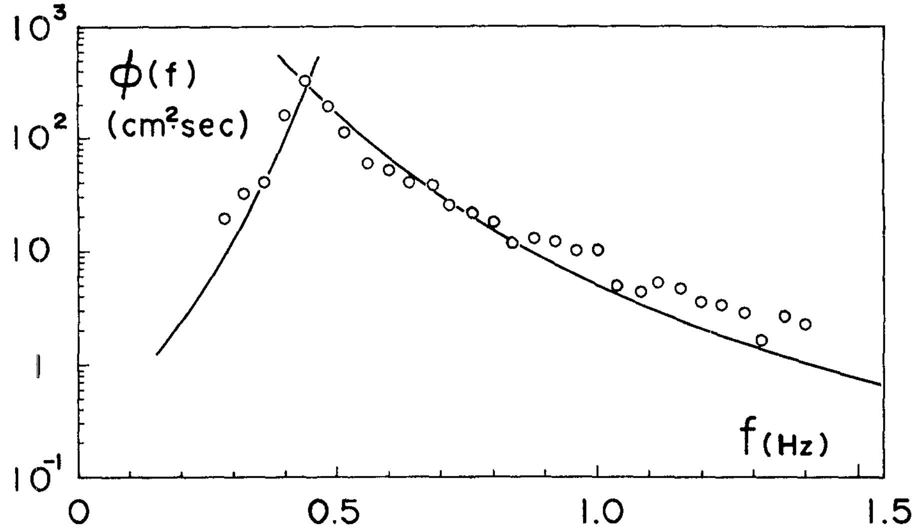


Fig. 9b COMPARISON OF THE PROPOSED SPECTRUM WITH THE MEASURED ONE.
(HAKATA BAY, $\hat{F} = 9.11 \times 10^5$)

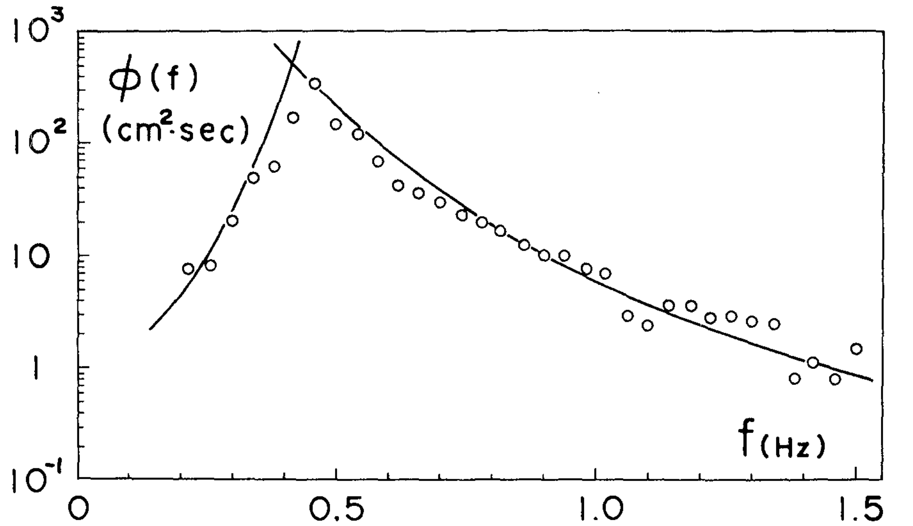


Fig. 9c COMPARISON OF THE PROPOSED SPECTRUM WITH THE MEASURED ONE.
(HAKATA BAY, $\hat{F} = 6.05 \times 10^5$)

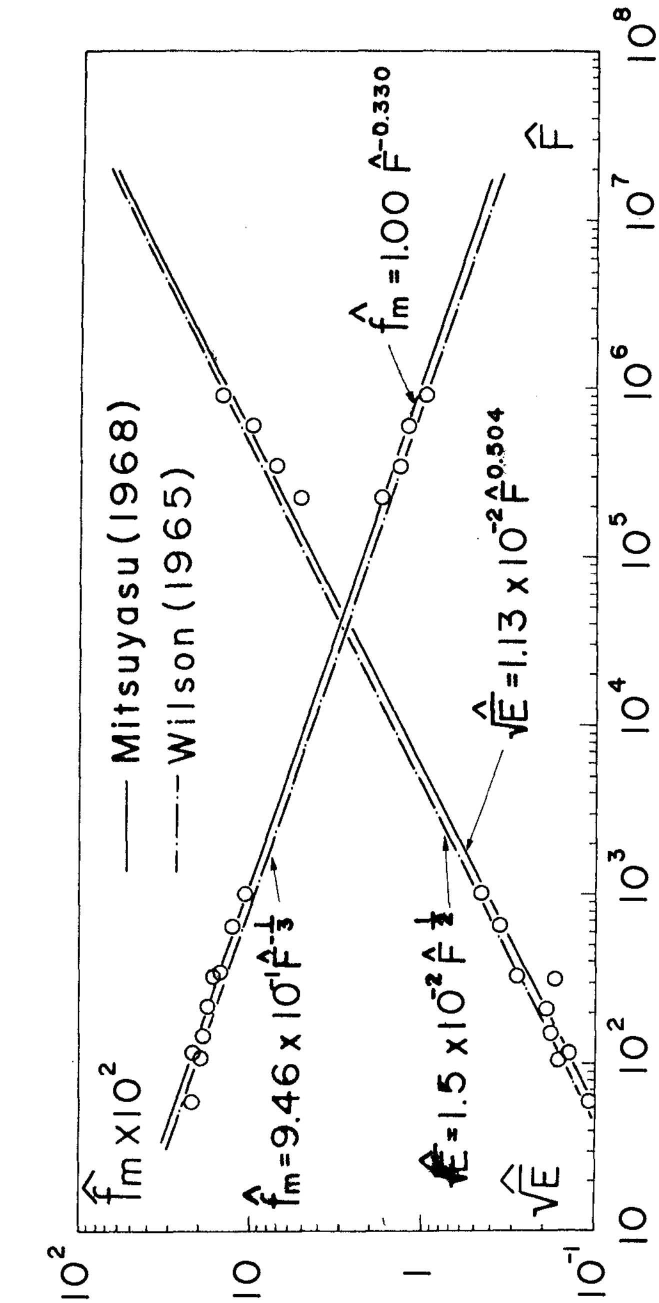


Fig. 10 FETCH GRAPH : DIMENSIONLESS SPECTRAL PEACK FREQUENCY $\hat{f}_m$ AND DIMENSIONLESS WAVE HEICHT $\sqrt{\hat{E}}$ VERSAS DIMENSIONLESS FETCH $\hat{F}$