Oceanologia, 18 (1984)
PL ISSN 0078-3234

CZESŁAW DRUET, RYSZARD SIWECKI
Polish Academy of Sciences,
Institute of Oceanology, Sopot

THE INFLUENCE OF EARLY STAGES OF DEVELOPMENT OF WIND WAVES ON THE EFFECTIVE ROUGHNESS OF THE WATER FREE SURFACE

(Received Apr. 19, 1982; in final form Aug. 30, 1982)

Abstract

The paper presents the results of measurements of high-frequency wind waves, carried out, during the "Kamchiya 79" experiment, in various anemobaric situations on the immovable platform situated at a depth of 6 m.
Spectral and frequency characteristics of wind waves are discussed and dimensionless estimator of the function of high-frequency spectrum of wind wave energy is formulated. The spectra on both slopes of the carrier wave are compared.
Correlations between wind velocity, variance of high-frequency waves, the Reynolds number and the stage of development of the wind waves are presented.

1. THE SUBJECT AND AIM OF INVESTIGATIONS

The free surface of the sea is the interface of two fluid media, i.e. water and air. Their density difference is great enough $\rho_a/\rho \approx 10^{-3}$, ($\rho_a$ and ρ are the densities of air and water, respectively) to screen the transfer of mass and energy fluxes between the sea and the atmosphere. For these reasons, various high-frequency irregularities occurring on the free surface of a water area may be considered as rough elements resistant to air masses dislocated above this surface. As opposed to land surfaces, however, rough elements of the sea surface are movable. Irrespective of wind velocity, they always constitute a structural part of the wave process called wind waves. In very light breezes or the initial stages of generation of such waves, fine ripples of the capillary wave category will constitute rough elements. In the remaining cases, more or less developed gravity waves will constitute such elements. Within the high-frequency range components of the wind waves random field, the phase velocity (C) of which is considerably lower than the wind velocity (U), it can be assumed, with an accuracy satisfactory for practical purposes, that roughness elements are immovable, i.e. they behave like the roughness elements of land surfaces. The indicator of air turbulence affecting the intensity of the momentum exchange processes in the near-surface layer can here be characterized by the Reynolds number [4, 10]

$$Re = \frac{l \cdot U_*}{\nu_a} \tag{1}$$

where l is the characteristic size scale of gravity waves with a phase velocity of $C \ll U$, v_a the kinematic coefficient of air viscosity, and U_* the dynamic friction velocity.

In higher stages of development of wind waves, the assumption on immovable elements of roughness becomes more and more problematic. In the random field of these waves, components with phase velocities comparable to those of the wind velocity, or even higher, occur more frequently. These components cannot be considered as immovable elements. Owing to the small velocity difference ($U-C$ small), they are "flown round" by air streams, similar to the case of higher elevations on the land. High-frequency waves located on these components act upon the displacing air mass with a considerably diminished efficiency caused by a decrease in the relative velocity $U-C$.

The developed field of wind waves will thus include a number of various components (irregularities), among which only the high-frequency band, responsible for the effective roughness of the free surface of the sea, and the low-frequency band, responsible for the "flowing round" processes, can be defined approximately as regards their effect upon the dynamics of exchange processes. The influence of the remaining components of the random field of wind waves has not been precisely determined as yet. It can only be stated, that when a fully developed field of wind waves occurs, the characteristics of turbulence and tangential stresses in the atmospheric near-water layer depend both on the Reynolds number and the stage of development of wind waves, this being characterized by the following parameter [4, 10]

$$F=\frac{g\cdot\sigma_\Sigma}{U_*^2}, \tag{2}$$

where σ_Σ is the standard deviation of the wind waves random process, related to the function of the full frequency spectrum of wind waves energy $S(\omega)$ by the zero moment of spectral density

$$\sigma_\Sigma^2=\int_0^\infty S(\omega)\,d\omega \tag{3}$$

where ω denotes the angular frequency of the waves.

Numerous investigations have been carried out in the field of the above-defined effect of wind waves upon the sea-air momentum exchange processes. Among the authors, Kitaigorodskii and his associates obtained some important results. In conformity with their findings, the estimator of the velocity distribution for the wind blowing over an undulating sea surface is represented by the higher approximation of the well known logarithmic distribution [4]

$$U(z)=\frac{U_*}{\kappa}\left\{\ln\left(\frac{z}{z_0}\right)-\frac{1}{2}\left[\frac{\sigma_\Sigma}{z}\cdot\exp(-k_0\cdot z)\right]^2\right\} \tag{4}$$

where k_0 is the wave number assigned to the highest maximum in the distribution of the frequency spectrum of wind waves energy, and $\kappa\approx 0.4$ – the Karman constant.

The roughness parameter z_0 in this formula denotes the quantity most sensitive to the influence of wind waves. This parameter determines the distribution of wind velocity in the near-water air layer through the aerodynamic coefficient of air resistance

$$C_\tau=\kappa^2\cdot\ln^{-2}\left(\frac{z}{z_0}\right) \tag{5}$$

which is connected with a similar coefficient determining the water-mass drift flow in the near-surface layer

$$\mu_0=\frac{\rho_a}{\rho}\cdot C_\tau \tag{6}$$

The relatively large number of experiments carried out to estimate the values of these coefficients pointed out their considerable differentiation ($C_\tau\approx 10^{-3}\div 3\cdot 10^{-3}$) due to variability of the parameter z_0. Ellison's investigations [3] proved that in the first approximation the tangential stress τ_0 was proportional to the roughness parameter ($\tau_0\sim\rho_a g z_0$). As this stress is also proportional to the dynamic friction velocity ($\tau_0\sim\rho_a U_*^2$), one can write

$$z_0\sim\frac{U_*^2}{g}=m\,\frac{U_*^2}{g} \tag{7}$$

This relationship is known as the Charnock-Ellison formula [1].

Initially, the factor of proportionality m was considered to be constant. It was later found that it is, unfortunately, variable (its variability within the range $10^{-2}\div$ $\div 8\cdot 10^{-2}$ [4], caused mainly by the influence of wind waves, has so far been proved experimentally). In accordance with theoretical and empirical investigations by Kitaigorodskii *et al.* [4, 10], the high-frequency range of the spectral density of wind waves energy is essentially responsible for the effective roughness of the free surface of the sea. Thus, the mean height of wind waves belonging to the high-frequency band, propagated at phase velocities much lower than the wind velocity, should be a measure of this influence. After Kitaigorodskii, the mean height of these waves can be expressed by the following form [4]

$$\bar{H}_w=\left[2\int_0^\infty S_w(\omega)\cdot\exp\left(-\frac{2\kappa g}{\omega U_*}\right)d\omega\right]^{\frac{1}{2}} \tag{8}$$

where $S_w(\omega)$ is the high-frequency spectrum of wind waves energy in the $\omega\gg\omega_0$ frequency band, and ω_0 denotes the frequency of the main maximum in the full distribution of the spectral density of energy.

The analysis of relationship (8) in the ranges characterizing various stages of development of wind waves [4, 10] gives rise to the conclusion as to the conditions affecting variability of the coefficient m in formula (7). This coefficient decidedly depends on two dimensionless quantities: F and Re (formulae 1 and 2). For these reasons, expression (7) may be written in the general form

$$z_0=f(F,Re)\,\frac{U_*^2}{g} \tag{9}$$

At very small wind velocities, both capillary waves and gravity ripples are completely immersed in the viscous sub-layer, the thickness of which is $\delta=\frac{v_a}{U_*}$ and which decreases rapidly with increasing *Re*. Under these circumstances, the coefficient *m* depends mainly on *Re* and, taking into consideration (1), expression (9) may take the form

$$z_0=f(Re)\frac{U_*^2}{g}=Re^{-1}\frac{U_*^2}{g}\approx m_0\frac{v_a}{U_*} \quad (10)$$

where $m_0\approx 0.1=\text{const}$ [10].

In later stages of generation of waves, expression (9) is conditioned mainly by wind waves. Knowing the function $m=f(F, Re)$ and the dynamic velocity U_* and using relationship (9) it would be possible to find the roughness parameter values in various stages of development of waves. Unfortunately, the function $m=f(F, Re)$ has not been determined precisely as yet, and attempts to assume its simplified and approximate representation have not afforded satisfactory results. Moreover, the problem is additionally complicated by the dependence of the dynamic velocity U_* on wind waves in the high-frequency band.

In this connection, the main purpose of the investigations under consideration was further examination of the relations between statistical characteristics of the random field of wind waves and the quantities which determine the roughness parameter affecting relationships (4) to (6).

2 THE METHODS AND SCOPE OF INVESTIGATIONS

The methods employed by the authors in the investigations consisted in recordings (in natural conditions) of random trains of wind waves using electronic capacitive wave recorders (Fig. 1). Each of the wave-trains was recorded on magnetic tape and analyzed subsequently by digital computer to determine such statistical characteristics as: correlation relations, spectral density of energy, variance, etc. The motion of the free surface of the water area investigated, measured at a fixed site by a wire sensor of the wave recorder, was transmitted to the processing apparatus, in which it was appropriately amplified, attenuated or filtrated, then recorded on magnetic tape. By this means, two records of a random train of wind waves were obtained for each 15-minutes' empirical run. The one characterized the full course of the wave process and the second represented the high-frequency band of this random wave train in the frequency range of $\omega\geqslant 6.28$. Realization of the high-frequency waves was obtained from the first record by filtering off the components with the frequencies of $\omega<6.28$ and by subsequent appropriate amplification of amplitude characteristics of the remaining waves.

Simultaneous with wave recordings by wire capacitive wave recorders, recordings via wire resistance wave recorders were conducted for intercalibration purposes. These recordings enabled proper work of the wave recorders to be monitored on the one hand, and on the other hand revealed an important advantage of capacitive

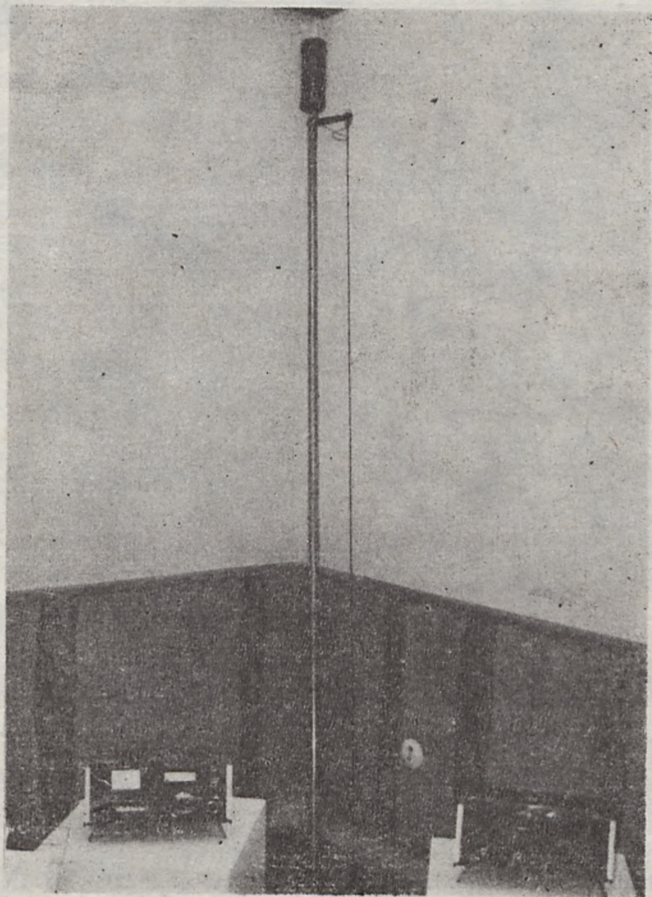

Fig. 1. View of the wire sensor of the capacitive wave recorder.

sensors for recording high-frequency bands. Namely, as opposed to resistance sensors, settlement of various impurity films on the capacitive wave-recorder wire, mostly at the zero ordinate, does not affect the amplitude characteristics of high--frequency waves. The dynamic parameters of the capacitive sensor used in the investigations are as follows: the frequency of the pulses modelled – 60 Hz (the waves recorded alter the pulse length), the possibility of recording the lowest wave amplitudes is restricted by the meniscus on the wire to 1–2 mm, the possibility of recording time variations (wave periods) is restricted to 20 Hz. The long-term stability of the device is about 2 mm.

The examination of the structure of the high-frequency band of wind waves constituted part of the "Kamchiya–79" complex international scientific experiment of the CMEA member countries carried out in the Black Sea coastal zone in Bulgaria. The wave recordings were made from an immovable platform (Fig. 2) on which a number of other physical quantities were also recorded, viz.: wind velocity and direction, pulsatory quantities characterizing heat and momentum fluxes in the

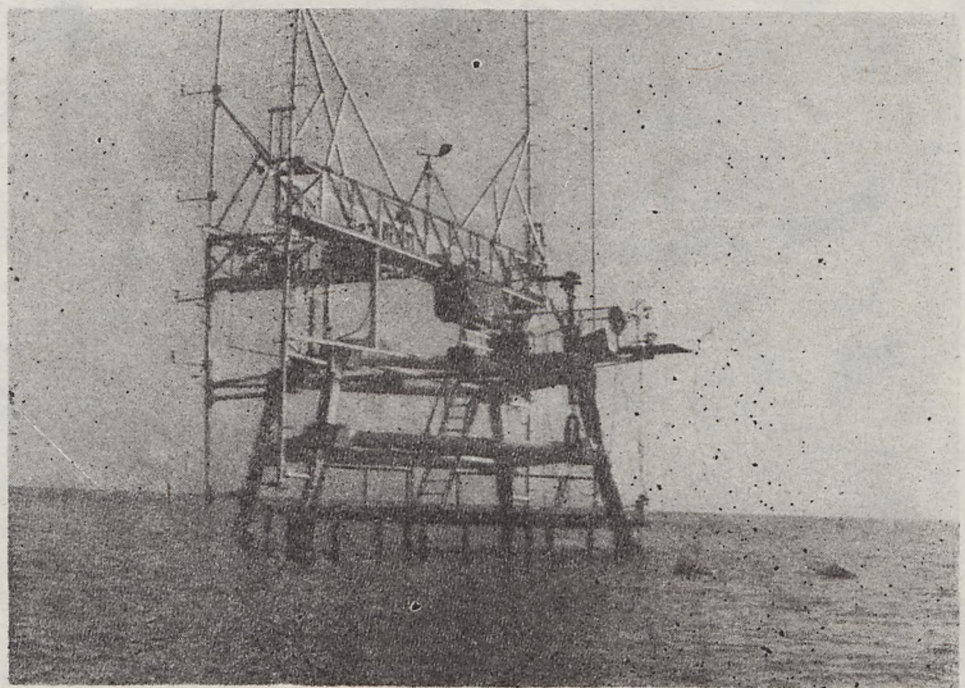

Fig. 2. View of the investigation platform at Shkorpilovtse (the base during the "Kamchiya – 79" experiment).

Table 1. List of hydro-meteorological data (date of measurements: 13 October 1979)

Initial time of recordings	Wind velocity U_{10} [m·s^{-1}]	Wind direction	Frequency of significant wave ω_0 [rad·s^{-1}]	Variance of the full-frequency wave-train σ_Σ^2 [m^2]	Variance of the high-frequency wave-train σ_w^2 [m^2]	Remarks on the state of wind waves development
09.55	1.0	SE	frequency of swell $\omega_0=1.4$	variance of swell $\sigma_0^2=1.9\cdot10^{-3}$	$4.13\cdot10^{-5}$	almost smooth surface, swell from the SE
10.13	2.6	SE	5.02	without swell $2\cdot10^{-4}$	$5.2\cdot10^{-5}$	wind waves developing
11.16	3.3	SE	5.78	without swell $7\cdot10^{-4}$	$5.2\cdot10^{-4}$	,,
11.30	4.1	SE	5.27	without swell $1.7\cdot10^{-3}$	$4.6\cdot10^{-4}$	,,
11.45	4.0	SE	4.08	$2.4\cdot10^{-3}$	$6.4\cdot10^{-4}$	,,
12.10	4.0	SSE	4.08	$2.2\cdot10^{-3}$	$5.6\cdot10^{-4}$	,,
13.28	6.5	SSE	2.51	$1.26\cdot10^{-2}$	$6.1\cdot10^{-4}$	,,
13.42	7.8	SSE	2.38	$1.65\cdot10^{-2}$	$5.8\cdot10^{-4}$	,,
14.05	7.8	SSE	2.38	$1.53\cdot10^{-2}$	$5.6\cdot10^{-4}$	,,

atmosphere, the quantities characteristic of solar energy transfer deep into the water, fine vertical distributions of sea-water temperature. Standard and surface measurements of air and water temperatures were also carried out. The depth of the water area in the measuring platform region was $h=6$ m.

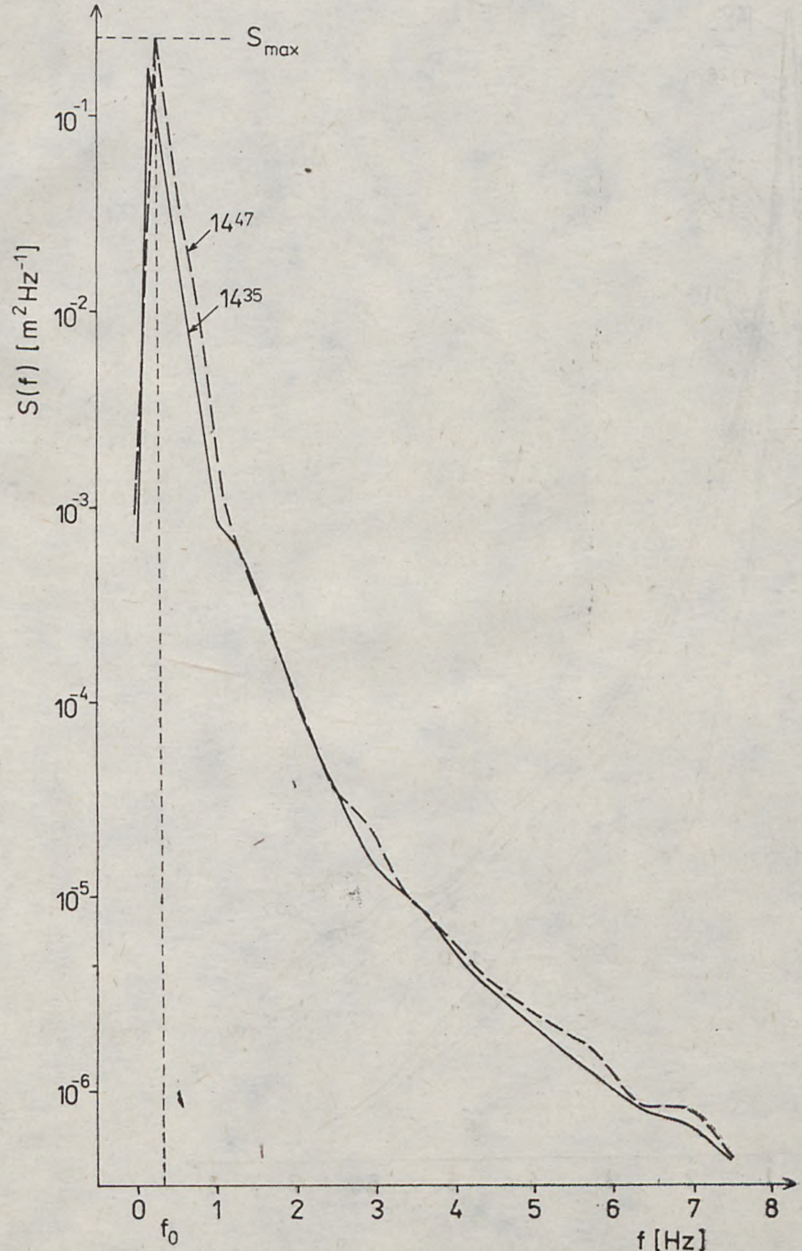

Fig. 3. Empirical distributions of the spectral density of wind waves energy (samples recorded on 29 September 1979, f – frequency in Hz).

The investigations conducted under the "Kamchiya-79" programme included statistical sampling of wind waves in a dozen or so anemobaric situations. Among them, the samples for which the development of wind conditions guaranteed the existence of direct causal connections between the wind and the waves generated,

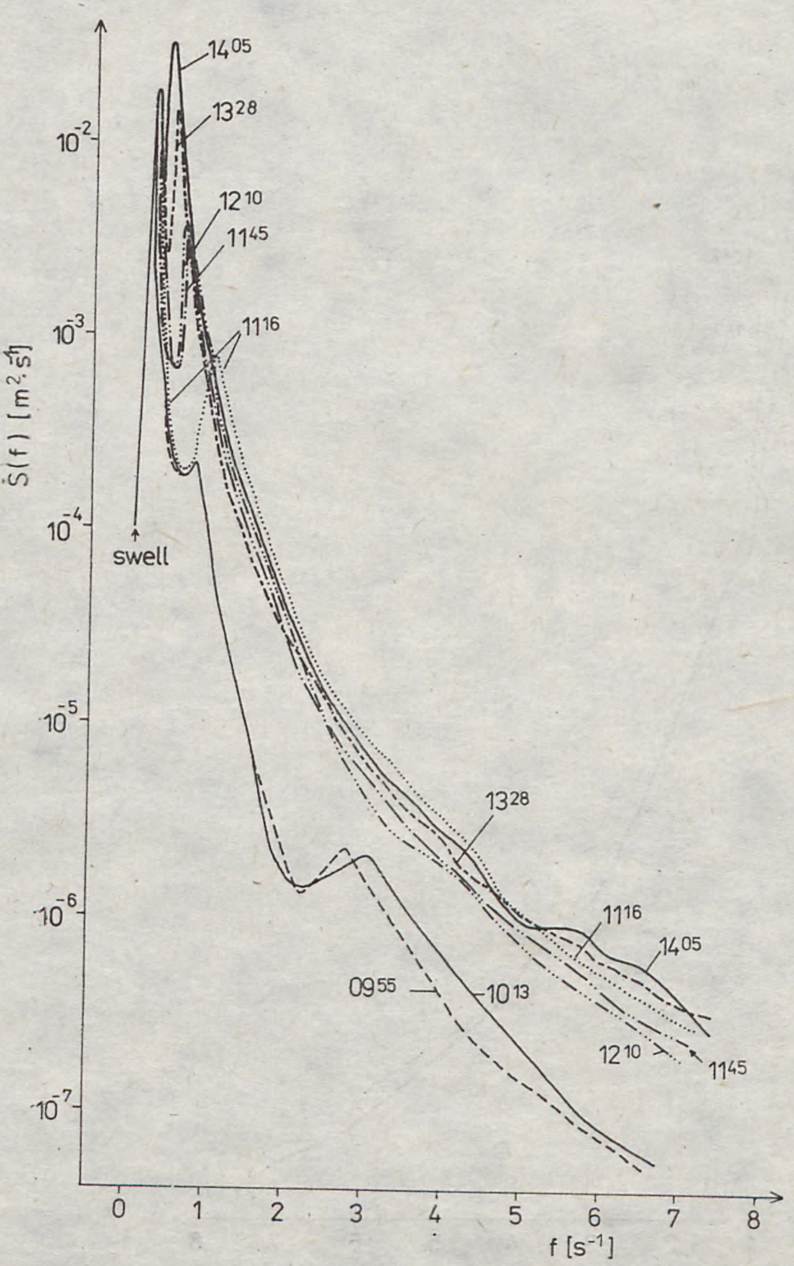

Fig. 4. Empirical distributions of the spectral density of wind waves energy (samples recorded on 13 October 1979).

were chosen for analyses. The samples collected on 13 October 1979 between 09.00 and 14.00 hrs. are worthy of particular mention in this respect. The development of meteorological conditions over this period and the main parameters of waves generated are shown in Table 1.

It follows from this that during the period from 09.00 to 14.00 hrs. the wind velocity increased gradually, the wind direction changed slightly and the wind waves developed continuously. The mean height of the full-frequency wave-train increased, the mean height of waves from the high-frequency band also increased weakly, and the frequency of the main maximum in the energy spectrum decreased gradually. Simultaneously, over the whole period of the measurements, the wind waves induced were accompanied by swell, the mean height of which was $\bar{H}_0=\sqrt{2\pi\sigma_0^2}\approx 11$ cm, period – $T_0=2\pi\omega_0^{-1}\approx 4.55$ s and length – $L_0\approx 1.56\cdot T_0^2\approx 33$ m. This process is distinctly visible in Fig. 4, in which the distributions of the spectral energy density function are shown. Thus, it can be said that the investigations carried out on 13 October 1979 concerned the structure of wind waves in the early stages of development, induced by monotonically increasing wind on the stable swell propagated at a depth of 6 m.

Each 15-minute random wave-train was recorded in two versions: the normal (full) version and the high-frequency one. In the latter version, the random train of wind waves in the high-frequency band was obtained, as mentioned, by filtrating off all the components at frequencies of $\omega<2\pi$ and subsequent appropriate amplification of the amplitudes of that wave-train. This process took place automatically in the wave-recorder processer, simultaneously with the *in situ* recordings.

3. THE ESTIMATOR OF THE ENERGY SPECTRUM

Each of the formulae in section 1 includes, in the explicit or the implicit form, the variance of the wind waves random process (the total variance σ_Σ^2 and the high--frequency variance σ_w^2) which depends on the frequency spectrum of energy (formula 3). Thus, the accuracy of the theoretical estimator of the spectral energy density function affects the accuracies of the other quantities depending on it. For these reasons, it is important that the proper estimator be chosen. In the authors' opinion, the existing possibilities of making such a choice enable the selection of the following three proposals:

(a) *the Phillips distribution* for the high-frequency equilibrium range of gravity waves [9]

$$S_w(\omega)=\beta\cdot g^2\cdot\omega^{-5} \tag{11}$$

where β is the dimensionless coefficient varying little, depending on the extent and duration of the wind [7]. For practical purposes, it can be assumed that

$\beta\approx 6.5\cdot 10^{-3} = \text{const}$ [4];

(b) *the Kitaigorodskii, Krasitskii and Zaslavskii distribution*, which introduces the effect of the depth of a water area into formula (11) [5]

$$S_w(\omega)=\beta\cdot g^2\cdot\eta(\omega_h)\cdot\omega^{-5} \tag{12}$$

where:

$$\eta(\omega_h)=\varphi^2(\omega_h)\left\{1+\frac{2\omega_h^2\cdot\varphi(\omega_h)}{\mathrm{sh}\,[2\omega_h^2\cdot\varphi(\omega_h)]}\right\},\qquad \omega_h=\left(\frac{\omega^2\cdot h}{g}\right)^{\frac{1}{2}}$$

h is the depth of the water area, and $\varphi(\omega_h)$ denotes the universal function satisfying the equation:

$$\varphi\,\mathrm{th}(\omega_h^2\,\varphi)=1;$$

(c) *the Massel non-dimensional distribution* connecting the depth of the water area with the main parameters of the full energy spectrum [2, 7, 8]

$$S\left(\frac{\omega}{\omega_0}\right)=\frac{S(\omega)\,\omega_0}{\bar{H}^{\,2}}=S_n\left(\frac{\omega}{\omega_0}\right)+S_w\left(\frac{\omega}{\omega_0}\right) \tag{13}$$

where:

$$S_n\left(\frac{\omega}{\omega_0}\right)=A_n\exp\left[-20\left(\frac{\omega}{\omega_0}-1\right)^2\right] \tag{14}$$

$$S_w\left(\frac{\omega}{\omega_0}\right)=A_w\left(\frac{\omega}{\omega_0}\right)^{-3}\exp\left[-12\left(\frac{\omega}{\omega_0}\right)^{-8}\right] \tag{15}$$

$$A_n=A_0\left(\frac{\omega_0^2\,\bar{H}}{g}\right)^{-m}\left(\frac{\bar{H}}{h}\right)^{n}$$

$$A_w=(M-NA_n)\,\frac{\omega_0^2\,h}{g}-\psi\left(\frac{\omega^2 h}{g}\right)$$

$$\bar{H}^2=2\pi\sigma_\Sigma^2,\qquad \psi\left(\frac{\omega^2 h}{g}\right)=(kh)^{-1}\,\mathrm{th}(kh)$$

$\bar{H}$ is the mean height of the wind waves random field, A_0, M, N, m, n denoting numerical coefficients and exponents. In the shallow-water zone of wave transformation: $A_0=1.12$, $M=2.52$, $N=6.98$, $m=0.71$ and $n=1.13$.

In the high-frequency range, function (13) is simplified to the form of function (15).

All three estimators (11, 12 and 15) of the high-frequency spectrum have a general characteristic feature. Namely, in the band of high frequencies $\omega\gg\omega_0$ and in areas with considerable depths $h\geqslant 2\pi k_0^{-1}$ (where $k_0=\omega_0^2\cdot g^{-1}$) these functions are characterized by the "-5" distribution law. Moreover, in an area with small relative depths functions (12) and (15) vary proportionally to ω^{-3}.

Experimental data are presented in Fig. 5, characterizing the non-dimensional distributions of empirical functions of spectral energy density shown in Fig. 4 for the frequency range $6.28\leqslant\omega\leqslant 44$. These data clearly do not confirm the "-5" distribution law. This band is not well known, as yet. The reason for this is that wind waves are usually recorded at the signal amplitude amplification level enabling the full amplitude spectrum of the wind waves random field, this including the highest waves, to be embraced. This method enables the high-frequency spectrum to be distinguished only in the band of much lower frequencies, for the most part not exceeding a value of 2π. The "-5" law, which characterizes the so-called equilibrium range of gravity waves [9], is not a universal law for all waves. Considering that the wavelengths corresponding to frequencies exceeding the mean value $\omega \approx 20$ of the band studied are less than $L = 15$ cm, it is almost certain that a great number of waves from the band under consideration are capillary waves which do not come

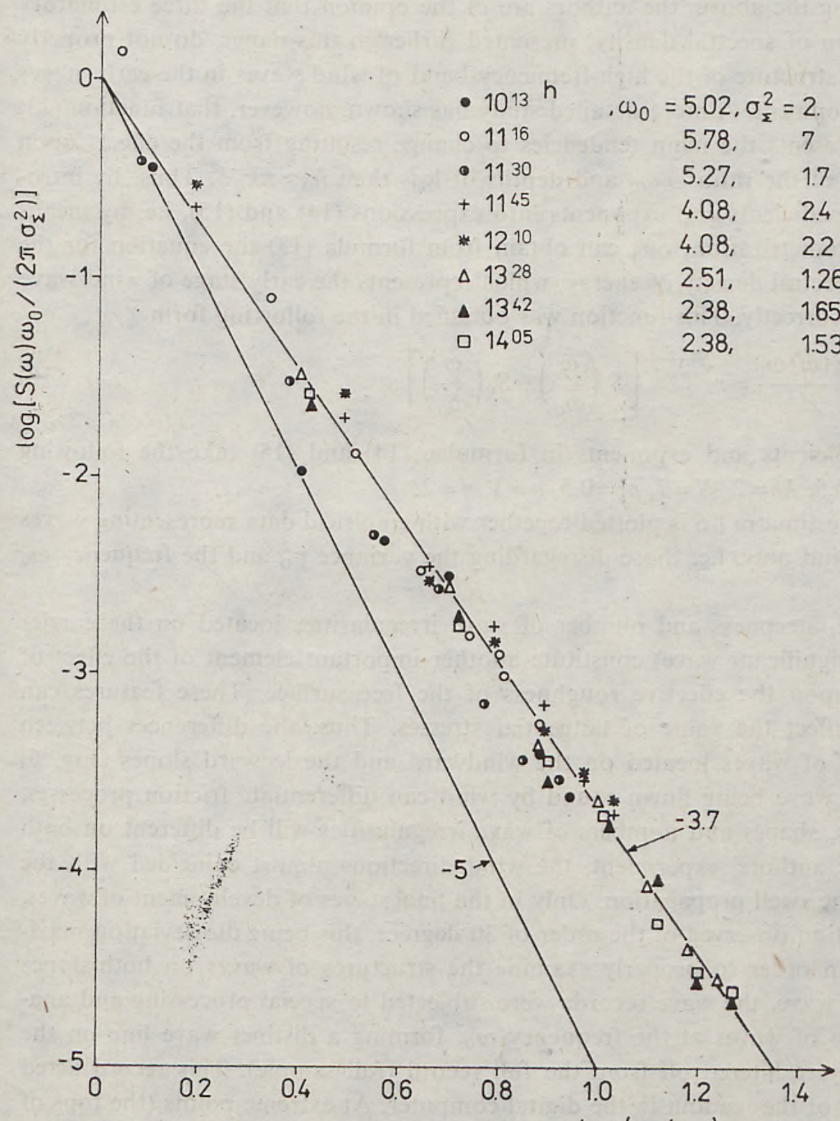

Fig. 5. Distribution of the non-dimensional function of the high-frequency spectrum of wind waves energy.

under the Phillips equilibrium criteria. Apart from this, the samples of wind waves examined by the authors characterize the early stages of development of wind waves generated on the carrier swell, for which the criterion $\omega \gg \omega_0$ is not satisfied. As follows from the above text, the discrepancies between the empirical distributions obtained and the "-5" distribution are likely to be caused both by the properties of early stages of development of waves and by the occurrence of numerous capillary waves.

Considering the above, the authors are of the opinion that the three estimators of the function of spectral density, presented earlier in this paper, do not properly represent the structure of the high-frequency band of wind waves in the early stages of their development. A more detailed study has shown, however, that function (13) correctly represents the main tendencies to change resulting from the effects upon the spectrum of the ratio ω/ω_0 and depths of less than $h_0 \approx \pi k_0^{-1}$. Thus, by introducing new coefficients and exponents into expressions (14) and (15), i.e. by means of proper parametrization, one can obtain from formula (13) the equation for the function of spectral density of energy, which represents the early stage of wind wave development correctly. This function was obtained in the following form

$$S\left(\frac{\omega}{\omega_0}\right) = \frac{S(\omega)\,\omega_0}{H^2} = \eta^{\sqrt{\omega \cdot \omega_0^{-1}}}\left[S_n\left(\frac{\omega}{\omega_0}\right) + S_w\left(\frac{\omega}{\omega_0}\right)\right] \tag{16}$$

and the coefficients and exponents in formulae (14) and (15) take the following values: $A_0 = 0.5$, $M = 2$, $N = 7$, $m = 0.5$, $n = 1$, $\eta = 2$.

In Fig. 5, estimator 16 is plotted together with empirical data representing waves induced by wind only, i.e. those disregarding the variance σ_0^2 and the frequency ω_0 of the swell.

The shape, steepness and number of wave irregularities located on the carrier wave (swell, significant wave) constitute another important element of the effect of wind waves upon the effective roughness of the free surface. These features can significantly affect the value of tangential stresses. Thus, the differences between the structures of waves located on the windward and the leeward slopes (Fig. 6) of the carrier wave being flown round by wind can differentiate friction processes, since the sizes, shapes and numbers of wave irregularities will be different on both slopes. In the authors' experiment, the wind directions almost coincided with the direction of the swell propagation. Only in the final stages of development of waves, was the deviation observed of the order of 30 degrees, this being the deviation maximum value. In order to properly examine the structures of waves on both slopes of the carrier wave, the wave records were subjected to special processing and analysis. A group of waves at the frequency ω_0, forming a distinct wave line on the oscillogram, were filtered off from the full record (full sample). This record acted as a regulator of the readout in the digital computer. At extreme points (the tops of the wave crests and troughs) the computer, following the program, started recording (reading) the part of the high-frequency record located between a given extreme point and the one following it. The latter extremum then switched off the reading of the part between itself and the next extremum. In practice, the computer cleared the data there. The next part was again read. In this way, a series of operations was selected, characterizing the waves on one slope. The sum of the operations constituted a full sample which was subsequently analyzed spectrally.

As a result, two empirical functions of the spectral density of wave energy were obtained, those characterizing two different wave slopes – the windward and the leeward. Those slopes are not identifiable, however, i.e. basing on the analysis one cannot decide which slope is leeward and which is windward. In the light of the results obtained (Fig. 6), this problem is unimportance, as the characteristics of both slopes are almost identical. The differences between them show no regularity and they are contained within the range of the error of estimation. Thus, it can be stated that carrier waves are "hermetically" encircled by wind and the irregularities generated on them have approximately the same geometrical and quantitative properties:

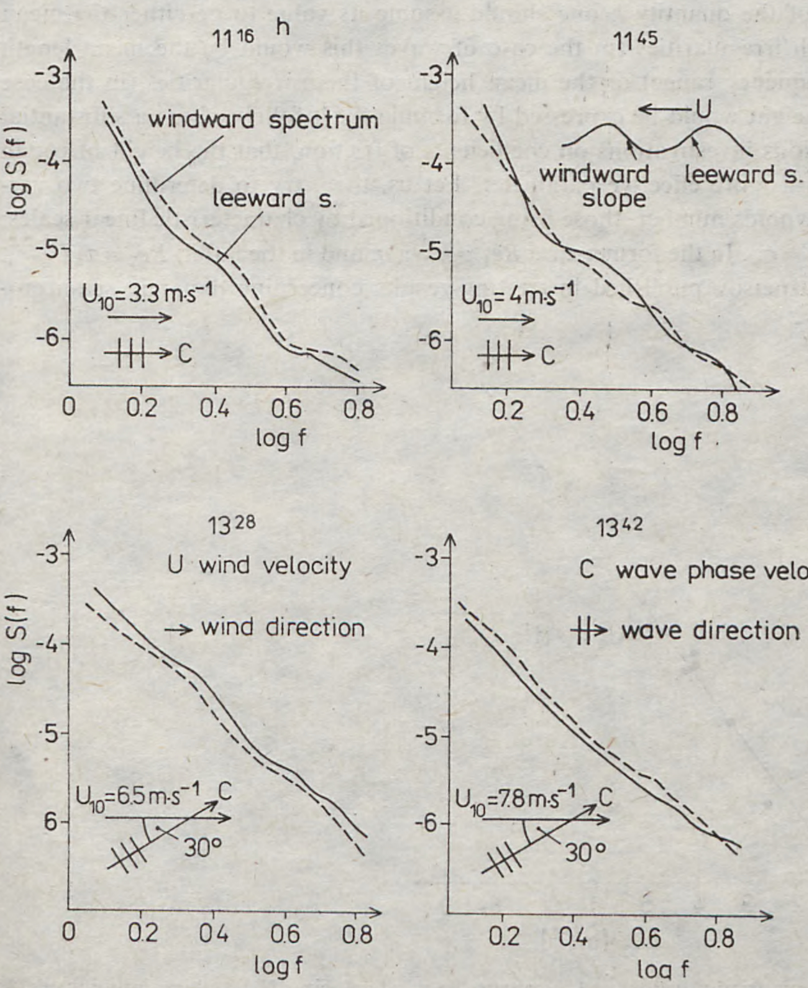

Fig. 6. Empirical distributions of the high-frequency spectrum of energy of wind waves on the slopes of the significant wave (swell).

Naturally, this regularity characterizes the wind action upon the free surface in the early stages of development of wind waves as well as the action of light breezes ($U_{10} \leqslant 10$ m·s^{-1}) on the swell. As can be seen in Fig. 6, the distributions of empirical functions of spectral density of energy come under the "-4" distribution law, i.e. the distribution of estimator 16.

4. THE REYNOLDS NUMBER AND THE INDICATOR OF THE STATE OF DEVELOPMENT OF WIND WAVES

Let us now try to find the relationship between the dimensionless quantities *Re* and *F*, which determine the coefficient $m = f(Re, F)$ occurring in formula (9), and both the characteristics of wind waves and velocity. Various authors differ as to the characteristic scale of linear dimensions of roughness elements, denoted in formula (1) by l. It is most often defined in the following forms: $l = U_*^2/g$, $l = \sigma$, $l = z_0$. With the definition of the quantity l, one should assume its value to be either the mean length of rough irregularities (in the case of waves this would be the mean length of the high-frequency range) or the mean height of these irregularities (in the case of waves this height would be expressed by formula 8). It follows from a substantial number of various investigations on coefficients of friction, that the height of rough irregularities is a more effective parameter. Let us, then, try to determine two versions of the Reynolds number, those being conditioned by characteristic linear scales: $l_1 = U_*^2/g$ and $l_2 = \sigma_w$. In the former case $Re_1 = U_*^3/\nu_a g$, and in the latter $Re_2 = \sigma_w U_*/\nu_a$.

In 1978 Kuznetsov published interesting results concerning dynamic sea-atmo-

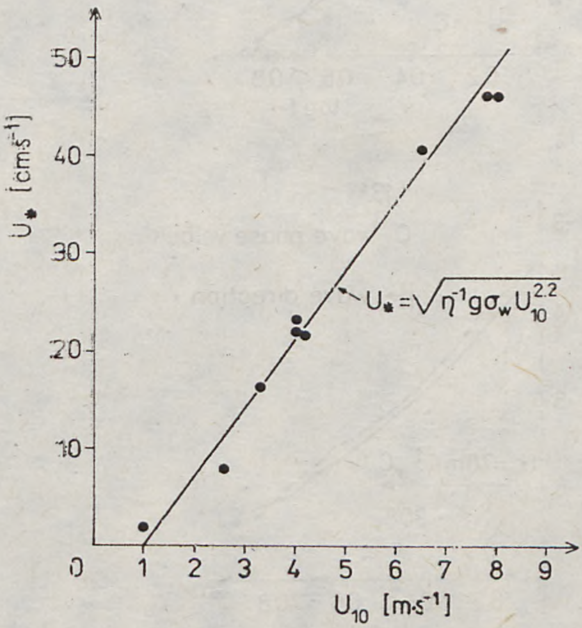

Fig. 7. The dynamic friction velocity, U_*, versus the wind velocity, U_{10}, taking into consideration the root mean square deviation, σ_w, of the high-frequency range of wind waves.

sphere interaction. One of them was the relationship found by Kuznetsov between the dynamic friction velocity and the mean square deviation of the high-frequency range of waves [6]:

$$U_*^2 \approx \lambda^{-1} \cdot g \cdot \sigma_w \cdot U_{10}^{2.2} \tag{17}$$

This relationship for the values of σ_w and U_{10} measured by the authors is presented graphically in Fig. 7.

Substituting relationship (17) into formula (2) and into the formulae for Re_1 and Re_2 one will obtain

$$F \approx \lambda \cdot \sigma_\Sigma \cdot \sigma_w^{-1} \cdot U_{10}^{-2} \tag{18}$$

$$Re_1 \approx (g \cdot \lambda^{-3} \cdot \nu_a^{-2})^{\frac{1}{2}} \sigma_w^{\frac{3}{2}} \cdot U_{10}^3 \tag{19}$$

$$Re_2 \approx (g \cdot \lambda^{-1} \cdot \nu_a^{-2})^{\frac{1}{2}} \cdot \sigma_w^{\frac{3}{2}} \cdot U_{10} \tag{20}$$

where $\lambda = 120\ \mathrm{m^2 \cdot s^{-2}}$, $g = 9.81\ \mathrm{m \cdot s^{-2}}$, $\nu_a = 13 \cdot 10^{-6}\ \mathrm{m^2 \cdot s^{-1}}$.

Division of the left-hand and the right-hand sides of expression (19) by the corresponding sides of expression (20) gives

$$Re_1 \approx 83 \cdot 10^{-4} \cdot U_{10}^2 \cdot Re_2 \tag{21}$$

Functions 19 and 20 are plotted in Fig. 8, revealing a significant discrepancy of the data. Thus, a dilemma arises as to the choice of formula representing the state of turbulence in the near-water layer, assuming that Kuznetsov's formula (17) is the correct relationship for the early stages of development of waves and for a wind velocity less than 10 m·s^{-1}, as this velocity range was dealt with in Kuznetsov's investigations [6].

Taking into consideration that in the overwhelming majority of cases of estimation of the Reynolds number limit it is assumed that laminar motion takes place at Re values of less than of the order of 1000 (e.g. in pipelines it is assumed that $(Re)_{\lim} =$

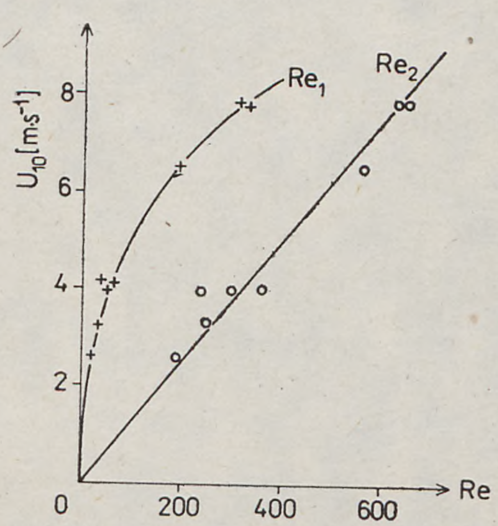

Fig. 8. The Reynolds number, Re, versus the wind velocity, U_{10}.

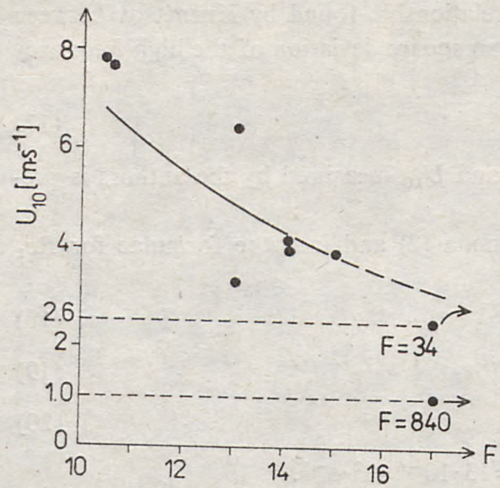

Fig. 9. The state of wind waves development, F, versus the wind velocity, U_{10}.

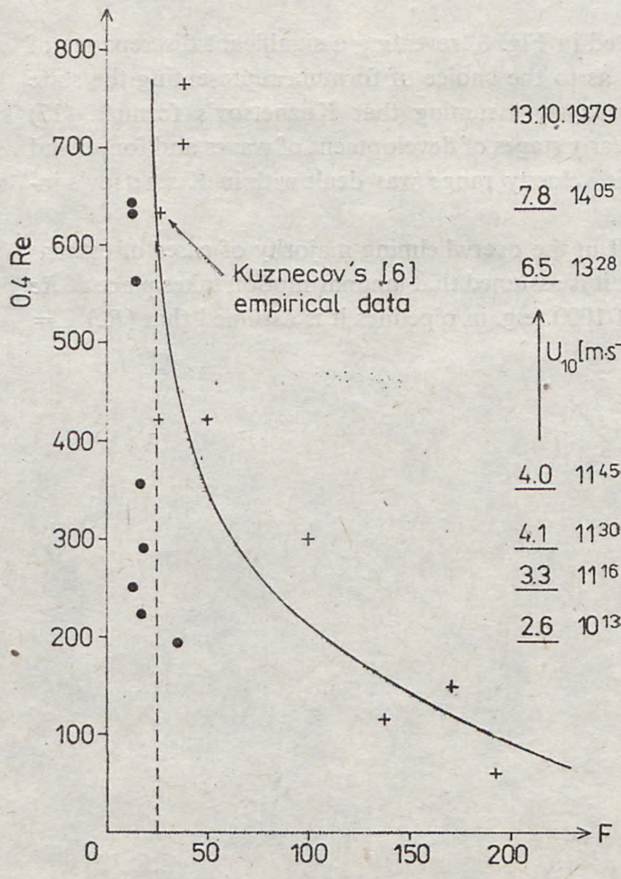

Fig. 10. The Reynolds number, Re, versus the state of development of wind waves, F

$=2000$), formula (20) seems to be the most useful for practical purposes, but in the authors' opinion the coefficient α should be considered to be an approximate value only, requiring further investigations, and relationship 20 should be written in the form

$$Re = \alpha \sigma_w^{\frac{3}{2}} U_{10} \tag{22}$$

The effect of the state of development of wind waves F upon the Reynolds number value is illustrated in Fig. 10. From those characteristics it follows that in the early stages of development of wind waves with the wind velocity increasing monotonicly up to 10 m·s^{-1}, one has to deal with intensive development of waves (low values of F of the order of magnitude $10 < F < 20$, Fig. 9). Under these conditions, the Reynolds number depends mainly on the wind velocity, whereas its dependence on the state of wave development is very weak (Fig. 10). Almost immediately, the variance σ_w^2 of the high-frequency waves (Table 1) reaches an almost constant value of the order of $(5 \div 6) \cdot 10^{-4}$ m, and the total variance σ_Σ^2 increases proportionally to the squared wind velocity ($\sigma_\Sigma^2 \approx 3 U_{10}^2$). Thus, the Reynolds number will change within the range $20 \leqslant F \leqslant 30$ in accordance with the following relationship

$$Re_2 \approx 80 \cdot U_{10}$$

5. PROBLEMS FOR FURTHER INVESTIGATIONS

Determination of the relationship combining the variance of high-frequency waves, the wind velocity U_{10} and the dynamic velocity U_* (Kuznetsov's formula 17) also the determination of the estimator of the spectral density of wind waves energy (formula 16) in the early stages of their development enables calculation of the parameters F and Re which condition the roughness parameter z_0 (formula 9), i.e. the effective roughness of the free surface of a water area in the early stages of development of wind waves generated either on the horizontal surface or on the undulating surface (when swell occurs). The findings presented in this paper, however, enable a certain estimation of this problem only and nothing more. The form of the function $m = f(F, Re)$ in eq. (9) and the effective value of the coefficient α in eq. (22) are still unknown. Moreover, in the light of the discrepancies between the findings presented and the results obtained from direct measurements of the wind profile in the range of values of the dynamic velocity U_*, further examination of function (17) is indispensable, this concerning the values of the coefficient λ and the exponent determining the dependence on the velocity U_{10}. Further investigations will also be necessary to determine the coefficients A_0, M, N and the exponents m, n in formulae (14) and (15) more precisely.

ACKNOWLEDGEMENTS

The authors wish to express their sincere gratitude to Dr Jacek Wyrwiński, Mr. Krzysztof Montwiłł and Mr. Benedykt Renk, the constructors of the unfailing wire wave recorders used during the investigations, for their outstanding contribution to the effective realization of the experiment "Kamchiya-79" in the field of investigations on the structure of wind waves.

REFERENCES

1. Charnock, H., *Wind stress on a water surface*. R. meteor. Soc., 81, 1955, 350.
2. Druet, Cz., *Modelirovanie sluchainovo pola vetrovykh voln*. Informatsionnyi Byulleten Koordinatsionnovo Tsentra po probleme "Mirovoi Okean", 11, Moskva 1981.
3. Ellison, T. H., *Atmospheric turbulence*. Surveys in Mechanics, University Press Cambridge, London 1956.
4. Kitaigorodskii, S. A., *Fizika vzaimodeistviya atmosfery i okeana*. Gidrometeoizdat, Leningrad 1970.
5. Kitaigorodskii, S. A., F. P. Krasitskii, M. M. Zaslavskii, *On Phillips theory of equilibrium range in the spectra of wind-generated waves*. J. phys. Oceanogr. 1975, 5.
6. Kuznetsov, O. A., *Rol' vysokochastotnykh gravitatsionnykh voln v aerodinamicheskom soprotivlenii morskoi poverkhnosti*. Okeanologiya, XVIII, 1978, 2.
7. Massel, S., Cz. Druet, *Spectra of wind waves in the coastal zone*. Rozpr. hydrotechn. 1980, 41.
8. Massel, S., *Falowanie wiatrowe na małych głębokościach*. V. *Parametryzacja widm falowania wiatrowego*. Arch. IBW PAN, 1979, 1815.
9. Phillips, O. M., *The equilibrium range in the spectrum of wind-generated waves*. J. Fluid Mech., V, 1958, 4.
10. Zilintikevich, S. S., A. S. Monin, S. V. Chalikov, *Wzajemne oddziaływanie morza i atmosfery*. Studia i Materiały oceanol. KBM PAN, 1978, 22.