Cercetări marine	I.R.C.M.	Nr.13	17 - 25	1980

ENERGY ASPECTS OF THE WIND PROFILE STRUCTURE OVER THE WAVE FIELD

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ABSTRACT:

Using the wave movement induced difference U^w between the logarithmic and real wind velocity profile the energy flux is calculated. The flux sign changes when shifting from generation to attenuation cases. Its magnitude agrees with that computed from consecutive wave energy spectra and depends, together with other profile parameters, on U^w and C_{10}.

The energy exchanged in the air-sea system is mainly kinetic. The parametric description of the energy flux under natural conditions requires a knowledge of the kinetic state of both system components, including also the effect of wave movement on the coefficients describing the energy transfer: the roughness parameter z_o and the friction velocity v_*.

The usual approach is to assume a logarithmic wind velocity profile and make some hypotheses about the way the two fields-wind and waves-influence each other. The hypotheses are subsequently tested on experimental data sets of high reliability.

The logarithmic wind velocity profile is of the form:

$$U(z) = A \ln z + B \qquad (1)$$

where z is the upward coordinate.

Aside from the parameters:

$$z_o = \exp(-B/A) \qquad (2),\text{and}$$

$$v_* = \mathcal{K}A \qquad (3)$$

with $\mathcal{K}$=0.4 -Karman's constant, the aerodynamic drag coefficient:

$$C_{10} = (v_*/U_{10})^2 \qquad (4)$$

is also defined and used in the description of the surface stress over the air-water boundary (2, 3, 4, 5).

Assuming a neutral stability, the wind profile can be expressed as:

$$U(z) = (v_*/\mathcal{K})\ln(z/z_o) \qquad (5).$$

Over a rigid surface, the profile would be:

$$U^t(z) = (v_{*o}/\mathcal{K})\ln(zv_{*o}/a\nu) \qquad (6)$$

where a = 0.11, and ν is air viscosity.

Assuming the upper anemometer height-z_{max}-large enough for the two profiles not to differ from each other, the theoretical friction velocity v_{*o} can be obtained from:

$$U(z_{max}) = (v_{*o}/\mathcal{K})\ln(z_{max}v_{*o}/a\nu) \qquad (7).$$

The perturbation velocity, due to wave movement, is defined as:

$$U^w(z) = U(z) - U^t(z) \qquad (8).$$

This quantity is an expression of the influence of the kinetic state of the sea surface on the adjacent atmospheric layer (1). The thickness H of the atmospheric layer affected by the sea state can be obtained from the condition of zeroing U^w:

$$(v_*/\mathcal{K})\ln(H/z_o) = (v_{*o}/\mathcal{K})\ln(Hv_{*o}/a\nu) \qquad (9).$$

The equality of U and U^t above the limit H allows calculation of the perturbation energy flux as:

$$\phi_E = \frac{\rho}{2}\int_{z_o}^{H}(U^2 - (U^t)^2)dz \qquad (10).$$

Using (5) and (6), this becomes after integration:

$$\phi_E = \frac{H\rho v_{*o}^2}{\mathcal{K}^2}\left(\left(1-\frac{v_*}{v_{*o}}\right)\ln\frac{Hv_{*o}}{a\nu} + \left(\frac{v_*}{v_{*o}}\right)^2 - 1\right) \qquad (11)$$

with $(z_o/H) \ll 1$, $(a\nu/Hv_{*o}) \ll 1$.

With the same approximation, the momentum flux $\phi_M = \int_{z_o}^{H}\rho U^w dz$ can be similarly evaluated.

Three series of 70,80 and 70 wind velocity profiles, measured at 0.5 nmi(the first two) and 10 nmi(the third) offshore, with anemometers placed between 3 and 13 m above sea surface, have been analysed.

The mean velocity profiles have been computer-processed in order to obtain the values of z_o, v_*, v_{*o}, U^t, U^w, ϕ_M and ϕ_E for each profile, as well as the values of U_{10}, U^t_{10}, U^w_{10}, C_{10} for the standard anemometer height (10 m).

The analysis of ϕ_E and others parameters behaviour has been carried out using the values averaged over 0.5 and 1 m/s intervals for U_{10} and U^w_{10}(discarding about 10 gross error-affected values out of the bulk of data).

The dependence of C_{10} on wind speed at the standard height(Fig.1)is in a quite good agreement with the data presented in the litterature (2,5) for $U_{10} > 7\ ms^{-1}$ and within this range can be fitted by the regression equation (obtained by the least squares method):

$$C_{10} = 6.68 \cdot U_{10}^{1.23} \cdot 10^{-5} \qquad (12)$$

For $U_{10} < 7\ ms^{-1}$, C_{10} is generally higher.The plotted points suggest the dependence shown by the dashed line, rather than an increase of C_{10} with decreasing U_{10}, as in Wu's formulae (2). Owing to the large scatter within and between intervals, no attempt to fit a curve was made. The jump in the behaviour of C_{10} at $U_{10} \approx 7\ ms^{-1}$ is not predicted by the model;it might be accepted that there is a relatively high friction in the attenuation case ($U^W > 0$); the friction coefficient decreases when shifting to the wave generation regime (the waves being "resonant" with the generating wind field).

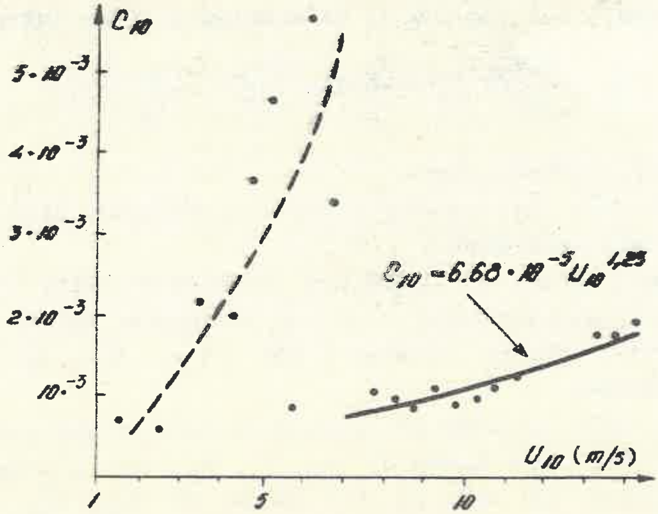

Fig. 1 – Variation of the drag coefficient C_{10} as a function of the wind speed U_{10}

This situation suggests analysis of the parameters z_0, C_{10}, v_* versus perturbation velocity U^W (Figs.2,3,4). In the generation case ($U^W < 0$) the sea is formally similar to a surface with high roughness z_0 (Fig.2), the perturbation velocity being also high (as absolute value).The shift to the attenuation regime ($U^W > 0$) causes a sensible decrease of z_0.For $U^W > 2 ms^{-1}$ the values are practically zero and the sea surface is formally smoother than physically possible. This type of "oversmoothness" (1) is a result of the reverse energy transfer, from the sea to the atmosphere; the less dense air is easily driven by the waves.

The behaviour of the drag coefficient C_{10} and of the friction velocity v_* (Figs.3,4) reveals the close relationship between these two quantities and, on the other hand, rises the question about the phenomena responsible for the sharp variation of both parameters at $U^W \approx 3.5\ ms^{-1}$.

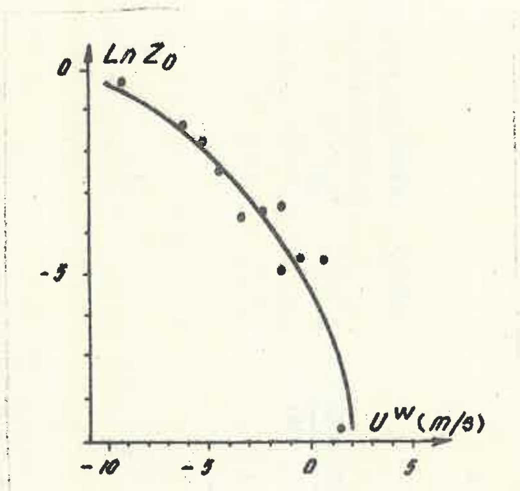

Fig. 2 - Variation of the drag coefficient C_{1o} as a function of the perturbation velocity U^W

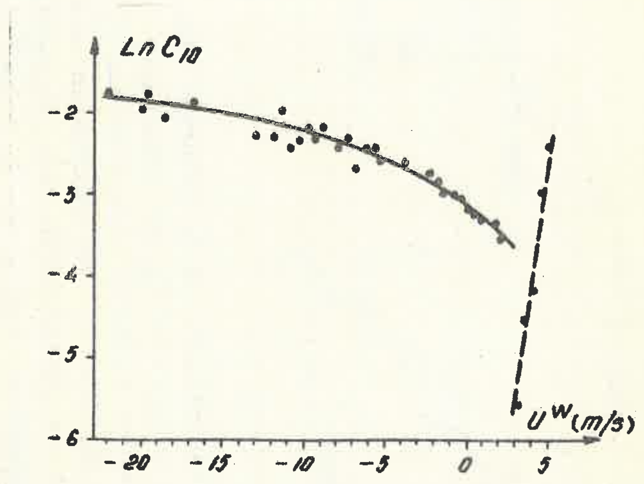

Fig. 3 - Behaviour of the roughness parameter z_o as a function of the perturbation velocity U^W

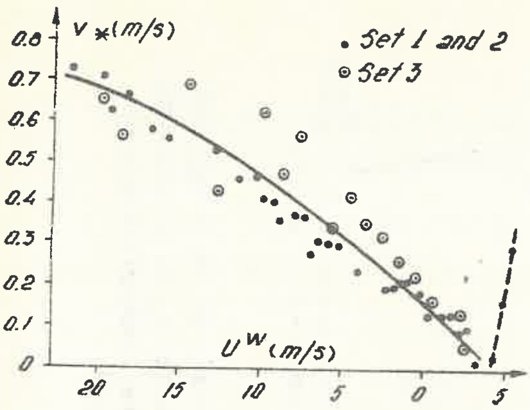

Fig. 4 - Behaviour of the friction velocity v_* as a function of the perturbation velocity U^W

From data analysis it can be inferred that the quantities involved in the energy flux $\emptyset_E$ are continuous with respect to U_{1o} and U^W and hence a similar variation can be expected for $\emptyset_E$, which should be negative in the generation cases-the atmosphere loses energy- and positive for the attenuation cases.The generation process generally begins at $U_{1o} > 7ms^{-1}$ (Fig.5), this value being also a discontinuity point for C_{1o} (Fig.1).

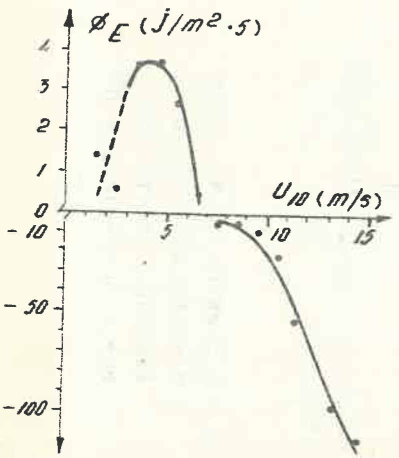

Fig. 5.- Average energy flux $\emptyset_E$ as a function of wind speed U_{1o}

Owing to the fact that all the data are mean values for the given intervals, there are also some discrepancies, such as a flux of $-2Jm^{-2}s^{-1}$ (generation) for $U_{10} < 3ms^{-1}$ or $7.4Jm^{-2}s^{-1}$ for $U_{10} > 9ms^{-1}$. They amount to about 15% of the data. This results in the necessity of using a further criterion, which can be taken as the C_{10} value. Grouping the ϕ_E values according to both U^W and C_{10} shows a remarkably good separation of fluxes according to the sign (positive or negative) depending on C_{10} being below or above a value of $7.5 \cdot 10^{-4}$. Even though the values are again obtained by averaging within the classes, the number of erratic values is only 4, all of them within the range $0 < U^W < 1$ and $C_{10} > 7.5 \cdot 10^{-4}$; it should be noted that this class contains only fluxes below $1Jm^{-2}s^{-1}$. Except the two classes with $C_{10} > 1.5 \cdot 10^{-3}$ and $-6 < U^W < -3$, all the classes show a regular distribution of points in either logarithmic (Fig.6A) or linear scale (Fig.6B) for ϕ_E, thus suggesting the possibility for much finer intervals (or even consideration of the individual data points) if there were more and better measurements.

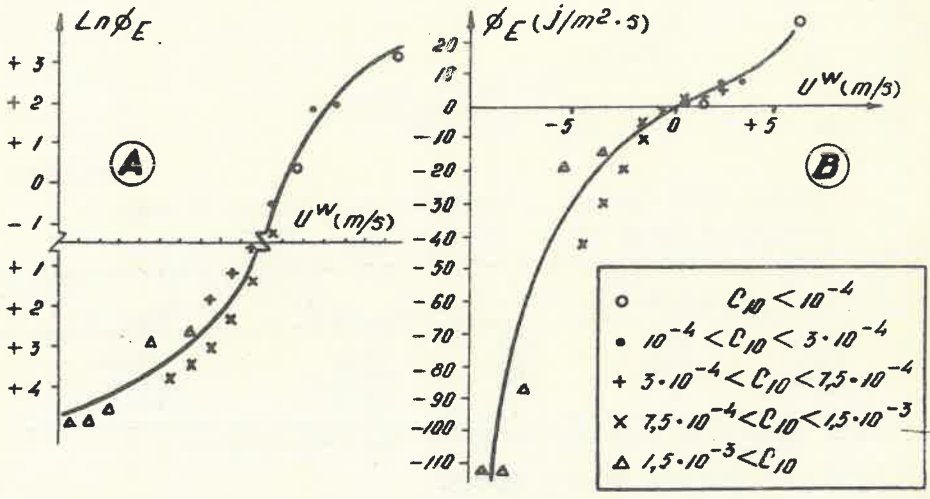

Fig. 6 (A,B) - Average energy flux ϕ_E as a function of the perturbation velocity U^W and of the drag coefficient C_{10}

It may be concluded that the model performs well, but, at the same time, it must be noted that the data analysis suggests the existence of some processes yet not comprised by the theory.

These results can be used for energy evaluations, after having previously checked for the agreement between computed and real fluxes. This was done by using three wave records made during the experiments. The records have been divided into several segments long enough to allow obtaining the energy spectra. These spectra computed by the aid of the Fourier transform, vary from one segment to another and are used to compute the average energy flux exchanged by the wave field (Fig.7, Table 1)

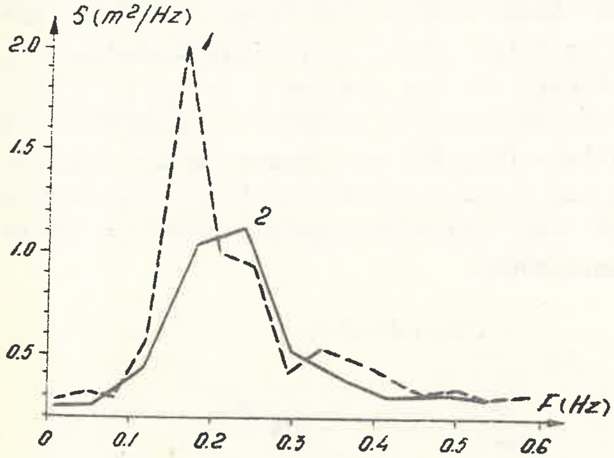

Fig.7- Energy spectra for the wave record no. 1.

Table 1

Total wave energy variations and energy fluxes computed from wave spectra and wind profiles

Nr.	$E_i (Jm^{-2})$	$E_f (Jm^{-2})$	$\Delta t(s)$	$\varnothing_{Ewave} (Jm^{-2}s^{-1})$	$\varnothing_{Ewind} (Jm^{-2}s^{-1})$
1	532o	387o	146	-9.9	-9.61
2	5446	6682	253	+4.9	+5.1
3	2o23	51o	95	-16.o	-12.o

E_i = wave energy at the beginning of the time interval
E_f = idem, at the end of Δ t period
$\varnothing_{Ewave}$ = energy flux computed as $(E_f - E_i)/\Delta t$
$\varnothing_{Ewind}$ = energy flux computed with eq. (11)

The agreement between the fluxes computed from the wind profiles and those inferred from wave energy spectra variations is fairly good, but one must take into account the difference in the averaging periods for the two parameters: 2-4 minutes for the wave spectra, and 2o minutes for the wind profiles, which precludes a precise comparison.

For the third data set the seried wind velocity measurements (loo seconds + 2o minutes + loo seconds) revealed rapid variations of the energy flux, as well as of the other parameters (C_{10},v_{*},U_{10}). More work is needed in this direction, using short-time average wind profiles and simultaneous wave records, which could prove more useful for the energy transfer investigations.

Modelling of the kinetic energy transfer in an integrated wave-wind system is to replace the usual approach of separate analysis of wave field and wind profile over a fixed ("freezed") wavy surface.

The approach used in this paper is only a first attempt and the solution of this problem is to be found by modifying the wave theory and using the equations for the aerodynamic flow over a wavy moving surface. Experimental researches in this field are of great necessity.

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