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PURELY WIND-GENERATED WAVES: THEIR CURRENT UNDERSTANDING AND OUTSTANDING QUESTIONS

Yoshiaki Toba

Physical Oceanography Group, Faculty of Science
Tohoku University, Sendai, 980-77 Japan

ABSTRACT There is a harmonious state between wind forcing and purely wind-generated waves, as expressed by the 3/2-power law, or the proportionality among the Stokes drift velocity, water turbulence intensities and the air friction velocity. Characteristic nature of wind-wave phenomena is first demonstrated by using flow visuarization in laboratory tanks, and then the above-mentioned harmonious state is described with physical interpretation. This characteristics remain as outstanding questions in wind-wave studies yet to be derived purely theoretically.

1. Introduction

Ocean surface waves have complexities, such as the existence of many swell components from different directions, changes in wind speed and direction. In this paper the subject is focused on pure cases, that is, on pure wind waves, where there is no swell and no change in the wind direction.

Even though the conditions are simple, wind waves are characterized by strong nonlinearity, which results in a harmonious state, where exist similarity laws which however has not yet been derived purely theoretically. This state is presumably governed by self-adjustment processes including wave breaking, wave-turbulence coupling, and strong wave interactions.

In the first place, a demonstration of wind-wave phenomena by using flow visualization is given, and then physical interpretation follows.

2. Flow Visualization of Microphysical Processes in Wind Waves

Wind-wave phenomena have been studied by using flow visualization in our laboratory wind-wave tanks. The techniques include almost neutral polystyrene particles[1], hydrogen bubble lines[2] and bubble clouds[3] in water side, suspended zinc stearate particles[4] and paraffin mist[5] in the air side with light sheet power stroboscope. Some optical techniques were also used to observe the surface structure[6]. Earlier works were reviewed in [7].

Figure 1 is an example of these, showing visualization of the wind-wave coupled turbulent boundary layer by using almost neutral particles[1]. This will be mentioned later again.

Microphysical processes at the air-water interface are characterized by the air-flow separation, reattachment of the high-shear layer of the air flow at the windward face of the waves[5] causing a high tangential stress toward the crests[8], which in turn gives rise to the high vorticity region under the crest[9], and breaking of wind waves. Wind waves are accompanied by ordered motions in water as well as in the air-flow above the wind waves[5, 10]. Figure 2 summarizes these microphysical processes at the air-water interface schematically.

Although this schematic picture is for young waves in a laboratory, the actual windsea field is of a continuous energy spectrum, which contains the high frequency part well expressed by this picture.

3. Overall Similarity Laws in Wind Waves --- u_*-Proportionality

The wind waves have randomness spatially as well as temporarily. Nevertheless there are well-defined regularities statistically. Among them there are the 3/2-power law and the form of

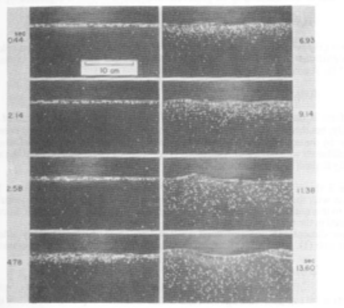

Fig. 1 Visualization of wind-wave coupled turbulent boundary layer just beneath laboratory wind waves, by using almost neutral polystyrene beads. Cited from [1].

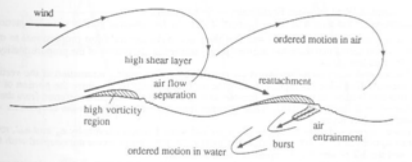

Fig. 2 A schematic picture of the microphysical processes at the air-water interface.

wind-wave energy spectra consistent with this law.

The 3/2-power law of wind waves as a macroscopic similarity law, which expresses the statistical state of windsea field in the generation area free of swells, is expressed by

$$H_* = BT_*^{3/2}, \quad B = 0.062 \tag{1}$$

where $H_* = gH_s/u_*^2$, $T_* = gT_s/u_*$, g is the acceleration of gravity, u_* the friction velocity of air, H_s the significant wave height, T_s the significant wave period, and B is an empirical constant[11]. A conceptual expression is given by

$$f(H_s, T_s, u_*) = 0 \tag{2}$$

and this form is interpreted as claiming that H_s and T_s cannot be independent of each other statistically, but there is a quasi-equilibrium state where H_s and T_s are strongly combined with each other by the action of the wind which is represented by u_* (the concept of wind waves in quasi-equilibrium with the wind). Equation (1) corresponds to the situation that the steepness is statistically limited[12].

Figure 3 shows Eq. (1) with a data set. Naturally the empirical constant B shows a fluctuation with the variation of the wind, within an order of 20% [13]. Physical processes involved in this quasi-equilibrium between the wind and windsea with intrinsic fluctuation will be discussed in the next section.

The one-dimensional form of wind wave spectra in the high-frequency side, which is consistent with (1), and which is assumed to have a self-similarity form, is expressed by

$$\phi(\sigma) = \alpha_s g_* u_* \sigma^{-4}, \quad \sigma > \sigma_p \tag{3}$$

where $\phi(\sigma)$ is the energy density, g_* the expanded acceleration of gravity to include the effect of surface tension, and σ_p is the peak angular frequency of wind waves[14, 15]. In wind waves actually observed, we can see this form of spectra in some main part of the high frequency side, called the equilibrium range. Figure 4 shows an actual example of these spectra observed at a tower station in the sea[16].

The value of the coefficient α_s seems to range between (6-12) x 10^{-2} [e.g., 15], and as will be discussed in the next section, fluctuates in response to gustiness of the wind.

4. Concept of Wind-Windsea Equilibrium --- Self Adjustment Processes

Equation (3) has a form of the u_*-proportionality. In the system of gravity wave interactions, Zakharov and Filonenko[17] showed that there is a wave spectral form proportional to σ^{-4}. However, it seems that there has been no purely theoretical derivation of the proportionality of the spectral level to u_*.

The air and water boundary layers are coupled by approximate continuation of the vertical momentum flux which is represented by the air friction velocity u_*, since the portion of the momentum retained as the wave momentum among the total momentum transferred from the air to the water is few percent[18]. Thus u_* is the characteristic velocity for the coupled air and water boundary layers.

If we express turbulent velocities in the air and water boundary layers by u_a' and u_w', route mean squares of these are proportional to u_* [19, 20, 10]. Wind waves are coupled with this u_*, and the 3/2-power law (1) represents such a situation.

Equation (1) is also equivalent to the proportionality of the Stokes drift velocity u_0 of individual waves (with wave height H and period T) of windsea, to u_*[11]:

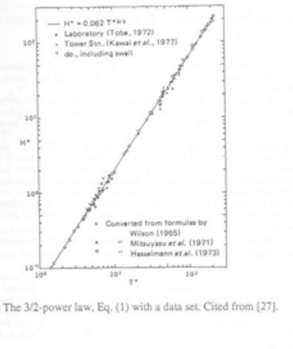

Fig. 3 The 3/2-power law, Eq. (1) with a data set. Cited from [27].

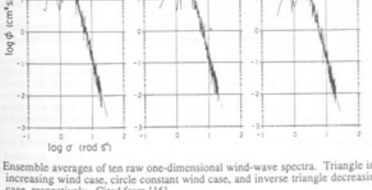

Fig. 4 Ensemble averages of ten raw one-dimensional wind-wave spectra. Triangle indicates increasing wind case, circle constant wind case, and inverse triangle decreasing wind case, respectively. Cited from [16].

$$u_0 \; [= 2\pi^3 H^2/gT^3] = 2\pi^3 B^2 u_* \qquad (4)$$

Also, combining the turbulent intensities of the air and water boundary layers, we have[10, 21].

$$u_* \propto (\overline{u_a'^2})^{1/2} \propto (\overline{u_w'^2})^{1/2} \propto u_{*w} \propto u_0 \qquad (5)$$

Figure 5 shows an example of normalized vertical distribution of turbulence intensities just below laboratory wind waves supporting this relation (5). These data were rearranged from observation data of [10].

At the same time, Fig. 5 indicates that there is a wind-wave coupled turbulence boundary layer below the sea surface with a depth several times H_s. A data set including this and Fig. 1 with others, indicates that this depth is (3-7)H_s, or about five times H_s, as will be published elsewhere.

Considering these observations, it is natural to suppose that the origin of the u_*-proportionality is combined phenomena of the wave modulation, the action of local stress of the air flow over instantaneous individual-wave forms, and thus induced very local shear flow at the individual wave surfaces, causing wave breaking either incipient or visible, which, in turn, is related to the turbulence intensities in water just beneath the wind waves. It is thus conjectured that the u_*-proportionality is eventually performed by strongly nonlinear processes. This is the concept of breaking adjustment of wind waves as proposed in concept of its earlier expression in [21].

Then, what determines the values of B in Eq. (1) or α_s in Eq. (3)? Or what actually controls the limit of wave steepness under the action of the wind? These questions are also issues to be solved.

To answer these questions, further elucidation of elementary processes which are relevant to the strongly nonlinear processes, including wind stress structure related to the air-flow separation, reattachment, the recirculation under the crest, wave modulation and wave breaking, in addition to purely water-wave processes such as capillary rollers, bores and crest instabilities as studied by Longuet-Higgins [22, 23]. Close studies by experiment and theory on strongly nonlinear interactions including wave breaking, such as reported by Tulin and Li [24], will be an important direction.

If we approach these questions from microphysical aspects, we might immediately face a tall wall by virtue of complication of the phenomenon. And if we want to approach it from a more macroscopic aspects, we might have to retreat to the level of some integral constraint such as the continuity of momentum fluxes.

The approach from the integral constraint may still be important. For example, there are ordered motions in the turbulent boundary layers [e.g., 25, 5]. However, in order to satisfy the constant flux of momentum, ordered motions themselves should perform a kind of self-adjustment so that the average velocity profile satisfies the logarithmic law.

Equations (1), (3), (4) and (5) are all consistent with one another. However, which is the most fundamental for the quasi-equilibrium state between wind and windsea to be established? It is the outstanding question yet to be solved.

In relation to those questions, delicate fluctuation around these local equilibrium conditions, occurring in processes for wind waves to adjust themselves to gustiness, is worthy to be studied. This delicate variation seems to correspond to a large fluctuation of the aerodynamic roughness parameter z_0 of the sea surface, which in turn corresponds to the variation of the drag coefficient C_D. From an observed data, it is seen that over- and under-saturation of the level of the equilibrium range of windsea occurs in relation to gustiness with short-time scale u_* fluctuation[26].

As a physical interpretation, we can conjecture as follows. First there is a strong constraint for the water waves to satisfy, such as the spectral form proportional to σ^{-4}. As stated above, although there is a u_*-proportionality for a steady state, the level of wind-wave spectra cannot follow gustiness instantaneously, since the total energy of windsea field is already large. Thus,

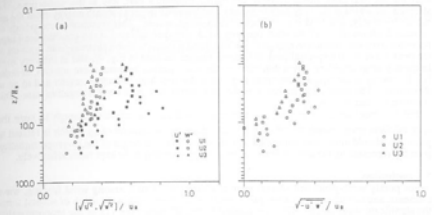

Fig. 5 Normalized vertical distribution of turbulence intensities (a) and Reynolds stress (b), under laboratory wind waves. Rearranged from [10].

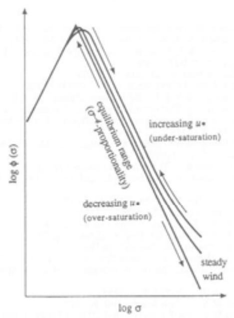

Fig. 6 A schematic picture of the response of windsea spectra to gustiness. Arrows indicate the expected direction of energy transfer. Cited from [28].

if the wind has increased, the energy level of windsea becomes under-saturation, and the energy near the spectral peak flows down to the higher frequency part, and at the same time, the steepness of waves at the very high frequency part becomes larger to absorb energy from the air more effectively, and feed it to the equilibrium-range waves. This situation corresponds to increased values of z_0. If the wind becomes weak, the spectral level at the equilibrium range becomes over-saturation, the energy in the equilibrium range near the spectral peak goes up to the peak wave for the spectral peak to become steeper (as seen in Fig. 4), and at the very high frequency range capillary waves diminish and the water surface becomes more smooth, in order for the energy at the equilibrium range to go up to the very high frequency region and to go to dissipation. The latter effect makes z_0 or the drag coefficient small for this negative gust. This situation is illustrated in Fig. 6.

For this mechanism to be real, wave interactions should be effective enough to keep the spectral form proportional to σ^{-4}. At the same time, the fluctuation of z_0, which is related to gustiness, should directly be connected with the question of the origin of the u_*-proportionality, possibly representing the mechanisms for the u_*-proportionality to be kept more effectively.

5. Conclusions

For purely wind-generated waves, there is a harmonious state among wind forcing, wave elements, and turbulence intensities just beneath wind waves within the depth of several times the significant wave height. This is expressed by the 3/2-power law (1), or the proportionality among the Stokes drift velocity, water turbulence intensities and the air friction velocity. This state will possibly be performed by strongly nonlinear self-adjustment processes between wind and windsea, including wave breaking and wave interactions. However, the purely theoretical derivation of this nature remains to be challenged.

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