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Quasi-linear approximation for description of turbulent boundary layer and wind wave growth

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Abstract

This study describes an approximate quasi-linear model for the description of the turbulent boundary layer over steep surface waves. The model assumes that wave-induced disturbances of the atmospheric turbulent boundary layer could be reasonably described in a linear approximation with the momentum flux from wind to waves retained as the only nonlinear effect in the model. For the case of periodic long-crested waves, the model has been verified with a set of the original laboratory and numerical experiments. The laboratory experimental study of the airflow over the steep waves was performed by means of the PIV technique. The numerical study was performed with direct numerical simulation (DNS) of the turbulent airflow over waved surface at Re=15,000 for quasi-homogeneous waves, wave trains and parasitic capillaries riding on the crest of a steep waves. Examples are given of the application of the quasi-linear approximation to describe the turbulent boundary layer over waves with the continuous spectrum under the assumption of random phases of harmonics. In the latter case the quasi-linear model provides the growth rate of surface waves in the inertial interval of the surface wave spectrum proportional to w7/3 in agreement with predictions in [1].

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Keywords: wind; turbulence; atmospheric boundary layer; wind waves; DNS

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1. Introduction

Interaction of the wind flow with surface waves is one of the central questions in the wave modelling, because it defines the wind input to waves. In spite of significant progress in the topic there is a number of questions, the most essential of which is strong dispersion in wind input obtained in different experiments, which is about 300–500% [1-3]. It is one of possible sources of errors in forecasts of wind waves.

Measuring wind input is a quite tricky experimental problem. The energy flux from wind to waves is determined by surface stresses (pressure and tangential stresses) at the water surface, which should be measured at curved liquid surface, including areas below the wave crests. These measurements can be performed by a wave-following contact technique [4-6]. Measurements of airflow below crests of the waves can be performed by seeding the flow with small particles visualized with a strobe source of light and application of special photograph technique [7]. Kawai's experiments demonstrated occurrence of the airflow separation from the crests of steep waves in a set of instant images. The state-of-art method applicable for investigation the structure of airflow over waves is the particle image velocimetry (PIV) [9]. In this method, the flow is seeded with small particles illuminated by laser beam, which makes them visible on digital images. Applications of the PIV in [10-14] clearly demonstrated a complex turbulent airflow with pronounced flow separation from the crests of waves and reattachment at the windward face of the wave on the instantaneous patterns of the vector velocity fields.

It should be noted that the separation of wind flow from the crest of the surface wave is a non-stationary turbulent process with a characteristic scale that is small compared with the period of the wave. It can be expected that the processes of turbulent exchange between the ocean and the atmosphere and wind induced generation of waves, whose timescales greatly exceed the period of the wave, are caused by the wind flow fields averaged over the turbulent pulsations. The velocity fields averaged over turbulent pulsations are smooth and un-separated. It was confirmed by averaging over the statistical ensembles of realizations of instantaneous velocity fields obtained with use of the time-resolved PIV in [13] and individual instantaneous vector velocity fields retrieved from the planar PIV in [14]. It encourage us to use the quasi-linear approximation for description of coupling of surface waves with turbulent atmospheric boundary layer, where wave-induced air-flow disturbances are described in linear approximation.

2. Formulation of the quasi--linear model of turbulent wind over waved water surface

There exists two classes of quasi-linear models, which can be distinguished by the model of wind wave growth. The first class (e.g., [15, 16]) is based on the quasi-laminar model [16, 17] model of wind wave growth. The second class (e.g., [19, 20]) assumes that the wind wave growth is governed by the effect of eddy viscosity.

Visualization of the air flow over steep wind waves [13] clearly demonstrates that turbulent vortices are much faster than waves. Then a model based on RANS (Reynolds-Averaged Navier-Stokes) equations can be used to describe the turbulent air flow over waves. The model reads:

$$\frac{\partial \langle u_i \rangle}{\partial t} + \langle u_j \rangle \frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{1}{\rho_a}\frac{\partial \langle p \rangle}{\partial x_i} = \frac{\partial \sigma_{ij}}{\partial x_j} \tag{1}$$

where the turbulence stress tensor is:

$$\sigma_{ij} = \langle u_i' u_j' \rangle = \nu \left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i} \right) \tag{2}$$

Here, <...> denotes the averaging operation over ensemble of turbulent fluctuations, ν is the turbulent eddy viscosity coefficient, which is a self-similar function of the distance, *z*, from the air-water interface: