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Laboratory study of temporal and spatial evolution of waves excited on water surface initially at rest by impulsive wind forcing

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Abstract

Evolution of waves excited by wind that varies in time is not yet understood sufficiently well. In the present study, waves generated from rest by an effectively impulsive wind forcing are studied in a small laboratory wind-wave tank. Multiple parameters characterizing evolution of the wave field in time as well as in space are presented. Measurements of the variation with time of the instantaneous surface elevation were performed simultaneously with determination of two components of the instantaneous surface slope at a number of fetches along the test section. For each wind forcing conditions, numerous independent realizations were recorded. Thus, sufficient data were collected for computation of statistically reliable ensemble-averaged values of parameters characterizing the evolving random wind-wave field as a function of time elapsed since the initiation of wind. In each realization, data acquisition started when the water surface was calm, and lasted until statistically steady random wave field conditions were attained. The analysis of the ensemble-averaged wind-wave characteristics indicated that distinct stages in the wind-waves evolution could be identified. These stages were compared with the predictions based on the viscous instability theory and on the random resonant wind-waves generation model.

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Keywords: Generation of waves by wind; unsteady wind forcing; waves under wind gusts; Phillips wind-wave generation model; Kawai model

1. Introduction

The process of generation of sea waves by wind remains at the center of scientific interest for more than 150 years [1]-[3]. About 60 years ago, two different possible mechanisms of water-wave generation by wind were suggested: the resonant pressure fluctuations model by Phillips [4] and the shear-flow model by Miles [5]. Only very limited and not very successful attempts have been made so far to validate the Phillips model. The compilation by Plant [6] of experimental results on wind-waves growth rate from numerous studies exhibits significant scatter around the predictions by Miles theory. Miles [7] stressed that his model is inapplicable to the initial stages of wind-wave generation. Spatial growth rates at the steady wind forcing for fixed Fourier frequency harmonics were measured directly in the experimental facility used in the present study [8]; the results show behavior that is qualitatively inconsistent with the Miles predictions however fall into the domain of data scatter in the Plant [6] plot. Numerous studies [9]-[11] demonstrated that coupled viscous shear flow at the gas-liquid interface has a significant effect on the wave growth rates.

It should be stressed that while most of those theories assume unidirectional waves, the essentially three-dimensional structure of wind-wave field was emphasized in numerous experimental studies [12]-[14]. Moreover, the wind-wave generation theories mentioned above usually consider evolution of the wind-wave field in time (the duration-limited case), often assuming spatial homogeneity, whereas in the experiments the spatial (fetch-limited) evolution of waves due to effects of dispersion, wind input,

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nonlinearity, and dissipation is measured. The wave field in this case may be statistically steady for steady wind forcing, but is spatially inhomogeneous.

Additional complexity of the problem of water waves' excitation by wind arises when wind forcing is unsteady, thus the statistical characteristics of waves that always depend on space now vary with time as well. Field experiments on wind waves under unsteady forcing are rare. Therefore, well-designed laboratory studies are needed that may provide detailed experimental data on wave evolution under controlled conditions needed for understanding the relative contribution of different mechanisms that govern the variation of the wind-wave field. However, even at laboratory scale only limited experimental data on waves under time-dependent wind under controlled conditions are currently available. Radars were used mostly in early studies of waves excited by impulsively started wind [15-16]. These data are restricted to waves with fixed lengths only defined by the Bragg resonance conditions.

First experimental and theoretical study of ripple excitation by abruptly started wind was carried out by Kawai [10] and provided evidence that viscous instability mechanism causes exponential growth of waves in time. Time-dependent results were often obtained by selecting short records and assuming quasi-steady conditions within each record. Veron & Melville [17] studied waves under slowly accelerating wind. The spectral information was obtained in this study assuming quasi-steadiness. Different techniques were applied in [18-19] to study wind stress under time-dependent wind, also effectively invoking the quasi-steady assumption.

The present paper is based on the experiments carried out by Zavadsky & Shemer [20] in a small wind-wave facility and presents time-resolved statistically reliable results on waves excited from rest by a (nearly) impulsive wind forcing. These experimental results are further discussed here. Different stages of wind-wave field evolution are delineated. Measurements were performed using multiple sensors and a fully automated experimental procedure. Running experiments without human intervention made it possible to carry out numerous independent realizations of temporally and spatially varying wave field under identical wind forcing conditions. The statistical wave parameters were computed at each fetch and wind forcing by averaging the data recorded for the accumulated ensemble of realizations as a function of time elapsed since the initiation of wind. The validity of different theoretical models is examined. Particular emphasis is given to the implications of nonexistence of spatial homogeneity on the evolution of the duration-limited wind-wave field.

2. Experimental facility and procedure

Experiments were carried out in a wind-wave facility that has a test section, which is 5 m long, 0.4 m wide and 0.5 m high. The test section is covered by removable transparent plates with a partially sealed slot along the centerline that facilitates positing of sensors. The test section is filled to water depth of about 0.2 m, thus deep-water conditions are satisfied for wind-waves with lengths pertinent to this study. Computer-controlled blower provides air flow rate with wind speed in the test section up to about 15 m/s. Instantaneous surface elevation was measured by a capacitance-type wave gauge made of 0.3 mm anodized tantalum wires and mounted on a computer-controlled vertical stage to enable its static calibration. The wind velocity in the test section, $U(t)$ was measured by a Pitot tube. Simultaneously with the surface elevation measurements, two components of the instantaneous surface slope, in the wind direction, $\partial\eta/\partial x$, and in the crosswind direction, $\partial\eta/\partial y$, were determined by a laser slope gauge (LSG). More details about the experimental facility and the instrumentation are given in [8] and [20]; for detailed description of the LSG set up and calibration procedure see [14].

Prior to activation of the blower in each experimental run, the water surface was calm. The blower output voltage represents the airflow rate; this voltage varies linearly at the rate of 1 V/s until the prescribed steady state is attained. The following set of the target wind velocities in the test section was used: U = 6.5 m/s, 7.5 m/s, 8.5 m/s, 9.5 m/s, and 10.5 m/s. Results of simultaneous measurements of the blower output voltage and of the wind velocity $U(t)$ as a function of time elapsed since the activation of the blower by the computer are presented in Fig. 1 for different target wind velocities. The duration of the ramp in the blower-driving signal varies from 3 s to 5 s. At each instant, the wind velocity lags slightly behind the blower output, the delay, however, does not exceed 1 s. Velocities below about 1.5 m/s are not measured adequately by the Pitot tube. Once the target velocity is attained, the blower maintains constant airflow rate in the test section for 120 s and is then shut down.

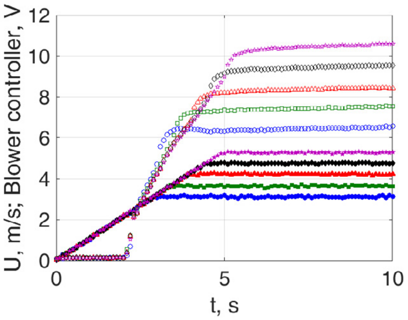

Fig. 1. Mean wind velocity (empty symbols) and the blower output voltage (filled symbols).