LABORATORY STUDY OF THE FINE STRUCTURE OF BREAKING WAVES FOR SCATTEROMETRY APPLICATIONS

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Abstract Laboratory measurements of the fine space-time structure of short gravity-capillary waves, as well as Ku-band scattering at grazing and moderate incidence from spilling and plunging breaking waves in a wave channel are presented. Unsteady breaking waves are generated by focusing the waves in space and time. A scanning laser slope gauge was used for measuring short waves of wavelength 0.2-20cm, and frequencies up to 150Hz. A dual polarized (VV, HH) coherent pulsed Ku-band scatterometer with good temporal resolution (3ns) was used to simultaneously obtain Doppler spectra of the scattered signals from the breaking area. It was found that the breaking splash is the main source of small-scale surface-wave generation. The short surface wave slope field produced by the breaking could be separated into regular short (5-10mm wavelength), fast, bound waves, and free gravity-capillary waves. Both types of waves were found to co- and counter-propagate relative to the direction of the dominant wave propagation.

Measurements of the Doppler frequency of the scattered signal are consistent with this description of the slope gauge measurements.

INTRODUCTION

Microwave scattering from breaking surface waves is poorly understood. Breaking is a strongly non-linear phenomenon comprised of a number of different processes. The best way to separate these processes is to simultaneously measure both the scattered signal and the fine structure of the surface which is responsible for the scattering. Laboratory experiments using mechanically generated waves under computer control offer the simplest means of generating breaking in a repeatable (in the mean) way without the complicating factor of the wind. We anticipate that the direct effects of the wind are only of consequence for the shorter breaking waves which do not actively entrain air to form a whitecap. Rapp and Melville [1] have used these techniques in a study of unsteady deep-water breaking. They used laser-Doppler anemometry to measure horizontal and vertical fluid velocities, and wave gauges for surface displacement measurements. The structure of the breaking region was examined in detail. The present study is an extension of this experiment to include microwave scattering. A scanning laser slope gauge (SLSG) was used to measure the 2-D space-time structure of the surface slope, and a Ku-band, dual-polarized, coherent, pulsed scatterometer was used for the microwave measurements.

Kwoh and Lake [2] attempted to describe deterministically the scattering from "gently" breaking 2.5 Hz paddle-generated waves at grazing and moderate incidence using an X-band CW dual-polarized scatterometer and SLSG. The different contributions from slow and fast scatterers, as well as specular facets, was discussed. Our data are in qualitative agreement with their results, but the more comprehensive wave slope and velocity measurements in our study (2-component velocity field and 2-D slope field measurements) permit a more detailed examination of the source of the scatterers.

EXPERIMENTAL METHODS

The experiments were conducted in a glass-walled channel in the Hydraulics Laboratory at the Scripps Institution of Oceanography. The channel is 30 m long, 0.5m wide, and filled to a depth of 0.6m with fresh water. The SLSG was designed for measuring short waves with wavelength from 0.1 to 20 cm and frequencies up to 150Hz. The SLSG consists of an underwater laser and scanner assembly, and the position-sensor assembly above the water surface. The 60kHz sampling rate produced two 50x300 pixel space-time images every second.

A coherent, 14 GHz (λ=2.1cm), dual-polarized, pulsed (3ns pulsewidth) scatterometer was used for obtaining the amplitude and frequency of the scattered signal. The scatterometer is described in detail in Rozenberg et. al.[3]. The scatterometer's antennas were fixed 40 - 140 cm above the water surface, with the grazing angle varying from 6 to 45 degrees. The scatterometer was mounted looking in an upstream direction at a common footprint with the SLSG and resistance wire wave gauge. Unsteady single breaking waves were generated by focusing wave groups, with center frequencies in the range 0.9-1.3 Hz, in space and time [1]. Two-dimensional filtering in the wavenumber-frequency domain was used for separating the direction of propagation of the surface waves as they appeared within the breaking region.

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RESULTS

Measurements of the slope-field fine structure for different strengths of breaking from gentle to plunging, as well as both VV and HH polarizations at grazing incidence angles from 6 to 45 degrees, were taken. Typical samples of simultaneous time series of the wire wave gauge and the SLSG for a single spilling wave are presented in Fig.1. From the top the figure shows surface displacement $\eta(t)$, wave slope s(t) from the SLSG without scanning, and the 2-D space-time slope field s(x,t) with the SLSG scanning in the direction of wave propagation. The last panel shows a sequence of interweaved patches with different frequencies and phase velocities depending on the wave profile. A burst of strongly nonlinear short waves can be seen both in the SLSG time series and in the space-time slope field. More detailed examination of these data show surprisingly regular sets of the short fast waves at the very moment of breaking and a lot of intermittent patches with smaller frequencies and phase velocities approximately 0.1-0.15s after breaking. Two-dimensional filtering to separate co- and counter-propagating waves shows approximately equal contributions from both fast and slow waves in both directions of propagation. Of particular interest are the characteristics of the wave field and scattered signal which could be associated with the same scatterers.

Fig.1 shows also spectrograms taken with a 0.25s window (0.1s overlap) for the slope and both VV and HH scatterometer signals for the same breaking wave parameters and 8 degree grazing angle looking towards the oncoming breaking wave. The similarity of all the spectrograms is readily apparent. Again, the moment of breaking is marked by the appearance of high frequencies in both the scattered signals and the slope field; while a short time after breaking all the local spectra rapidly shift to lower frequencies.

The large differences between the high-frequency patches of the scattered signals, as well as the high frequency slope features on the breaking crests of the dominant waves, versus the relatively slow waves following breaking may be characterized in terms of "fast" (or bound), and "slow" (or free) scatterers. The velocities of "fast" scatterers (150-170 cm/s) correspond to phase velocity of the dominant waves; their wavelengths at the moment of breaking are in the range 0.5-1.0cm, and they are surprisingly regular. All these features are consistent with parasitic (bound) capillary waves, generated by the steepening wave immediately prior to breaking. After breaking, the scatterers with smaller phase velocities are clearly associated with Bragg scattering from free surface capillary waves. A noteworthy difference between the VV and HH signals, especially in the post-breaking region, is that the local VV spectra have a more continuous tail, with the HH spectra more intermittent. The presence of the long-lived turbulent velocities following breaking were reported in [1]. This could be considered as a potential source of the observed differences in the polarized scattering. The possibility of scattering by turbulent wakes and their influence on the Doppler bandwidth was discussed in [2] and by Jessup et al.[4]. Measurements of the spatial and temporal decorrelation scales should clarify the source of these phenomena.

CONCLUSIONS

i. Laboratory measurements of Ku-band scattering at grazing incidence, as well as the fine space-time structure of mechanically-generated breaking waves are presented.

ii. Both VV and HH local Doppler spectra could be separated into two groups. The first group corresponds to scattering at the onset of breaking and shows large values of the Doppler frequency ("fast" scatterers). No significant difference between VV and HH signals in this area is found (HH spectra are slightly higher). The second corresponds to scattering following breaking and has much lower values of the Doppler frequencies ("slow" scatterers).

iii. Direct comparison of the measured fine space-time structure of short wave slopes and parameters of the scattered signals, demonstrates the differences between the fast and slow scatterers. The slow group is consistent with the Bragg scattering from the free capillary waves, while the fast group is associated with scattering from the bound capillary waves on the crests of the dominant breaking waves.

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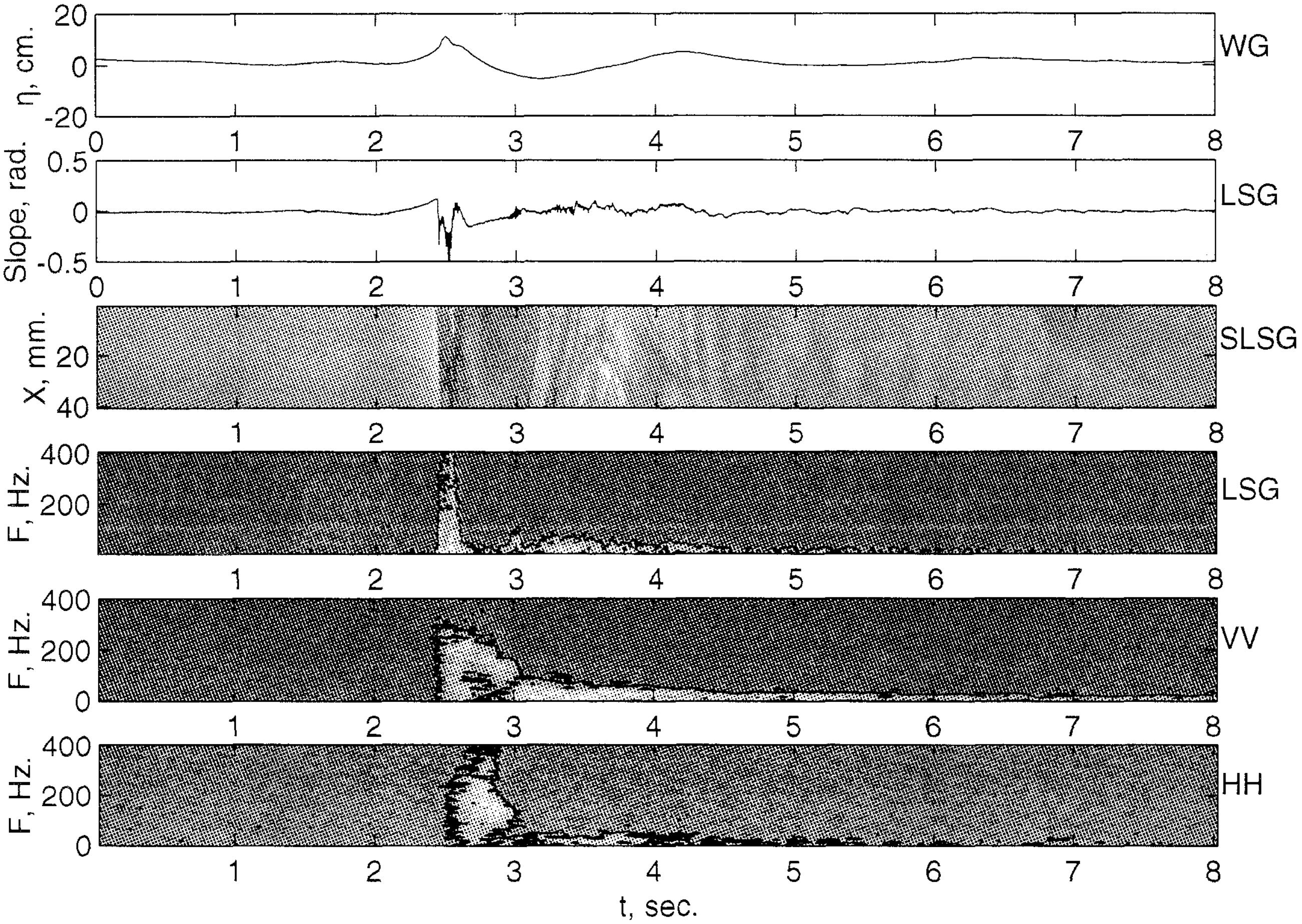

Fig.1. Time series and spectrograms for wave gauge, laser slope gauge, and scatterometer signals. Spilling breaking, 8 deg. grazing angle.