LABORATORY STUDY OF SWELL WAVES PROPAGATING IN A WINDY DOMAIN

Luca Chiapponi, University of Parma, luca.chiapponi@unipr.it
Fabio Addona, University of Parma, fabio.addona@unipr.it
Sandro Longo, University of Parma, sandro.longo@unipr.it

INTRODUCTION

Swell is defined as waves which have left their originating area while maintaining a stable shape. Whether in open sea or coastal regions, swell can be influenced by winds blowing from various directions. Numerous theoretical models have been developed to understand the physical mechanisms underlying the interplay between wind-generated waves and swell. Laboratory studies are rare, due to the difficulty of reproducing the conditions that occur in the open sea. Swell propagating with an opposing wind has generally received less attention, although some interesting features, like swell attenuation and wind-waves amplification, were revealed in field observations.

EXPERIMENTS

To enhance our understanding of the general interaction between wind and swell, a series of experiments were conducted at the Ocean-Atmosphere Interaction Flume at the Andalusian Institute for Earth System Research (IISTA), Universidad de Granada, see Figure 1. This experimental setup includes a flume equipped with two paddles for generating waves in both directions and a closed-loop wind tunnel capable of generating air velocities of up to 12 m/s. The flume has a rectangular cross-section, measures 16 meters in length and 1 meter in width and is designed for a water depth of approximately 0.7 meters. The distance between the roof of the wind tunnel and the free water surface is around 1.5 m.

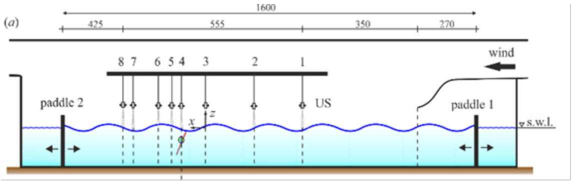

Figure 1 - A sketch of the wind/wave flume used for the experiments.

In this activity, we describe and interpret some experiments involving mechanical regular waves and wind-generated waves, with the following combinations: (i) mechanical regular waves, (ii) mechanical regular waves perturbed by following wind, (iii) mechanical regular waves propagating against the wind, and (iv) wind-generated waves. The mechanical regular waves have a nominal height, H, of 0.05 cm and a period, T = 1.45 s. The wind velocity, U_w, ranging from 4.8 to 7.2 m/s, was measured 5 cm above the still water level using a Pitot tube. For this activity, we employed the Stereoscopic Particle Image Velocimetry technique (S-PIV) to reconstruct the three-dimensional velocity field in water in a single plane. This technique allows for simultaneous measurement of two-component velocity within an entire plane, along with the transverse velocity. Two cameras mounted on a remotely controlled traverse system observed particles crossing the measurement plane with a stereoscopic view. To ensure a suitable signal-to-noise ratio in the measurement field, the water was seeded with TiO_2 particles. The measurement area covered 140 x 140 mm^2 with a resolution of 2 or 4 mm (depending on the size of the interrogation window during the processing of the images). The free water surface was monitored using eight Ultrasound acoustic probes (US) distributed along the channel, covering a length of approximately 170 cm. Each experiment involved five vertical positions (stations) of the traverse system, with the initial position set to capture the air-water interface. The data acquisition system (DAQ) was programmed to acquire and process the US signal in real time, also triggering the PIV measurements. In each test, a sequence of 1000 frames were acquired at a data rate of 7.25 Hz, with each test lasting approximately 138 s. This procedure was repeated at each vertical station.

DATA ANALYSIS

We consider the horizontal longitudinal direction along the channel as x, the vertical direction as z and the horizontal axis perpendicular to the formers as y. The corresponding velocities were u along x, v along y and w along z.

Experimental data obtained from S-PIV require additional preprocessing steps, including the removal of background noise, identification of outliers, and interpolation to address missing data. Several techniques are available for this purpose (refer to Clavero et al., 2016 and related references), and we have chosen the Proper Orthogonal Decomposition (POD) method initially introduced by Sirovich in 1987. In the POD technique, the signal is analyzed to determine the most appropriate basis represented by multiple modes. Each snapshot can then be reconstructed as a linear combination of these basis elements (modes). The number of modes used in the POD technique corresponds to the number of available snapshots. These modes can be sorted based on their energy contribution. A spectral representation of the most energetic modes for one experiment is reported in Figure 2.

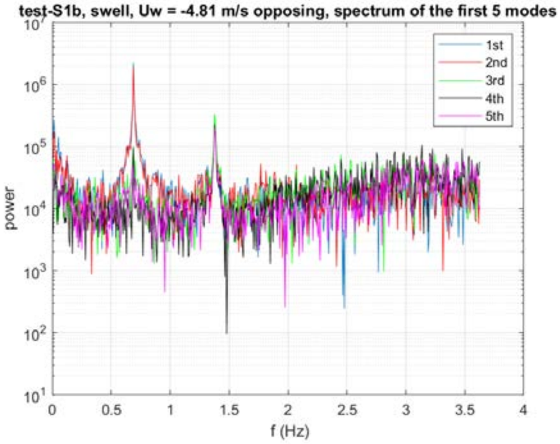

Figure 2 - Spectrum of the first 5 modes for test S1b (swell with opposing wind, U_w = 4.81 m/s, station close to the free surface).

The ultimate outcome of this approach is the capacity to describe a substantial dataset using a restricted set of parameters without sacrificing information. Simultaneously, it helps in the elimination of noise and unrealistic fluctuations in the data. The more organized the source signal, the fewer modes are needed for an accurate reconstruction. POD serves to characterize how energy is distributed among the organized modes of the flow. Additionally, it operates as an effective filter, making it possible to separate turbulence from the mean or periodic flow field. Figure 3 shows, for a single snapshot, the velocity component of the wind wave (in red) and the periodic component of the paddle wave (in light grey). The difference between the recorded velocity data and the reconstructed data corresponding to the eigenvalues containing 95% energy is considered to be turbulence.

The availability of the three velocity components makes it possible, after applying separation techniques (with thresholds that we admit are pragmatic), to calculate the Reynolds stress tensor in its 6 independent components and to correlate the turbulent fluctuations with the average phase wave velocities. The picture that emerges is a detailed snapshot of the interactions between the wind waves and the swell wave.

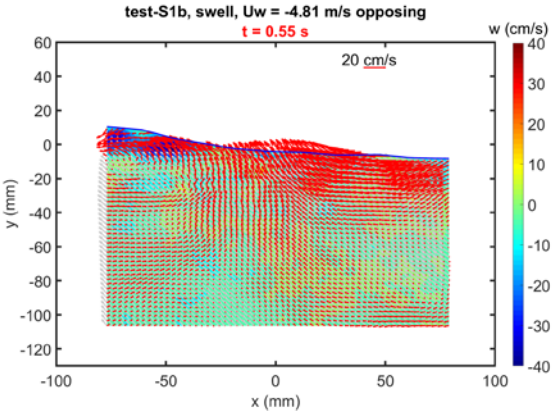

Figure 3 - Instantaneous velocity after POD analysis for test S1b (swell with opposing wind, U_w = 4.81 m/s, station close to the free surface).

RESULTS

Preliminary analyses indicate that the transverse dynamics are dominant, with turbulent jets in the z-direction contributing to the transformation of wind waves from short crested to long crested. Consequently, the contribution of the transverse component to the kinetic energy is more important than that of the two components in the plane of the S-PIV.

A second analysis was performed by mapping the domain into a rectangular domain with the vertical coordinate attached to the instantaneous free surface. The number of modes of the new POD sufficient to reach the 95% energy threshold is significantly lower than in the case of the domain varying with the free surface (coincident with the S-PIV internal coordinate system). Furthermore, the second (Lagrangian-like) analysis allows the analysis of the turbulent kinetic energy diffusion generated near the surface, eliminating the vertical advection of the swell flow field.

Finally, the possibility of applying the analysis of the evolution of the POD modes using the Galerkin collocation method is verified, with the aim of identifying the efficiency of the coupling for the purpose of energy transfer between the different modes.

REFERENCES

Zou (2017): Zou, Q., Chen, H. Wind and current effects on extreme wave formation and breaking, Journal of Physical Oceanography, 2017, 47, 1817-1841.
Chambarel (2010): Chambarel, J., Kharif, C., Kimmoun, O. Generation of two-dimensional steep water waves on finite depth with and without wind, 2010, Eur. J. Mech. B/Fluids, 29, 132-142.
Liu (2015): Liu, K., Chen, Q., Kahiatu, J.M. Modeling wind effects on shallow water waves, 2015, J. Waterw. Port Coastal Ocean Eng., 142, 04015012.
Longo (2012): Longo, S., Liang, D., Chiapponi, L., Aguilera Jiménez, L. Turbulent flow structure in experimental laboratory wind-generated gravity waves, 2012, Coastal Engineering, 64, 1-15.
Clavero (2016): Clavero, M., Longo, S., Chiapponi, L., Losada, M., 3D flow measurements in regular breaking waves past a fixed submerged bar on an impermeable plane slope, 2016, JFM, 802, 490-526.