

The instability of wave trains propagating over an oblique current: a laboratory experiment in a directional wave basin

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Introduction

Extreme waves represent a serious threat for marine structures and operations. Numerical and theoretical work has already demonstrated that the modulational instability plays a relevant role in the formation of extreme waves (Janssen 2003, Onorato et al. 2006, Onorato et al. 2001). However, strong deviations from Gaussian statistics can only be expected if waves are rather long crested i.e. the spectral energy is concentrated on a narrow range of directions (Onorato et al. 2002, Socquet-Juglard et al. 2005, Onorato et al. 2009). For more realistic short crested seas (i.e. broad directional distributions), the effect of modulational instability becomes less prominent and, as a result, the occurrence of extreme waves does not exceed predictions from second-order theory (e.g. Socquet_juglard et al. 2005). This transition between strongly to weakly non-Gaussian behavior is determined by a balance between nonlinearity (which promotes non-Gaussian behavior) and directionality (which suppresses non-Gaussian behavior). Thus, if there are circumstances when the nonlinearity is locally enhanced, we can expect that non-Gaussian behavior would persist also at broader directional spreads. In this respect, when waves propagate against an ambient current, wave steepness, and hence nonlinearity, increases as a consequence of the shortening of the wavelength, making nonlinear processes, such as the modulational instability mechanism, more likely. A number of laboratory experiments have been carried out to verify the behaviour of regular and irregular waves when opposing a strong current. Most experimental results until now have been obtained in wave flumes, where only one-dimensional propagation can be addressed. For the present study, we have accessed one of the largest directional wave tank in the world to address the more general two dimensional problem, where a multi directional wave field propagates obliquely over a uniform current in partial opposition. The aim is to explore the role of increasing wave steepness due to wave-current interaction on the modulational instability mechanism and the formation of large amplitude waves.

Laboratory experiments

The laboratory facility is a large rectangular wave basin with dimensions of 70 m X 50 m. The basin is fitted with a directional wave-maker along the 70 m side and a water circulation system along the 50 m side (see Stansberg 2008). For the present experiments the water depth was uniform over the basin and fixed at 3 m.

The methodology of the experiment was fairly simple. It consisted in monitoring the spatial evolution of regular and irregular wave fields as they propagate over an oblique current. In this respect, time series were recorded at a sampling frequency of 75 Hz along the mean wave direction. Regular fields were characterized by a monochromatic wave (carrier wave) and two side band perturbations. We used a carrier wave with period of 0.8 s and steepness $ka=0.1$, where k is the wavenumber of the carrier wave and a is its amplitude, while the two perturbations had amplitude equal to $0.25a$ and bandwidth $\Delta k = 0.25$. According to the instability diagram of Benjamin-Feir (see, e.g. Yuen and Lake 1982), this configuration is stable. Irregular waves were defined by a JONSWAP spectrum with peak period $T_p=1$ s, significant wave height $H_s=0.08$ m and peak enhancement factor $\gamma=6$. A frequency-independent $\cos^N(\theta)$ directional function was then applied to describe the energy in the directional domain. A number of values of the spreading coefficient N were used, ranging from long to short crested conditions: $N = 840; 200; 90; 50; \text{ and } 24$. At the wave-maker, waves were generated as an inverse Fourier transform with random amplitudes and phases approximation.

For both regular and irregular experiments, a uniform current was run at its maximum speed of 0.2 m/s. In the wave tank, the current flows in the longitudinal basin direction, so that it crosses directional wave fields. An angle of 110 deg was considered; this configuration generates a partial opposition, which is expected to increase the wave steepness of about 8-10%. For reference, tests were also performed in the absence of current.

For each random test, 30-minute time series were recorded. Experiments were also repeated four times with the same spectral configuration but different random amplitudes and phases to ensure a sufficiently large data set for statistical analysis.

Results

In Fig. 1, the evolution of the maximum amplitude of the wave packets is shown as a function of the dimensionless distance from the wave-maker. In the absence of an ambient current, the wave packets are basically stable, i.e., the amplitude does not change significantly as waves propagate along the tank.

However, when waves interact with a partial opposing current, the steepness of the carrier wave increases due to the shortening of the wavelength. This increase triggers effects related to the nonlinear dynamics of the wave packets. In this respect, we observed a robust increase of the maximum surface elevation along the tank; a peak is evident after about 23 wavelengths and it is almost twice the value of the initial wave train. Note that this behavior is expected from the evolution of unstable wave packets (see, for example, Yuen and lake 1982).

If the current is able to trigger the instability of wave packets and hence extreme waves, then it is feasible to suspect that in a random wave fields the percentage of extreme events can substantially increase. For irregular wave fields, the occurrence of extreme events can be summarized conveniently by the fourth order moment of the probability density function of the

surface elevation, namely the kurtosis. For reference, we mention that the kurtosis of a Gaussian (linear) wave field is equal to 3.

In the absence of an ambient current, it is well established that random wave fields strongly deviate from Gaussian statistics, provided waves are sufficiently steep and narrow banded both in frequency and direction (Onorato et al. 2009). In a more realistic condition, however, wave fields are characterized by a broader directional distribution and, as a result, the percentage of extreme waves decreases substantially. The overall effect of directionality is highlighted in Fig. 2, where the maximum kurtosis detected in the tank is presented as a function of the directional spreading coefficient.

In the presence of an ambient current, extreme waves still remain less likely in directional wave fields rather than in long crested conditions (Fig. 2). Nonetheless, we observed a systematic enhancement of the kurtosis as a consequence of the wave-current interaction. It is interesting to note that this difference becomes a bit more prominent for broader directional sea states: the kurtosis is about 1.5% higher for $N > 90$, while it is about 3% higher for $N \leq 90$. This seems to suggest that the weak increase of steepness related to the wave-current interaction slightly compensates the suppression of non-Gaussian behavior due to directionality.

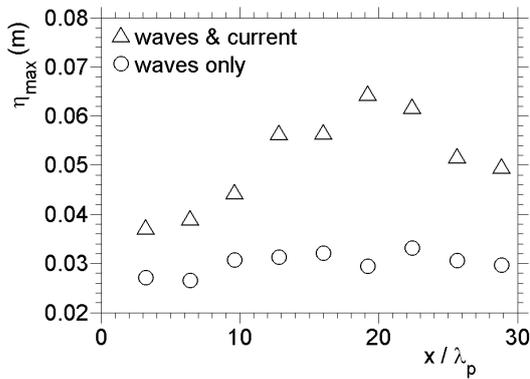


Fig. 1 Regular waves experiments evolution of wave amplitude.

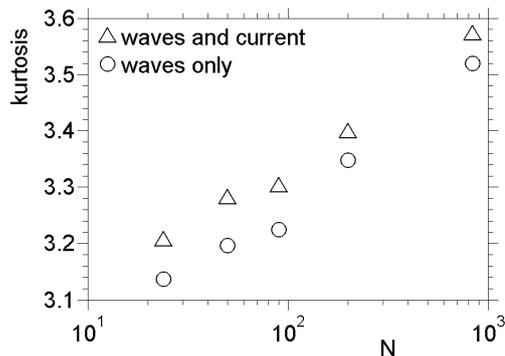


Fig. 2 irregular waves experiments: kurtosis as function of the directional spreading coefficient.

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