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Experimental study of the formation of steep waves and breakers

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Abstract

Breaking waves (whitecaps) are one of the most important and least understood processes associated with the evolution of the surface gravity wave field in the open sea. This process is the principal means by which energy and momentum are transferred away from a developing sea. However, an estimation of the frequency of breaking waves or the fraction of sea surface covered by whitecaps and the amount of dissipated energy induced by breaking is very difficult to carry out under real sea conditions. A controlled experiment, funded by the European Commission under the Improving Human Potential Access Infrastructures programme, was carried out in the Ocean Basin Laboratory at MARINTEK, Trondheim (Norway).

Simulation of random waves of the prescribed spectra by wave makers provided a very realistic pattern of the sea surface. The number of breaking waves was estimated by photographing the sea surface and recording the noise caused by the breaking waves. The experimental data will serve for calibration of the theoretical models of the sea surface fraction related to the whitecaps.

1. Introduction

Breaking waves (whitecaps) are one of the most important and least understood processes associated with the evolution of the surface gravity wave field on the open sea. This process is the principal means by which energy and momentum are transferred away from a developing sea. Whitecaps are also basic sources of the marine aerosol fluxes transported from the sea surface to the atmosphere. Breaking waves disrupt the chemical and organic surface films and produce fluxes of the sea-salt aerosols (Petelski & Chomka 1996, Chomka & Petelski 1997). Most of the aerosol generated from natural waters is in the form of jet and film drops from the bursting of air bubbles (Monahan & Van Patten 1989). The aerosol droplets may transfer water vapour, heat, pollutants and bacteria through the air-water interface. They can be very easily transported by wind over large distances. In this way, marine aerosols influence the optical features of the atmosphere, which are of fundamental importance for the remote sensing of the sea surface; they also play an important role in climate formation.

The intensity of fluxes is proportional to the fraction of sea surface covered by whitecaps and to the rate of energy dissipated by them. However, an estimation of the frequency of breaking waves between given locations, or the fraction of the sea surface covered by whitecaps and the amount of dissipated energy induced by breaking is very difficult to carry out under real sea conditions. It can only be done by a controlled wave experiment. Such an experiment, funded by the European Commission under the Improving Human Potential Access Infrastructures programme, was carried out in the Ocean Basin Laboratory at MARINTEK, Trondheim (Norway).

In this paper we briefly describe the link between the percentage of sea surface covered by whitecaps and storm intensity. The technology of the experiment and some preliminary results are also discussed.

Whitecap coverage for irregular waves

Estimating the limiting wave height for wind-induced waves is complicated as our present understanding of most aspects of wave breaking remains fragmentary. Most of the available statistics of breaking waves are based on the limiting steepness criterion. This criterion is used to identify the part of the joint probability density function of wave height and wave period where the waves are assumed to be breaking (Ochi & Tsai 1983). Integration over the joint probability function yields the fraction of breaking waves (or the probability distribution of breaking wave heights). According to Srokosz (1986), the probability that a crest of any height will break is

$$F_{\mathrm{cr}} = \exp\left(-\frac{\alpha^2 g^2}{2m_4}\right), \tag{1}$$

in which F_{cr} represents the probability that breaking will occur at a crest at a given point on the sea surface, m_4 is the fourth spectral moment, g is the acceleration due to gravity and α is an experimental constant varying from 0.3 to 0.55.

The probability F_{cr} should be distinguished from that of Snyder & Kennedy (1983), which deals with the fraction of the sea surface covered by breaking water. They assumed that wave breaking occurs in the fluid regions, where the surface motion (not only in the wave crest vicinity) requires the downward acceleration to exceed the dynamical threshold αg. Hence, the final form of the percentage of sea surface covered by white-caps is

$$F_{\mathrm{cov}} = 1 - \Phi\left(\frac{\alpha g}{\sqrt{m_4}}\right), \tag{2}$$

in which $\Phi(x)$ is the Laplace integral.

The probabilities F_{cr} and F_{cov} are independent of any assumption about the spectral width, assuming that moment m_4 exists, i.e.

$$m_4 = \int_0^{\infty}\int_{-\pi}^{\pi} \omega^4 S(\omega,\theta)\, d\omega\theta, \tag{3}$$

where $S(\omega,\theta)$ is the two-dimensional frequency and directional spectrum. $S(\omega,\theta)$ is usually represented as the product of the frequency spectrum $S_1(\omega)$ and directional spreading $D(\theta)$. The frequency properties of wind-induced waves in deep water are usually modelled by the Pierson-Moskowitz spectrum (Pierson & Moskowitz 1964) or by the JONSWAP spectrum (Hasselmann et al. 1973). It is well known that the Pierson-Moskowitz spectrum can be obtained as a special case of the JONSWAP spectrum when the peak enhancement factor γ is equal to 1. Therefore, in our experiment we used mainly the JONSWAP spectrum (Hasselmann et al. 1973). For the purpose of the experiment, the directional spreading $D(\theta) = A \cdot \cos^n(\theta)$ was used. θ is the angle between the direction of propagation of a particular spectral component and the main axis of the main measuring profile, and n is a power coefficient depending on the directional spreading width. In the particular tests, values of n equal to $0, 2, 10$ or 40 were used. It should be noted that for $n = 0$, the wave train is unidirectional.

The experimental data on the breaking of the irregular waves and whitecapping coverage are very limited. Whitecap coverage was investigated by Monahan (1971), Toba & Chaen (1973), Wu (1979), Monahan and O'Muircheartaigh (1980), Koepke (1984), Marks (1987) and others. In particular, Monahan (1971) collected 71 observations of whitecapping at locations on the Atlantic Ocean and adjacent salt water basins. He presented the optimal power-law expression for the dependence of oceanic whitecap coverage fraction $F_{\rm cov}$ on 10 m elevation wind speed V in the form

$$F_{\rm cov} = a\,V^{\lambda}. \tag{4}$$

The least squares fitting method based on Monahan's (1971) data suggests that $a = 1.35 \times 10^{-5}$ and $\lambda = 3.4$ for $4 \text{ m s}^{-1} < V < 10 \text{ m s}^{-1}$.

Marks (1987) analysed the data collected during a cruise of the research vessel 'Polarstern' in the North Atlantic and Greenland Sea (Arkis–III polar expedition). The whitecap coverage was recorded by a modern video-camera-system mounted about 15 m above the sea surface. The final result is given by the following relationship:

$$F_{\rm cov} = 2.54 \times 10^{-6}\,V^{3.58}, \tag{5}$$

in which V is the wind speed at the standard 10 m above sea surface.

It is generally recognised that whitecap coverage is negligibly small for wind speeds less than 3 m s^{-1}. Furthermore, the mechanical tearing away of wave crests, which results in the formation of spume lines, is an additional mechanism of white water formation. It becomes of special importance for wind speeds above 9 m s^{-1}. All these facts suggest strongly that the use of a more complex form of $F_{\rm cov}(V)$ than a simple power-law is required to describe precisely the dependence of $F_{\rm cov}$ upon V.

Technology of the experiment

Estimating the fraction of sea surface covered by whitecaps and the amount of dissipated energy induced by breaking is very difficult to perform under real sea conditions. The only solution is to carry out large-scale controlled laboratory experiments. Such experiments on whitecap coverage have been carried out in the Ocean Basin at MARINTEK. This is the largest basin of this type in the world, with the dimensions: length – 80 m, width – 50 m and depth – down to 10 m. The basin is equipped with two wave makers – a hydraulically driven, hinged double-flap wave maker and an electrically driven, hinged multi-flap wave maker. The former can reproduce regular waves with a maximum wave height up to 0.9 m and wave spectra simulated by computer or reproduced from magnetic type.

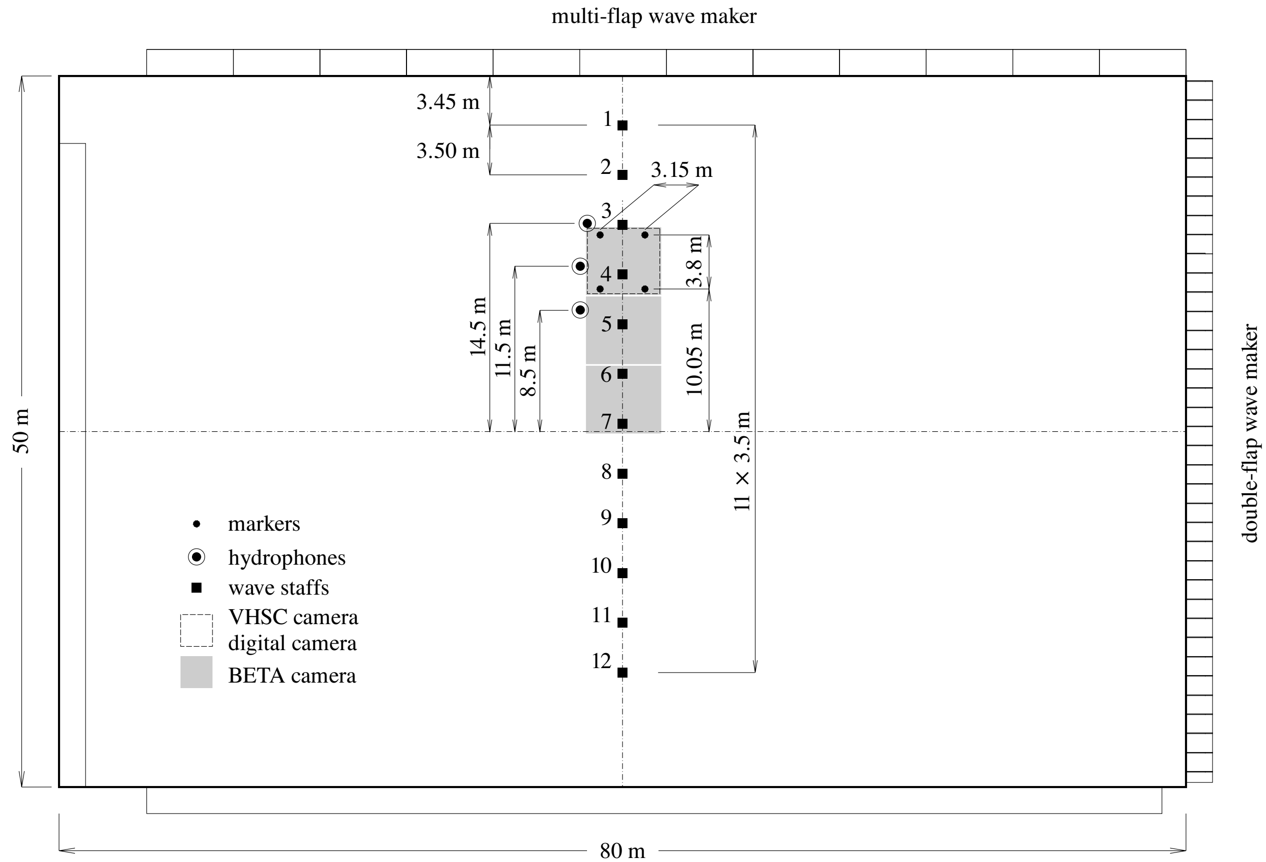

Fig. 1. Arrangement of instruments

The latter consists of 144 individually controlled flaps. The multi-flap wave maker is able to reproduce regular waves with a maximum wave height up to 0.4 m and computer-generated random short-crested or long-crested waves of specific direction. The water depth during experiment was kept constant at 2.5 m.

The main measuring profile was located perpendicular to the multi-flap wave maker (see Fig. 1). The profile consists of 12 wave staffs, 4 video cameras (VHSC camera, 2 BETA cameras and digital camera) and 4 hydrophones. The signals from the wave staffs were recorded simultaneously. The cameras located 5 m above the still water level were synchronised with the wave staffs. Two cameras covered the same basic recording area of 3.8 m $\times$ 3.1 m. The other two cameras covered the areas located further from the multi-flap wave maker. The layout of the hydrophones is shown in Fig. 1. Initially they were situated 1 m below still water level (SWL). During the second stage of the experiment, the hydrophones were moved closer to the surface, i.e. 0.5 m below SWL. However, one hydrophone was always located 1 m deeper than others. In all 30 tests, the duration of the recording was 23 minutes.

Preliminary results

The five-day laboratory experiment resulted in 30 wave tests of various wave parameters. Moreover, 111 records of 10 seconds' duration of the acoustic pressure wave were obtained and more than 6 hours of video camera pictures were recorded. Now all the collected data are being analysed comprehensively. In this analysis, both the traditional spectral and statistical approach, as well as the more modern wavelet (Massel 2001) or fractal methods (Hastings & Sugihara 1993) are being used. For example in Fig. 2, a segment of the wave record is shown. For this segment the resulting spectrogram and wavelet amplitude (Morlet's wavelet) are shown.

As the basic aim of the project is the detection of steep and breaking waves, the wavelet approach and its evolution during wave breaking will be used extensively. For example, in the time segment from 820 sec to 830 sec, the wave becomes very steep and is close to breaking. It is believed that the fractal dimension will change as the wave surface becomes steeper. The breaking process involves the generation of higher frequency components. Therefore, the fractal dimension should be bigger. However, the link between the breaking process and the fractal dimension is not known.

The main purpose of the acoustic measurements during the experiments was to explore the relationship between the noise spectral parameters and the energy of breaking waves. Bubbles entering the water column during

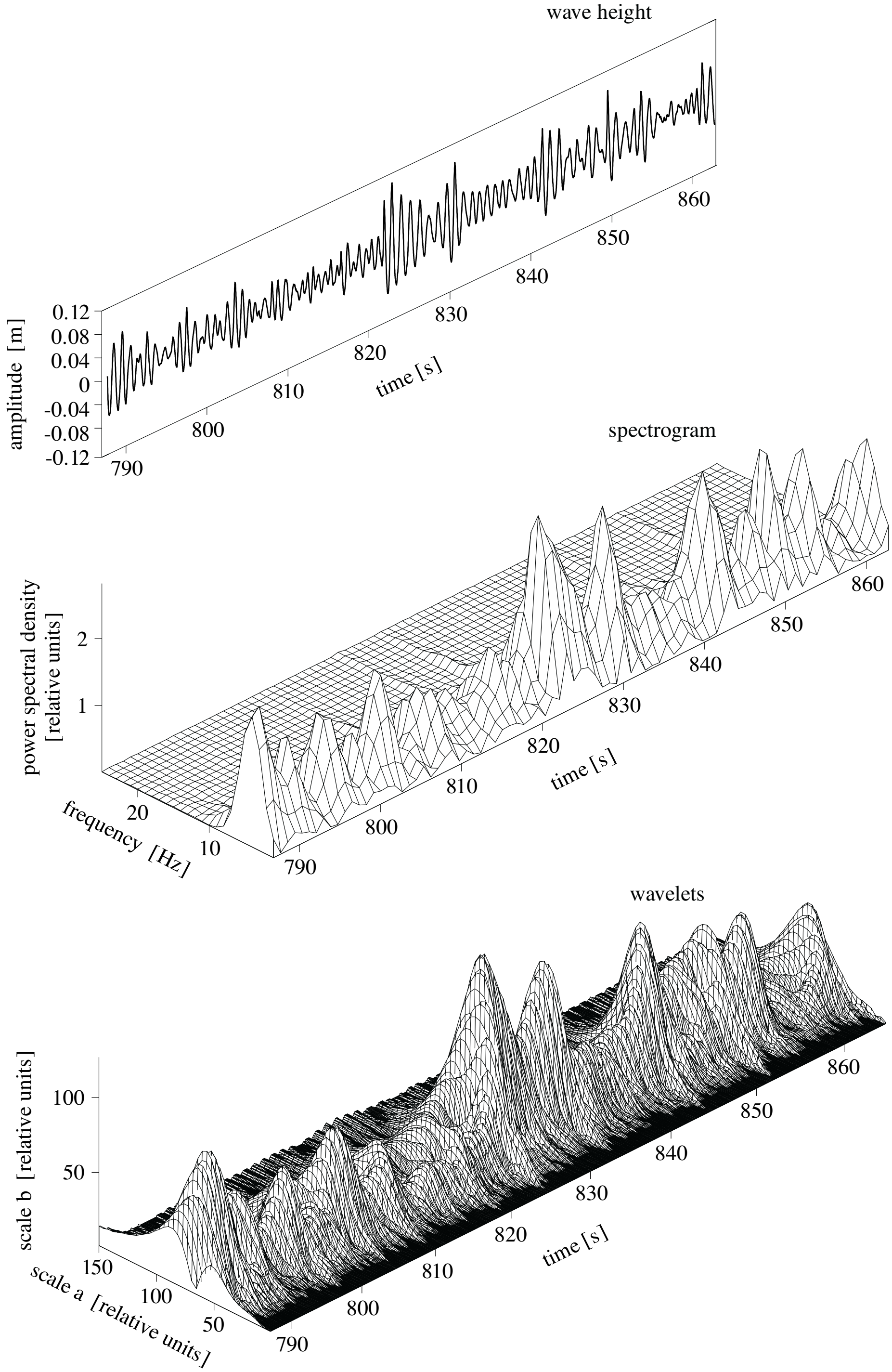

Fig. 2. Example of a wave record, spectrogram and wavelet amplitude versus time

wave breaking are the sound-generation mechanism and may contribute to sound generation individually or collectively in clouds of coupled oscillating bubbles. The signal from each hydrophone was sampled at a frequency of 25 or 50 kHz and stored synchronously with wave amplitudes and video recordings. Analysis of simultaneous video observations and wave staff records of the wave surface close to hydrophones, and the hydrophone signals reveals a close correlation. An example of a segment of the wave staff and hydrophone is shown in Fig. 3. A sudden jump in the acoustic pressure close to time $t \sim 6$ s corresponds to the very steep wave shown in the upper figure.

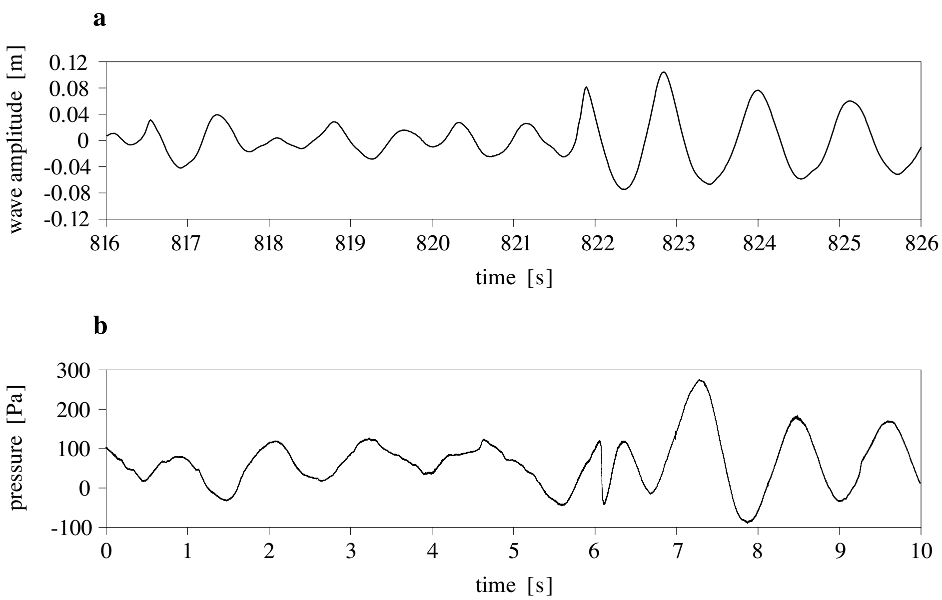

Fig. 3. Surface wave variation in time (a) and the corresponding hydrophone record (b)

Wave staff and hydrophone records represent the evolution of the wave surface and acoustic pressure at the particular points; however, they are not able to provide any information about the space distribution of breaking waves. Such information can only be obtained from the video records. Example of such data is shown in Fig. 4. In this figure whitecaps are formed in the area between wave staffs 3 and 4. The wave is propagating from the lower part of the figure. The four black dots denote the markers of the basic recording area.

Fig. 4 contains a negative picture of the 'saturation' component of the HSV method for the breaking event recorded during the experiment. This component enhances the area of whitecapping in the most effective way.

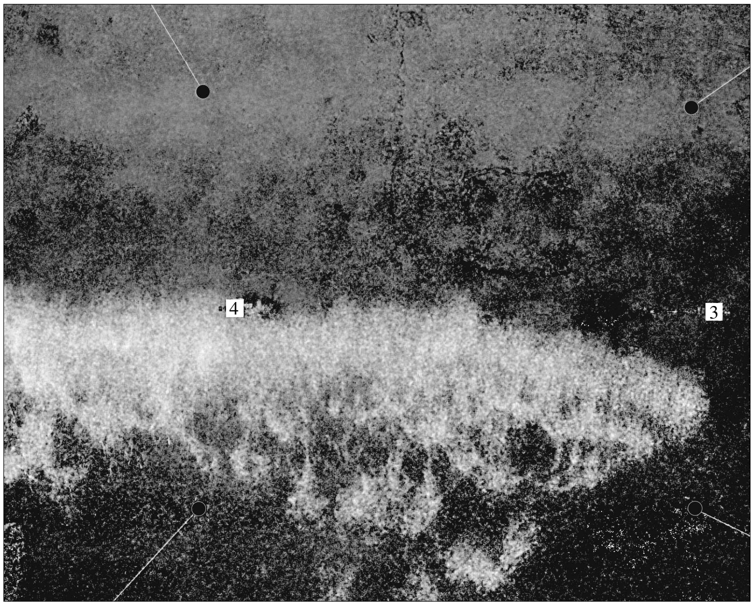

Fig. 4. Whitecapping pattern selected by the ‘saturation’ component of the HSV method

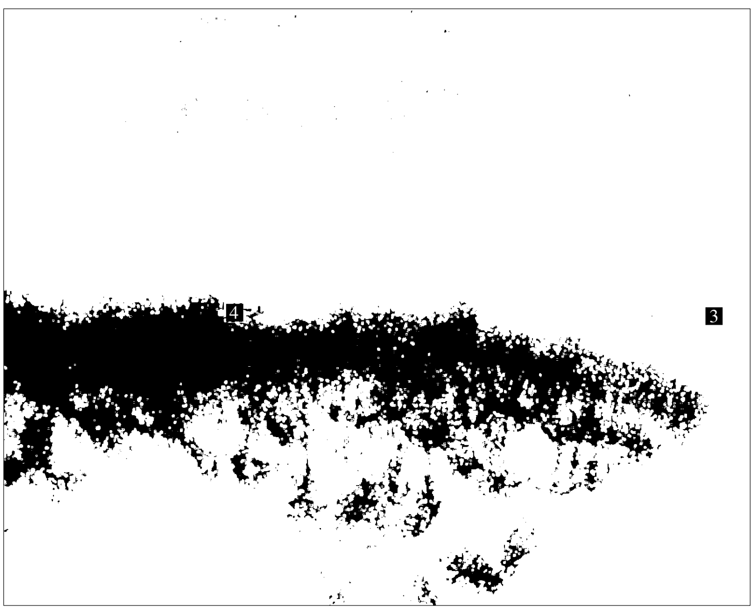

Fig. 5. Whitecapping as in Fig. 4 after thresholding and elimination of separated pixels

The white area in the middle shows bubbles of air in the water. In Fig. 5 the same event is presented after thresholding and eliminating the separated pixels. The required area of whitecapping is now proportional to the number of black pixels in this picture. All the collected experimental data will serve to calibrate the theoretical models of the sea surface fraction covered by whitecaps.

Further studies

The tests carried out in MARINTEK are only the first attempt to parameterise the fraction of sea covered by whitecaps and to determine the corresponding aerosol fluxes. The second stage of the project will include two parts. The first will be an extension of the experiments in Trondheim. However, the proposed studies will be focused on the detailed recording of wave breaking, with and without the presence of an ambient current. In the second part of the planned experiment, field observations will be carried in the Baltic Sea. In particular, the sea surface will be recorded using digital cameras and the sea state will be determined from the Wave Rider Buoy records.

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