ON THE ACOUSTICAL INTENSITY OF BREAKING WAVES

Li DING[1,2]
1. Dept. of Electrical and Computer Engr.
University of Victoria
Victoria, B. C., Canada

David FARMER[2]
2. Institute of Ocean Sciences
Sidney, B. C., Canada

INTRODUCTION

Breaking surface waves have been identified as the main source of wind-generated ambient sound in the ocean[1]. The sound radiated from breaking waves has been used to track these waves and measure their spatial and temporal statistics[2]. Recent laboratory work[3] has further suggested that the acoustic power released by breaking waves is correlated with the energy dissipation due to breaking. In this paper, we perform statistical analysis of the acoustic intensity of breaking waves measured in the open ocean and discuss the potential use of the result in remote measurement of wave energy dissipation.

OBSERVATION

Our observations were made during the Surface Wave Process Program, in February/March 1990. Breaking waves were tracked with a hydrophone array deployed at a depth of 25 m beneath the ocean surface. For each tracked breaking wave, its position, velocity and duration were determined using the correlation technique discussed in Ref. 2. Previous analysis[4] has suggested that breaking waves radiate sound predominantly over the range 100 – 500 Hz. We therefore calculated a time series of acoustic power in this frequency band from one hydrophone, as shown in Fig. 1. Occurrences and locations of breaking waves during this period were simultaneously tracked. The horizontal bars on the top of the figure indicate the period of each tracked event, and the received acoustic intensity from each of these individual events can be found in this time series. However, the background noise intensity should be subtracted from the total intensity I_A, to obtain the actual received intensity from the event. Due to the nonstationarity of ambient noise over a longer period, the noise intensity must be estimated locally. For each event, we search for a local minimum within the neighbourhood of the instant of occurrence, and the corresponding noise intensity I_N is estimated at the location of the minimum (Fig. 1). The actual received intensity from the event is given by $I = I_A - I_N$.

The acoustic intensity of breaking waves at 1 m distance is then calculated by assuming a dipole radiation pattern and neglecting aborption. Such calculations were performed over a period of 30 min in an area of radius 40 m. The estimated distribution of the source intensity (in dB) based on all the tracked events is given in Fig. 2. The source intensity is also shown against the travel speed of the breaking events in Fig. 3, where a low speed cutoff is imposed to reduce noise interference and the effect of swell advection on low event speeds. There is considerable scatter in the data (correlation coefficient r=0.37), possibly caused by lack of dipole radiation from a rough surface, or at least, tilting of dipole sources. The least squares fit is difficult to apply in this case. Nevertheless, a principal component analysis of these data shows that the two eigenvalues of the scatter matrix are $\lambda_1 = 1.37$ and $\lambda_2 = 0.63$ respectively, and that in the principal direction corresponding to λ_1 (as shown in Fig. 3), the source intensity is proportional to the 2.33 power of the breaking event speed.

DISCUSSION

The travel speed of breaking waves represents the scale of breaking which can be related to energy dissipation due to breaking.[5] Thus the result in Fig. 3, within the limits of the low correlation, shows that the acoustic power released by individual breaking waves increases with the amount of dissipated energy. More direct evidence supporting the above observation comes from recent laboratory work using colliding plane waves that demonstrated that the acoustic power radiated by a breaking wave is proportional to the energy dissipated due to breaking[3]. The dissipated energy is proportional to the difference of the upstream and downstream surface displacement variances (a_1^2 and a_2^2 respectively) of the breaking wave. Note that the acoustic power radiated from a source is proportional to the source intensity at 1 m distance, I_0. Therefore, by accepting the laboratory observation, we have

$$I_0 \sim E_{dis} \sim a_1^2 - a_2^2.$$

It is well known that the distribution of wave amplitude is closely Rayleigh[6], and hence a^2 is found to be exponentially distributed. Assuming a_1^2 and a_2^2 are independent with the same exponential distribution, it can be shown that $z = (a_1^2 - a_2^2) \geq 0$ is also exponentially distributed. Therefore we expect that I_0 has an exponential distribution[7]. In order to facilitate comparison between the data and this model, we make a transformation $x = 10 \log_{10} I_0$ to reduce the dynamic range of I_0. The resulting distribution of x is found to be

$$f_x(x) = \alpha e^{-\alpha\beta} \exp\{\alpha x - e^{\alpha(x-\beta)}\} \qquad (1)$$

where $\alpha = \ln 10/10$ and $\beta = 10 \log_{10} \bar{I}_0$.

Equation (1) is then fitted to the data in Fig. 2, where the resulting curve is also plotted. It can be seen that the fit is fairly good in general, though deviations from the curve due to statistical errors must exist. Consequently this result appears to support the hypothesis that the acoustic power released by breaking waves is proportional to the dissipated wave energy.

In summary, observations of the acoustic intensity statistics of individual breaking waves in the ocean appear to be consistent with the dependence of the radiated acoustic power on the dissipated wave energy obtained for the special case of colliding plane waves in the laboratory. This suggests that energy dissipation by wave breaking at the ocean surface may be probed by using ambient sound.

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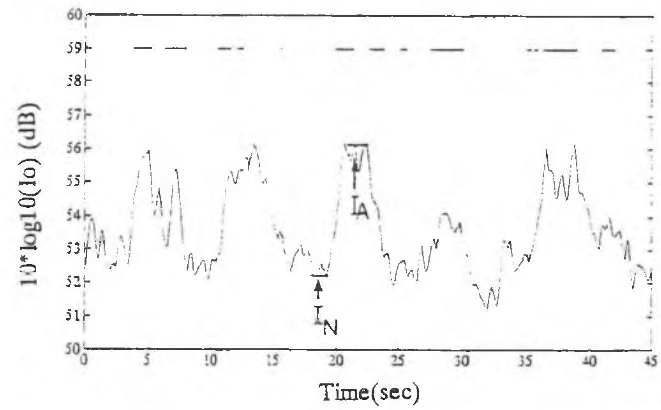

Figure 1: Time series of acoustic power in arbitrary unit. The horizontal bars indicate the occurrences of breaking waves.

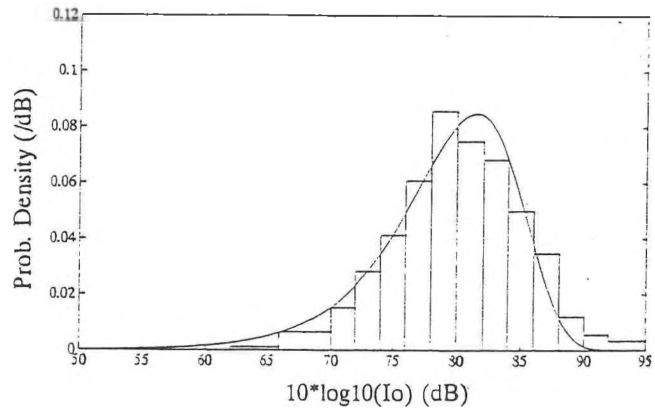

Figure 2: Probability distribution of acoustic source intensity of breaking events. The curve is Eq. (1) with β obtained using the least squares fit.

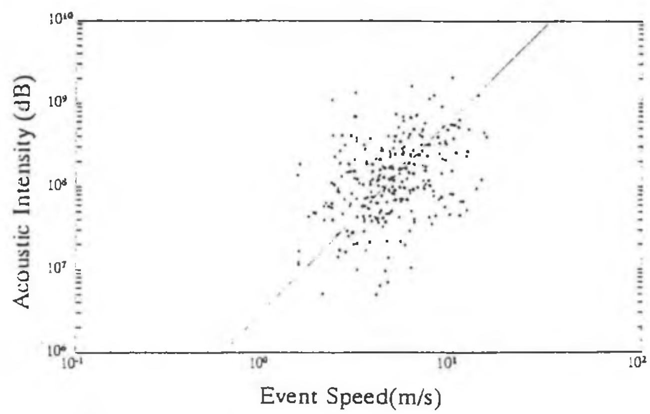

Figure 3: Acoustic source intensity of breaking events against the event speed. The straight line is in the principal direction corresponding to the higher eigenvalue.