Physical Mechanisms Underlying the Acoustic Signatures of Breaking Waves

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1 Introduction

The characteristics of waves breaking along the shoreline have been extensively researched over the past century, including wave breaking motions and aftereffects [1], as well as the relationships among bathymetry, wave shape (plunging, spilling, or surging) and wave breaking location [2]. The resulting underwater sound generation has also been well studied and has been elucidated as the individual and collective oscillations of bubbles and bubble plumes produced by the breaking waves [3] [4] [5].

In spite of this large body of research, the airborne sound generated by breaking waves is not as well-understood. Bolin and Åbom [6] proposed a model in which sound from the underwater bubble clouds propagate through the air-water interface, but also concluded that the main airborne sound generation mechanism remains a mystery. The aim of this paper is to analyze acoustic data from breaking waves and determine the dominant airborne sound generating mechanisms.

2 Methods

Recordings were made of breaking waves at Osborne Head, Nova Scotia, Canada (44.612 N, 63.420 W) from June 1 to August 22, 2011. A microphone was situated on a cliff 6 m above a rocky beach which experiences abundant breaking wave activity. Five minutes of uncompressed audio data sampled at 25.6 kHz were recorded every half hour. A camera mounted on a nearby building acquired photographs of the surf zone every five minutes. Directional wave spectra and significant wave height (SWH) were measured at a location 800 m from the microphone site, while weather data were obtained from a weather buoy 12.5 km SE of the microphone site. Further details can be found in a previous paper [7].

Thirteen isolated plunging breaking wave events were selected from the dataset, for which the significant wave height ranged from 0.8 m to 1.08 m. The time of the wave break was determined by listening to the audio recordings and marking the time at which the water jet from the curling wave appeared to impact the water surface. All data analysis was performed in Python using the Scikits Audiolab library. The data were highpass filtered with a cutoff frequency of 20 Hz to remove the infrasound vibrations.

3 Results

Time series of the third-octave band levels were constructed by calculating the Fourier transform of the sound pressure signal in lengths of 0.4 seconds (10240 samples) with a Hann window and 2.5% overlap (256 samples) and then summing the energy in each band with centre frequencies ranging from 40 to 2500 Hz. Figure 1 is a time series of the third-octave band level in the 50-Hz band for each breaking wave event. The higher overall band levels correspond to periods with larger significant wave height. The plots of the other bands are similar to Figure 1, including the large variability in power (±10 dB) and waveform in the time surrounding the break.

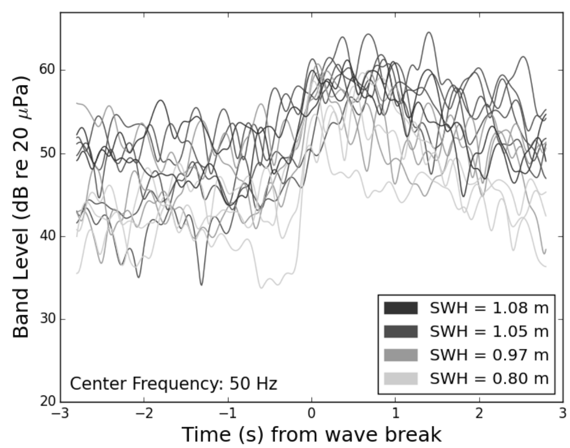

Figure 1: Time series of the third-octave band level for the 50-Hz band for each breaking wave in the data set. Greyscale of plot lines indicates significant wave height.

The band level change ΔBL was calculated for each wave and each third-octave band time series by manually marking the minimum BL_{min} and maximum BL_{max} band levels before and after the wave break and calculating their difference ($\Delta BL = BL_{max} - BL_{min}$). Figure 2 is a plot of the band level change averaged over all thirteen waves $\overline{\Delta BL}$ as a function of third-octave band centre frequency. As a wave breaks, the level in every band increases by 5 to 12 dB. At frequencies below 250 Hz, the band level change increases with decreasing frequency and reaches a peak of 12 dB at 50 Hz, while the band level change is constant (5-6 dB) for frequencies between 300 Hz and 800 Hz, and slightly larger (6-7 dB) for frequencies greater than 1000 Hz.

Plunging waves have a distinctive ‘whoomphing’ or bellowing sound that is absent when waves are merely spilling or surging. Figure 3 is a power spectrum for a plunging wave which exhibits this distinctive sound, computed for the 0.4 s immediately following the breaking, using a window length of 0.2 s and a 50% overlap. The spectrum contains first-order (and possibly second-order) harmonics of the prominent low-frequency maxima at 34 Hz, 48 Hz, and 78 Hz.

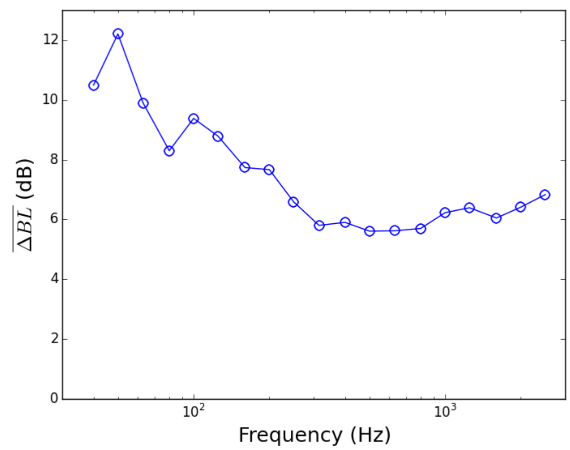

Figure 2: Average change in band level $\overline{\Delta BL}$ during the wave break as a function of third octave band centre frequency.

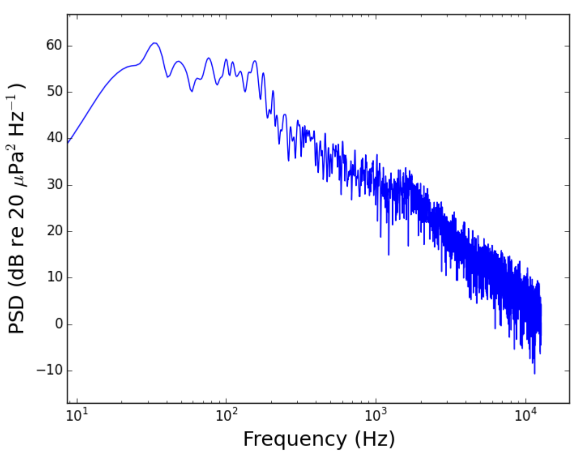

Figure 3: Power spectrum of the 0.4 s immediately following the plunging wave break.

4 Discussion

The mechanisms generating the airborne sounds are obscured to some extent by the observed variability : the band level increases differ in timing and magnitude among individual waves. The smaller peak in band level change centred at 100 Hz in Figure 2 may be caused by the plunging jet of water impacting the ocean surface. The same frequencies were found to be affected when Galbrun and Ali [8] measured the sound generated by small artificial waterfalls.

We postulate that the maximum in band level change near 50 Hz during the wave break is caused by the air column entrained by the plunging wave, which behaves like a hollow cylindrical pipe that is closed at one end. As a plunging wave breaks, the centrifugal force of the water will be briefly balanced by the pressure in the enclosed air tube [1]. The wave breaks in one direction, creating a bellows effect that sends a burst of air and aerated water through the opening in the side of the wave, much like the forcing in a flue organ pipe. The resonance frequency f_0 of a cylinder closed at one end is

$$f_0 = \frac{c}{4(L + 0.6R)} \quad (1)$$

where L and R are the length and radius of the cylinder, respectively, and c is the speed of sound in air [9]. The photographs were used to estimate the physical dimensions of representative breaking waves. Using values of $L = 1.0$ m and $R = 0.25$ m in Equation 1 yields a resonance frequency of $f_0 = 74.6$ Hz, which is typical of the sharp maxima in the observed spectra (e.g., Figure 3).

5 Conclusions

Recordings of airborne wave breaking sound demonstrated large variability in the signature of plunging breaking waves. Increases of 5-12 dB were observed in the third-octave band levels between 40 and 2500 Hz during the wave breaking. The two most prominent increases were postulated to be caused by the plunging jet impacting the water surface (100 Hz) and the resonance of the air cylinder entrained by the plunging wave (50-80 Hz). The resonance frequency of the wave modelled as a closed cylinder was comparable to the observed sharp frequency maxima in the spectrum.

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