RADIATED AUTOSPECTRA OVER [160 Hz, 2000 Hz] OF INDIVIDUAL BREAKING OCEAN WAVES

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The radiated autospectrum of breaking wind waves has a broad maximum in [50 Hz, 1000 Hz]: the spectral profile above the peak is believed to be due to the resonant contributions of individual, small, freshly entrained bubbles oscillating in their fundamental mode. The sound source mechanism for the spectral profile below the peak is less certain. The resonant-contribution model is unlikely because it would require large radius (>1 cm) bubbles which have not been heretofore observed. Alternatively, the source must involve some ``off-resonance" mechanism. One such theory is ``collective oscillations"[1].

Collective oscillation theory involves an inclusion of bubbly fluid entrained by a breaker. The inclusion is then considered analogous to a fluidic inclusion with an anomalous sound speed. For the idealized geometry of a hemispherical inclusion, the inclusion acts like a spatial acoustic filter for sound radiated from sources at the hemisphere base (i.e., at the water surface). Oguz [2] analyzed this ideal case and showed that a spectrally smooth source resonant above 1600 Hz yields a radiated (far-field) signal with multiple sharp (i.e., high-Q) harmonic peaks in [50 Hz, 1500 Hz]. These peaks are related to the resonant modes of the fluidic inclusion. Means and Heitmeyer [3] predicted that only the fundamental harmonic would leak through if the sources are concentrated along the leading edge of the breaker. Neither analysis, however, made predictions for a spectral profile involving both resonant and off-resonance regimes.

Such predictions can be tested but comparisons to data are lacking because there have been few experimental measurements in this frequency regime. These measurements are difficult to obtain due to the location of the source, the stormy environment, overwhelming man-made contributions, and inherent signal non-stationarity. We achieved direct measurements using a nearsurface hydrophone array at a fetch-limited site at a wind speed of about 7 m/s [4] . It is important to note that the breaking waves observed during this event were predominantly spilling breakers, as opposed to plunging breakers.

The data presented here are from the array center hydrophone. The (time-domain) radiated signal is nonstationary: at best, it must be partitioned "by eye" into segments that appear quasi-stationary. This is done for two typical waves, W3 (fig. 1) and W5 (fig. 2). The system transfer function is provided in fi.g 3, showing the system high-pass cut-off at »160 Hz. The acquired data are further high-pass filtered with a fifth order Butterworth filter with cut-off frequency 160 Hz to remove residual low-frequency strum energy.

As these segments are short (»200 ms), careful spectral estimation must employ the multi-taper method [5]: 5 tapers are used here with a time-bandwidth product of 3. The results from wave W3 (W5) are shown in figs. 4-7 (figs. 8-12). In each figure, the background ambient noise autospectral estimator is also shown: this was estimated using a much longer data segment judged not to contain nearby breaking wave events. The radiated spectral profiles have a signal excess of up to 6 - 10 dB over ambient. Jackknifed 90% confidence intervals [6] are provided for both the radiated and ambient sound.

These spectral profiles show statistically significant evidence of harmonic structure, with peaks near 500 Hz and 800 Hz. There is some evidence of another peak around 250 Hz. This harmonic structure bolsters the prediction that a bubbly inclusion will act like a spatial acoustic filter.

The autospectral profile has at best, however, only low-Q peaks, with the predominant energy in [250 Hz, 700 Hz]. This cannot be explained if we assume a linear problem with small bubbles resonating at frequencies above 700 Hz. In fact, the profiles above 1000 Hz, where small bubbles are likely to be contributing resonantly, are consistently lower than the spectral peak region. This suggests that the source forcing near and below the spectral peak involves other mechanisms in addition to off-resonance contributions from small bubbles.

[1] W. M. Carey and D. Browning, in Sea Surface Sound, B. R. Kerman, ed., Kluwer Academic, 1988.

[2] H. N. Oguz, J. Acous. Soc. Am. 95(4), 1994.

[3] S. L. Means and R. M. Heitmeyer, submitted to J. Acoust. Soc. Am., 1999.

[4] R. K. Andrew, D. M. Farmer, and R. L. Kirlin, J. Acous. Soc. Am. 101(5), 1997.

[5] D.J. Thomson, Proc. IEEE 70(9), 1982.

[6] D. J. Thomson and A.D. Chave, in Advances in Spectrum Analysis and Array Processing, vol. 1, S. Haykin, ed., Prentice-Hall, New Jersey, 1991.

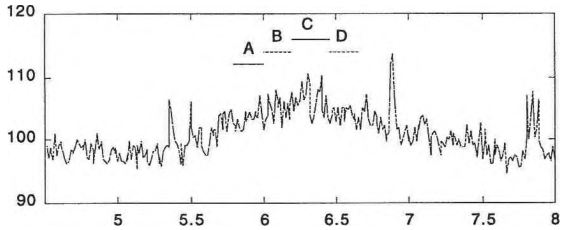

Figure 1. Wave W3. Array depth = 3.1 m, source slant range = 3.7 m.

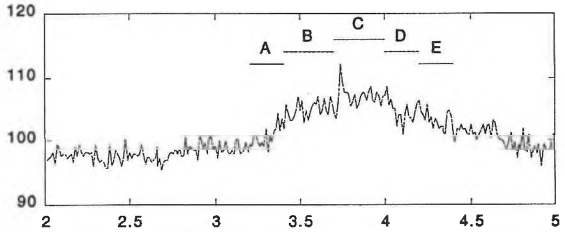

Figure 2. Wave W5. Array depth = 3.1 m, source slant range = 3.7 m.

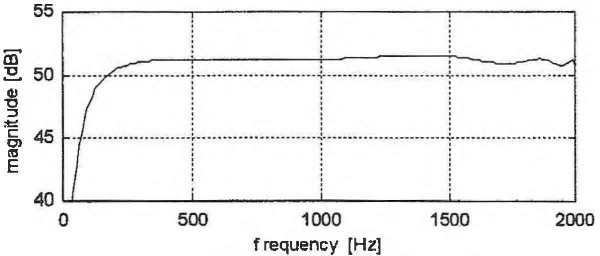

Figure 3: System Transfer Function

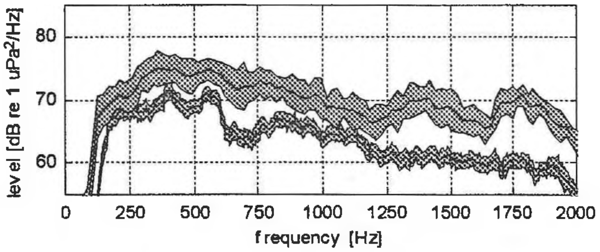

Figure 4: Wave segment W3A.

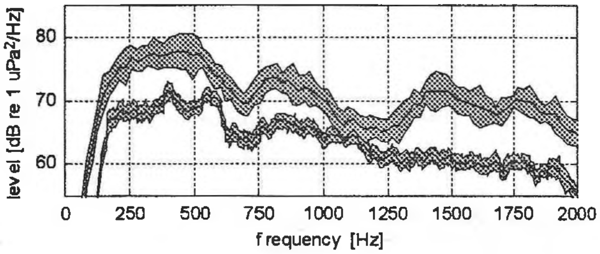

Figure 5: Wave segment W3B.

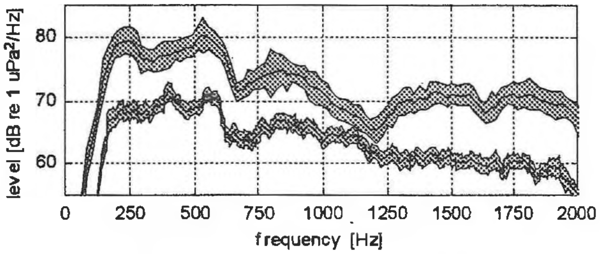

Figure 6: Wave segment W3C.

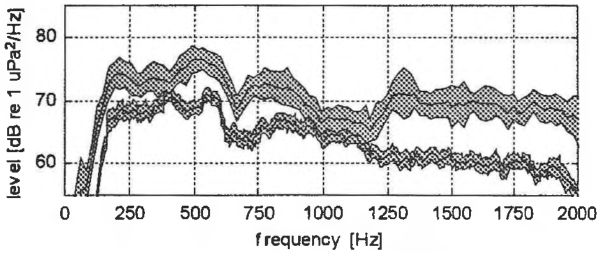

Figure 7: Wave segment W3D.

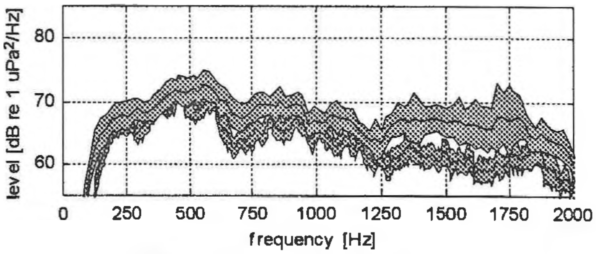

Figure 8: Wave segment W5A

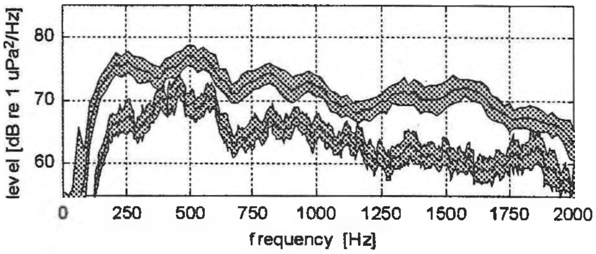

Figure 9: Wave segment W5B.

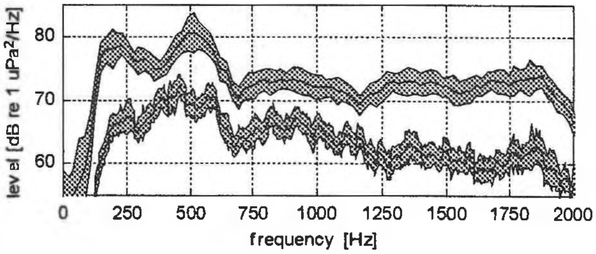

Figure 10: Wave segment W5C.

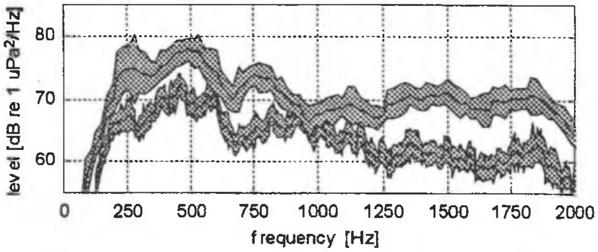

Figure 11: Wave segment WCD.

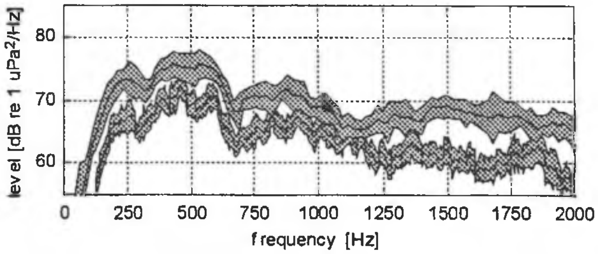

Figure 12: Wave segment W5E.