

LETTERS TO THE EDITOR

This Letters section is for publishing (a) brief acoustical research or applied acoustical reports, and (b) comments on articles or letters previously published in this Journal. Extensive reports should be submitted as articles, not in a letter series. Letters are peer-reviewed on the same basis as articles, but usually require less review time before acceptance. Letters cannot exceed four printed pages (approximately 3000–4000 words) including figures, tables, references, and a required abstract of about 100 words.

An investigation of the acoustic emissions from a bubble plume

Ali Kolaini, Ronald A. Roy, and Lawrence A. Crum

National Center for Physical Acoustics, The University of Mississippi, Coliseum Drive, University, Mississippi 38677

(Received 26 October 1990; accepted for publication 9 January 1991)

This letter presents some preliminary results of an experimental study of the underwater sound field emitted by a bubble plume. The densely populated bubble plumes were generated by dropping a fixed volume of water, held in a cylindrical container, onto a still water surface. The characteristics of plumes were varied by changing the container volume and height above the surface. Acoustic emissions from these plumes appear to depend on the volume of the injected water, with the emitted frequency band decreasing with increasing plume volume. In addition, large-amplitude, low-frequency emissions correlate well with the observed detachment of “substructures” within the plume. The frequencies of the acoustic signals associated with the formation of these structures range as low as a few tens of Hertz.

PACS numbers: 43.30.Lz

INTRODUCTION

Breaking waves are thought to be a source of ambient noise, with the sound generation mechanism still unknown. Probably, the first observation of the underwater sound was given by Knudsen *et al.* (1948). Surprisingly since then, few advances have been made toward a more complete understanding of the observed noise spectrum. Recently, the ambient noise produced in the ocean has received some attention, especially with regard to the understanding of source mechanisms at the sea surface (Kerman, 1988). It has been shown that some underwater sound generation mechanisms have reasonably well-defined acoustic signatures. Some of these mechanisms are resonant bubbles (Crowther, 1988), nonlinear bubble excitation by turbulence generated in the breaking wave region (Kerman, 1984), linear bubble excitation in the breaking region (Hollett and Heitmeyer, 1988), splash or rain noise (Pumphrey *et al.*, 1989; Pumphrey and Crum, 1990), bubble cloud oscillations (Yoon *et al.*, 1989), and bubble entrapment by capillary waves (Kolaini *et al.*, 1990).

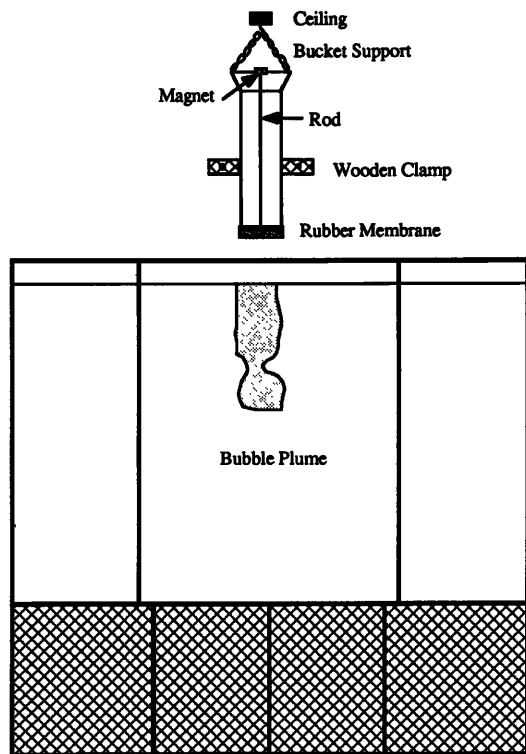
It is well known that bubble plumes generated by breaking waves may penetrate to depths of 10 m from the sea surface (Thorpe, 1982), and so it is crucial to understand the acoustic behavior of a plume, the physical parameters of which can easily be controlled and repeated. Because of the complexity of the wave-breaking process and the associated sound generation mechanisms, only a few experimental and theoretical data for breaking waves are available (Farmer and Vagle, 1988; Longuet-Higgins, 1989; Shonting and Tay-

lor, 1988; Banner and Cato, 1988). The Knudsen wind noise spectrum was reproduced in laboratory by Medwin and Beaky (1989) and Medwin and Daniel (1990), and they suggested that air entrainment processes was primarily responsible for the noise generation. Most of the available data indicate that the power spectrum noise generated by breaking waves peaks at a frequency near 500 Hz, but is very broadband. Furthermore, laboratory and sea measurements of noise generated by breaking waves are emerging that suggest it could range as low as several tens of hertz (McConnel *et al.*, 1990).

This study was designed to generate bubble plumes by releasing a small volume of water onto the free surface of a large tank of water using cylindrical containers of various water heights and sizes. The time-dependent acoustical and spatial characteristics of the plume are presented.

I. EXPERIMENTAL PROCEDURES

The measurements reported here were made in two separate tanks. The first one was a Plexiglas laboratory tank with dimensions of 2.1 m × 2.1 m × 1.8 m (width, length, and height). The cylindrical containers were suspended above the tank and were restrained from lateral movement. The water was held in the container by a tightly stretched, thin rubber sheet, which was secured to the bottom of the container by a rubber band. The rubber membrane was ruptured by a thin, sharpened rod, which was coaxially suspended inside the container a few inches above the membrane



Front View of Experimental Plexiglass Wall Tank (2.1m, 2.1m, 1.8m)

FIG. 1. Schematic drawing of the experimental arrangement.

(Fig. 1). The second tank employed was the swimming pool at the University of Mississippi. At the pool, containers were suspended from the diving board by extending them about 5 m into the pool and 5.5 m from the side wall of the pool; the depth of the pool at the test site was about 4 m.

Various bucket sizes with different water heights were used. In this preliminary report, results of only one container size with an inside diameter of 10.8 cm are presented. Once the membrane was ruptured, the volume of water was trans-

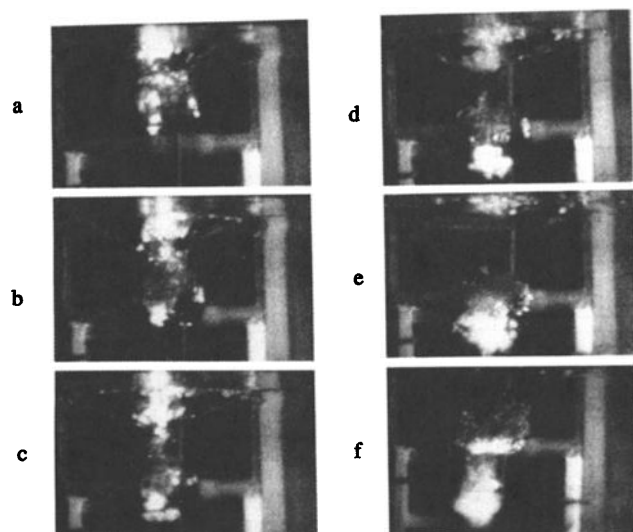


FIG. 2. Photographs of a sequence of frames from the high-speed video camera depicting the plume growth and the substructure detachment.

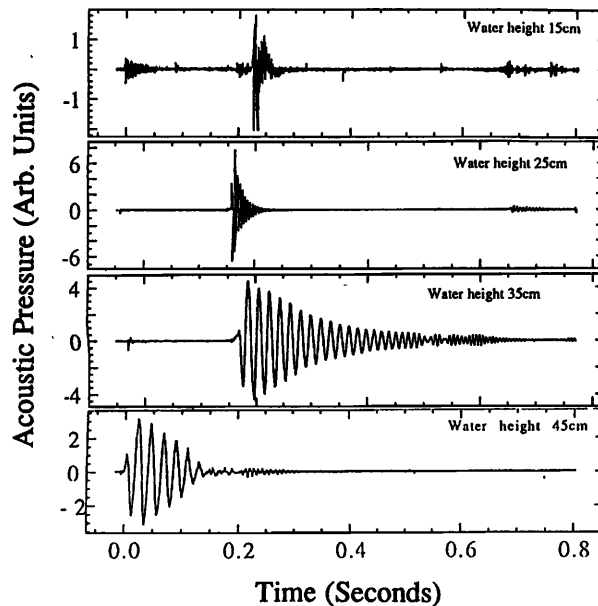


FIG. 3. The pressure traces of substructures generated by releasing various water heights onto a still water surface.

ported immediately onto the still water, thus generating a cylindrical plume (Fig. 2). The air was initially entrained shortly after water impact and continued to be entrained at the jet circumference as the entry progressed. The evolution of the bubble plume in the laboratory tank was recorded with a Kodak Ekta-Pro high-speed video camera operating at 1000 frames a second. The observations were made using a Nikon 28-mm lens directed perpendicular to the plume axis. The sound emission from the plume was measured using a B&K 8103 broadband hydrophone, which was connected to a digitizing HP 5183 oscilloscope via a B&K type 2635

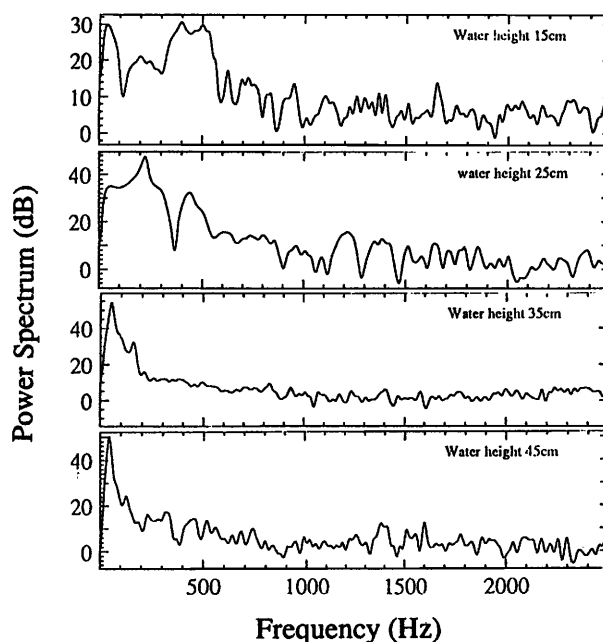


FIG. 4. The power spectrum of the pressure traces shown in Fig. 3.

charge amplifier and was digitized with sampling rate of 40 k/s. The recorded data were then saved on floppy disks for further analysis. The hydrophone was located 40 cm from the plume axis and was submerged about 50 cm in the tank. This distance was changed to 100 cm with the same submergence depth in the swimming pool.

The container was filled with water heights ranging from 5 to 45 cm and incremented by 5 cm for additional trials. Each set of experiments was performed three times to verify the repeatability of the plume shape and acoustic emission.

II. RESULTS

The pressure-time traces and corresponding power spectrum of bubble plumes emissions are shown in Figs. 3 and 4 for water heights of 15, 25, 35, and 45 cm with a container suspension height of 15 cm from the still surface level, respectively. Figure 4 indicates the frequency shift with increasing water volume. The video images reveal the formation of a cylindrical plume, which grows in length until all the water volume is injected into the tank. Then, as the leading end of the plume advances, a "substructure" separates from the rest of the plume [frames (c) and (d), Fig. 2]. The large-amplitude, low-frequency sound emissions correlate well with the detachment of these substructures within the plumes. After detachment, visual observation suggests that the separated plume is roughly spherical in shape and of high void fraction. It eventually dissipates and rises to the surface. To give a rough preliminary interpretation of the radiated sound from these detached plumes, let us look at the acoustic emission from 45 cm water height (4.1 ℓ), which generates a detached substructure of 10.2 cm in radius and radiated frequency of 46 Hz. Observations suggest that the substructure probably consists of a spherical region, densely populated with bubbles, with a region of water positioned near the center of the bubbly sphere. If we assume a radius of R_2 for the sphere and R_1 for the liquid region and if we assume that the void fraction is uniform within the bubbly region, it is possible to estimate the volume resonance frequency for such a system. For the measured ratio of $R_1/R_2 \approx 0.33$, this procedure suggests that an assumed void fraction of approximately 40% is required to generate the measured resonance fre-

quency of 46 Hz. This figure, although high, is not implausible given the apparent effectiveness with which the water jet entrains air. Figure 5 is a plot of the detachment oscillation frequency versus the volume of the released water obtained from measurements in both the laboratory tank and the swimming pool. This figure shows the repeatability of the resonance frequency of substructures recorded in two different size water tanks. Larger water volumes produce larger plume sizes with varying void fraction, therefore, lower resonance frequency.

The experimental results presented here, as was mentioned before, are preliminary findings of the acoustic emissions of detached structures. In the near future, the results of a more detailed investigation will be presented.

III. CONCLUSIONS

The principal preliminary observations of this study can be summarized as follows.

(1) Plumes of different sizes can be generated by dropping differing masses of water onto a still water surface. These plumes, which are characterized by densely populated region of bubbles of various sizes, exhibit a curious detachment into substructures that oscillate at relatively low frequencies.

(2) The frequency of the oscillation of the detached plume depends on the released water volume, which correlates with plume sizes and void fraction, and decreases by increasing the water volume.

(3) The acoustic emissions of these resonant substructures extend down to the tens of hertz.

(4) If these laboratory observations are duplicated in the open ocean, a mechanism for low-frequency emissions from breaking waves may have been discovered.

ACKNOWLEDGMENTS

The authors would like to thank Andrea Prosperetti for providing valuable comments and suggestions, Charles Church for assisting in calculations, and Yi Mao and Jeff Schindall for assisting in the experiment. This work was supported by the Office of Naval Research.

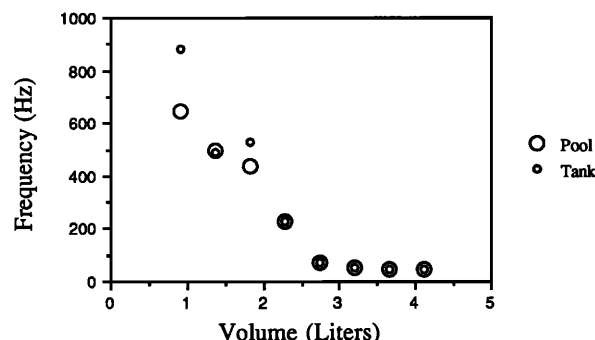


FIG. 5. Frequency dependence of substructures on the volume of the released water obtained from measurements in two different size water tanks.

- Banner, M. L., and Cato, D. H. (1988). "Physical mechanisms of noise generation by breaking waves—A laboratory study," in *Sea Surface Sounds: Natural mechanisms of surface generated noise in the ocean*, edited by B. R. Kerman (Kluwer, Dordrecht, The Netherlands), pp. 429–436.
- Crowther, P. A. (1988). "Bubble noise creation mechanisms," in *Sea Surface Sounds: Natural mechanisms of surface generated noise in the ocean*, edited by B. R. Kerman (Kluwer, Dordrecht, The Netherlands), pp. 131–150.
- Farmer, D. M., and Vagle, S. (1988). "Observations of high frequency ambient sound generated by wind," in *Sea Surface Sounds: Natural mechanisms of surface generated noise in the ocean*, edited by B. R. Kerman (Kluwer, Dordrecht, The Netherlands), pp. 403–415.
- Hollett, R. D., and Heitmeyer, R. M. (1988). "Noise generation by bubbles formed in breaking waves," in *Sea Surface Sounds: Natural mechanisms of surface generated noise in the ocean*, edited by B. R. Kerman (Kluwer, Dordrecht, The Netherlands), pp. 449–461.
- Kerman, B. R. (1984). "Underwater sound generation by breaking wind waves," *J. Acoust. Soc. Am.* **75**, 149–165.
- Kerman, B. R. (Ed.) (1988). "Natural mechanisms of surface-generated

- noise in the ocean," in *Sea Surface Sound* (Kluwer, Dordrecht, The Netherlands), p. 639.
- Knudsen, V. O., Alford, R. S., and Emling, J. W. (1948). "Underwater ambient noise," *J. Mar. Res.* **7**, 410–429.
- Kolaini, A., Roy, R. A., and Crum, L. A. (1990). "The production of high-frequency ambient noise by capillary wave," in *Natural Physical Sources of Underwater Sound*, edited by B. Kerman (Kluwer, Dordrecht, The Netherlands) (in press).
- Longuet-Higgins, M. S. (1989). "Noise generation by newly created bubbles," *J. Acoust. Soc. Am. Suppl.* **1** **85**, S144.
- McConnel, S. O., Schilt, M. P., and Dworski, J. G. (1990). "Ambient noise measurements from 100 Hz to 80 kHz in an Alaskan fjord," *J. Acoust. Soc. Am.* (submitted).
- Medwin, H., and Beaky, M. M. (1989). "Bubble sources of the Knudsen sea noise spectra," *J. Acoust. Soc. Am.* **86**, 1124–1130.
- Medwin H., and Daniel Jr., A. C. (1990). "Acoustical measurements of bubble production by spilling breakers," *J. Acoust. Soc. Am.* **88**, 408–412.
- Pumphrey, H. C., and Crum, L. A., and Bjørnø, L. (1989). "Underwater sound produced by individual drop impacts and rainfall," *J. Acoust. Soc. Am.* **85**, 1518–1526.
- Pumphrey, H. C., and Crum, L. A. (1990). "Free oscillations of near-surface bubbles as a source of the underwater noise of rain," *J. Acoust. Soc. Am.* **87**, 142–147.
- Shonting, D., and Taylor, N. (1988). "On the spectra of wind generated sound in the ocean," in *Sea Surface Sounds: Natural mechanisms of surface generated noise in the ocean*, edited by B. R. Kerman (Kluwer, Dordrecht, The Netherlands), pp. 417–427.
- Thorpe, S. A. (1982). "On the clouds of bubbles formed by breaking wind-waves in deep water," *Philos. Trans. R. Soc. A* **304**, 155–210.
- Yoon, S. W., Crum, L. A., and Prosperetti, A. (1989). "An experimental investigation of bubble clouds as sources of ambient noise," *J. Acoust. Soc. Am. Suppl.* **1** **86**, S588.