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Underwater Sound Associated with Splashes and Breaking Waves

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This paper presents some results of a preliminary experimental study of underwater sounds produced by the splashes of water droplets on a free surface of water in a rectangular tank and by the small-scale breaking waves on a sloping floor submerged in a wave tank. Sound spectra obtained with the use of a precision hydrophone system are presented and their characteristic features are described.

1. Introduction

Acoustic probing of various flow phenomena associated with splashes near the surface of water is of interest in oceanography and hydrology, since the sound produced by them is common and its measurement is easy. It is not easy, however, to form a correct picture about the related flow structures based solely on the acoustic data. Although many investigations have been concerned with the acoustic interactions of bubbles due to the splashes of water, much work seems to remain to be done before acoustic information can be very useful for featuring detailed flow structures^{1) - 5)}. Many aspects of such an underwater sound problem is reviewed recently by Prosperetti and Oguz⁶⁾ and Leighton⁷⁾.

The purpose of this paper is to report some results of a preliminary experimental study on the spectral characteristics of sounds produced by splashes and breaking waves in rectangular tanks of three different sizes. In section 2, the experimental procedure is described. In section 3, the experimental results and discussion are presented. Finally, section 4 is devoted to conclusions.

2. Experimental Procedure

In all the experiments, underwater sound was received with a Bruel & Kjaer type 8103 hydrophone. This is a small-sized cylindrical transducer of 50 mm in length and 9.5 mm in diameter, with a high-sensitivity of 30 mV/Pa. The working frequency range of this transducer is 0.1 to 200 kHz. Sound signals received with the transducer were amplified using a precision conditioning amplifier (type 2650); another signal amplifier was also used in combination with the precision amplifier when the frequency range concerned was below approximately 15 kHz. The amplified signals were analyzed with a single channel FFT analyzer equipped with a direct video-printer.

All the water tanks used were of rectangular shapes and were made of acrylic resin. The single droplet, multiple splash, and breaking-wave experiments were carried out using, respectively, the small, the medium-sized, and the large tank. The apparatus with the smallest water tank is illustrated in **Fig. 1**. This tank is 58 cm in length, 28 cm in width, and 34 cm in height. It was filled with tap water at various depths. Single droplets with the diameter of about 5 mm were produced by slowly draining a water from a 1 liter funnel tube equipped with a small cock. The distance between the lower end of the funnel tube above the tank and the water surface was kept at 25 cm. The transducer was immersed in the water at the depth of about

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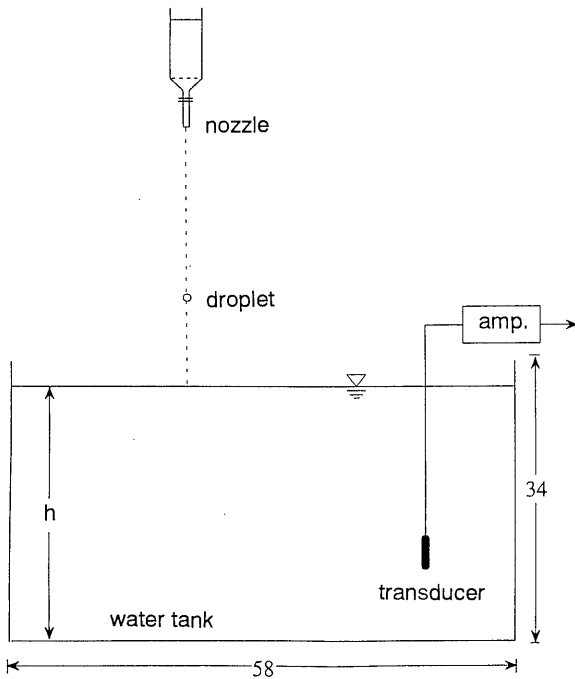


Fig. 1 Rectangular tank used for single-droplet experiment; dimensions in cm

11 cm. Another medium-sized tank is 53 cm in length and width and 95 cm in height. This tank was used in combination with the same funnel tube as described above, and the distance between the lower end of the tube and the water surface was 66.0 cm when the water depth was kept at 53.0 cm.

The large tank is a 6.2 m — long wave channel, of which a schematic diagram is illustrated in **Fig. 2**. This tank is equipped with a motor-driven oscillating flap as a wave maker and a sloping floor which serves waves to break on it. The maximum frequency of the flap oscillation was 1.0 Hz. The angle of the floor was kept at 3.0 degrees from horizontal. The pressure transducer was submerged between the end of the slope and the flap.

3. Experimental Observations

3.1 Splashes of single water droplet

When a single water droplet impacts the surface of water at rest, splashes of the water are formed and characteristic sound is produced around them. This type of sound produced in the small tank was observed with attention focused on standing wave modes of the sound. A typical pressure (p) - time (t) trace produced by single water droplets which impacted successively the water surface is shown in **Fig. 3**. There the vertical unit is mV; no absolute sound-pressure measurements were made in this study. In the trace are observed signals due to an initial impact of a droplet and following reverberations due to the existing nearby walls. The interval of dropping of water droplets was about 1.8 s. The FFT spectral pattern for this trace is shown in **Fig. 4** in which f is the frequency of sound in kHz and the vertical scale unit is again mV⁸⁾. Many peaks showing splashing and standing sound waves in the tank are seen approximately between 4 and 14 kHz.

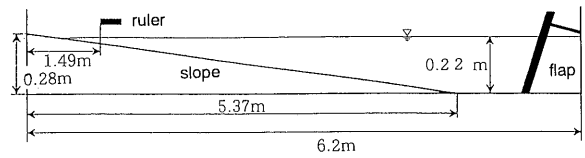


Fig. 2 Wave tank equipped with a flap and a sloping floor; dimensions in m

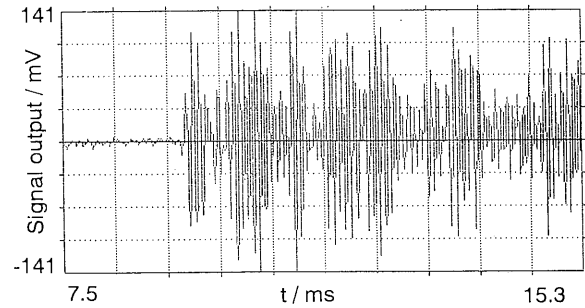


Fig. 3 Pressure-time trace for sound produced by splashes of a single droplet

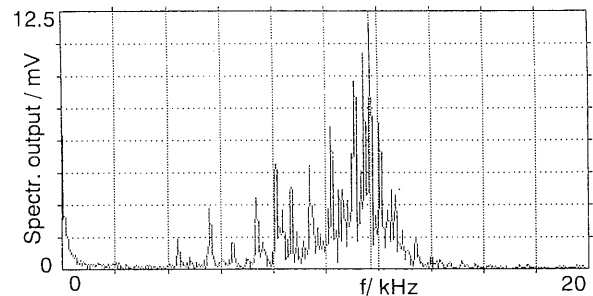


Fig. 4 FFT spectra of trace shown in Fig. 3

It was observed that, when a conspicuous peak appears at the left end of a set of spectral peaks, the lowest frequency (f_0) of the peak depends on the depth of water (h) in the tank. A typical example for such a case is shown in **Fig. 5**, where a conspicuous peak appears at the left end of a set of several peaks at $f_0 = 5.60$ kHz. The rate of the water draining was about 2 ml/s. At $f = 0$ kHz also appears a peak, which is discarded here because of its irrelevance to the sound produced by splashes. The depth of the water (h) was varied between 3 and 30 cm.

The measured frequency f_0 is plotted against h in **Fig. 6**, where f_0 decreases with increasing h monotonically. The characteristic frequencies of sound waves in a rectangular tank are well known. The curves for low wave modes calculated by using the values of $c = 1477$ m/s and the horizontal length scales of the tank, however, are not found to agree well with the data over the measured range of h , possibly because of the boundary conditions imposed at the free water surface. In the experiment, the transducer depth was also decreased as h was and the distances between the transducer and side walls became smaller. The limiting value of f as h tends to infinity is 2.9 kHz.

The above result shows that the lowest frequency mode of the underwater sound produced by the splashes has been observed using the small-sized water tank. It should be also noted that, a high-pitched metallic sound was frequently audible in air when a single droplet impacted the water surface. The appearance of higher frequency modes of the sound in the tank water may be responsible for this phenomenon. In order to get some information on the underwater sound produced by the splashes when the tank was not rectangular, a rigid plate was placed obliquely at one end of the tank and a similar measurement of the sound was made. It was found that the value of f_0 is affected by the sloping angle of the plate.

3.2 Splashes of multiple droplets

Underwater sound produced by the splashes of multiple droplets impacting the free water surface was investigated using the medium-sized water tank. A 5 liter polystyrene bottle equipped with a shower head for making the shower of many water droplets was placed above the water tank. The vertical distance between the shower head and the free water surface was 67.0 cm. The draining facet of the shower head is an elliptical plate of 7.0 and 5.2 cm in major and minor axes, respectively; within it are bored 94 small circular holes each having the diameter of

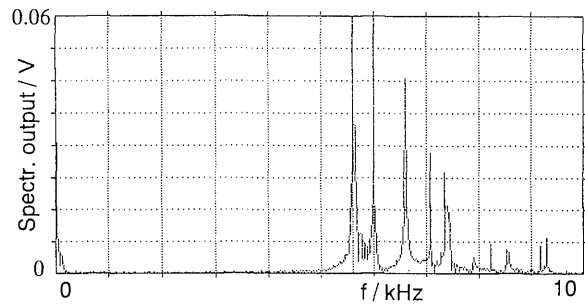


Fig. 5 Spectra with separate peaks for shallow water in tank

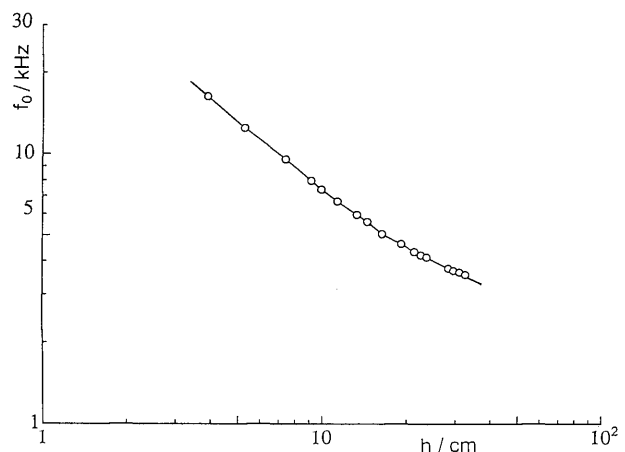


Fig. 6 Lowest frequency f_0 plotted against water depth h

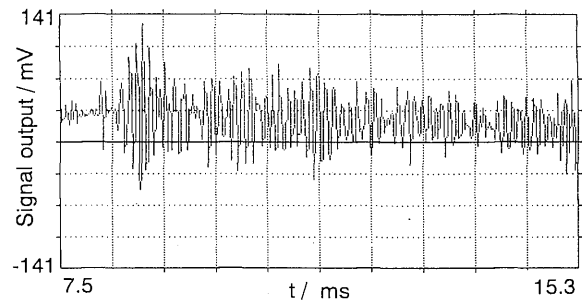


Fig. 7 Pressure-time trace for sound produced by splashes of multiple droplets

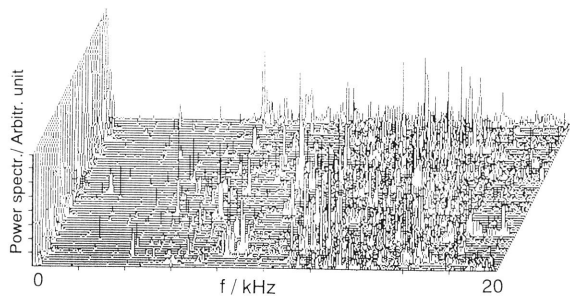


Fig. 8 Successive trace patterns of power spectra for sound produced by multiple droplets

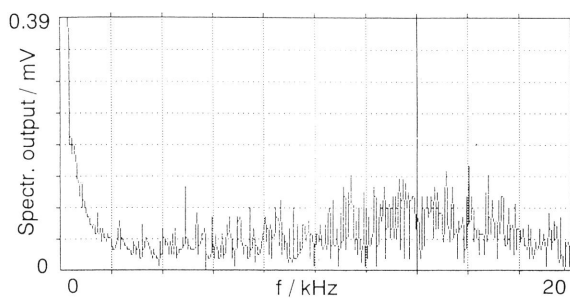


Fig. 9 Spectral pattern averaged over 302 traces for sound produced by multiple droplets

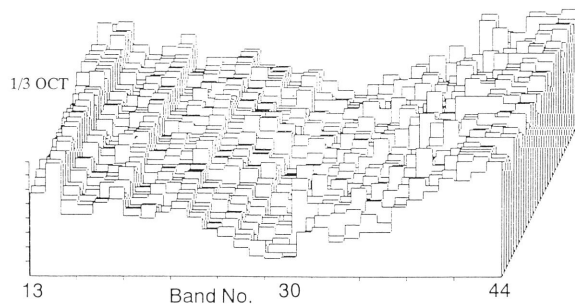


Fig. 10 1/3-octave analyzed pattern for sound produced by multiple droplets

gram of the FFT power spectral pattern for the sounds produced by the showers is shown in **Fig. 8**, where 63 traces for the time interval of 60 s is displayed at f less than 20 kHz. Many peaks appear between 10 and 16 kHz, though the peak pattern is different from trace to trace. An example of the linear spectral pattern obtained by averaging over 302 instantaneous traces is shown in **Fig. 9**. It will be seen from the figure that peaks appear over the whole range of the measured frequency including the tall one at $f = 0$ kHz. The average peak heights are slightly taller in the frequency range roughly between 10 to 18 kHz.

It is known that the characteristic spectral peaks appear in the frequency range between 14 and 16 kHz, which is associated with real rain³⁾. It seems interesting to note that the latter range is within the above range 11-18 kHz. A 1/3 - octave analysis was also made of the sound produced by the splashes of multiple droplets. The result is shown in **Fig. 10**, where 35 traces for the time interval of 217 s is displayed. In the horizontal coordinate are shown the band numbers ranging from 15 to 42 which correspond to the central frequencies of 31.5 Hz and 16.0 kHz. The trough of the figure appears around the band number of 30 which corresponds to 10.0 kHz.

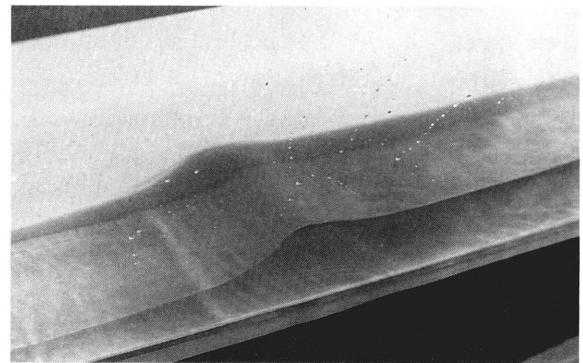


Fig. 11 Breaking wave at flap frequency of 0.51 Hz

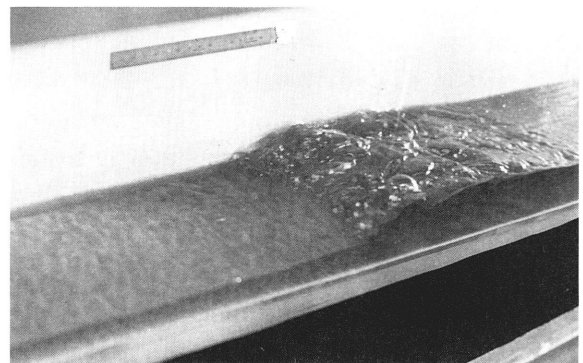


Fig. 12 Breaking wave at flap frequency of 1.0 Hz

0.60 mm. The maximum flow rate in the present setup was about 55 ml/s.

A typical pressure-time trace associated with the sound produced by the splashes of multiple droplets is shown in **Fig. 7**, in which the maximum amplitude on the left is connected with the signal for the first impact of the shower on the water surface. The rate of draining was about 40 ml/s. A 3D dia-

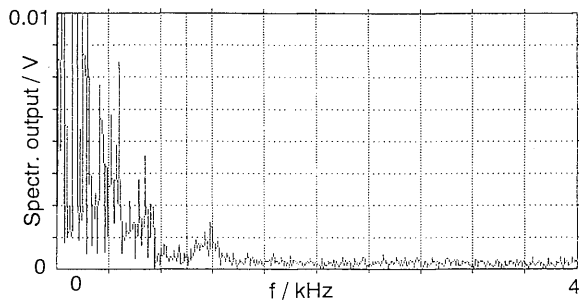


Fig. 13 Spectra for breaking wave at flap frequency of 0.51 Hz

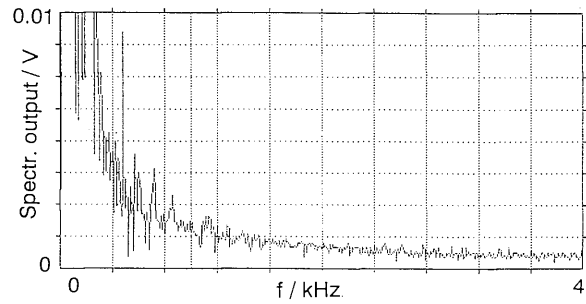


Fig. 14 Spectra for breaking wave at flap frequency of 1.0 Hz

3.3 Breaking Waves

When a wave on the surface of water breaks on a sloping floor as an artificial beach, characteristic sounds are produced because many air bubbles are formed in the breakers. The formation of bubbles and their entrainment under wind waves was investigated by Koga⁹⁾. The breaker formed in the wave tank illustrated in Fig. 2 was of spilling type, which accompanied foams at the wave crest. Two wave patterns are displayed in Figs. 11 and 12, which show bird's-eye-views of the breakers on the sloping floor. The surface of the breaker shown in Fig. 12 is disturbed more vigorously than that shown in Fig. 11; the frequencies of oscillatory flap motions are 1.0 Hz for the former breaker and 0.51 Hz for the latter one.

A typical linear spectral pattern at the flap frequency of 0.51 Hz is shown in Fig. 13, and that at the flap frequency of 1.0 Hz in Fig. 14. When a comparison is made between these two similarly amplified signals, it will be seen that the signal level for the latter case of a higher flap frequency is larger than that for the former case, reflecting the vigorous disturbance of the wave crest shown in Fig. 12. In the former low flap-frequency case, the signal level is almost flat at $f > 1.5$ kHz up to 4.0 kHz. In the latter high-flap frequency case, however, the average level decreases gradually as f increases. Other characteristic features can hardly be seen in these preliminary data, and further detailed studies are expected to be done using a much larger channel, which can set up plunging breakers.

4. Conclusions

Spectral patterns of the sounds produced by the splashes of single droplets, multiple droplets, and breaking waves have been presented and some of their characteristic features have been described. Standing sound-wave modes were observed in the spectral pattern associated with single droplets impacting the surface of water in the small rectangular tank. Between 10 and 18 kHz in the frequency range associated with multiple droplets, a slight increase of average signal level was observed. The sound level associated with the spilling breakers was found to decrease with increasing sound frequency, and found larger at a larger frequency of the flap oscillation.

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