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STATISTICS OF NOISE GENERATED BY TRAVELLING BUBBLE CAVITATION

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ABSTRACT

This paper presents the details of the collapse process for single bubbles generated in travelling bubble cavitation around two axisymmetric headforms. The details of the bubble collapse process have been examined acoustically to understand the phenomena of rebounding and multipeaking. We find that both rebounding and multipeaking increased with reduction in the cavitation number for the ITTC headform. However with the Schiebe headform, rebounding increases and multipeaking is decreased with reduction in the cavitation number. Some possible physical explanations for these phenomena are presented.

1. INTRODUCTION

This paper presents some observations on the details of the bubble collapse process in travelling bubble cavitation. These observations were made for the purpose of improving understanding of the bubble collapse process and its effect on the spectra of the resulting noise. Fitzpatrick and Strasberg (1956) were the first to model cavitation noise based on Rayleigh's analysis. Since Rayleigh's analysis of the collapse of spherical bubbles does not consider the effect of the presence of a solid wall or the interaction of collapse process with local flow structures such as separation and vortices, it may be inadequate for the modelling and prediction of travelling bubble cavitation noise. Baiter (1974, 1986) has provided a framework for the synthesis of the cavitation noise from single bubble cavitation noise once the details of the latter are known.

A number of researchers have acoustically and photographically studied travelling bubble cavitation noise. These include studies of a hydrofoil (Blake *et al.* 1977) and a Schiebe headform (Marboe *et al.* 1986, Hamilton *et al.* 1982 and Hamilton 1981). The bubble dynamics have been documented photographically for both the Schiebe (Hamilton 1981, Hamilton *et al.* 1982, Ceccio and Brennen 1991) and the ITTC (Ceccio and Brennen 1991) headforms. Recently Ceccio and Brennen (1991) found that a single cavitation event can produce an acoustic signal which consists of more than one pulse, each of which may consist of more than one peak. These phenomena are the result of interaction between the bubble and the local flow structure. The present paper reports on an investigation of the bubble collapse process with particular attention to rebounding and multipeaking and their impact on the noise generated by the cavitation event. The effect of these phenomena on the spectrum of the resulting noise has also been investigated and will be presented at the forum.

2. NOMENCLATURE

I_m	acoustic impulse (see Fig. 3)
I_s	a measure of strength of the pulse
P	peak amplitude of the main or the rebound pulse (see Fig. 3)

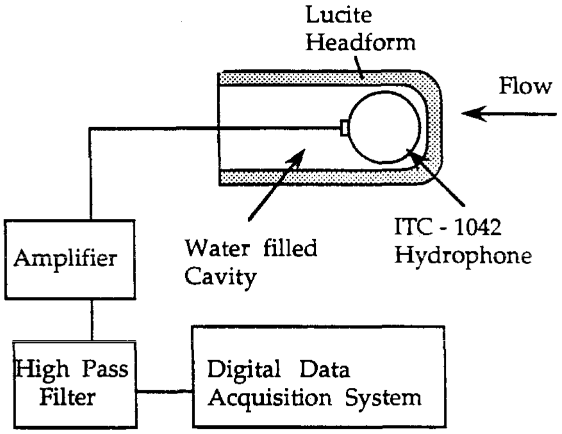

Figure 1. Schematic illustrating the instrumentation of the headform.

r	ratio of maximum peak of the rebound pulse to maximum peak of the main pulse
t_1	time of begining of the main or the rebound pulse
t_2	time of end of the main or the rebound pulse
U	flow velocity
σ	cavitation number
τ	duration between maximum peak of the main pulse and maximum peak of the rebound pulse (see Fig. 3)
τ_s	peak separation (see Fig. 3)
τ_w	duration of main or rebound pulse (see Fig. 3)

3. EXPERIMENTAL METHODS

The experiments were conducted in the Low Turbulence Water Tunnel (Gates 1977) at the California Institute of Technology. The experimental equipment and installation used by Ceccio and Brennen (1991) was employed in these experiments. All the experiments were conducted at a fixed velocity with the desired cavitation number obtained by lowering the static pressure in the water tunnel. The air content was measured using a Van Slyke apparatus and was maintained between 8 and 10 *ppm*. Travelling bubble cavitation was produced on the two axisymmetric headforms used by Ceccio and Brennen (1991), namely a Schiebe headform and a ITTC headform with diameters of 5.08 and 5.59 cm respectively. The signal emitted during bubble collapse was recorded using an ITC–1042 hydrophone which has a flat frequency response up to about 80 *kHz*. The hydrophone was placed inside the headforms which were made of lucite in order to make them acoustically transparent. The interior of the headforms were filled with water to produce a relatively reflection-free path between the cavitation bubbles and the hydrophone. An experimental schematic is included as Fig. 1.

The signal from hydrophone was amplified and extremely low frequencies ($\ll 1\ Hz$) were removed by a high pass filter. The filtered signal was digitally sampled at 500 *kHz*. Around 500 acoustic traces were collected for each operating condition, namely for 3 cavitation numbers (0.45, 0.50 and 0.55) and two flow velocities (8 and 9 m/sec). The signal sampling duration was adjusted to capture one complete acoustic trace from a bubble collapse. These records were then digitally processed in following way. First peaks were detected and classified as belonging to a main or a rebound pulse. Then quantities such as the peak amplitude and the time intervals between the peaks were evaluated. In addition, the following quantities were obtained:

$$I_m = \int_{t_1}^{t_2} p\,dt \qquad (1)$$

$$I_s = \int_{t_1}^{t_2} p^2\,dt \qquad (2)$$

$$\tau_w = t_1 - t_2 \qquad (3)$$

Here I_m is the acoustic impulse, t_1 and t_2 being the times of the begining and the end of main pulse or of the rebound pulse. The integral I_s is an alternative measure of the strength of the pulses and τ_w is the duration of each pulse. Also measured were the time between maximum peaks in the main and the rebound pulses, d, and the ratio of the amplitude of maximum peak in the main pulse to the maximum peak in the rebound pulse, r. A typical acoustic trace is shown in Fig. 2 and a sketch illustrating the definition of some of the parameters is included as Fig. 3.

4. EXPERIMENTAL RESULTS

The probabilities of occurrence of the phenomena of rebounding and multipeaking were examined statistically in order to gain some insight into these phenomena. The dependence of these probabilities on cavitation number, σ , and, to a limited

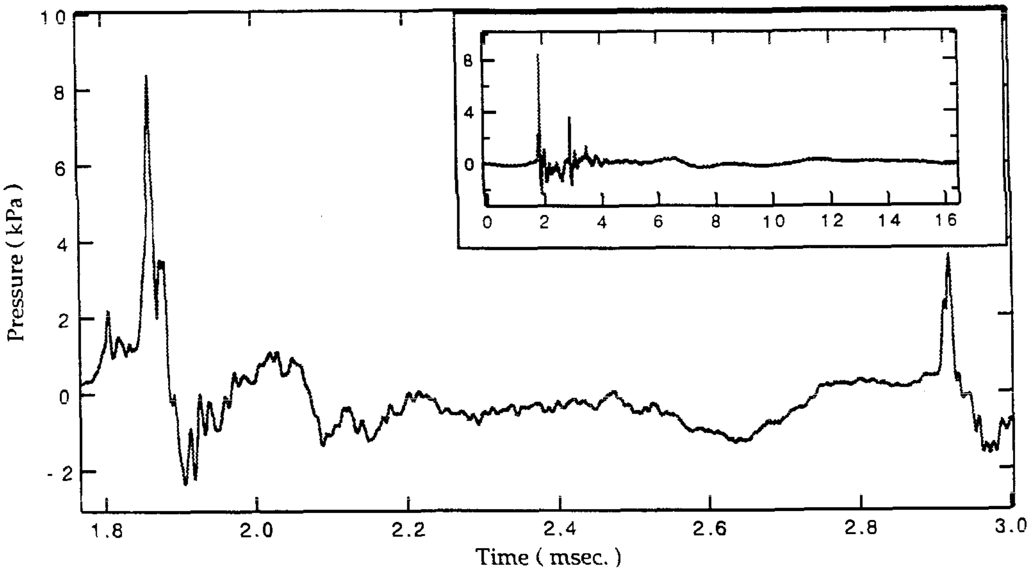

Figure 2. A typical amplified and filtered signal for a single cavitation event illustrating multiple peaks and a rebound. Inset shows the complete acoustic trace.

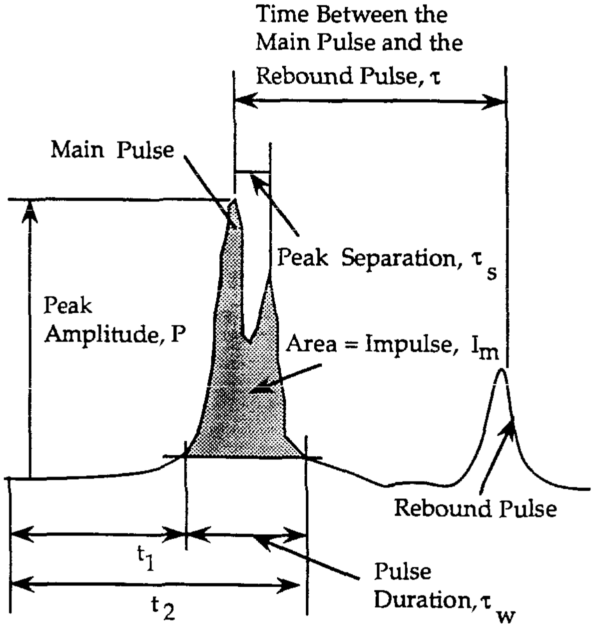

Figure 3. Sketch of a typical acoustic trace with definition of some measured quantities.

extent on flow velocity, u, are presented in Fig. 4 for the ITTC headform and in Fig. 5 for the Schiebe headform. Consider first the phenomenon of multipeaking in the main pulse. The following trends can be clearly seen in the data. First note that changing the flow velocity from 8 to 9 m/sec has little effect on the results. Secondly, the probability of rebounding increases as σ is reduced and this appears to be the case for both the headforms. It is particularly evident that rebounding almost never occurs at highest of three cavitation numbers tested, $\sigma = 0.55$. The main difference between the two headforms is in the probability of occurrence of multipeaking. For the ITTC headform, the probability of occurrence of double–peaked events is almost independent of σ . However, the probability of occurrence of events with more than two peaks increases as the cavitation number is reduced. Events with more than two peaks almost never occur for the Schiebe headform. The probability of occurrence of both multipeaking and rebounding is higher for the ITTC headform than for the Schiebe headform.

The probability of occurrence of multipeaking in the rebound pulse was also examined and exhibited trends similar to those for the main pulse. Rebounds are predominantly single peaked (approximately 80 % for the ITTC headform and 90 % for the Schiebe headform). It is convenient to classify the events

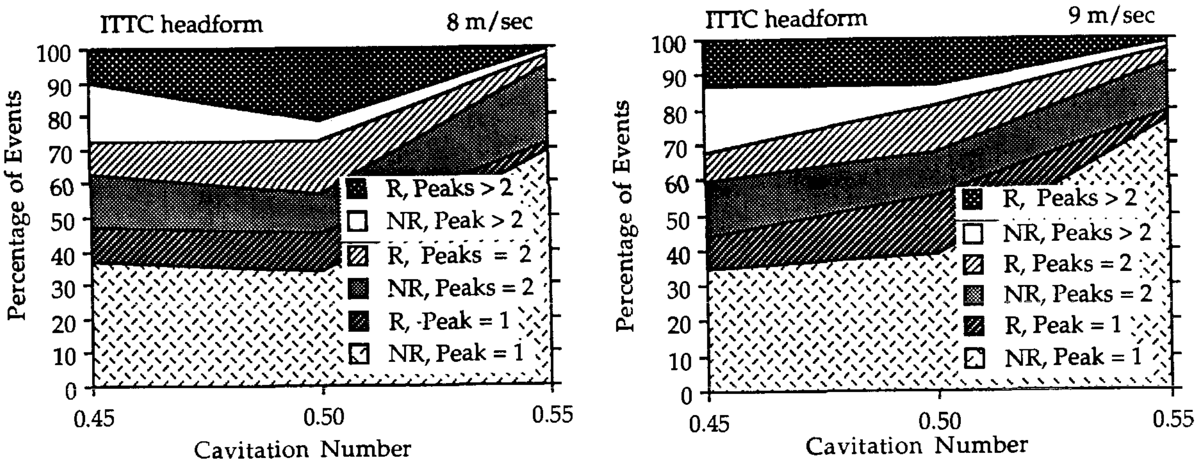

Figure 4. Probabilities of different types of cavitation events on the ITTC headform indicating the occurrence of multiple peaks or a rebound. R and NR respectively denote events with and without rebound. The number alongside indicates the number of peaks in the main pulse.

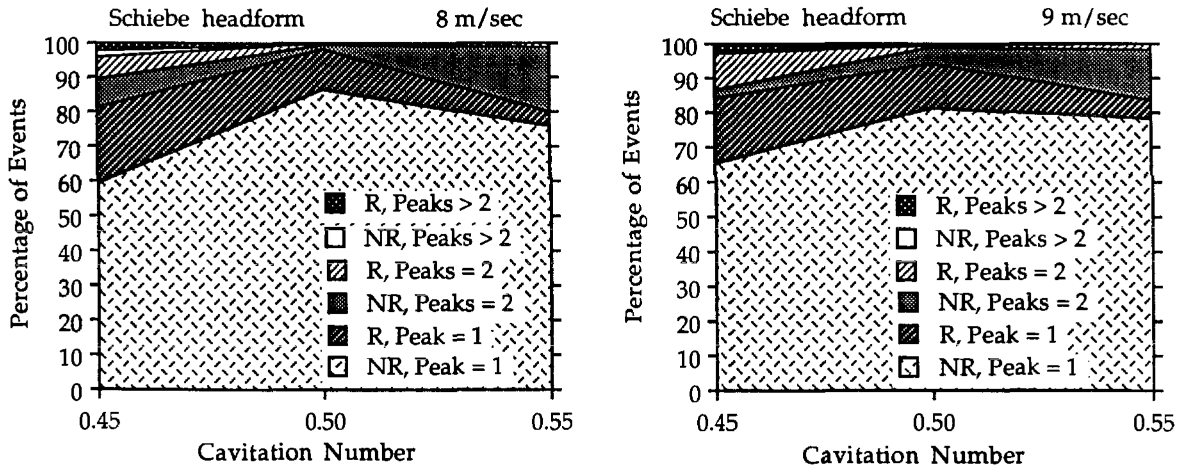

Figure 5. Probabilities of different types of cavitation events on the Schiebe headform indicating the occurrence of multiple peaks or a rebound. R and NR respectively denote events with and without rebound. The number alongside indicates the number of peaks in the main pulse.

with a rebound by a combination of two letters, where the first letter represents the number of peaks in the main pulse and the second letter the number of peaks in the rebound pulse. We use *m* to denote multiple peaks and *s* to denote a single peak. It is found that the ITTC headform has mostly *ms* type rebounds [50 %] but *mm* and *ss* type rebounds are also present in significant numbers [25 %]. The Schiebe headform has mostly *ss* type rebounds with *ms* type rebounds also present about 20 % of the time.

Obviously, the nature of the events are quite different for the two headforms because of differences in the interaction between the bubble dynamics and the flow structure for the two headforms. Specifically, the presence of boundary layer separation on the ITTC headform and its absence on the Schiebe

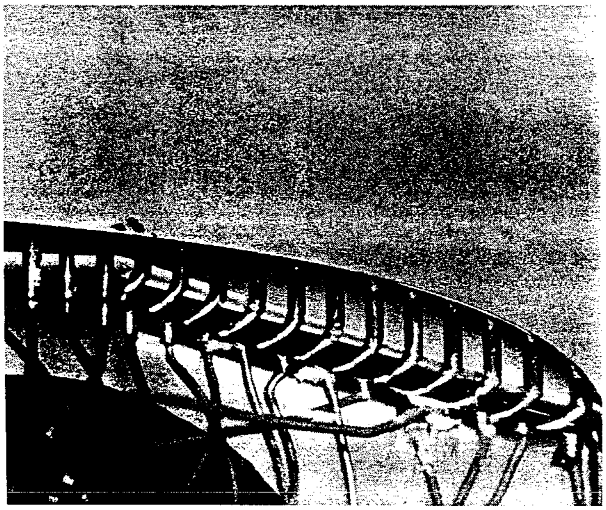

Figure 6. A typical photograph from Ceccio and Brennen (1991) illustrating the bubble breaking up into two or more pieces during the collapse.

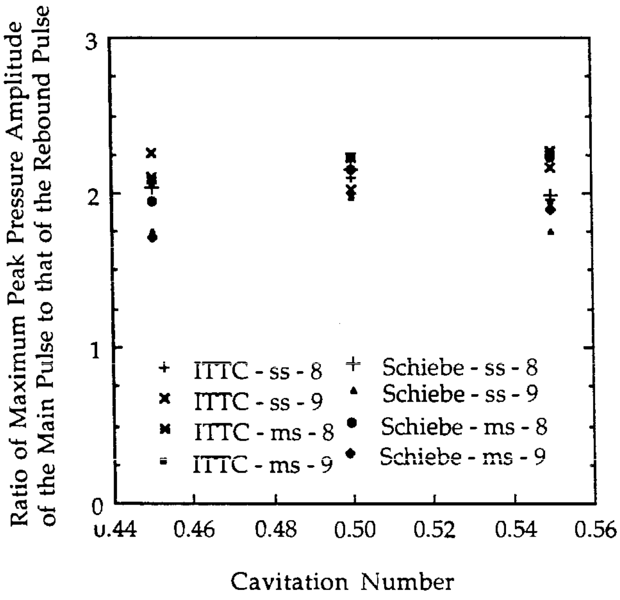

Figure 7. Ratio of peak pressure amplitude of the rebound pulse to peak pressure amplitude of the main pulse, r, as a function of cavitation number.

headform is probably responsible for the observed effects. The rebound pulse indicates a second collapse separated by a growth phase from the first collapse. The multipeaking, on the other hand, could be result of several mechanisms:

[a] Multiple peaks may be the result of several shock waves emitted during the collapse process (Mellen 1955 and 1956, Kimoto 1987 and Vogel *et al.* 1989). Kimoto (1987) has separately measured the pulses resulting from microjet impact as well as a shock wave emitted from the final bubble collapse. It can be seen from those observations that pressure resulting from the shock wave is the larger one. Also, the peaks from the microjet and the shockwave appear 0.1 *msec* apart whereas in present experiment peak separation was roughly 0.015 *msec*. Using Schlieren technique, Vogel *et al.* (1989) have observed two shock waves emitted due to non-spherical bubble collapse. Hence, the multiplicity of peaks could also be result of a number of shockwaves due to the non-spherical bubble collapse.

[b] The bubble can breakup into several pieces while collapsing (as seen by Ceccio and Brennen (1991) and shown in Fig. 6) and therefore generate two or more peaks. Considering the two bubble pieces to be roughly 1 *mm* apart (as seen from the photographs in Ceccio and Brennen 1991) the resulting peaks could be roughly 100 *msec* apart. Here, the bubble may breakup during the collapse as a result of the onset of higher order surface oscillations due to presence of the solid wall or due to the shearing action of the local flow.

[c] Volume oscillations during the collapse process could cause multiple peaks. By comparison with observed peak separation of roughly 0.015 *msec*, the natural period of oscillation for a 20 μm microbubble is also 0.015 *msec*. Thus, volume oscillations during the collapse may be a plausible reason for the multiple peaks.

We now examine other features of the results. The ratio of the maximum main pulse amplitude to maximum rebound pulse amplitude, r, is presented against the cavitation number in Fig. 7 for two velocities and various types of events. It is seen that most of the data is clustered around the value of 2. With a 95 % confidence level, we find that the mean value of r will lie between 1.5 and 2.5. It seems that bubble fission observed by Ceccio and Brennen (1991) happens in such a way that the remnant nucleus generates approximately half the maximum pressure. This may mean that during the first collapse certain nonlinear modes of surface oscillation are set up which cause the bubble to breakup

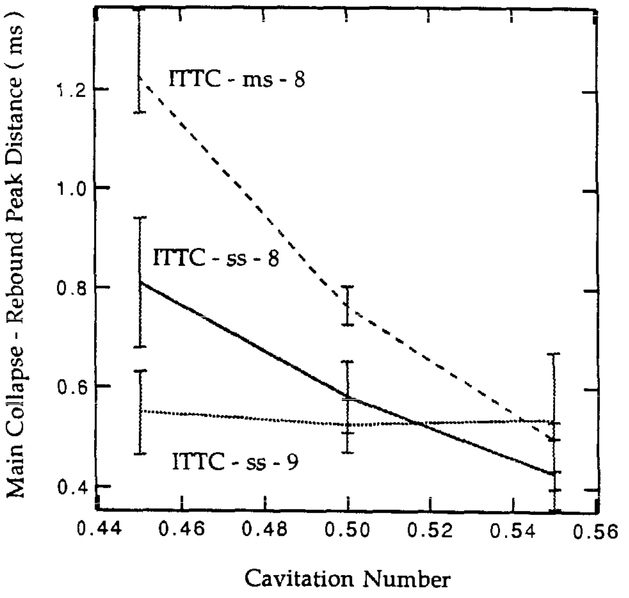

Figure 8. Dependence of time between the main and rebound pulses, τ on the flow condition and the type of rebound. The legend indicates the headform, type of rebound and the flow velocity. Type of rebound is indicated by 2 letters; the first letter indicates the number of peaks in the main pulse and the second letter the number of peaks in the rebound pulse; *m* indicates multiple peaks and *s* indicates a single peak.

in a repeatable way. The present observations differ from those of Hamilton (1981) who found that the acoustic energy emitted by the main and the rebound pulses were roughly the same.

The time interval between the main pulse and the rebound pulse, τ, is presented as a function of cavitation number in Fig. 8 for various type of events and two flow velocities. It can be seen that τ is in the range of between 0.3 to 1.3 *msec* and generally increases as σ is reduced. Multiple peaks appear to delay the rebound. This feature and the differences between two flow velocities are not easily explained.

The quantities P, I_m, I_s, τ_w, τ_s and spectra were also examined to understand their dependence on the flow condition and multipeaking and rebounding. These results will be presented at forum and in a later publication.

5. CONCLUSIONS

On the basis of above observations it may be concluded that multipeaking and rebounding increase with the reduction in the cavitation number for the ITTC headform. However for the Schiebe head form, multipeaking decreases and rebounding increases as the cavitation number is reduced. Also, both the multipeaking and rebounding occur more frequently for the ITTC headform compared to the Schiebe headform. The flow velocity seems to have little effect on these results. Most events with rebound for the ITTC headform are of *ms* type whereas they are mostly *ss* type for the Schiebe headform. The ratio of the peak amplitude of the rebound pulse to the peak amplitude of the main pulse is close to 2.0 for all flow conditions and types of events. This may indicate a fairly repeatable process of bubble fission and rebound. The time between the main pulse and the rebound pulse, τ, is seen to decrease with increase in σ . Multiple peaks in the main pulse are observed to delay the rebound.

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