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A minimum hydrophone bandwidth for undistorted cavitation noise measurement

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Abstract When measuring cavitation noise, the hydrophone represents a critical part in an acquisition chain because of its limited bandwidth. In this paper a minimum hydrophone's bandwidth required for undistorted cavitation pulses recording is examined. The procedure suggested in the paper is used to verify the validity of the recorded waves radiated by bubbles generated by underwater spark discharges. Extrapolation formulas for determining the necessary hydrophone's bandwidth when smaller or larger bubbles than generated in this work are studied are also suggested.

1 INTRODUCTION

Cavitation noise can be described as a superposition of many random pressure pulses [1]. Each of these pressure pulses has been radiated by an oscillating cavitation bubble and is therefore carrying information regarding properties of this bubble. To be able to extract this information, the true form of the pressure pulses must be recorded as precisely as possible. To cope with this task one needs a measuring apparatus with a suitable bandwidth extending from some lower cutoff frequency f_l to some upper cutoff frequency f_u.

A typical apparatus for cavitation noise recording consists of a measuring hydrophone, preamplifier and data acquisition device. At present time preamplifiers and data acquisition boards are available having a band-pass fulfilling even the most demanding requirements. However, a typical electro-acoustic transducer usually has a rather limited bandwidth. Thus the critical part in the measurement chain is the hydrophone.

In the following we shall describe a procedure we used to determine the required minimum hydrophone's bandwidth. The procedure is based on processing measured records of waves radiated by oscillating spark generated bubbles. The aim of this research was to find out which records can be considered to be reliable and to find extrapolation formulas usable in planning next experiments.

2 EXPERIMENTAL SETUP

The experimental setup used to study the minimum hydrophone's bandwidth is schematically shown in Fig. 1. The oscillating bubbles have been generated in a water tank using spark discharges. The spark discharges have been initiated between two electrodes made of tungsten wire of diameter 1.3 mm submerged in water at a depth of 2.75 m. The electrodes have been connected to a condenser bank, the capacity of which could be varied between 40 μF and 360 μF. The condensers have been charged from a high voltage source to about 2.5 kV. The laboratory water tank had dimensions 6 x 4 x 5 m.

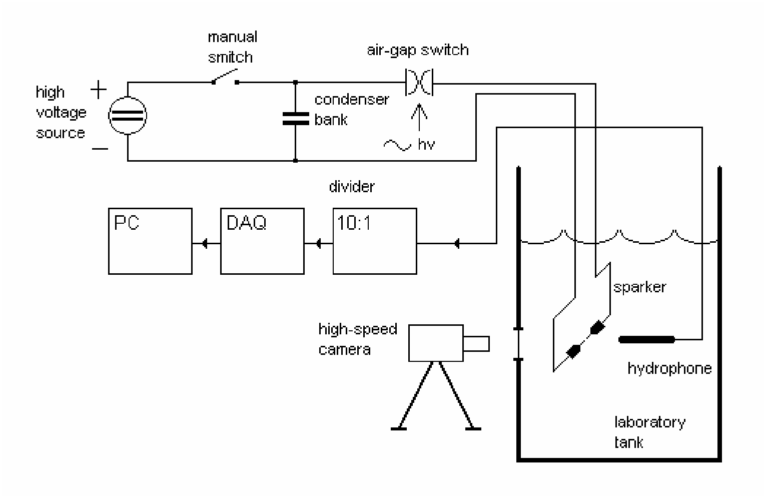

Figure 1. *Experimental setup used to study spark generated bubbles*

The pressure waves radiated by the oscillating bubbles have been recorded using a broadband hydrophone (Reson, type TC 4034) with a nominal usable frequency range from 1 Hz to 470 kHz (+3 dB, -10 dB) and a nominal receiving sensitivity of – 216.5 dB re 1V/μPa. The hydrophone has been positioned at a distances *r* from the bubble center ranging from 0.1 to 0.5 m. The hydrophone has been connected to a data acquisition board (National Instruments, type NI 6115) having a resolution of 12 bits and sampling frequency 10 MHz. The length of each record has been set to 20 000 samples.

3 PRESSURE RECORDS

An example of a pressure wave radiated by an oscillating bubble is given in Fig. 2. The recorded wave consists of an initial pulse radiated during the spark discharge and of several sharp pressure pulses called bubble pulses radiated when the bubble is compressed to a minimum volume. The peak pressure of the first bubble pulse p_{p1} is a very important quantity as it can be used to describe the bubble oscillation intensity. For this purpose it is convenient to define a non-dimensional peak pressure p_{zp1} [2]

$$p_{zp1} = \frac{p_{p1}}{p_\infty} \frac{r}{R_{M1}} \quad . \tag{1}$$

Here p_∞ is an ambient pressure at the place of the hydrophone, R_{M1} is a first maximum bubble radius and r is a distance of the hydrophone from the bubble center.

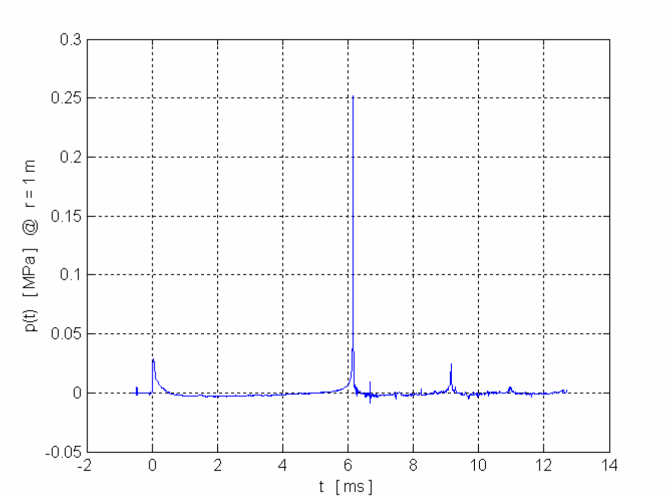

Figure 2. *Pressure wave radiated by a spark bubble*

The first maximum bubble radius, R_{M1}, can also be determined from the pressure records. Denoting the time interval between the initial pulse and the first bubble pulse as T_{o1} (the time of the first bubble oscillations), then [2]

$$R_{M1} = \frac{T_{o1}}{1.84\sqrt{\dfrac{\rho_\infty}{p_\infty}}} \quad . \tag{2}$$

Here ρ_∞ is the liquid density. The first maximum bubble radius, R_{M1}, thus determined, will be used in the following not only when computing p_{zp1} from eq. (1), but also as a suitable measure of the bubble size.

It follows from the above discussion that the proper recording of p_{p1} is very important for assessing the intensity of bubble oscillations. Unfortunately, determining the true value of p_{p1} is not a simple task because p_{p1} is very sensitive to the bandwidth of the recording apparatus and we have no prior knowledge of its real value.

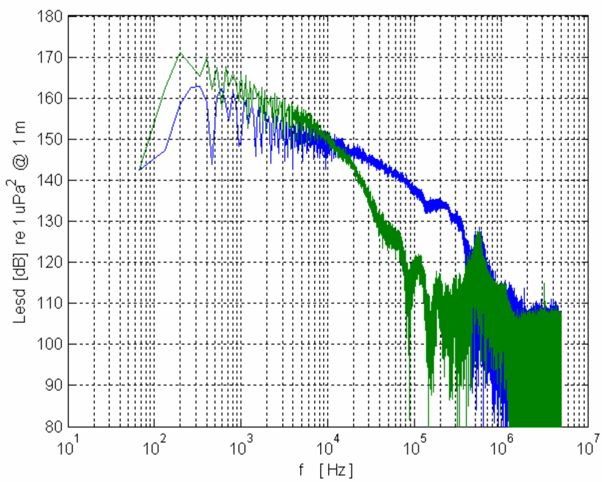

Figure 3. *Energy spectral densities of two recorded waves. The 1st record (blue): R_{M1}=24.7 mm, p_{zp1}=131, the 2nd record (green): R_{M1}=41.3 mm, p_{zp1}=26.8*

Energy spectral densities (ESD) of two recorded pressure waves are shown in Fig. 3. The records used to compute the ESD displayed in Fig. 3 have been selected in such a way as to represent two distinct cases: a small intensively oscillating bubble and a larger bubble oscillating with low intensity.

As can be seen, at the middle frequency range the spectra decrease with frequency f with a slope of about 5 dB/decade in the case of the intensively oscillating bubble and with a slope of about 8 dB/decade in the case of the less intensively oscillating bubble. At high frequencies the fall of both spectra is much steeper. It is about 60 dB/decade for the intensively oscillating bubble and about 40 dB/decade for the less intensively oscillating bubble. At low frequencies the spectra grow with a slope of about 40 dB/decade. It can also be seen that the frequency, at which the ESD has a maximum, depends on R_{M1}. For the larger bubble the maximum in the spectrum is located at about 200 Hz, while for the smaller bubble it is located at about 400 Hz.

4 ESTIMATE OF THE MINIMUM BANDWITH

A rough estimate of the necessary bandwidth for correct waveform recording can be drawn from Fig. 3. As the hydrophone's usable bandwidth starts as low as at f_{lh}=1 Hz, there is no doubt that the low frequency components in the waveform have been recorded properly. However, it is not clear at all whether the upper cutoff frequency of the hydrophone, f_{uh}=470 kHz, is satisfactory for our measurements. The basic problem in this respect is the fact that we do not know which recorded waveform is a reliable copy of the radiated pressure wave and which recorded waveform has been distorted during acquisition due to insufficient hydrophone's bandwidth. And this is true in the case of the most interesting waveforms radiated by small intensively oscillating bubbles first of all. It is the aim of this Section to throw some light on this problem.

An oscillating bubble is described by its size, R_{M1}, and by intensity of oscillations, p_{zp1} [2]. And as already shown in Fig. 3, the small and most intensively oscillating bubbles radiate waves the spectra of which extend to very high frequencies, and may even exceed the frequency f_{uh}.

To determine the minimum allowable value of f_{uh} from experimental records, two approaches have been used. The first approach is based on computing the ESD of a record and determining a frequency, within the upper steep spectrum slope, at which the spectrum level has just dropped by about 40 dB as compared with the maximum value at the spectrum. This frequency is denoted as f_{40}. It is then assumed that all important frequency components of the radiated pressure wave have frequencies lower than f_{40}. It is also hoped that, should the filtering of the high frequency components occur, due to the insufficient value of f_{uh}, then this effect could be detected by comparing the values of f_{40} from the pressure records corresponding to similar values of p_{zp1}.

Frequencies f_{40} have been computed for all available records. Variation of the computed values of f_{40} with R_{M1} is displayed in Fig. 4. As can be seen in Fig. 4, in accordance with our expectation, f_{40} is growing with p_{zp1} first of all. It is also growing partially when the bubble size R_{M1} is decreasing. However, the dependence of f_{40} on p_{zp1} is dominant. For bubbles oscillating with small or moderate intensities (p_{zp1}<100), f_{40} evidently falls below f_{uh}. However, there may be some doubts in the case of small and most intensively oscillating bubbles.

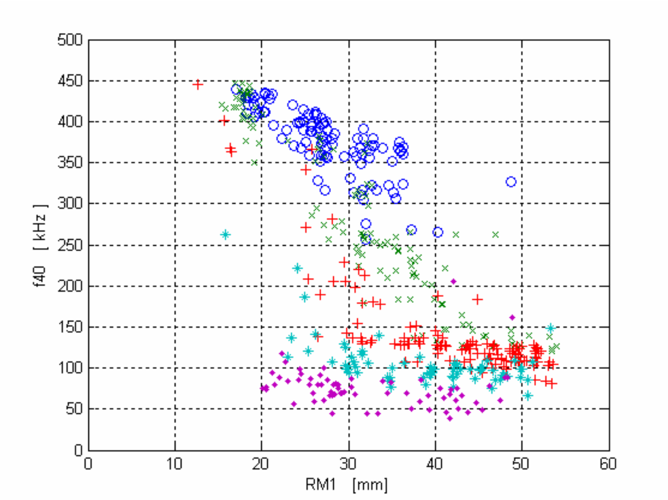

Figure 4. *Variation of f_{40} with R_{M1}. o - (p_{zp1}>100), × - (100> p_{zp1} >80), + - (80> p_{zp1} >60), ∗ - (60> p_{zp1} >40), • - (40> p_{zp1})*

The second approach we used to determine the minimum allowable frequency f_{uh} is based on passing a recorded signal repeatedly through a low-pass filter whose upper cutoff frequency f_{uf} can be varied. After each signal passage the filter upper cutoff frequency f_{uf} has been partially lowered. The peak pressure p_{p1} of the unfiltered and filtered signals have been compared. The procedure started with f_{uf}=1 MHz and terminated when the peak pressure p_{p1} in the filtered signal dropped about 5%. The corresponding upper cutoff frequency of the filter has been designed f_{ub} and the whole procedure has been repeated with a new record. All available records have been examined in this way. Variation of the computed f_{ub} with R_{M1} is given in Fig. 5.

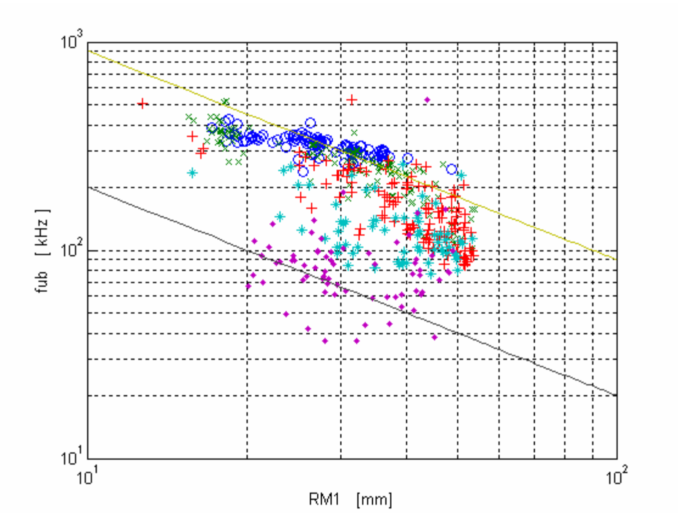

Figure 5. *Variation of f_{ub} with R_{M1}. o - (p_{zp1}>100), × - (100> p_{zp1} >80), + - (80> p_{zp1} >60), ∗ - (60> p_{zp1} >40), • - (40> p_{zp1})*

As can be seen in Fig 5, the upper cutoff frequency of the hydrophone f_{uh} was high enough to acquire most records with sufficient fidelity. However, some records, namely those corresponding to small R_{M1} and high p_{zp1} could be distorted due to insufficient f_{uh}.

The results obtained are useful not only to check the validity of measured signals. Another very useful application is the extrapolation of our data to obtain estimates of f_{ub} even for smaller or larger bubbles than examined here. Two possible extrapolation curves are given in Fig. 5. One curve corresponds to the highest intensities of the bubble oscillations (p_{zp1}>100) and one to the lowest intensities of the bubble oscillations (p_{zp1}<40). The corresponding extrapolation formulas are

$$f_{ub} = \frac{9000}{R_{M1}} \qquad \text{[kHz, mm]} \qquad , \qquad p_{zp1}>100 \qquad (3)$$

and

$$f_{ub} = \frac{2000}{R_{M1}} \qquad \text{[kHz, mm]} \qquad , \qquad p_{zp1}<40 \qquad (4)$$

respectively.

As it can be seen, in the case of small bubbles oscillating with high intensities (the upper left corner in Fig. 5) the calculated points of f_{ub} lay under the extrapolation curve (3). This might be due to the record distortion because of insufficient hydrophone's frequency f_{uh} or because these bubbles are not scaling bubbles, for which the extrapolation curve has been designed.

Even though the hydrophone's lower cutoff frequency f_{lh} represented no problem in our measurements, it can be useful to determine the allowable maximum hydrophone's cutoff frequencies f_{lh} and to find the corresponding extrapolation formulas for cases when a hydrophone with a higher f_{lh} is available or bubbles of different sizes then examined here are generated.

To solve this problem a procedure similar to finding f_{ub} has been used. Each record has been passed through a high-pass filter repeatedly and the lower cutoff frequency of the filter f_{lf} has been increased partially after each signal passage. The peak pressure p_{p1} of the unfiltered and filtered signals have been compared again. The procedure started with a filter having f_{lf}=10 Hz and terminated when the peak pressure p_{p1} in the filtered signal dropped about 5%. The corresponding lower cutoff frequency of the filter has been designated f_{lb} and the whole procedure has been repeated with a new record. In this way all the available records have been examined again. Variation of the computed values of f_{lb} with R_{M1} is shown in Fig. 6.

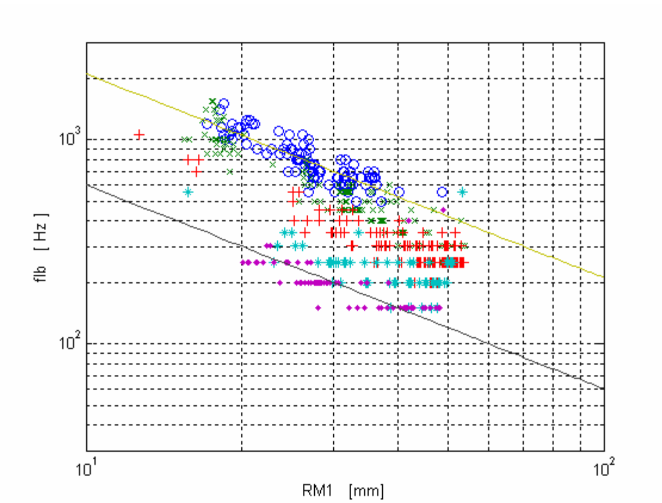

Figure 6. *Variation of f_{lb} with R_{M1}. o - (p_{zp1}>100), × - (100> p_{zp1} >80), + - (80> p_{zp1} >60), * - (60> p_{zp1} >40), • - (40> p_{zp1})*

In Fig. 6 two extrapolation curves are also displayed. One curve corresponds to high intensities of bubble oscillations (p_{zp1}>100) and the other to low intensities (p_{zp1}<40). In the first case the extrapolation formula is

$$f_{lb} = \frac{21000}{R_{M1}} \qquad \text{[Hz, mm]} \qquad , \qquad p_{zp1}>100 \qquad (5)$$

and in the second case it is

$$f_{lb} = \frac{6000}{R_{M1}} \qquad \text{[Hz, mm]} \qquad . \qquad p_{zp1}<40 \qquad (6)$$

As can be seen in Fig. 6, now the two curves fit the displayed data points relatively well. However, this could be expected as the frequency f_{lh} is much lower than all f_{lb} and thus no distortion due to the insufficiently low f_{lh} should occur.

To show possible application of the above formulas let us consider a following example. In the case of experiments with a single bubble oscillations (SBO) [3] the generated bubble has a size of about R_{M1}=0.1 mm typically and it is assumed that it oscillates with the highest intensity (p_{zp1}>100). In planning experiments for recording acoustic emission from SBO, the necessary hydrophone's bandwidth must be determined. From formula (5) one obtains immediately that f_{lb}=210 kHz and from formula (3) it follows that f_{ub}=90 MHz. Thus the hydrophone's usable bandwidth should extend from about 100 kHz to 100 MHz.

5 CONCLUSIONS

Two procedures have been suggested to find the optimum hydrophone's bandwidth. The methods made it possible to verify whether the experimentally determined records of the bubble pulses can be considered to be valid. Extrapolation formulas have also been suggested. These formulas make it possible to determine the necessary hydrophone's bandwidth when new experiments are planned.

ACKNOWLEDGMENTS

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