Semester Project : Cavitation Detection Using an Ultrasound Acoustic Field
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1 Motivation of this study

Cavitation is a physical phenomenon that has many consequences particularly harmful to hydraulic machines such as exessive structural vibrations, material erosion and flow instabilities. All of this resulting in a diminution of the machine performance. The problem is that it is very difficult to apply corrective procedures in existing units [2] and also very difficult to eradicate cavitation once it has appeared in the machine [1]. For theese reasons it seems more realistic and accurate to detect and monitor cavitation in order to avoid dangerous and exessively damaging situation for the hydraulic machine. It is important to notice that there are three types of cavitation : travelling bubbles, attached cavities and vortex cavitation. In this present study, focusing will be on travelling bubbles only.

Cavitation can be detected in various fashions in hydraulic machines [2]. The purpose of this study is to try a new cavitation detection approach that might result interesting : cavitation detection by ultrasound. This method presents various advantages a priori :

- it is non intrusive up to a certain degree that we will discuss later on
- it can be easily installed, in fact flow velocity are often measured with ultrasounds and the general idea is to use this existing ressource to measure both velocity and cavitation
- an experimental set up is very easy to realise : two transmitter/receiver, one oscilloscope and a function generators were needed to monitor cavitation in the cavitation tunnel
- ultrasound technology is widely used in scientific studies and turn to be very reliable

The detection of a body (bubble) in a medium (water) with ultrasounds is possible because acoustics properties of the body differs from those of the medium. These differences can have three consequences on the acoustic field : it is scattered, absorbed or its speed of propagation in the medium is changed. The largest detectable effects occur if the body is capable of resonating to an incident sound. When the bubble is excited at or near its natural frequency it will very effectively absorb and scatter the sound [3]. Minnaert proved that the natural frequency of a bubble of radius r filled with a gas of heat-capacity ratio γ at the hydrostatic pressure p_0 in a medium (water) of density ρ is :

$$f = \frac{1}{2\pi r}\left(\frac{3\gamma p_0}{\rho}\right)^{\frac{1}{2}} \tag{1}$$

Considering an air-filled bubbles at atmospheric pressure (100 kPa) in water, equation (1) writes $fr = 3$ Hz m [4]. The transmitters used for this study emitt ultrasound at a frequency of 500 kHz. Using equation (1) the radius of resonating bubbles for the 500 kHz frequency is then approximately $r = 6$ μm for air-filled bubbles. Considering water at temperature of 10 °C of density $\rho = 999.77$ kg/m^3 and a water vapor-filled bubble at water vapor pressure $p_v = 1227$ Pa and specific heat ratio $\gamma = 1.33$, equation 1 gives $fr = 0.35$ Hz m wich is an order of magnitude lower than the case of an air-filled bubble. At 500 kHz the radius of vapor-filled bubbles is $r = 700$ nm, wich is also an order of magnitude lower than air-filled bubbles.

In order to detect and caracterize the presence of cavitation with ultrasounds, two experimental set ups will be used. The first experimental set up main goal will be to test the theoretical and experimental accuracy and the limits of ultrasounds in a single air-filled bubble immerged in water. The radius of the bubbles will be changed but will still remain in ther order of magnitude of the millimeter. For this reason detection by measuring the effects of resonating bubble can reasonably be discarded. The second experimental will take place in the cavitation tunnel. The main goal is to apply the results of the first experiment in a cavitation field and not only on a single bubble. The measurements will be at differents values of σ to check how they vary with the cavitation regime.

2 Case of a single bubble in an acoustic field

The strategy of this study is :

- first try to determine how to detect the presence of a single bubble with an acoustic field
- identify which accoustic parameter functions best
- go on the cavitation tunnel to test our method in a real cavitation case

In order to do so single bubbles have to be generated. It is reasonable to assume that the radius of the generated bubbles will mainly depend on the pressure of air injected in the water to generate the bubble and on the diameter of the hole of the injecter. A device capable of injecting air throught a precise hole at a precise pressure had to be used for this experiment. The laboratory of LMH provided such a device. It consisted of a metallic block pierced with 5 holes of different diameters (4, 2, 1.5, 1 and 0.6 mm). This block was connected to the pressure network of the LMH throught a cable which had a pressure gauge. From this pressure gauge the pressure in the metallic block was regulated. A schematic representation of the device is found on figure 1. If needed, the holes can be covered in order to generate only a specific type of bubble.

Once the device at disposition, the radius of the outgoing bubbles need to be known. The next step of the study consists in determining the diameter of the bubble by measuring them directly. A high-speed camera was used to take very high frame rate movies in order to capture the exact depratture point. A bubble at the departure point is shown on figure 2. The pressure of air inside the bubble is $p_v = 0.17$ bar and the diameter of the hole is 0.6 mm.

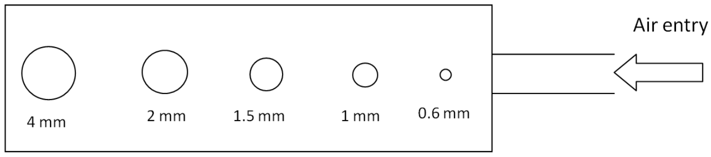

FIGURE 1 – Experimental device for single bubble generation

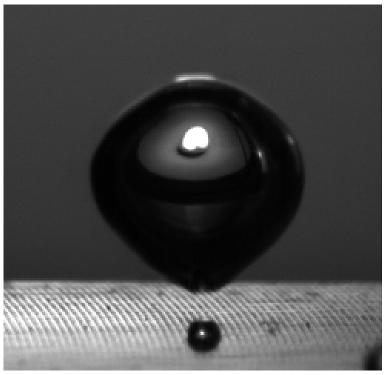

FIGURE 2 – Bubble at the departure point. The diameter of the hole is 0.6 mm

The movies were then analysed with MATLAB in order to get the diameter of the bubbles for each diameter holes. These diameters are consigned in table 1.

Hole	0.6	1	1.5	2	4
Bubble	6.96	8.24	6.57	5.32	5.55

TABLE 1 – Measured bubble diameters in function of the diameter of the hole (in mm)

It has to be noticed that the measured diameters of bubbles is rougthly an estimation of the real diameter. This is mainly due to instabilities on the surface of the bubbles that appear just a few instants after the departure point, when the bubble finally detaches from the air flow that arrives throught the hole. These instabilities provoke a vibrating mode on the bubbles, thus rendering the radius variable in time. An exemple of those instabilities is shown on figure 3.

FIGURE 3 – Instabilities on a bubble

Once the diameter of the bubbles is known, the next step of the experimentation is to compare the variations of the acoustic signal in the presence of bubbles. For this purpouse, two emitters/receptors are place facing each others across a water filled tank. The bubble generator is place in the water underneath the acoustic signal. A schematic representation of the experimental set up is shown on figure 4.

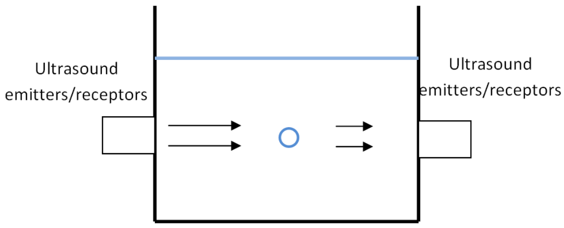

FIGURE 4 – Experimental set up

The emitters are connected to a function generator and can be excited as comanded. They are designed to work best at a frequency of 500 kHz. They work both as emitters or receptors. The receptor is connected to an oscilloscope, and the variation of the ultrasound field will be monitored only throught it. As mentioned in the first section, the only two effects of the bubble can be measured, the absorption and the change in the speed of propagation of sound. Since there are only a few bubble at the time in the water it can be assumed that they will have a quasi inexistant impact on water compressibility, thus no measurable effects on the speed of sound will appear. The only aspect left to mesure is the absorption of the sound wich is not a minor aspect. Later an acoustic model will be provide and it will turn out that it is not really the absorption of sound that occurs but a reflection. In fact the specific acoustic impedance of air is about 420 Pa s/m whereas the specific acoustic impedance of water is about 1.5 MPa s/m, three orders of magnitude greater. It is then expected that as little as the bubble can be it has to have an measurable absorption percentage. It is fair to assume that this percentage will depend directly on the radius of the bubble since this radius determines the amount of air contained in the bubble. The data acquisition consists in taking 20 consecutives "screenshots" of the oscilloscope at the moment when the bubble is passing through the acoustic field for each of the radii. The number 20 was chosen because it is supposed to be large enough to capture sufficients attenuations of the signal so that the differences we measure are not biaised an tend to the real attenuation. Statiscally if we increase this number we increase the precision of the measure. But since the triggering of the "screenshot" had to be done manually a larger number of shots has been discarded. It would have been possible to trigger the screenshots automatically if the bubble generation frequency and the ascent the bubbles was well known and controlled. All the data was post-processed on MATLAB. An example of one measurement of these passing bubbles is shown on figure 5. The results of the calculations of attenuation are presented in table 2.

The gap presented in table 2 is calculated in three steps :

- first all the maxima of one set of acquisitions (Cf. Fig. 5) are determined and stocked
- the maximum of these maximima a and the minimun of these maxima b are used to calculate the gap and the attenuation, which ultimately is the relative difference between them : $(a-b)/a$
- the mean value of the maxima is determined

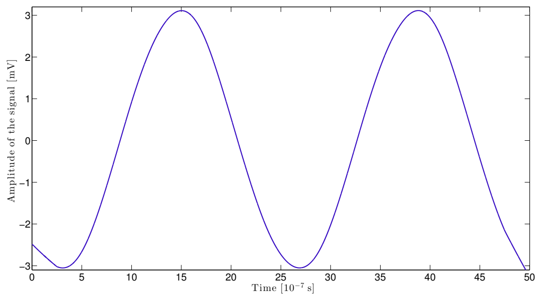

FIGURE 5 – Exemple of a measurement of the attenuation caused by the crossing of a bubble

D_b	Gap	Mean max.	Attenuation [-]
6.96	0.0112	3.1181	0.0036
8.24	0.0081	3.1307	0.0026
6.57	0.0128	3.1178	0.0041
5.32	0.0158	3.1296	0.0050
5.55	0.0115	3.1140	0.0037

TABLE 2 – Values of mesurated attenuation, maximum gap (mV) and mean maximum (mV) for different diameters of bubbles

It appears that despite of the radius change the attenuation of the acoustic field remains quite similar in absolute. They are from the same order of magnitude. But they don't appear to be correlated. For exemple a 18.39% increase in diameter form 6.96 to 8.24 results in a 27.78% decrease in attenuation. The only pattern that seem to appear is that the bigger the diamter the lower the attenuation. It seems quite counter-intuitive since a bigger radius bubble is a bigger "obstacle" to the sound in comparison to a smaller one. In all the models proposed further a way this tendency will not appear.

A little model is proposed to evaluate the energy loss. It is based on an evaluation of the void fraction that a single bubble produce upon the acoustic field. A supposition is made on this acoustic filed, it is supposed to be cylindrical from the emetter to the receptor, as shown in figure 6.

Knowing the radius $R_c = 3.5$ cm of the cone of sound and the distance between the emitters $d = 28.5$ cm, the volume of the cylinder is then $V_c = \pi R_c^2 d =$. The volume of a single bubble being $V_b = \frac{4}{3}\pi R_b^3$ the void fraction is simply $\epsilon = \frac{V_b}{V_c}$. This void

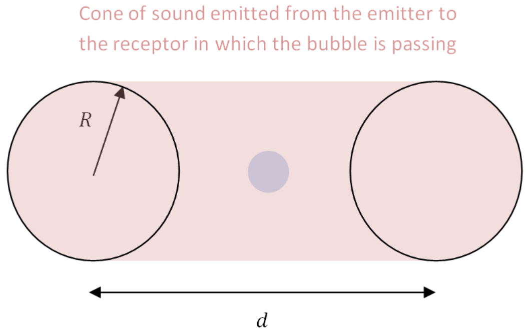

FIGURE 6 – Cylindrical cone of sound in which a bubble passes

fraction can be compared to the attenuation values mesured directly from the oscilloscope. The resume of these values is found in table 3

$D_b(mm)$	Attenuation [-]	ϵ [-]
6.96	0.0036	$5.123 \cdot 10^{-5}$
8.24	0.0026	$8.502 \cdot 10^{-5}$
6.57	0.0041	$4.309 \cdot 10^{-5}$
5.32	0.0050	$2.288 \cdot 10^{-5}$
5.55	0.0037	$2.598 \cdot 10^{-5}$

TABLE 3 – Values of mesurated attenuation compared to the void fraction for different diameters of bubble

This quite simplistic approximation gives a very poor estimation of the energy loss. Another analytical estimation has to be. From a more fundamental point of view the acoustics aspects of the problem have to be taken into account. As mentioned before the characteristic acoustic impedance of water and air are very different by an order of magnitude of 10^3. These impedances are calculated in based of the following formula : $Z = \rho c$ where ρ is the density of the medium and c is the speed of sound in that medium. The speed of sound in air is given by $c_a = \sqrt{\gamma R T}$ whereas the speed of sound in water is given by $c_w = \frac{1}{\sqrt{\rho_w \kappa}}$ where κ is the adiabatic compressibility coefficient. For water $\kappa = 4.6 \cdot 10^{-10}$ Pa^{-1} [8]. We have used the following values : $\gamma = 1.4$, $R = 286.9$ J/(kgK)and $T = 283$ K. The numerical values are $Z_a = 413.008$ and $Z_w = 1.4742 \cdot 10^6$ Pa s/m. The problem to be solved is the passing of a pressure wave throught an interface, as shown in figure 7.

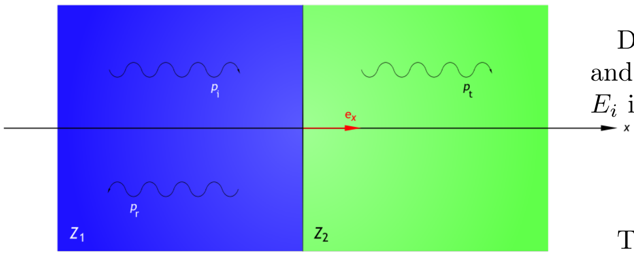

FIGURE 7 – Cylindrical cone of sound in which a bubble passes

In this case the curvature of the buble is neglected and it is assumed to be a disk of the same diameter as the bubble, $Z_1 = Z_w$ and $Z_2 = Z_a$. The transmission an reflection coefficient are define respectively as $t_p = p_t/p_i$ and $r_p = p_r/p_i$. These coefficients can be related to the characteristic impedance by the following relations [8] :

$$t_p = \frac{2Z_a}{Z_w + Z_a} \qquad r_p = \frac{Z_a - Z_w}{Z_w - Z_a} \tag{2}$$

Replacing the numerical values in 2 yields $t_p = 5.6014 \cdot 10^{-4}$ and $r_p = -0.9994$. Knowing that the intensity of a pressure wave is

$$I = \frac{1}{\rho c} \left\langle \Delta p^2 \right\rangle \tag{3}$$

and $p_r = r_c p_i$ and $p_t = t_p p_i$ it appears that almost all the energy is reflected. In fact we can calculate it by replacing the expression of p_r in (3) it yields :

$$I_r = \frac{1}{\rho_w c_w} \left\langle \Delta p_r^2 \right\rangle = r_p^2 I_i = 0.9989 I_i \tag{4}$$

Almost all of the energy of the sound that incounters a bubble is reflected by it. For simplicity in the rest of the study it is considered that all the energy is in fact reflected. An energy balance is done by considering the surface of the cone of sound as the source of energy and the surface of the disk of same radius as the bubble as the reflector. These surfaces are defined respectively as $S_c = \pi R_c^2$ and $S_d = \pi R_b^2$. The emitted and reflected energy are $E_i = S_c I_i$ and $E_r = r_p^2 S_b I_i$. Therefore the transmited energy is :

$$E_t = E_i - E_r = \pi I_i (R_c^2 - r_p^2 R_b^2) \tag{5}$$

Definig the relative energy loss $\varepsilon_E = (E_i - E_t)/E_i$ and replacing the result of (5 and the definition of E_i it yields :

$$\varepsilon_E = \frac{r_p^2 R_b^2}{R_c^2} \tag{6}$$

This realtion only depends on the radius of the cone of sound, the radius of the bubbble and the characteristic impedances of air and water. The values of ε_E can be found in table 4.

$D_b(mm)$	ε_E [-]
6.96	$9.875 \cdot 10^{-5}$
8.24	$1.384 \cdot 10^{-4}$
6.57	$8.799 \cdot 10^{-5}$
5.32	$5.769 \cdot 10^{-5}$
5.55	$6.279 \cdot 10^{-5}$

TABLE 4 – Values of mesurated attenuation compared to the relative energy loss for different diameters of hole

The values of ε_E are a bit higher than the values of ϵ but from the same order of magnitude, yet the physical model used to establish ε_E is significantly more precise. But in both cases their order of magnitude (10^{-5}) is nowhere near the amplitude decrease (order of magnitude of 10^{-3}) measured in the experiment. Since the results from the two models are relatively close, it must mean that the error come from a parameter or a hypothesis common to both models. There is one parameter common to both models that could very easily account for the errors ; it is the radius of the cone of sound. It is actually an unknown parameter and it has been estimated from the emitter by mesuring the size of it. Even the cylindrical shape of the cone of sound is a supposition. The only real information about this cone of is that the emitted sound go on a straight path, it does not act like a loudspeaker.

A major hypothesis in our models is that in all of them the bubble appears to be at rest. In the void fraction calculation it is as if sperical whole was pierced in a cylindrical volume. In the pressure calculations the interface between the two medium was supposed to be at rest when it is clearly not the case since the bubble is going up to the surface and passes through the acoustic field. A case have to be made for the bubble surface instability. As shown in figure 3 major instabilities appear on the bubble, they must have a consequence (either positive or negative) on the energy transmission.

3 Case study in the cavitation tunnel

The previous section has shown that on a single bubble of air the only measurable effect is the absorption. But it has also shown that as little a bubble can be it still has quite an impact on the acoustic field. The experiment will now take place in the cavitation tunnel of the LMH. In this tunnel the acoustic field is crossed by a cavitation field. This implies that the mesurement of the dispersion of the speed of sound is a viable option. The radii of cavitation bubbles is unkwnon in this case. Theory says that it can vary from μm to mm [1]. The same emitters/receptors used in the previous experiment will be used. They are placed right behind the blade so they can focus only on travelling bubbles and not on the attached cavities on the blade. The metodology is the same used in the previous experiment, 20 screenshots of the oscilloscope are taken and the data is then analysed. In this case we take the shot for various cavitation configuration whereas in the previous experiment it was in various radii configurations. This time two parameters will be changed, the cavitation number σ and the angle of attack of the balde α.

However in this case the measurements are not as simple to analyse as before, something that is quite natural since the physics of the phenomenon is much more complex. In the previous experiment the signal sent from the emitter was sinusoidal and the signal received was still sinusoidal but attenuated. In the present experiment the signal emitted is sinusoidal but the signal received is not sinusoidal anymore. An exemple of various signal received is shown on figure 8.

It is almost impossible to say anything about a data like the one shown on figure 8 without using Fourier analysis or some other powerful mathematical tools. This was not the purpouse of this study.

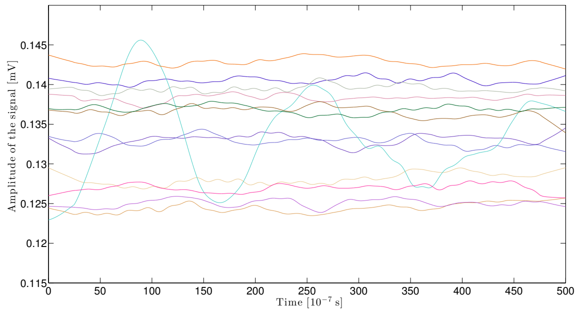

FIGURE 8 – Exemple of various signal received once the sound has passed through the cavitation field

Besides this types of analysis without having a clear idea of what their goal is would probably lead to meaningless results. Using the basis of the previous experiment a basic data analysis will be computed on MATLAB. It will consists on calculating a mean value of the attenuation, the minimum and maximum for all the cavitation configuration. The results can be found on tables 5 and 6 respectively.

α	σ	Mean signal
5	0.8	0.1341
5	1	0.1316
5	1.2	0.1322
5	1.4	0.1322
5	1.6	0.1321
3	1	0.1353
6	1	0.1343
8	1	0.1353
10	1.2	0.1337

TABLE 5 – Mean signal measured in the cavitation tunnel

The main idea, in order to get something out of the data, was to calculate the mean value of each signals from its respective set of data. In addition to that the maximum and minimum value of each set of data was calculated in order to have a sense of magnitudes. The main motivation behind this approach was that there is no sense in trying to work with absolute values ; the interesting part of the problem was to compare one set of data from a cavitation configuration with another one. It is the relative difference between them which is interes-

α	σ	Minimum	Minimum
5	0.8	0.1216	0.1447
5	1	0.1237	0.1428
5	1.2	0.1236	0.1429
5	1.4	0.1227	0.1437
5	1.6	0.1209	0.1451
3	1	0.1237	0.1444
6	1	0.1224	0.1431
8	1	0.1240	0.1420
10	1.2	0.1229	0.1456

TABLE 6 – Minimum and maximum of the signal measured in the cavitation tunnel

ting and not the properties of one. That is part of the reason why a ponderation method of the data was chosen. Another part of the reason is purely practical, without such ponderation the comparisons are just impossible.

Before having a deeper look at the results, the characteristic impedance of vapor will be calculated since cavitation bubbles are filled with vapor. First the speed of sound in vapour is calculated : $c_v = \sqrt{\gamma_v R_v T}$ where $\gamma_v = 1.33$, $R_v = 461.5$ J/(kgK) and $T = 283$ K. This yields $c_v = 416.78$ m/s. It is assumed that the cavitation bubbles where immerged in a flow at atmospheric pressure, this gives $\rho_v = 0.590$ kg/m^3. The calculation of $Z_v = \rho_v c_v$ 245.8991 Pa s/m. The characteristic acoustic impedance of vapor is lower than the one from air, the reflection coefficient r_p will the be higher, so will the energy reflection be. The calculation of the reflection coefficient for vapor yields : $r_p v = -0.9997$. The relative energy loss ε_E will be greater for a pure cavitation case than for an air bubble case.

Looking at the results shown on table 5, it appears that there is a clear tendency of diminution of the signal when the cavitation number increases and when the angle of attack increases. This should not be looked as a surprise. The results of the previous experiment have shown that in presence of a bubble the signal is not fully transmitted. In this case we are in the presence of a field of bubbles (even if they can be micrometrics or even less). The opposite effect, the increase of the mean signal in presence of more cavitation would have been very surprising. It still has to be noticed that it is not an absolute measurement, it is merely a "mise en pratique" of the little models developped earlier.

A case still has to be made for the speed of propagation in presence of cavitation. As mentioned earlier it is one of the three main components of the consequences of introducting a body in a medium. In [3] a relationship between this speed and the frequency of the acoustic filed and the density of bubbles :

$$c = c_0 \left[1 - \frac{3UY^2}{2a^2 k_R^2} \frac{Y^2 - 1}{(Y^2-1)^2 + \delta^2} \right] \qquad (7)$$

Where :
- c_0 is the speed of propagation of sound in the bubble free medium
- $U = U(a)$ is the fraction of volume in bubble form (bubble density)
- $Y = f_R/f = \omega_R/\omega$ is the frequency ration, where f_R is the resonating frequency
- a is the radius of the bubble
- k_R is the wave number at resonating frequency
- δ is the damping constant

Acording to equation(7) knowing the frequency of the acoustic field and measuring the new speed of propagation of this field, the bubble density U can be determined. There are still two cases of particular interest. For very low frequencies, $f \ll f_R$ and equation 7 then becomes :

$$c_{\text{lf}} = c_0 \left[1 - \frac{3U}{2a^2 k_R^2} \right] \qquad (8)$$

The bubble density is therefore proportional to the difference between c_{lf} and c_0. For very high frequencies, $f \gg f_R$ and equation 7 then becomes :

$$c_{\text{hf}} = c_0 \left[1 + \frac{3UY^2}{2a^2 k_R^2 (1 + \delta^2)} \right] \to c_0 \qquad (9)$$

For very high frequencies the propagation of sound tends to the bubble free proagation of sound. This means that at those frequencies bubbles do not affect the sound propagation speed.

4 Conclusions

The idea of this project was to study the viability of using ultrasounds to detect cavitation and if possible caraterize it. The first step of the project was to create single bubbles of air and to analyse the effects that they have on the ultrasound wave. As expected ultrasound are not insensitive to the bubbles. An analytical model based on pretty basic acoustic theory provided an insight of the phenomenon. At the interface between the bubble and the water because there is reflection of almost all energy from the sound beacause the characteristic impedance of water is much higher than the characteristic impedance of air and vapor. This will cause the signal to be attenuated and this attenuation can give us a first appreciation of cavitation. Another approche which has been discussed but not examintated is the measurement of the speed of propagation of sound . Since a bubbly water changes its compressibility it also changes the speed of propagation of sound, and if one property is known the other can be deducted by the dispersion relation. One has to be carefull for the extreme cases of high and low frequency of sound.

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