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Uniform Acoustic Cavitation of Liquid in a Disk *

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A dynamical propagation model coupled to the oscillation of cavitation bubbles is applied to describe the imploding acoustic field in a cavitating liquid where the acoustic waves transmit from the outside to the inside of a circle disk. Numerical simulation shows that the imploding ability of a ring source can elevate the sound pressure or partly eliminate the decay due to both the bulk attenuation and the attenuation caused by cavitation. However, the imploding ability is limited and there exists a critical radius. When the radius of the disk is larger than the critical one, the imploding ability is not enough to eliminate the attenuation. Fortunately, the cavitation region can be effectively expanded if a hot plate is attached under the center of the disk because the cavitation threshold is related to the temperature of the liquid, which means that a region with good uniformity of cavitation can be enhanced by adjusting the temperature difference between the central and side liquid.

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Acoustic waves are the propagation of vibrations generated by sounding bodies in media. If a medium is ideal, there is no dissipation of energy, and the medium does not absorb acoustic waves. However, when they propagate in a non-ideal medium, the amplitudes of acoustic waves decrease gradually with the increase of propagation distance, which is the common attenuation effect of the medium on acoustic waves. The sound waves emitted by a point acoustic source propagate along the space after leaving the wave source. If the space is three-dimensional, even if the medium is ideal, the amplitudes of sound pressure will still decrease and exhibit $1/r$ attenuation with the increase of the propagation distance r. Of course, if the space is one-dimensional, this attenuation does not exist. During the propagation of acoustic waves, there will be alternating changes of pressure in time and space. At some time, certain areas of the liquid will have a negative pressure below ambient static pressure. When sufficiently strong sound waves propagate in the liquid, the generated negative pressure can activate the cavitation nuclei to form visible bubbles in the liquid, which is called cavitation.[1,2] Of course, the amplitudes of acoustic waves must exceed the cavitation threshold,[3] so that the liquid can be cavitated. This cavitation threshold is related to many liquid parameters, such as the saturated vapor pressure, viscosity, and surface tension of the liquid. The cavitation threshold of the liquid is approximately equal to the ambient pressure minus the saturated vapor pressure of liquid.[4] After the liquid cavitation, a great number of cavitation bubbles appear. Cavitation bubbles can not only absorb, but also scatter acoustic waves, leading to an additional attenuation from the cavitating liquid, and further weakening the propagation ability of acoustic waves. It can be seen that a large number of bubbles generated by the cavitation will in turn suppress the sound propagation in the liquid,[5] forming a cavitation shield. The point sound source with amplitude exceeding the cavitation threshold will face triple attenuation, i.e. bulk attenuation, spatial dimension attenuation, and cavitation shield in liquids. As a result, the sound waves decay quickly after leaving the source, and make cavitation impossible in a large-scale area with the exception of a small region near the radiation surface of the emitter. In industrial production, a uniform large-scale field of cavitation is required. Therefore, instead of a point acoustic source, multiple (surface) sound sources which emit sound waves from the outside to the inside are used to improve the uniformity of acoustic cavitation with the imploding effect of sound waves, such as common ultrasonic cleaners.

The attenuation caused by liquid absorption can be partially eliminated by the imploding effect when an annular sound source is used to transmit inward sound waves. However, it is easy to understand that the imploding ability of the annular source may partly eliminate the decay due to both bulk attenuation and cavitation. There should be a critical radius beyond which the imploding effect is not enough to offset the bulk attenuation and the cavitation shielding effect. That is to say, for a given sound pressure, frequency, and liquid damping attenuation coefficient, the imploding effect of a disk whose radius is less than the critical radius can keep the center of the disk cavitation, otherwise, the center of the disk cannot obtain sound pressure amplitudes higher than the cavitation threshold to achieve cavitation. In this Letter, we study the correlation between the critical radius and the parameters of both ultrasound and liquid. Furthermore, a method of changing the cavitation thresh-

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old of liquid with temperature[6] is proposed. In detail, placing a thermal plate under the center of the disk and adjusting its temperature obtain a suitable distribution of the cavitation threshold, so that it matches the sound field produced by the annular sound source to ensure more areas can be cavitated. In other words, a non-isothermal liquid has a high cavitation threshold at high sound pressure and a low cavitation threshold at low sound pressure.

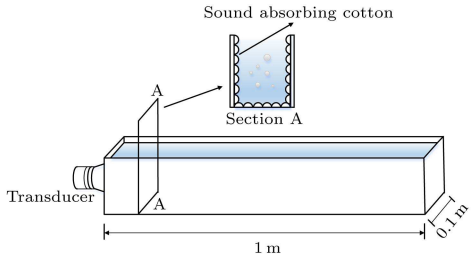

Fig. 1. The schematic diagram of the trough.

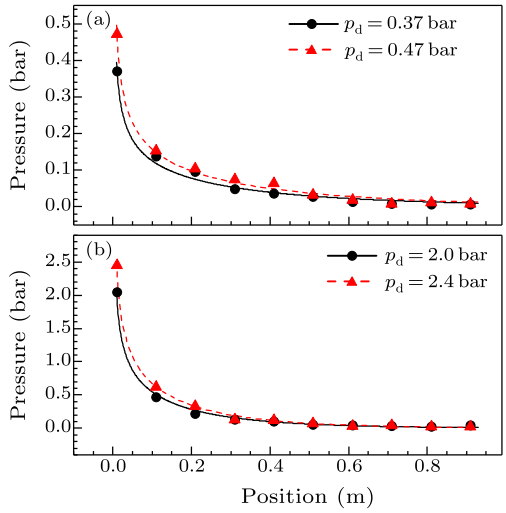

Fig. 2. The distribution of sound pressures in the water trough: (a) no cavitation and (b) cavitation.

We need to understand sound attenuation in water, especially in a cavitating liquid. First, we measured the distribution of the sound field in a long trough driven by different sound pressures to obtain the acoustic attenuation coefficient, as shown in Fig. 1. We attached sound-absorbing cotton to the inner wall of the trough, which could greatly weaken the influence of reflected sound waves on the transmission of sound waves. The experiment was started from a small driving sound pressure under the cavitation threshold to a large driving sound pressure beyond the cavitation threshold and in total four sets of sound pressure distributions were measured along the length of the trough. Under the first two sets of sound pressure, the water is not cavitated, while the water is cavitated under the latter two sets. The data are shown in Figs. 2(a) and 2(b).

The experimental data are best fitted by the curve

$$p = ax^n e^{-\mu_1 x}, \tag{1}$$

where a, n, and μ_1 are the fitting parameters, and n is a parameter related only to the geometry of the trough. For our trough it is about 0.4. It is easy to see from Fig. 1 that the curves fit well with the experimental data. This indicates that all four cases can be expressed by the same rules of sound decay. In other words, the cavitation screening effect can be approximately regarded as an additional attenuation. The measurement results show that the attenuation coefficient μ_1 is in the order of magnitude of 1/m. It is $1.95\,\mathrm{m}^{-1}$ and $1.97\,\mathrm{m}^{-1}$ for no-cavitation cases driven by a pressure amplitude of 0.37 bar and 0.47 bar, respectively, as shown in Fig. 2(a). The almost identical values of μ_1 tell us that the sound bulk attenuation does not vary with the sound amplitude in the no-cavitation case. However, μ_1 is $3.7\,\mathrm{m}^{-1}$ and $3.8\,\mathrm{m}^{-1}$ for the cavitation cases driven by pressure amplitudes of 2.0 bar and 2.4 bar, respectively, in Fig. 2(b), and the attenuation coefficient increases with the driven pressure p_d due to cavitation. Although limited by the range of the hydrophone, we have not measured the coefficient under larger driving; it is straightforward that μ_1 increases with the increase of driven pressure p_d.

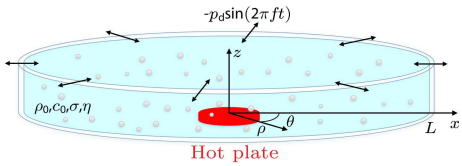

Fig. 3. Cavitation of water in a disk.

For a thin disk of bubbly water with a radius of L (see Fig. 3), we take the standard values of water on the surface of the earth as a reference, i.e. the sound velocity $c_0 = 1500\,\mathrm{m/s}$, the density of water $\rho_0 = 1000\,\mathrm{kg/m^3}$, the viscous coefficient $\eta = 8.9 \times 10^{-4}\,\mathrm{m^2/s}$, and the surface tension coefficient $\sigma = 7.6 \times 10^{-2}\,\mathrm{N/m}$. Since the liquid layer is infinitely thin, it can be seen as a plane, and we can describe it with polar coordinates. Furthermore, we set the driving sound pressure $p(\rho, t)|_{\rho=L} = -p_\mathrm{d} \sin 2\pi f t$, where p_d and f are the amplitude and frequency of driving sound, respectively. Because the driving sound pressure is spherically symmetrical, the whole formulas in this work are independent of θ.

The acoustic wave equation in bubbly liquids has the form[7,8]

$$\frac{\partial^2 p}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial p}{\partial \rho} - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \frac{4\mu}{3c_0^2}\frac{\partial^2}{\partial \rho}\left(\frac{\partial p}{\partial t}\right) = -4\pi\rho_0 \tilde{N}(\rho)(2R\dot{R}^2 + R^2\ddot{R}), \tag{2}$$

where R is the radius of the bubbles, μ is decided by the acoustic attenuation and cavitation shield, and the number density of bubbles $\tilde{N}(\rho)$ is related to space and has a complex correlation with time, respectively. The terms on the right-hand side of the equals sign represent the non-linear effect of bubbles on the sound field.

The dynamics model of the bubble can be expressed as[9]

$$\rho_0\Big(R\ddot{R}+\frac{3}{2}\dot{R}^2\Big)+P_0-P_{\rm g}-\frac{R}{c_0}(\dot{P}_{\rm g}-\dot{p}) +\frac{4\eta}{R}\dot{R}+\frac{2\sigma}{R}+p=0, \tag{3}$$

where P_0 is the ambient pressure, $P_{\rm g}$ is the pressure in the bubble which has the form[10]

$$P_{\rm g}=\Big(P_0+\frac{2\sigma}{R_0}\Big)\Big(\frac{R_0^3-b^3}{R^3-b^3}\Big)^{\gamma}, \tag{4}$$

with γ the polytropic exponent of gas, R_0 the ambient radius, and b the van der Waals radius which can be expressed as[11]

$$b=\frac{8.5}{R_0}. \tag{5}$$

Cavitation is irreversible, and the time correlation of the number density of bubbles is quite complicated. To simplify the calculation, we calculate $\tilde{N}(\rho)$ at the end of each cycle and this result will be used in the calculation of the next cycle in our study. This means that the number density of bubbles in the same position does not change in the same cycle, but each cycle is variable. Here $\tilde{N}(\rho)$ is calculated according to the minimum negative sound pressure $\tilde{p}(\rho)$ in a cycle, which satisfies[12–14]

$$\tilde{N}(\rho)=\frac{N_{\max}}{2}\Big[1+\tanh\Big(\frac{P_{\rm th}-\tilde{p}(\rho)}{\Delta P}\Big)\Big], \tag{6}$$

where $N_{\max}$ is the maximum bubble number density in liquids, ΔP decides the slope of the increasing stage, and $P_{\rm th}$ is the cavitation threshold varying with liquid temperature. Furthermore, the number density of bubbles will change if we adjust the temperature.

The other parameters used in the simulation are $f=28\,{\rm kHz}$, $R_0=5\,\mu{\rm m}$, $\gamma=1.4$, $\Delta P=1\,{\rm bar}$, $N_{\max}=9\times10^4{\rm m}^{-3}$, $P_0=1.013\,{\rm bar}$, $p_{\rm d}=2.7\,{\rm bar}$, and $\mu=3.4\,{\rm m}^{-1}$. Meanwhile, we take different disk radii L to simulate. The distribution of sound pressures with distance is shown in Fig. 4.

The imploding acoustic wave in Fig. 4(a) shows that the sound pressure at the center is higher than the driving sound pressure in a small disk. From Fig. 4(b) we can find that there is a critical radius at which the driving sound pressure is equal to the sound pressure at the center of the disk when we increase the radius of the disk. However, if the disk radius continues to be increased, the sound wave will not be able to implode at the center, as shown in Fig. 4(c). To improve the uniformity of the acoustic cavitation field, we adjust the temperature of water at different positions to change the cavitation threshold, so as to match the sound field produced by the annular sound source, as shown in Fig. 4(c). It can be seen that the sound pressure at the center of the disk is higher than the cavitation threshold here, thus cavitation can occur and the uniformity of the cavitation field is improved.

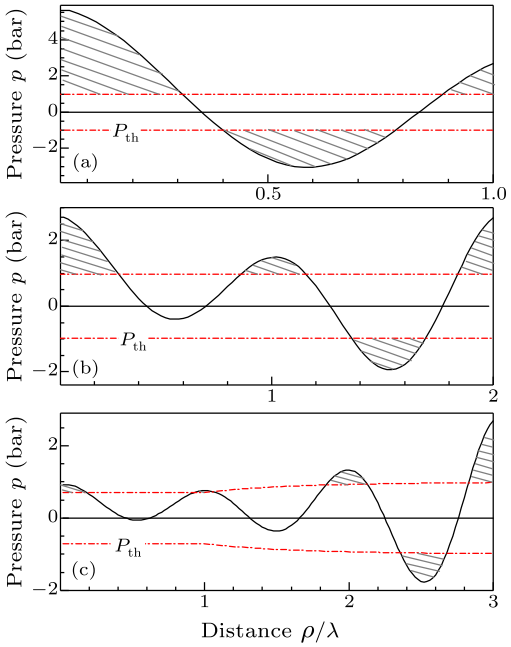

Fig. 4. Sound pressure distribution. The dotted line represents the distribution of cavitation threshold and the shadow indicates cavitation region at this time.

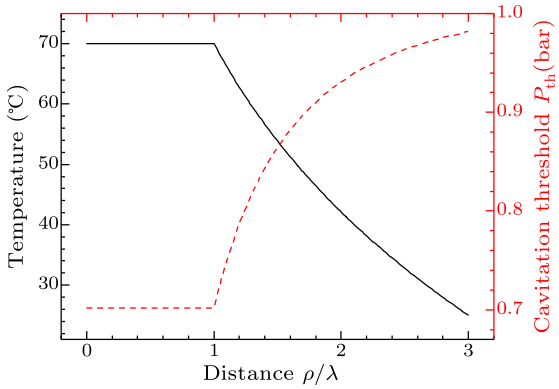

Fig. 5. Temperature and cavitation threshold distributions.

The imploding ability of a ring source is limited. Based on the theory that the cavitation threshold is approximately equal to the standard atmospheric pressure minus the saturated vapor pressure, we set the ambient temperature to 25℃ and put the hot plate under the center of the disk until the central temperature is 70℃. Since the detailed distribution of temperature is not the focus of this work and has little effect, we use COMSOL simulation instead of the experimental measurement. Moreover, we take the center of the disk as the origin, and the COMSOL simulation values of the radial temperature distribution are shown in the solid line of Fig. 5. The dotted line in Fig. 5 reflects the cavitation threshold $P_{\rm th}(\rho)$ of the water at different locations. From Figs. 4 and 5 we can find that the region with no cavitation can eventually be cavitated by increasing the temperature and the uniformity of the cavitation field is finally improved.

In summary, it is verified by numerical simulation that under the same conditions, the imploding abil-

ity of an annular sound source is negatively correlated with the radius. The larger the radius, the weaker the imploding ability; the smaller the radius, the stronger the imploding ability. On this basis, we propose a method to change the cavitation threshold of the liquid by temperature, which effectively improves the uniformity of the cavitation field.

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