Research on cavitation pulsation characteristics under liquid breakdown mechanism

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Abstract. The SGR series solid-state laser system with adjustable pulse energy is adopted. The system uses solid-state Nd: YAG laser to generate laser cavitation in distilled water, High speed camera is used to observe the pulsation process of laser cavitation in distilled water, and candy algorithm is used to detect the edge of cavitation, extract the edge features of cavitation, calculate the circumference of the edge of cavitation, and analyze the pulsation characteristics of cavitation in distilled water. The results of laser acoustic signal collected by hydrophone, high-speed photography and MATLAB image analysis are compared, and the initial expansion of cavitation is in different stages It is concluded that the initial expansion rate and the final pulsation rate of the cavity are faster.

Keywords: laser cavitation, high speed photography, candy algorithm, edge detection, laser acoustic signal, pulsation rate.

1. Introduction

Cavitation erosion caused by cavitation is always the core problem in the field of hydraulic machinery, which seriously limits the development of hydraulic machinery. The harm of cavitation to hydraulic machinery is mainly as follows: destroy the continuity of liquid flow, reduce the efficiency of hydraulic machinery; produce cavitation, damage the surface morphology of runner; produce radiation cavitation noise, aggravate the vibration problem of hydraulic machinery and bring noise pollution. Cavitation phenomenon has brought many adverse effects to human production and life, so it has become a hot issue for people to study. Vogel et al. [1-3] used high-speed photography technology to calculate that when the bubble pulsation shrinks to the minimum bubble radius of 50 \( \mu \)m, the amplitude of sound pulse intensity produced reaches 6 GPa. Thornycroft et al. [4] have shown that when the propeller is running underwater, the water pressure in the local area of the water will be reduced, and a large number of bubbles will be produced. Under the action of water pressure, the bubbles will expand and contract periodically, and finally collapse and collapse. The bubble collapse is the cause of vibration. This is the first time in history to make a reasonable explanation for the cavitation phenomenon. In China, Huang Jingquan [5-9], Huang Jitang [10-11], Qi Dingman [12], Xia Weihong [13] and others considered the influence of surface tension, gas content, gas core composition, liquid viscosity and other factors on cavitation growth and collapse, as well as cavitation noise. The results are in good agreement with those of classical calculation.
At present, there are few literatures on the research of the pulsation characteristics of laser cavitation in water by using image processing technology. The use of intense pulse laser to break down the liquid medium has the characteristics of good symmetry and controllability. The data analysis of high-speed photography with regular shape is carried out by using candy algorithm. The organic combination of theory and experiment is more conducive to our analysis of laser cavitation. The pulsation characteristics of cavitation in water. The experimental platform of high-speed camera measurement for laser cavitation is established. Aiming at the particularity of underwater high power laser focusing, an experimental system is designed. In this paper, the pulsation characteristics of single laser cavity in free field at initial stage and collapse stage are studied, and the following laws are obtained: the initial expansion and final collapse rate of the cavity is faster; with the expansion of the cavity, the maximum radius becomes larger and the pulsation period becomes shorter; the gas content of the liquid slows down the pulsation speed of the cavity, and the pressure difference between the internal and external environment of the cavity increases, which accelerates the pulsation process of the cavity.

In the experimental study, the cavity can be produced in the flowing liquid, or in the static liquid by ultrasonic, spark laser or other methods. In contrast, the latter is relatively simple and can be solved by mathematical method, and the motion process of cavitation in static liquid can be easily detected by experimental method. Compared with spark bubble and dynamic bubble, the cavity produced by laser has the characteristics of good spherical symmetry, strong controllability and no mechanical deformation. Therefore, this paper will take the laser cavity in still water as the research object, and reveal the dynamic characteristics of single cavity from both theoretical and experimental aspects. Using laser-induced cavitation technology, the relative position of the laser breakdown point and the high-speed camera is set, and the high-speed camera is used to observe the cavitation pulsation at the laser breakdown point. The candy algorithm is used to analyze the experimental results in detail, and the Gaussian filtering method is used to fit the data, and the motion law of the initial and collapse stages of the underwater cavitation is summarized. It can provide a reference for the research on the characteristics of cavitation pulsation under water.

2. Theoretical analysis

2.1. The equation of motion of the cavity is as follows

The academic circles started the theoretical study of cavitation dynamics as early as 1917. Rayleigh [14] was the first to carry out theoretical analysis of cavitation phenomenon. Based on the continuity equation and motion equation of liquid medium, he assumed that the cavity was a vacuum and the pressure at infinity was set as the static pressure $p_\infty$.

The Rayleigh equation is described below. $U$ is defined as the radial component of velocity and $R$ as the radial coordinate from the bubble center. Because the water around the cavity is also an irrotational motion, it is defined $\phi$ as the velocity potential function. The results are as follows:

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial r^2} + 2 \frac{\partial \phi}{\partial r} = 0$$

(1)

$$u = \frac{\partial \phi}{\partial r}$$

(2)

By substituting formula (1) into formula (2), it is concluded that:

$$r \frac{\partial u}{\partial r} + 2u = 0$$

(3)

From the solution of formula (3), it can be concluded that:
\[ \frac{u}{r} = \frac{M}{r} \quad (4) \]

Where \( M \) is a constant. When \( r = R \), the particle velocity on the cavity wall is the velocity of the cavity wall \( \dot{R} \), by substituting this condition into formula (4), we can get: \( M = R^2 \dot{R} \), therefore formula (4) shows that:

\[ u = \frac{R^2 \dot{R}}{r^2} \quad (5) \]

\[ \phi = -\frac{R^2 \dot{R}}{r} \quad (6) \]

Under the condition of incompressible liquid, the motion equation of each particle in liquid is as follows:

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = -\frac{1}{\rho} \frac{\partial p}{\partial r} \quad (7) \]

\( p \) is the liquid pressure, \( \rho \) is the liquid density. By substituting formula (5) into (7), we get the following result:

\[ \frac{\dot{R}}{r^2} + \frac{2 \dot{R}}{r} - \frac{R^2 \ddot{R}}{r^3} = \frac{1}{\rho} \frac{\partial p}{\partial r} \quad (8) \]

In the integral of formula (8) \( r \to (R, \infty) \), we can get:

\[ \frac{\dot{R}}{r} + \frac{2 \dot{R}}{r} - \frac{R^2 \ddot{R}}{2r^4} = -\frac{1}{\rho} \left( p - p_r \right) \quad (9) \]

The equation of motion shown in formula (9) is applied to the cavity wall, that is \( r = R \), the ideal cavity equation of motion (Rayleigh equation) can be obtained:

\[ \ddot{R} + \frac{3}{2} R^2 = -\frac{1}{\rho} \left( p - p_r \right) \quad (10) \]

Where: \( p \) is the ambient pressure at infinity, \( p_r \) is the pressure at the cavity wall. Because the influence of gas content, surface tension, compressibility and other factors on the bubble motion is ignored in the derivation of Rayleigh equation, it can be found that when the bubble shrinks to the minimum radius, the velocity and acceleration of the bubble surface tend to infinity, and there will be no rebound phenomenon, which is inconsistent with the actual situation. However, the motion equation of Rayleigh ideal cavity lays the foundation for the development of cavity dynamics. Plesset modified the Rayleigh equation and obtained the Rayleigh Plesset equation [15] considering the surface tension of the cavity, the viscosity of the liquid and the vapor in the cavity. Considering air content and surface tension, formula (10) can be written in the following form:

\[ \ddot{R} \left( \frac{3}{2} R^2 \right) - \frac{1}{\rho} \left( p_v + p_g - \frac{2\sigma}{R} - p \right) \quad (11) \]
Where: \( p_v \) is the vapor pressure in the cavity; \( p_g \) is the partial pressure of air pressure in the cavity; \( \sigma \) is the surface tension coefficient.

Formula (11) replaces the pressure \( p_g \) on the cavity wall with the following formula:

\[
\sigma = \frac{N T}{R^3} + \frac{2 \sigma}{R} - p_\infty - \frac{f(R)}{R} = 0
\]

Where: \( \sigma \) is the surface tension coefficient. In an ideal state, it can be expressed \( p_g \) as:

\[
p_g = \frac{N T}{R^3}
\]

Where: \( N \) is the gas constant in the cavity and \( T \) is the absolute temperature in the cavity.

By substituting formula (13) into formula (11), we can get:

\[
\frac{\partial f(R)}{\partial R} = \frac{\partial}{\partial R} \left( p_v + \frac{N T}{R^3} - \frac{2 \sigma}{R} - p_\infty \right) = 0
\]

When \( f(R) > 0 \), the cavity tends to expand; when \( f(R) < 0 \), the cavity tends to collapse; when \( f(R) = 0 \), the cavity is in equilibrium:

\[
f(R) = p_v + \frac{N T}{R^3} - \frac{2 \sigma}{R} - p_\infty = 0
\]

The critical radius \( R^* \) of the cavity can be obtained by calculating the derivative of formula (15):

\[
R^* = \sqrt{\frac{3 N T}{2 \sigma}}
\]

By substituting formula (17) into formula (15), \( N T \) can be reduced to the following formula:

\[
R^* = \frac{4 \sigma}{3(p_\infty - p_v)}
\]

Set the ambient temperature as 20\(^\circ\)C, under the condition of standard atmospheric pressure, liquid surface tension \( \sigma = 0.075 N/m \), calculate the relationship between void radius and pressure under different values, and calculate the critical radius, and get the simulation results under different isothermal conditions, as shown in figure (1):
According to the simulation results, the following conclusions can be drawn:

Under the same isothermal condition, when the radius of the cavity $R < R^*$, the small change of the radius of the cavity will lead to a large pressure change. In the original equilibrium state, the liquid around the cavity produces a larger pressure $p_o - p_i > 0$, which compresses the cavity and makes it return to the original equilibrium state;

Under the same isothermal condition, if the cavity radius $R > R^*$, if the cavity radius increases, the pressure difference $p_o - p_i < 0$, the internal pressure of the cavity is greater than the surrounding water pressure, and the cavity expands outward, the radius of the cavity will become larger and larger, resulting in cavitation;

When the radius of the cavity in water is larger than the critical radius, cavitation is easy to occur. With the increase of $NT$, the critical radius increases rapidly, and the size of the cavity increases correspondingly. Therefore, with the increase of external temperature, the radius of cavitation is larger.

2.2. The interaction process and mechanism between laser and liquid

In the process of laser liquid interaction, laser plasma and shock wave will be produced, and its unique physical phenomenon: cavitation. On the one hand, we can understand the physical mechanism of cavitation occurrence and development and the influence of various factors on the cavitation process. On the other hand, it is also the basis of studying the mechanism of cavitation radiation and cavitation erosion. Hydraulic cavitation and acoustic cavitation are two classical cavitation modes. According to Bernoulli’s theorem, we can get the so-called hydraulic cavitation: for objects moving at high speed in liquid (such as the high-speed rotation of ship propeller), the higher the speed is, the lower the pressure is. If the speed of the object reaches a certain limit value, enough to make the liquid gas (or liquid itself) vaporize, then there will be a cavity. When the sound wave passes through the liquid, because the sound pressure is alternating, the positive half period increases the local pressure of the liquid, and the negative half period decreases the local pressure of the liquid. Therefore, when the amplitude of sound pressure reaches a certain limit value (cavitation threshold), a cavity will be formed in the negative half period, which is called acoustic cavitation [16]. No matter what form of cavitation occurs, when the cavitation occurs, the corresponding cavitation dynamics phenomenon is very similar. Firstly, the cavity expands under the pressure difference between the inside and outside of the bubble, which makes the surrounding liquid flow radially. When the bubble pressure drops to the hydrostatic pressure of the surrounding medium, due to the inertia effect, the bubble will continue to expand and do work until it reaches the maximum bubble radius. At this time, because the pressure in the bubble is lower than the equilibrium pressure of the surrounding medium, the surrounding liquid begins to move in the opposite direction, that is, converges to the center, and compresses the bubble to make it shrink continuously, and the pressure in the cavity increases gradually. At the same time, due to the inertia of the liquid, the bubble is "excessively" compressed, so that its internal pressure is
higher than the equilibrium pressure of the surrounding liquid medium again, until the cavity pressure is high enough to prevent the bubble from compressing and reach a new equilibrium. So far, the first cycle of bubble expansion and compression has ended. But at this time, because the pressure inside the bubble is greater than the static pressure of the surrounding medium, the bubble will rebound and experience a second expansion and compression process. This process is often called cavitation pulsation. Due to the high density of water and the existence of inertia, the cavitation in water usually experiences such pulsating process many times. With the decrease of bubble energy and gas (steam) content in bubbles, bubbles collapse and dissipate. At the same time, some shock waves will radiate from the cavity in the process of pulsation. Fig. (3) is a sequence diagram of laser cavitation pulsation in water captured by high-speed photography technology. The duration of each frame is about 5.5 μs.

3. Experimental system
The system structure of the experimental platform for studying the characteristics of laser cavitation pulsation is shown in Figure 1. SGR series solid-state laser system with adjustable pulse energy is used. The system uses solid-state Nd: YAG laser. The main parameters of the output laser are as follows: the output wavelength is 1.064 m, the pulse width is 8 ns, the energy is adjustable, and the pulse energy is controlled at 360 MJ in the experiment. The laser beam is expanded and focused through the optical system. After the laser beam is expanded through the negative lens, the laser convergence angle and aberration elimination are increased, and then the focus quality is improved through the positive lens. The laser is focused in the distillation tank shown in the figure, and the generated laser bubbles are photographed by the high-speed camera. The frame rate of the high-speed camera is set to 180000 frames, and the breakdown point distance is set to 180000 frames 15 cm above the water surface, the photos of cavitation pulsation are stored by computer. The laser radiometer developed by China Academy of Metrology was used to measure the laser pulse energy before the experiment. LR laser energy meter can provide stable and reliable laser energy measurement.

Figure 2. Experimental system.
Fig. (3) is a picture of cavitation pulsation taken by a high-speed camera. At the laser focus, when the laser energy density exceeds the breakdown threshold of water, the laser breaks down and forms plasma, which expands to form pulsating cavitation. In the experiment, the position of the high-speed camera is adjusted by the micro adjustment platform to ensure a better observation of cavitation pulsation. The high-speed camera is FastCAM sa1.1 with a frame rate of $1.8 \times 10^5$ frame / s. The special light source enters into the lens of the high-speed camera through glass fiber reinforced plastic to fill the light. In order to further ensure the quality of photos, a high-speed camera fine-tuning platform is adopted. The fine-tuning platform can fine tune in the horizontal and vertical directions, and the fine-tuning accuracy is ensured by adjusting the knob.
4. Experimental results and analysis
When the high power laser is focused on distilled water, plasma will be produced in the focusing region. The high pressure acoustic pulse radiated by the bubble in the collapse stage is the result of the intense contraction inside the bubble. At the same time, with the shock wave and bubble jet phenomenon, the energy of the bubble is gradually consumed in the process of movement, which makes the amplitude of the acoustic signal gradually decrease and the movement period gradually shorten. The cavity produced by laser breakdown does not disappear after expanding to the maximum radius, but after several cycles of expansion and compression. From the photos taken by high-speed camera, it can be seen that there are many pulsating processes from the generation to the final disappearance of laser cavitation in liquid. The causes of cavitation pulsation are as follows:

(1) The pressure difference between the inside and outside of the laser cavity causes the expansion of the cavity, which promotes the liquid flow around the cavity. The pressure in the bubble decreases with the expansion of the bubble. When the pressure drops to the hydrostatic pressure of the surrounding medium, the cavity will continue to expand due to the inertial effect of the liquid, and expand to the maximum volume for the first time, with a regular spherical shape.

(2) When the cavity reaches the maximum volume, the pressure in the cavity is lower than the equilibrium pressure of the surrounding liquid. At this time, the surrounding liquid moves in the opposite direction and converges to the center. At the same time, it compresses the cavity to make it shrink continuously, and the pressure in the cavity increases gradually. At the same time, due to the inertia of the polymerization liquid flow, the internal pressure is higher than the surrounding equilibrium pressure again until the pressure in the cavity is high enough to prevent the cavitation compression and reach a new equilibrium.

(3) Because the pressure inside the bubble is larger than the static pressure of the surrounding medium, the cavity expands again and radiates the shock wave, completing the second expansion and compression process.

(4) After the cavity continues to expand and compress for many times, it disappears in the liquid. In the second expansion process of the laser cavity in distilled water, it will become two cavities. At this time, the cavity is no longer spherical, and the cavity will eventually merge into a cavity. After that, it will undergo two pulsating processes, and finally collapse and dissipate in water.

The hydrophone can be used to measure the period of cavitation pulsation. Compared with the results of high-speed camera experiment and acoustic signal simulation, it can be seen that the shock wave radiates outward at the beginning of the bubble pulsation and at the end of each collapse. The shock wave attenuates into an ordinary underwater sound wave after transmitting for a short distance. At this time, the sound wave can be measured by the hydrophone, and the corresponding pulsation period can be obtained according to the time interval between the two shock waves. As shown in Fig.
3 (a), Fig. 3 (d), Fig. 3 (E) and Fig. 4, the bubble pulsation time measured by hydrophone is basically consistent with the time recorded by high-speed camera; the sound energy of cavitation plasma shock wave is larger than that of the first collapse shock wave, while that of the second collapse shock wave is smaller, which is similar to that of the second collapse shock wave observed in high-speed photography experiment. The energy attenuation of cavitation is more and more in the process of pulsation, which is consistent with the fact that there is no obvious shock wave signal. The Fourier transform analysis of the laser acoustic signal in figure (4) shows that figure (5) is the spectrum of the laser acoustic signal. It can be seen that the spectrum of the laser acoustic signal is very wide, about 400kHz, which corresponds to the characteristics of narrow pulse width in the time domain.

Figure 4. Laser acoustic signal.

Figure 5. Laser acoustic spectrum.

The regular photos in the process of cavitation pulsation are selected, and the edge extraction of candy algorithm is used to calculate the perimeter. MATLAB software is used to simulate and analyze the obtained curve. After Gaussian filtering, figure (6) is obtained. Through the curve, it is obvious that the speed of cavitation expansion and final compression is faster at the beginning, which is due to the power density of laser pulse in the focus area at the initial stage. When the pressure is higher than...
the breakdown threshold of the liquid, the high temperature and high pressure plasma is formed in the focus area of the beam. At this time, the pressure inside the cavity is higher, so the expansion speed is faster. When the expansion reaches the maximum value, the pressure inside the cavity is lower than the pressure of the surrounding liquid due to the energy loss inside the cavity. At this time, the cavity begins to contract. With the further loss of the energy in the cavity, the pressure inside the cavity further decreases, and the cavity becomes smaller. The compression rate is further accelerated.

![Figure 6. First expansion pulsation rate of cavitation.](image)

5. Conclusion
The regular photos in the process of cavitation pulsation are selected, and the edge extraction of candy algorithm is used to calculate the perimeter. MATLAB software is used to simulate and analyze the obtained curve. After Gaussian filtering, figure (6) is obtained. Through the curve, it is obvious that the speed of cavitation expansion and final compression is faster at the beginning, which is due to the power density of laser pulse in the focus area at the initial stage. When the pressure is higher than the liquid breakdown threshold, the high temperature and high pressure plasma is formed in the focus area of the beam. At this time, the pressure inside the cavity is higher, so the moving speed is faster. When the expansion reaches the maximum value, the pressure inside the cavity is lower than that of the surrounding liquid due to the energy loss inside the cavity. At this time, the cavity begins to contract. With the further loss of the energy in the cavity, the pressure inside the cavity further decreases, and the cavity becomes smaller. The speed of the movement is further accelerated.

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