Quantitative evaluation of the microjet velocity and cavitation erosion on a copper plate produced by a spherical cavity focused transducer at the high hydrostatic pressure

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\begin{abstract}
Cavitation erosion at the high hydrostatic pressure causes the equipment to operate abnormally for the huge economic losses. Few methods can quantitatively evaluate the cavitation erosion intensity. In order to solve this problem, the cavitation erosion on a copper plate was carried out in a spherical cavity focused transducer system at the hydrostatic pressure of 3, 6, and 10 MPa. Meanwhile, the corresponding cavitation threshold, the initial bubble radius, and the microjet velocity in the ultrasonic field are theoretically analyzed to determine the dimension and velocity of microjet based on the following hypotheses: (1) the influence of the coalescence on the bubble collapse is ignored; (2) the dimension of the microjet is equal to the largest bubble size without the influence of gravity and buoyancy. Using the Westervelt equation for the nonlinear wave propagation and the Johnson-Cook material constitutive model for the high strain rate, a microjet impact model of the multi-bubble cavitation was constructed. In addition, through the analogy with the indentation test, an inversion model was proposed to calculate the microjet velocity and the cavitation erosion intensity. The microjet geometric model was constructed from the dimension and velocity of the microjet. The continuous microjet impact was proposed according to the equivalent impact momentum and solved by the finite element method. The relative errors of the pit depth are 4.02\%, 3.34\%, and 1.84\% at the hydrostatic pressure of 3, 6, and 10 MPa, respectively, and the relative error in the evolution of pit morphology is 7.33\% at 10 MPa, which verified the reliability of the proposed models. Experimental and simulation results show that the higher the hydrostatic pressure, the greater the pit depth, pit diameter, the pit-to-microjet diameter ratio, and the cavitation erosion intensity, but the smaller the pit diameter-to-depth ratio. The cavitation erosion intensity becomes significant with the ongoing ultrasonic exposure. In addition, a comparison of the cavitation pit morphology in the microjet pulsed and continuous impact modes shows that the continuous impact mode is effective without the elastic deformation caused by the residual stress. Using the cavitation pit morphology at the different hydrostatic pressures, the microjet velocity can be estimated successfully and accurately in a certain range, whose corresponding errors at the lower and upper limit are 5.98\% and 0.11\% at 3 MPa, 6.62\% and 9.14\% at 6 MPa, 6.54\% and 5.42\% at 10 MPa, respectively. Our proposed models are valid only when the cavitation pit diameter-to-depth ratio is close to 1. Altogether, the cavitation erosion induced by multi-bubble collapses in the focal region of a focused transducer could be evaluated both experimentally and numerically. Using the cavitation pit morphology and the inversion model, the microjet velocity in a certain range could be estimated successfully with satisfactory accuracy.
\end{abstract}

1. Introduction

Acoustic cavitation is a nonlinear dynamic process induced by ultrasound. In the acoustic field, cavitation bubbles in the liquid repeatedly expand and collapse violently \cite{1}, resulting in localized and transient high temperature and pressure (i.e., up to several 1000\degree C and...
100 MPa at a hydrostatic pressure of 0.1 MPa, respectively) [2]. Cavitation has been applied widely in ultrasonic honing [3], ultrasonic cleaning [4], material synthesis [5], etc. When the cyclic impact intensity from the bubble cavitation near a solid wall exceeds the material threshold, such as the yielding stress or ultimate strength of the material, the local damage will occur [6,7]. Such a phenomenon has become a research hotspot in aviation, navigation, shipbuilding, and chemical engineering. Especially in the field of hydraulic machinery, valves, and ship propellers, it causes extremely severe damages for the very high repair costs, 150 billion yuan in China [8].

The research of cavitation corrosion mainly focuses on the interconnection between cavitation bubbles and the material. Kato et al. [9] used the experimental data of the cavitation generation rate, bubble distribution/ collapse, and impact force/pressure distribution to predict the degree of cavitation damage. Fortes et al. [10,11] performed the cavitation load assessment by combining a cavitation erosion test and an inverse iterative finite element model, which provides a theoretical basis for the inversion of cavitation impacting load according to the cavitation pit morphology data. Tzanakis et al. [12] determined the hydrodynamic shock pressure generated by the implosion of a single cavitation bubble. Dular’s research on cavitation erosion at different temperatures revealed that the trend of cavitation corrosion can be predicted effectively by using the microjets [13]. The study on the impact of a microjet caused by laser-induced bubble collapse on a metallic copper surface found that the liquid-jet was the main damage mechanism in cavitation erosion [14]. Pain et al. [15] studied the jet flow induced by a nearby cavitation bubble and discovered its speed up to 250 m/s. Ye et al. [16] constructed a microjet impact model for a single cavitation bubble with the inversely obtained microjet velocity of about 310–370 m/s. Besides, a numerical method by coupling the computational fluid dynamics (CFD) and the cavitation model was proposed for the prediction of cavitation erosion [17].

In the above work, cavitation erosion occurred only at the ambient pressure. Previous research has indicated that at the high hydrostatic pressure range of 20 MPa to 110 MPa the shock wave intensity is between 43 MPa and 5.6 GPa, more severe cavitation than that at the ambient pressure [18-23]. In addition, the influence of multiple cavitation bubbles on the cavitation erosion evaluation model was not considered in the current researches. Driven by ultrasound, multi-bubble cavitation activities occur randomly in the location where the acoustic pressure is beyond the cavitation threshold, and therefore, cavitation erosion caused by them is more severe and complicated than that of a single bubble [23]. In order to clarify the multi-bubble cavitation phenomenon under high hydrostatic, we conducted a tungsten wire fracture test, studied its fracture process, and analyzed the macro- and micro-morphological characteristics [26]. Our results indicated that (1) the higher cavitation intensity, the shorter the fracture time; (2) the fracture caused by acoustic cavitation was different from the mechanical fracture and can be used to evaluate the cavitation erosion intensity; and (3) the greater the ultrasonic irradiation power and hydrostatic pressure, the greater the sonoluminescence intensity and the stronger the cavitation erosion. However, only qualitative analysis is available at the current stage.

In this study, we intend to obtain quantitatively analyze the cavitation erosion at high hydrostatic pressure. A microjet impact model produced by multi-bubble cavitation was proposed. In the analogy with the indentation test, a microjet velocity inversion model was developed to predict the microjet velocity from which the cavitation erosion intensity at the different hydrostatic pressures was evaluated. Finally, numerical simulation and experiment results were compared to verify the reliability of the proposed model.

2. Materials and methods

2.1. Cavitation erosion experiment

2.1.1. Experimental setup
A spherical cavity focused transducer [24] (Chongqing Haifu Technology Co., Ltd, Chongqing, China) with an inner diameter of D = 480 mm and two open ends (opening aperture of d = 219 mm and the height of H = 427 mm) was used to induce the serious bubble cavitation (see Fig. 1). The interior surface of the transducer is mounted by a total of 48 pieces of high-power piezoelectric ceramics. The transducer was excited at one of its spherically symmetric eigen-frequencies at about 600 kHz [25,26]. The signal generator, power amplifier (the maximum power output of 100 kW), and impedance matching box were used to generate the signal, amplify the signal, and match the electrical impedance of the transducer, respectively. The three-axis mechanically scanning module has a spatial resolution of 10 μm, and its motion was controlled by a LabView (National Instruments, Austin, TX) program. The water treatment module was for degassing the aqueous solutions during the experiment. The chamber was filled with degassed water whose oxygen content (<0.8 mg/L) was measured by a dissolved oxygen meter (YSI Pro20i, Yellow Springs, OH) and then pressurized to a certain hydrostatic pressure (up to 10 MPa) which was determined by an automatic pressure measurement unit (SUP-XT-70, Jinan Super Technology Co. Ltd., Jinan, Shandong, China) and data acquisition software (SUPV 1.0, Zhejiang Siming Technology Co. Ltd., Siming, Zhejiang, China).

2.1.2. Acoustic pressure on the transducer surface
It is necessary to determine the acoustic pressure on the surface of spherical cavity focused transducer in the experiment and consequently use it in the numerical simulation. The electric-to-acoustic conversion efficiency of all piezoceramic elements, which were fabricated using the same material under the same processing protocol, is assumed to be identical [41]. Thus, a concave transducer with a curvature radius of 240 mm and aperture size of 95 mm made of the same piezoelectric material was used for the measurement. According to the International Electrotechnical Commission (IEC) standards of 62555-2013 and 1088-2001 for ultrasonic transducer measurement, an electric power meter (R&S NRT, Rohde & Schwarz GmbH, Muenchen, Germany) and a radiation force balance (Chongqing Haifu Technology Co., Ltd, Chongqing, China) was used to measure the forward electric power P_f, the reflected electric power P_r, and the output sound power P_s, respectively. Thus, the electric-to-acoustic conversion efficiency of the transducer, η_{FA}, is determined as:

$$\eta_{FA} = \frac{P_s}{P_f} \times 100\% = \frac{P_s}{P_f - P_r} \times 100\%$$  (1)

where P_f is the net input electrical power to the transducer. The acoustic pressure on the transducer surface P_s is given by

$$P_s = \sqrt{2\rho_0 c_s P_f / S} = \sqrt{2\rho_0 c_s P_f \eta_{FA} / S}$$  (2)

where P_0, c_s, and S are the density of water, the speed of sound in water, and the surface area of the concave transducer, respectively.

2.1.3. Pit morphology characterization
Copper plates (Jinjia Metal Materials Co. Ltd., Qinghe, Hebei, China) with the length × width × thickness of 10 mm × 10 mm × 1 mm and purity of 99.999% were used in this study for cavitation erosion. After the metal sample was ground and polished with the abrasive paper of different granularity (400, 800, 1000, 2000, and 3000 mesh), it was aligned at the focal plane under the guidance of a lab-built optical tracking system and then treated at the electrical power output of 2 kW continuously for a certain time up to 1 s at a hydrostatic pressure up to 10 MPa. Afterward, the erosion profile on the surface of the copper plate
was obtained through a scanning electron microscopy (LEO Supra 35, ZEISS, Germany) in a step size of 0.15 μm and a laser confocal microscope (LEXT OLS4000, Olympus, Shinjuku, Japan) with a resolution of 0.5 μm and then smoothed by Gaussian curves in MATLAB (MathWorks, Natick, MA). The row data of the deepest cavitation pit was used as the representative one-dimensional pit morphology. In addition, the dynamic characteristics of the erosion morphology were obtained by gradually increasing the ultrasound exposure time (i.e., 50 ms, 100 ms, 150 ms, 200 ms, 300 ms, 500 ms, 700 ms, and 1000 ms) under the same power output and hydrostatic pressure.

2.2.1. Acoustic field of the spherical cavity focused transducer

The spherical cavity focused transducer has an extremely high focus condition. In a step size of a focused ultrasound transducer, the following hypotheses were made:

\[
\nabla^2 \rho - \frac{1}{c_0^2} \frac{\partial^2 \rho}{\partial t^2} - \frac{1}{\rho_0} \nabla p \nabla \rho + \frac{\delta}{c_0^2} \frac{\partial^2 \rho}{\partial t^2} + \frac{\beta}{\rho_0 c_0^2} \frac{\partial^2 \rho}{\partial t^2} = 0
\]

(3)

where \(\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\) is the Laplace operator, \(\delta = \frac{2\rho_0}{c_0^4}\) is the sound diffusivity, \(\alpha\) is the acoustic absorption coefficient, \(\omega = 2\pi f\) is the angular frequency, \(f\) is the frequency of the acoustic wave, \(\beta = 1 + \frac{2\alpha}{\omega c_0^2}\) is the nonlinear coefficient. The pressure acoustic transient module of COMSOL (v5.2, Burlington, MA) was used to solve the Westervelt equation.

2.2.2. Cavitation threshold

The cavitation threshold \(p_0\) is determined by the hydrostatic pressure \(p_0\) [28]:

\[
p_0 = 1.92p_v + 34.64
\]

Thus, when the acoustic pressure is greater than the cavitation threshold, the nucleated particles will evolve into cavitation bubbles. According to the pressure balance condition on the bubble wall, the relationship between the cavitation threshold and the initial radius of the cavitation bubble is described as [29]:

\[
p_n = p_0 - p_v + \frac{2}{3} \sqrt{\frac{2\sigma}{R_0}}
\]

(4)

where \(p_v\), \(\sigma\) and \(R_0\) are the saturated vapor pressure, surface tension of liquid, and initial radius of a cavitation bubble, respectively. At the ambient liquid temperature of 20°C, \(p_v = 2.34\text{kPa}\) and \(\sigma = 0.0278\text{N/m}\) [16].

2.2.3. Distribution of microjet velocity

Cavitation bubbles in the focal region periodically collapse by the acoustic excitation [23] and form multiple microjets to hit the metal wall and cause damage to it [30]. The distance between the bubble center and wall is assumed to be the same as the bubble radius [16]. According to the work of Plesset and Chapman [31], the distribution of the microjet velocity is given by:

\[
v(x, y, z) = 8.97 \sqrt{\frac{p_0 + p(x, y, z) - p_v}{\rho_0}}
\]

(6)

where \(p(x, y, z)\) is the acoustic pressure at the position of \((x, y, z)\).

2.2.4. Hypotheses

In order to establish a theoretical model to estimate the strength and distribution of cavitation erosion induced by multiple bubbles at the focal plane of a focused ultrasound transducer, the following hypotheses are made:
2.2.6. Impact model of multi-bubble cavitation

The impact process of the microjet on the metal wall is described briefly as follows [16]. Multiple bubbles located in the focal region of the transducer collapse, and the produced microjets in the different positions almost simultaneously impact the surface of the metal plate around them. Immediately after the impact, the speed of the microjet drops rapidly, and at the same time, a shock wave radiates into the fluid. Because of the presence of the shock waveform, the density of the liquid and the static pressure vary suddenly so that the liquid compressibility plays a major role (i.e., in the disturbed zone). However, the physical properties of the undisturbed medium remain unchanged with negligible liquid compressibility. After the shock wave is isolated by the disturbed and non-disturbed zone, liquid pressure reduces and lateral jet forms. Compared with the impact of a single microjet, that of multiple microjets simultaneously is a more strong and complex short-lived nonlinear fluid–solid coupling phenomenon [16]. Therefore, a three-dimensional mathematical model of microjet impingement was established to study the impact process of the microjet and the evolution of pit morphology. The i-th microjet (i = 1, 2, ..., N, where N is the total number of microjets) impacts the wall with the initial velocity of √2, the acoustic period, ultrasonic exposure time, actual impact time in the pulsed mode, and continuous impact time of the microjet, respectively (see Fig. 2).

\[
\begin{align*}
\rho_i &= \rho_0 + \rho' \\
p_i &= p_0 + p' 
\end{align*}
\]

where \(v_i, \rho_i, \) and \(p_i\) are the velocity, density, and pressure caused by fluid compression of the shock wavefront, respectively. Based on the momentum equation, continuity equation, and state equation of the fluid, the disturbed zone can be described as [16],

\[
\begin{align*}
\frac{\partial \rho'_i}{\partial t} + \nabla \cdot (\rho'_i v'_i) &= 0 \\
\rho'_i \left( \frac{\partial v'_i}{\partial t} + v'_i \cdot \nabla v'_i \right) + \nabla p'_i &= 0 \\
\rho'_i &= \left( \frac{\partial \rho'_i}{\partial p'_i} \right)_S
\end{align*}
\]

Fig. 2. Illustration of (a) the pulsed impact and (b) continuous impact mode of microjets with the equivalent acting time on the metal material in the numerical model.
where $\nabla = \frac{\partial}{\partial x} + \hat{\mathbf{e}}_j \frac{\partial}{\partial j} + \hat{\mathbf{e}}_k \frac{\partial}{\partial k}$ is the differential operator, $(\cdot)'$ represents the isentropic condition.

Compared with the water hammer pressure generated by the impact of microjet in the disturbed zone, the viscosity, surface tension, and gravity of the liquid are too small to be considered. Moreover, since the microjet impact is strong and short-lived, the other influences (i.e., acoustic pressure) can also be ignored. The water hammer pressure in the disturbed zone is so large that the nonlinear, as well as the acoustic attenuation effects, must be considered [23,34]. Combining Eqs. (7) and (8), we can describe the liquid velocity in the disturbed zone [27,34],

$$\nabla^2 v^i_j = \frac{1}{\rho_0} \frac{\partial^2 v^i_j}{\partial t^2} - \frac{\delta}{\rho_0} \frac{\partial v^i_j}{\partial t} + \frac{\beta}{\rho_0 c^4} \frac{\partial^4 v^i_j}{\partial t^4} = 0 \quad (9)$$

In the solid wall domain, the Lagrange method is used to describe the mechanical properties of the material. Considering that the material is impacted by the microjet in the z-direction (perpendicular to the material surface), the motion equation is:

$$\rho_s \frac{\partial^2 U_{i,j}}{\partial t^2} + \nabla^2 \sigma_{ij} = 0 \quad (10)$$

where $\rho_s$ is the density of solid, $U_{i,j}$ and $\sigma_{ij}$ represent the displacement and stress caused by the $i$-th microjet, respectively. Because the solid material undertakes the significant short-term high-intensity impact from the microjet, the strain rate of the material must be sufficiently large for the simulation of material deformation. The Johnson-Cook material constitutive model (J-C constitutive model) was used to describe the deformation process of the solid [33]. Compared with high-temperature thermal strain, the impacting duration of the microjet is extremely short, the response time of the material to the mechanical strain is faster than that to the thermal strain, and the thermal softening effect has less effect on the plastic deformation of the material than the hardening effect caused by the microjet. Therefore, considering the microjet as the main mechanism of cavitation erosion and ignoring the effect of high temperature generated by the collapse of cavitation bubbles and subsequently, the thermal softening effect, the J-C constitutive model is given by,

$$\sigma_e = \left( \sigma_0 + B \varepsilon_e \right) \left( 1 + C \ln \left( \varepsilon_e / \varepsilon_0 \right) \right) \quad (11)$$

where the equivalent stress, equivalent strain, yield strength, equivalent strain rate, reference strain rate are expressed as $\sigma_e$, $\varepsilon_e$, $\sigma_0$, $\varepsilon_0$, and $\dot{\varepsilon}_0$, respectively, the strain hardening and strain rate hardening parameters are given by $B$, $n$, and $C$, respectively. In this study, the parameters of copper material in the J-C constitutive model are listed in Table 1 [33].

Combining Eqs. (9) and (10) with the initial and boundary conditions, the multi-microjet impact model is derived:

$$\begin{cases}
\sum_{i=1}^{N} \nabla^2 v^i = -\frac{1}{\rho_0} \frac{\partial^2 v^i}{\partial t^2} - \frac{\delta}{\rho_0} \frac{\partial v^i}{\partial t} + \frac{\beta}{\rho_0 c^4} \frac{\partial^4 v^i}{\partial t^4} = 0 \\
\text{initial condition: } \sum_{i=1}^{N} v^i \bigg|_{t=0} = 0 \\
\text{boundary condition: } \sum_{i=1}^{N} \frac{\partial v^i}{\partial t} \bigg|_{z=0} = 0 \\
\end{cases} \quad \text{liquid}$$

$$\begin{cases}
\sum_{i=1}^{N} (\rho_s \frac{\partial^2 U_{i,j}}{\partial t^2} + \nabla^2 \sigma_{ij}) = 0 \\
\text{initial condition: } \sum_{i=1}^{N} U_{i,j} \bigg|_{t=0} = 0 \\
\text{boundary condition: } \sum_{i=1}^{N} \sigma_{ij} \bigg|_{z=0} = \sum_{i=1}^{N} p_i \bigg|_{z=0} \\
\end{cases} \quad \text{solid} \quad (12)$$

The above-mentioned three-dimensional fluid–solid coupling model describing the impact of microjets is a strongly nonlinear model so that it is difficult to directly obtain the analytical results. To solve this problem, we constructed a microjet geometric model using the parameters determined by Eqs. (11) and (12) and the fluid–solid coupling model and then calculated the cavitation pit morphology characteristics using the derived microjet velocity.

![Fig. 3. The simulated distribution of (a) peak positive and negative acoustic pressure (the red, blue, and black dashed lines represent the cavitation thresholds at the hydrostatic pressure of 3, 6, and 10 MPa, respectively) at the focal plane of the spherical cavity focused transducer at the electrical output power of 2 kW and frequency of 600 kHz and (b) the corresponding distribution of microjet velocity at the different hydrostatic pressures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
2.2.7. Microjet velocity inversion model

In order to evaluate the cavitation erosion intensity, the pit morphology characteristics were used to predict the microjet velocity using an inversion model. In nano-indentation experiments, an inversion model is constructed for the quantitative analysis of the impact load using the produced pits morphology and the constitutive model [35,36]. Since the cavitation erosion pits induced by the microjet impact are similar to those in the nano-indentation experiment. Therefore, a similar model of the microjet impact load can be applied for the inversion analysis of the microjet velocity. Under the condition that the cavitation pit diameter is much larger than the cavitation pit depth and the ratio of the cavitation pit-to-microjet diameter is close to 1, the characteristics of the cavitation pit can be obtained from the pit geometry and the plastic strain field utilizing the analogy between the material deformation under the microjet impact and the spherical indentation [35]. The detailed description of the indentation is referred to [37]. The indentation stress \( \sigma \) can be expressed as [36],

\[
\sigma = \frac{1}{\psi} \frac{L}{A}
\]  

(13)

where \( L \) is the indentation load over the projected area \( A \), \( \psi \) is the dimensionless constraint factor which is 2.87 for the indentation with pure plastic deformation [38].

The stress–strain relationship on the surface of the metal material can be characterized by the J-C constitutive model in Eq. (11) by replacing \( \varepsilon \) with \( \varepsilon_p \). The indentation strain \( \varepsilon_p \) is determined by the cavitation pit depth and diameter

\[
\epsilon_p = 0.2 \frac{H_D P}{\left( \frac{\mu}{\pi} \right)^2} + H_p^2
\]  

(14)

where \( D_p \) is the pit diameter, \( H_p \) is the pit depth. According to Eqs. (11) and (14), the stress, \( \sigma_p \), imposed into the cavitation pit is expressed as,

\[
\sigma_p = (\sigma_0 + B \varepsilon_p)^\left(1 + C \ln\left( \frac{\varepsilon_p}{\varepsilon_0} \right) \right)
\]  

(15)

Thus, the impact load is given by [38],

\[
L_p = \psi \sigma_p A_p
\]  

(16)

where \( A_p \) is the deformed area of the cavitation pit. On the other hand, the indentation load is represented as,

\[
L = \frac{\sigma_p D^2}{4}
\]  

(17)

where \( D \) is the indentation diameter. Assuming that the impact load of the indentation in the stress analysis is the same as that of the microjet, \( L = L_p \), and \( D_1 \) is the diameter of the microjet (\( D_2 \geq D_0 \)). Thus, the hydrodynamic pressure impact \( \sigma_p \) is given by,

\[
\sigma_p = \frac{4L_p}{\pi \varepsilon_p D_1^2}
\]  

(18)

Finally, according to the relationship between \( \sigma \) and the jet speed \( v_j \) described in [12], \( v_j \) can be expressed as,

\[
v_j = \frac{\sigma_p}{\rho c_0} + \frac{\rho c_0}{\rho c_s}
\]  

(19)

where \( c_s \) is the sound speed of the metal material.

2.2.8. Error analysis

In this study, the errors in the analysis or estimation are determined in a second-order form:

\[
\text{error} = \left\| \frac{M_{\text{actual}} - M}{M_{\text{actual}}} \right\|_2 \times 100\%
\]  

(20)

where \( M_{\text{actual}} \) and \( M \) are the actual value and calculated/estimated value, respectively, \( \| \|_2 \) represents the second-order norm.

3. Results

3.1. Comparison of the simulation and experiment

The electric-to-acoustic conversion efficiency of the concave transducer was measured to be 57.94%. Thus, the acoustic pressure on the transducer surface at the driving electric power of 2 kW was 0.1245 MPa. The distribution of positive and negative acoustic pressure distribution in the focal region of the spherical cavity focused transducer obtained by solving the Westervelt equation is shown in Fig. 3a. Because the \(-6 \, \text{dB} \) acoustic beam width of the spherical cavity focused transducer is sub-wavelength, 1.07 mm = 0.41\( \lambda \), where the wavelength \( \lambda = 2.6 \, \text{mm} \) at the frequency of 600 kHz, the acoustic energy is concentrated into a confined region. In addition, literature [24] verifies the reliability and accuracy of the acoustic field calculation approach. The dimension and velocity distribution of the microjet was then calculated from the simulated acoustic field (see Fig. 3b). The diameters of the microjets at the hydrostatic pressure of 3, 6, and 10 MPa are 115.10 \( \mu \text{m} \), 72.34 \( \mu \text{m} \), and 51.48 \( \mu \text{m} \), respectively. The corresponding spatial ranges of the multi-microjets taken as the diameter of the overall induced bubbles at the focal plane are 0.982 mm, 0.832 mm, and 0.630 mm shown as the red, blue, and black dashed lines in Fig. 3a, respectively.

At the excitation power to the transducer of 2 kW and exposure time of \( T = 1 \, \text{s} \), a strong cavitation effect under high hydrostatic pressure can be induced. A representative two-dimensional pit morphology on the surface of the copper plate is shown in Fig. 4. The cavitation pit depth under 3, 6, and 10 MPa are 64.68 \( \pm \) 3.25 \( \mu \text{m} \), 155.06 \( \pm \) 7.48 \( \mu \text{m} \), and 342.23 \( \pm \) 5.77 \( \mu \text{m} \), respectively. The one-dimensional distribution of the pit morphology was obtained by extracting the pit morphology data.

According to hypothesis (4), in the continuous impact mode, the impact time \( T_{\text{continuous}} = 0.6 \, \mu \text{s} \) under the conditions of \( T = 1 \, \text{s} \), \( f = 600 \, \text{kHz} \), and \( T_{\text{pulsed}} = 1 \, \text{ps} \). The microjet impact model constructed in the Section 2.2.6 was calculated by the finite element method (FEM) to simulate the morphology of a one-dimensional cavitation pit. Among the 12 sets of testing results, a one-dimensional cavitation pit depth distribution result that is the closest to the average value is compared with the numerical simulation (see Fig. 5). Taking the measurement result as the actual value, the relative errors of the pit depth at the hydrostatic pressure of 3, 6, and 10 MPa in the simulation are 4.02%, 3.34%, and 1.84%, respectively. It suggests the feasibility and accuracy of our microjet impact model. From the pit distribution data, the cavitation pit depth, \( H_0 \), the pit diameter, \( D_0 \), the pit diameter-to-depth ratio, \( D_0/H_0 \), and the pit-to-microjet diameter ratio, \( D_0/D_1 \), at the different hydrostatic pressures were obtained and listed in Table 2. It is shown that the velocity and spatial range of the microjet increase with the hydrostatic pressure.

In addition, the evolution of pit morphology, such as the pit depth, in the measurement was also compared with that of simulation (see Fig. 5d). It is shown that with the ongoing ultrasonic exposure up to 1 s, the equivalent collapse time of \( T_{\text{continuous}} = 0.6 \, \mu \text{s} \), the pit depth increases exponentially in both experiment and simulation. The average error between the simulation and experiment is 7.33%, showing the satisfactory performance of the microjet impact model on progressive erosion.

Comparison of the experimental measurement and numerical simulation results proved the reliability of hypotheses (1), (2), and (3). In order to verify the validity of hypothesis (4), the simulated morphological features distribution of the cavitation erosion pit at the hydrostatic pressure of 3, 6, and 10 MPa in the 16.7 ms-pulsed mode (about 10,000 cycles) and 10 ms-continuous mode were compared (see Fig. 5d). It is found that simulation results using these two modes are comparable, the errors (the result in the pulsed mode as the actual value) of the...
overall pit morphology at the hydrostatic pressure of 3, 6, and 10 MPa being 13.05%, 12.87%, and 14.65%, respectively, while those within the pit aperture, are caused by the residual stress-induced plastic deformation [39]. The results show that with the increase of hydrostatic pressure, the pit depth $H_p$ increases from 0.6441 μm to 1.2898 μm and from 0.6348 μm to 1.3942 μm in the pulsed and continuous mode, respectively. In comparison, due to the relatively short ultrasonic exposure time, the influence of the microjet velocity on the pit diameter is smaller than that on the microjet diameter which is 0.982 mm, 0.832 mm, and 0.488 mm at the hydrostatic pressure of 3, 6, and 10 MPa, respectively, causing the pit diameter $D_p$ to decrease with the increase of hydrostatic pressure (from 0.6844 mm to 0.5128 mm and from 0.6160 mm to 0.5401 mm in the pulsed and continuous mode, respectively).

### 3.2 Microjet velocity inversion

The pit diameter and depth obtained experimentally are put into the microjet velocity inversion model to calculate the microjet velocity at different hydrostatic pressures and then to evaluate the cavitation erosion intensity. The estimated microjet velocities at 3, 6, and 10 MPa are 2388.8 m/s, 2162.5 m/s, and 1755.7 m/s, respectively. The reliability and applicable range of the inversion model were further verified and determined in the simulation. Microjet velocity in the range from about 100 m/s to 2500 m/s was set as the input for the inversion model. Moreover, because the simulated cavitation pit morphology is in good agreement with the measured results (the relative error of less than 5%), these microjet velocities are regarded as the actual values for the inversion model. A comparison of the estimated and actual microjet velocities is shown in Fig. 7. If the inversion error is no more than 10%, the inversion model is considered reliable and effective.

Although the diameter of the cavitation pit is much larger than the depth of the cavitation pit at the low microjet velocity, the cavitation pit-to-microjet diameter is much larger than 1, which invalidates the inversion model. When the actual microjet velocity $v_{\text{actual}}$ reaches a certain lower threshold (i.e., 1389.1 m/s, 1165.3 m/s, and 919.9 m/s at the hydrostatic pressure of 3 MPa, 6 MPa, and 10 MPa, respectively, as the black dashed lines in Fig. 7), the cavitation pit diameter-to-depth ratio and the cavitation pit-to-microjet diameter ratio gradually decrease to less than 1000 and around 1, respectively (see Fig. 8), which meets 2 premises of the inversion model [33,35]. With the further increase of the microjet velocity, although the cavitation pit diameter is not much larger than the cavitation pit depth, the cavitation pit-to-microjet diameter ratio is maintained at around 1, which also leads to stable performance of the inversion model. When the actual microjet velocity exceeds a certain upper threshold, i.e., 2380.7 m/s, 2206.8 m/s, and 1749.8 m/s at the hydrostatic pressure of 3 MPa, 6 MPa, and 10 MPa, respectively (the black short-dashed line in Fig. 7), the cavitation pit diameter-to-depth ratio $D_p/D_H$ rebounds from about 1 (see Fig. 8b) and results in its inversion upper limit of the microjet velocity smaller than the others (see Fig. 7). Within the lower and upper limits of the actual microjet velocity, the inversion performance is quite stable and satisfactory, the inversion errors at the upper and lower limit being 5.98% and 0.11% (3 MPa), 6.62% and 9.14% (6 MPa), 6.54% and 5.42% (10 MPa), respectively.

### 4 Discussion

In this study, we proposed a multi-microjet impact model suitable for high hydrostatic pressures, conducted cavitation erosion experiments in an ultrasonic cavitation system composed of a spherical cavity focused transducer with high acoustic energy in a sub-wavelength focal region, and analyzed the impact process of the microjets on a copper plate at the different hydrostatic pressures. It indicates that the relative errors of the pit depth between the measured and simulated results at the hydrostatic pressure of 3, 6, and 10 MPa are only 4.02%, 3.34%, and 1.84%, respectively. In addition, the average error between the evolution of pit morphology in the simulation and experiment is 7.33%, which shows the satisfactory performance of the microjet impact model with the
equivalent continuous collapse time up to 0.6 μs. Finally, based on the analogy with the indentation test, a microjet velocity inversion model was proposed to evaluate the cavitation erosion intensity. It is found that in a certain range of microjet velocity (i.e., 1310.8–2383.2 m/s, 1093.0–2428.8 m/s, and 863.4–1850.1 m/s at the hydrostatic pressure of 3 MPa, 6 MPa, and 10 MPa, respectively), which means the cavitation pit diameter-to-depth ratio is close to 1, the inversion model can estimate the microjet velocity accurately and reliably (i.e., the relative error of no more than 10%).

Table 2
Comparison of the pit morphology characteristics on the copper plate produced by cavitation erosion (D_p: pit diameter, H_p: pit depth, D_j: microjet diameter, D_p/H_p: pit diameter-to-depth ratio, and D_p/D_j: pit-to-microjet diameter ratio) in the simulation and experiment at the hydrostatic pressure of 3 MPa, 6 MPa, and 10 MPa.

| Simulation | Experiment |
|------------|------------|
| 3 MPa | 6 MPa | 10 MPa | 3 MPa | 6 MPa | 10 MPa |
| H_p (μm) | 53.62 | 158.9 | 340.2 | 66.28 | 164.4 | 346.6 |
| D_p (μm) | 852.2 | 907.1 | 1417.5 | 840.0 | 1040.0 | 1395.1 |
| D_p/H_p | 13.4 | 5.7 | 4.2 | 12.7 | 6.3 | 4.0 |
| D_p/D_j | 0.87 | 1.09 | 2.25 | 0.85 | 1.25 | 2.21 |

Fig. 5. Comparison of the simulated and measured one-dimensional pit morphology distribution (r is the lateral distance from the focus) on the surface of a copper plate produced by the cavitation erosion at the hydrostatic pressure of (a) 3 MPa, (b) 6 MPa, (c) 10 MPa and, (d) the evolution of the pit depth at the hydrostatic pressure of 10 MPa (according to hypothesis (4) in Section 2.2.4, the actual impact time T_{pulsed} is converted into the impact time T_{continuous} in the continuous mode up to 0.6 μs).

4.1. Comparison of microjet impact models

In the acoustic field, the gaseous nuclei in the liquid will evolve into multiple bubbles, whose collapse produces more severe cavitation and complicated erosion pattern than a single bubble [23]. Besides, under the high hydrostatic pressure, the shock wave intensity from the microjet impacting on the metal wall is much larger than that at the atmospheric pressure. Unfortunately, the previously established microjet impact model did not consider these two factors, resulting in a large error in the cavitation pit morphology, a large difference in the estimated microjet velocity, and thereby a low evaluation accuracy of the cavitation intensity. Thus, compared with the literature [16], our model has several advantages. Firstly, the proposed microjet impact model includes the effect of multi-bubble cavitation and high hydrostatic pressure. Secondly, the nonlinear and attenuation effects of the shock wave from the microjet impact on the wall surface are considered. Finally, the method of determining the geometric parameters of the microjet is given. It is shown that the pit depth is determined by the microjet velocity and diameter while the pit diameter is mainly relevant to the microjet diameter [16]. However, the impact load of the microjet related to the deformation of the cavitation pit is mainly affected by the microjet velocity (2.98 GPa, 5.37 GPa, 11.2 GPa at the hydrostatic pressure of 3, 6, and 10 MPa, respectively). Overall, the pit depth and diameter are found to be more affected by the microjet velocity than its diameter.

The microjet impact model is constructed under specific hypotheses,
whose validity was verified by comparing the measurement and simulation results, to effectively characterize the cavitation erosion at the high hydrostatic pressure. However, there are some limitations. With the increase of ultrasonic exposure time, fragments of the previously collapsed cavitation bubbles will serve as the nuclei for the following cycles of acoustic excitation. Subsequently, the cavitation bubbles will be enriched \[40\] and proliferate \[41\] into larger ones, which will affect the applicable range of the microjet impact model as well as the accuracy of the pit morphology distribution. Furthermore, the gradually enhanced microjets and shock waves produced by the periodic collapse of cavitation bubbles \[23\] will make the hypothesis of identical impinge on each acoustic excitation period invalid. The buoyancy and gravity cause the cavitation bubbles to deform (not being approximated as the spherical shape) \[42\], and the unreliable hypothesis of microjet shape as a cylinder with a hemispherical head will introduce error to the pit morphology distribution. Finally, only cavitation bubbles at the focal plane are considered here. However, all cavitation activities in the focal region have a contribution to the erosion on the solid material, which makes the microjet impact model more complicated and inevitably affects the accuracy of the pit morphology distribution.

### 4.2. Acoustic cavitation in a sub-wavelength focal region

Compared with the concave transducer, the spherical cavity focused transducer-induced acoustic cavitation has some uniqueness. Firstly, at the resonant frequency of 600 kHz, the focusing gain is much higher (i.e., 1500 vs. 16 at the curvature radius of 112 mm) \[26\] so that the accumulated acoustic energy is much higher for more occurrence of cavitation at the high hydrostatic pressure. Secondly, due to the geometric symmetry of the spherical cavity, a much higher focusing angle reduces significantly the acoustic diffraction effect in the acoustic field and leads to the sub-wavelength focal region \[25\]. Subsequently, the region of cavitation erosion is more confined. Finally, the consequent cavitation erosion intensity is greater due to the concentrated acoustic energy.

### 4.3. Influence of material properties on the pit morphology

The mechanical properties of the material, such as the plasticity, vary dynamically with the microjet impact \[43-45\]. However, the continuous microjet impact suppresses the elastic deformation of the material caused by the residual stress, resulting in a slightly lower pit depth than the experimental results (see Fig. 6). In comparison, in the pulsed mode, the residual stress causes more plastic deformation of the
Fig. 7. Comparison of the estimated and actual microjet velocities in the range from 100 m/s to 2500 m/s at the hydrostatic pressure of (a) 3 MPa, (b) 6 MPa, and (c) 10 MPa. The black dashed and short-dashed lines present the lower and upper microjet velocity thresholds for the reliable inversion with the error of no more than 10%, respectively.

Fig. 8. Comparison of (a) the cavitation pit diameter-to-depth ratio and (b) the cavitation pit-to-microjet diameter ratio at the actual microjet velocity from 100 m/s to 2500 m/s at different hydrostatic pressures of 3 MPa, 6 MPa, and 10 MPa, respectively.
material and consequently the formation of the bulged pit edge. In addition, with the increase of the ultrasonic exposure time, the elastic deformation caused by the residual stress has less and less influence on the cavitation pit morphology distribution (see Fig. 5d, the relative error of pit depth being less than 10%).

4.4. Evaluation of cavitation intensity

The cavitation erosion intensity is evaluated by the shock load \cite{17,46-48}. However, the shock load originates from not only the microjet impact but also the shock waves generated by the bubble collapse. Moreover, in the experiment, such a shock load cannot be accurately measured by a hydrophone which has limited compressive strength and frequency response due to its high intensity and quick attenuation \cite{23}. In contrast, the proposed method of using the microjet characteristics (i.e., microjet velocity) to evaluate the cavitation erosion intensity will not be affected by the secondary physical effects, such as shock waves generated by the bubble collapse. In addition, using the inversion model, the microjet velocity can be obtained only from the cavitation pit morphology which is determined easily and accurately using the confocal laser microscope.

The proposed inversion model is based on the premise that the pit diameter is much larger than the pit depth \cite{33,35} and the cavitation pit-to-microjet diameter ratio is close to 1. Although the first premise is found unavailable in this study, the second one can be maintained, which guarantees the good performance of the microjet inversion model. In addition, as listed in Table 2, both the cavitation pit-to-microjet diameter ratio and the cavitation pit diameter-to-depth ratio at the hydrostatic pressure of 3 MPa satisfy these 2 premises better than the others, resulting in better inversion results.

In summary, the proposed evaluation method is helpful to establish the relationship between the microjet characteristics and the cavitation erosion intensity through the analysis of the cavitation pit morphology. However, the applicable range of the proposed microjet velocity inversion model is also limited. Only when the cavitation pit diameter-to-depth ratio is close to 1, the proposed inversion model can accurately predict the microjet velocity at the high hydrostatic pressure and consequently evaluate the cavitation erosion intensity. Moreover, the inversion model is constructed for the plastic material without its elastic characteristics. In the follow-up work, it is necessary to include the constraint factor \( \psi \) described in Eq. (13) in the inversion model.

4.5. Applications

In the field of aviation, navigation, hydraulic machinery, and shipbuilding, the equipment must have high anti-cavitation capabilities. The proposed model and the investigation results have the potential of predicting the cavitation erosion intensity induced by the instrument or produced naturally at the various conditions (i.e., at the high hydrostatic pressure) and evaluating the anti-cavitation materials or technologies. In the field of chemical engineering, the high-intensity cavitation effect contributes to harsh chemical reactions \cite{49} and improves the efficiency of material synthesis \cite{50}. Moreover, in the field of ultrasound therapy, such as histotripsy \cite{51} and lithotripsy \cite{52}, the cavitation effect is the major mechanism. However, due to the complicated biological structure of the human body and the interaction between the bubble and the therapeutic target, how to quantitatively evaluate the cavitation dose or efficacy of histotripsy or lithotripsy is a great challenge. However, the relationship between cavitation secondary effects (i.e., localized high temperature and pressure microjet) and the ultrasonic energy in the target zone, mechanical deformation of the impacted material should be included and needs further investigation.

5. Conclusions

Aiming at cavitation erosion to the solid material under the high hydrostatic pressure, we firstly performed the cavitation corrosion test of the copper plate in a spherical cavity focused transducer system that can provide high hydrostatic pressure and high acoustic energy. Then under the same conditions as the experiment, we constructed a microjet impact model and a microjet velocity inversion model to quantitatively characterize the cavitation erosion process and cavitation intensity, respectively. The reliability and performance of the proposed models are verified through the comparison between the experimental and simulation results. The results show that the proposed model can effectively characterize the microjet impact on the solid wall produced by the collapse of multiple bubbles at the high hydrostatic pressure. The proposed inversion model is reliable and can quantitatively evaluate the cavitation erosion density at the high hydrostatic pressure only when the cavitation pit diameter-to-depth ratio is close to 1.

CRediT authorship contribution statement

Juipeng Xiong: Investigation, Methodology, Data curation, Visualization, Software, Writing – original draft, Writing – review & editing.
Yalu Liu: Investigation, Data curation. Chenghai Li: Data curation, Software. Yufeng Zhou: Validation, Formal analysis, Data curation, Writing – review & editing. Faqi Li: Conceptualization, Resources, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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