Simulation and experimental study of cavitation region caused by longitudinal and transverse vibration of casting ultrasonic radiator

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Abstract. The dynamic simulation of casting ultrasonic vibration system were studied based on dynamic characteristics of the system and numerical simulation of ultrasonic sound pressure field under different vibration depths in water was performed. According to the simulation results, the cavitation region was estimated, and the experiment of cavitation erosion of aluminum foil in water and amplitude test were done to verify simulation results. The results showed that the longitudinal vibration at the end of face was the major vibration of ultrasonic radiation, while there was a strong vibration on cylindrical surface. Results of amplitude test are consistent with simulation results. Cavitation region caused by ultrasonic vibration mainly below the end face of radiation. The scope and intensity of cavitation were inversely related to the distance from the end face of radiation. With the vibrating depth increased, some small cavitation regions were found at the side of radiation, cavitation region distributed un-continuously below radiation. Cavitation field measurement and simulation results were basically consistent.

1. Introduction
In ultrasonic casting, ultrasonic cavitation generated in the molten metal is considered to be the main reason to promote nucleation and grain refinement. With the effect of the strong ultrasonic wave in melt, sparse acoustic phase and compression phase alternating, based on the above effect, the micro-bubbles would expand, compress, vibrate and eventually collapse, when they collapse, high-intensity shock wave in a very limited volume is produced instantly, prompting to break primary crystal in aluminum alloy melt and increase the number of heterogeneous crystallization nuclei, so that ultrasonic cavitation significantly refine solidification structure [1-4]. In the molten metal, due to high-temperature, internal invisible and high strength chemical changes, there is no effective, quantitative measurement to measure the intensity and range of cavitation. Most of the existing research to test cavitation is in the water [5-7], or observing aluminum alloy solidification treated by ultrasound to characterize the effect of ultrasonic cavitation indirectly.

In this paper, modeling and simulation of ultrasonic vibration system and sound field distribution in water were studied, the sound pressure field distribution in water and the amplitude of longitudinal and
transverse vibration were got. Cavitation region was pre-estimated, amplitude and water cavitation tests verified the simulation results.

2. Simulation of ultrasonic vibration and cavitation region

2.1. Model and parameters

Figure 1 shows the structure diagram of ultrasonic casting system and the finite element model for sound-fluid-temperature coupled field. Ultrasonic system mainly contain sandwich transducer, the first amplitude transformer, the secondary amplitude transformer and radioactive rod. In this paper, the electrodes, connecting bolts dynamic between the amplitude amplifiers and flange in the nodal plane position was ignored because of tiny effects on dynamic characteristics. However, front and rear covers of piezoelectric ceramic transducer and pre-loaded bolts should be taken into account. Fluid field is analyzed at the infinity, and the fluid units are adopted to simulate the acoustic absorbing boundary which extends to infinity in the two-dimensional plane. The fluid field is simulated by the infinite semicircle region. As shown in figure 1(b).

Material of ultrasonic vibration system is shown in figure 1 mainly comprises titanium, aluminum, 45 steel and piezoelectric ceramics PZT-8. The fluid medium is water. As to fluid material, density of water is 1000 kg/m$^3$, sound velocity is 1500 m/s in water.

2.2. Governing equations

2.2.1. Kinetic equation. Structural dynamics analysis based on the following basic equation:

$$M \{\dot{u}\} + C \{\dot{u}\} + K \{u\} = \{F\} \tag{1}$$

$M$, $C$, $K$ are mass matrix, damping matrix and stiffness matrix of the system, $\{F\}$ is load force vector, $\{u\}$ is displacement vector. In this paper, the above matrices and vectors are extended to a more generalized form, so physical problems can be transformed into the same equation form, finally the individual physics problems will be solved as pure mathematics problem.

2.2.2. Sound field control equation. When the ultrasonic wave propagation in the fluid, the sound pressure distribution obey Helmholtz equation[8]:

$$\omega^2 \cdot c^2 P + \Delta^2 P = 0 \tag{2}$$

where $P$ is sound pressure amplitude in fluid, N/m$^2$. Angular frequency $\omega=2\pi f$, $f$ is the vibration frequency of the sound wave, Hz. $c$ is propagation velocity of sound waves in the fluid, m/s. Solution
of the partial differential equations is only connected with $\omega$, $c$ and boundary conditions, as long as those parameters are determined, it will determine the ultrasound field distribution in the region.

2.2.3. The fluid-structure coupling equations. When analyze fluid-structure coupling problems, the sound pressure of the fluid interface should be taken into account. Integrate Sound pressure at the interface $S$ and take the sound pressure shape function matrix into equation (1), then combined the equation with interface energy waves of the discrete equation, fluid-structure coupling problems are got as equation (3),

$$
\begin{bmatrix}
[M_e][0] \\
[M^h_e][M^p_e]
\end{bmatrix}
\begin{bmatrix}
{U_e} \\
{P_e}
\end{bmatrix}
+
\begin{bmatrix}
[C_e][0] \\
[0][C^p_e]
\end{bmatrix}
\begin{bmatrix}
{U} \\
{P}
\end{bmatrix}
+
\begin{bmatrix}
[K_e][K^h_e] \\
[0][K^p_e]
\end{bmatrix}
\begin{bmatrix}
{U_e} \\
{P_e}
\end{bmatrix}
=
\begin{bmatrix}
{F_e} \\
{0}
\end{bmatrix}
$$

(3)

where $[M^h_e] = \rho_0[R_e]^T$, $[K^h_e] = -[R_e]$. This is the sound-fluid-structure coupling equation.

2.3. Boundary conditions and solving

1) Harmonic responding analysis, respectively coupling the positive and negative electrode node voltage freedom of the piezoelectric ceramic sheet, the negative electrode with a load Volt =0, the load applied to the positive electrode is 300 V. Set the frequency range is 15-30 kHz, the minimum frequency step size is 4 Hz.

2) Fluid-structure coupling analyze, applying fluid-structure coupling boundary condition at the junction of the ultrasonic radiation and fluid. Make each node in equipotential state. Frequency range is 17000 Hz~22000 Hz, sub-step is 1000 steps, each step interval is 5 Hz, define full structural damping ratio is 4.2%.

2.4 Simulation results and analysis

2.4.1 Amplitude distribution on end face and side face of ultrasonic radiation rod. Figure 2 indicates longitudinal amplitude distribution was sinusoidal on the end face, the vibration amplitude was the largest at the center, and then decreases monotonously from the center to the edge, but the overall distribution was relatively uniform, the vibration amplitude was more than 10 μm in each point of end face. Distribution of lateral transverse vibration was obvious inequality, the displacement peak was located in 50 mm from the end, the size was 3.15 μm. It’s monotonically decreasing along with the peak to two sides, vibration amplitude attenuate to less than 1 μm near the location on the end face of radiation rod.

![Figure 2. Simulation results of amplitude distribution: (a) on end face, (b) side face.](image-url)
2.4.2 Sound pressure field distribution in water. The simulation results of sound pressure field distribution in water with different ultrasonic immersed depth shown in figure 3 indicated that sound pressure field distribution mainly below the end face of radiation. With the vibrating depth increased, some small regions were found in the side of radiation. The scope and intensity of sound pressure were inversely related to the distance from the end face of radiation.

![Figure 3](image1.png)

**Figure 3.** Sound pressure field distribution in water, ultrasonic immersed depth is: (a) 10mm, (b) 40mm and (c) 70mm.

To further analyze the sound field distribution, we defined ultrasonic cavitation range in water. The condition cavitation generated is that the sound pressure amplitude value exceeds the cavitation threshold value. Previous studies have shown that the cavitation threshold value is usually 0.1-1MPa in water, and it’s 0.9 MPa when the water is in the air. Therefore, demarcate the area where amplitude value of sound pressure exceeds 0.9 MPa in figure 3, the ultrasonic cavitation range is shown in figure 4.

![Figure 4](image2.png)

**Figure 4.** Ultrasonic cavitation region with different ultrasonic vibration depth in water: (a) 10mm, (b) 40mm and (c) 70mm.

Figure 4 indicates cavitation region caused by ultrasonic vibration mainly below the end face of radiation. The maximum value of cavitation appeared below the end face, the farther away from the end face, the smaller the range of cavitation region and the lower the cavitation intensity. When vibrating depth was 10 mm, there was only one region below the end face. When it was 40mm, there were three dispersive zones below the end face. Cavitation region also appeared on the side of...
radiation, but it was very small. When vibrating depth was 70 mm, there were four dispersive zones below the end face, but there was no region on the side of radiation.

3. Cavitation erosion of aluminum foil in water and amplitude test

3.1 Testing program
Amplitude test diagram is shown in figure 5. On the end face of the radiation along the diameter direction there are 13 measuring points. The origin is set in the center of the circle, the interval between each measurement point is 4 mm. On the side face of the radiation along the longitudinal direction there are 22 measuring points. The position of origin is 1 mm away from the end face, the interval between each measurement point is 5 mm. To minimize the effects of external interference in the measurement process, all testing were completed in the vibration isolator.

Cavitation erosion of aluminum foil test is shown in figure 6. Cut aluminum foil appropriately according to the size of beaker and ultrasonic radiation, so that it can precisely fixed in the beaker. After ultrasonic vibration remove the foil from breaker, dry it and observe cavitation morphology and distribution of cavitation pore.

![Amplitude test schematic](image)

**Figure 5.** Amplitude test schematic: (a) schematic diagram of the test, (b) location map of test points.

![Cavitation erosion test of aluminum foil](image)

**Figure 6.** Cavitation erosion test of aluminum foil: (a) schematic of test, (b) photo of test.

3.2 Experimental results and discussion
Amplitude distribution test results of ultrasonic radiation compared with the simulation results as shown in figure 7 indicates that there was some deviation in longitudinal vibration distribution on side surface, the measured value were bigger than simulation results. And there was another small peak appear on lateral surface where is 90 mm away from end face. This was mainly because the connecting bolts between amplitude transformer were not considered in finite element modeling process. But on the whole test measurement and simulation results were basically consistent. This indicates that the radiation pole resonant vibration in the test is a single frequency, the vibration type determine there were a certain extent longitudinal vibration on the side surface.
Figure 7. Amplitude distribution test results of ultrasonic radiation compared with the simulation results.

Aluminum foil cavitation erosion morphology is shown in figure 8. Figure 8(a) shows that the corrosion pits concentrated in the range of about 40mm below the end face of the tool head. The farther away from the end face, the number of corrosion pits gradually reduced and distributed gradually thinning. This indicates that the sound pressure amplitude decreased, cavitation intensity weakens. Figure 8 (a1, a2) which is a partially enlarged view shows that in cavitation region the corrosion pit size about 0.1-1mm and in the area of non-cavitation foil surface is smooth. Measured results agree well with the simulation results. The results shown in figure 8(b, c) suggest that the cavitation region was mainly distributed below the end face and nearby side surface of radiation, when ultrasonic immersed depth is 40 mm and 70 mm. There were three discrete cavitation region appeared below the end face, where the cavitation area below the rod end face was the most obvious area, its range was largest and cavitation erosion pore distribution is the most densely as shown in figure 8(b2, c2), which indicates the cavitation effect was most significant in this place, with the place farther away from the end face of radiation, the cavitation zone range was greatly reduced and the pore distribution was increasingly sparse, but it could be clearly observed as shown in figures 8(b3, c3). This suggests that the cavitation also happened in this region, but its intensity decreased. Through measuring, the cavitation area farthest away from the end face is approximately 150mm. The range of cavitation is small nearby the radiation side surface, and pore distribution is sparse, this suggest the cavitation also happened in this region, but the strength is weak.

Figure 8. Aluminum foil cavitation erosion region distribution when ultrasonic immersed depth is: (a) 10mm, (b) 40 mm and (c) 70mm in water.

Compare simulation results with test results which is shown in figures 5 and 8, it can be found that the range of ultrasonic cavitation measured by test was bigger than that measured by simulation. The reasons for this phenomenon could be found from amplitude simulation and test, actual amplitude value of transverse vibration of radiation rod was bigger than simulation results. Overall, the measured
cavitation field and simulation results were basically consistent, which indicated that the sound pressure field finite element simulation is accurate.

4. Conclusion

1) The amplitude simulation and test results show that the longitudinal vibration in the end face was the major vibration of ultrasonic radiation. Longitudinal amplitude distribution was sinusoidal on the end face, the vibration amplitude was the largest at the center, and then decreases from the center to the edge. Distribution of lateral transverse vibration is obvious inequality, It is monotonically decreasing along with the peak to two sides.

2) Cavitation region test and simulation results indicate that cavitation region caused by ultrasonic vibration mainly below the end face of radiation. The scope and intensity of cavitation were inversely related to the distance from the end face of radiation. With the vibrating depth increased, cavitation region distributed un-continuously below radiation, some small cavitation regions were found in the side of radiation. Cavitation field measurement and simulation results were basically consistent.

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