Research Article

Near-Field Measurements of Water-Entry Sound of Low-Speed Metal Balls in a Non-Anechoic Tank

Qi Li,^{1,2,3} Yihan Yang^{ID},^{1,2,3} Dajing Shang^{ID},^{1,2,3} Rui Tang,^{1,2,3} and Fangzhou Deng^{1,2,3}

¹Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin 150001, China

²Key Laboratory of Marine Information Acquisition and Security, Harbin Engineering University, Ministry of Industry and Information Technology, Harbin 150001, China

³College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin 150001, China

Correspondence should be addressed to Dajing Shang; shangdajing@hrbeu.edu.cn

Received 18 May 2021; Revised 10 July 2021; Accepted 15 July 2021; Published 31 August 2021

Academic Editor: Yang Li

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As one of the target characteristics, water-entry sound characteristics are of great significance to study, and its research has certain reference value for the detection of sea target. The water-entry sound of an underwater target is a transient sound signal, and it is mainly measured in open water such as the sea and lakes. However, due to the short duration of the acoustic signal and the modulation effect of the measuring environment, it is difficult to measure water-entry sound. To deal with this problem, in this work, the water-entry sound of a metal ball was measured in a water tank in a laboratory. The measurements were made in the direct acoustic control area 0.45 m away from the drop point of the ball to eliminate the influence of reflection. Through a time-domain integration, the power of the transient signal of the water-entry sound of the metal ball was obtained. The energy of the initial impact sound and the pulsating-bubble sound was investigated, as was the impact of ball size, entry velocity, and other factors on the characteristics of the water-entry sound. The results show that by combining the virtual-source method with the time-domain integral in the near field, the energy of the incoming sound can be obtained accurately. The results are consistent with closed-space measurements. The water-entry sound includes the initial impact sound and the pulsating-bubble sound. The energy of the pulsating-bubble sound is 3–5 orders of magnitude larger than that of the initial impact sound. The average power level of the water-entry sound is proportional to the ball size and the $2/3$ power of the slamming velocity. The relation between the average power level and the $1/3$ power of the kinetic energy is an exponential function with base 10. Based on the kinetic energy variety of metal balls entering the water, an acoustic model of this system is established. The results can be used for reference to other transient sound measurements.

1. Introduction

The phenomenon of objects entering the water is common in our life, such as the airdrop of torpedoes, raindrops landing on the sea, and lifeboats being dropped from a ship [1, 2], which is a complex physical process with important research significance. When an object enters a body of water, the transient acoustic signals will be generated. The object carries air into the water, which forms a cavity behind it. The larger the cavity, the larger the size and frequency range of the bubbles. The sound energy generated radiates to the surrounding area [3].

In the early years, scientists focused on air conduction based on the interactions between a two-dimensional rigid

body and an ideal liquid. In 1900, Worthington undertook many insightful and systematic studies on objects entering the water. He took photographs of metal balls entering water using the flash photography technology of the time. These show the flow of liquid around the metal balls, the formation of a cavity, and the splash [4]. Some of Worthington's photographs of a metal ball falling into water are shown in Figure 1.

Following Worthington's experiments, in 1918, Mallock studied the sound field induced by the underwater motion of an object as it enters the water through a large number of experiments [5]. In 1924, Bell conducted research into a sphere entering water vertically, laying the foundations for

FIGURE 1: Worthington's photographs of a metal ball entering water [4].

subsequent research [6]. In 1929, von Karman proposed Attached Water Quality and energy conversion for objects entering water [7].

Over time, we have gained a deeper understanding of water-entry problems. In 1932, Wagner derived the classical—and most widely used—formula and proposed that a model with a small ramp angle could be approximated as a flat plate [8]. In 1949, Birkhoff and Caywood developed a new device that measured more accurately the flow field around an object when it enters water [9].

Research into the sound made by objects entering the water has been developed these years. In 2006, Fairlie-Clarke and Tveitnes studied the effects of momentum and gravity when wedge-shaped sections entered the water at a constant velocity [10]. In 2007, Grumstrup et al. concluded that when an object enters the water, it creates a goblet-shaped bubble at its tail due to the flow of liquid [11]. In 2017, Jalalisendi and Porfiri studied, theoretically and experimentally, flexible slender objects entering water [12]. In 2019, Gao JG et al. studied the main characteristics of oblique water entry of high-speed cylindrical projectile, which involved multiphase flow caused by cavitation [13]. In 2020, Wang et al. conducted a numerical study on the entry into the water of several different bow-flared sections [14]. It can be seen that most of the studies on the entry of objects into water are from the perspective of fluid dynamics, but in fact the entry sound is closely related to the hydrodynamic process.

For general transient sound, the research focus has mainly been on processing signals. Schedin et al. studied the transient acoustic near-field of cantilever plates with two different geometric shapes and different materials in the air using optical double-pulse holographic interferometry [15]. Huang Shichu et al. studied water-entry sound detection in

strong noise by using the spectrogram matrix decomposition method [16]. However, due to the lack of technical methods, the difficulty of measuring and quantifying the acoustic characteristics of objects entering the water, few people pay attention to the quantitative measurement and research of the transient acoustic characteristics.

In a shallow sea, water-entry sound is affected by reflections from the sea surface and seabed, which distort the signal and make measurements difficult. Previous works mainly considered water-entry sound from the perspective of signal detection and measuring the physical characteristics and mainly characterized it using sound pressure. However, the experimental results are significantly affected by the experimental conditions, such as measurement distance, water depth, and the liquid used.

To avoid the impact of the complex marine environment, in this paper, the water-entry sound is measured in a nonacoustic tank, and the influence of reflected sound is eliminated in the direct acoustic control area. In this area, the virtual-source method is combined with a time-domain integral to calculate the acoustic power of water-entry sound, which can reduce the uncertainty of calculation and modeling. The acoustic model of the measuring system is established, which can be used as a reference for other transient sound measurements.

2. Classical Theories

2.1. Water-Entry Sound. The entry of an object into water is a relatively complex physical process. Generally, the entry can be divided into four processes: initial impact, flow formation, bubble formation, and bubble closure. When a metal ball enters the water at low speed, a bubble with air inside forms at its tail.

The water-entry sound mainly includes an initial impact sound and a pulsating-bubble sound (as shown in Figure 2). As can be seen from the figure, both the amplitude of the sound pressure and the duration of the initial impact sound are much lower than for the pulsating-bubble sound. The initial impact sound signal is very short, so that it is a transient sound signal. A pulsating-bubble sound signal is a damped oscillation with, usually, a long duration.

It is assumed that when an object enters water, the water surface remains horizontal and the signal of the water-entry sound is equivalent to a radiation sound source. For a non-anechoic tank [17],

$$p^2 = W\rho_0 c_0 \left(\frac{1}{4\pi r^2} + \frac{4}{R} \right), \quad (1)$$

where p is the sound pressure, W is the sound power, $\rho_0 c_0$ is the characteristic impedance of water, r is the distance from the measuring point to the sound source, and R is a constant for the pool. Here, $R = S\bar{\alpha}/(1 - \bar{\alpha})$, where S is the total area of the wall of the tank and $\bar{\alpha}$ is the average sound absorption coefficient of the wall of the tank. In equation (1), the first term represents the contribution of direct sound and the second represents the contribution of reverberated sound. When the two are equal, $r = r_h$, so the reverberation radius is as follows:

$$r_h = \frac{1}{4} \sqrt{\frac{R}{\pi}}. \quad (2)$$

When $r \ll r_h$, direct sound plays the main role, and reverberated sound can be ignored, so that

$$p^2 = W\rho_0 c_0 \frac{1}{4\pi r^2}. \quad (3)$$

For sound measured by a hydrophone in the near field, the distance from the drop point to the hydrophone is the Rayleigh distance:

$$d = \frac{a^2}{\lambda} = \frac{a^2}{c/f_0} = \frac{a^2 f_0}{c}, \quad (4)$$

where λ is the wavelength of the sound wave. If the experimental research frequency band exceeds the calculated frequency f_0 , the far-field condition is not satisfied and the measured value is not accurate. The frequency f_0 is

$$f_0 = \frac{dc}{a^2} = \frac{\sqrt{1+L^2}c}{a^2} = \frac{\sqrt{1+0.45^2} \times 1500}{0.007^2} = 3.36 \times 10^7 \text{ Hz}, \quad (5)$$

where $a = 0.007$ m is the radius of the ball, $L = 0.45$ m is the horizontal measurement distance, d is the Rayleigh distance (the distance from the hydrophone to the drop point), and c is the speed of sound in water. All physical quantities are in SI units. Here, f_0 is far larger than the frequency range studied in the experiment, so the signals in the frequency band 0–20 kHz measured in the near field meet the far-field conditions.

When a metal ball falls into water and the incoming sound is measured very close to the water surface, the virtual-source method can be used to approximate the

radiation sound field as it is almost a dipole sound field [18], as shown in Figure 3.

The distance between the two sound sources is d_0 , the distance from the point M to the center of the sound source is r , and the distances from the sound sources 1 and 2 are r_+ and r_- , respectively. The total velocity potential of the two-point sources at point M is

$$\begin{aligned} \Phi(r, \theta, t) &= \Phi_+(r, \theta, t) + \Phi_-(r, \theta, t) = \frac{Q}{4\pi r_+} (e^{-jkr_+} + e^{jkr_-}) e^{j\omega t} \\ &= -\frac{Q_1}{4\pi} \frac{\partial}{\partial r} \left(\frac{e^{-jkr}}{r} \right) \cos \theta e^{j\omega t} (r \gg d), \end{aligned} \quad (6)$$

where $Q_1 \equiv Qd_0$ is the dipole moment. The sound pressure function for the acoustic dipole is

$$\begin{aligned} p(r, \theta, t) &= \rho \frac{\partial}{\partial r} \Phi(r, \theta, t) = j\omega \rho \Phi(r, \theta, t) \\ &= \frac{jk\rho c Q_1}{4\pi r^2} \sqrt{1 + (kr)^2} \cos \theta e^{j(\omega t - kr + \varphi)}, \end{aligned} \quad (7)$$

where φ satisfies $tg\varphi = kr$. The particle velocity of an acoustic dipole consists of two components, r and θ . Using $\vec{u}(r, \theta, t) = -\nabla \Phi(r, \theta, t)$, the components of the particle velocity u_r and u_θ in the radial and perpendicular directions are

$$\begin{aligned} u_r(r, \theta, t) &= -\frac{\partial}{\partial r} \Phi(r, \theta, t) = \frac{Q_1}{4\pi} \frac{\sqrt{4 + (kr)^4}}{r^3} \cos \theta e^{j(\omega t - kr + \varphi)}, \quad (8) \\ u_\theta(r, \theta, t) &= -\frac{\partial \Phi}{\partial(r\theta)} = -\frac{\partial \Phi}{r \partial(\theta)} = -\frac{Q_1 e^{j(\omega t - kr + \varphi)}}{4\pi r^3} \sqrt{1 + (kr)^2} \sin \theta. \end{aligned} \quad (9)$$

Since $r \gg d$, the expressions for the far-field sound pressure and particle velocity can be further simplified. Using equations (7)–(9) and the far-field conditions gives

$$p(r, \theta, t) \approx -\frac{Q_1}{4\pi r} k^2 \rho c \cos \theta e^{j(\omega t - kr)}, \quad (10)$$

$$u_r(r, \theta, t) \approx -\frac{Q_1}{4\pi r} k^2 \cos \theta e^{j(\omega t - kr)} = \frac{p(r, \theta, t)}{\rho c}, \quad (11)$$

$$u_\theta(r, \theta, t) = \frac{Q_1}{4\pi r^2} k \sin \theta e^{j(\omega t - kr + (\pi/2))}. \quad (12)$$

Using equations (11) and (12), the radial and perpendicular components of the radial sound intensity for the far field are

$$\begin{aligned} I_r(r, \theta) &= \frac{1}{T} \int_0^T \vec{\omega}_r(r, \theta, t) dt = \frac{1}{2\rho c} \left(\frac{Q_1}{4\pi r} k^2 \cos \theta \rho c \right)^2, \\ I_\theta(r, \theta) &= \frac{1}{T} \int_0^T \vec{\omega}_\theta(r, \theta, t) dt = 0, \end{aligned} \quad (13)$$

FIGURE 2: Sound signal in the time domain.

FIGURE 3: Schematic diagram of the virtual-source method for an object entering water.

where $\vec{w}(r, \theta, t) = \text{Re}[p(r, \theta, t)]\text{Re}[u(r, \theta, t)]$. Thus,

$$I(r, \theta) = I_r(r, \theta) = \frac{\rho c}{2} \left(\frac{Q_1 k^2}{4\pi} \right)^2 \frac{1}{r^2} \cos^2 \theta. \quad (14)$$

According to the formula for the total sound intensity, the radiation sound power and sound power level of the dipole sound source can be calculated as

$$W = \iint_S I_r \sin \theta d\theta = 2\pi \frac{\rho c}{2} \left(\frac{Q_1 k^2}{4\pi} \right)^2 \frac{2}{3}, \quad (15)$$

$$L_W = 10 \log \left(\frac{W}{W_{\text{ref}}} \right), \quad (16)$$

$$W_{\text{ref}} = 0.67 \times 10^{-18} \text{ W}.$$

2.2. Calculation of Bubble Radius. When an object enters water, it produces many bubbles. These have a range of sizes, which affects the pulsating-bubble part of the sound signal. There is a functional relationship between the equivalent radius of a bubble and its resonance frequency. It is assumed that the bubbles generated by a solid steel ball entering water at a low speed are approximately spherical and ideal. The relationship between their equivalent radius and resonance frequency is

$$a_0 = \frac{1}{2\pi f} \sqrt{\frac{3\gamma P_0}{\rho_0}}, \quad (17)$$

where f is the resonance frequency of the bubble, a_0 is the radius of the bubble, and γ is the specific heat ratio of air, which is generally assumed to be $\gamma = 1.4$. P_0 is the local pressure at the hydrophone.

3. Experiments and Methods

The experiment was carried out in the non-anechoic tank of the Key Laboratory of Underwater Acoustic Technology of Harbin Engineering University.

3.1. Experimental Measuring System. The experimental system is shown in Figure 4. The length, width, and height of the pool are 15 m, 9.3 m, and 6 m, respectively. The walls and floor of the pool are covered with ceramic tiles. The reverberation radius of the pool corresponding to the study frequency is $r_h = 1.7$ m [17]. The main parts of the equipment used in the experiment included the PULSE data collector, a 8103 hydrophone, a release device with an adjustable height (which has a support frame, lifting rod, release rod, and lifting and adjusting knobs, as shown in Figure 5), and a net.

During the experiment, the hydrophone was approximately at the same height as the drop point of the ball, and the horizontal distance from the metal ball was 0.45 m, which allowed the hydrophone to collect clear signals with a high signal-to-noise ratio. The distance between the drop point and the hydrophone was much less than the reverberation radius, and the influence of sound reflected from the walls of the tank can be ignored. To prevent the ball from hitting the bottom of the tank and making a noise, the ball was caught by a net fixed at a depth of 2-3 m as a recovery device.

3.2. Experimental Method. According to the scale effect in fluid mechanics, the size of the ball itself has little effect on the surrounding fluid. For a constant entry velocity and fixed experimental conditions, the initial impact sound and pulsating-bubble sound depend on the size of the ball. In contrast, if the size of the steel ball remains unchanged, the initial impact sound and pulsating-bubble sound depend on the entry velocity. According to Newton's second law, the entry velocity can be calculated using $v = \sqrt{2gH}$.

FIGURE 4: Schematic diagram of the experimental measurement system.

FIGURE 5: Photograph of the release device.

After the sound pressure was experimentally obtained, the sound power level was calculated according to equation (16), and the power spectrum of the pulsating-bubble sound was used to obtain the range of the bubble resonance frequency. The corresponding range for the bubble radius was then calculated according to equation (17).

Before the experiment began, the accuracy of the experimental method was verified. According to the method described in references [17, 19] a transient acoustic signal can be measured in a closed space. The water-entry sound power is then obtained using a spatial average. In the experiment, four hydrophone arrays were each arranged in a U-shaped layout in the control area of the reverberation sound, as shown in Figure 6. Each line array of hydrophones is 8 m long with 30 hydrophones. The distance between each hydrophone array and the sound source is sufficient to meet the far-field conditions, as much as possible.

Each experiment collected data for 5 s and was repeated at least 30 times to ensure the accuracy of the results. The signals collected by the hydrophone were processed by the PULSE collector, which read the data, isolated the initial impact sound and pulsating-bubble sound for further analysis and processing, and determined the sound pressure, sound power, and other physical quantities. MATLAB was

then used to process the data using the near-field virtual-source time-domain integration method to obtain a time-domain image of the sound signal. A power law was fitted to the data collected in the experiments. Three experiments were run to measure the sound of metal balls entering water, as listed in Table 1.

4. Results

4.1. Eliminating Reflected Sound in Near-Field Experiments.

The data obtained from the transient sound measurements in the far field of the closed space were compared with those obtained by the near-field virtual-source time-domain integration method with a virtual source in the near field (taking the pulsating-bubble sound, as an example). When transient sound is measured in a closed space, the direct sound and reflected sound are superimposed on each other due to reflections from the walls, so it is difficult to identify the characteristics of the sound signal, as shown in Figure 7. Moreover, the signal duration is longer than for near-field measurements. Thus, near-field measurements were used to eliminate the influence of the reflected sound in the time domain.

4.2. Verification of Measurement Methods. The near-field virtual-source time-domain integration method and the far-field closed-space method were used to measure the transient noise [17, 19]. The results are shown in Table 2. It can be seen from the data in the table that the differences between the power level of water-entry sound obtained by the time-domain integration method for a near-field virtual source and the reverberation method are less than 1 dB.

4.3. Experiment 1: Different Ball Sizes for the Same Entry Velocity. The experimental method described in Section 3.1 can be used to measure the pressure of the initial impact sound and pulsating-bubble sound for different sizes of the metal ball. The method described in Section 2.1 can then be used to calculate the power level for the initial impact sound (Figure 8) and the pulsating-bubble sound (Figure 9). The data points were fitted to linear relations:

$$\begin{aligned} L_{W_1} &= 6.8 \times 10^2 D + 1.3 \times 10^2, \\ L_{W_2} &= 1.7 \times 10^3 D + 1.3 \times 10^2, \end{aligned} \quad (18)$$

FIGURE 6: Water-entry sound measurement system based on the spatial average in the non-anechoic tank: (a) stereogram and (b) planform.

TABLE 1: Experimental conditions.

Experiment	Working conditions	Parameters
1	Virtual-source integration in time domain for near-field validation	Entry angle $\theta = 90^\circ$
		Horizontal measuring distance $L = 0.45$ m
		Entry speed $v = 9.02$ m/s
2	Fixed ball size, different entry speeds in near-field	Ball size $D = 6, 8, 10, 12$ mm
		Ball size $D = 8$ mm
		Entry speed $v = 5.89, 6.37, 6.82, 7.14, 7.54, 7.92$ m/s
3	Fixed entry speed, different ball sizes in near-field	Entry angle $\theta = 90^\circ$
		Horizontal measuring distance $L = 0.45$ m
		Ball size $D = 4, 6, 8, 10, 12, 14, 16, 18, 20$ mm
		Entry speed $v = 5.89$ m/s
		Entry angle $\theta = 90^\circ$
		Horizontal measuring distance $L = 0.45$ m

FIGURE 7: Measurement of water-entry sound: (a) near-field virtual-source time-domain integration and (b) far-field closed-space measurement.

R^2 is the ratio of the regression sum of squares to the total sum of squares. The closer it is to 1, the better the fit is.

Table 3 shows that the energy conversion rate for the initial impact sound is much lower than that for the

pulsating-bubble sound, about 3–5 orders of magnitude. Alternatively, the conversion efficiency relative to the kinetic energy was the same for both types of sound. Thus, the kinetic energy of the ball is partly converted into initial

TABLE 2: Measurements of water-entry sound.

Far-field closed-space measurements		Near-field virtual-source time-domain integration	
Kinetic energy (J)	Sound power level (dB)	Kinetic energy (J)	Sound power level (dB)
0.1901	142.6	0.1901	143.1
0.4506	147.4	0.4506	147.1
0.8801	151.7	0.8801	151.1
1.5208	155.5	1.5208	155.0

FIGURE 8: Initial impact sound power level versus ball size.

FIGURE 9: Pulsating-bubble sound power level versus ball size.

impact sound and pulsating-bubble sound but mainly remains as kinetic energy since the ball continues to move.

4.4. Experiment 2: Different Entry Velocities for the Same Ball Size. As above, the power level was calculated for the initial impact sound (Figure 10) and the pulsating-bubble sound (Figure 11) for different entry velocities. These were plotted against $v^{2/3}$. The fitted power laws are

$$\begin{aligned} L_{W_3} &= 1.509 \times v^{2/3} + 128.9, \\ L_{W_4} &= 4.708 \times v^{2/3} + 129.6. \end{aligned} \quad (19)$$

Table 4 shows that there is a difference of about 4 orders of magnitude between the energy conversion rates for the initial impact sound and the pulsating-bubble sound. As before, the kinetic energy is mainly not converted as the ball continues to move.

4.5. Acoustic Model of Water-Entry Sound

4.5.1. Relations between Sound Power Level and Kinetic Energy. The results in Sections 4.3 and 4.4 can be converted and combined to kinetic energy (Figures 12 and 13). Thus, the model of underwater sound is established. The unified power laws are then

$$\begin{aligned} L_{W_5} &= 8.289 \times E_k^{1/3} + 128.2, \\ L_{W_6} &= 20.85 \times E_k^{1/3} + 131.1. \end{aligned} \quad (20)$$

4.5.2. Relation between Bubble Radius and Kinetic Energy. Figure 14 shows the power spectrum for the pulsating-bubble sound (red) and the background sound (black). According to equation (17), the range of the bubble radius depends on the resonance frequency of the bubble. In

TABLE 3: Water-entry sound energy corresponding to each ball size.

Ball size (m)	Kinetic energy (J)	Initial impact sound energy (J)	Initial impact energy conversion rate (%)	Pulsating-bubble sound energy (J)	Pulsating-bubble sound energy conversion rate (%)
0.006	0.1243	2.10×10^{-10}	1.69×10^{-7}	9.84×10^{-7}	7.91×10^{-4}
0.008	0.2937	2.19×10^{-10}	7.46×10^{-8}	1.87×10^{-6}	6.34×10^{-4}
0.010	0.5757	3.59×10^{-10}	6.24×10^{-8}	3.95×10^{-6}	6.86×10^{-4}
0.012	0.9947	4.79×10^{-10}	4.82×10^{-8}	8.98×10^{-6}	9.03×10^{-4}
0.014	1.5796	8.32×10^{-10}	5.27×10^{-8}	2.42×10^{-5}	1.53×10^{-3}

FIGURE 10: Initial impact sound power level versus $v^{2/3}$. FIGURE 11: Pulsating-bubble sound power level versus $v^{2/3}$.

TABLE 4: Water-entry sound energy for each entry velocity.

Entry velocity (m/s)	Kinetic energy (J)	Initial impact sound energy (J)	Initial impact energy conversion rate (%)	Pulsating-bubble sound energy (J)	Pulsating-bubble sound energy conversion rate (%)
5.89	0.2937	2.78×10^{-10}	9.46×10^{-8}	1.87×10^{-6}	6.37×10^{-4}
6.37	0.3435	3.31×10^{-10}	9.62×10^{-8}	2.57×10^{-6}	7.47×10^{-4}
6.82	0.3933	3.96×10^{-10}	1.01×10^{-7}	3.42×10^{-6}	8.71×10^{-4}
7.14	0.4315	4.46×10^{-10}	1.03×10^{-7}	4.23×10^{-6}	9.81×10^{-4}
7.54	0.4813	5.23×10^{-10}	1.09×10^{-7}	5.47×10^{-6}	1.14×10^{-3}

FIGURE 12: Initial impact sound power level versus entry kinetic energy.

FIGURE 13: Pulsating-bubble sound power level versus entry kinetic energy.

Section 4.5.1, the power level of the water-entry sound was shown as a function of the kinetic energy. Thus, the bubble radius can be described in terms of kinetic energy (Figure 15). As can be seen from the figure, the minimum radius seems to change from about 0.003 m to about 0.004 m, which is an increase of about 1/3, hardly constant. An expression for the maximum bubble radius is

$$R_{\max} = 1.65 \times 10^{-2} E_k^{1/3} - 8.24 \times 10^{-4}. \quad (21)$$

FIGURE 14: Pulsating-bubble sound power spectral density. The bottom panel is a magnified version of the area circled in the top panel.

FIGURE 15: Bubble radius versus kinetic energy.

5. Discussion and Conclusions

In this paper, a metal ball, released by a self-developed device, was dropped into a non-anechoic tank. In the near field, the virtual-source method was combined with the time-domain integration method to measure the acoustic power of the metal ball when it entered the water.

Relations between the water-entry sound power and ball size, entry velocity, and kinetic energy of the metal ball were determined. The theoretical and experimental results show that

- (1) Near-field measurements of the water-entry sound of the metal ball in the non-anechoic tank can eliminate the influence of reflected sound so that the characteristics of the water-entry sound can be determined.
- (2) In the near field of the sound source, the sound power of a metal ball entering water obtained by the virtual-source method combined with time-domain integration is basically consistent with that obtained by spatial averaging in the far field in a non-anechoic tank. This confirms the accuracy of the method of measuring the transient sound of a metal ball entering water used in this paper.
- (3) The contribution of the pulsating-bubble sound to the water-entry sound energy is about 4 orders of magnitude larger than the contribution of the initial impact sound. Both have a low conversion efficiency relative to the water-entry kinetic energy. The kinetic energy mainly remains as kinetic energy since the ball continues to move.
- (4) The power levels of the initial impact sound and pulsating-bubble sound are both proportional to the ball size for fixed entry speeds. The power levels of the initial impact sound and the pulsating-bubble sound are proportional to the $2/3$ power of the entry velocity for fixed ball size.
- (5) An acoustic model of the water-entry sound was established. The sound power level is proportional to the $1/3$ power of the kinetic energy. The maximum bubble radius is also proportional to the $1/3$ power of the kinetic energy, whereas the minimum bubble radius is almost constant.
- (6) The methods applied in this paper could also be used as a reference for other transient sound measurements.

The conclusions of this paper may not apply to large-scale objects, and the experimental conditions are limited, such as setting the water height, the ball of the particle size, and density. In addition, we only studied the case of the ball entering water vertically, and whether the angle of the ball entering water and the rotating motion of the ball have influence on the sound power still needs further study, and these can be improved in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (grant 11874131) and by the Stable Support Fund of the Acoustic Science and Technology Laboratory (grant 6142108190110).

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