Measurement of the Stable Sound Field in the Small Tank for Simple Calibration

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Abstract:
We propose a simple calibration method for a hydrophone using a small tank. Even a tank equivalent in size to the wavelength of a projected sound can be used for the measurement of hydrophone sensitivity at the fundamental resonant frequency of the tank. Under such circumstances, the sound pressure level in the tank is high and nearly constant within the proposed stable area. A stable exposure level can be observed as a 0.3-m sphere at the center of the tank up to 3 dB, which is sufficiently large compared to the size of a piezoelectric sensor. A relatively constant sound field area appears only at the resonant frequency of the tank, which can be used for a quantitative measurement of hydrophone sensitivity. When a sound is projected at a frequency higher than the fundamental resonant frequency, the sound pressure level changes in a complex manner, owing to constructive or destructive phase interference. A received sound pressure level at a frequency lower than the fundamental resonant frequency exhibits a quick reduction. In either case, the sound pressure level is location-sensitive, which makes the calibration of a hydrophone in a small tank difficult.

Classification: Fisheries acoustics · Bioacoustics
Keywords: hydrophone sensitivity, fundamental resonant frequency, passive acoustic monitoring, bioacoustics, reverberation

1. Introduction
Ocean noise pollution is currently attracting some public attention.\(^1\) There are several sources of anthropogenic low-frequency noise, including shipping,\(^2,3\) windmill farms,\(^4,5\) airguns,\(^6\) and navy sonar.\(^7\) Ambient noise levels in offshore waters have risen by 3 dB per decade, probably due to ship noise.\(^8\) The minimum sound pressure level required to induce a negative effect on marine organisms appears to be species-dependent. The hearing threshold levels of marine organisms differs based on type of species and sound frequency.\(^9\) In this paper, we define a “low-frequency range” as several thousand hertz or lower, which is

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equivalent to the sensitive range of marine mammals and fishes. Baleen whales have a wide and thin membrane in their inner ear, which is suitable for detecting low-frequency underwater sounds. In the case of fish, conditioning experiments\(^\text{13}\) and auditory electrophysiological methods\(^\text{14}\) have shown a highly sensitive audiogram in the low-frequency range.

For the measurement of underwater noise and its effects on marine organisms, a calibrated hydrophone is an essential instrument. Several hydrophone calibration methods have been established.\(^\text{15-17}\) One is called the reciprocity method. This method involves three transducers, with at least one of them operating as a reciprocal device, and the others operating as a transmitter and receiver. These transducers measure electrical responses, transmit, and receive them, respectively. This method enables absolute calibration of a hydrophone when there is no calibrated hydrophone for comparison.\(^\text{18-20}\) The optical method is another that has been employed in recent years. This method directly measures the acoustic particle velocity or displacement using an optical light.\(^\text{21, 22}\) Although these methods enable absolute calibration of the hydrophone, they also require specific devices and facilities.

The comparison method is an alternative easy method for calibrating a hydrophone. In this method, an uncalibrated hydrophone can be placed in a stable, noiseless sound field area that has no interference.\(^\text{23}\) The sound pressure level of the sound projected from a transducer should be measured by a calibrated hydrophone before projection. The limitation of this method is that it requires a noiseless field without interference.

In the pelagic zone, the interference of a projecting sound is less effective; however, there are many noise sources, including soniferous marine organisms and anthropogenic activities such as shipping, pile driving, and airgun surveys. In the laboratory, a water tank is preferred for hydrophone calibration in an ultrasonic range. The transducer and sensor are placed precisely in the middle of the tank with very low noise contamination. The measurement platform and electric power supply are kept stable. The most difficult part of low-frequency calibration in a tank is the severe distortion of the waveform due to reverberation.

A 1-kHz tone burst has a wavelength of 1.5 m. If the tone burst has 10 cycles, the total wavelength is 15 m. If the depth of a small water tank is 1 m, which is not significantly small, the tone burst wave will fold 15 times and cause complex interference. Unlike the ultrasonic calibration of echo sounders, the separation of a tone burst sound in the time domain is impossible in the low-frequency range in a small tank.

Calibration in a small tank requires a stable sound field. Here, we propose a novel, simple method for calibrating a hydrophone in a cylindrical small tank using the tank’s fundamental resonant frequency. We first describe the theoretical sound field of the resonance frequency in the small tank. We then measure the sound field in the small tank at the resonant frequency. Finally, we propose the calibration procedure.

2. Materials and methods
2.1 Theory

The thin plastic tank wall and water surface are soft boundaries and act as a mirror to generate the same sound pressure with an opposite phase, because sound pressure is equivalent to air pressure. Assuming a pressure-equivalent boundary between the tank wall and water surface, low-frequency sounds tend to disappear, because of the destructive phase of the reverberated sounds,
except for a specific sound at the resonant frequency of the tank.\textsuperscript{24,25} The stable sound field survives when the reverberated sound has a constructive phase compared to the projected sound.

The resonant frequency of a cylindrical tank can be calculated as

$$F_{\text{m},n} = \frac{c}{2} \sqrt{\left(\frac{\alpha_{m,n}}{\pi r}\right)^2 + \left(\frac{l}{d}\right)^2}$$

where $c$ is the sound velocity in water, and $r$ and $d$ are the radius of the tank and the water depth, respectively. The sound velocity depends on water temperature and salinity. In this report, fresh water was used to fill the tank. Therefore, sound velocity depended only on water temperature.\textsuperscript{20} To continue with Eq. (1), $\alpha_{m,n}$ is $n$-th solutions where the $m$-th order of the Bessel function of the first kind equals zero, $l$ and $n$ are natural numbers ($l, n=1, 2, 3, \cdots$), and $m$ is an integer ($m=0, 1, 2, 3, \cdots$). The resonant frequency is calculated according to the designated combination of $l$, $m$, and $n$, which is called the “mode number.” The minimum resonant frequency that defines the fundamental resonant frequency is described as mode $(m, n, l)=(0, 1, 1)$. For the fundamental resonant frequency, $B_{0,1}$ is 2.405, and sound pressure in the tank is expected to be the highest at the center, and to decrease towards the tank wall (Fig. 1(A)).

A higher elicited mode of the resonant frequency can be calculated using Eq. (1). For example, a calculated sound pressure field at the resonant frequency at mode $(0, 2, 1)$ shows a donut-shaped distribution of local maximum sound pressure along the diameter axis (Fig. 1(B)). The higher the mode of combination, the more complex the sound field. In theory, higher resonant components can also survive in a tank.

However, two major issues should be noted for higher resonant frequencies. The first is the highly variable sound pressure field at different locations in the tank due to the shorter wavelength. This means that the positioning of the hydrophone must be precise, or the received sound pressure could change by a couple of cm. The second issue is the imperfect symmetry of the tank. Usually, the top diameter of a circular tank is larger than the bottom diameter. It is therefore possible that the sound field in an asymmetric tank will be disturbed. The sound field of the higher mode becomes more complex, because this mode is originally more complex than the sound field of the lower mode. Therefore, prediction of the sound field in the water tank becomes difficult, and it becomes hard to place the hydrophone in a specific sound field.

Note that the resonant frequency depends not only on the height and diameter of the tank, but also on the sound velocity. This means that the temperature of the water in the tank has a slight impact on resonant frequency.

2.2 Sound projection and reception systems in a small tank

A commercially available polycarbonate tank with an upper inside radius of 0.68 m, bottom
inside radius of 0.66 m, and a height of 0.82 m was used as the test field (Fig. 2). It was filled with fresh water up to a depth of 0.60 m. The water temperature was measured just before the sound projection. A small transducer (8103, B&K, Denmark) was placed at a distance of 0.35 m from the center of the tank, which is half of the radius of the test tank. The depth of the transducer was half of the water depth (0.30 m). The sound projection responses of the transducer increased by 12 dB with each octave up to a frequency of 20 kHz, and reached 104 dB re 1 µPa/V at 1 m. The generated wave was fed into the audio amplifier (A-C3, Pioneer, Japan), and the output was connected to the transducer.

A continuous wave was used as the test sound. The waveform was created using a function generator (1940, NF, Japan). We selected three frequencies for projection. The first was a frequency lower than the fundamental resonant frequency. The second and third were the fundamental and higher resonant frequency modes of (0, 1, 1) and (0, 2, 1) of the tank, respectively. The projected frequencies were varied in steps of 1 Hz within ±20 Hz from the calculated theoretical resonant frequency. Moreover, the frequency that measured the maximum sound pressure level at the center of the tank was used as the experimental resonant frequency.

A calibrated receiver (TC4023, RESON, Denmark) with a flat frequency response range from 15–40 kHz within ±2.0 dB was used as the reference, which provided the ground truth of the sound pressure field. The receiver was positioned in one location in the tank, and then was moved to other locations separated by 0.1-m intervals on six radial lines (the angle between lines was 60°) (Fig. 2) for each measurement. This measurement was replicated on six depth layers from 0.1–0.6 m, where a sound pressure level was present at each 0.1-m interval, or smaller areas were precisely measured.

The received waveform detected by the calibrated hydrophone was fed into an audio amplifier (EC6070, RESON, Denmark). The output voltage level was measured to calculate the received sound pressure level in pascal. The received amplitude was measured as the peak-to-peak voltage (V_{p-p}) using an oscilloscope (TDS2002, Tektronix, Japan). Received sound pressure (Pa) was calculated with reference to the calibration chart of RESON TC4023. Based on the measured sound pressures at all grid positions, the contours of sound pressure in the water tank were calculated using the MATLAB function “linspace.”

3. Results

Table 1 lists the parameters of theoretical and experimental resonant frequencies. The water temperature was 14°C, and the difference between the theoretical and experimental resonant frequencies was 2 Hz in mode (0, 1, 1) and 7 Hz in mode (0, 2, 1). The theoretical resonant frequency varied depending on the water temperature and the depth of the tank, as shown in Fig. 3. The solid and bro-
ken lines in Fig. 3 indicate the theoretical resonant frequency in modes (0, 1, 1) and (0, 2, 1), with water depths of 0.4, 0.6, and 0.8 m, and varying water temperature. Experimental resonant frequencies were nearly identical to the theoretical values within the width of the line, and therefore, are not visible in the figure. Theoretical resonant frequency increases with an increase in water temperature, and decreases with water depth.

Figure 4 shows the vertical distribution of the sound pressure across the center of the tank. The abscissa scale shows the horizontal distance from the center of the tank and the area that setting on the hydrophone (left side) is minus. Sound pressure received at 1300 Hz was reduced with increasing distance from the transducer, as theoretically predicted. The highest sound pressure level was 125.4 dB re 1 µPa at a 0.4-m depth and −0.4 m horizontal position, which is close to the transducer. However, on the other side of the transducer (right side in Fig. 4), the sound pressure level varied, ranging from 120.6–123.5 dB re 1 µPa.

In contrast, at the resonant frequency, a high sound pressure level was observed over the entire tank in mode (0, 1, 1) at 1469 Hz. The received sound pressure level was higher at the center of the tank than closer to the transducer. As predicted, the sound pressure level near the tank wall was reduced, and pressure was highest at the center of the tank. The highest sound pressure level was 149.1 dB re 1 µPa at a depth of 0.3 m at the center of the tank. The observed sound pressure level was 23.7 dB higher than that at 1300 Hz, despite the difference of 169 Hz. At 1469 Hz, a stable sound field within −3 dB from the local maximum was found within a horizontal distance of ±0.2 m at a depth of 0.3 m, and within a horizontal distance of ±0.1 m at a depth of 0.2 m. At a depth of 0.4 m, the measured sound pressure level ranged from 141.5–142.0 dB re 1 µPa within ±0.2 m horizontal position. However, the measured sound pressure level was decreased by approximately 7 dB compared to that at a 0.3-m depth.

With sound projection at 2255 Hz, three local highlights of the sound pressure level were observed at a depth of 0.2 m. The highlights of the sound pressure level decreased with depth from 0.2 m to the bottom or surface of the tank. The highest sound pressure level in the center was 155.9 dB re 1 µPa at a 0.2-m depth and 0.1-m horizontal position. The sound pressure levels of

| Depth (m) | Radius (m) | Temp (°C) | Theoretical resonant frequency (Hz) | Experimental resonant frequency (Hz) |
|-----------|------------|-----------|-------------------------------------|-------------------------------------|
|           |            |           | (0, 1, 1)                            | (0, 2, 1)                            |
| 0.60      | 0.68       | 14.0      | 1471                                | 2248                                |
| 0.60      | 0.68       | 14.0      | 1469                                | 2255                                |

Fig. 3 Theoretical resonant frequency change with temperature and depth at (0, 1, 1) and (0, 2, 1) modes. The solid line indicates the (0, 1, 1) mode and the broken line the (0, 2, 1) mode. The values on the right represent depth (m). The fundamental resonant frequency increases monotonically with increasing temperature and decreasing depth.
the other two local highlights were at depths of 0.2 m and ±0.5-m horizontal position at 152.8 dB re 1 µPa. The phases of the received sound wave at the center and the other two highlights were opposite. The local minimum value of the sound pressure levels (123.9–135.2 dB re 1 µPa) was confirmed at the ±0.3 m horizontal position. A mere difference of 0.1 m in the horizontal position caused a difference of 20 dB re 1 µPa in the received sound pressure level.

**Figure 5** shows the top view of the sound field on the horizontal plane and at a depth of 0.3 m. At 1300 Hz, we observed a significant reduction in sound pressure level with increasing distance from the transducer, as theoretically predicted. Sound pressure level was reduced from 125.0 to
120.8 dB re 1 µPa according to the distance from the transducer. In contrast, sound pressure level at the experimental resonant frequency (1469 Hz) was not correlated to distance from the transducer. The sound pressure level was highest at the center of the tank (149.1 dB re 1 µPa) and decreased at positions close to the tank wall, which was also predicted theoretically (see Fig. 1(A)). It was nearly constant within a 0.3-m radius circle (−2.5 dB). At 2255 Hz, two peaks of sound pressure levels were found in a concentric circle. The sound pressure level in the concentric circle of radius between 0.4–0.5 m (150.3–152.3 dB re 1 µPa) was approximately 4 dB higher than that of a concentric circle of radius 0.2 m (146.6–148.5 dB re 1 µPa). A reduction in sound pressure level was observed in the area close to the tank wall, and the received sound pressure level did not depend on the distance from the transducer, like the sound projections at 1469 Hz.

4. Discussion
4.1 Stable sound pressure field at the center of the small tank

To date, low-frequency underwater calibration has not been considered possible in a small tank because of multiple reflections in the limited size of the water column compared with the wavelength. In this study, the surviving sound under the reverberation condition was intentionally used for calibration in a small tank. As predicted theoretically, the measured sound pressure level at the resonant frequency of mode (0, 1, 1) in the small tank was stable and highest at the center of the tank. This is consistent with the standing wave in mode (0, 1, 1), as shown in Fig. 1.

The sound emitted at one point in the water tank at resonant frequency is repeated by multiple reflections on the tank wall and surface of the water, and forms a standing wave. Therefore, the maximum sound pressure level depends on the transmission sound pressure level, the ratio of reflections of the tank wall and water surface, and propagation loss. Assuming the transmission response of the transducer (12 dB gain for each octave), the difference in sound transmission level between 1469 and 2255 Hz was calculated to be 7.4 dB, which is close to the measured difference in the received level of 6.8 dB. The ratio of reflections and propagation loss by the difference in sound frequency has little influence, because the experimental condition was the same. Hence, the received level at a higher mode simply depends on the transmission efficiency of the transducer. On the other hand, the received level at 1300 Hz was 20 dB lower than at that of 1469 Hz, despite the difference in the sound transmission level between 1300 and 1469 Hz being 2.1 dB. These results were caused by the exponential attenuation of the sound pressure level below the minimum resonant frequency of the tank.

In the present experiment, we obtained a stable area of received sound pressure level within ±3 dB at 0.3 m on the horizontal plane (Fig. 5) and 0.1 m on the vertical plane (Fig. 4); this was sufficiently large to cover the entire piezoelectric sensor in the hydrophone. The sound pressure level of the standing wave of mode (0, 1, 1) can be described simply as a sine curve. Therefore, we compared the theoretical and experimental values of the reduction in sound pressure at the center of the tank. The theoretical value of the reduction in sound pressure level at a radius of 0.68 m of the small tank was −2.3 dB, which agreed with the experimental value of approximately −2.3 to −2.5 dB within ±0.2 dB at a distance of ±0.3 m from the center on the horizontal plane.

On the other hand, on the vertical plane, the decreasing rate of received sound pressure was
lower than the theoretical one (Fig. 4). In particular, below a depth of 0.4 m, the received sound pressure did not match the theoretical values. The attenuation was approximately $-7$ dB at every 0.1-m depth interval. The small tank was not completely cylindrical in shape. The radius of the tank was smaller towards the bottom. The bottom shape of the tank was curved inwards to the center. Even while projecting experimental fundamental resonant frequency, the reverberated sounds might not have been completely phase constructive. The asymmetric distribution of the sound pressure level along the vertical line could have been due to the asymmetric shape of the tank, as described above.

4.2 Cancellation of near-field effect and soft boundary condition

In the fundamental mode in the present experiment, nodes exist along the tank wall (Fig. 1). By definition, particle motion is the differential of the sound pressure, which is highest on the tank wall. In contrast, particle motion is nullified at the center of the tank owing to its symmetrical shape and the standing wave. At the center of the tank, the water was compressed and decompressed alternatively from all directions equally.

The soft boundary condition at the tank wall, where the sound pressure is equivalent to the air pressure, was supported experimentally. This assumption is also justified by the following calculation. The small tank was constructed using polycarbonate with a Young's modulus of 2.45 GPa. This value is similar to the Young's modulus of fresh water, which is 2.19 GPa (at 20°C). This means that the tank wall expands and shrinks with the sound pressure wave. If the tank wall receives a pressure of 10 Pa (140 dB re 1 µPa), it will warp by $4.08 \times 10^{-8}$%, assuming the thickness of the wall to be 10 mm. This corresponds to a displacement of $4.08 \times 10^{-8}$ mm. On the boundary of the polycarbonate wall and fresh water, most of the sound waves push and pull the tank wall as if it were a water boundary. In other words, the reflected sound wave has a phase that is almost the inverse of the incident wave. Therefore, the resistance of the tank wall is negligible, and it allows the formation of simple resonant modes in the water column, which agrees with the theory.

4.3 Low-frequency calibration procedure using a small tank

This method has two significant limitations. First, a calibrated hydrophone is required as a reference to measure the absolute sound pressure level in the tank. Second, only a specific frequency is available for the calibration. Only after satisfying these conditions can the simple, quantitative low-frequency calibration procedure be carried out using a small tank.

Once the exposed sound pressure at the center of the tank is determined using a calibrated hydrophone, any hydrophone can be calibrated in the small tank in the laboratory environment. This procedure is similar to the standard procedure of comparison calibration except that it requires a specific frequency. At other frequencies, the sound pressure changes within a couple of centimeters, which makes the positioning of the hydrophone difficult. With low-frequency calibration of an acoustic device in the laboratory environment, a background noise introduced from the ground is unavoidable, and most of the frequency components do not survive because of the reverberation. Therefore, the projected frequency component is dominated by a background noise except for specific frequency component.

As long as a pure-tone sound at the resonant frequency of the tank is used, the sound field will remain stable. The projection frequency can easily be fine-tuned using a function generator or
computer-generated wave. The resonant frequency depends on the water temperature and depth, which should be kept constant during the measurement. If the water temperature changed from 5 to 25°C, the resonance frequency in mode (0, 1, 1) would vary from 1434 to 1505 Hz at a water depth of 0.6 m. The change in depth from 0.4 to 0.8 m causes a reduction in the resonant frequency from 2005 to 1230 Hz, as shown in Fig. 3. Evaporation of water from the tank should be prevented. Water depth and temperature should be measured at the beginning and end of the calibration procedure to ensure no variation in the experimental conditions.

A drawback of this method is the fixed frequency for calibration. It can be modified using tanks with different dimensions or depths. According to Eq. (1), any frequency can be selected when an appropriate tank radius and depth is considered. For high-frequency calibration, drain the water to make the tank shallow. This will shrink the stable sound field diameter because of the shorter wavelength of the fundamental resonant frequency. If a deeper tank is used with a low-resonance frequency, care should be taken about the background noise introduced from the floor. Moreover, larger or deeper tanks require extra efforts for measurements.

Here, we propose a procedure for low-frequency calibration of a hydrophone in a small tank.

1. Prepare a tank filled with freshwater. Maintain stable room temperature during the experiment.
2. Measure the water depth, temperature, and radius of the tank. If the tank shape is tapered, use the average radius at the top and bottom of the water level.
3. Calculate the resonant frequency using Eq. (1).
4. Fix a transducer at a distance of half the tank radius, at half the water depth.
5. Project a continuous wave at the fundamental resonant frequency calculated in step 3.
6. Adjust the source level without any saturation of the sound projection systems such as preamplifier and transducer.
7. Fine-tune the projecting frequency and measure the exposure level. Measure the received sound pressure level using a calibrated hydrophone at the center of the test tank, at half the water depth. Change the projecting frequency by ±20 Hz from the calculated resonant frequency. The frequency with the maximum received sound pressure level is used as the test frequency, and the corresponding sound pressure level is used as the exposure level. Note that the experimental and theoretical resonant frequencies are slightly different, owing to the asymmetric shape of the tank.
8. Set the acoustic device at the center of the tank and project the fundamental resonant frequency.
9. Playback the recorded sound and measure the recorded amplitude level, which should represent the received sound pressure level measured in step 7.

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