Calibration Method Simulation of Linear-array Hydrophone in Underwater Acoustic Network

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Abstract

Aiming at the problem that the amplitude and phase consistency of linear-array hydrophones in underwater acoustic network is difficult to calibrate accurately, this paper proposes a straightforward, high-accuracy calibration method for amplitude and phase of linear hydrophones arrays. First, the hydrophone array is submerged vertically far field of the transmitting transducer, and then the hydrophone array is lifted by a mechanical lifting device without horizontal movement during lifting. Each hydrophone receives and records the signals when it is at the same depth as the transmitting transducer. All the signals received are intercepted and proposed by Fourier transformation to obtain the amplitude-frequency and phase-frequency characteristic curves. Amplitude and phase values corresponding to a given frequency can be determined from these curves. This paper also analyzes the feasibility of the method and several factors which may cause measurement error during simulation. Finally, the calibration of the linear-array hydrophones in underwater acoustic network with ten elements is performed in the laboratory tank. Its results show that the method is effective in calibrating hydrophones for amplitude and phase and easier to operate than any other methods.

Keywords: Hydrophone, Amplitude, Phase, Calibration

1 Introduction

Amplitude and phase readings of different hydrophones in underwater acoustic network usually vary. This refers to differences in recorded amplitudes and phases between hydrophones subjected to identical instantaneous sound pressures. The level of consistency in phase sensing between hydrophones in underwater acoustic network is an important indicator of system performance [1-7]. Hydrophone calibration for amplitude sensing consistency is easy to perform since minor positioning errors during installation of the hydrophones have negligible impact in this regard. Phase, however is difficult to measure accurately with hydrophones, because it is difficult to measure the related distances and medium velocities accurately. The accuracy of these measurements is critical for accurate phase measurement.

In recent years, many scholars have been exploring and studying how to calibrate hydrophones for amplitude and phase [8-9]. There are many methods of calibration, among which the reciprocity method is more commonly used [10-14]. However, this method, at least one, though not necessarily all, of the transducers should be reciprocal to comply with the method requirements. Moreover, this method is unduly complex in operation and requires high installation accuracy. The effect of distance measurement on the calibration results is not eliminated completely. Also, during measurement, for calibration of one hydrophone, the installation of three groups of transducers and measurement of transfer impedance must be repeated four times. In order to solve the problem that the reciprocal calibration method can't guarantee distance measurement accuracy, Xu P. Fei T. et al. [15] decided to measure hydrophone phase consistency by using a coupled resonator to generate a uniform plane wave. However, this method not only requires design and processing of a rigid wall pipe, but also requires consideration of the interference of the pipe's wall resonance on the pipe's surroundings. Another approach to calibration is to use laser [16-18]. However, this method requires sophisticated laser measurement equipment, which is not applicable to the simplicity of the experiment. Comparative method is also one of the calibration methods [19]. This method requires reference hydrophones and is difficult to achieve if the experimental conditions are relatively simple. Besides, there are other methods for calibration. Such as measuring time using phase [20], accurately measuring the phase-shift sensitivity of the head of the fiber optic hydrophone using phases generated using

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DOI: 10.3966/160792642019072004021

the carrier demodulation technique [21] and using coupled resonators [22]. These methods are more or less difficult in practical operation, not only inconvenient in operation, but also strict in instrument requirements.

Different from any other previous research methods, this paper studies a measurement method performed in an open tank in the laboratory, aiming at the measurement of amplitude and phase inconsistencies of linear-array hydrophones in underwater acoustic network. In this method, high installation accuracy is not required (see in Chapter 4 "Error Analysis"). At the same time, accurate measurement of distance, time and medium velocity can be dispensed with. This is the biggest innovation in this research. Moreover, the whole experiment is relatively easy to perform.

The analysis will proceed as follows. First, the measurement method will be introduced in detail. It includes not only the installation of measuring equipment, but also the specific operation methods and steps. Then, the receiving signal and signal processing are analyzed. Next, the error in the method is analyzed. Such as influence of hydrophone spacing or mechanical lifting positional error, the influence of hydrophone depth error, the influence of noise on measurement results and the influence of intercepted signal length on measurement accuracy. Last, experiment is performed to test and verify feasibility of the measurement method in practical operation.

2 Measurement Method

Equipment used in the experiment is shown in Figure 1. Hydrophones are assembled into a linear array (installation error may make the array less than perfectly linear) with each fixed distance intervals between each adjacent pair of hydrophones. The linear array is affixed to the mechanical lifting device which can lift the hydrophone array to predetermined heights (to match the distance intervals between hydrophone pairs). As shown in the Figure 1, the uppermost hydrophone is marked as #1 hydrophone, then hydrophone #2, #3 and so on, from top to bottom. A transmitting transducer is lowered into the water at a distance from the hydrophone array that qualifies as being far afield. To begin of the measuring, the #1 hydrophone and transmitting transducer are lowered to the same depth. Generally it is difficult to guarantee absolutely that the hydrophone and transmitting transducer are at the same depth, but this does not affect the measurement results as long as sufficient accuracy is achieved. The hydrophone array and the lifting device are mechanically fixed, so during lifting, the hydrophone array stays vertical and does not swing or move horizontally.

The detailed procedure is as following:

(1) To begin measuring, #1 hydrophone is lifted to the same depth as the transmitting transducer. Then, the transmitting transducer sends a single-frequency pulse signal whose frequency is f and only #1 hydrophone receives and records the signal, and the time of signal transmission is recorded as the time of initial signal acquisition. Next, the hydrophone array is lifted by a distance equal to the distance interval between two adjacent hydrophones. Next, the transmitting transducer sends a second identical signal, which is received and recorded by hydrophone #2. Measurement is performed in sequence, so N groups of time series signals will be obtained (N is the number of hydrophones).

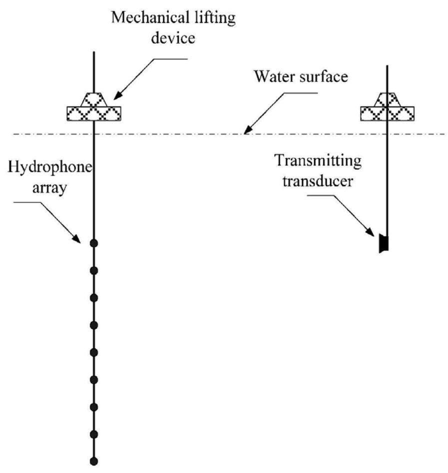


Figure 1. The arrangement of experimental apparatus

(2) For signals received by hydrophone #1, the signal, from initial to steady state, is intercepted and processed by Fourier transformation to obtain characteristic curves for amplitude-frequency and phase-frequency. Then amplitude and phase values are read at frequency f (the frequency of transmitting signal). Last, the signals received by the other hydrophones in the same time frame as when the signal was intercepted by hydrophone #1, are processed with Fourier transformation. Thus, the amplitude and phase values for a plurality of hydrophones can be obtained.

(3) Owing to the fact that the amplitude and phase values of intercepted signals do not necessarily match the set values, the amplitude and phase values need to be processed in the following ways: the N amplitude values obtained above are normalized to get amplitude consistency results for the hydrophone array; a referential hydrophone phase value is subtracted from the N phase values obtained above to get phase consistency results for the hydrophone array.

In the experimental procedure described above, the hydrophone array moved vertically by the mechanical lifting device, which avoids phase errors caused by horizontal positioning errors as seen in traditional methods where hydrophones are moved horizontally and lowered into the water repeatedly. Moreover, this new method is highly efficient because it allows measurement of amplitude and phase consistency of all hydrophones in one linear array at the same time just by moving it with a mechanical lifting device.

Furthermore, this method allows calibration of the hydrophones' consistency after assembling them in a linear array, not only allowing manufacturing inconsistencies between hydrophones to be taken into account, but also considering the impact on consistency caused by installation error during the array assembly process. This provides improved measurement accuracy of inconsistencies between hydrophones.

During actual experimental operation, the following several points need to be considered:

(1) Concerning the transmitting transducer; if the transmitting transducer employed is directional, it is necessary to ensure that the receiving hydrophone is located within the transmitting transducer's directional field. Furthermore, the transmitting transducer and receiving hydrophone should be lowered as far below the water surface as possible to ensure the transmitted sound wave cannot reach the water's surface. This eliminates the multipath effect. If the transmitting transducer employed is non-directional, the location, distance and depth of transmitting transducer and hydrophone need to be considered to ensure the sound wave reflected from water surface does not coincide with the sound wave which travels directly to the hydrophone. Assuming that the path of direct wave is L_1, the path of reflective wave is L_2, and L_2 is longer enough than L_1, the reflected and direct waves must not overlap.

(2) In laboratory water tanks, if the tank is anechoic (echo-proof), it is unnecessary to consider whether the transmitting transducer is directional. This only needs to be considered to confirm whether or not the hydrophone is positioned in the transmitting transducer's far field. Otherwise, that is if the tank is non-anechoic, it is necessary not only to consider whether the transmitting transducer is directional, but also to consider whether the hydrophone is positioned in the transmitting transducer's far field. It is also critical to take into account reflection off of the tank's walls and bottom.

3 Simulation Analysis

Simulation condition: the linear array to be calibrated consists of 10 hydrophones, and from top to bottom the hydrophones are numbered #1, #2,……; assuming that the amplitude and phase settings of the hydrophones are all different, the hydrophones' amplitude setting values are 10 random numbers in the range of [0.5 ,1] and the phase setting values are 10 random numbers in the range of [-20°, 20°]. Moreover, the emitted signal is a single-frequency sound which has a frequency *f* of 35kHz, speed in water of 1500m/s, a wavelength of 4.29cm. The sampling frequency f_s is 500kHz.

3.1 Signal Receiving

At the beginning of the experiment, the #1 hydrophone is positioned at the same depth as the transmitting transducer. Next, the 1# hydrophone receive sand records the signal, a single-frequency (f=35kHz) pulse sent by the transmitting transducer. Then the hydrophone array is lifted sequentially. During each lift, the transmitting transducer sends another identical pulse signal and the hydrophone at the same depth as the transmitting transducer receives and records the signal. In sequence, 10 groups of signals will be collected. Finally, the received signal is, in fact, not stable. The received signals are need to be recorded while they are stable. It is important to note that all hydrophones record their respective signals during the same time interval relative to the time when their respective signals are emitted.

3.2 Signal Processing

Fourier transform is used in signal processing. The sound source signal used in the simulation is:

$$s(t) = A_i \cos(w_0 t + \phi_i) \quad \textbf{(1)}$$

where A_i is amplitude of *i*# hydrophone, ϕ_i is phase of i# hydrophone, $w_0 = 2\pi f_0$, f_0 is the center frequency.

Through Fourier transformation, (1) becomes:

$$\begin{aligned} F(s(t)) &= A_i \cos\phi_i \pi[\delta(w - w_0) + \delta(w + w_0)] \\ &+ jA_i \sin\phi_i \pi / [\delta(w - w_0) - \delta(w + w_0)] \end{aligned} \quad \textbf{(2)}$$

So when $w = w_0$ the real part $A_i \cos\phi_i \pi$ is the amplitude information can be obtained from the curve, and the ϕ_i is the phase can be read.

Taking the recorded signal from hydrophone #1 as an example, using Fourier transformation, the amplitude-frequency and phase-frequency characteristic curves will be obtained as shown in Figure 2.

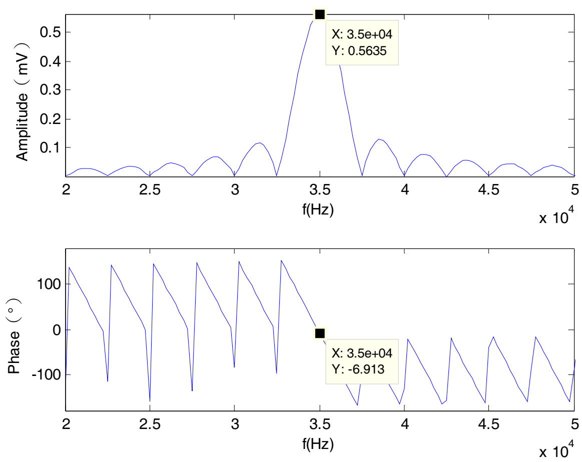


Figure 2. Amplitude-frequency and phase-frequency characteristic curves

Signals recorded by the other hydrophones' intercepted are processed in the same way to get amplitude and phase values from all the 10 hydrophones. Then the amplitude values are normalized to get amplitude consistency, and the phase value from the #1 hydrophone is subtracted from all 10 phase values yield phase consistency. The 10 hydrophones' amplitude and phase settings values are processed in the same way. Thus the settings and measurements can be contrasted, as shown in Table 1. It is observed that the amplitude and phase simulation results are consistent with their theoretical settings without any difference.

Table 1. The simulation results

Hydrophone	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Normalized	Settings	0.86	0.54	0.96	1	0.87	0.91	0.90	0.72	0.86
amplitude	Measurements	0.86	0.54	0.96	1	0.87	0.91	0.90	0.72	0.86
Relative	Settings	0	-27.0	-17.2	-26.4	-24.4	4.7	-0.4	-15.6	9.8
phase	Measurements	0	-27.0	-17.2	-26.4	-24.4	4.7	-0.4	-15.6	9.8

4 Error Analysis

(1) Influence of Hydrophone Spacing or Mechanical Lifting Positional Error

First of all, it can be seen that the influence of hydrophone spacing or mechanical lifting positional error on amplitude can be neglected from the contents above, so hydrophone spacing or mechanical lifting positional error can only influence the phase measurement.

In Figure 1, the height that the lifting device moved the array equals the hydrophones' spacing interval, so the next hydrophone will rise to the position where the last hydrophone was located. Due to the mechanical lifting device inaccuracy and installation positioning error, there will be variations in hydrophone position with each lift, as shown in Figure 3.

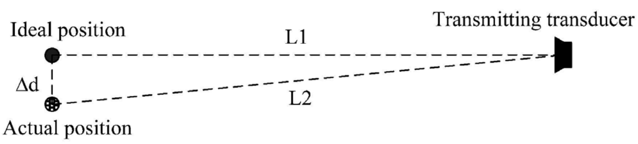


Figure 3. Positional error of hydrophone

Assuming that there is a Δd deviation between hydrophone actual position and ideal position in Figure 3, the distance between the transmitting transducer and hydrophone (ideal position) is L_1, and the distance between the transmitting transducer and hydrophone (actual position) is $L_2 = \sqrt{L_1^2 + \Delta d^2}$. When measuring in laboratory, Δd is very small and generally measured in millimeters, but L_1 can be measured in meters to meet the requirements of far field calibration. $\Delta d \ll L_1$, $L_2 \approx L_1$. Therefore, the influence of hydrophone spacing or mechanical lifting positional error on actual measurement can be neglected.

To explain why this lifting error can be neglected further, the following table is made. The diameter of the transmitting transducer used in this experiment is 9cm, and wavelength mentioned above is 4.29cm. To satisfy far field condition, $L > d^2/4\lambda$, so $L_1 = 1m$, then $L_2 = \sqrt{L_1^2 + \Delta d^2}$, $\Delta t = (L_2 - L_1)/\mathrm{c}$, $\Delta\varphi = 2\pi f_0 \Delta t \times 180/\pi$, then the data can be obtained.

Table 2 shows that when Δd is very small and is generally measured in millimeters, so the impact on phase is so small that it can be neglected.

Table 2. The influence of Δd on phase

4	5	6	7	8	9	10
0.0672	0.1050	0.1512	0.2058	0.2688	0.3402	0.4200

(2) The Influence of Hydrophone Depth Error

In Figure 1, the hydrophone and the transmitting transducer are required to be at the same depth during measurement, but it is difficult to guarantee that in practice, as shown in Figure 4.

Figure 4. Depth error of hydrophone

This method does not require measuring distance precisely between hydrophone and the transmitting transducer. What is required is that between two measurements, the two corresponding hydrophones are at the same position to receive signals sent by the transmitting transducer. Whether the hydrophone and the transmitting transducer are at the same depth or not has no effect on the measurement results. However, for directional transmission transducers, when the hydrophone position deviates from its main lobe range, the hydrophone cannot receive strong enough signals. There is no such problem for non-directional transmission transducers. This method requires the given hydrophone and the transmitting transducer to be at almost the exact same depth because directionality of the transmitting transducer must be taken into account. Analysis of the measurement accuracy seen in Figure 6 can be helpful. In practice, the hydrophone needs to be situated so that is within the depth range of the transmitting transducer's main lobe.

(3) The Influence of Noise on Measurement Results

In practice, environmental noise and other interference cannot be neglected. The following analysis shows the impact of noise on the measurement. Gaussian white noise with SNR (signal-to-noise ratio) ratings of 30dB, 20dB and 10dB is to 10 groups of signals, then the signals are processed by the same method as for Table 1 to get the amplitude and phase consistency differences between measurements and settings. See Table 3. It can be seen that when the SNR is 30dB, the settings of normalized amplitude and relative phase are consistent with measurements, while when the SNR changes from 30dB to 20dB and then to 10dB, the error between measurements and settings increase. To observe the relationship between amplitude and phase consistency and SNR, a specific hydrophone signal needs to be analyzed.

The data from #5 hydrophone is taken as an example to analyze the concrete influence of SNR on amplitude and phase consistency. The amplitude and phase consistency are calculated 500 times at each SNR which was varied from 10dB to 50dB to obtain the error bar chart, see Figure 5. The error bar is a line drawn in the direction of the size of the measured value, with the mean value of the measured object as midpoint, the maximum minus the mean value equals the upper length of the given line and the mean value minus minimum equals the lower length of the line. Usually, this method is used to show the size of the uncertainty about the measured data. In the figure, the curves present the relationship between mean differences between simulation and experimental results at various amplitude/phase settings and environmental noise at various SNRs. Each vertical bar represents the difference between the simulation value and the setting value at each SNR value. This reflects the degree of possible deviation between simulation results and settings.

Table 3. Simulation measurements at different SNRs

SNR=30dB

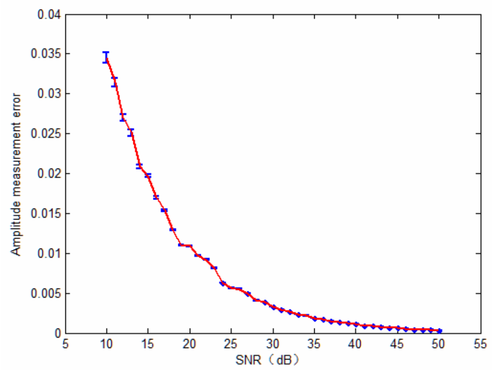
Hydrophone		1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Normalized amplitude	Settings	0.80	0.77	0.98	1	0.66	0.83	0.81	0.92	0.95	0.98
	Measurements	0.79	0.79	0.98	1	0.66	0.83	0.81	0.92	0.95	0.98
Relative phase	Settings	0	18.2	18.7	11.6	23.4	22.7	-10.5	10.9	4.2	-12.3
	Measurements	0	17.7	18.7	11.4	23.4	22.6	-11.2	10.7	4.1	-12.7

SNR= 20dB

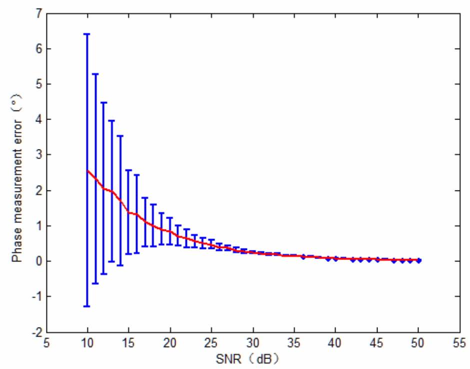
Hydrophone		1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Normalized amplitude	Settings	0.80	0.77	0.98	1	0.66	0.83	0.81	0.92	0.95	0.98
	Measurements	0.80	0.77	1	0.99	0.66	0.83	0.80	0.92	0.95	0.97
Relative phase	Settings	0	18.2	18.7	11.6	23.4	22.7	-10.5	10.9	4.2	-12.3
	Measurements	0	19.9	19.3	11.4	24.4	23.2	-10.7	10.7	5.0	-11.8

SNR=10dB

Hydrophone		1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
Normalized amplitude	Settings	0.80	0.77	0.98	1	0.66	0.83	0.81	0.92	0.95	0.98
	Measurements	0.80	0.72	0.96	1	0.61	0.88	0.85	0.93	0.99	0.99
Relative phase	Settings	0	18.2	18.7	11.6	23.4	22.7	-10.5	10.9	4.2	-12.3
	Measurements	0	20.9	20.5	7.2	21.6	20.7	-10.4	8.3	7.7	-14.9



(a) Amplitude consistency measurement accuracy



(b) Phase consistency measurement accuracy

Figure 5. Measurements accuracy at different SNRs

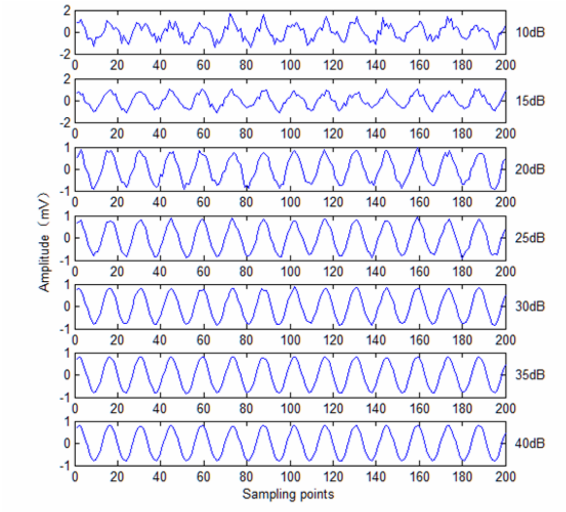


Figure 6. The signals at different SNRs

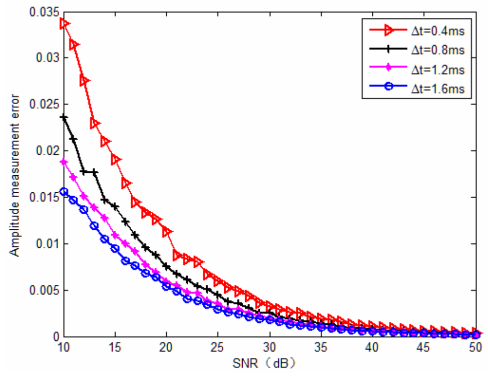
From Figure 5 and Figure 6, it can be seen that with decreasing SNR values, the waveform becomes distorted and measurement accuracy is decreased. But even when SNR drops to about 25dB, measurement accuracy is still highly satisfactory. In fact, signals with high SNR (>25dB) can easily be generated in the laboratory tank. Therefore, although noise can introduce some error into measuring, it does not have too much impact on measurement results. If high accuracy measurements results are needed, reducing noise interference is an appropriate method.

In order to make the effect of the noise on the signal waveform clearer, Figure 6 shows all the signals received of 5# hydrophone under different SNRs.

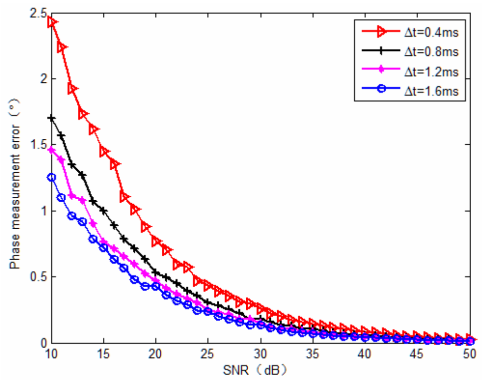
(4) The Influence of Intercepted Signal Length on Measurement Accuracy

Also, taking hydrophone #5 as an example, signals were received at hydrophone #5 with noise interference for different lengths of time: $\Delta t = 0.4ms$, $\Delta t = 0.8ms$, $\Delta t = 1.2ms$, $\Delta t = 1.6ms$. The number of sampling points corresponding to each time segmentwere 200, 400, 600 and 800, and the number of signals received during each time segment were 14, 28, 42 and 56 respectively. Each during of signal interception was simulated 500 times to analyze amplitude and phase consistency, see Figure 7.

It can be seen that with increasing lengths of signal interception time, the measurement accuracy of amplitude and phase consistency can be improved without change in SNR. Spectrum energy leakage effects, caused by signal truncation and periodic extension in the Fourier transform, contribute to this phenomenon. Also, it can be seen that with increases in SNR, measurement errors for signals of various interception time lengths decrease and trend toward zero.



(a) Amplitude measurement accuracy

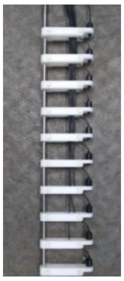


(b) Phase measurement accuracy

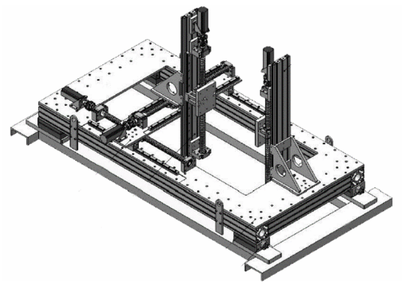
Figure 7. Measurements accuracy at different interception lengths

5 Experimental Measurement

In order to test and verify feasibility of the measurement method in practical operation, the method is used in an experiment. In a laboratory tank, the amplitude and phase consistencies of the linear-array of hydrophones are measured. The linear array consists of 10 hydrophones and the interval between adjacent hydrophones is 10cm, as shown in Figure 8(a). The transmitting transducer is a directional cylindrical piston transducer. The linear-array hydrophones are placed in the far field of the transmitting transducer. Figure 8(b) is the schematic diagram of the mechanical structure used to affix the hydrophone array and transmitting transducer. Figure 8(c) is an actual photograph. The hydrophone array is fixed vertically on the mechanical frame so that the linear array can move horizontally and vertically. However, during experiment, the position of the hydrophones and the transmitting transducer are adjusted to meet the requirements of far field positioning. The hydrophones and transmitting transducer are fixed on the mechanical frame. The hydrophones can only be lifted vertically with no horizontal movement.



(a) The linear-array hydrophones



(b) The mechanical structure

(c) The actual equipment

Figure 8. The experimental equipment

In this experiment, the tank is anechoic, so whether the transmitting transducer is directional or not is not considered and the hydrophones are positioned in the transmitting transducer's far field.

As shown in Figure 1, a linear array with 10 hydrophones is submerged vertically. The distance between array elements is 10cm, and the distance between the hydrophone array and transmitting transducer is about 0.7m. The transmitted signal is a CW pulse signal whose frequency is 35kHz, consisting of 40 waves. The sampling rate of the received signal is 500kHz. Hydrophone array elements from top to bottom are numbered #1, #2, #3 through #10. Figure 9 is the signal waveform received by hydrophone #1.

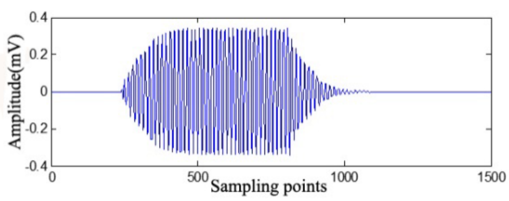


Figure 9. The signal received of 1# hydrophone

It can be seen that the pulse signal received above is not stable, so it is intercepted with 500~700 sampling points when it reaches steady state. The other hydrophones intercept signals for the same length of time. All the signals intercepted are as shown in Figure 10. From top to bottom are signals from hydrophone #1, 2#... and so on.

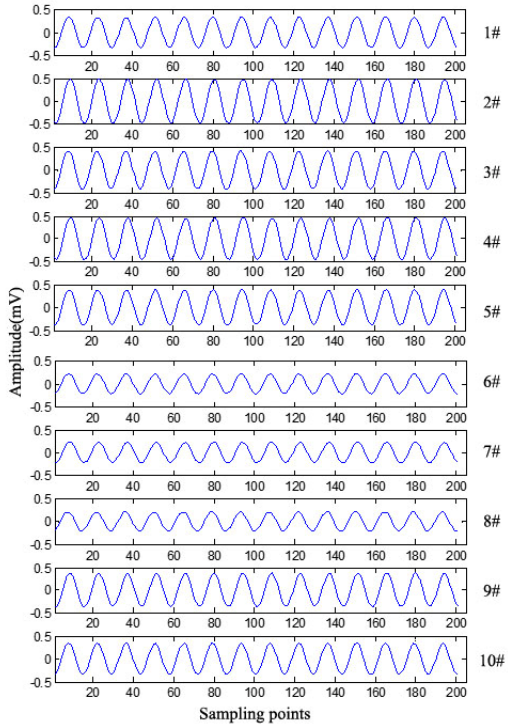


Figure 10. Signals intercepted by all hydrophones

The signals in Figure 10 are processed by Fourier transformation. Amplitude and phase values at 35kHz will be obtained. Then the 10 amplitude values obtained were normalized. At the same time, hydrophone #1's phase value was subtracted from the 10 phase values. Therefore, the final measurement results were obtained, as shown in Figure 11.

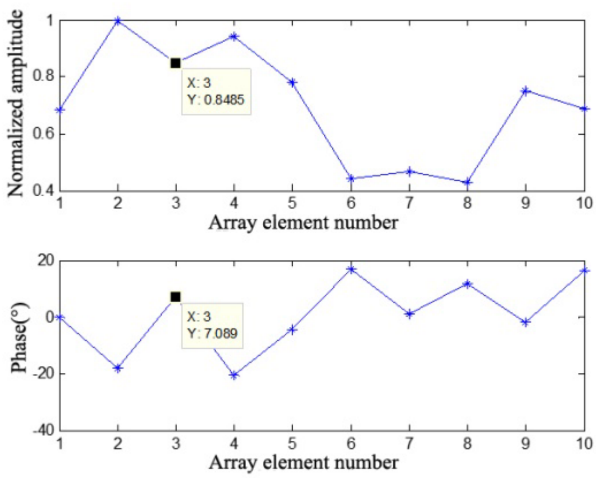


Figure 11. Experimental measurements in a pool

Measurement values in Figure 11 are the amplitude and phase consistency results from the hydrophone array. In Figure 11 it can be seen that the amplitude and phase in consistencies which existed in hydrophones were obvious. This variability exits in all hydrophones because of standard manufacturing tolerances, so their amplitudes and phases are different under the same instantaneous sound pressure. Moreover, when these hydrophones are put in array, they may not be positioned perfectly in line with each other, so they may receive signals indifferent positions. These positioning errors can lead to differences in amplitudes and phases.

To further verify the correctness of the measurement results from this experiment, the hydrophone array consistency results were modified by artificially changing the hydrophone's amplification and time delay of received signals. Here the #3 hydrophone signal amplification is decreased to half, which means that the amplitude decreases to half, and the amplitude sensitivity reduced by half; delaying by 1 sampling point, then the time delay is adjusted to $\Delta t = 1/f_s$, the phase delay to $\Delta\varphi = 2\pi f \Delta t$ *rad*. This means that about a 25.20 degree equivalent phase delay was introduced. Results of measurement data processing are shown in Figure 12.

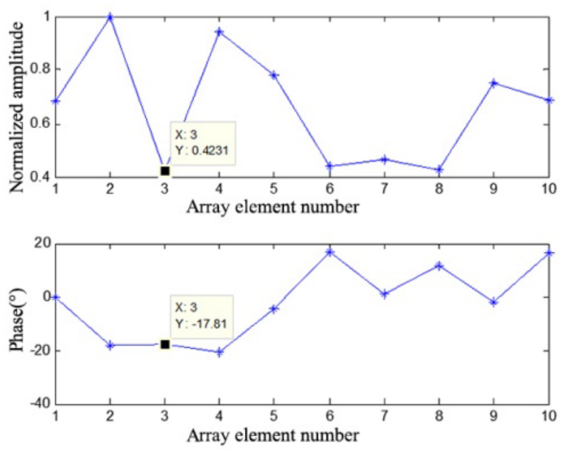


Figure 12. The measurements from hydrophone #3 after changing consistency

As can be seen from Figure 12, the amplitude of hydrophone #3 is reduced by approximately 1/2, and the phase is reduced by about 24.90 degrees. There are some errors existing in the amplitude and phase values, which are mainly caused by discrete sampling of signals. The method proposed is verified since it can measure the consistency of hydrophone amplitude and phase precisely as seen in the experimental measurements shown in Figure 11 and Figure 12. In practice, the effect of SNR on measurement can usually be ignored because the SNR is usually high enough to avoid having any serious impact. Proof is given as follows: The method for calculating SNR is to divide received signal power by environmental noise power when no signals are being transmitted. The SNR in the laboratory tank was calculated from measurements to be 38.3dB. The amplitude error was 0.0013 and phase error 0.0947, as seen in Figure 5. From this data, it seems that in practice, the influence of environmental noise on experimental results can be neglected.

6 Conclusion

This paper presents research into method for calibrating the amplitude and phase consistency of linear-array hydrophones in underwater acoustic network. Firstly, the method of measuring amplitude and phase consistency of linear-array hydrophones in underwater acoustic network was introduced. The hydrophone array moves vertically to avoid the phase error caused by horizontal positioning error. Besides, this method is highly efficient because it can measure amplitude and phase consistency of all hydrophones in one linear array with a single process. Then some factors of measurement error, such as hydrophone installation spacing and mechanical lift positioning errors, hydrophone depth errors, environmental noise, and time length of signal interception, are analyzed. The analysis indicates that the influence of hydrophone spacing and mechanical lift positional errors and hydrophone depth errors can be neglected when the transmitting transducer is directional. And the measurement data obtained by computer simulation shows that calibration accuracy changes with different SNR's and different lengths of signal interception time. Laboratory results from testing large hydrophone arrays, of 10 hydrophones, show that the method is verified to precisely measure hydrophone amplitude and phase sensing consistency by adjusting the hydrophones' amplitude sensitivity and phase delay.

By measuring hydrophone amplitude and phase consistency using linear arrays, calibration for these hydrophones is easily performed. This is the focus of a future patent application which will concentrate on hydrophones assembled in arrays. But for a large number of hydrophones in underwater acoustic network, this method cannot be applied, because the depth of the pool is limited. So, in the future study, the calibration for a large number of hydrophones is main research direction.

Acknowledgments

This research was funded by the National Key R&D Program of China (2018YFC1405900), the National Natural Science Foundation of China (Grant No. 61631008, No.11404077 and No. 51779061), The Fok Ying-Tong Education Foundation, China (Grant, No. 151007), The Heilongjiang Province Outstanding Youth Science Fund (JC2017017), and the Innovation

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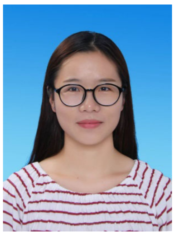

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