

ANALYSES OF SIGNAL PROCESSING METHODS APPLIED IN WIDE BAND FREE-FIELD CALIBRATIONS OF HYDROPHONES

Guanghai Jia^{1,2}, Yi Chen,^{1,2} and Liuqing Yang^{1,2}

¹ Hangzhou Applied Acoustics Research Institute, Hangzhou, 311400, China

² Zhejiang Key Laboratory of Acoustical Testing Technology

Guanghai Jia, Hangzhou Applied Acoustics Research Institute, Fuyang District, Hangzhou, Zhejiang Province 311400, China, 13732264446@163.com

Abstract: *In free-field underwater acoustic measurements, wide band free-field calibrations of hydrophones are limited by the reflecting acoustic waves from boundaries. The free-field calibration model containing the directing acoustic wave and reflecting acoustic waves are established, and signal processing methods can be used to eliminate the reflections from boundaries, which are widely applied in wide band hydrophone calibrations and expanding their frequency limitations. The characteristics of the directing acoustic wave and reflecting acoustic waves of free-field calibrations are discussed based on a linear response system. The applications of signal processing in time domain and frequency domain which enable wide band free-field calibration to be undertaken in a limited space and decrease the reflections from boundaries are described. The wide band experiments of hydrophones were respectively performed using noise signals and chirp signals in several laboratory underwater tanks, and the wide band sensitivities were obtained. The responses of different signal processing methods were analysed which can give instructions of wide band hydrophone calibrations in laboratory underwater tanks.*

Keywords: *calibration, wide band, signal processing, free-field*

1. INTRODUCTION

Hydrophones are widely used in underwater measurements to detect the pressure variations of acoustic waves in water and produce an output voltage proportional to the acoustic pressure [1], [2]. Hydrophones are usually calibrated in a laboratory water tank with limited volume. Reflecting acoustic waves from boundaries and water surface will interfere the free-field measurement acoustic environment. To perform hydrophone calibrations in these water tanks, gated sinusoidal are utilized in discrete acoustic frequencies. These gated sinusoidal signals can be used to eliminate the reflecting acoustic waves in time domain through the arriving time interval of the directing acoustic wave and reflecting acoustic waves. In that condition, the receiving signals of hydrophones need reach the steady-state conditions before the reflecting acoustic waves interfere the directing acoustic wave [3]. However, some hydrophones are widely applied in underwater acoustic monitors, which receive wide band signals, such as noise signals and chirp signals, and they are preferred to be calibrated by wide band signals as well. However, wide band calibration cannot be performed using gated sinusoidal signals because they will last long time, and the receiving signals by a hydrophone is the combination of the directing acoustic wave and reflecting acoustic waves, which is hardly distinguishable in time domain.

There are two ways to perform wide band calibration in limited water tanks. One is to perform in a larger water region, and the reflecting acoustic waves will be attenuated by spherical transmitting and boundaries. Some primary calibrations were performed in large water regions [4]. However, the large water region is not an ideal place for wide band calibrations, because the calibration environments are hard to control, and the background noise will influence the calibration processing, especially for wide band noise signals. The noise signals and background noises can hardly be distinguished by the method of coherent average. The other way is to perform signal processing in the calibration. The complex moving weighted average (CMWA) technique can obtain the wide band transform impedance of the projector and the receiver and eliminate the reflecting acoustic waves [5]. The frequency domain filter processing (FDFP) is another signal processing technique based on the space relationship between the projector and the receiver [6], [7]. Chirp signals are used in the method of CMWA, and the moving average process is performed in time domain, where the dependence of time and frequency is known. Random signals can be used in the method of FDFP, where the relationship between the frequency and time is hard to obtain. The processes are performed in frequency domain.

The CMWA and FDFP are used in free-field primary calibrations and optical calibrations. The frequency response of transfer function is simulated and analysed in this paper, which is crucial to realise wide band calibrations. The differences between the CMWA and FDFP is also discussed which is performed in different water tanks.

2. PRINCIPLE OF WIDE BAND CALIBRATIONS

For a wide band free-field calibration, the system consisting of a projector and a hydrophone can be considered as a linear time invariance system, the frequency response of the transform impedance in the reverberation condition can be expressed as follows

$$Z(f) = \frac{S(f)H(f)M(f)}{r} \quad (1)$$

where, $Z(f)$ is the transform impedance, $H(f)$ is the frequency response of the water tank transfer function, $S(f)$ is the transmitting current response of the projector, $M(f)$ is the sensitivity of the hydrophone, r is the distance between the projector and the hydrophone.

If the measurement is performed in a free-field acoustic environment without reflecting acoustic waves, the circumstance can be considered as a spherical wave radiated by a source, where the water tank transfer function can be expressed as $H(f)=1$. When the receiving acoustic wave is the superposition of the directing acoustic wave and reflecting acoustic waves, that water tank transfer function can be expressed as

$$H(\Delta d_n, f) = \frac{p_0(d, f) + \sum_{n=1}^N p_n(d, f)}{p_0(d, f)} = 1 + \sum_{n=1}^N A_n e^{-\frac{j\omega\Delta d_n}{c}} \quad (2)$$

where, $p_0(d, f)$ is the directing acoustic wave, $p_n(d, f)$ is the n th reflecting acoustic waves, A_n is the ratio of n th reflecting acoustic wave to the direct acoustic wave, Δd_n is the acoustic propagation difference between the reflecting acoustic waves and the directing acoustic wave, $\omega=2\pi f$.

The transform impedance can be expressed as

$$Z(f) = \frac{S(f)M(f)}{r} \left(1 + \sum_{n=1}^N A_n e^{-\frac{j2\pi f\Delta d_n}{c}} \right) \quad (3)$$

In the processing of CMWA, the frequency response of the transfer impedance at frequency f_0 is $Z(f_0)$, which can be calculated as

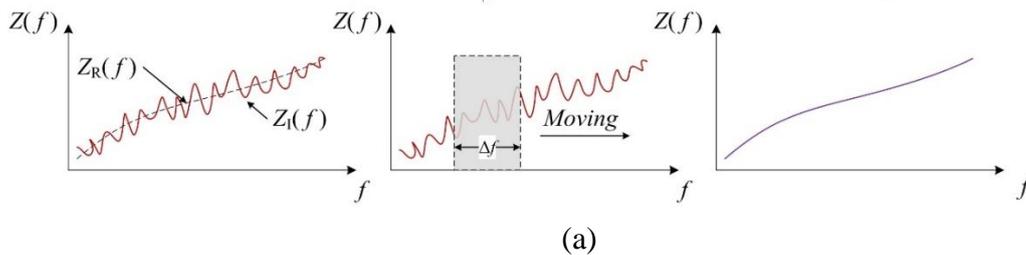
$$\bar{Z}(f_0) = \frac{1}{\Delta f} \int_{f_0 - \frac{\Delta f}{2}}^{f_0 + \frac{\Delta f}{2}} Z(f) df \quad (4)$$

where, $\bar{Z}(f_0)$ is the transform impedance at frequency f_0 after CMWA, Δf is the frequency interval. In equation (4), the transmitting current response $S(f)$ is symmetrical, and the sensitivity $M(f)$ is flat. This processing can be shown in Figure 1 (a), the frequency response of $Z_R(f)$ is the free-field transform impedance without interference, and the frequency response of $Z_I(f)$ is the transform impedance with interferences.

By using Fourier transform, the transfer function $H(f)$ can be expressed in space function $h(\Delta r)$ in the spatial domain as

$$\begin{aligned} h(\Delta r) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \left(1 + \sum_{n=1}^N A_n e^{-jk\Delta d_n} \right) e^{jk\Delta r} d\Delta r = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{jk\Delta r} d\Delta r + \sum_{n=1}^N \frac{A_n}{2\pi} \int_{-\infty}^{\infty} e^{-jk(\Delta r_n - \Delta r)} d\Delta r \\ &= \delta(\Delta r) + \sum_{n=1}^N A_n \delta(\Delta r_n - \Delta r) \end{aligned} \quad (5)$$

where, the first term $\delta(\Delta r)$ is directing acoustic wave, and $A_n \delta(\Delta r_n - \Delta r)$ in the second term is the n th reflecting acoustic waves. Since the acoustic propagation path difference Δr_n is a discrete value, it is possible to design a lowpass spatial filter to reduce the acoustic reflecting waves with propagation path differences Δr_n . The equation (5) and the low-pass filter can be simplified shown in Figure 1 (b). To realize the linear phase response, the finite-duration impulse response filter is used to reduce the reflecting acoustic waves.



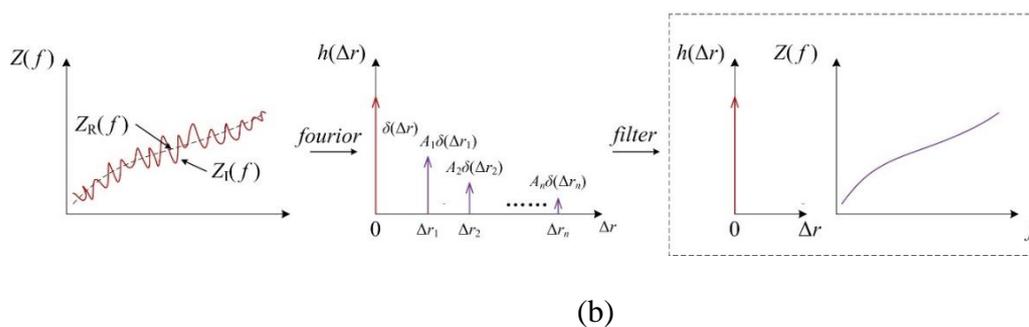


Fig.1: The processing of CMWA and FDFP, (a) the processing of CMWA, (b) the processing of FDFP.

3. COMPARISON BETWEEN DIFFERENT METHODS

3.1 Simulations and analyses of reflections in a water tank

According to the principle of the wide band calibration theory, the frequency response of the transform impedance is determined by the frequency response of water tank transfer function $H(f)$. The frequency response of the water tank transfer function is dependent on the time delay, spatial position, and reflections. However, the frequency response of water tank transfer function cannot be obtained directly. To analyse these methods, a simulation of water tank with reflections was established, and the water tank transfer function can be analysed.

A small water tank always has high strength of reflections, and the simulation is performed in this kind of water tank condition. A projector and receiver are deployed in the centre of a small water tank with size of 1.8 meters length, 1.2 meters depth, and 1.0 meters width. The distance between the projector and the receiver is 0.3 meter, and the acoustic propagation distance between the direction and the first-reflection of different boundaries is approximately to 1.24 meters, 1.04 meters, and 1.8 meters. The strength of the multiple reflections is small which can be ignored. To ensure the simulation is efficient, absolute reflections are hypothesised.

The CMWA is only available to wide band signals that the information of time and frequency is known, and the water tank transfer function can be obtained through the chirp signals in time domain. FDFP can attenuate reflections in spatial domain, and it is available to any wide band signals without the information of time and frequency. To compare these two methods, the chirp signal is used in this simulation. The original and processed water tank transfer function is shown in Fig.2. For amplitude frequency response of the water tank transfer function, it converges to 1 in theory. Fig.2 (a) and Fig.2 (b) show that these two methods are efficient in wide band calibration of hydrophones. The maximum deviation of these two methods is less than 2%. For phase frequency response of the water tank transfer function, the maximum deviation is 1° , which is approximate to theoretical 0° . The method of CMWA has high resolution than FDFP, however, the resolution of FDFP is also enough to analyse the frequency response for hydrophone calibrations. In addition, the projector-receiver system is a reasonable, which has low frequency limitation after processing. Thus, the low frequency limitation of this simulation is 2500 Hz.

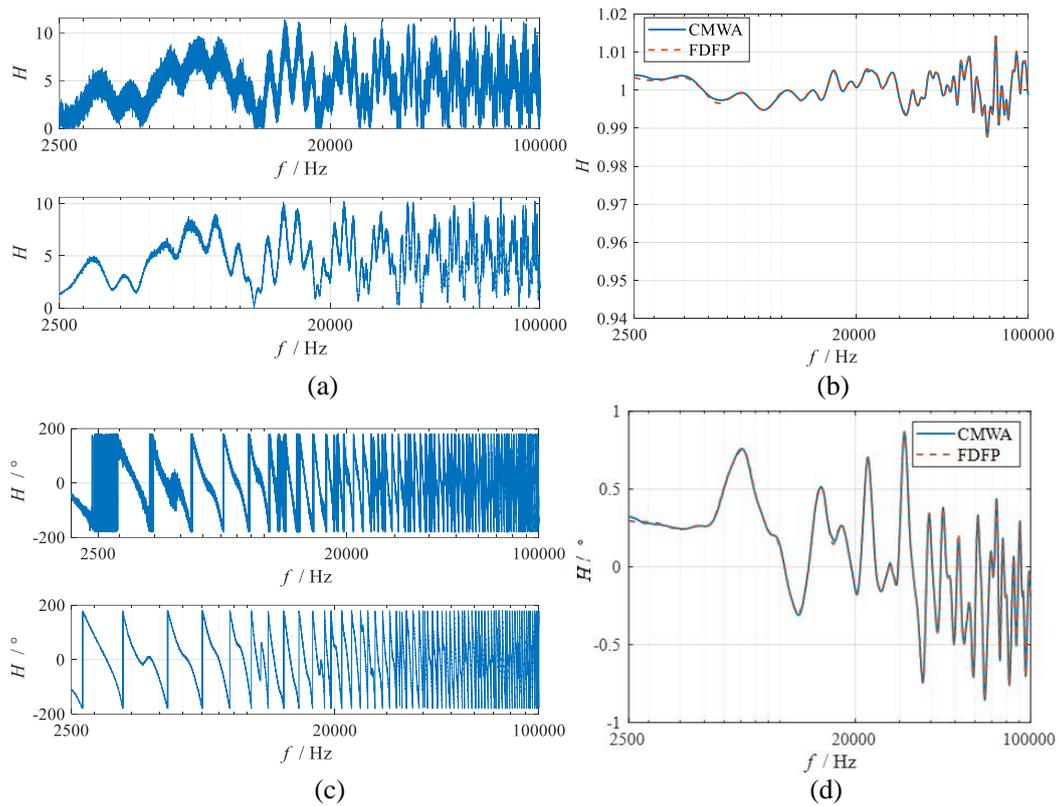


Fig.2: Water tank transfer function $H(f)$, (a) the amplitude response of the original water tank transfer function, (b) the amplitude response after processing, (c) the phase response of the original water tank transfer function, (b) the phase response after processing.

3.2 Wide band calibration results of hydrophones

Several wide band hydrophone experiments are performed in different water tanks. The hydrophone of B&K 8103 was calibrated in a water vessel of 1.8 meters length and 1.2 meters radius through an optical method, and the method of FDFP and CMWA are utilized respectively. In these experiments, the frequency resolution of CMWA is calculated through the relationship of time and sweep rate. The frequency resolution of FDFP is calculated through Fourier transform. Although the frequency resolution is different in these experiments, the frequency responses will be obtained correctly in both methods. The sensitivity results show that the method of CMWA and FDFP are consistent with each other, and the maximum deviation between these two methods is approximately to 0.3 dB. The same hydrophone is also calibrated by a primary method in a larger water tank, and the discrete frequency tone burst signals are used in the calibration. These results are shown in Figure 3.

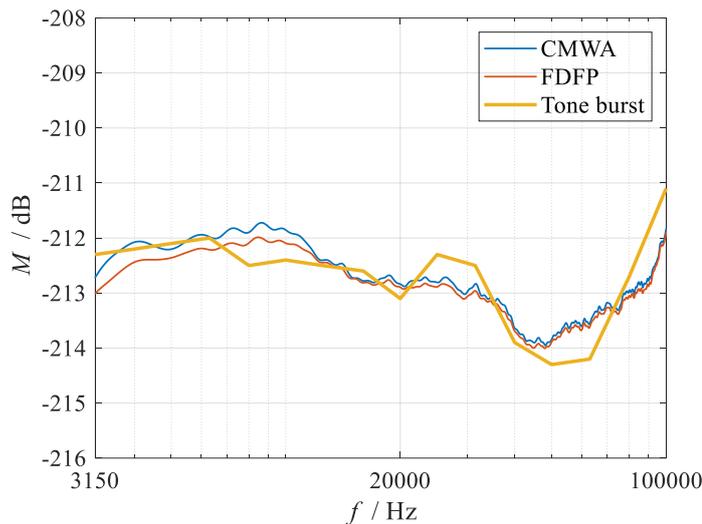


Fig.3: Sensitivity of the B&K 8103 hydrophone calibrated by different methods in a vessel.

A hydrophone of B&K 8106 was wide band calibrated using random noise signals in a large water tank by a primary calibration method, and the calibration range was 250 Hz to 10 kHz. The wide band frequency response of the sensitivity can be obtained directly, and the reflections were eliminated by the method of FDFP. The discrete frequency tone burst signals were also used in the free-field calibration as well, and this calibration can only be performed in the frequency range 1 kHz to 10 kHz. The calibration results are shown in Fig.4, and the maximum deviation between the tone burst signal and FDFP is less than 0.7 dB, which validates that the wide band calibration by FDFP is accurate.

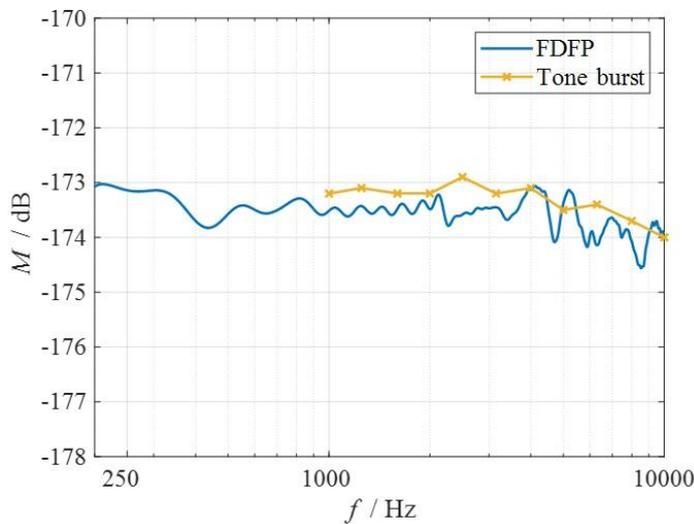


Fig.4: Sensitivity of the B&K 8106 hydrophone calibrated by different methods in a large water tank.

4. CONCLUSION

Wide band sensitivity is crucial for hydrophones, and, it is a big challenge to calibrate in free-fields. For discrete frequency tone burst signals, which is widely used in the free-field

calibration of hydrophones, it is difficult to distinguish the directing acoustic wave to reflecting acoustic waves, and the acoustic interference will influence the calibration accuracy. To increase the wide band calibration accuracy and eliminate the reflecting acoustic waves from boundaries and water interface, the signal processing technique is applied in free-field calibrations.

Two well-known signal processing methods applied in free-field calibrations are introduced, and the characteristics of these methods are analysed through the simulation and experiments. Although different processing is performed and analysed, the frequency response of transfer impedances can be obtained accurately. The amplitude and phase response are approximate to theoretical quantity. The commercial hydrophones type of 8103 and 8106 manufactured by B&K were calibrated in different water tanks using wide band method of CMWA and FDFP respectively. These hydrophones were also measured by traditional primary method using tone burst signals. The methods of CMWA and FDFP are in a good agreement with each other in wide band frequency range. In addition, the sensitivities calibrated by wide band calibration method is approximate to the results calibrated by primary method in 1/3 octave frequency points. Therefore, the wide band calibration methods of CMWA and FDFP can be accurately applied to hydrophone calibrations

5. ACKNOWLEDGEMENTS

This work is supported by the National Key R&D Program of China (Grant No. 2022YFF0607503).

REFERENCES

- [1] **R. J. Bobber**, Underwater Electroacoustic Measurements, Peninsula Press, Los Altos CA, pp. 27–31, 1988.
- [2] IEC 60565-1: 2020, Underwater acoustics – Hydrophones – Calibration of hydrophones – Part 1: Procedures for free-field calibration of hydrophones, International Electrotechnical Commission, Geneva, Switzerland, 2020.
- [3] **S. P. Robinson, G. Hayman, P. M. Harris, and G. A. Beamiss**, Signal modelling methods applied to the free-field calibration of hydrophones and projectors in laboratory test tanks, *Meas. Sci. Technol.* 29, 085001, 2018.
- [4] **S. P. Robinson, P. M. Harris, B. Ford, J. Ablitt, Y. Chen, A. Biber, A. C. Corakci, R. Costa-Felix, S. Crocker, A. E. Isaev, V. Tyalimpi, and G. Latha**, CCAUV.W-K2 final report – Key comparison CCAUV.W-K2: Calibration of hydrophones in the frequency range from 250 Hz to 500 kHz, *Metrologia*, 59, Number 1A 09003, 2022.
- [5] **A. E. Isaev and A. N. Matveev**, Calibration of hydrophones in a field with continuous radiation in a reverberating pool, *Acoustical Physics* 55, 762–770, 2009.
- [6] **Yi Chen, Liuqing Yang, Lisheng Zhou, Xiaofeng Jin, Guanghui Jia**, Calibration of hydrophones using a frequency domain filter processing method: theory and experiment, *Meas. Sci. Technol.* 32 035012, 2021.
- [7] **Guanghui Jia, Yi Chen, Juan. Tu, and Dong Zhang**, A primary wideband calibration method for noise hydrophones based on three-transducer spherical wave reciprocity in the frequency domain, *J. Acoust. Soc. Am.* 156, 1633–1645, 2024.

