SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •

June 2016, Vol. 59 062311:1–062311:8
doi: 10.1007/s11432-015-5448-x

An on-line calibration hydrophone with electrostatic actuator

Jingbin WANG[1], Zhaoli YAN[1]*, Bin CHEN[2] & Xiaobin CHENG[1]

[1]*Key Laboratory of Noise and Vibration Research, Institute of Acoustics, Chinese Academy of Sciences, Beijing* 100190*, China;*
[2]*School of Automation, Beijing University of Posts and Telecommunications, Beijing* 100876*, China*

Received May 23, 2015; accepted July 20, 2015; published online March 16, 2016

Abstract On-line sensitivity calibration of hydrophones is of considerable significance for their practical application. An on-line method using an electrostatic actuator is proposed in this paper for a radially polarized cylindrical piezoelectric hydrophone. The theory of this calibration method is analyzed. A calibration structure with an electrostatic actuator is designed, and is integrated with the hydrophone sensing element. The sensitivity and frequency characteristics of the electrostatic actuator are measured experimentally. The sensitivity of the hydrophone is calibrated and compared with its free-field sensitivity. Uncertainty analysis shows that the expanded uncertainty of the proposed calibration method is about 1.1 dB at a confidence probability of 95%, which meets the uncertainty requirements for hydrophone sensitivity calibration.

Keywords underwater measurement, hydrophone, on-line sensitivity calibration, electrostatic actuator, uncertainty

Citation Wang J B, Yan Z L, Chen B, et al. An on-line calibration hydrophone with electrostatic actuator. Sci China Inf Sci, 2016, 59(6): 062311, doi: 10.1007/s11432-015-5448-x

1 Introduction

Hydrophones have a wide range of applications in marine research, the fishing industry, military uses and other areas. Underwater noise measurement, target detection, and sound source localization have been subjects of extensive research in recent years [1–3]. For hydrophones, long-term stability, especially stability of sensitivity, is an essential attribute, owing to limitations on access imposed by the underwater environment where they are installed. The piezoelectric ceramic sensing elements of hydrophones are prone to age-related sensitivity reduction, which affects their response characteristics and results in measurement errors. Periodic sensitivity calibration of hydrophones is required to ensure measurement precision. The comparison and reciprocity methods are frequently used for free-field calibration [4–6]. Reciprocity calibration is an absolute method, which is usually used for reference hydrophone calibration, while comparison calibration is a relative method used for calibrating measurement hydrophones. Calibration with a vibrating liquid column is used for the frequency band below 1 kHz [7]. The problems of all of these calibration methods are that they need to be performed in the laboratory and therefore

* Corresponding author (email: zl_yan@mail.ioa.ac.cn)

© Science China Press and Springer-Verlag Berlin Heidelberg 2016

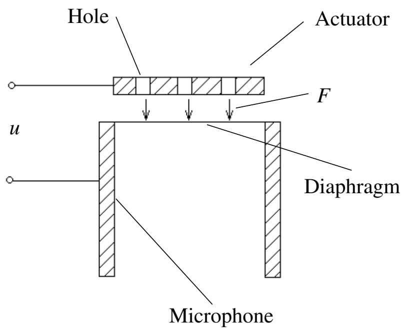

Figure 1 Schematic diaphragm of microphone with electrostatic actuator.

require that the hydrophone is removed from its underwater operating location, which is not an easy task normally. Therefore, research into real-time on-line hydrophone calibration is of practical significance for the field of underwater acoustics.

The electrostatic actuator method is widely used for electret condenser microphone calibration, including frequency response calibration and measurement of microphone sensitivity [8, 9]. In this context, B&K have produced an electrostatic calibration device for electret condenser microphones [10], Shams and Soto have analyzed the contribution of crosstalk to uncertainty in electrostatic actuator calibration of microphones for practical applications [11]. An alternating voltage is imposed between an actuator and the microphone diaphragm, and thereby, instead of sound pressure, an alternating electrostatic pressure is produced to excite the microphone diaphragm. The microphone response characteristics are obtained from the microphone output. The electrostatic pressure on the microphone diaphragm does not depend on the environmental conditions but rather on the driving signal. Figure 1 is a schematic diagram of a microphone with an electrostatic actuator.

Inspired by this approach to microphone calibration, and noting that electrostatic pressure can also be used to simulate sound pressure for exciting the sensing element of a hydrophone, Cheng and Zhang proposed an on-line hydrophone calibration method based on an electrostatic actuator [12, 13], while the theory and performance analyses are insufficient, and the system is not mature enough for practical application.

In this paper, an on-line calibration system with an electrostatic actuator is designed to match a radially polarized cylindrical piezoelectric hydrophone. A theoretical analysis is performed, an expression is derived for the relationship between driving voltage and electrostatic pressure, and an on-line hydrophone calibration algorithm is proposed. The method is validated by experiments using a prototype self-calibrating hydrophone. Finally, the uncertainty of the method is analyzed and its range of applicability is assessed.

2 Theory of the electrostatic actuator system for a cylindrical piezoelectric hydrophone

The electrostatic actuator system for a cylindrical hydrophone is shown schematically in Figure 2. The actuator is made of brass with good electrical conductivity. The sensing element, a cylindrical piezoelectric ceramic, is radially polarized, and both cylindrical surfaces are coated with silver. The actuator and the sensing element are fixed concentrically with electrically insulating materials.

The actuator and the outer surface of the cylindrical ceramic together form a coaxial cylindrical capacitor, the capacitance and electrostatic energy of which are given respectively by

$$C = \frac{2\pi\varepsilon L}{\ln(R/r)}, \tag{1}$$

$$W_e = \frac{1}{2}CU^2 = \frac{\pi\varepsilon L}{\ln(R/r)}U^2, \tag{2}$$

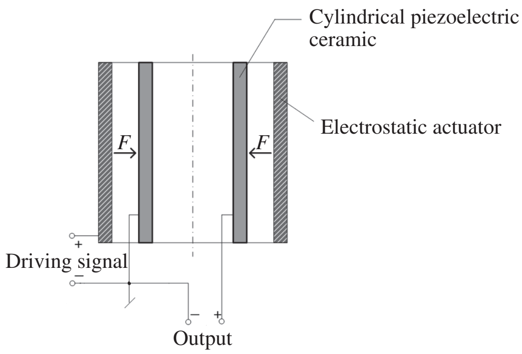

Figure 2 The electrostatic actuator system for the hydrophone.

where ε is the absolute dielectric constant of the medium between the cylindrical ceramic and the actuator, R is the inner radius of the actuator and r is the outer radius of the cylindrical ceramic, L is the axial length of the area of overlap of the actuator and the cylindrical ceramic (which may be of different lengths), and U is the actuator driving voltage. The electrostatic force F between the actuator and the cylindrical ceramic is

$$F=\left(\frac{\partial W_e}{\partial R}\right)_U=-\frac{\pi\varepsilon L}{R\ln^2(R/r)}U^2, \tag{3}$$

where the minus sign indicates that the electrostatic force is attractive. The electrostatic pressure on the outer surface of the cylindrical ceramic p is then

$$p=\frac{F}{S}=-\frac{\varepsilon}{2Rr\ln^2(R/r)}U^2\cdot \tag{4}$$

Eq. (4) shows that the electrostatic pressure p is proportional to the square of the actuator driving voltage U. To obtain a linear relationship between these quantities, a sufficiently high DC voltage U_0 (800 V) is added to the driving voltage U:

$$U=U_0+u_0\sin(\omega t)\cdot \tag{5}$$

Substitution of Eq. (5) into (4) then gives

$$p(t)=-\frac{\varepsilon}{2Rr\ln^2(R/r)}\left[U_0^2+\frac{u_0^2}{2}+2U_0u_0\sin(\omega t)-\frac{\cos(2\omega t)}{2}u_0^2\right]\cdot \tag{6}$$

We define

$$p_{\rm stat}=-\frac{\varepsilon}{2Rr\ln^2(R/r)}\cdot\left(U_0^2+\frac{u_0^2}{2}\right),$$
$$p_{\rm AC}=-\frac{\varepsilon}{Rr\ln^2(R/r)}U_0u_0\sin(\omega\cdot t),$$
$$p_d=\frac{\varepsilon}{4Rr\ln^2(R/r)}u_0^2\cos(2\omega\cdot t),$$

$p_{\rm stat}$ is a static pressure component without any effect on the AC output signal. $p_{\rm AC}$ is the desired output, an AC signal component, to simulate the sound pressure. p_d, the harmonic component of the simulated sound pressure, which contributes harmonic distortion to the electrostatic pressure output, can be suppressed by a low-pass filter, and, in particular, ignored if $u_0\ll U_0$. Then, an approximately linear relationship between the simulated sound pressure p and the driving voltage u is given by

$$p\approx-\frac{\varepsilon}{Rr\ln^2(R/r)}U_0u=\phi(R)u, \tag{7}$$

where

$$\phi(R)=\frac{\varepsilon U_0}{Rr\ln^2(R/r)},\ u=u_0\sin(\omega t)\cdot$$

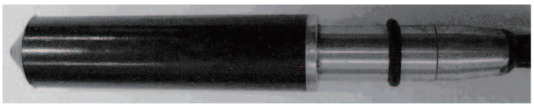

Figure 3 On-line self-calibrating hydrophone prototype.

3 Calibration algorithm

$\phi(R)$ in Eq. (7) is a constant for a given hydrophone structure, and the simulated pressure p can be determined if the driving voltage u is known. The hydrophone sensitivity is then calculated from the hydrophone output V. However, even small errors in the measurement of R and r will lead to large deviations in $\phi(R)$. At the same time, the free-field response of a hydrophone is different from its electrostatic actuating response as a result of the effect of the hydrophone itself on the sound field. Therefore, it is not feasible to obtain $\phi(R)$ directly according to Eq. (7). An on-line calibration method for hydrophone sensitivity is proposed here.

Related parameters are defined as follows:

$V_{\rm ea}$: AC driving voltage on electrostatic actuator;

$p_{\rm ea}$: pressure on outer surface of cylindrical ceramic;

$p_{\rm h}$: free-field sound pressure on hydrophone;

$V_{\rm h}$: output signal of hydrophone;

$M_{\rm h}$: free-field sensitivity of hydrophone: $M_{\rm h} = V_{\rm h}/p_{\rm h}$;

$M_{\rm ea}$: sensitivity of electrostatic actuator, which is the driving voltage of the actuator under the condition that the actuator applies a pressure of 1 Pa on the cylindrical ceramic: $M_{\rm ea} = V_{\rm ea}/p_{\rm ea}$.

It should be noted that under the driving voltage $V_{\rm ea}$ of the actuator, the pressure $p_{\rm ea}$ applied on the cylindrical ceramic is effectively the free-field sound pressure $p_{\rm h}$, since $p_{\rm ea}$ and $p_{\rm h}$ satisfy a fixed relationship $p_{\rm h} = p_{\rm ea}H$. The values of H and the sensitivity $M_{\rm ea}$ defined above are determined by the structure of the hydrophone under consideration.

According to the parameter definitions given above,

$$\frac{M_{\rm h}}{M_{\rm ea}} = \frac{V_{\rm h}/p_{\rm h}}{V_{\rm ea}/p_{\rm ea}} = \frac{V_{\rm h}}{V_{\rm ea}H} \Rightarrow M_{\rm ea} = \frac{V_{\rm ea}H}{V_{\rm h}} M_{\rm h} = M_{\rm eao}H, \tag{8}$$

where $M_{\rm eao} = \frac{V_{\rm ea}}{V_{\rm h}} M_{\rm h}$.

On-line calibration of the hydrophone can proceed once $M_{\rm eao}$ has been determined. First, an AC driving voltage $V'_{\rm ea}$ is applied to electrostatic actuator, then the hydrophone output $V'_{\rm h}$ is measured, and finally the free-field sensitivity $M'_{\rm h}$ of the hydrophone is obtained as follows:

$$M'_{\rm h} = \frac{V'_{\rm h}}{V'_{\rm ea}H} M_{\rm ea} = \frac{V'_{\rm h}}{V'_{\rm ea}} M_{\rm eao}. \tag{9}$$

4 Calibration experiment

To validate this method for on-line hydrophone sensitivity calibration, a hydrophone prototype was constructed, as shown in Figure 3.

The free-field sensitivity frequency response of the hydrophone prototype is shown in Figure 4. The vibrating liquid column method and the comparison method are used for calibration in the frequency bands 0.01–1.00 kHz and 1–20 kHz, respectively. At a confidence probability of 95%, the measurement uncertainties of these calibration methods are 0.6 and 1.0 dB, respectively.

The proposed calibration method has less stringent requirements on sound field conditions than existing methods. In fact, the background noise is the main factor that needs to be considered in this experiment. The experimental equipment is shown in Figure 5. The background noise level is about 100 dB. An AC signal u from a signal generator (Agilent 33220 A) is input to the amplifier with 30 dB gain, with 800 V DC offset being added. Pressure is applied on the cylindrical ceramic by the actuator, which is driven by

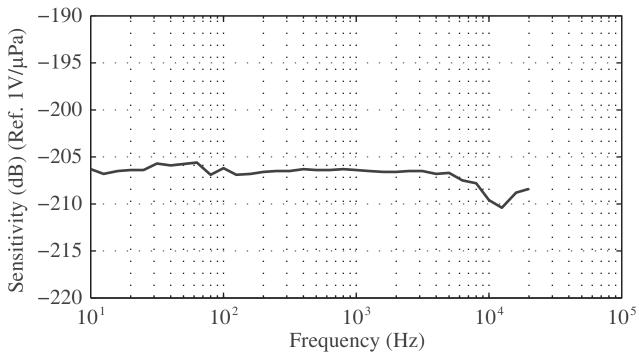

Figure 4 Free-field sensitivity frequency response of the hydrophone prototype.

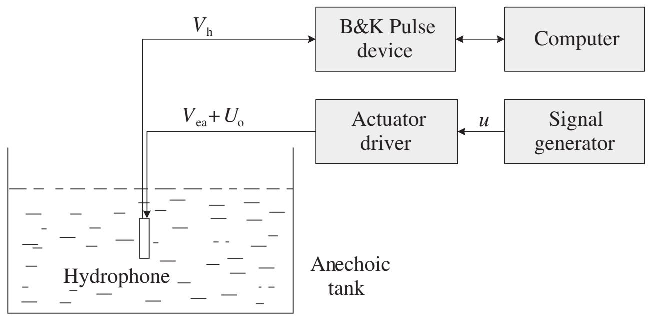

Figure 5 Experimental installation for hydrophone calibration with an electrostatic actuator.

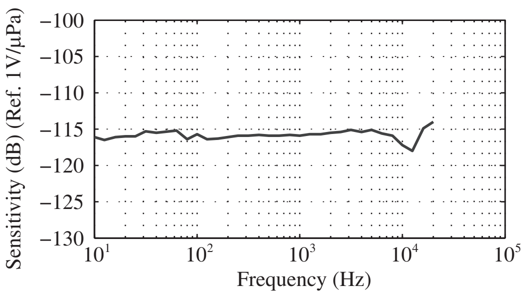

Figure 6 Frequency response of electrostatic actuator.

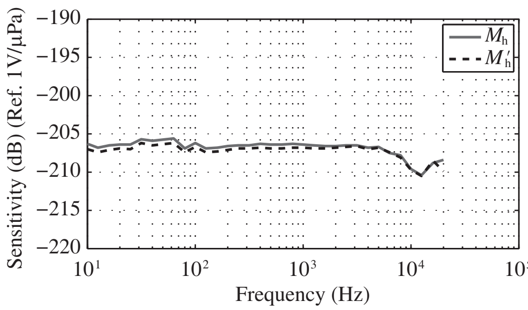

Figure 7 Comparison of frequency response using the electrostatic actuator method and free-field sensitivity frequency response of the hydrophone prototype.

the output of the amplifier. A B&K Pulse device type 3050 is used for signal sampling. The frequency response of the actuator is obtained from the hydrophone free-field sensitivity $M_{\rm h}$, the hydrophone output $V_{\rm h}$, and the actuator driving voltage $V_{\rm ea}$, as shown in Figure 6.

The actuator input $V'_{\rm ea}$ and hydrophone output $V'_{\rm h}$ are measured during the process of calibration, and the free-field sensitivity of the hydrophone, $M'_{\rm h}$, is then calculated according to Eq. (9). As shown in Figure 7, the maximum difference between two calibration results is 0.6 dB. This stability of the calibration results is validated by repeated experiments, and measurement uncertainty is analyzed in the next section.

5 Error and uncertainty analysis

Denoting the free-field sensitivity of the hydrophone by $M_{\rm h}^{\sim}$ and the sensitivity calibrated using the

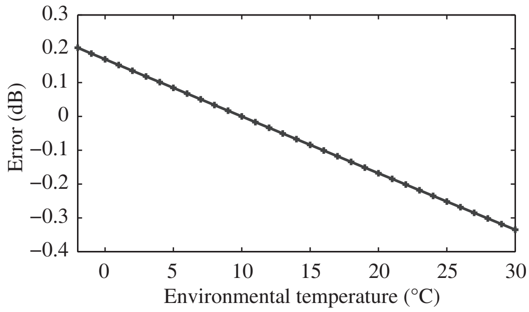

Figure 8 Effect of marine temperature on calibration results.

proposed method by M_{h}, the error is given by

$$\Delta M_{\mathrm{h}} = 20\lg\frac{M_{\mathrm{h}}}{M_{\mathrm{h}}^{\sim}}. \tag{10}$$

Because M_{ea} and H are regarded as constants, as mentioned above, all the factors affecting M_{ea} and H should contribute to the measurement errors. In addition, the environmental background noise and measurement errors also affect the calibration results.

5.1 Temperature

The ambient temperatures for the on-line calibration experiment and the calibration of the actuator sensitivity M_{ea} are denoted by $T^{''}$ and $T^{'}$ respectively. It is known that M_{ea} is a function of ε, R, and r as follows:

$$M_{\mathrm{ea}} = \phi(R)^{-1} = \frac{Rr\ln^2(R/r)}{\varepsilon U_0}. \tag{11}$$

The absolute dielectric constant ε varies with temperature. R and r, the radii of the actuator and the cylindrical piezoelectric ceramic, also vary with temperature: expanding with heat and contracting with cold. Thus, variations in ambient temperature inevitably introduce errors.

The experimental parameters are as follows: $T' = 10\,^{\circ}\mathrm{C}$, $R = 5.1$ mm, $r = 5$ mm, and $\varepsilon = 2.8$ mm. The linear expansion coefficients of brass and the piezoelectric ceramic are $a_c = 16.5 \leftrightarrow 10^{-6}$ and $a_{\mathrm{PZT}} = 1 \leftrightarrow 10^{-6}$ mm/(mm $\cdot$ °C), respectively. The fluctuation amplitude of the dielectric constant ε is 0.1 per 100 °C temperature variation. Assuming a linear dependence of ε on the ambient temperature, the following relationship is obtained:

$$\left.\begin{array}{l} R' = R \times (T'' - T') \times a_c + R \\ r' = r \times (T'' - T') \times a_{\mathrm{PZT}} + r \\ \varepsilon' = \frac{-0.1}{100} \times (T'' - T') + \varepsilon \end{array}\right\} \Rightarrow M'_{\mathrm{ea}} = \frac{R'r'\ln^2(R'/r')}{\varepsilon' U_0}, \tag{12}$$

where ε', R' and r' are the corresponding parameters in the on-line calibration experiment. The effect of temperature on the calibration results can be obtained from Eq. (9)–(12). The marine temperature ranges from −2 to 30 °C, and the resulting effect on calibration error is as shown in Figure 8. This error may be corrected as part of the on-line calibration process, if necessary.

5.2 Ambient noise

The ambient noise interference with hydrophone signals is regarded as additive, consisting of sea surface noise (wind and wave breaking), traffic noise, biological noise, and so on [14, 15]. The sea surface noise level is described using the spectrum level NL [16], which is assumed to have a Knudsen spectrum [17]. Then,

$$NL = 109.2 + 20\lg n + 10\lg(f_2 - f_1) - 8.3\lg(f_1 \times f_2), \tag{13}$$

where n is the sea state code, and f_1 and f_2 are respectively the bottom and top of the signal frequency band. NL is 115.2 dB (0.575 Pa) under the condition of sea state three ($n = 3$). The frequency band of the hydrophone prototype is from 20 Hz to 20 kHz. The electrostatic pressure of the actuator on the sensing element is about 20 Pa in the experiment. According to Eq. (10), it can be concluded that the effect of ambient noise on the calibration results is about 0.25 dB if a wide-band exciting signal is used under sea state three. In practice, a sweep-frequency exciting signal is used for calibration, so the influence of sea surface noise is much smaller than 0.25 dB. Ship noise is also wide-band noise, the influence of which is limited. Biological noise is intermittent, and therefore an averaging method can be used to reduce its contribution to deviations in the calibration results. To achieve higher calibration accuracy, a spectrum subtraction method can be applied to reduce stationary noise such as sea surface and traffic noises. Ambient noise reduction will be considered further in future research.

5.3 Uncertainty analysis

Uncertainty is an evaluation of the error distribution of measured values. It is an estimate of the fluctuation range of measurement results, within which the true value is considered to lie to a specified degree of confidence. The uncertainty should be given for hydrophone sensitivity calibration to provide the degree of confidence with which the calibration results can be accepted [14, 18, 19]. From Eqs. (8) and (9), the on-line calibration result from the electrostatic actuator method is

$$M'_{\mathrm{h}} = \frac{V'_{\mathrm{h}}}{V'_{\mathrm{ea}}}\frac{V_{\mathrm{ea}}}{V_{\mathrm{h}}}M_{\mathrm{h}}. \tag{14}$$

To evaluate the uncertainty in M'_{h}, the uncertainties in V_{h}, V_{ea}, V'_{h}, V'_{ea} and M_{h} should first be evaluated. There are two classes of uncertainty: type A and type B. Type A uncertainty is described as random uncertainty, and may be assessed by statistical methods. Type B uncertainty refers to systematic uncertainty, indicating the potential systematic bias of a measurement. The variables in Eq. (14) are potential factors affecting the measurement accuracy, uncertainties in which come from errors in the measurement devices themselves. Hence, type B uncertainty is considered in the evaluation in this paper. Most commonly, the standard uncertainty is assumed to be normally distributed, and the overall uncertainty is scaled using the coverage factor $k = 1.96$ to give a level of confidence of 95% [18]. After the range of fluctuation $[-a,\ a]$ of the measurement error has been determined, the standard uncertainty can be obtained from

$$u_b = a/k. \tag{15}$$

The relative standard uncertainty in V_{ea} is shown in the following as an example. V_{ea} is measured using a Tektronix TDS2024 oscilloscope, for which the measurement error range is $[-3.20\%, 3.20\%]$, hence, the relative standard uncertainty of V_{ea} is

$$\frac{u_b(V_{\mathrm{ea}})}{V_{\mathrm{ea}}} = \frac{3.2\%}{k} = 1.63\%.$$

Uncertainties in the other variables are calculated as follows:

- V'_{ea} is also measured using the Tektronix TDS2024 oscilloscope:

$$\frac{u_b(V'_{\mathrm{ea}})}{V'_{\mathrm{ea}}} = 1.63\%.$$

- V_{h} and V'_{h} are measured using a B&K Pulse device with a measurement fluctuation range of ±0.05 dB, and the relative standard uncertainties are

$$\frac{u_b(V_{\mathrm{h}})}{V_{\mathrm{h}}} = 0.29\%, \quad \frac{u_b(V'_{\mathrm{h}})}{V'_{\mathrm{h}}} = 0.29\%.$$

- The expanded uncertainty in M_{h} is given as 1.0 dB; its relative standard uncertainty is then

$$\frac{u_b(M_{\rm h})}{M_{\rm h}} = 6.10\%.$$

All these variables are measured independently, and can therefore be used for combined uncertainty calculation according to the following equation:

$$\frac{u(M'_{\rm h})}{M'_{\rm h}} = \sqrt{\left(\frac{u(V_{\rm ea})}{V_{\rm ea}}\right)^2 + \left(\frac{u(V_{\rm h})}{V_{\rm h}}\right)^2 + \left(\frac{u(V'_{\rm ea})}{V'_{\rm ea}}\right)^2 + \left(\frac{u(V'_{\rm h})}{V'_{\rm h}}\right)^2 + \left(\frac{u(M_{\rm h})}{M_{\rm h}}\right)^2}. \tag{16}$$

The relative standard uncertainty in $M'_{\rm h}$ is 6.53%; accordingly, the expanded uncertainty of hydrophone sensitivity measured using the electrostatic actuator is 1.1 dB at a confidence probability of 95%, which meets the requirement for expanded uncertainty of hydrophone sensitivity calibration (0.9–1.5 dB) [20].

6 Conclusion

The development of an on-line hydrophone sensitivity calibration method as an alternative to the existing laboratory-based comparison and reciprocity methods is of considerable importance for practical applications. Borrowing the electrostatic actuator technique from microphone calibration, an on-line hydrophone sensitivity calibration method is proposed in this paper. The free-field sensitivity of a hydrophone can be calibrated without the need to remove the instrument from its operating location. In addition, the output of the hydrophone sensing element has a high signal-to-noise ratio under the excitation of the electrostatic actuator, so that less stringent requirements are imposed on the measurement environment. Error and uncertainty analyses show the validity of this method for on-line hydrophone sensitivity calibration.

Conflict of interest The authors declare that they have no conflict of interest.

References

1 Yan H C, Xu J, Xia X G, et al. Wideband underwater sonar imaging via compressed sensing with scaling effect compensation. Sci China Inf Sci, 2015, 58: 020306
2 Wang S G, Zeng X Y. Robust underwater noise targets classification using auditory inspired time-frequency analysis. Appl Acoust, 2014, 78: 68–76
3 Feng Y, Tao R, Wang Y. Modeling and characteristic analysis of underwater acoustic signal of the accelerating propeller. Sci China Inf Sci, 2012, 55: 270–280
4 Robert J B. Underwater Electroacoustic Measurements (in Chinese). Beijing: National Defend Industy Press, 1977
5 Zheng S J, Yuan W J, Mu R X, et al. Underwater Acoustic Measurement Technology (in Chinese). Harbin: Harbin Engineering University Press, 1995
6 An L. Research and development of underwater electroacoustic measurements and calibrations. Dissertation for the Master Degree. Nanjing: Southeast University, 2005. 5–15
7 Schloss F, Strasberg M. Hydrophone calibration in a vibrating column of liquid. J Acoust Soc Am, 1962, 34: 958–960
8 Gibbings D L H, Gibson A V. The wide-band calibration of capacitor microphones. Metrologia, 1984, 20: 95–99
9 Jarvis D R. The accuracy of the electrostatic actuator method of determining the frequency response of condenser microphones. J Sound Vibration, 1988, 123: 63–70
10 B&K. Microphone Handbook. Vol. 1: Theory. 1996
11 Shams Q A, Soto H L. Contribution of crosstalk to the uncertainty of electrostatic actuator calibrations. J Acoust Soc Am, 2009, 126: 1107–1110
12 Cheng X B, Li X D. An on-line self-calibration hydrophone. Chinese Patent, 200610066307.7, 2006-10
13 Zhang Y. Research on smart self-calibration hydrophone. Dissertation for the Master Degree. Taiyuan: North University of China, 2007
14 Robinson S, Lepper P, Hazelwood R. Good practice guide for underwater noise measurement. NPL Good Practice Guide. No. 133. 2014
15 Urick R J. Ambient Noise in The Sea. Washington: Undersea Warfare Technology Office, 1984
16 Wang D Z, Shang E C. Hydroacoustics (in Chinese). Beijing: Science Press, 1981
17 Knudsen V O, Alford R S, Emling J W. Underwater ambient noise. J Marine Res, 1948, 7: 410–429
18 Wang Z Y, Liu Z M. Measurement Error and Evaluation of Uncertainty (in Chinese). Beijing: Science Press, 2008
19 Robinson S. Uncertainties in Free-Field Hydrophone Calibration. Underwater Acoustics Technical Guidance Note, 2014
20 Wang Y B, Chen Y, Yuan W J. Verification Regulation of Standard Hydrophones in the Frequency Range 1 kHz–1 MHz JJG 1017-2007. Beijing: China Zhijian Publishing House, 2007