Underwater Calibration of Hydrophones at Very Low Frequencies from 30 Hz to 2 kHz

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Abstract. An underwater hydrophone calibration system based on vibrating column method has been established in the National Metrology Centre, Agency for Science Technology and Research, (NMC, A*STAR), the national metrology institute (NMI) of Singapore. It is used to determine sensitivities of hydrophones at very low frequencies ranging from 30 Hz to 2 kHz. The system is capable of calibrating hydrophones with measurement uncertainties less than 1.6 dB in the stated frequency range. This paper presents the methodology, system setup, measurement uncertainty evaluation, and performance validation. The system enables traceable underwater acoustic measurement at low frequency which has important applications in oil and gas exploration, defense technologies and ocean seismo-acoustic studies.

Keywords: underwater acoustics, hydrophone calibration, low frequency, vibrating column

1. Introduction
There are many applications of low-frequency underwater acoustics such as in oil and gas exploration and environmental monitoring of ocean. Such applications rely on measurements by hydrophones. To ensure the measurements taken by the hydrophones are accurate and reliable, it is essential to calibrate them periodically.

There are various hydrophone calibration methods as reported in the literatures and the international standards [1-6]. For very low frequencies below 2 kHz, currently there are only two national metrology institutes (NMIs), namely VNIIFTRI, Russia and National Physical Laboratory (NPL), UK whose Calibration and Measurement Capabilities (CMCs) are published in the Bureau International des Poids et Mesures (BIPM) key comparison database [7]. The work described in this paper aims to establish traceable calibration of hydrophones by comparison against a reference hydrophone in a vibrating water column in the frequency range from 30 Hz to 2 kHz.

2. Methodology
Currently, the most popular realisation of underwater acoustic standard is by free-field reciprocity method [1]. However, for frequencies below 2 kHz, such method requires measurement to be conducted in a large body of water which in some cases has to be realised in a quiet lake/reservoir, making the realisation costly. The alternative vibrating water column method described in [1] therefore has the potential to enable relatively low-cost realisation of underwater hydrophone calibration below 2 kHz. Using the vibrating water column method, Schloss and Strasberg performed absolute pressure calibrations of hydrophones below 800 Hz of frequency and found it to be agreed within ½ dB compared with the free field reciprocity method [2].

The work reported in this paper applies the vibrating column concept and investigate the effectiveness of hydrophone calibration by comparison against a reference hydrophone calibrated by a NMI using free-field reciprocity method. A reference hydrophone denoted as R and an unknown hydrophone or unit under test (UUT) denoted as T are placed in a hydrodynamic pressure field with the acoustic centres aligned preferably within ±1 cm. The sensitivity (level) of the unknown hydrophone can be written as Eq. (1),
\[ M_T = M_R + H \] (1)

\[ H = 20 \log \left( \frac{U_T}{U_R} \right) \] (2)

where \( M_T \) and \( M_R \) are the sensitivity level (dB re 1V/µPa) for the UUT and the reference hydrophone respectively. \( H \) is a function that can be expressed as the ratio of \( U_T \) and \( U_R \) which are the voltage outputs from the unknown and the reference hydrophones respectively as shown in Eq. (2).

3. System Setup
The low-frequency underwater hydrophone calibration system consists of a test vessel, a shaker, a data acquisition/controller unit as illustrated in Fig. 1 and its operating software. The test vessel is composed of a very rigid cylindrical water column, which has 306 mm inner diameter and contains a small volume of water of approximately 30 litres. Two hydrophones, a reference standard hydrophone and a hydrophone under test, are held in place at a distance apart from each other which can be easily adjusted with the aid of a supporting frame.

![Figure 1. Comparison of a hydrophone-under-test against a reference hydrophone.](image)

The reference standard hydrophone contains cylindrical piezoelectric ceramic active elements of nominal sensitivity -205 dB (up to 120 kHz), where decibel is defined relative to 1 V/µPa in each case. Both hydrophones are exposed to the same hydrodynamic pressure in the test vessel generated by a shaker (vibration generator), as their acoustic centres are aligned at the same depth. Instead of using single-tone sinusoidal inputs, random noise input, specifically band-limited pink noise is used as the excitation signal. That enables very fast measurement at about 20 seconds. The system is able to calibrate hydrophones of various shapes with corresponding mounting jigs. The voltage outputs from both hydrophones are simultaneously captured by a data acquisition system. A dampening panel is placed under the system to reduce interference from undesired floor vibration. As a mechanical interference was observed at around 50 Hz, the damping panel used is specifically designed to filter 50 Hz vibration. With the damping panel, the signal to noise ratio at around 50 Hz is improved by about 10 dB.

4. Measurement Uncertainty Evaluation
The typical achievable calibration uncertainty of a primary underwater calibration of hydrophones based on reciprocity method is around 0.5 dB expressed at 95 % confidence level [8]. The proposed hydrophone calibration system is a secondary calibration system by comparison method, and hence, the total system measurement uncertainty contains the primary calibration uncertainty of reference hydrophone (type B), contributions from the system setup (type B), and short-term repeatability (type A). In this section, the major uncertainty contributions from the system setup are discussed and the overall system measurement uncertainty is evaluated based on [9].

4.1. Reference Hydrophone Calibration
The reference hydrophone used in this experiment has been calibrated by NPL, UK, and the uncertainty contribution can be obtained from the calibration report.

4.2. Temperature Influence
Hydrophones have temperature dependency in their sensitivities. Reference hydrophone is used to measure the hydrodynamic pressure that UUT hydrophone is experiencing. As the lab condition is within \((23 \pm 3)\) °C, there is \(\pm 3\) °C variation that the reference hydrophone may experience. The associated measurement uncertainty is evaluated at 0.12 dB with rectangular distribution. The evaluation is based on the reference hydrophone’s product description that its temperature sensitivity is at 0.04 dB/°C.

In the test vessel, the temperature difference in reference hydrophone and UUT hydrophone will have an impact to the calibration results as well. It is observed that the temperature variation in liquid during one calibration is less than 0.5 °C. Assuming the temperature different between reference hydrophone and UUT hydrophone is less than 1 °C and of rectangular distribution, its uncertainty contribution is evaluated at 0.04 dB with rectangular distribution. The estimation is based on the reference hydrophone’s product description that its temperature sensitivity is at 0.04 dB/°C.

4.3. Test Vessel Glitches

It is challenging to have a perfect mechanical and structural design for the test vessel. The inhomogeneity of material distribution, the dimensional variations in the test vessel’s cylindrical structure and the coupling of shaker armature with test vessel could all contribute to mechanical glitches as seen during calibration. The glitch across 30 Hz to 2 kHz can be seen in Fig. 3. Its uncertainty contribution is estimated at 0.4 dB or 0.5 dB peak-to-peak with rectangular distribution, depending on the frequency range.

4.4. Overall Uncertainty Evaluation Budget

There are other minor uncertainty contributions from acoustic centre alignment error (immersion depth difference) of hydrophones, channel gain difference in data acquisition, short term instability and some residual effects. In short, the overall system measurement uncertainty is evaluated based on [9] and summarised as shown in Table 1 below.

| Frequency (Hz) | 30 - 100 | 100 - 1000 | 1000 - 1600 | 1600 - 2000 |
|---------------|----------|------------|-------------|-------------|
| Expanded uncertainty (dB) | 0.8 | 1.6 | 1.3 | 1.4 |

4.5. Validation

The system performance validation is carried out by calibrating the same UUT hydrophone with two different reference hydrophones, namely Reference 1 and Reference 2. All three hydrophones are of the same brand and model. These two sets of calibration results are compared based on their measurement equivalence ratio \(E_n\), as expressed by Eq. (3) and (4),

\[
E_n = \frac{|S_{REF1} - S_{REF2}|}{\sqrt{U^2_{REF1} + U^2_{REF2}}} \quad (3)
\]

\[
\sqrt{U^2_{REF1} + U^2_{REF2}} = \sqrt{2} U_{\text{system}} \quad (4)
\]

where \(S_{REF1}\) is the sensitivity of the UUT hydrophone calibrated by Reference 1 and \(S_{REF2}\) is the sensitivity calibrated by Reference 2. \(U_{REF1}\) and \(U_{REF2}\) represent the system expanded measurement uncertainties associated with the calibration process to obtain \(S_{REF1}\) and \(S_{REF2}\). As the same calibration system has been used for the performance validation, essentially \(U_{REF1} = U_{REF2} = U_{\text{system}}\). Fig. 3 shows the UUT sensitivities \(S_{REF1}\) and \(S_{REF2}\) calibrated by Reference 1 and Reference 2, respectively.
The system validation criteria is set as $E_n < 1$. It can be observed in Fig. 4 that the $E_n$ ratio is high and reaches 0.6 at 48.7 Hz but is less than one throughout the whole frequency range of 30 Hz to 2 kHz. This validated the system’s performance within the expanded uncertainties as shown in Table 1.

5. Conclusion
A low-frequency underwater hydrophone calibration system based on vibrating column method was established at the National Metrology Centre of Singapore. It is capable of calibrating hydrophones with measurement uncertainties less than 1.6 dB in the frequency range of 30 Hz to 2 kHz. The system performance has been validated within its expanded uncertainty by comparing the same UUT hydrophone with two different reference hydrophones.

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