A Design of an Acoustic Coupler for Calibration of Hydrophones at Low Frequencies

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Abstract

The purpose of this article is to present a coupler developed for the calibration of hydrophones at low frequencies in the Central Office of Measures (GUM). Due to the growing demand for marine environment research in the field of underwater noise, implemented in accordance with Directive 2008/56/EC, many models of autonomous underwater noise recorders have been developed. Ensuring the reliability of recorded data begins with the reliable calibration of hydrophones and/or the entire recorder. The choice of the calibration method was made on the basis of a detailed and broad analysis of calibration methods and similar solutions of coupling constructs worldwide. The analysis mainly took into account the documents of the last few years. On the basis of this analysis, the vibrating water column method was chosen and the construction of the coupler was developed. Regular calibration of hydrophones will contribute to reliable underwater noise monitoring in the Baltic region.

Keywords: acoustical coupler, calibration of hydrophone, low frequencies, receiving sensitivity

1. Introduction

The development of calibration methods and constructional solutions of calibrators at low frequencies from 1 Hz to 2 kHz is very important. There are many different types of autonomous underwater noise recorders in the world [1]. These recorders are calibrated by the manufacturer. Typically, the calibration of autonomous underwater noise recorders is limited to the calibration of hydrophones and internal electronics without testing the influence of the housing on their sensitivity. The growing number of recorders means that the task of periodic calibration requires more and more attention and time from their users, among others due to the time of delivery to the manufacturer, waiting time for calibration and delivery time to the consumer. It was investigated how hydrophones produced by manufacturers B&K and Reson change the receiving sensitivity between calibrations but only from 4 kHz (B&K) and 5 kHz (Reson) to ca. 200 kHz [2, 3]. Manufacturers rarely provide accurate calibration of hydrophones in the frequency range of 1 Hz to 2 KHz. It is assumed that, in the calibration process the receiving sensitivity of the hydrophone in the low frequency range is constant up to the first resonance. An analysis of the results of recalibrations of the same hydrophone receiving sensitivity has shown the results may differ significantly from the previous values given in the earlier calibration chart. The reason is the poor time stability of the receiving sensitivity reaching 1.6 dB (B & K – 3 recalibrations in 10 years) and 2.2 dB (Reson 1 recalibration in 3 years). In addition, the changes are non-linear.

In accordance with Directive 2008/56/EC, the quantity of acoustic recorders has grown; therefore a framework for Community action in the field of marine environmental policy (Marine Strategy Framework Directive) was established, which is the basis for monitoring underwater noise. The quality of the collected data is very important. Guidelines for the calibration of hydrophones and recorders are included in [4]. It is recommended that a full laboratory calibration is undertaken before and after every major deployment or sea-trial according to IEC 60565 2006 [5], ANSI S1.20 2012 [6]. The hydrophone calibrations are typically performed using couplers. Work on the division of the IEC 60565 2006 standard into two parts are underway; the second part exclusively concerns procedures for low frequency pressure calibration: IEC FDIS[1] 60565-2 2019 [7].

Increasing the availability, functionality and the need to shorten the time for calibration are the basis for the development of new and improved old calibration methods for hydrophones at low frequencies.

There is currently no standardization of the methods used to calibrate autonomous recorders.

Taking the above into consideration, the main objective of developing a calibration coupler at low frequencies at the GUM is to participate in improving the metrological capacity in underwater acoustic calibration for low acoustic frequencies.

2. Methods of calibrating hydrophones at low frequencies

In general, we can distinguish two calibration methods: primary methods that do not require reference to any acoustical standard, and secondary methods that require the calibrated reference standard to be used. Regardless of the method applied, the calibration includes at least the determination of the pressure sensitivity or pressure sensitivity level in accordance with one of the methods specified in the standard [5, 6] and estimation of measurement uncertainty shall be determined in accordance with [8]. Recently published papers present a method for an initial calibration of magnitude and phase of hydrophone sensitivity at frequencies in the range of 1 Hz to 2 kHz [9].

Different methods for calibrating hydrophones are well documented [10]. One of the most important projects carried out in recent years in the field of underwater acoustics is the EURAMET EMPIR project UNAC-LOW "Underwater Acoustic Calibration Standards for Frequencies Below 1 kHz" [11]. Goals of this project are the development of measurement consistency for the calibration of hydrophones and autonomous underwater noise recorders covering the frequency range of 20 Hz to 1 kHz. This frequency band covers the EU MSFD guideline requirements - Part I-III – which established one-third octave centre frequencies: 63 Hz and 125 Hz [4], also developing a multi-faceted and long-term strategy for each participant of the project, coinciding with the European Metrology Strategy and increasing the research potential in this area included upgrading standard IEC 60565.

The review of the latest calibration solutions for hydrophones at low frequencies will start with calibrators produced and tested as part of the EURAMET EMPIR UNAC-LOW

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[1] Final Draft International Standard (FDIS)

project mentioned above. In the project description, the NPL reports that it has the ability to calibrate hydrophones for frequencies up to 1 kHz by the following methods:

- the air pistonphone method,
- the absolute method by a laser pistonphone,
- the vibrating column method.

The first method used by TUBITAK was to place the tested hydrophone with a calibrated reference receiver and a sound source in a closed chamber, so that the source interacted with both receivers at the same time. The reference receiver can be both a microphone and a hydrophone, depending on whether the chamber is filled with air or water. The estimated uncertainty amounted to ±1 dB.

The standing wave method is used by the Swedish Defense Research Agency (FOI) using a calibration system (model C100, Underwater Science, Research & Development, Inc., USA) and is included in the standing wave tube method [12]. Calibration was performed entirely with an autonomous underwater noise recorder (Wildlife Acoustics SM2M). Tests for frequencies between 100 Hz and 1 kHz were carried out by comparison with a B&K 8104 reference hydrophone. The results of the tests showed a good agreement within ±1 dB for frequencies from 100 Hz up to 700 Hz. Unexpectedly large deviations, from 3 dB up to 8 dB, were observed for frequencies between 800 Hz and 1 kHz. An explanation for this large discrepancy should be given.

Another method demonstrated in the EURAMET UNAC-LOW project was the method of air calibration using a pistonphone. It is generally recommended to use air pistonphone to check hydrophones before (and after) each dipping (pick up) during marine research. Over the research, the hydrophone was calibrated together with an autonomous underwater noise recorder in the frequency range of 20 Hz to 315 Hz [10]. The positive result of the research determined that this method be included in the project. The advantage of this method is the lack of liquid in the chamber, which makes the whole system lighter and easier to move. The disadvantage of this method is (as all methods using a calibration chamber) that the influence of the autonomous recorder housing on the obtained calibration results cannot be determined. For this method, the measurement uncertainty that occurred during the hydrophone calibration was not given.

In the National Physical Laboratory, an experimental hydrophone calibration was carried out using an interferometer and pistonphone [11]. The beam of the interferometer laser examined the vibrations of the piston. The purpose of this experiment was to investigate measurement uncertainty in the 20 to 158 Hz frequency range, which includes the required acoustic measurements for the 1/3 octave frequency of 63 Hz and 125 Hz.

At the VNIIFTRI (the All-Russian Research Institute of Physical-technical and Radiotechnical Measurements), the Russian Federation examined low frequency hydrophone calibration using a tensometric pressure sensor [13]. The acoustic chamber is a thick-walled chamber mounted to lattice on the floor where the hydrophone is located, and the reference transducer is screwed to the inner vertical wall in the form of a tensometric pressure sensor. The range of the tested frequencies ranges from 2 Hz to 3.15 kHz and the obtained uncertainty of measurement increases towards the upper frequency limit reaching a maximum of ± 0.6 dB.

In addition to Europe, in the US (Department of Sensors and SONAR, Naval Undersea Warfare Center), the recently developed primary method deserves special attention, which is characterized by the combination of 1 Hz and 0.1 dB re 1 V μPa^{-1} and ± 1^{O}, respectively. The calibration takes place in a coupler reciprocity chamber depending on changes in frequency, temperature and pressure [14].

Ocean Networks Canada (ONC) measurements of near-field earthquake energy occur primarily below 60 Hz. The same calibrator can be used at low frequencies to calibrate hydrophones usually used to measure underwater noise. The VLF calibrator has a small volume chamber (50 mm diameter) filled with water or light oil (1325 m/s) [15]. The chamber is equipped with a tested hydrophone, a reference hydrophone, a pressure sensor and a temperature sensor. A piston with a diameter of 4 cm is moved by an actuator made of a piezoelectric stack with a maximum pitch of 10 μm. The total measurement error includes error due to chamber dimensioning, ADC converter error, reference hydrophone error and investigated hydrophone error. The total error for 1 Hz is 0.12% and increases towards higher frequencies, reaching 0.35% for 1 kHz.

Another example of the use of a vibrational water column for the calibration of hydrophones are interlaboratory comparisons carried out by the Russian Metrological Institute of Technical Physics and Radio Engineering (VNIIFTRI) and Hangzhou Applied Acoustics Research Institute (HAARI – China), which took place in 2015. The research was based on the IEC 60565 2006 standard and the previous experience of F. Schloss et al. [16]. Before preparing the coupler for calibration of hydrophones, mathematical simulation of various sizes of calibration chamber was used. This enabled the resonance frequencies of the calibration chamber to be determined and, as a consequence, avoid resonance during calibration. The results of the calculations meant that the planned primary method was switched to a comparative method. Based on these simulations, a calibration chamber made of aluminum with a diameter of 30 cm and a wall thickness of 2 cm was made. The design allows the liquid level in the chamber to be modified (change of the resonant frequency). The authors report that the design allows the hydrophones to be calibrated from 30 to 1 kHz, with measurement uncertainties dependent on the hydrophone being tested, e.g. less than ±1 dB for the Bruel & Kjaer type 8103 hydrophone [17].

At the National Metrology Center, the Science and Research Agency (NMC, A* STAR), the national metrology institute (NMI) in Singapore, a hydrophone calibration system based on the vibrating column method was developed. It is used to determine the sensitivity of hydrophones for low frequencies in the range of 30 Hz to 2 kHz. The test chamber consists of a very rigid cylinder containing a water column with a volume of approximately 30 liters and an internal diameter of 30.6 cm. In the comparative method, two hydrophones were placed inside: a standard reference hydrophone and a tested hydrophone on an adjustable frame. The system provides calibration hydrophone with measurement uncertainty of less than 1.6 dB in the given frequency range. The system authenticates the measurement results of hydroacoustic sensors in applications related to oil and gas exploration, defence technologies and oceanic seismic-acoustic surveys [16].

3. Coupler design description

After studying the standards and analyzing the literature and test reports, a decision was made to choose the vibrating water column method. This approach has been extensively described, and is relatively simple and economical to make. It is divided into two basic procedures. In the first, only one hydrophone is calibrated (the calibrated hydrophone can be calibrated first and then the reference one) and reference is made to the absolute value of the liquid pressure at the point of the geometric centre of the sensitive part of the calibrated hydrophone (the value of the modulus of the hydrophone sensitivity only). This approach does not require a reference hydrophone, although repeating the test with a reference hydrophone will make the test more reliable. The second option involves simultaneous immersion in a liquid at a selected reference depth and taking into consideration the test hydrophone and a comparison of the measurement results.

The first approach was chosen. This will allow you to achieve the ability to absolute calibration measurement of underwater sound. The acoustic coupler in this method is made in the form of a cylindrical calibration chamber filled with water. The hydrophone being tested is submerged immobile and stable in the water column. The calibration chamber is mounted on a sinusoidal vibration exciter that causes vertical sinusoidal vibration of the liquid column in the chamber. The design of the acoustic coupler for calibrating hydrophones via the vibrating water column method is presented in Figures 1 and 2.

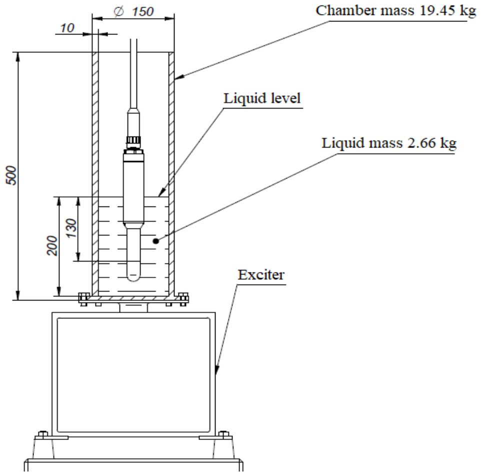

Figure 1. Design of an acoustic coupler for calibrating hydrophones via the vibrating water column method

The modulus of the pressure sensitivity of the hydrophone $|M_p|$ shall be calculated as the ratio of the amplitudes of the sinusoidal signals of the open-circuit voltage U_0 and pressure p_0 (The height of the water column above the center of the sound-sensitive part expressed in pascals):

$$|M_p| = \frac{U_0}{p_0} \tag{1}$$

The depth of immersion of the centre of the hydrophone (*d*) should be measured in the centre of the sound-sensitive part responsible for sound reception (which can be very difficult to achieve), or it can be omitted if the hydrophone sensitivity measurements are taken at two different depths. This depth difference can be established without knowledge of the location of the acoustic centre of the hydrophone, in this case we use formula (2) [4, 6]:

$$\left|M_p\right| = \frac{\Delta U_0}{\Delta d} \frac{1}{\rho_f x_0 \omega^2} \tag{2}$$

where:

ΔU_0 – difference of the peak values of the output voltages at the hydrophone for two different hydrophone immersion depths,
Δd – depth difference for 2 different measurements,
ρ_f – density of fluid,
x_0 – vibration amplitude,
ω – angular frequency.

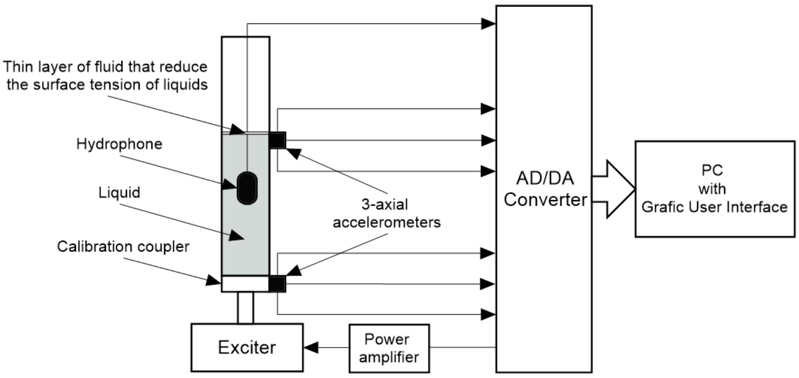

Figure 2. Measurement scheme

For check-ups the vibrating column method by alternately calibration the hydrophone under test and the reference hydrophone *H*, the following formula for calculating the voltage sensitivity of an unknown hydrophone can be used from [12]:

$$M_T = M_H + 20 \log[U_T/U_H] \tag{3}$$

where:

U_T – output voltage of the hydrophone under test *T*,
U_H – output voltage of the reference hydrophone *H*,
M_H – sensitivity level of the reference transducer (dB re V/μPa),
M_T – sensitivity level of the hydrophone *T* (dB re V/μPa).

4. Conclusions

In recent years, it can be observed that autonomous underwater noise recorders have become increasingly popular. This is probably the reason why the number of projects, interlaboratory tests and individual solutions connected with ensuring the calibration of hydrophones at low frequencies has been growing over the last several years. In addition to previously known and improved calibration methods in the free field, there was interest in developing a method based on calibration in a chamber filled with water or air.
"… developing a multi-faceted and long-term strategy for each project participant, consistent with the European Metrological Strategy and increasing research potential in this area included updating the IEC 60565 standard."

The above sentence accurately reflects the current view on the calibration of hydroacoustic devices and hydrophones. This article shows that there is a broader aspect: What about the reliability of calibration during the period of validity of the recalibration function, are all the functions cited available that users may have measurement uncertainty is less than 1 dB, and test results that are calibrated hydrophones is not time stable? Room changes between recalibrations reach 2.2 dB. What real uncertainty does the hydrophone have at the end user? As in the case when one of the solutions is to go to the period of recalibration of hydrophones, it excludes sending hydrophones abroad and for use in applications with hydrophone calibrators (unless additional hydroacoustic devices / hydrophones are available). In this article, based on the analysis of current solutions, the method of calibrating hydrophones by vibrating water column in an acoustic coupler was selected. It is a simple method, often used and the costs of its technical implementation and maintenance are economically justified and smaller compared to other methods.

At present, a calibrator project has been drafted and presented in this paper. The construction of a hydrophone calibration station with a vibrating water column is the first stage in the development of metrological infrastructure in the area of underwater acoustics in Poland (in the Central Office of Measures) [19].

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