

# Designing a comparison coupler for low-frequency calibration of hydrophones in air

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**Abstract** – Requirements of traceability for measurements of sound pressure in the maritime environment demand that hydrophones are calibrated to frequencies down to 20 Hz. A recently completed European project entitled “Underwater Acoustic Calibration Standards for Frequencies Below 1 kHz (UNAC-LOW)”, within the European Metrology Programme for Innovation and Research (EMPIR) presented a proposal for some methods of providing traceability at that frequency range. One of these methods was based on direct comparison to reference microphones in an air-filled coupler. A design of the coupler was proposed by TÜBITAK, and used by some participants in the project, including DFM. Preliminary results of the sensitivity of the hydrophone determined from measurements in the coupler showed that there was a growing deviation from the sound pressure uniformity assumption as the frequency increased. This limitation was solved using an *ad-hoc* correction based on known sensitivity values of a hydrophone at 1 kHz. Due to the hydrophone-specific nature of the correction, the design of the coupler was revisited so such a correction was not needed. This paper presents the new design of the coupler, and results of its application.

## I. INTRODUCTION

The growth of anthropogenic noise sources in the ocean, and its disruption of marine life is a source of concern for agencies devoted to the management and conservation of the environment. Most of noise sources generate sound in the low frequency region, up to 1 kHz, therefore the need for traceable measurements covering this frequency range. Furthermore, the European Marine Strategy Framework Directive (MSFD)[1] requires that measurements at the third-octave frequency bands centred at 63 Hz and 125 Hz are traceable. The project “Underwater Acoustic Cal-

ibration Standards for Frequencies Below 1 kHz (UNAC-LOW)” [2] has been carried out under the auspices of the European Metrology Programme for Innovation and Research (EMPIR)[3] with the goal of providing this missing traceability. UNAC-LOW’s participants approached the calibration of hydrophones at low frequencies using different methods, both primary and secondary. A participant used a moving water column, another participant used an interferometric air-filled pistonphone for primary and secondary calibration, and other participants used an air-filled comparison coupler where the hydrophones were compared to reference microphones. For the latter method, a first design of the comparison coupler was devised. This design was tested and it was found out that a deviation of the assumption of uniform sound pressure in the coupling cavity failed as frequency increased. A solution for this deviation was to find a specific correction based on results of a free-field calibration at 1 kHz, and the differences seen in the results obtained from the comparison coupler.[4] Due to the *ad-hoc* nature of this correction it was quite evident that a general, measurement-based solution should be found. This solution should be based on a redesign of the coupling cavity in such a way that the deviations from the uniform sound pressure in the coupler is minimised. This paper presents the considerations for this revisited design, and results from a new coupler built after this concept.

## II. PRINCIPLES OF PRESSURE COMPARISON CALIBRATION

The suggested calibration method is a secondary method, that is, it involves a direct comparison of the hydrophone under test with a reference microphone or a set of reference microphones. The method for pressure calibration of microphones by comparison is described in the standard IEC 61094-5 [5]. The method is based on the assumption that a hydrophone under test (DUT) is subjected

simultaneously to the same sound pressure as a reference microphone. The result of this comparison is the ratio of output voltages of the hydrophone to the reference microphone. Because the output voltages are proportional to the sensitivity of the microphones, it follows that the sensitivity of the DUT,  $M_{p,DUT}$ , can be determined by multiplying the ratio of the output voltages of DUT and reference microphone,  $R_M$ , and the pressure sensitivity of the reference microphone,  $M_{p,Ref}$ :

$$M_{p,DUT} = M_{p,REF} R_M, \quad (1)$$

$$R_M = \frac{u_{DUT}}{u_{REF}}. \quad (2)$$

This can also be expressed in terms of levels as

$$L_{M_{p,DUT}} = L_{M_{p,DUT}} + \Delta_M, \quad (3)$$

$$\Delta_M = 20 \log_{10} \frac{u_{DUT}}{u_{REF}}. \quad (4)$$

Changes in environmental conditions will affect the sensitivity of the reference microphones in different ways. However, because it is likely that the environmental coefficients of the DUT hydrophone may be unknown, typically its sensitivity will only be calculated at measurement conditions. Hence it is only needed to apply a correction on the sensitivity of the reference microphone to measurement conditions. This correction can be determined using:

$$\Delta_{Env} = \delta_p(p_s - p_0) + \delta_t(t - t_0) \quad (5)$$

where  $\delta_p$  is the static pressure coefficient in dB/kPa,  $\delta_t$  is the temperature coefficient in dB/K,  $p_s$  and  $t$  are the static pressure and temperature at measurement conditions, and  $p_0$  and  $t_0$  are the reference static pressure and temperature. The comparison pressure sensitivity is then realised by determining  $\Delta_M$  as indicated in equation (3) and applying the correction defined in equation (5) to obtain the pressure sensitivity of the DUT microphone. Finally, the above procedure can be applied at any frequency where there is a reference microphone with a traceable calibration (potentially from 2 Hz and up to 2 kHz for some types hydrophones).

### III. CONCEPTUAL DESIGN OF THE COMPARISON COUPLER

As mentioned above, the main requirement to be fulfilled in order to realise the calibration by comparison is that the sound pressure acting on the reference microphone and the hydrophone under test is the same. When calibrating microphones, this condition is easier to fulfill whenever the membranes of the microphones are closer to each other [6]. This is possible when the distance between membranes is much smaller than the smallest wavelength of interest. In the case of the comparison between microphones and hydrophone this becomes slightly more unclear due

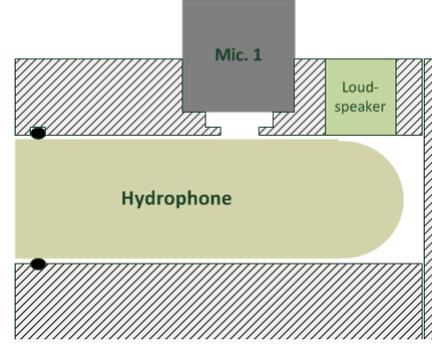


Fig. 1. Schematic representation of the original design of the comparison coupler.

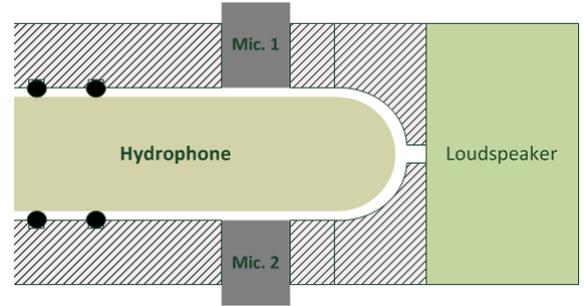


Fig. 2. Schematic representation of the proposed redesign of the comparison coupler.

to the inherent differences in the geometry, materials and positions of the sensing elements, and eventual pressure differences are to be expected.

The original coupler uses only one reference microphone, and the internal dimensions (including the distance between the microphone's membrane and the surface of the hydrophone) may put a limitation to the highest frequency at which the coupler can be used, and this may fall well below the intended 1 kHz. A graphic representation of the original coupler is shown in Figure 1

The revised coupler uses two microphones on opposite sides of the hydrophone at a very close distance from it, and has a minimal volume and length that ensures that the first longitudinal and non-symmetrical modes have a frequency above 1 kHz. The use of two microphones makes up for the lack of symmetry of the sound field caused by positioning differences. This means that the measurement procedure must include an additional measurement in which the microphones switch positions. Then, the calculation of the sensitivity involves the determination of the sensitivity for two microphones at two positions —Using equation (3)- and determining the average of these four estimates. An schematic representation of the proposed coupler is shown in Figure 2

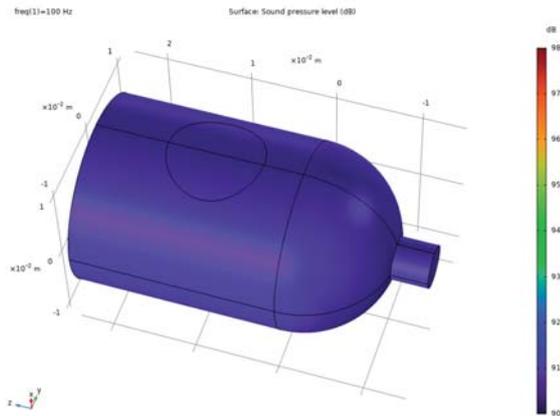


Fig. 3. Sound pressure level in the redesigned coupler at 100 Hz.

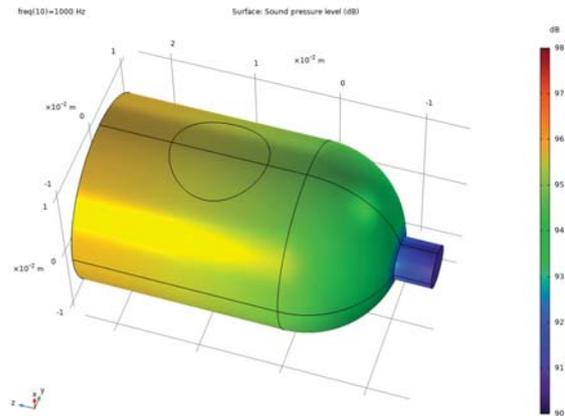


Fig. 4. Sound pressure level in the redesigned coupler at 1000 Hz.

#### IV. NUMERICAL SIMULATIONS OF THE REDESIGNED COUPLER

Based on the above considerations, simplified numerical calculations were carried out in order to estimate the uniformity of the sound pressure inside the cavity. The simplifications are originated by the fact that the a hydrophone is a relatively complicated device, in this case the Bruel and Kjaer types 8104 and 8106 composed of several piezoelectric sensing elements, and covered with isolating rubber. Equally, the microphones have a changing impedance in the frequency range of interest. In the simulations all surfaces were assumed to be rigid, and this has an effect on the sound pressure field inside the coupler. The loudspeaker was substituted using a finite sound pressure boundary condition.

The simulations were carried out using the commercial software COMSOL®. Figures 3 and 4 show the pressure distribution of the free space between the coupler and microphones and hydrophone for the frequencies of 100 Hz and 1 kHz. At 100 Hz the sound pressure level seems to be quite uniform. At 1 kHz the variation seems to grow, particularly along the axis of the hydrophone (longitudinal direction). This may imply that the free space within the coupler should be as short as possible.

Prototypes following this design principle have been built and tested on some types of microphones with reasonable results. The modified design can in principle be adjusted to fit different types of reference hydrophones.

#### V. MEASUREMENT SET-UP

The measurement set-up must include signal conditioners that enable the measurement of the output of the reference microphone, and the output of the hydrophone. The output of these signal conditioners can be fed to a signal analyser that provides the generator signal to drive the loudspeaker attached to the coupler. Additional instru-

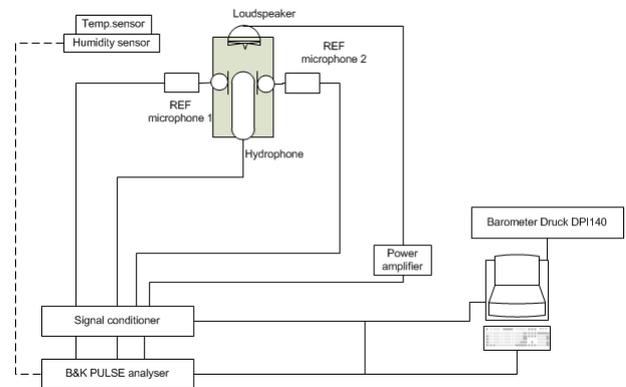


Fig. 5. Schematic representation of the measurement system for hydrophones.

ments are intended to measure the environmental conditions in which measurements are carried out. A sound SNR is a must, particularly because the hydrophone's output voltage will be much smaller than the output of the microphones. For this reason, sinusoidal signals are used in the measurements. The core instrument in the measurement system is a signal analyzer that provides the voltage that excites the loudspeaker, and the measurement channels for the hydrophone and the reference microphones; one for the hydrophone and another for the reference microphone in the case of the original coupler, and an additional one in the case of the redesigned coupler. The measurements are carried out using a 1/12th-octave frequency steps in the frequency range from 20 Hz to 2 kHz. Figure 5 shows a schematic representation of the measurement system used at DFM.

##### A. Calibration coupler

One can notice that in the schematic representation there are two reference microphones beside the hydrophone.



Fig. 6. Picture of the new coupler for hydrophones B&K type 8104

This is because the coupler has been optimised from an earlier version [4]. The original coupler uses only one reference microphone, and the internal dimensions (including the distance between the microphone’s membrane and the surface of the hydrophone) may put a limitation to the highest frequency at which the coupler can be used, and this may fall well below the intended 1 kHz. The optimised coupler uses two microphones on opposite sides of the hydrophone at a very close distance from it, and has a minimal volume and length that ensures that the first longitudinal and non-symmetrical modes have a frequency above 1 kHz. The use of two microphones make up for the lack of symmetry of the sound field caused by positioning differences. This means that the measurement procedure must include an additional measurement in which the microphones switch positions. Then, the calculation of the sensitivity involves the determination of the sensitivity for two microphones at two positions —Using equation (3)- and determining the average of these four estimates. Figure 6 shows the actual coupler with microphones and hydrophone readily mounted for a complete measurement.

## VI. MEASUREMENT RESULTS AND DISCUSSION

### A. Original versus redesign

Figure 7 presents the sensitivity of a hydrophone Bruel & Kjaer type 8104 determined from measurements made in the original coupler, and with the proposed redesign. There is a stark difference between these results. The original coupler shows a strong high frequency roll-off that limits the frequency range in which the coupler can be used down to about 400 Hz to 500 Hz. A so-called *empirical correction* could be used to bring the sensitivity obtained in the original coupler to levels similar to a free-field sensitivity [4]. However such an approach may not be appropriate because there is little evidence that the observed roll-off is consistent for all hydrophones of the same type coupled to

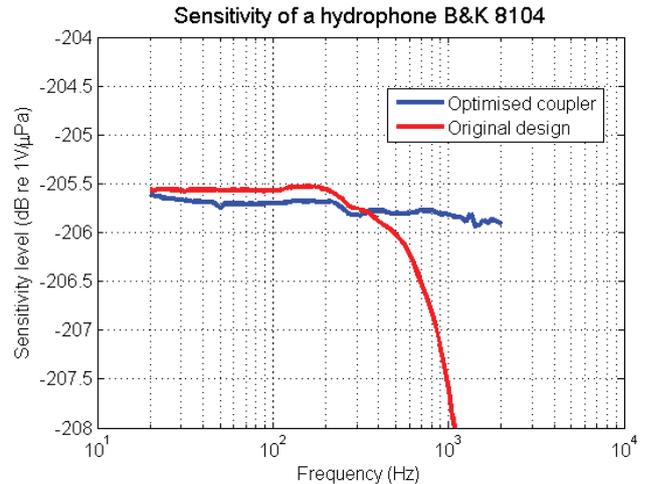


Fig. 7. Sensitivity results of a hydrophone Bruel & Kjaer type 8104 obtained from measurements in the original and the redesigned coupler

this type of hydrophone.

### B. Consistency with other methods

The next step is to compare the results obtained with the redesigned coupler and other methods. Figure 8 shows the difference to a common average of the sensitivity determined using three different methods at different laboratories, namely, an interferometric pistonphone (National Physical Laboratory, NPL, UK), a moving water column (FOI, Sweden), the new coupler (DFM, Denmark), and the original coupler plus the *empirical, ad-hoc* correction (MAM, Turkey). The agreement among the different methods is reasonable. The results obtained with the redesigned coupler fall within 0.4 dB from the average. On the other hand, the results obtained with the original design and the *empirical* correction seem to be reasonable. However, the fact that the correction is based on the assumption that the response of the hydrophone is flat under 1 kHz makes it unreliable and with little metrological value.

### C. Design adapted to other hydrophone types

It would be desirable to apply the design concept of the new coupler to build couplers for other types of hydrophones. A version of the coupler in which hydrophones Bruel & Kjaer type 8106 could fit was also built. Figure 9 shows the difference to a common average of the sensitivity determined using the same three methods as in the previous section. In this case, the measurements were extended down to 5 Hz to find out about the low-frequency roll-off present in this type of hydrophones. As in the case of the hydrophone type 8104, the agreement among methods is again good, slightly better in fact. This implies that the design principle can be used to calibrate hydrophones

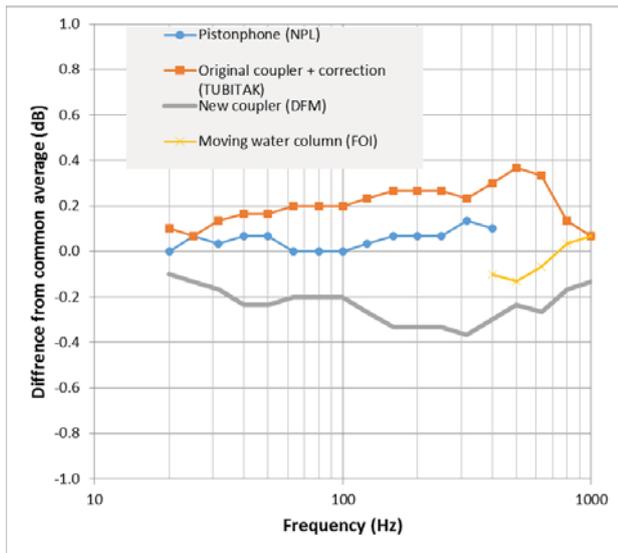


Fig. 8. Sensitivity results of a hydrophone Bruel & Kjaer type 8104 from 3 different methods

with other geometries, such as the B&K type 8105. It is important, in any case, to have all the available information about the targeted hydrophone type. The configuration of the sensing elements may play a relevant part in the way the sound pressure distributed on the free space in the coupler is registered by the hydrophone.

## VII. CONCLUSIONS AND OUTLOOK

A revised design of an *air-filled* coupler for calibrating hydrophones by comparison against condenser microphones has been proposed. The design is based on an earlier coupler based on a single microphone. The redesigned coupler adds a second microphone, and moves the sound generating device to an symmetrical position. Prototypes of the two couplers have been built, and tested.

The results obtained with the redesigned coupler seem to be better in a wider frequency range; this is confirmed when those results are compared against the sensitivities obtained in other laboratories. The results indicate that the design concept can be extended to other types of hydrophones.

## VIII. ACKNOWLEDGMENTS

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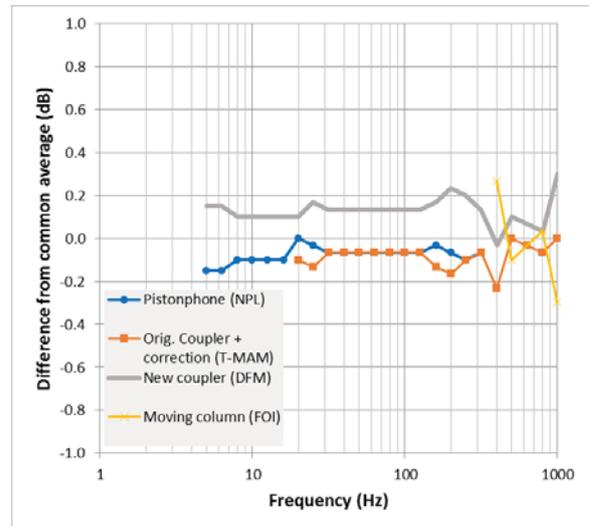


Fig. 9. Sensitivity results of a hydrophone Bruel & Kjaer type 8106 from 3 different methods

ported by the European Metrology and Program for Innovation and Research (EMPIR).

## IX. \*

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