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## **I. Methodology for Onda's Hydrophone Calibrations**

Calibration is obtained by comparison techniques to reference hydrophones calibrated by the National Physical Laboratory (NPL) in the UK. For calibration below 20 MHz, the stepped single frequency comparison technique is used, and for calibration above 20 MHz, the harmonic comparison technique is employed. The procedures are as follows:

### **Stepped single frequency comparison technique:**

- 1) The reference hydrophone is placed at the focus of a broadband source [1], which is driven by a sinusoidal tone burst. The reference hydrophone is aligned by maximizing the hydrophone signal with the source driven at the maximum end of its frequency range (20 MHz for a 1-20 MHz calibration, 5 MHz for a 0.25-1 MHz calibration). The voltage driving the source is then swept in across the frequency range (i.e., 1 to 20 MHz, or 0.25 to 1 MHz). At each frequency, the output of the reference hydrophone is measured and digitally filtered to separate the primary frequency component from any harmonics that may be present in the signal. The reference hydrophone has previously been calibrated by NPL, so that the voltage it detects can be translated into a pressure value, hence calibrating the pressure output of the source as a function of frequency, at the source's focal position.
- 2) The reference hydrophone is then replaced by the hydrophone to be calibrated, and re-aligned. The voltage driving the source is again swept across the same frequency settings, and the output of the hydrophone at the fundamental of the driving signal is determined and recorded. This voltage is then divided by the pressure amplitude (measured in step 1) to determine the output of the hydrophone in Volts per Pascal (V/Pa).

### **Harmonic comparison technique:**

- 1) The reference hydrophone is placed at a position in the non-linear acoustic field produced by a plane circular source transducer driven by a 2.25MHz sinusoidal tone-burst signal. The position was chosen where many strong harmonics of the fundamental frequency are generated in the distorted pressure waveform due to non-linear propagation. Using a 50 MHz high-pass filter, the reference hydrophone is aligned by maximizing the hydrophone's high frequency components in the plane at that position to an optimal orientation. The pressure waveform at that position is recorded after the high-pass filter was removed. An

FFT of the waveform is calculated, and the voltage amplitude at each harmonic is determined. The reference hydrophone has previously been calibrated by NPL, so that the voltage it detects can be translated into a pressure value, hence calibrating the pressure output of the source at each harmonic.

- 2) The reference hydrophone is replaced by the hydrophone to be calibrated, which is then aligned the same way at the same position as the reference hydrophone. The pressure waveform is recorded with the absence of the high-pass filter. An FFT of the pressure waveform is then calculated, and the voltage at each harmonic is determined. This voltage is then divided by the pressure amplitude (measured in step 1) to determine the output of the hydrophone in Volts per Pascal (V/Pa).

## **II. Calibration Uncertainty**

The uncertainties in the calibration are predominantly systematic in origin, the random error is negligible in comparison. The dominant source of uncertainty is the uncertainty in the calibration of the reference hydrophone (as provided by NPL). The other sources of uncertainty are temperature variation ( $\pm 1$  °C, resulting in calibration variations of  $\pm 1\%$ ) source stability ( $\pm 2\%$ ) digitizer error ( $\pm 2\%$ ) and positional repeatability (this effect varies with frequency, from  $\pm 2.5\%$  at 1 Mhz to  $\pm 5\%$  at 20 MHz). The combined effect of these error sources is calculated according to [2-3], with a coverage factor of  $k = 2$  to calculate the uncertainty with a 95% confidence level. This yields uncertainties that are typically within  $\pm 1.5$  dB from 0.5 to 1 MHz,  $\pm 1$  dB from 1 to 15 MHz,  $\pm 1.5$  dB from 15 to 20 MHz,  $\pm 2.2$  dB from 20 to 40 MHz and  $\pm 3$  dB from 40 to 60 MHz.

### III. Important Considerations Regarding Electrical Loading Conditions

HMA and HMB hydrophones are sold with a standard 1-20 MHz calibration into a 50-ohm load. HGL, HNP (formerly HNV), HNC (formerly HNZ), and HNR hydrophones are modular—i.e., they allow the user to choose different amplifiers or no amplifier at all. Because a hydrophone's sensitivity depends on the electrical impedance of the detector or amplifier it is attached to, modular hydrophones are sold with an open-circuit calibration, called formally the "End-of-cable Open Circuit Sensitivity", or EOC sensitivity for short, and designated as  $M_c(f)$  [4-5].  $M_c(f)$  is determined by measuring the sensitivity of the hydrophone with a laboratory amplifier, and then subtracting the effect of that amplifier's gain, as well as that of its finite (i.e., non-infinite load). Note that the HGL, HNP, and HNC hydrophones may be connected directly to an amplifier without any cable, so the EOC sensitivity is defined as the sensitivity that would be measured at the hydrophone's connector into an infinite load.

Of course, actual hydrophone usage is made with the customer's choice of amplifier and/or other form of detector. In such cases, the customer may calculate the effect of the amplifier/detector configuration on the hydrophone sensitivity, by mathematically combining hydrophone calibration data and amplifier data, as described below:

#### Obtaining amplifier-loaded sensitivity from EOC data

The sensitivity of the hydrophone/preamp combination ( $M_L(f)$ ) can be determined using the following formula [4]:

$$M_L(f) = G(f)M_c(f) \left[ \frac{\text{Re}(Z_A)^2 + \text{Im}(Z_A)^2}{\{\text{Re}(Z_A) + \text{Re}(Z_H)\}^2 + \{\text{Im}(Z_A) + \text{Im}(Z_H)\}^2} \right]^{1/2} \quad (1)$$

where

$G(f)$  = amplifier gain (as a function of frequency)

$Z_A$  = input impedance of amplifier

$Z_H$  = impedance of hydrophone

$\text{Re}(Z)$  indicates the real part of a complex number  $Z$

$\text{Im}(Z)$  indicates the imaginary part of a complex number  $Z$

If the hydrophone and amplifier impedances are primarily capacitive (as is the case with all Onda hydrophones and amplifiers), Eq. (1) can be approximated:

$$M_L(f) = G(f) M_c(f) \frac{C_H}{C_H + C_A} \quad (2a)$$

where  $C_A$  and  $C_H$  are the capacitance of the amplifier and hydrophone, respectively.  $C_H$  is provided with the EOC calibration data shipped with each modular hydrophone. Onda provides  $C_A$  with the calibration sheets for all AH2010 and AH2020 amplifiers, and can be purchased for an additional price for other Onda amplifiers.

Note that in some cases, adaptors or short cables may be used between the hydrophone connector and the amplifier. This additional connection length may have an effect which can be approximated by a connection capacitance, designated  $C_C$ , which can be accounted for by the following modification to Eq. (2):

$$M_L(f) = G(f) M_c(f) \frac{C_H}{C_H + C_C + C_A} \quad (2b)$$

*A common example of such a connector is the right angle SMA connector (Onda part number AR-AMAF) which is used to connect an Onda HGL hydrophone to an AH2010 or AH2020 in a right-angle configuration;  $C_C = 1.6$  pF for this case.*

**Note: Customers are advised to perform their own assessment of the accuracy of Eqs. (2a-b) for their configuration. In particular, customers should be aware that extension cables connecting the hydrophone to the preamplifier or detector may not be accurately modeled as purely capacitive at higher frequencies; in such cases, customers are advised to consider purchasing a separate calibration which includes the use of their extension cables.**

## IV. Other Common Calibration Units

$M_L(f)$  is in units of voltage divided by pressure and is typically expressed in V/Pa. Alternatively, it can be expressed in units of dB re 1V/ $\mu$ Pa using Eq. (3):

$$dB_{re\ 1V/\mu Pa}[M_L(f)] = 20 * \log_{10}[M_L(f)] - 120 \quad (3)$$

It is also common to express the calibration in terms of acoustic intensity. Strictly speaking, a simple calibration factor exists only under conditions of a sinusoidal signal and under the assumption that intensity is equal to the time-averaged value of the pressure squared divided by the acoustic impedance of the medium. Under these conditions the following relation applies:

$$I = V_{RMS}^2 / K \quad (4)$$

where  $I$  is the acoustic intensity, and  $V_{RMS}$  is the root-mean-square voltage of the sinusoidal signal. The calibration factor  $K$  is given by

$$K = z_a [M_L(f)]^2 \quad (5)$$

where  $z_a$  is the acoustic impedance of the medium (1.5 MRayls for water). Because it is common to express  $I$  in units of W/cm<sup>2</sup>,

$$K\{\text{volts}^2 \text{cm}^2 / \text{Watt}\} = 1.5 \times 10^{10} [M_L(f)\{\text{volts} / \text{Pa}\}]^2 \quad \textbf{for water} \quad (6)$$

## V. Examples

Example I. An HNV-0400 is supplied by Onda with an EOC calibration:

$$M_c(f) = 50 \text{ nV/Pa at } 5 \text{ MHz, and } C_H = 80 \text{ pF}$$

We now wish to determine the sensitivity for this hydrophone connected to an AH-2010 preamplifier.

As determined from the datasheet for the AH-2010, the amplifier impedance is capacitive with  $C_A = 7 \text{ pF}$ , and the gain is 20 dB ( $G(f) = 10$ ). Application of Eqs. (2a) and 3 shows that  $M_L(5\text{MHz}) = 460 \text{ nV/Pa}$ , or  $-246.7 \text{ dB re } 1\text{V}/\mu\text{Pa}$ . Application of Eq. (6) yields  $K(5 \text{ MHz}) = 3.17 \times 10^{-3} \text{ V}^2 \text{ cm}^2/\text{W}$ .

Example II. An HGL-0200 is supplied by Onda with an EOC calibration:

$$M_c(f) = 45 \text{ nV/Pa at } 5 \text{ MHz, and } C_H = 13 \text{ pF}$$

We now wish to determine the sensitivity for this hydrophone connected to an AH-2010 preamplifier through an AR-AMAF connector:

As determined from the datasheet for the AH-2010, the amplifier impedance is capacitive with  $C_A = 7 \text{ pF}$ , and the gain is 20 dB ( $G(f) = 10$ ). Application of Eqs. (2b) and 3 shows that  $M_L(5\text{MHz}) = 271 \text{ nV/Pa}$ , or  $-251.3\text{dB re } 1\text{V}/\mu\text{Pa}$ . Application of Eq. (6) yields  $K(5 \text{ MHz}) = 1.10 \times 10^{-3} \text{ V}^2 \text{ cm}^2/\text{W}$ .

### References

- [1] A. Selfridge and P.A. Lewin, "Wideband Spherically Focused PVDF Acoustic Source for Calibration of Ultrasound Hydrophone Probes," IEEE Trans. UFFC, 47(6) 1372-1376, 2000.
- [2] R. C. Preston, D.R. Bacon, and R. A. Smith, "Calibration of Medical Ultrasound Equipment: Procedures and Accuracy Assessment," IEEE Transactions on Ultrasonics, ferroelectrics, and Frequency Control, Vo. UFFC-25(2), pp. 110-121, 1988.
- [3] M. C. Ziskin, "Measurement Uncertainty in Ultrasonic Exposimetry," in Ultrasonic Exposimetry, M.Ziskin and P. Lewin, eds. (CRC Press), Chapter 14, 1993.
- [4] ALUM/NEMA: Acoustic Output Measurement Standard for Diagnostic Ultrasound Equipment. American Institute of Ultrasound in Medicine, 14750 Sweitzer Lane, Suite 100, Laurel MD 20707-5906; National Electrical Manufacturers Association, 1300 North 17<sup>th</sup> Street, Suite 1847, Rosslyn VA 22209, 1998.
- [5] IEC 62127-2: Ultrasonics – Hydrophones – Part 2: Calibration for Ultrasonic Fields Up to 40 MHz.