Ultrasonics 58 (2015) 87–95

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Primary reciprocity-based method for calibration of hydrophone magnitude and phase sensitivity: Complete tests at frequencies from 1 to 7 MHz

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A R T I C L E I N F O

Article history:
Received 1 October 2014
Received in revised form 22 December 2014
Accepted 22 December 2014
Available online 31 December 2014

Keywords:
Transducer
Hydrophone
Calibration
Phase sensitivity
Magnitude sensitivity

A B S T R A C T

A primary reciprocity-based method for calibration of hydrophone magnitude and phase sensitivity is proposed. The method starts determining the transmit transfer function of an auxiliary transducer, based on the self-reciprocity method and using a stainless steel cylinder as reflecting target. Afterwards, the hydrophone, to be calibrated, is positioned facing the auxiliary transducer. The pressure field waveform, calculated at the hydrophone spot and based on the transmit transfer function of an auxiliary transducer, is used together with the output end of cable voltage waveform signal from the hydrophone to yield the calibrated hydrophone sensitivity. The method was tested with two similar membrane hydrophones, at frequencies within the 1.0–7.0 MHz range, in steps of 1.0 MHz. Results for magnitude sensitivity agree, within a confidence level of 95%, with those from previous calibration of same hydrophones at the National Physical Laboratory, in the UK ($E_{nor} \leqslant 1.0$). Phase sensitivity results agree with literature reported ones concerning the achieved uncertainty. Additionally, the phase sensitivities measured at 5.0 MHz for two similar hydrophones and employing two distinct auxiliary transducers presented no statistical significant difference. The method yielded a relative expanded uncertainty ($p = 0.95$) for the sensitivity magnitude ranging between 6.6 and 7.0%, and an expanded uncertainty ($p = 0.95$) ranging between 12° and 17° for the phase sensitivity. The results obtained so far lead to conclude that the proposed hydrophone calibration method is a validated alternative to the different existing methods.

1. Introduction

Calibration of ultrasound hydrophones means determining their sensitivity, i.e., their voltage response (output) to a dynamic pressure (input) incident on its active element. The transducer phase sensitivity is one of the fundamental quantities to be determined when its input waveform shape is of concern. If a distorted ultrasonic pressure wave is to be quantified regarding its maximum or minimum peak of pressure, the output voltage signal must be "corrected" to overcome the incidental phase shift inputted to the time signal. The straightforward way to do that is rectifying the (output) time signal, such as applying a deconvolution signal processing, taking out the phase influences due the transducer (hydrophone) phase response [1]. The deconvolution could be done in the frequency domain, if the hydrophone phase response is available. Calibration of hydrophone phase sensitivity plays a key role in that approach.

Among hydrophone calibration methods, the reciprocity one is traditional, long time validated and well known between ultrasound technicians [2–4], and standardized by the International Electrotechnical Commission (IEC) [5]. The method comprises the use of a reciprocal auxiliary transducer [6], with transfer functions on transmission and reception related by a proportionality constant named "reciprocity parameter" [7], which is related to the wave type (spherical, plane, etc.), and the calibrations occur, typically, at discrete frequencies above 1 MHz [8]. The measurement setup is relatively simple, as far as the reciprocity method demands, basically, electrical measurements. Nevertheless, the method requires an elaborated measurement of an open-circuit voltage difference between the transducer terminals, when it is operating as a receiver in the pulse-echo mode [9]. In general, the "open circuit" measurement is actually a correction to the output voltage measurement obtained with a post procedure of end-of-cable short circuit measurement (detailed arrangement in [5];

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http://dx.doi.org/10.1016/j.ultras.2014.12.006
0041-624X/

Section 3.1 and Eq. (32) further in the text detail the open circuit voltage assessment).

The traditional reciprocity method provides only the sensitivity magnitude of the calibrated hydrophone. Regarding sensitivity phase calibration, the literature reports some approaches claiming the merit of being able to disclose the sensitivity phase as well, although the reported methods are mainly of comparison, instead of absolute, i.e., there is a need of a calibrated device to depict the hydrophone phase sensitivity. These approaches rely on time delay spectrometry [10–16] or optical reference hydrophone [17–20].

Recently, another method was introduced to determine the complex transfer function, for either transmission or reception, of ultrasonic transducers [21]. This particular approach forms the basis of the reciprocity-based method proposed in the present work to determine the hydrophone complex sensitivity. The approach disclosed in the present work employs an auxiliary transducer, as in the reciprocity calibration method, without the need for self-sensitivity calibration prior to the hydrophone calibration. Considering the so far standardized self-reciprocity calibration method, the novelty of the present work relies on the complex transfer function approach. With the procedure presented herein, it is possible to determine the hydrophone phase response in a primary reference measurement procedure. According to the International Vocabulary of Metrology [22], a primary reference measurement procedure demands the realization of a quantity without relation to a measurement standard for a quantity of the same kind (Section 2.8, p. 18 of [22]).

Regarding the paper where the complex transfer function of ultrasonic transducers was presented [21], an effort was done in this paper to not oversimplify the terms with phase contribution. The reformulation and step-by-step theoretical development is presented in Section 2, with relevant aspects for phase determination due diffraction and directivity (Sections 2.2.2 and 2.2.6) and water propagation path (Sections 2.2.4 and 2.2.7). Finally, as an innovative contribution, the transfer function theory was extended and the experimental procedure redesigned to allow the primary complex calibration of a hydrophone (1–7 MHz), what was not proposed in the reviewed references so far.

2. Basic formulation

2.1. Hydrophone sensitivity

The starting point for the approach used in the present work considers determining the complex transmit transfer function, T_t, of an auxiliary ultrasonic transducer, based on the setup depicted in Fig. 1 and defined in van Neer et al. [21] as:

$$T_t\omega) = \frac{p_{tx}(\omega)}{V(\omega)}, \tag{1}$$

with $\omega = 2\pi f$, f is the ultrasound frequency, p_{tx} = the average pressure generated on the emitting surface of the transducer when excited with the electrical signal V.

Considering the auxiliary transducer to be a reciprocal flat circularly symmetric piston, with effective radius a, and d_1 the distance between transducer and reflector, then T_t becomes expressed [20] by:

$$T_t(\omega,d_1) = \sqrt{\frac{i\omega\rho_0 V_{open}(\omega,d_1)}{8\pi d_1 Z(\omega)V(\omega)\exp[-2\alpha(\omega)d_1]\exp(-i2kd_1)[1-\exp(-ika^2/4d_1)]DS_{tt}(\omega,d_1)R(\omega)}}, \tag{2}$$

where ρ_0 = the density of the medium between transducer and reflector, V_{open} = the output signal of the transducer, loaded by an infinite electrical impedance, upon arrival of the echo from the reflector, Z = the transducer electrical input impedance, α = the acoustic wave attenuation coefficient of the medium between transducer and reflector, $\exp(-ik2d_1)$ = the phase variation due to the distance traveled by the wave front, with $k = 2\pi/\lambda$ and λ = acoustic wavelength, DS_{tt} = the term related to diffraction, due to the auxiliary transducer finite aperture during transmission, and also to spatial averaging, due to the auxiliary transducer finite aperture receiving a non-planar acoustic wave, and $R(\omega)$ = the reflection coefficient of the plane reflector. For general representation, R is a function of ω, but in practice the magnitude and phase influence of the reflection coefficient is considered frequency independent.

Replacing the reflector replaced by a hydrophone positioned aligned with the transducer axis of symmetry and distant d_1 from the transducer face, then the hydrophone electrical output signal, V_h, is expressed [23] by:

$$V_h(\omega,d_1) = T_h(\omega)[V(\omega)T_t(\omega,d_1)\exp(-\alpha d_1)\exp(-ikd_1)DS_{th}(\omega,d_1)], \tag{3}$$

considering T_h = the hydrophone receive transfer function and DS_{th} = the term related to diffraction, due to the finite aperture of auxiliary transducer (transmitter) and to the spatial averaging owing to a non-planar acoustic wave incident upon the hydrophone finite aperture.

The hydrophone sensitivity, M_h, is defined as:

$$M_h(\omega) = \frac{V_h(\omega,d_1)}{p(\omega,d_1)}, \tag{4}$$

with $p(\omega,d_1)$ = the average acoustic pressure incident upon the hydrophone face, which is the term inside the brackets in (3).

Therefore, from (3) and (4) comes:

$$M_h(\omega) = T_h(\omega). \tag{5}$$

Combining (1)–(5) results in the expressions for magnitude, $|M_h|$, and phase, $\angle M_h$, of M_h in terms of parameters measured experimentally or related to an experimental setup:

$$|M_h(\omega)| = \frac{|V_h(\omega,d_1)|}{|V(\omega)T_t(\omega,d_1)\exp(-\alpha d_1)DS_{th}(\omega,d_1)|} \tag{6}$$

and

$$\angle M_h(\omega) = \angle V_h(\omega,d_1) - \angle V(\omega) - \angle T_t(\omega,d_1) - \angle\exp(ikd_1) - \angle DS_{th}(\omega,d_1). \tag{7}$$

2.2. Practical considerations concerning some of the terms in equations of $|M_h|$ and $\angle M_h$

2.2.1. Effective transducer radius

One possible way to determine the effective radius of a transducer, modeled as a flat circularly symmetric piston, comes from mapping the on-axis pressure distribution and determining the last axial minimum, d_m. In this case, the radius is determined [24] by:

$$a = \sqrt{2\lambda d_m + \lambda^2}. \tag{8}$$

In this paper, values of d_m were experimentally determined after a field mapping. It is worth to mention that the position of a minimum is experimentally determined more accurately than the position of a maximum. It occurs because the last minimum is more "sharp" than the "flat" last maximum, so it is easier to locate within an on axis pressure plot. That is the reason why Eq. (8) was chosen.

2.2.2. Diffraction term DS_{tt} in the expression of T_t

The magnitude of DS_{tt}, $|DS_{tt}|$, is a factor that corrects the pressure amplitude of the wave returning from the reflector and