Ultrasonics 71 (2016) 51–58

Contents lists available at ScienceDirect

Ultrasonics

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

Spatial averaging effects of hydrophone on field characterization of planar transducer using Fresnel approximation

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ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form 25 May 2016
Accepted 26 May 2016
Available online 27 May 2016

Keywords:
Spatial averaging
Hydrophone
Planar transducer
Fresnel approximation
Field characterization

ABSTRACT

The purpose of this work was to improve the existing models that allow spatial averaging effects of piezoelectric hydrophones to be accounted for. The model derived in the present study is valid for a planar source and was verified using transducers operating at 5 and 20 MHz. It is based on Fresnel approximation and enables corrections for both on-axis and off-axis measurements. A single-integral approximate formula for the axial acoustic pressure was derived, and the validity of the Fresnel approximation in the near field of the planar transducer was examined. The numerical results obtained using 5 and 20 MHz planar transmitters with an effective diameter of 12.7 mm showed that the derived model could account for spatial averaging effects to within 0.2% with Beissner's exact integral (Beissner, 1981), for $\sqrt{k\frac{(a+b)}{2}} \gg \pi$ (where k is the circular wavenumber, and a and b are the effective radii of the transmitter and hydrophone, respectively). The field distributions along the acoustic axis and the beam directivity patterns are also included in the model. The spatial averaging effects of the hydrophone were generally observed to cause underestimation of the absolute pressure amplitudes of the acoustic beam, and overestimation of the cross-sectional size of the beam directivity pattern. However, the cross-sectional size of the directivity pattern was also found to be underestimated in the "far zone" (beyond $Y_0 = a^2/\lambda$) of the transmitter. The results of this study indicate that the spatial averaging effect on the beam directivity pattern is negligible for $\frac{\pi(\gamma^2+4\gamma)}{s} \ll 1$ (where $\gamma = b/a$, and s is the normalized distance to the planar transducer).

1. Introduction

The purpose of this work was to improve the existing models that allow spatial averaging effects of piezoelectric hydrophones to be accounted for. Miniature hydrophones are widely used to detect the spatial and temporal characteristics of ultrasound fields [1]. The hydrophone is used to measure the averaged acoustic pressure over the active area of the element. This technique is recommended for the measurement of many field parameters that are considered important in the International Electrotechnical Commission (IEC) standards [2]. The effective radius of the hydrophone should ideally be comparable to or smaller than one quarter of the acoustic wavelength, as indicated in paragraph 5.1.6.1 of IEC 62127-1 [2]. This is to ensure that the phase and amplitude variations over the active element do not significantly contribute to the measurement uncertainties. In the far field of the ultrasonic transmitter, the criteria can be relaxed based on the dimensions of the transducers, the acoustic wavelength and the distance between the hydrophone and the transmitter surface [2,3]. The error caused by the finite aperture size is termed the spatial averaging error [4]. Umchid and Gopinath also noted that the effective diameter of the hydrophone should be on the order of the half-wavelength at the highest frequency to be measured to eliminate the effect of spatial averaging [5]. In water, this requires the use of an active aperture on the order of 50 μm at 15 MHz. However, although a special 50-μm-diameter hydrophone has been reported [6], the majority of commercially available piezoelectric hydrophones has nominal active apertures (or diameters) within 0.2–1 mm, which is too large for measurement in an ultrasonic fields above a few MHz. Hydrophones that do not meet the requirements for a point detector produce spatially averaged values of the acoustic pressure.

For the applications which require sensors with high temporal and spatial resolution, the interferometric [7–9] and fiber-optic methods [10–13] are noteworthy. A fiber-optic hydrophone with a tip diameter of approximately 7 μm has been reported by Lewin et al. [12]. The hydrophone enables extension of the working frequency to 100 MHz without inducing spatial averaging effects. Although the fiber-optic hydrophones are promising in biomedical

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http://dx.doi.org/10.1016/j.ultras.2016.05.022
0041-624X/

ultrasound applications, they are primarily found in well-equipped university- or testing houses laboratories and are relatively expensive. The spatial averaging effects due to the finite aperture size of piezoelectric hydrophones have attracted much attention from investigators. Boutkedjirt and Reibold [14,15] addressed this issue as an inverse problem and used numerical methods to deconvolve the averaging effects. Other methods for correcting the spatial averaging effects have been proposed although their discussions were restricted to idealized models. For the measurement arrangement in which the hydrophone is located along the acoustic axis of the transmitting transducer, Daly and Rao [16] derived a set of closed-form expressions based on the Lommel diffraction formulation for both planar and spherically focused transmitters. In addition, Preston et al. [17] and Smith [18] used a beam-plot method based on the theoretical model of the pressure distribution in the focal plane to estimate the spatial averaging effects. Zeqiri and Bond [19] and Radulescu et al. [20] numerically calculated the theoretical pressure distribution over the hydrophone in the focal plane, with the purpose of estimating the same effects. Harris [21,22] used the generalized spatial impulse response function of the velocity potential to evaluate the averaging effects in the transient field of planar transducers. Markiewicz and Chivers [23]used the spatial impulse response method [21,22] to investigate the typical errors involved in far field measurements. Furthermore, Beissner [24] derived an exact integral expression for the spatial averaging effects in the steady state of a planar transducer field when the acoustic axes of the transmitter and the hydrophone are coaxial. Goldstein et al. [25] estimated the spatial averaging effects of a hydrophone along the acoustic axis by determining the effective radius of a planar transducer used as a transmitter. Later Goldstein [26] determined the magnitudes of the axial and lateral pressures for the field characterization of a planar transducer in a steady-state field that contained no hydrophone.

The present study was undertaken to supplement the current spatial averaging models that were developed to satisfy the geometry in which the receivers are located along the acoustic axis of the transmitting transducer. The model developed in this study is based on Fresnel approximation and enables the correction of an off-axis measurement arrangement. The properties of the acoustic fields produced by the planar transducers were theoretically investigated using the Rayleigh integral algorithm, which is a mathematical formulation of the Huygens–Fresnel principle. For a planar transducer mounted on an infinite baffle, the formulation is an exact solution. The Rayleigh integral for the acoustic pressure and the use of other approaches based on Huygens elementary wavelets are not strictly valid for curved transducer surfaces [27]. This is because the hemispherical elementary waves are initially diffracted by the focused transmitter surface. Thus, only planar transducers were considered in the present study. In Section 2, a single integral for estimating the spatial averaging effect along the acoustic axis is first deduced and compared with Beissner's exact integral [24]. A formulation of the lateral acoustic pressure of the planar transducers measured by the hydrophone is then derived. A formulation of the averaged pressure measured by a hydrophone in an attenuating fluid is subsequently derived. In Section 3, the validity of the Fresnel approximation in the near field of planar transducers is discussed. The effects of spatial averaging on estimation of the cross-sectional size of the beam directivity pattern are also analyzed. Knowledge of the axial and lateral field distributions of transmitters as measured by a hydrophone is essential for proper interpretation of the experimental results.

2. Theory and results

The several basic assumptions regarding the conditions of the present study are first briefly noted here. It was assumed that the planar piston transmitter was surrounded by an infinite rigid baffle. The radiating surface moved uniformly with the velocity $V\exp(i\varpi t)$. The sound propagating fluid was also assumed to be lossless. The experimental approach was restricted to linear acoustics and nonlinear propagation phenomena were avoided. The transducer was driven by a tone burst signal (voltage) to avoid reflection and to simulate steady-state wave fields. Fig. 1 shows the off-axis measurement geometries for a planar circular piston transducer and planar circular piston hydrophone of radii a and b, respectively. The transmitter is located in the XY plane and centered at the origin. The source point q on the transmitter surface emits spherical waves and is located at a distance$\sigma$from the origin and inclined at an angle φ to the Y-axis. The surface of the hydrophone, which is located at an axial distance z, is parallel to the transmitter. The center of hydrophone is located at a lateral distance x from the acoustic axis. The distance between the centers of hydrophone and the transmitter is denoted by r. The point Q is located on the hydrophone surface, at a distance η from the center of the hydrophone along an inclination ϕ to the Y-axis. The distance from the point Q to the source point q on the transmitter surface is denoted by r_2.

The Rayleigh integral for the acoustic pressure at point Q is [28]

$$p = i\frac{\rho_0 \varpi V}{2\pi}\int_0^{2\pi}\int_0^a \frac{e^{i(\varpi t - kr_2)}}{r_2}\sigma d\sigma d\varphi. \tag{1}$$

Thus, the acoustic pressure on the hydrophone surface is averaged as

$$\begin{aligned}\overline{p}_{ex}(r,\theta,t) &= \frac{1}{A_b}\iint_{A_b} p\,dS \\ &= \frac{i\rho\varpi V}{2\pi A_b}\int_{\varphi=0}^{2\pi}\int_{\phi=0}^{2\pi}\int_{\sigma=0}^{a}\int_{\eta=0}^{b}\frac{e^{i(\varpi t - kr_2)}}{r_2}\sigma\eta d\sigma d\varphi d\eta d\phi\end{aligned} \tag{2}$$

where A_b is the area of the hydrophone surface, and the bar indicates the spatial average. As derived in Appendix A,

$$r_2 = \left(r^2 + \sigma^2 + \eta^2 + 2r\sin\theta(\eta\sin\phi - \sigma\sin\varphi) - 2\sigma\eta\cos(\varphi - \phi)\right)^{1/2}. \tag{3}$$

2.1. On-axis measurement

Along the acoustic axis, $r = z$ and $\theta = 0$. Eq. (3) thus reduces to

$$r_2 = \left(z^2 + \sigma^2 + \eta^2 - 2\sigma\eta\cos(\varphi - \phi)\right)^{1/2}. \tag{4}$$

An expression of the exact averaged pressure measured by the hydrophone can be obtained by substituting Eq. (4) into Eq. (2),

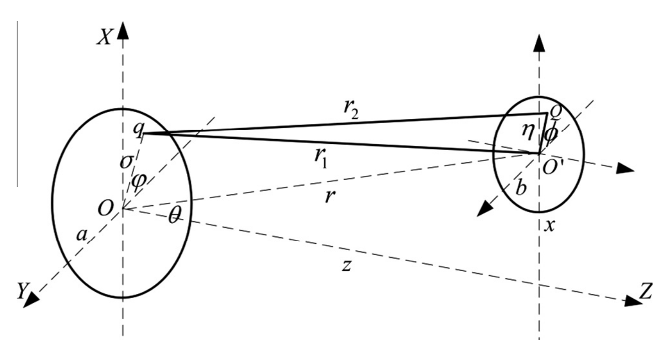

Fig. 1. Off-axis measurement geometry considered with transmitter of radius a and hydrophone of radius b. The transmitter surface is in the XY plane, and Q is a point on the hydrophone surface.