



COVER PAGE

Document downloaded by @DAEL

Wed Oct 28 01:07:02 2026

For personal use

When automatic English translation is provided, only the original document is authentic.

The EAA cannot be held responsible of any translation error

Bibliographical reference

A Nearfield Acoustic Holography-Based Method for Measuring the Sensitivity of a Particle Velocity Sensor, Wen-Qian Jing, Yong-Bin Zhang and Chuan-Xing Bi, *Acta Acustica* **vol. 101** (Number 4), 2015, pp. 855-858

DOI

<https://doi.org/10.3813/AAA.918879>

A Nearfield Acoustic Holography-Based Method for Measuring the Sensitivity of a Particle Velocity Sensor

Wen-Qian Jing, Yong-Bin Zhang, Chuan-Xing Bi
Institute of Sound and Vibration Research, Hefei University of Technology, 193 Tunxi Road, Hefei 230009, People's Republic of China. ybzhang@hfut.edu.cn

PACS no. 43.58.Fm, 43.60.Sx

Abstract

Unlike the pressure sensor (p -sensor), the sensitivity of the particle velocity sensor (u -sensor) of a pressure-velocity (p - u) sound intensity probe is rather difficult to obtain because the standard reference particle velocity sensor is not available. Usually the sensitivity of the u -sensor is obtained by exposing the probe to a sound field where the acoustic impedance has a closed-form solution. This paper develops a nearfield acoustic holography (NAH)-based method to measure the sensitivity of the u -sensor, in which the acoustic impedance is reconstructed from the measured pressure and particle velocity, and therefore the proposed method is still applicable when the acoustic impedance does not have a closed-form solution. The feasibility of the proposed method was examined through two experiments with two sound sources: a dodecahedron source and a loudspeaker. The results show that the sensitivity obtained by using the proposed method agrees well with that given in the calibration report provided by the manufacturer.

1. Introduction

The pressure-velocity (p - u) sound intensity probe which is composed of a Microflown (u -sensor) and a miniature pressure microphone (p -sensor) has been available for some years [1]. The potential applications of such a probe include the measurement of sound intensity, sound power, transmission loss, absorption coefficient, etc. [2, 3]. When using this probe, the sensitivities of the p -sensor and u -sensor play a very important role. For the p -sensor, it is very easy to obtain its sensitivity by comparing it with a standard reference pressure sensor. However, it is not easy to obtain the sensitivity of the u -sensor because there is not any standard reference particle velocity sensor available. Currently, the solution for obtaining the sensitivity of the u -sensor is to create an environment where the relation between the particle velocity and the pressure, i.e., the acoustic impedance, is known [4]. So the key point is how to get a sound field with the acoustic impedance known *a priori*. To achieve this purpose, some facilities or sound sources have been designed specially, such as a standing wave tube [5], a very long acoustic wave guide installed under the ground [6], a rigid plastic sphere with a loudspeaker mounted inside it and with a small hole in front of the loudspeaker (deemed to be a monopole on a sphere) [7], a big wooden baffle with a small hole and with a small loudspeaker behind the baffle (deemed to be a monopole on an infinite plane baffle) [7]. In such sound fields, the acoustic impedance has a

closed-form solution related with the design parameters of the facilities or sound sources.

This paper develops an alternative method to measure the sensitivity of the u -sensor by acquiring the acoustic impedance from the measured pressure and particle velocity. Thus the sound field where the acoustic impedance does not have a closed-form solution can also be used to help measure the sensitivity of the u -sensor. In this method, nearfield acoustic holography (NAH) is used to reconstruct the acoustic impedance because NAH has the ability of reconstructing the pressure as well as the particle velocity. In theory, all the NAH methods can be used to reconstruct the acoustic impedance, such as the spatial Fourier transform method [8], the inverse boundary element method [9], the statistically optimized NAH (SONAH) [10], the Helmholtz equation least-squares method (HELS) [11], and the equivalent source method (ESM) [12, 13, 14, 15, 16]. However, in practice, the NAH method that can be directly applied to a patch case (i.e., the measurement surface is small and the sound field does not drop to a sufficiently low value near the edges of the measurement surface) is more attractive because the measurement surface should be as small as possible to reduce the workload. The ESM, SONAH and HELS are such natural patch NAH methods, and in this paper the NAH based on the ESM is adopted. Although both the pressure and the particle velocity can be used as the input of NAH, the particle velocity is recommended here because it has been demonstrated in some previous papers that it is advantageous to use the particle velocity rather than the pressure as the input [17, 18, 19]. The theory of NAH based on the ESM and measurements of particle velocity is briefly reviewed in Section 2.1: See [18] for more detail. And in Section 2.2, the theory of the NAH-based method for measuring the sensitivity of a p - u probe is described. Finally, the proposed method is experimentally examined by using two sound sources: a dodecahedron source and a loudspeaker.

2. Outline of the theory

2.1. NAH based on the ESM and measurements of particle velocity

The main idea of the ESM is to approximate the sound field radiated by a vibrating structure by using the superposition of a set of simple sources placed in the interior of the structure. Given that there are M measurement points and N equivalent simple sources, the normal particle velocity vector, $\mathbf{U}_{nh}$, at these measurement points can be represented in matrix form as

$$\mathbf{U}_{nh} = \mathbf{G}_{hu} \mathbf{Q}, \quad (1)$$

where $\mathbf{Q} = [q(\mathbf{r}_{o1}), q(\mathbf{r}_{o2}), \dots, q(\mathbf{r}_{oN})]^T$ is the column vector of equivalent source strengths $q(\mathbf{r}_{on})$, the superscript T represents the matrix transpose, $\mathbf{r}_{on}$ is the location vector of the n th equivalent source, and $\mathbf{G}_{hu}$ is the transfer matrix relating the particle velocity on the measurement surface to the equivalent sources,

$$\begin{aligned} [\mathbf{G}_{hu}]_{m,n} &= \frac{\partial g(\mathbf{r}_{hm}, \mathbf{r}_{on})}{\partial n_h}, \\ g(\mathbf{r}_{hm}, \mathbf{r}_{on}) &= -\frac{e^{ikr}}{4\pi r}, \quad r = |\mathbf{r}_{hm} - \mathbf{r}_{on}|, \end{aligned} \quad (2)$$

where $\mathbf{r}_{hm}$ is the location vector of the m th measurement point, g is the free space Green's function with the $e^{-i\omega t}$ sign convention, and $\mathbf{n}_h$ is the outward normal of the measurement surface. The unknown source strength vector $\mathbf{Q}$ can be obtained as

$$\mathbf{Q} = \mathbf{G}_{hu}^+ \mathbf{U}_{nh}, \quad (3)$$

Received 14 December 2014,
accepted 26 March 2015.

where G_{hu}^+ is the pseudo inverse matrix of G_{hu} . Then the pressure at a field point $\mathbf{r}$ can be reconstructed as

$$p(\mathbf{r}) = i\rho\omega G_p Q, \quad (4)$$

where ρ is the density of the medium, ω is the angular frequency, and G_p is the transfer matrix relating the pressure at the point $\mathbf{r}$ to the equivalent sources,

$$[G_p]_n = g(\mathbf{r}, \mathbf{r}_{on}). \quad (5)$$

2.2. Sensitivity measurement by using a NAH-based method

With knowledge of the sensitivity of the reference pressure sensor, the sensitivity of the p -sensor, S_p , can be directly determined by

$$S_p = \frac{p_{out}}{p_{ref}} S_{ref}, \quad (6)$$

where p_{out} and p_{ref} are the outputs of the p -sensor and the reference pressure sensor, respectively, and S_{ref} is the sensitivity of the reference pressure sensor.

The sensitivity of the u -sensor is much more difficult to be obtained than the p -sensor because no reference particle velocity sensor exists [2]. However, the output of the u -sensor can be related to the output of the reference pressure sensor through the acoustic impedance at the measurement point, i.e.,

$$Z = \frac{p_{ref}/S_{ref}}{u_{out}/S_u}, \quad (7)$$

where u_{out} and S_u are the output and the sensitivity of the u -sensor, respectively.

Then the sensitivity of the u -sensor can be determined by

$$S_u = \frac{u_{out}}{p_{ref}} Z S_{ref}. \quad (8)$$

If the p - u probe is exposed to a special sound field where the acoustic impedance has a closed-form solution, using Equation (8) can easily calculate the sensitivity of the u -sensor. But in an ordinary sound field, the acoustic impedance needs to be estimated. When using NAH to estimate the acoustic impedance, the calculation procedure for getting the sensitivity of the u -sensor can be described as follows:

1. The first step is to measure the sound pressure (denoted by a column vector $\mathbf{P}_{out}$) and the normal particle velocity (denoted by a column vector $\mathbf{U}_{out}$) on a plane near the sound source by a p - u probe under test. The measurement is done by scanning from one measurement point to another.
2. Using $\mathbf{U}_{out}$, which is the output of the u -sensor without calibration, as the input of NAH, the sound pressure at each measurement point can be reconstructed by using the NAH method described in Section 2.1. And the reconstructed sound pressures at all the measurement points are to be denoted by a column vector $\mathbf{P}_r$. Note that $\mathbf{P}_r$ is also an uncalibrated quantity.
3. The acoustic impedance at these measurement points can be calculated as

$$Z_m = [\mathbf{P}_r]_m / [\mathbf{U}_{out}]_m, \quad m = 1, 2, \dots, M, \quad (9)$$

where Z_m is the acoustic impedance at the m th measurement point.

Substituting Equation (9) to Equation (8), and using Equation (6), the sensitivity of the u -sensor, S_u^m , at the m th measurement point can be obtained as

$$S_u^m = \frac{[\mathbf{U}_{out}]_m}{p_{ref}^m} Z_m S_{ref} = \frac{[\mathbf{P}_r]_m}{[\mathbf{P}_{out}]_m} S_p, \quad (10)$$

where p_{ref}^m is the output of the reference microphone at the m th measurement point.

Equation (10) is the final formulation to calculate the sensitivity of the u -sensor. It can be found that the acoustic impedance just plays a role of intermediate quantity, which does not need to be reconstructed explicitly. In fact, as shown in Equation (10), the NAH-based method can also be interpreted in another point of view: the sensitivity of the u -sensor is obtained by matching the reconstructed-and-calibrated pressure, $[\mathbf{P}_r]_m/S_u^m$, with the measured-and-calibrated pressure, $[\mathbf{P}_{out}]_m/S_p$.

The final sensitivity of the u -sensor is defined as the average of the sensitivities at all the measurement points, i.e.,

$$S_u = \frac{1}{M} \sum_{m=1}^M S_u^m. \quad (11)$$

3. Experiments

Two experiments were carried out to examine the feasibility of measuring the sensitivity of the u -sensor of a p - u probe produced by Microflown Technologies by NAH-based method. For each p - u probe, a corresponding calibration report is attached to supply the sensitivities of p - and u -sensors. The sensitivity of the u -sensor given in the report was obtained by using a special loudspeaker, consisting of a hard plastic sphere in which a loudspeaker is placed. This specially designed spherical source can be modeled as a sphere with a moving piston, which generates a known sound field. The calibration procedure is described detailedly in [4]. The sensitivities of the p -sensor and u -sensor in the calibration report were given by

$$S_{ap} = S_{ap}@1\text{kHz} \frac{\sqrt{1+f^2/f_{c3p}^2}}{\sqrt{1+f_{c1p}^2/f^2} \sqrt{1+f_{c2p}^2/f^2}}, \quad (12a)$$

$$\varphi_p = \arctan \frac{C_{1p}}{f} + \arctan \frac{C_{2p}}{f} + \arctan \frac{f}{C_{3p}}, \quad (12b)$$

$$S_{au} = S_{au}@250\text{Hz} \left[\sqrt{1+f_{c1u}^2/f^2} \sqrt{1+f^2/f_{c2u}^2} \cdot \sqrt{1+f^2/f_{c3u}^2} \sqrt{1+f_{c4u}^2/f^2} \right]^{-1}, \quad (13a)$$

$$\varphi_u = \arctan \frac{C_{1u}}{f} - \arctan \frac{f}{C_{2u}} - \arctan \frac{f}{C_{3u}} + \arctan \frac{C_{4u}}{f}, \quad (13b)$$

where S_{ap} and φ_p are the amplitude and phase of the sensitivity of the p -sensor, respectively, S_{au} and φ_u are the amplitude and phase of the sensitivity of the u -sensor, respectively. $S_{ap}@1\text{kHz}$ is equal to 49.2 mV/Pa, and $S_{ap}@250\text{Hz}$ is equal to 68.44 V/(m/s). The corner frequencies required in Equations (12) and (13) are given in Tables I and II, respectively.

Since we could not get the same reference microphone as the one used in the calibration report, the sensitivity of the p -sensor (Equation 12) was directly used in both experiments. And the



Figure 1. The measurement scenes: the first experiment (a) and the second experiment (b).

Table I. Corner frequencies (in Hz) required in Equation (12).

f_{c1p}	f_{c2p}	f_{c3p}	C_{1p}	C_{2p}	C_{3p}
13	26	6892	13	24	21191

Table II. Corner frequencies (in Hz) required in Equation (13).

f_{c1u}	f_{c2u}	f_{c3u}	f_{c4u}	C_{1u}	C_{2u}	C_{3u}	C_{4u}
56	823	7127	60	13	951	14430	60

sensitivity of the u -sensor (Equation 13) would serve as the reference for comparison. To obtain raw measured signals, the sensitivities of the p -sensor and the u -sensor were set to be equal to 1 mV/Pa and 1 V/m/s, respectively, in the acquisition software.

A dodecahedron source (OS002, shown in Figure 1a, produced by BSWA) was used in the first experiment. The diameter of the dodecahedron was 0.3 m. The center of the dodecahedron was set as the origin of the Cartesian coordinate system. The measurement plane was located at $z = 0.266$ m with the size of $0.7 \text{ m} \times 0.7 \text{ m}$. The measurement interval was 0.05 m in both the x axis and y axis. The signal synthesized by using a series of sinusoidal signals with the frequency range from 200 to 3000 Hz and the frequency interval of 50 Hz was used to drive the sound source.

In the second experiment, a loudspeaker shown in Figure 1b was used. The size of the loudspeaker was $0.60 \text{ m} \times 0.15 \text{ m} \times 0.14 \text{ m}$. The origin of the Cartesian coordinate system was assumed to locate at the center of the upper surface of the loudspeaker. The measurement plane was located at $z = 0.135$ m with

the size of $0.8 \text{ m} \times 0.5 \text{ m}$. The other parameters were the same as in the first experiment.

Figure 2 shows the sensitivities of the u -sensor corresponding to each frequency obtained in the two experiments. It can be seen that the results of both experiments agree well with the reference obtained by Equation (13). In Figure 2a, the absolute error of the amplitude (obtained by subtracting the result of NAH-based method from the reference) in the first experiment ranges from -0.89 dB to 0.27 dB and in the second experiment ranges from -1.0 dB to 0.66 dB. And in Figure 2b, the absolute error of the phase ranges from -6.2° to 4.59° in the first experiment and from -7.04° to 11.84° in the second experiment. The results shown in Figure 2 indicate the feasibility of the proposed method.

4. Conclusions

A NAH-based method was proposed to measure the sensitivity of the u -sensor of a p - u sound intensity probe. Different from the previous method that requires the acoustic impedance in the sound field have a closed-form solution, this method reconstructs the acoustic impedance from the measured pressure and particle velocity by using NAH, and therefore the sound field where the acoustic impedance does not have a closed-form solution can also be used to help obtain the sensitivity of the u -sensor. But the proposed method inherits the limitations of NAH at the same time, such as the frequency band is limited and more time is needed to measure the sound field.

Two sound sources, a dodecahedron source and a loudspeaker, were used to examine the feasibility of the proposed method. The experimental results show that the sensitivity obtained by using the proposed method agrees well with that given in the calibration report provided by the manufacturer.

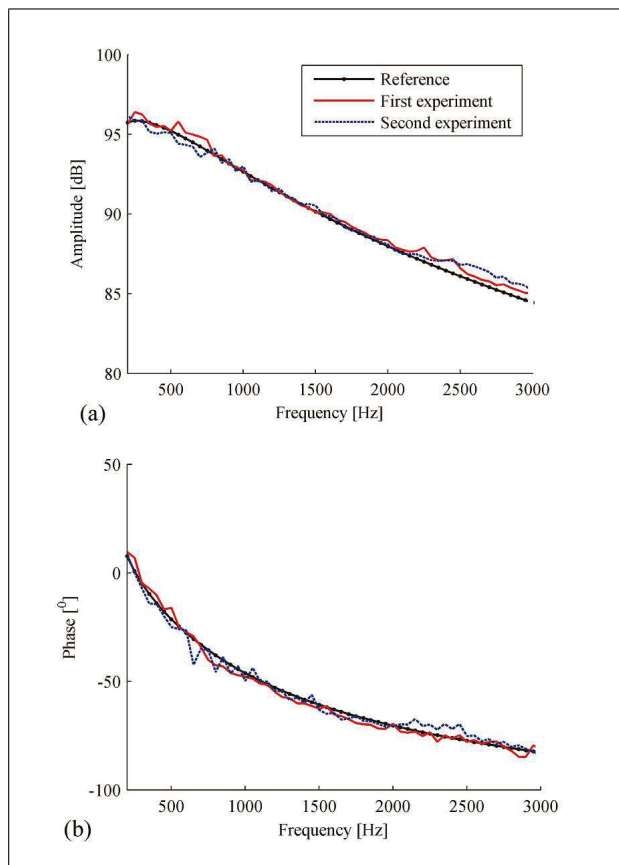


Figure 2. Amplitude (a) and phase (b) of the sensitivities of the u -sensor obtained by using the NAH-based method versus frequency.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant Nos. 51322505, 11274087 and 11004045).

References

- [1] H. E. de Bree: The microflow: an acoustic particle velocity sensor. *Acoust. Aust.* **31** (2003) 91–94.
- [2] F. J. Fahy: *Sound intensity*. 2nd ed. London, 1995.
- [3] Y. Liu, F. Jacobsen: Measurement of absorption with a p - u sound intensity probe in an impedance tube. *J. Acoust. Soc. Am.* **118** (2005) 2117–2120.
- [4] T. Basten, H. E. De Bree: Full bandwidth calibration procedure for acoustic probes containing a pressure and particle velocity sensor. *J. Acoust. Soc. Am.* **127** (2010) 264–270.
- [5] H. E. de Bree, W. F. Druyvesteyn, M. Elwenspoek: Realization and calibration of a novel half inch p - u sound intensity probe. *J. Audio Eng. Soc.* **106** (1999) 4974.
- [6] D. Stanzial, G. Sancchi, G. Schiffrer: Calibration of pressure-velocity probes using a progressive plane wave reference field and comparison with nominal calibration. *J. Acoust. Soc. Am.* **129** (2011) 3745–3755.
- [7] F. Jacobsen, V. Jaud: A note on the calibration of pressure-velocity sound intensity probes. *J. Acoust. Soc. Am.* **120** (2006) 830–837.
- [8] E. G. Williams, J. D. Maynard, E. Skudrzyk: Sound source reconstruction using a microphone array. *J. Acoust. Soc. Am.* **68** (1980) 340–344.
- [9] B.-K. Kim, J.-G. Ih: On the reconstruction of vibro-acoustic field over the surface enclosing an interior space using the boundary element method. *J. Acoust. Soc. Am.* **100** (1996) 3030–3016.
- [10] J. Hald: Basic theory and properties of statistically optimized near-field acoustical holography. *J. Acoust. Soc. Am.* **125** (2009) 2105–2120.
- [11] S. F. Wu: On reconstruction of acoustic fields using the Helmholtz equation-least-squares method. *J. Acoust. Soc. Am.* **107** (2000) 2511–2522.
- [12] N. P. Valdivia, E. G. Williams: Study of the comparison of the methods of equivalent sources and boundary element methods for near-field acoustic holography. *J. Acoust. Soc. Am.* **120** (2006) 3694–3705.
- [13] D.-G. Yang, Z.-T. Wang, B. Li, X.-M. Lian: A hybrid acoustic holography technique for moving sound source identification based on wave superposition algorithm. *Noise control Eng. J.* **60** (2012) 113–120.
- [14] A. Sarkissian: Extension of measurement surface in near-field acoustic holography. *J. Acoust. Soc. Am.* **115** (2004) 1593–1596.
- [15] A. Sarkissian: A method of superposition applied to patch near-field acoustic holography. *J. Acoust. Soc. Am.* **118** (2005) 671–678.
- [16] E. Fernandez-Grande, F. Jacobsen, Q. Leclerc: Sound field separation with sound pressure and particle velocity measurements. *J. Acoust. Soc. Am.* **132** (2012) 3818–3825.
- [17] F. Jacobsen, Y. Liu: Near field acoustic holography with particle velocity transducers. *J. Acoust. Soc. Am.* **118** (2005) 3139–3144.
- [18] Y.-B. Zhang, F. Jacobsen, C.-X. Bi, X.-Z. Chen: Near field acoustic holography based on the equivalent source method and pressure-velocity transducers. *J. Acoust. Soc. Am.* **126** (2009) 1257–1263.
- [19] E. Fernandez-Grande, F. Jacobsen: Sound field separation with a double layer velocity transducer array. *J. Acoust. Soc. Am.* **130** (2011) 5–8.