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Broadband planar nearfield acoustic holography based on one-third-octave band analysis

Hefeng Zhou [a,*], Ines Lopez-Arteaga [a,b], Henk Nijmeijer [a]

[a] Department of Mechanical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
[b] Department of Aeronautical and Vehicle Engineering, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden

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ABSTRACT

Planar nearfield acoustic holography (PNAH) is usually based on narrow-band, single frequency analysis, which is time consuming when the source behavior over a broad frequency range is of interest, as is the case with many industrial sources. In this paper a method, broadband planar nearfield acoustic holography based on one-third-octave band analysis (BPNAH), is described. Data relating to the complex band pressure on the hologram is obtained by combining the root-mean-square pressure corresponding to a one-third-octave band with the phase of the pressure corresponding to a single frequency line. Numerical simulations and measurements show that the BPNAH method allows a significant reduction in processing time, while keeping a similar accuracy to the conventional reconstruction, which is based on the summation of frequency by frequency in the corresponding band. As a simple, time-saving and robust technique, the BPNAH method is particularly well adapted to industrial studies.

1. Introduction

Nearfield acoustic holography (NAH) was first proposed by Williams and Maynard [1,2] in the mid-1980s. Its major attraction is its solution to the inverse problem that traces the sound field in space and time back towards sources. More specifically, with the introduction of evanescent waves detected in the nearfield together with propagating waves, not only source details greater but also those smaller than the sound wavelength can be retrieved. Although during the past decade, NAH has developed in a variety of directions [3–14], Fourier-based NAH still finds a wide range of applications for its efficient computation ability, which makes it possible for the sound field to be decomposed into wave-number components, providing physically meaningful information.

As a powerful and fast acoustic imaging technique, Fourier-based planar nearfield acoustic holography (PNAH) reconstructs the surface sound field of plane radiators from a measurement of the pressure on a parallel plane at a small distance from the plane [15]. Until now, research on PNAH has been focused on the reconstruction of single frequency components. However, in more practical situations such as manufacturing, most sound and vibration signals are complex broadband signals. On the one hand, it is difficult to identify a representative frequency line. Therefore it is incomplete to select a frequency at random and analyze it. On the other hand, it will be time-consuming to study frequency by frequency in this case. Although a great deal of effort [16,17] has been dedicated to solving these problems, an efficient nearfield method working in the frequency domain has yet to be developed.

For frequency analysis in engineering applications, a scale of 1/3-octave bands is widely used [18]. Specifically, the whole frequency range is divided into a set of frequencies called 1/3-octave bands. Each band covers a specific range of frequencies and all frequency components in one band are represented by the same parameter. The energy distribution of a broadband sound signal can be expressed very well in this way. In addition, a 1/3-octave band is close to the human ear's logarithmic sensitivity to sounds of different frequencies.

To benefit from these advantages, attempts have been made to use this analytical tool to simplify the conventional approach, which requires the inversion of many frequency components to reconstruct a source signal in a given 1/3-octave band. A new method-broadband planar nearfield acoustic holography based on 1/3-octave band analysis (BPNAH)-is proposed. This method solves the inverse problem through a single reconstruction, and as a simple, time-saving and robust technique with little accuracy loss, it is particularly suitable for studying industrial sources.

This paper is organized as follows: In the next section, the principle of Fourier-based PNAH is illustrated briefly and then the derivation of our proposed BPNAH method, especially the

* Corresponding author.
E-mail address: h.zhou1@tue.nl (H. Zhou).

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determination of an appropriate phase, is introduced. Numerical simulations are performed in Section 3 and some practical source experiments are carried out for further validation in Section 4, where a large number of results are shown and discussed. Finally, conclusions are drawn in Section 5.

2. Theory

2.1. Fourier-based PNAH

Consider an infinite plane at $z = z_S$ with a number of sources in it. In a plane at $z = z_H > z_S$ parallel to the source plane, named the hologram plane, the complex sound pressure is observed as a function of x and y and a two-dimensional spatial Fourier transform is calculated. The result is a wavenumber spectrum, which is defined as

$$P(k_x, k_y, z_H, f) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x, y, z_H, f)e^{-j(k_x x+k_y y)}dxdy, \quad (1)$$

where $p(x, y, z_H, f)$ is the sound pressure evaluated on the hologram plane corresponding to a frequency f, $j^2 = -1$ is the imaginary number, $P(k_x, k_y, z_H, f)$, which stands for its angular spectra, and k_x and k_y represent wavenumbers of the acoustic waves in the x- and y-axis directions, respectively.

The key issue in PNAH is how to transform acoustic quantities from the measurement surface to a parallel surface in a source-free region [19]. This special capability is represented in the following formulation:

$$P(k_x, k_y, z_S, f) = P(k_x, k_y, z_H, f)G_{pp}^{-1}(k_x, k_y, z_S - z_H, f), \quad (2)$$

where $G_{pp}^{-1}(k_x, k_y, z_S - z_H, f) = e^{jk_z(z_S - z_H)}$ is known as the propagator for reconstructing the sound pressure. Then $p(x, y, z_S, f)$ is given by the inverse two-dimensional Fourier transform,

$$p(x, y, z_S, f) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(k_x, k_y, z_S, f)e^{j(k_x x+k_y y)}dk_x dk_y, \quad (3)$$

For a given acoustic wavenumber $k = 2\pi f/c = \omega/c$, two regions can be distinguished according to the complex values of k_z, where $k_z = \sqrt{k^2 - (k_x^2 + k_y^2)} = \sqrt{k^2 - k_r^2}$. When $k_r \leqslant k$, k_z is real. For any given value of (k_x, k_y) inside the so-called radiation circle that lies at $k_r = k$, a plane wave propagates in the (k_x, k_y, k_z) direction with only a phase shift. On the other hand, when $k_r > k$, k_z is imaginary. Outside the radiation circle the wavenumber spectrum represents that the amplitude of the sound pressure decays exponentially with distance, known as an evanescent wave.

If the normal velocity on the source plane $v(x, y, z_S, f)$ is sought, then the mathematics behind PNAH is summarized in the single statement:

$$v(x, y, z_S, f) = \mathcal{F}_x^{-1}\mathcal{F}_y^{-1}\{\mathcal{F}_x\mathcal{F}_y[p(x, y, z_H, f)]G_{pv}^{-1}(k_x, k_y, z_S - z_H, f)\}, \quad (4)$$

where $\mathcal{F}$ represents the Fourier transform operation and the velocity propagator $G_{pv}^{-1}(k_x, k_y, z_S - z_H, f) = (k_z/\rho_0 ck)e^{jk_z(z_S - z_H)}$.

2.2. Principle of BPNAH

Let $\mathbf{r}_S = (x, y, z_S)$ and $\mathbf{r}_H = (x, y, z_H)$ be the position vectors of a point on the source and hologram plane, respectively. The root-mean-square (RMS) normal velocity on the source plane in a 1/3-octave band is defined as

$$v_B(\mathbf{r}_S) = \sqrt{\frac{1}{I}\sum_{i=1}^{I}|v(\mathbf{r}_S, f_i)|^2}, \quad (5)$$

where the 1/3-octave band is divided into I sub-bands and f_i stands for the central frequency of the ith sub-band. Accordingly, the 1/3-octave band RMS pressure on the hologram plane is given by

$$p_B(\mathbf{r}_H) = \sqrt{\frac{1}{I}\sum_{i=1}^{I}|p(\mathbf{r}_H, f_i)|^2}, \quad (6)$$

It is customary to refer to 1/3-octave band level when the measurement band is 1/3-octave wide. Thus we have the 1/3-octave band level of the normal velocity on the source plane

$$L_v(\mathbf{r}_S) = 10log_{10}\frac{\sum_{i=1}^{I}|v(\mathbf{r}_S, f_i)|^2}{v_{ref}^2}, \quad (7)$$

where $v_{ref} = 5 \times 10^{-8}$ m/s, and the 1/3-octave band level of the pressure on the source plane

$$L_p(\mathbf{r}_S) = 10log_{10}\frac{\sum_{i=1}^{I}|p(\mathbf{r}_S, f_i)|^2}{p_{ref}^2}, \quad (8)$$

where $p_{ref} = 2 \times 10^{-5}$ Pa.

According to conventional PNAH, when people are interested in the source behavior over a broad frequency range, e.g., $L_v(\mathbf{r}_S)$, the complex hologram pressure at each frequency in the band has to be measured. Then the corresponding source normal velocity is reconstructed, summed together to obtain $L_v(\mathbf{r}_S)$.

It is time-consuming to measure and reconstruct frequency by frequency, especially for high frequency bands. In addition, plenty of unnecessary information will be produced and has to be abandoned eventually. Therefore, the feasibility to obtain $L_v(\mathbf{r}_S)$, that is, reconstructing $v_B(\mathbf{r}_S)$ essentially, through a single reconstruction, gradually becomes a problem worthy of consideration.

One has to notice that a complex pressure spectrum (amplitude and phase) is required in Eq. (4) in order to reconstruct the velocity. Consider that $p_B(\mathbf{r}_H)$ can be provided and serve as amplitude. By expressing the complex pressure in the form $p = |p|e^{j\phi}$, we get the complex 1/3-octave band RMS pressure on the hologram plane

$$p_B(\mathbf{r}_H, f_i) = p_B(\mathbf{r}_H)e^{j\phi(\mathbf{r}_H, f_i)}, \quad (9)$$

where $\phi(\mathbf{r}_H, f_i)$ is the phase of the hologram pressure corresponding to a certain f_i in the 1/3-octave band.

Next, as stated in Eq. (4), by following the general process of PNAH at f_i we have:

$$\tilde{v}_B(\mathbf{r}_S) = |\mathcal{F}_x^{-1}\mathcal{F}_y^{-1}\{\mathcal{F}_x\mathcal{F}_y[p_B(\mathbf{r}_H, f_i)]G_{pv}^{-1}(k_x, k_y, z_S - z_H, f_i)\}|. \quad (10)$$

With $p_B(\mathbf{r}_H)$ provided, the key to the success of BPNAH, which requires that $\tilde{v}_B(\mathbf{r}_S)$ approximates $v_B(\mathbf{r}_S)$ over the total source plane, is a desirable selection of $\phi(\mathbf{r}_H, f_i)$.

2.3. Determination of the phase

In order to simplify our approach, let us start by investigating a single point source located at $\mathbf{r}_{S1} = (x_1, y_1, z_S)$. The relationship between amplitudes of normal velocities on the source plane corresponding to two frequencies in the same band, $v(\mathbf{r}_{S1}, f_i)$ and $v(\mathbf{r}_{S1}, f_q)$, is $|v(\mathbf{r}_{S1}, f_i)| = v_{i,q} \cdot |v(\mathbf{r}_{S1}, f_q)|$.

According to Rayleigh's first integral, we have

$$p(\mathbf{r}_H, f_i) = \frac{-j\rho ck_i}{2\pi}\int_S v(\mathbf{r}_{S1}, f_i)\frac{e^{jk_i R_1}}{R_1}dS \quad (11)$$

where $k_i = \omega_i/c$ and $R_1 = |\mathbf{r}_{S1} - \mathbf{r}_H| = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_S - z_H)^2}$.

Taking the point source into account, the integral in Eq. (11) can be evaluated as

$$|p(\mathbf{r}_H, f_i)| = \frac{\rho cQk_i}{2\pi R_1}|v(\mathbf{r}_{S1}, f_i)|. \quad (12)$$

with Q a small constant. Moreover, the relationship between $|p(\mathbf{r}_H, f_i)|$ and $|p(\mathbf{r}_H, f_q)|$ is obtained as