

Reconstruction of the sound field radiated from a source in a noisy environment based on three-dimensional scanning measurements

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ABSTRACT

Three-dimensional (3D) scanning measurement method has been successfully applied to the inverse boundary element method (IBEM)-based near-field acoustic holography to improve its measurement efficiency. However, it is based on the assumption that all sources are located on one side of the measurement surface whereas the other side is source free, which may not be fulfilled in practice. In the present paper, the 3D scanning measurement method is further applied in a noisy environment to reconstruct the sound field radiated by a target source. To achieve this goal, the IBEM algorithm is extended to account for the influence of the disturbing sources that are located on the other side of the measurement surface, and the acoustic inputs are acquired by continuous 3D scanning measurement on a closed surface surrounding the target source. An experiment is carried out to demonstrate the effectiveness of the proposed method. Results show that the proposed method can suppress the influence of the disturbing sources and reconstruct the sound field radiated by the target source effectively in the frequency range of interest.

Keywords: Three-dimensional scanning measurement, Inverse boundary element method, Noisy environment

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1. INTRODUCTION

Near-field acoustic holography (NAH) (1-6) is a very powerful tool for identifying sound source and visualizing acoustic field. By this technique, the sound field radiated by a sound source can be reconstructed by using the data (sound pressure or particle velocity) measured on a hologram surface near the source. The NAH requires the sound pressure or particle velocity on a surface. However, a problem still exists in the conventional measurement methods (7-10), i.e., the measurement efficiency is low in

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the case of requiring large number of measurement points, for example when the scale of the source is large or the frequency of interest is high. A possible way to improve the measurement efficiency has been presented and successfully applied to the inverse boundary element method (IBEM)-based NAH, namely the continuous three-dimensional (3D) scanning measurement method (11).

However, the previous study (11) is based on the assumption that all sources are located on one side of the measurement surface whereas the other side is source free. But in practice, this requirement might not be fulfilled. For instance, some sound sources cannot be stopped or displaced and measurements have to be done in a noisy environment. Hence, the measurement data not only contain sound generated by the target source, but also contain sound generated by disturbing sources. In order to reconstruct the sound field radiated by the target source, an extended IBEM algorithm is developed in the present study. This extended IBEM algorithm requires the sound pressure and particle velocity on a closed surface surrounding the target source, and these data are acquired by using the 3D scanning measurement method.

The paper is organized as follows. Section 2 introduces the basic theories of the conventional IBEM algorithm and the extended IBEM algorithm, and the data acquisition by using the 3D scanning measurement method is also introduced. In Sec. 3, an experiment is performed to validate the proposed method. Finally, conclusions are drawn in Sec. 4.

2. BASIC THEORY

2.1 The conventional IBEM (CIBEM) algorithm

Figure 1 shows the geometrical description of the CIBEM algorithm. As is shown, S is the source surface and it is discretized into N constant boundary elements, H is a hologram surface near the source. According to the theory of IBEM (6), the acoustic relationship between the boundary elements and field points can be expressed by the following matrix equations

$$\mathbf{P}_h = \mathbf{T}_{\mathrm{pv}} \mathbf{V}_s \,, \tag{1}$$

$$\mathbf{V}_h = \mathbf{T}_{vv} \mathbf{V}_s, \qquad (2)$$

where \mathbf{P}_h and \mathbf{V}_h are the vectors that contain the pressures and particle velocities at M field points on the hologram surface H, respectively, \mathbf{P}_s and \mathbf{V}_s are the vectors that contain the pressures and normal velocities (with the direction **n** shown in Fig. 1) of the boundary elements, respectively, \mathbf{T}_{pv} is the transfer matrix relating the normal velocities on S to the field pressures on H, and \mathbf{T}_{vv} is the transfer matrix relating the normal velocities velocities on S to the field particle velocities on H.

Once the holographic data are acquired at M field points, either of the sound pressures \mathbf{P}_h or particle velocities \mathbf{V}_h , the normal velocities on the source surface S can be reconstructed by

$$\mathbf{V}_{s} = \left(\mathbf{T}_{pv}\right)^{+} \mathbf{P}_{h}, \qquad (3)$$

$$\mathbf{V}_s = (\mathbf{T}_{vv})^+ \mathbf{V}_h, \tag{4}$$

where the superscript "+" denotes the pseudo-inverse of a matrix. Because the backpropagation process is highly ill-conditioned, regularization is required to avoid a large reconstruction error. In the present work, the standard Tikhonov regularization (12) is used, and the L-curve method (13) is applied to choose the suitable regularization parameter.



Fig. 1. The geometrical description of the CIBEM algorithm.

2.2 The extended IBEM (EIBEM) algorithm

The CIBEM algorithm can reconstruct the sound field radiated by sound sources located on one side of the measurement surface. However, when the other side is not source free, the reconstructed results become inaccurate since the conventional method cannot account for the influence of the disturbing sources. In this subsection, an EIBEM algorithm is developed to solve this problem.



Fig. 2. The geometrical description of the EIBEM algorithm.

Figure 2 shows the geometrical description of the EIBEM algorithm, which indicates the spatial relationships between the source surfaces S1 and S2, the hologram surface H and the disturbing source. The source surface S1 is used to represent the target source, and the fictitious source surface S2 which is located between the hologram surface H and the disturbing source is used to represent the influence of the disturbing source. Assume that the source surface S1 and fictitious source surface S2 are discretized into N1 and N2 constant boundary elements, respectively, the sound pressures and particle velocities on the hologram surface H can be expressed as follows

$$\mathbf{P}_h = \mathbf{P}_1 + \mathbf{P}_2 \,, \tag{5}$$

$$\mathbf{V}_h = \mathbf{V}_1 + \mathbf{V}_2,\tag{6}$$

where \mathbf{P}_1 and \mathbf{P}_2 are the vectors that contain the sound pressures produced by S1 and S2, respectively, and \mathbf{V}_1 and \mathbf{V}_2 are the vectors that contain particle velocities produced by S1 and S2, respectively.

Similarly as Section 2.1, the sound pressures and particle velocities produced by S1 and S2 can be expressed by the following matrix equations

$$\mathbf{P}_{1} = \mathbf{T}_{pv}^{1} \mathbf{V}_{s1}, \tag{7}$$

$$\mathbf{V}_{1} = \mathbf{T}_{vv}^{1} \mathbf{V}_{s1}, \qquad (8)$$

$$\mathbf{P}_2 = \mathbf{T}_{\mathrm{pv}}^2 \mathbf{V}_{s2} \,, \tag{9}$$

$$\mathbf{V}_2 = \mathbf{T}_{vv}^2 \mathbf{V}_{s2},\tag{10}$$

where \mathbf{V}_{s1} and \mathbf{V}_{s2} are the normal velocity (with the direction **n1** and **n2** shown in Fig. 2) vectors of *N1* and *N2* constant boundary elements, respectively, \mathbf{T}_{pv}^{1} is an *M* by *N1* matrix and indicates the acoustic transfer matrix relating the normal velocities on S1 to the field pressures on H, \mathbf{T}_{vv}^{1} is an *M* by *N1* matrix and indicates the acoustic transfer matrix relating the normal velocities on S1 to the field particle velocities on H, \mathbf{T}_{pv}^{2} is an *M* by *N2* matrix and indicates the acoustic transfer matrix relating the normal velocities on S1 to the field particle velocities on H, \mathbf{T}_{pv}^{2} is an *M* by *N2* matrix and indicates the acoustic transfer matrix relating the normal velocities on S2 to the field pressures on H, \mathbf{T}_{vv}^{2} is an *M* by *N2* matrix and indicates the acoustic transfer matrix relating the normal velocities on S2 to the field pressures on H, \mathbf{T}_{vv}^{2} is an *M* by *N2* matrix and indicates the acoustic transfer matrix relating the normal velocities on S2 to the field pressures on H, \mathbf{T}_{vv}^{2} is an *M* by *N2* matrix and indicates the acoustic transfer matrix relating the normal velocities on S2 to the field particle velocities on H.

Equations 5-10 can be reformulated as the following matrix equation

$$\begin{bmatrix} \mathbf{P}_{h} \\ \mathbf{V}_{h} \end{bmatrix} = \begin{bmatrix} \mathbf{T}_{pv}^{1} & \mathbf{T}_{pv}^{2} \\ \mathbf{T}_{vv}^{1} & \mathbf{T}_{vv}^{2} \end{bmatrix} \begin{bmatrix} \mathbf{V}_{s1} \\ \mathbf{V}_{s2} \end{bmatrix}.$$
 (11)

Once the holographic data are acquired at *M* field points, including sound pressures \mathbf{P}_h and particle velocities \mathbf{V}_h , the normal velocities on S1 and S2 can be reconstructed by

$$\begin{bmatrix} \mathbf{V}_{s1} \\ \mathbf{V}_{s2} \end{bmatrix} = \begin{bmatrix} \mathbf{T}_{pv}^{1} & \mathbf{T}_{pv}^{2} \\ \mathbf{T}_{vv}^{1} & \mathbf{T}_{vv}^{2} \end{bmatrix}^{+} \begin{bmatrix} \mathbf{P}_{h} \\ \mathbf{V}_{h} \end{bmatrix}.$$
 (12)

2.3 Data acquisition by using the 3D scanning measurement method

It can be seen that Equation 12 requires the sound pressure and particle velocity at M field points as inputs. When M is large, the data acquisition process becomes timeconsuming or even impractical. To improve the measurement efficiency, the data acquisition process is accomplished by using the 3D scanning measurement method. Figure 3 shows the schematic diagram of the 3D scanning measurement system. The system consists of two main parts: the acoustic information sampling system and the real-time sensor tracking system. The sound field are scanned continuously by using this measurement system first. And then, the holographic data, i.e., the sound pressures and particle velocities at some discrete field points, can be obtained by a data postprocessing step. Detailed descriptions of the measurement system and the data postprocessing procedure can be found in Reference (11).



Fig. 3. The schematic diagram of the 3D scanning measurement system

It should be noted that in Reference (11) the microphone was used as the scanning sensor, so that only sound pressure was recorded. However, both sound pressure and particle velocity are required in this study. Thus, a 3D sound intensity probe is used as the scanning sensor instead of the microphone. The 3D sound intensity probe comprises four transducers, one microphone and three orthogonally placed particle velocity sensors. Since the sensor orientation is also recorded by the tracking system, the tri-axis particle velocity can be obtained, from which the particle velocity in any direction can be further synthesized. For the sake of simplicity, the particle velocity in the direction from the coordinate origin to the field point is inserted into V_h .

3. EXPERIMENTAL VALIDATION

An experiment with two loudspeakers was carried out to validate the effectiveness of the proposed method. Both the conventional IBEM algorithm and the extended IBEM algorithm were applied to reconstruct the sound field radiated by a target source.

3.1 Experimental set-up and data acquisition

Figure 4 shows the experimental set-up. Two loudspeakers were used as the target source and disturbing source, respectively. The two sources were driven by the same signal comprising a series of sinusoids in the frequency range from 300 Hz to 2000 Hz with a frequency interval of 100 Hz. A 3D sound intensity probe was used as the scanning sensor and a microphone was used as the reference sensor. During the measurement process, the scanning sensor which is integrated with a tracked sphere was manually swept around the target source and the reference sensor was fixed near the target source.

Once the measurement was finished, the sound pressures and particle velocities at field points could be obtained by the post-processing. In this study, a spatial discretization grid of 2 cm cell size was applied, yielding 646 field points.



Fig. 4. Experimental set-up.

3.2 Results

Figure 5 shows the source surface meshes and field points of the two algorithms. It should be noted that "Source surface S1" represents the boundary surface of the target source, while "Source surface S2" is a fictitious surface defined in the EIBEM algorithm.



Fig. 5. The source surface meshes and field points of the (a) CIBEM algorithm; (b) EIBEM algorithm.

Figures 6 and 7 show the amplitudes of normal velocity reconstructed by the CIBEM algorithm and EIBEM algorithm on surface S1, respectively. The reconstructed results at four frequencies are presented. "View angle 1" displays the front surface, right surface and top surface of S1 and "View angle 2" displays the back surface, left surface and bottom surface of S1. It can be seen that for the CIBEM algorithm, at lower frequencies (300 Hz and 800 Hz), the identified major source differs from the real source (the cone of the loudspeaker). Moreover, at higher frequencies (1300 Hz and 2000 Hz), the reconstructed results are obviously incorrect. Those results indicate that

the CIBEM algorithm cannot identify the location of the real source of the target loudspeaker in a noisy environment, especially at high frequencies. On the contrary, it can be seen that the EIBEM algorithm can accurately identify the location of the real source at all the frequencies.



Fig. 6. The amplitudes of normal velocity on surface S1 reconstructed by the CIBEM algorithm.



Fig. 7. The amplitudes of normal velocity on surface S1 reconstructed by the EIBEM algorithm.

4. CONCLUSIONS

In this study, in order to reconstruct the sound field radiated by a target source in a noisy environment, the IBEM algorithm is first extended to account for the influence of the disturbing sources that are located on the other side of the measurement surface. Then the 3D scanning measurement method is used to obtain the required sound pressures and particle velocities on the hologram surface simultaneously by a single continuous scanning measurement, which can significantly improve the measurement

efficiency. Experimental results show that the proposed method can remove the influence of the disturbing source and accurately identify the location of the real source in the frequency range of interest, while the CIBEM algorithm cannot.

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