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Reconstruction of the sound field above a reflecting plane using the equivalent source method

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ABSTRACT

In practical situations, vibrating objects are usually located above a reflecting plane instead of exposing to a free field. The conventional nearfield acoustic holography (NAH) sometimes fails to identify sound sources under such situations. This paper develops two kinds of equivalent source method (ESM)-based half-space NAH to reconstruct the sound field above a reflecting plane. In the first kind of method, the half-space Green's function is introduced into the ESM-based NAH, and the sound field is reconstructed based on the condition that the surface impedance of the reflecting plane is known *a prior*. The second kind of method regards the reflections as being radiated by equivalent sources placed under the reflecting plane, and the sound field is reconstructed by matching the pressure on the hologram surface with the equivalent sources distributed within the vibrating object and those substituting for reflections. Thus, this kind of method is independent of the surface impedance of the reflecting plane. Numerical simulations and experiments demonstrate the feasibility of these two kinds of methods for reconstructing the sound field above a reflecting plane.

1. Introduction

Nearfield acoustic holography (NAH) [1–3] has attracted many attentions due to its effectiveness for noise source identification and sound field visualization. Currently, several kinds of NAH methods have been developed, such as the spatial Fourier transform method [1–3], the inverse boundary element method [4–6], the Helmholtz equation least squares method [7,8], the statistically optimized nearfield acoustic holography [9], and the equivalent source method (ESM) [10–12]. All these methods are initially developed for free-field condition, which is either an unbounded exterior region or an enclosed interior region. In practice, most vibrating objects are mounted on or located above a plane which may be rigid or absorptive, and therefore the effect of reflections from that plane must be considered.

The field separation techniques [13–19] that are able to distinguish the incoming and outgoing waves can be used to reconstruct the sound field generated by a vibrating object in half-space by combining with the classic NAH. The major advantage of those techniques is that the location and surface impedance of the reflecting plane could be unknown. But this kind of techniques require measurements of pressure [13–15] or particle velocity [16,17] on two surfaces or measurements of pressure and particle velocity on a single surface [18,19], and the measurement surfaces should surround the vibrating object at a close range when used to solve the half-space problem. Besides field separation techniques, the effect of reflections can also be accounted for by introducing the half-space Green's function into the conventional NAH [15,20–23],

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based on which the location and surface impedance of the reflecting plane should be known *a prior*. However, few literatures have focused on the half-space NAH above an impedance plane. Although Refs. [20] and [21] considered both the rigid and the absorptive reflecting planes, it was assumed that the sound were reflected as plane waves instead of spherical waves, which might make the technique inaccurate if the vibrating object was close to the reflecting plane.

In this paper, two kinds of ESM-based half-space NAH are developed to reconstruct the acoustic quantities in the sound field generated by a vibrating object located above a reflecting plane. In the first kind of method, the half-space Green's function [24–27] that automatically satisfies the boundary condition of the reflecting plane is introduced into the ESM-based NAH. Because the half-space Green's function involves the surface impedance of the reflecting plane, this kind of method depends on the surface impedance of the reflecting plane. In the second kind of method, the reflections due to the reflecting plane are regarded as being radiated by equivalent sources located under the reflecting plane, and the direct sound radiated by the vibrating object and the reflected sound are both expressed as the superposition of a series of equivalent sources. Thus, this kind of method is independent of the surface impedance of the reflecting plane. For the sake of simplicity, the first kind of method is called D-ESM and the second is called I-ESM in the following.

The paper is organized as follows. In Section 2, the theory of D-ESM and I-ESM are described in detail. In Section 3, numerical simulations are carried out to examine the feasibility and effectiveness of the proposed methods; and in Section 4, the results of two experiments are presented. Finally, conclusions are drawn in Section 5.

2. Outline of theory

2.1. ESM-based half-space NAH depending on the surface impedance of the reflecting plane (D-ESM)

According to the idea of ESM, the sound field generated by a vibrating object can be replaced by the superposition of the fields generated by a series of simple sources placed within the object [28,29]. If the vibrating object is located above an infinite reflecting plane, as shown in Fig. 1, the pressure at a field point, $\mathbf{r} = (x, y, z)$, in half-space can be expressed by

$$p(\mathbf{r}) = \mathrm{i}\rho\omega \sum_{i=1}^{I} q_i^{\Gamma} g_{half}(\mathbf{r}, \mathbf{r}_i^{\Gamma}), \tag{1}$$

where ρ is the density of air, ω is the angular frequency, I is the number of equivalent sources on a fictitious surface Γ, q_i^{Γ} is the strength of the ith equivalent source on Γ, $\mathbf{r}_i^{\Gamma} = (x_i^{\Gamma}, y_i^{\Gamma}, z_i^{\Gamma})$ is the position of the ith equivalent source on Γ, and $g_{half}(\mathbf{r}, \mathbf{r}_i^{\Gamma})$ is the half-space Green's function, expressed as [26,27]

$$g_{half}(\mathbf{r}, \mathbf{r}_i^{\Gamma}) = \frac{e^{\mathrm{i}kR_i^{\Gamma}}}{4\pi R_i^{\Gamma}} + \frac{e^{\mathrm{i}kR_i^{\Gamma'}}}{4\pi R_i^{\Gamma'}} - \frac{k}{2\pi Z_0}\int_0^{\infty} \frac{e^{\mathrm{i}k\sqrt{(D_i^{\Gamma})^2+(z+z_i^{\Gamma}+\mathrm{i}\zeta)^2}}}{\sqrt{(D_i^{\Gamma})^2+(z+z_i^{\Gamma}+\mathrm{i}\zeta)^2}} e^{-\frac{k\zeta}{Z_0}} d\zeta, \tag{2}$$

where k is the wave number, $R_i^{\Gamma} = \sqrt{(D_i^{\Gamma})^2 + (z - z_i^{\Gamma})^2}$ is the distance between $\mathbf{r}$ and $\mathbf{r}_i^{\Gamma}$, $R_i^{\Gamma'} = \sqrt{(D_i^{\Gamma})^2 + (z + z_i^{\Gamma})^2}$ is the distance between $\mathbf{r}$ and $\mathbf{r}_i^{\Gamma'} = (x_i^{\Gamma}, y_i^{\Gamma}, -z_i^{\Gamma})$ which is the position of the image source corresponding to the ith equivalent source, and $D_i^{\Gamma} = \sqrt{(x - x_i^{\Gamma})^2 + (y - y_i^{\Gamma})^2}$ is the horizontal distance between $\mathbf{r}$ and $\mathbf{r}_i^{\Gamma}$. $Z_0 = Z/(\rho c)$ is the normalized impedance where Z is the surface impedance of the reflecting plane and c is the sound speed in air. The integral in Eq. (2) can

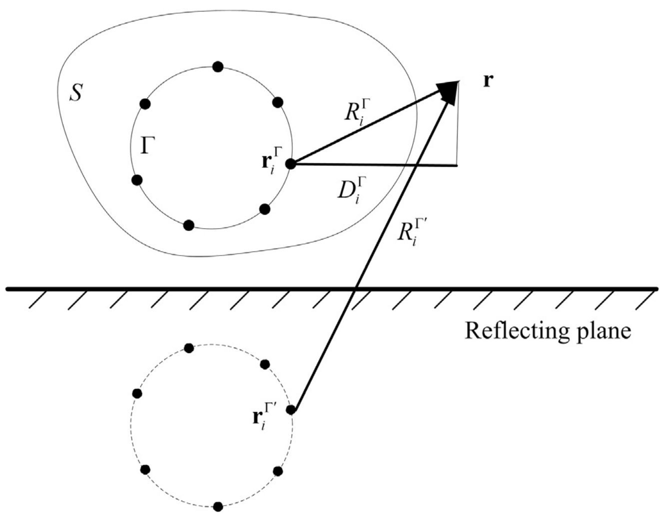

Fig. 1. The schematic diagram for formulating the sound field generated by a vibrating object above a reflecting plane by using the ESM.