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Sound source identification in a noisy environment based on inverse patch transfer functions with evanescent Green's functions

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ABSTRACT

A modified inverse patch transfer function (iPTF) method is used to reconstruct the normal velocities of the target source in a noisy environment. The iPTF method simplifies the Helmholtz integral equation to one term by constructing a Green's function satisfying Neumann boundary conditions for an enclosure, which is generally constructed by slowly convergent modal expansions. The main objective of the present work is to provide an evanescent Green's function to improve the convergence of calculations. A brief description of the iPTF method and two sets of Green's functions for a rectangular cavity are presented firstly. In simulations, both the Green's functions are used to calculate the condition numbers of impedance matrices describing the relation between source and measurement patches, and the time cost of calculation based on the two sets of Green's functions at 450 Hz is compared. Double pressure measurements are then employed as the input data instead of pressure and velocity measurements. The normal velocities of two baffled loudspeakers are reconstructed by the combination of a measurement method and a Green's function in the presence of a disturbing source in the frequency range of 50–1000 Hz. In addition, the double pressure measurements are examined by an experiment. The precise identification of the sources indicates that the double pressure measurements are capable of localizing sources in a noisy environment. It is also found that the reconstruction with the evanescent Green's functions is slightly better than that with the modal expansions.

1. Introduction

Nearfield acoustic holography (NAH) is an effective technique for localization and identification of sound sources. It was firstly proposed by Williams et al. [1,2] to reconstruct the surface velocity of a rectangular plane based on the two-dimensional (2D) spatial Fourier transform (SFT) method. After that, inverse boundary element method (iBEM) [3–5], Helmholtz equation least squares method (HELS) [6], statistically optimized nearfield acoustic holography (SONAH) [7], equivalent source method (ESM) [8] and other NAH techniques have been developed. Wu [9,10] reviewed these methods and compared their advantages and limitations. The theory and implementation of nearfield acoustic array technologies aimed at sound source identification are summarized in a book [11]. Early NAH methods require an anechoic chamber to

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satisfy the free field condition. However, it is not always realistic to move industrial sources to anechoic rooms to implement measurements, especially for certain large or heavy machines, thus limiting the application of NAH techniques.

To realize NAH of machines in situ, where reflection from walls and disturbing sound sources may exist, Villot et al. [12] presented a modified NAH technique based on Fourier series enabling reconstruction of acoustic fields in enclosed spaces with an anechoic end, and called it phonoscopy. By consideration of ceiling reflections and wall reflections, Hallman et al. [13] extended NAH to identify sources in enclosed spaces. Kim and Nelson [14] estimated the acoustic source strength within a cylindrical duct by inversion of frequency response functions and singular value decomposition (SVD). Kim and Ih [15] reconstructed the field of a half-scaled automotive cabin by using iBEM and regularization methods. Kim et al. [16] proposed a measurement method to obtain active sources in an enclosure by measuring the admittance of the enclosed surface. The iBEM was also performed by Williams et al. [17] to reconstruct the normal velocities of a fuselage in situ.

Another solution to remove the influence of reflection and disturbing sources is the sound field separation technique (FST). The technique can separate the sound waves crossing a measurement surface in opposite directions, i.e., the outgoing field and the incoming field. The outgoing field is then used to reconstruct the sound field radiated by the target source. Technically, the FST can be recognized as a preprocessing method, and thus most NAH algorithms can combine it to improve the reconstruction accuracy. The sound field separation technique using the spatial Fourier transform was performed to measure reflection coefficients [18,19] and to identify sound sources in a noisy environment [20]. Jacobsen et al. [21,22] extended the SONAH procedure to distinguish sources on the two sides of the measurement array. The efficiency of the FST based on spherical harmonic expansions for the identification of sound sources in small spaces was investigated by Braikia et al. [23]. To further remove the scattering on a target source from the outgoing field, an iBEM-NAH was proposed by Langrenne et al. [24,25] to recover the free field conditions from noisy bounded space situations. The combination of SFT and ESM also gave a satisfactory solution to perform NAH in a noisy environment [26–28].

Instead of separating the radiation field of target sources, inverse patch transfer functions [29–31] (iPTF), directly use the acoustic quantities of the superposition field, and the disturbing sources can be self-eliminated during the process of velocity reconstruction. To compute the patch transfer function, the Green's functions for a rigid-walled cavity should be obtained first. Classically, the Green's functions satisfying Neumann boundary conditions for a cavity are expressed by a modal expansion method [32], i.e., normal modes or eigenfunctions of the described cavity. However, the normal mode expansions of Green's functions converge very slowly and are forced to sum over many modes to match the decay of a single evanescent wave. A set of two-dimensional Green's functions, reducing one of the summations was used to calculate pressure in a rectangular room and showed a great improvement for algorithm efficiency [33,34]. The functions, named as evanescent Green's functions by Williams [35], exactly matches the decay of evanescent waves, which characterizes the exponentially convergent form. Williams presented advantages of the evanescent Green's functions for a cylindrical cavity. In this paper, to obtain better series convergence, an evanescent Green's function for a rectangular cavity is suggested to compute patch transfer functions and to reconstruct source velocities by the iPTF method.

Owing to the existence of the evanescent waves, the vast majority of NAH methods above, has to invert an ill-conditioned matrix, and the iPTF method is no exception. The inversion of an ill-conditioned matrix may lead to a large error enlargement of measurement noise. To address this problem, solution regularization is required. Yoon and Nelson [36] gave a full detail for choosing regularization parameters by inverse techniques. Williams [37] summarized several regularization methods for NAH and showed that the generalized cross-validation (GCV) did not require a knowledge of the noise variance. Aucejo [38] introduced a generalized iteratively reweighted least-squares (GIRLS) algorithm to identify mechanical exciting forces from vibration measurements. One main problem of regularization is the selection of breakpoints of the filter factors. Gauthier et al. [39] defined the filter factors and adjust the regularization amount by using signal-to-noise ratio in acoustical inverse problems.

In this paper, the combination of truncated SVD and GCV is employed to stabilize the process of source reconstruction. In addition, double pressure measurements, instead of measurements of sound pressure and particle velocity, are performed to generalize the iPTF method, mainly because microphones are more easily calibrated and more common than pressure–velocity (p–u) probes. In Section 2, a brief description of the iPTF method and two sets of Green's functions are presented. Two baffled loudspeakers radiating in the presence of a coherent source are investigated using simulations and experiments in Sections 3 and 4, respectively. The results demonstrate that the modified iPTF method is a promising technique to realize NAH in a noisy environment.

2. Methodology

2.1. Theory of the iPTF method

The following example of Fig. 1 gives a brief description of iPTF method. Details of theoretical derivation have been presented in [29,31]. Assume that the normal velocity of the acoustic source is v_k, the virtual acoustic cavity is Ω_i (without disturbing sources inside), and the point Q' is located on the virtual surface S_c (see Fig. 1). Moreover, disturbing sources exist inside the volume Ω_o but outside the cavity Ω_i. The pressure $p(Q')$ on the boundary is solved by using Helmholtz integral equation with a e^{jwt} time dependence convention: