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Real-time nearfield acoustic holography in a uniformly moving medium

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ABSTRACT

Real-time nearfield acoustic holography (RT-NAH) is an effective tool to identify nonstationary sound sources and predict the time-dependent sound field via a temporal convolution between the time-dependent wavenumber spectrum on the hologram plane and an impulse response. However, the conventional RT-NAH procedures are developed for sound sources situated in a static medium. As for sound sources located in a moving medium, the conventional RT-NAH procedures cannot be applied directly due to the fact that the impulse response will be changed by flow effects. In this paper, two analytical impulse responses in a uniformly moving medium, corresponding to two cases that the flow direction is parallel to and perpendicular to the hologram plane, are derived first with consideration of flow effects, and then RT-NAH is extended to realize forward and backward propagation of time-dependent signals in the moving medium. Numerical simulations are conducted to check the performances of the proposed method. The results show that the proposed method not only can be used to predict nonstationary sound fields but also can be utilized to identify nonstationary sources in a moving medium for both the parallel and perpendicular cases.

1. Introduction

Nearfield acoustic holography [1,2] (NAH) is a well-known technique to predict sound field and identify sound sources by forward and backward projecting the acoustic quantities measured in the near field. Generally, NAH is applied to the case of sources located in a static medium. As for sound sources situated in a fluid flow, the measured acoustic quantities will contain flow effects, and thus the conventional NAH cannot be used directly. To resolve this problem, Ruhala et al. [3,4] proposed a planar NAH procedure in a moving medium at subsonic and uniform velocity. In that work, the convective wave equation is used to derive a modified Green's function and a modified wavenumber filter that includes a shift due to the mean flow in the radiation circle. However, this procedure is based on low-speed approximations which would result in significant errors when the medium flows at a high Mach number (e.g., $0.2 < |M| < 1$). In view of that, an improved NAH procedure for sound sources radiating in a high Mach number flow was developed by Kwon et al. [5], in which the convective wave equation is used to derive a mapping function between static and moving medium cases, giving convective Green's functions and wavenumber filter. In order to realize sound field calculation in a moving medium with a relative small hologram aperture, Kim et al. [6] proposed an improved statistically optimal NAH that includes the flow effects of a moving medium, and Dong

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et al. [7] developed a patch NAH in a moving medium based on sound field extrapolation. Considering that there is an underlying aerodynamic problem for in-flow microphones at a high Mach number, Dupuis et al. [8,9] proposed a non-intrusive planar NAH in a moving medium with the particle velocity measured by Laser Doppler Velocimetry as the acoustic input.

The above-mentioned NAH procedures in a moving medium focus on calculating sound fields in the frequency domain, which is suitable for harmonic signals emitted by sound sources. However, in practice, many sound sources in a moving medium generate nonstationary sound fields (e.g., impact noise of a structure in a wind tunnel). So far, some methods have been developed for calculating nonstationary sound fields in a static medium, e.g., the time domain holography [10–13] (TDH) and real-time nearfield acoustic holography [14,15] (RT-NAH). The TDH needs transforms from the time domain to the frequency domain, while the RT-NAH is directly performed in the time-wavenumber domain, and thus the RT-NAH can be regarded as a real-time method, which can realize continuous and real-time propagation of nonstationary signals. In RT-NAH, the time-wavenumber domain impulse response is critical to realize the propagation of sound fields. Although the impulse responses relating the pressures, the pressure and the normal velocity, the pressure and the normal acceleration on two different planes have been given in the literature [16–19], they are all developed for nonstationary sources in a static medium and unsuitable for the case of a moving medium as a result of flow effects. To realize forward and backward propagation of sound fields radiated by nonstationary sources in a moving medium, two analytical impulse responses relating the pressures on two different planes in a moving medium, corresponding to two cases that the flow direction is parallel to and perpendicular to the hologram plane, are first derived in the present paper, and then a RT-NAH procedure in a moving medium is proposed.

This paper is organized as follows. In Sec. 2, two analytical impulse responses corresponding to the flow direction parallel to and perpendicular to the hologram plane are derived, based on which the basic theory of the RT-NAH in a moving medium is presented. In Sec. 3, numerical simulations are conducted to test the performances of the proposed method. Finally, conclusions are summarized in Sec. 4.

2. Theory

2.1. Analytical impulse responses in a uniformly moving medium

The convective wave equation in a uniformly moving medium can be represented as [20].

$$\nabla^2 p(x,y,z,t) - \frac{1}{c^2}\left(\frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla\right)^2 p(x,y,z,t) = 0, \tag{1}$$

where c, t and p represent the sound speed in a static medium, time and sound pressure, respectively, $\mathbf{V}$ is the velocity of the moving medium, ∇^2 denotes the Laplace operator defined as $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$, and ∇ is defined as $\nabla = \frac{\partial}{\partial x}\mathbf{i} + \frac{\partial}{\partial y}\mathbf{j} + \frac{\partial}{\partial z}\mathbf{k}$, in which $\mathbf{i}$, $\mathbf{j}$ and $\mathbf{k}$ represent the unit vectors in x, y and z directions, respectively. According to the cases that the flow direction is parallel to and perpendicular to the hologram plane, two analytical impulse responses in a moving medium are derived in the following.

2.1.1. Parallel case

Assume that the velocity of a moving medium is in the positive x direction. Then, Eq. (1) can be written as

$$\nabla^2 p(x,y,z,t) - \frac{1}{c^2}\left(\frac{\partial^2}{\partial t^2} + 2V\frac{\partial^2}{\partial t \partial x} + V^2\frac{\partial^2}{\partial x^2}\right) p(x,y,z,t) = 0, \tag{2}$$

where V is the amplitude of $\mathbf{V}$.

Using the Laplace transform

$$F(s) = \int_0^\infty e^{-st} f(t)\mathrm{d}t, \tag{3}$$

Eq. (2) can be expressed as

$$\nabla^2 p(x,y,z,s) - \frac{1}{c^2}\left(s^2 + 2Vs\frac{\partial}{\partial x} + V^2\frac{\partial^2}{\partial x^2}\right) p(x,y,z,s) = 0, \tag{4}$$

in which s represents the variable in the Laplace domain.

Then, applying the three dimensional Fourier transform