



A time-domain inverse technique for the localization and quantification of rotating sound sources



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ABSTRACT

A time-domain inverse technique based on the time-domain equivalent source method is proposed for the localization and quantification of rotating sound sources. In this technique, the actual rotating sound sources are modeled by a series of rotating equivalent sources distributed on the source surface. The strengths of these equivalent sources are solved based on the exact transfer relationship between the measured pressure at the receiver time and the desired equivalent source strengths at the source time. Compared to the known time-domain rotating beamforming that just owns the function of source localization, the proposed inverse technique not only can locate rotating sources accurately but also can predict sound fields quantitatively. Moreover, due to the use of retarded time approach, the proposed inverse technique avoids the interpolation of measured pressure that is needed in the time-domain rotating beamforming, thus providing the ability of real-time calculation of source strengths. Numerical simulations and experiments examine the validity of the proposed technique and demonstrate its advantages of locating sources more accurately and enabling to predict sound fields quantitatively by comparing with the time-domain rotating beamforming.

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1. Introduction

Localization and quantification of rotating sound sources, such as propellers, fans, rotor of turbofan engines, helicopter blades and wind turbine blades, by a microphone array is helpful to analyze source mechanisms and predict their radiated sound fields.

Several different microphone array-based techniques have been developed for locating rotating sound sources in recent years. Among them, the frequency-domain beamforming with a microphone array is the popular one in virtue of its simple measurement procedure and high computational efficiency. Lowis and Joseph [1] first developed a frequency-domain beamforming method to investigate the ducted rotating sources with the help of an in-duct Green's function and the spinning mode decomposition method. And, that method was subsequently extended to locate rotating sources in free space conditions with the use of a free-field Green's function expressed in spherical coordinates [2]. On the basis of the conventional frequency-domain beamforming technique, Dougherty and Walker [3] developed a virtual rotating microphone imaging technique to locate broadband fan noise sources by applying a resampling technique to calculate the microphone data in the rotating reference frame. Recently, Mo and Jiang [4] developed a combined beamforming approach to separate stationary and rotating mono-frequency sound sources. Since the above-mentioned frequency-domain beamforming allows building a

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cross-spectral matrix, its formulation makes it possible to apply high resolution methods like DAMAS [5], CleanSC [6] or Orthogonal beamforming [7].

Another popular microphone array-based approach that can be used for rotating sources localization is known as the inverse technique, in which sound source strengths are reconstructed from measurements of pressure by inverting a transfer matrix of source–receiver Green's functions. A number of such inverse techniques have been developed for identifying rotating sources in a free-field based on the inversion of the Farassat's integral solution of FW-H equation [8] or a discrete form of Morse and Ingard's analytical direct model [9], and in a duct system based on the equivalent source method [10] or the modal summation method [11–13]. Compared to beamforming, the inverse technique not only can identify the locations of sources, but also can quantify the source strengths. But, it should be mentioned that in the inverse technique, the transfer matrix is often ill-conditioned with regard to the geometry and number of equivalent sources, the configuration of microphone array or the number of modes. To avoid the ill-conditioned solutions dominated by errors in pressure measurements, the inverse process is often dealt with by using the singular value decomposition and Tikhonov regularization [14,15].

The above-mentioned works of both beamforming and inverse technique are all performed in the frequency domain, because special techniques that exploit the structure of the cross spectral matrix in beamforming and the source–receiver transfer matrix in the inverse technique can be formulated in the frequency domain. Nevertheless, the treatments in the frequency domain usually restrict the application to stationary signals or narrowband signals. The time-domain processing is more general than the frequency-domain treatment because it applies directly to nonstationary signals or broadband signals, and also because it is easily used in the moving cases including the rotation. Time-domain rotating beamforming (TRB) has been developed by Sijtsma et al. [16,17] to identify the rotating sources in wind tunnels and on wind turbines. Their work introduced a transfer function relating the source strength in the rotating reference frame to a stationary microphone position, for incorporating the Doppler effect due to the source rotation. In the reconstruction of source strengths, the measured data is needed at the receiver time. Unfortunately, TRB employs the advanced time approach to calculate the receiver time by giving the source time, which leads to that the calculated receiver time does not coincide with the time at which the measurement system samples the data. Therefore, the interpolation of the measured data is required to deal with the inconsistency problem. Besides, in the case of multiple rotating sources, the source strengths reconstructed by using the mixed pressure based on the delay-and-sum approach always deviate from the actual strengths, and thus TRB cannot be used to predict the radiated sound fields quantitatively.

In the present paper, a time-domain inverse technique (TIT) based on the time-domain equivalent source method [18–21] is proposed to locate and quantify rotating sources. Because the time-domain equivalent source method can establish the exact transfer relationship between the measured pressure at the receiver time and the desired source strengths at the source time regardless of multiple rotating sources, the source strengths reconstructed by this method can match with the actual strengths, which gives the TIT an ability of quantifying the radiated sound fields. Moreover, in the proposed TIT, the retarded time approach is used to calculate the source time by giving the receiver time, which avoids the interpolation of measured pressure and provides the ability of real-time calculation of source strengths.

This paper is organized as follows. To elaborate the difference between TRB and TIT, their theoretical models are given in Sections 2.1 and 2.2, respectively. Numerical simulations are described in Section 3 to show the performances of both TRB and TIT and to assess the localization quality of TIT, and experiments are carried out to demonstrate their application effects in Section 4.

2. Theory

2.1. Model of time-domain rotating beamforming

As shown in Fig. 1, suppose that there is a rotating monopole source with the time-evolving position $\vec{r}_s(\tau)$ at the source time τ , the time-dependent pressure signal $p(\vec{r}_{nn}, t)$ recorded by a microphone at the position $\vec{r}_{nn}$, can be written as [16]

$$p(\vec{r}_{nn}, t) = Q(\tau)G(\vec{r}_{nn}, \vec{r}_s(\tau)), \quad (1)$$

where $n = 1, 2, \dots, N$, $Q(\tau)$ is the time-dependent source strength, and $G(\vec{r}_{nn}, \vec{r}_s(\tau))$ is the transfer function given by

$$G(\vec{r}_{nn}, \vec{r}_s(\tau)) = \frac{1}{4\pi R_n(\tau)}, \quad (2)$$

where $R_n(\tau) = |\vec{r}_{nn} - \vec{r}_s(\tau)|$ is the time-dependent distance from the n th microphone to the source.

Due to the discrete sampling in practical measurements, the pressure signal is composed of discrete values located at the sampling receiver time $t^j, j = 1, 2, \dots, J$. Accordingly, when using these discrete pressure values to calculate the source strengths, the source time τ has to be discretized as $\tau^j, j = 1, 2, \dots, J$. In the advanced time approach employed by TRB, it is easy to calculate the receiver time by giving the discretized source time τ^j in advance, i.e.,

$$t_n^j = \tau^j + R_n(\tau^j)/c, \quad (3)$$

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