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In-duct identification of fluid-borne source with high spatial resolution

Yong-Ho Heo [a], Jeong-Guon Ih [a,*], Hans Bodén [b]

[a] Center for Noise and Vibration Control (NoViC), Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea

[b] Marcus Wallenberg Laboratory for Sound and Vibration Research (MWL), Aeronautical and Vehicle Engineering, KTH, 100 44 Stockholm, Sweden

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ABSTRACT

Source identification of acoustic characteristics of in-duct fluid machinery is required for coping with the fluid-borne noise. By knowing the acoustic pressure and particle velocity field at the source plane in detail, the sound generation mechanism of a fluid machine can be understood. The identified spatial distribution of the strength of major radiators would be useful for the low noise design. Conventional methods for measuring the source in a wide duct have not been very helpful in investigating the source properties in detail because their spatial resolution is improper for the design purpose. In this work, an inverse method to estimate the source parameters with a high spatial resolution is studied. The theoretical formulation including the evanescent modes and near-field measurement data is given for a wide duct. After validating the proposed method to a duct excited by an acoustic driver, an experiment on a duct system driven by an air blower is conducted in the presence of flow. A convergence test for the evanescent modes is performed to find the necessary number of modes to regenerate the measured pressure field precisely. By using the converged modal amplitudes, very-close near-field pressure to the source is regenerated and compared with the measured pressure, and the maximum error was -16.3 dB. The source parameters are restored from the converged modal amplitudes. Then, the distribution of source parameters on the driver and the blower is clearly revealed with a high spatial resolution for $kR < 1.84$ in which range only plane waves can propagate to far field in a duct. Measurement using a flush mounted sensor array is discussed, and the removal of pure radial modes in the modeling is suggested.

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1. Introduction

Acoustic source identification for fluid machinery such as blower, pump, turbine, etc. is essential in determining the major noise radiators from the sources and understanding the noise generation mechanisms to redesign for noise reduction.

Some researches have been focused on the characterization of sources, in which the main application area is the use of the given source data in the design of the acoustic loading system, e.g., silencer to reduce the radiated sound power. The analogy between electric circuit and acoustic system is adopted, and the acoustic source is characterized by the source

* Corresponding author. Tel.: +82 42 350 3035; fax: +82 42 350 8220.
E-mail address: J.G.Ih@kaist.ac.kr (J.-G. Ih).

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strength and source impedance. When successful the technique makes it possible to predict the sound field in any duct system connected to the source. It has however mainly been used for low frequency plane-wave applications [1–3] and in a few cases to application with a few propagating modes [4,5]. Other researches have mainly dealt with the identification of source parameter distributions [6–8] such as acoustic pressure and particle velocity to understand the source behavior in the specific duct system. Once the detailed source distribution is obtained, the main sound radiating parts of a source can be known, and the refinement strategy for a quiet machine can be set. This work deals with the latter, that is, the identification of source parameter distributions.

There are several difficulties in the in-duct source identification methods. The noise source is an aero-acoustic source at which the surface velocity cannot be measured by using a laser vibrometer or accelerometer. Due to the presence of the gas flow, the measured acoustic pressure signal is corrupted by the flow generated noise and the pseudo sound. Therefore, measurement methods either in the inside [1–8] or outside [9–12] of the duct system and the flow noise suppression technique [1–3] in the measured signal have been developed. Additionally, a reference signal of the source, which is used for the broad frequency band, is not possible to obtain. Therefore, far-field pressure signal is alternatively used as the reference signal [1–3].

The inverse estimation method is usually used for the identification of in-duct noise sources. The measured pressure signal and the modeled transfer matrices from source plane to measurement plane are used for this method. In the modeling of the transfer matrices, currently, the equivalent source method and modal summation method are mainly used. Both methods and their limitations are briefly introduced.

In using the equivalent source method, the sources are modeled as either monopoles [7] or dipoles [8], which are distributed over the source plane. Then, the source strength is estimated by solving the inverse problem. It was suggested that a well-designed near-field measurement is necessary for the result with high spatial resolution. However, the accuracy of restored source strengths highly depends on the position of the equivalent sources, which cannot be known in advance. To overcome this problem, one may try to distribute many equivalent sources in the source plane, but it is usually recommended that the number of equivalent sources should be smaller than the number of measurement points.

A modal summation method has been proposed as an alternative. Instead of distributing assumed equivalent sources in the source plane, one can consider the in-duct sound field as the superposition of many acoustic modes. Modal amplitudes are inversely estimated, and the source parameters can be predicted from those. This method was applied to the axial fan [4,5] and loudspeakers [6]. For the current modal summation method, the spatial resolution for the identification depends on the number of propagating modes used for the reconstruction, which depends on the Helmholtz number. This means that the source cannot be identified in detail at low Helmholtz numbers.

In this work, to estimate the source parameters with a high spatial resolution, inverse technique using near-field data with the modal summation method is proposed. The basic principle suggested by this work is resembles near-field acoustical holography. The present method includes both propagating and evanescent waves in the formulation, and the spatial resolution is adjusted by changing the number of evanescent modes. Near-field measurement is necessary to capture the evanescent waves. For testing the derived formulation, sensor arrangement, and treatment for inversion process, verification test is conducted in a duct system excited by a compression driver and an air blower.

2. Sound propagation model in a duct

2.1. Acoustic field in a circular duct

The sound propagation within a hard walled duct is considered under the following assumptions: time-harmonic oscillation, isentropic process, homogeneous medium, nonviscous condition, convection of a mean flow in the axial direction, constant temperature of medium, and small amplitude oscillations. Then, the acoustic pressure p and the axial particle velocity u_z in a cylindrical coordinate are given by [13,14]

$$p(r,\theta,z,t)=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\psi_{mn}(C_{mn}^{+}e^{-jk_{z,mn}^{+}z}+C_{mn}^{-}e^{jk_{z,mn}^{-}z})e^{j\omega t},\tag{1}$$

$$u_z(x,y,z,t)=\frac{1}{\rho_0 c_0}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\psi_{mn}\left(\frac{k_{z,mn}^{+}}{k-Mk_{z,mn}^{+}}C_{mn}^{+}e^{-jk_{z,mn}^{+}z}-\frac{k_{z,mn}^{-}}{k+Mk_{z,mn}^{-}}C_{mn}^{-}e^{jk_{z,mn}^{-}z}\right)e^{j\omega t}.\tag{2}$$

here ψ_{mn} is the cross-sectional mode, $k_{z,mn}^{\pm}$ the axial wave number, C_{mn}^{+} and C_{mn}^{-} the modal amplitudes for two progressive waves moving in positive and negative directions, z the axial distance from the source plane, which is positive in the downstream direction, k the wave number ($=\omega/c_0$), U the axial mean flow speed, M the Mach number ($=U/c_0$), and ρ_0 and c_0 the density and sound speed at the medium temperature, respectively. The superscript sign in the axial wave number and the modal amplitudes shows the propagating axial direction. The subscripts m and n indicate the integer order of the circumferential and radial modes, respectively.

For a circular section, the cross-sectional mode ψ_{mn} and the axial wave number $k_{z,mn}^{\pm}$ are given by

$$\psi_{mn}=J_m(k_{r,mn}r)e^{\pm jm\theta},\tag{3}$$

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