IN-DUCT SOURCE IDENTIFICATION OF A BLOWER USING THE NEAR-FIELD MEASUREMENT

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The detailed information on the distribution of acoustic pressure and axial particle velocity at a source plane in a duct is useful for the low noise design of the source because it provides the position and strength of major noise sources. However, due to the limited spatial resolution of the conventional methods, the source behavior could not be observed in detail. In this work, a method to identify the pressure and axial velocity distribution at the source plane with high spatial resolution is suggested. Modal summation method including the evanescent waves is formulated, in which data can be provided from the near-field measurement. For the validation of the present method, the near-field array measurement in a duct excited by a blower is conducted. In the measurement of the nearfield and farfield acoustic pressures, the flush mounted microphone array is employed, and reference microphone technique using the cross correlation is adopted to suppress the turbulent flow noise. As a result, the measured nearfield pressure is well restored with 26 evanescent modes, and the error between measured and restored pressure spectra is less than -20 dB in the Helmholtz number range of 0.57 < kR < 1.84. It is observed that the flush mounting measurement tends to over-estimate the pure radial modes, which results in the unphysical error in the predicted source parameters at the center of source plane. As a remedial action, pure radial modes are removed from the model that results in a successful reconstruction of the source distribution.

1. Introduction

Aero-acoustic source in ducts is used for many industrial applications. To design for a quite fluid machine, the noise generation mechanism of the source needs to be well understood, and the effect of the source parameter variations to the radiated power should be known. Therefore, in-duct source identification method is required.

Modal summation method is one of the well-known conventional techniques to describe the sound propagation in duct, and it has been applied to the source identification problem for both electrical source¹ and aero-acoustic source²,³. Since the conventional modal summation method suffers from the poor spatial resolution at low Helmholtz number, the modal summation method including the evanescent wave in the modelling is suggested in this work. The nearfield measurement and the reference microphone technique⁴-⁶ are used with the suggested method to measure the nearfield acoustic pressure with the suppression of flow noise. The present method is practiced on the
duct system at which a part of the source plane is excited by a blower. It is shown from the result that the estimated source parameter distribution can pinpoint the installation position of blower with high spatial resolution.

2. Sound propagation in duct

In this work, the mathematical derivation of sound propagation in duct is based on 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.

Infinite number of modes are generated at the source plane, and they either freely propagate or evanescently decay depending on the axial wave number $k_{z,mn}$ as follows:

$$k_{z,mn}^2 = \mp Mr_0 \pm \sqrt{r_0^2 - \frac{1}{1-M^2}}.$$

where $k_0$ is the wave number ($= \omega/c_0$), $r_{nm}$ the wave number at cross-section, $U$ the axial mean flow speed, $M$ the Mach number ($= U / c_0$), the subscript $m$ and $n$ indicate the order of radial and circumferential mode, respectively. When the value within the square root in Eq. (1) is positive, the generated mode from the source propagates to the farfield. On the other hand, when it is negative, the generated mode exponentially decays, and such an evanescent mode is only observable in the nearfield.

The in-duct pressure and velocity including both propagating and evanescent modes is developed, and it is written as

$$\begin{align*}
p & = \begin{bmatrix} M_{p+} T_{p+} & M_{p+} T_{p-} & \text{M}_{e+} T_{e+} & \text{M}_{e+} T_{e-} \end{bmatrix} \begin{bmatrix} c_{p+} & c_{e+} & c_{e-} \end{bmatrix}^T, \\
v & = \begin{bmatrix} M_{p+} L_{p+} T_{p+} & M_{p+} L_{p+} T_{p-} & M_{e+} L_{e+} T_{e+} & M_{e+} L_{e+} T_{e-} \end{bmatrix} \begin{bmatrix} c_{p+} & c_{e+} & c_{e-} \end{bmatrix}^T,
\end{align*}$$

where $M$ is the cross-sectional mode matrix, $T$ the axial transmission matrices, $L$ the pressure to velocity conversion matrix, and $c$ the modal amplitude. The subscript $p$ and $e$ indicate the propagating mode and evanescent mode, respectively. The subscript $+$ and $-$ sign regards the axial direction.

With the correct estimation of propagating and evanescent modal amplitudes from the measured nearfield and farfield pressure data, the source behavior in duct can be fully described even in the nearfield including the source plane, which is not possible with the conventional method shown below. Conventional modal summation method models the in-duct pressure and velocity is given by

$$\begin{align*}
p & = \begin{bmatrix} M_{p+} T_{p+} & M_{p+} T_{p-} \end{bmatrix} \begin{bmatrix} c_{p+} & c_{p-} \end{bmatrix}^T, \\
v & = \begin{bmatrix} M_{p+} L_{p+} T_{p+} & M_{p+} L_{p+} T_{p-} \end{bmatrix} \begin{bmatrix} c_{p+} & c_{p-} \end{bmatrix}^T.
\end{align*}$$

Although the conventional method is appropriate for the simulation of radiated power and radiated pattern from the duct breakout, it is not adequate to observe the source behavior in detail because it does not contain the high spatial frequency component, the evanescent wave. Therefore, in this work, modal summation method including the evanescent mode is developed and applied for the source identification in detail.
3. **In-duct source identification**

The measurement is conducted on a duct system excited by a blower. By using the obtained pressure and the present modal summation method, the modal amplitudes of propagating and evanescent waves are identified. Then, the source parameters at the source plane are predicted by using the obtained modal amplitudes.

3.1 **Measurement setup**

A duct system is excited by a blower. The conceptual measurement setup is shown in Fig. 1. The measurement rig is composed of standard acryl ducts having circular cross section with inner diameter 250 mm, thickness 10 mm, and length 510 mm. The distance from source to measurement planes can be easily adjusted by assembling more acryl ducts between two of them. The verification measurement is carried out on a duct system at which a part of source plane is excited by a blower under the standard atmospheric conditions ($c = 343$ m/s). The air blower is operating at 0.7 Mpa, and it is used as the both flow and acoustic source. The flow speed is measured by a flow meter (AIRPRO FCO65), and the flow speed at the end of air blower is 6.5 m/s. Microphone array (B&K 4935, 1/4 inch) was used to measure at 16 positions at the duct wall at each standoff distances, and the measurement were conducted at the 4 different standoff distances from the source, so 64 points are measured in total at nearfield. The standoff distances are 15, 30, 45 and 60 mm detached from the source plane. Two microphones (B&K 4189, 1/2 inch) were placed at 800 and 960 mm from the source plane, and they are used for the farfield pressure measurement. A reference microphone (B&K 4189, 1/2 inch) is placed 1.5 m from the source plane. A signal analyzer (B&K Pulse 3560D) is employed for data acquisition and signal analysis. Four hundred number of frequency averaging was used. By considering the performance of the anechoic termination and the high frequency limit of the given spacing, the valid Helmholtz range is given as $0.57 < kR < 1.84$.

![Measurement setup](image)

Figure 1. Measurement setup. Four flush-mounted microphone arrays are used for the nearfield measurement. The axial interval of arrays is 15 mm. Farfield measurement is conducted by two microphones at $z = 800$ and 960 mm. The reference microphone is placed at $z = 1.5$ m. The air blower is installed on an aluminium plate, and the placement position is shown as the red circle, which is near to the fifth microphone of nearfield array.

3.2 **Measured pressure spectrum**

The reference microphone technique\(^4\) is applied on the measurement of pressure both at nearfield and farfield to remove the effect of turbulence noise. The measured pressure spectrum with and without the reference microphone technique is compared at two different points at which one is
under the strong turbulent flow, the point 5, and the other is under the weak turbulent flow, the point 13. The position 5 is the nearest point to the end of the blower, and the position 13 is the farthest point. The position of each measurement point is shown in Fig. 1, and the measured pressure spectrum is shown in Fig. 2. Two points in comparison are measured at the first measurement plane, which is 15 mm from the source plane.

The measured pressure spectrum at point 5 shows that the reference microphone technique is able to remove the elevated pressure trend induced by the turbulent flow at the range of $kR < 0.6$, but it is still under the severe minor fluctuation due to the pseudo sound effect. By comparing the measured pressure spectrum at point 5 and point 13, it is expectable that the pressure spectrum at point 5 is bigger than that of point 13 because the point 5 is much more close to the actual noise source, the blower, which means it contains more evanescent waves, compared to point 13. The measured pressure spectrum is used for the estimation of the propagating and evanescent modal amplitudes by taking the inverse process in Eq. 2. For more accurate estimation of propagating modal amplitudes, the multiple microphone methods can be adopted. In the estimation of evanescent modal amplitudes, the inversion process tends to be ill-posed, so Tikhonov regularization and GCV function is used from Hansen’s regularization package.

![Figure 2. Sound level spectra measured at z = 15 mm with the air blower excitation; - - - , measured pressure spectrum at point 5, - - - measured pressure spectrum with the reference microphone technique at point 5, - - - - measured pressure spectrum at point 13, ---- measured pressure spectrum with the reference microphone technique at point 13.](image)

### 3.3 Comparison of measured and restored pressure spectrum

By using the estimated modal amplitudes, the pressure spectrum at point 5 and 13 are restored. To verify the present method, and the error between the measured and restored pressure is defined as

$$e = 10 \log_{10} \left( \frac{|p_r - p_m|}{|p_m|} \right),$$

where $p_r$ is the restored pressure spectrum, and $p_m$ the measured pressure spectrum. The defined error goes to minus infinity when the restored pressure and measured pressure are perfectly same. The convergence test is conducted by increasing the number of evanescent modes for the description of nearfield pressure, and 28 modes are selected for the calculation of the restored pressure spectrum. The calculated error at point 5 and 13 of the first measurement plane is shown in Fig. 3,
and it results in around -20 dB in $0.57 < kR < 1.84$.

Figure 3. Estimation error between measured and restored pressure spectra at the first measurement plane ($z = 15$ mm): (a) —— at point 5, ---- at point 13.

3.4 Detailed source parameters on the source plane

The source identification result at $kR = 1$ and 1.5 is shown in Fig. 4, and the result is shown in a linear scale. In both Helmholtz numbers, the position of the blower is correctly pointed out by higher pressure and axial velocity compared to other sectional places, which means that the main noise radiator is exactly identified. The minor peak at the center of the source plane is observed at $kR = 1.5$, which comes from the over-estimated pure radial modal amplitudes even though there should be no active noise source for this test example. The flush mounting measurement tends to over-amplify the pure radial modal amplitudes even with small measurement error, and it is the cause for the erroneous peak at the center of source plane.

Figure 4. Restored pressure and axial velocity field at the source plane with 27 modes: (a) pressure field at $kR = 1$, (b) pressure field at $kR = 1.5$, (c) axial velocity field at $kR = 1$, (d) axial velocity field at $kR = 1.5$. Tikhonov regularization and GCV function is used for the estimation of evanescent modal amplitudes.
Figure 5. Restored pressure and axial velocity field at the source plane with 25 modes by neglecting the two pure radial modes in the modelling: (a) pressure field at $kR = 1$, (b) pressure field at $kR = 1.5$, (c) axial velocity field at $kR = 1$, (d) axial velocity field at $kR = 1.5$. Tikhonov regularization and GCV function is used for the estimation of evanescent modal amplitudes.

For the source identification of noise sources of which the main radiators are distributed around the duct wall, the removal of the pure radial modes in the modelling stage is suggested, because it can be safely assumed that the contribution of the pure radial modes would be small compared to the other circumferential modes in the sound propagation. The result of the source identification without pure radial mode is shown in Fig. 5, and it is shown that the unphysical error at the center is suppressed. The present technique will be further applied to the axial fan of which the main noise radiators are known to be distributed around the duct wall.

If the conventional modal summation method is applied for this test, the distribution of source parameters such as pressure and axial particle velocity cannot be observed because the conventional technique only uses planewave to describe the source behaviour in $kR < 1.84$.

4. Conclusions

A method to identify the pressure and axial velocity distribution at the source plane with high spatial resolution is suggested. The pressure measurement is conducted on the duct system of which a part of source planes is excited by a blower. The estimated modal amplitudes are able to restore the pressure spectra with less than -20 dB error in the Helmholtz number range of $0.57 < kR < 1.84$, and the installation position of the blower can be exactly identified. This technique will be further applied for the rotating noise source for the detailed source identification.

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REFERENCES


