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IN-DUCT PRESSURE MEASUREMENTS TO DETERMINE SOUND GENERATION, CHARACTERISTIC REFLECTION AND TRANSMISSION FACTORS OF AN AIR MOVING DEVICE IN AIR-FLOW

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INTRODUCTION

A method to determine acoustic properties of a duct component in the presence of air flow and under arbitrary terminations have been introduced and tested.

RELATIONS BETWEEN ACOUSTIC PROPERTIES AND TRAVELING WAVES

As shown in fig.1 for a two port device, below first cross-mode cut-on frequency, the relations between the traveling waves around the device are represented as

\[ a_{I}^+ = \rho_{I} a_{I}^- + \tau_{II} a_{II}^- + f_{1I}, \quad a_{II}^+ = \rho_{II} a_{II}^- + \tau_{I} a_{I}^- + f_{II} \]  

(1)

where \( a_{m}^+ \) and \( a_{m}^- \) denote sound pressures of traveling waves.
waves in the positive and negative directions at the m-th point respectively, $a_m$ their total pressure, the subscripts I and II the reference surfaces for the I-st and II-nd duct respectively, $\rho_K$, $\tau_K$ and $f_K$ characteristic reflection, transmission factor of the device and sound pressure exciting towards respective ducts from the device at the reference surfaces $K=1$ and $2$ respectively.

DETERMINATION OF DRIVING SOUND PRESSURES OF A DEVICE

Taking pressure ratio between eq. (1) and $a_I$, we obtain the following relations from eq. (2) to (5)

$$f_I/a_I = \rho_I \beta_I H_I + \tau_{II} \beta_{II} H_{II} - a_I H_I$$

(2a)

$$f_{II}/a_I = \rho_{II} \beta_{II} H_{II} + \tau_I \beta_I H_I - a_{II} H_{II}$$

(2b)

$$\alpha_K = a^+_K/a_K = 1/(1+R_K), \quad \beta_K = a^-_K/a_K = \alpha_K R_K$$

(3)

$$R_K = a^+_K/a^-_K = (H^+_K - H_{KK'})/(H_{KK'} - H^-_K)$$

(4)

where subscript $K'$ denotes a observation point close to $K$. $R_K$ is also applied to give reflection factor of the termination $R_{TK}$ to have driving point impedance.

$H^+_K = a^+_K/a^+_K = \exp(jk^+_K(x_K-x_K'))$, $H^-_K = a^-_K/a^-_K = \exp(jk^-_K(x_K-x_K'))$

where $k^+_K$ and $k^-_K$ denotes wave number of traveling wave in the positive and negative direction in the K-th duct.

$$H_K = a_K/a_I, \quad H_{KK'} = a_K/a_K$$

(5)

The driving sound pressures $f_I$ and $f_{II}$ are determined by eq. (2) after $H_K$, $H_{KK'}$, $a_I$, $\rho_K$ and $\tau_K$ have been given.

ACOUSTIC PRESSURE OBSERVATION IN THE PRESENCE OF AIRFLOW

The m-th microphone pressure $p_m$ consists of acoustic pressure $a_m$ and flow induced pressure $t_m$. Direct cross-spectrum $SP_{ij}$ between $p_i$ and $p_j$ is written as

$$SP_{ij} = <p^*_i p_j>/2 = S^a_{ij} + S^t_{ij}$$

(6a)

$$S^a_{ij} = <a^*_i a_j>/2, \quad S^t_{ij} = <t^*_i t_j>/2$$

(6b)

The superscript (*) denotes complex conjugate and the symbol < > ensemble mean. As the distance between the points increases, $S^t_{ij}$ / $S^a_{ij}$ approach to 0. For $H_K$, $H_{KK'}$ and $a_I$, employing 3rd and 4th points far apart from the others, indirect spectra(prime attached) are observed.

$$H_K = H'_K = SP_{3K}/SP_{3I}, \quad H_{KK'} = H'_{KK'} = SP_{3K'}/SP_{3K}, \quad a_I = 2(S'_{I I})^{1/2}$$

$$S^a_{ij} = S'_{ij} = SP_{13}SP_{4j}/SP_{43}, \quad S^t_{ij} = <p^*_i p_j>/2$$

(7)

DETERMINATION OF CHARACTERISTIC FACTORS UNDER AIRFLOW

Superposing in turn independent sound fields $A$ and $B$ originated from a test signal $e$ via acoustic drivers installed in the ducts, $\rho_K$ and $\tau_K$ can be determined.
Superposing the test field $A$, taking system functions between eq.(1) and $e$, and substituting $H^A_K$, $H^A_{K'}$, $\alpha^A_K$ and $\beta^A_K$ for $H_K$, $H_{K'}$, $\alpha_K$ and $\beta_K$ respectively, we obtain

\begin{align}
\alpha^A_I H^A_I &= \rho_I \beta^A_I H^A_I + \tau_{II} \beta^A_{II} H^A_{II} \\
\alpha^A_{II} H^A_{II} &= \rho_{II} \beta^A_{II} H^A_{II} + \tau_I \beta^A_I H^A_I
\end{align}

(8a)

(8b)

For $H_K$ and $H_{KK'}$, we observe $H'_K$ and $H'_{KK'}$ defined as

\begin{align}
H'_K &= S^{\text{em}}_K / S^{\text{ee}}_K, \\
H'_{KK'} &= S^{\text{em}}_{KK'} / S^{\text{ee}}_K
\end{align}

(9)

Next, superposing the test field $B$ and substituting the superscript (B) for (A) above, we have

\begin{align}
\alpha^B_I H^B_I &= \rho_I \beta^B_I H^B_I + \tau_{II} \beta^B_{II} H^B_{II} \\
\alpha^B_{II} H^B_{II} &= \rho_{II} \beta^B_{II} H^B_{II} + \tau_I \beta^B_I H^B_I
\end{align}

(8c)

(8d)

Solving the Eqs. (8) simultaneously, we can determine the characteristic factors $\rho_K$ and $\tau_K$ without using anechoic termination and in operation of the device under test.

**EXPERIMENTAL RESULTS**

Acoustic pressure extraction from contaminated signal

Tests have been carried out on the test arrangements as shown in Fig.2. Typical results are shown in fig.3. Indirect cross spectrum $S'_{ij}$ extracts acoustic $S^a_{ij}$ from contaminated $S^p_{ij}$ by flow induced pressures, roughly when $|S^a_{ij}| > S'_{ii}/10$, or translating this to observable form

\[ S'_{ii} = |S'_{ij}| = |S^a_{ij}| > S^p_{ii}/10. \]

(10)

**Fig.2 Test arrangement for acoustic pressure extraction**

**Fig.3 Comparison between direct and indirect spectra**
Validity of characteristic factor determination
Experiments under no flow have been conducted replacing the axial fan by a loud speaker in the test set up of Fig.1. Fig.4 shows the results comparing with those by anechoic termination method. The agreement is excellent.

Acoustic properties of a ducted small semi-axial fan
Test are carried out for a small semi-axial fan on the test rig shown in fig.1. Results are shown in fig.5 and 6. The driving sound pressure has been checked and reliable because $S'_{11}>S_{11}/10$ as typical given in fig.6. The fan tested excites sound pressures to both sides in almost the same magnitude and in out of phase at the blade pass frequency and at its few harmonics.

SUMMARY
A method to determine the acoustic properties of a duct component in-situ has been presented and experimentally confirmed effective.