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

$$a^+_I = \rho_I a^-_I + \tau_{II} a^-_{II} + f_I \ , \quad a^+_{II} = \rho_{II} a^-_{II} + \tau_I a^-_I + f_{II} \tag{1}$$

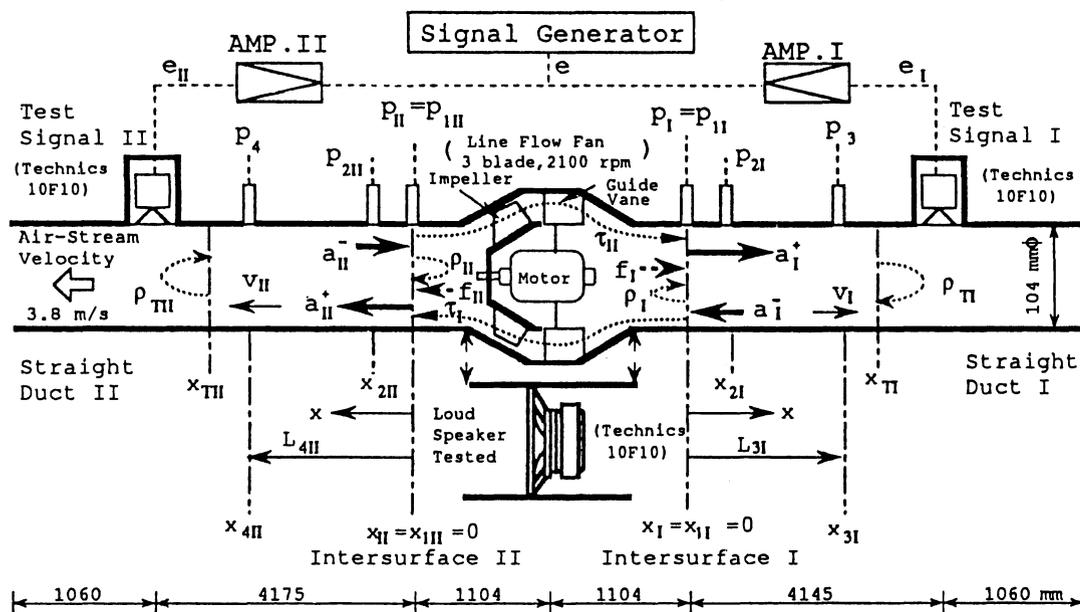where a^+_m and a^-_m denote sound pressures of traveling

Fig.1 Test arrangement for acoustic property determination

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, ρ_K, τ_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)

$$f_I/a_I = \rho_I \beta_I H_I + \tau_{II} \beta_{II} H_{II} - \alpha_I H_I \qquad (2a)$$

$$f_{II}/a_I = \rho_{II} \beta_{II} H_{II} + \tau_I \beta_I H_I - \alpha_{II} H_{II} \qquad (2b)$$

$$\alpha_K = a^+_K/a_K = 1/(1+R_K), \quad \beta_K = a^-_K/a_K = \alpha_K R_K \qquad (3)$$

$$R_K = a^+_K/a^-_K = (H^+_K - H_{KK'})/(H_{KK'} - H^-_K) \qquad (4)$$

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

$$H^+_K = a^+_{K'}/a^+_K = \exp\{jk^+_K(x_K - x_{K'})\}, \quad H^-_K = a^-_K/a^-_K = \exp\{jk^-_K(x_{K'} - x_K)\}$$

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

$$H_K = a_K/a_I , \qquad H_{KK'} = a_{K'}/a_K \qquad (5)$$

The driving sound pressures f_I and f_{II} are determined by eq.(2) after H_K, $H_{KK'}$, a_I, ρ_K and τ_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

$$SP_{ij} = <p^*_i p_j>/2 = S^a_{ij} + S^t_{ij} \qquad (6a)$$

$$S^a_{ij} = <a^*_i a_j>/2 , \quad S^t_{ij} = <t^*_i t_j>/2 \qquad (6b)$$

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.

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

$$S^a_{ij} \approx S'_{ij} = SP_{i3}SP_{4j}/SP_{43} , \quad SP_{ij} = <p^*_i p_j>/2 \qquad (7)$$

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, ρ_K and τ_K can be determined.

Superposing the test field A, taking system functions between eq.(1) and e, and substituting H^A_K , $H^A_{K\,K'}$, α^A_K and β^A_K for H_K , $H_{K\,K'}$, α_K and β_K respectively, we obtain

$$\alpha^A_I\,H^A_I\quad = \rho_I\,\beta^A_I\,H^A_I\ + \tau_{II}\,\beta^A_{II}\,H^A_{II} \tag{8a}$$

$$\alpha^A_{II}\,H^A_{II} = \rho_{II}\,\beta^A_{II}\,H^A_{II} + \tau_I\,\beta^A_I\,H^A_I \tag{8b}$$

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

$$H_K\ \approx\ H'_K\ = SP_{eK}\ /S_{ee}\ ,\quad H_{KK'}\ \approx\ H'_{KK'} = SP_{eK'}\ /SP_{eK}$$

$$SP_{em} = <e^*\,p_m>/2,\qquad S_{ee} = <e^*\,e>/2 \tag{9}$$

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

$$\alpha^B_I\,H^B_I\quad = \rho_I\,\beta^B_I\,H^B_I\ + \tau_{II}\,\beta^B_{II}\,H^B_{II} \tag{8c}$$

$$\alpha^B_{II}\,H^B_{II} = \rho_{II}\,\beta^B_{II}\,H^B_{II} + \tau_I\,\beta^B_I\,H^B_I \tag{8d}$$

Solving the Eqs.(8) simultaneously, we can determine the characteristic factors ρ_K and τ_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 SP_{ij} by flow induced pressures, roughly when $|S^a_{ij}|>S^t_{ii}/10$, or translating this to observable form

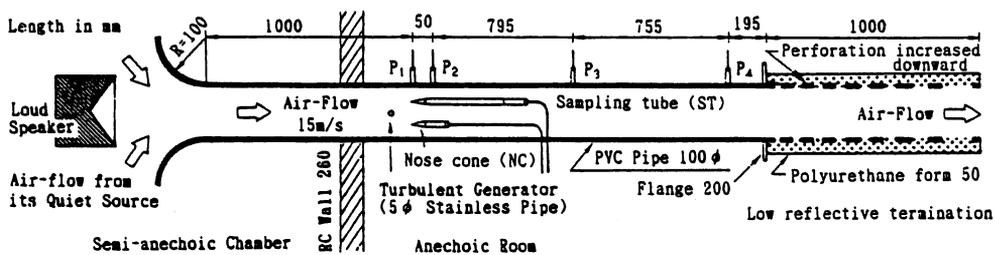$$S'_{ii}\approx|S'_{ij}|\ \approx\ |S^a_{ij}|\ >SP_{ii}/10. \tag{10}$$
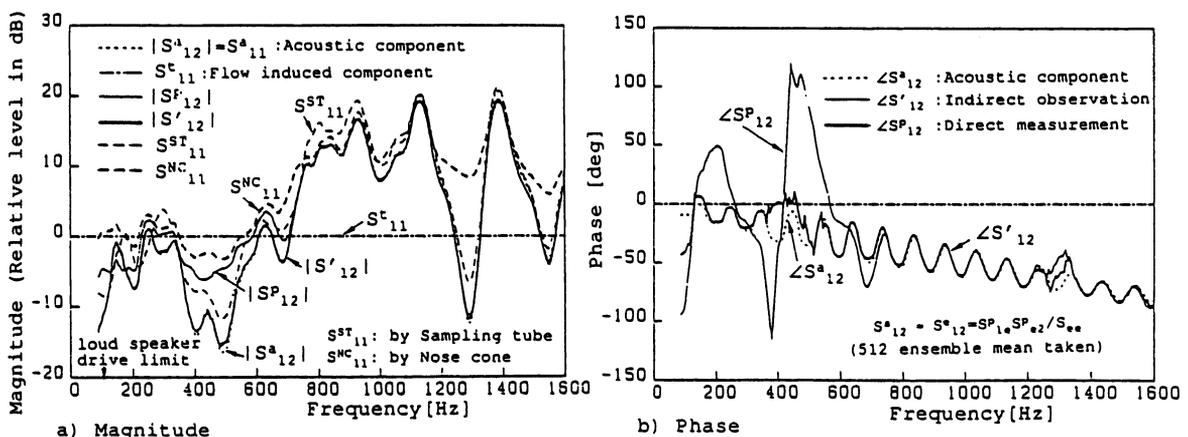

Fig.2 Test arrangement for acoustic pressure extraction

a) Magnitude
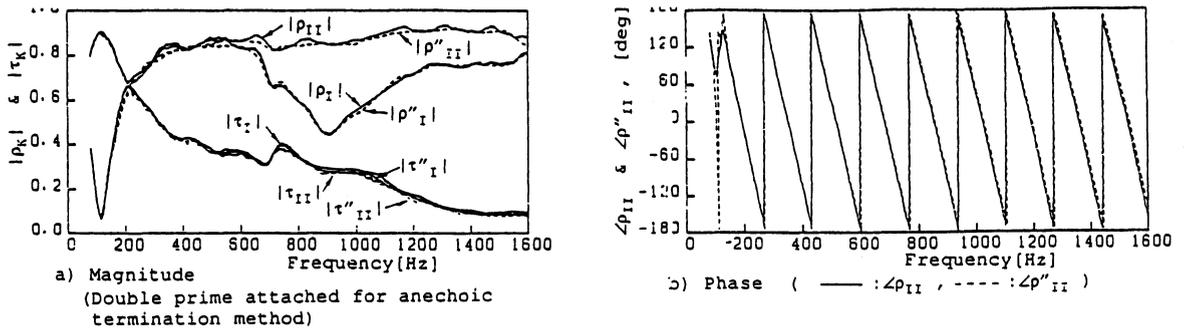b) Phase

Fig.3 Comparison between direct and indirect spectra

a) Magnitude
(Double prime attached for anechoic
termination method)

b) Phase (——— :∠ρ$_{II}$, ---- :∠ρ″$_{II}$)

Fig.4 Characteristic factors of the loud speaker shown in Fig.1

a) Magnitude

b) Phase (——— :∠τ$_{I}$, ---- :∠ρ$_{II}$)
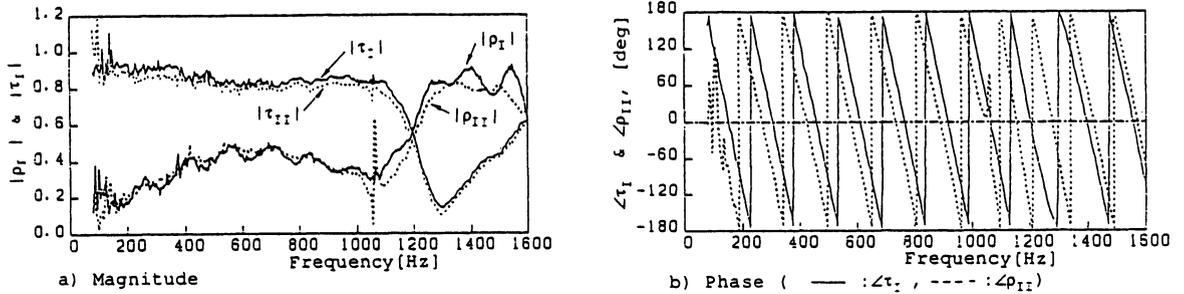
Fig.5 Characteristic factors of the fan shown in Fig.1
of the fan shown in Fig.1

a) Magnitude

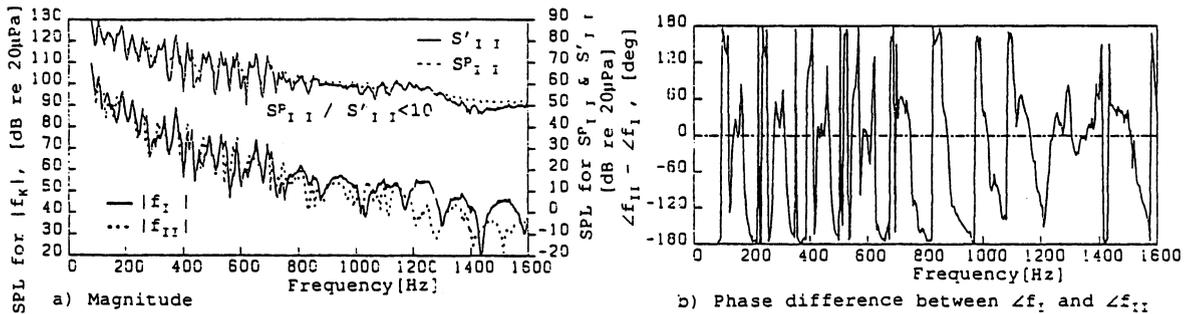b) Phase difference between ∠f$_{I}$ and ∠f$_{II}$

Fig.6 driving acoustic pressures of the fan shown in Fig.1
and their reliability check

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 $S'_{ii} > S^P_{ii}/10$ 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.