inter•noise 94
YOKOHAMA-JAPAN, AUGUST 29-31

A REJECTION METHOD OF THROTTLE NOISE CONTRIBUTION IN MEASUREMENT OF SOUND GENERATED FROM A HVAC DUCT COMPONENT

Michihito TERAO and Hidehisa SEKINE

Kanagawa University, Rokkaku-bashi,
Kanagawa-ku, Yokohama-shi, 221, Japan

11.3.2, 11.4.1, 21.6.6, 26.1.2, 72.4, 72.5

The objective of the investigation is to determine characteristic acoustical properties of duct components under operation for sound pressure prediction of a HVAC duct system in lower frequency region. The acoustical property required for a duct component is both passive one, typically, in terms of the characteristic transmission and reflection factors, and active one, typically, in terms of the driving wave pressure towards every duct which corresponds to the sound pressure given by the anechoic end method and their complex coherence factors [1].

A difficulty in determination of these acoustical properties is in rejection of flow induced noises of the test system, especially flow induced microphone and throttle noise. At the passive property measurement, rejection of these noises can be attained by superposition of a test signal from every duct end and cross-spectrum measurement between the test signal and pressure of every microphone location [1-3]. A remaining difficulty is in rejection of volume control throttle noise at active property determination of air moving devices.

This paper presents a new determination method which uses three microphones in every duct, instead of using anechoic ends and tubular wind screens, employs relationships among every cross-spectrum between port pressures, passive properties of the test duct system and driving wave pressures from all the sources, and provides rejection of the flow induced noises. An experimental conformation of the effectiveness of its throttle noise rejection and its application to fan acoustic characterization on a realistic test system with a throttle are also given.

SOURCE DRIVING WAVE PRESSURES AND A LOCAL PRESSURE

Contribution of Primary Source to a Local Pressure

For a M-port duct component, as shown in Fig.1(a), and at a frequency below the lowest cut-on of the cross-modes at the ports, we can write relationships between the driving wave pressure from a port L of the primary source, f_L^+, and its contribution to the complex pressures of outgoing and incoming plane waves at the port L, a_{LL}^+ and a_{LL}^- respectively [2], as

$$a^+_{LL}=T_{LL}a^-_{LL}+f^+_L\ ,\ a^-_{LL}=R_La^+_{LL}\ ,\ \text{and}\ a^+_{LL}=f^+_L/(1-T_{LL}R_L) \quad (1)$$

where T_{LL} and R_L are the reflection factors of the test system, as seen from duct end side and from the primary source side respectively. The superscripts (+) and (–) represent outgoing and incoming waves respectively, as seen from the primary source side. From this the contribution of f^+_L to pressure at port L, a_{LL}, and outgoing wave pressure at another port K, a^+_{KL}, respectively, are given by

$$a_{LL}=a^+_{LL}+a^-_{LL}=\Phi_{LL}f^+_L\ \text{and}\ \Phi_{LL}=(1+R_L)/(1-T_{LL}R_L) \quad (2)$$

and $a^+_{KL}=T_{KL}a^-_{LL}=T_{KL}R_Lf^+_L/(1-T_{LL}R_L)$, for $K(\neq L)=1, 2, \ldots ,M$ (3)

where T_{KL} is the load-coupled transmission factor from port L to port K.
Using eq.(3), we have the contribution of f^+_L to local pressure at port K, a_{KL}, as

$$a_{KL}=a^+_{KL}(1+R_K)=\Phi_{KL}f^+_L\ \text{and}\ \Phi_{KL}=T_{KL}R_L(1+R_K)/(1-T_{LL}R_L) \quad (4)$$

Exchange of L for K in eq.(2) gives relationships between the Kth port driving wave pressure from the primary source f^+_K, and its contribution to Kth port local pressure, a_{KK}, as

$$a_{KK}=\Phi_{KK}f^+_K\ \text{and}\ \Phi_{KK}=(1+R_K)/(1-T_{KK}R_K). \quad (5)$$

<u>Contribution of External Sources to a Local Pressure</u>

As shown in Fig.1(b), relationships between the driving wave pressure from the external source of port L, f^-_L, and its contribution to the traveling wave pressures at port L, b^+_{LL} and b^-_{LL}, can be written instead of eq.(1) as

$$b^-_{LL}=R_Lb^+_{LL}+f^-_L\ ,\ b^+_{LL}=T_{LL}b^-_{LL}\ \text{and}\ b^-_{LL}=f^-_L/(1-T_{LL}R_L). \quad (6)$$

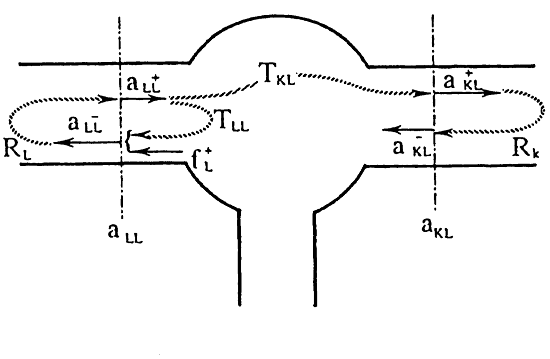
Relationships between each driving wave pressure of external sources, f^-_L and f^-_K, and each of their contributions to Kth port pressure, b_{KL} and b_{KK}, respectively, can be given similarly to the preceding paragraph as

$$b_{KL}=\Omega_{KL}f^-_L\ \text{and}\ \Omega_{KL}=T_{KL}(1+R_K)/(1-T_{LL}R_L) \quad (7)$$

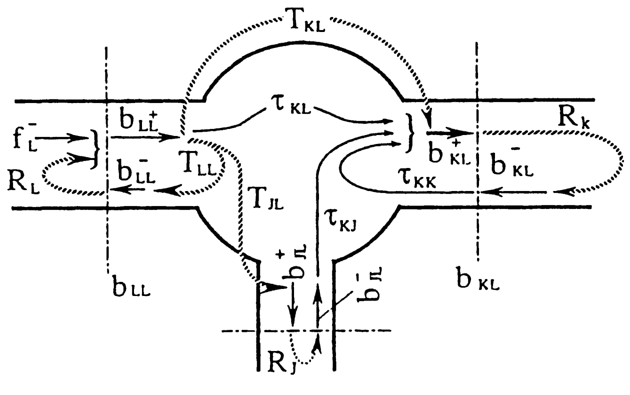
and $b_{KK}=\Omega_{KK}f^-_K$ and $\Omega_{KK}=(1+T_{KK})/(1-T_{KK}R_K)$. (8)

<u>Local Pressures at a Primary Port K and at a Reference Port K"</u>

The sum of eqs.(4), (5), (7) and (8) gives the pressure at a port K, p_K, as



(a) For primary source: f^+_L and its contribution to pressure at K, a_{KL}



(b) For external source: f^-_L and its contribution to pressure at K, b_{KL}

Fig. 1 Driving wave pressure of a source and local pressure at a port.

$$p_K=\sum_{L=1}^{M}(a_{KL}+b_{KL})=\sum_{L=1}^{M}(\Phi_{KL}f_L^{+}+\Omega_{KL}f_L^{-}),\ \text{for } K=1,2,\dots,M. \quad (9)$$

Incidentally, when every port is anechoically terminated and every external source can be disregarded, i.e., $R_K=f_K^{-}=0$ for every K, eq. (9) reduces to $p_K=f_K^{+}$.

Employing an reference microphone at a location, K", far from the primary one K, to reject the contribution of the flow induced test system noises, we make additional measurement of two kind of the transfer functions between the pressures at K and K", $H_{KK''}$ and $H_{KK''}^{(K)}$, for incident sounds from the primary and external source side at each port K, respectively, i.e.,

$$H_{KK''}=b_{K''L}/b_{KL}=a_{K''L}/a_{KL}=a_{K''K}/a_{KK} \text{ and } H_{KK''}^{(K)}\equiv b_{K''K}/b_{KK}. \quad (10)$$

Using eqs.(7) and (8), we have relationships between the external sources f_L^{-} and f_K^{-}, and each of their contributions to the reference pressure at location K", $b_{K''L}$ and $b_{K''K}$, as

$$b_{K''L}=H_{KK''}b_{KL}=\Omega_{K''L}f_L^{-} \text{ and } \Omega_{K''L}\equiv H_{KK}\Omega_{KL} \quad (11)$$

and $$b_{K''K}=H_{KK''}^{(K)}b_{KK}=\Omega_{K''K}f_K^{-} \text{ and } \Omega_{K''K}\equiv H_{KK''}^{(K)}\Omega_{KK} \quad (12)$$

For the primary sources, f_L^{+} and f_K^{+}, similarly, from eqs.(4), (5) and (10) we have

$$a_{K''L}=\Phi_{K''L}f_L^{+},\ \Phi_{K''L}\equiv H_{KK''}\Phi_{KL},\ a_{K''K}=\Phi_{K''K}f_K^{+} \text{ and } \Phi_{K''K}\equiv H_{KK''}\Phi_{KK}. \quad (13)$$

The sum of eqs.(11), (12) and (13) gives relationships between K"th reference pressure, $p_{K''}$, and the driving wave pressures of all sources as

$$p_{K''}=\sum_{L=1}^{M}(a_{K''L}+b_{K''L})=\sum_{L=1}^{M}(\Phi_{K''L}f_L^{+}+\Omega_{K''L}f_L^{-}),\ \text{for } K''=1,2,\dots,M. \quad (14)$$

<u>Characteristic Transmission Factors and Load-Coupled Transmission Factors</u>

Considering the relationships between traveling wave pressures at an arbitrary location J and at a port L, as seen in Fig.2(b),

$$b_{JL}^{-}=R_J T_{JL} b_{LL}^{-},\ R_J=b_{JL}^{-}/b_{JL}^{+} \text{ and } T_{JL}=b_{JL}^{+}/b_{LL}^{-} \quad (15)$$

we have the relationships between Lth port incoming wave and Kth port outgoing wave caused by Lth port external source [1] as

$$b_{KL}^{+}=\sum_{J=1}^{M}\tau_{KJ}b_{JL}^{-}=T_{KL}b_{LL}^{-} \quad \text{and} \quad T_{KL}=\tau_{KL}+\sum_{J(\neq L)=1}^{M}\tau_{KJ}R_J T_{JL}. \quad (16)$$

Observation of R_K and T_{KL} for all combination of ports K and L gives every characteristic transmission factor τ_{KL} by solving the set of equations (16).

OBSERVATION OF ACOUSTICAL PROPERTIES

<u>Observation of Passive Properties</u>

To obtain the reflection factors R_K and T_{KK} employing the in-duct two-microphone technique for impedance [4], we make measurement of an additional reference pressure at K' in the vicinity of each port K, $b_{K'L}$, and obtain the transfer function, $H_{K'K}^{(L)}=b_{K'L}/b_{KL}$, between the pressures b_{KL} and $b_{K'L}$, introducing an external test source from each port L. To reject flow induced noises, specifically, superposing a test signal e_L through a loudspeaker from Lth port end (L=1, 2, ... ,M), we make measurement of the transfer function $H_{LJ}^{(e)}$

between e_L and the pressure p_{JL} for every J=1,2, ... ,M,1',2', ... ,M',1",2", ... ,M", we have the output pressure coherent to the test signal at J, $b_{JL}^{(c)}$, as

$$b_{JL}^{(c)}=H_{LJ}^{(c)}|e_L| \text{ and } H_{LJ}^{(c)}=<e_L^* p_{JL}>/|e_L|^2 \qquad (17)$$

where the symbols $<\cdot>$ and $|\cdot|$ denote the ensemble average and the ensemble averaged absolute value, respectively, and the superscript (*) denotes the complex conjugate. By using $b_{JL}^{(e)}$ instead of b_{JL}, we obtain $H_{KK''}$ and $H_{KK''}^{(K)}$ directly from eq.(10), then R_K and T_{KK} giving $H_{K'K}^{(L)}=b_{K'L}^{(c)}/b_{KL}^{(e)}$ and applying the in-duct two-microphone technique, then $b_{KL}^{(e)+}$ and $b_{KL}^{(c)-}$ applying eq.(15), and finally T_{KL} by applying eq. (16) for every combination of ports K and L.

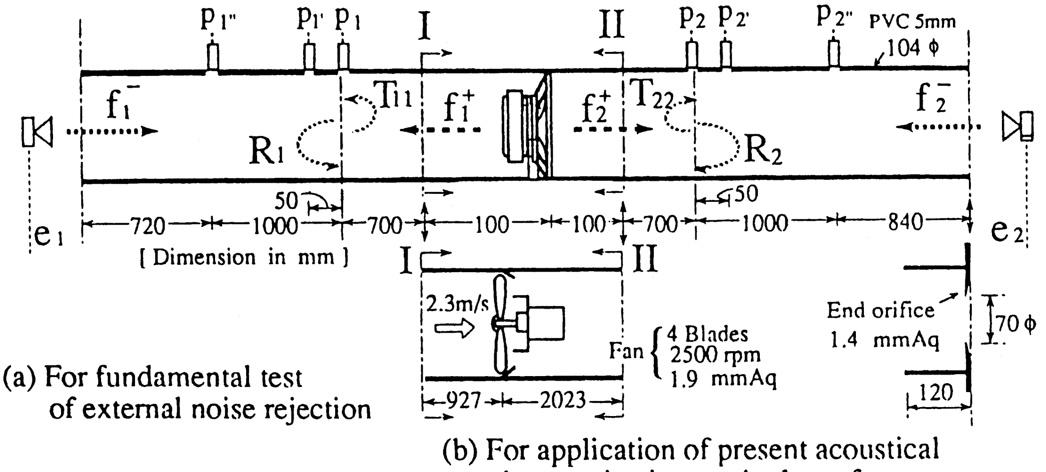
Observation of Active Properties

Assuming that the external sources and the primary source are mutually independent, we can relates the characteristic active properties to the cross-spectrum of the pressure, $<p_K^* p_L>$, between each port K (for K=1,2, ... ,M) and its reference or another port L (for L=K" or for L(≠K) =1,2, ... ,M) as

$$<p_K^* p_L>=\sum_{I=1}^{M}\{\Phi_{KI}^*\Phi_{LI}|f_I^+|^2+\Omega_{KI}^*\Omega_{LI}|f_I^-|^2+\sum_{J(\neq I)=1}^{M}\Phi_{KI}^*\Phi_{LJ}<(f_I^+)^*(f_J^+)>\}. \qquad (18)$$

Flow induced microphone noise has been disregarded in eq.(18), because every spacing between the two locations K and L (which is not necessarily to be straight duct section) has been taken large compared to the correlation length of turbulence. This flow induced noise suppression method without using the tubular wind screens is a simplified alternative of that by M.Abom, H.Boden and J. Lavrentjev [3], and two-reference microphone method by ourselves [2].

Giving the passive acoustic properties of the test duct system and measuring the M(M−1)/2 cross spectra $<p_K^* p_L>$ and the M cross spectra $<p_K^* p_{K''}>$, we have the M(M+1)/2 complex equations (18). Solving a set of these equations, we can determine the M(M+1) real unknowns which are the 2M driving wave pressures $|f_I^+|$ and $|f_I^-|$, and the real and imaginary part of the M(M−1)/2 cross-spectra $<(f_I^+)^*(f_J^+)>$. An explicit relationship between the driving wave pressures and the driving pressures acting on the ports have



(a) For fundamental test of external noise rejection

(b) For application of present acoustical characterization method to a fan.

Fig.2 Experimental test set up

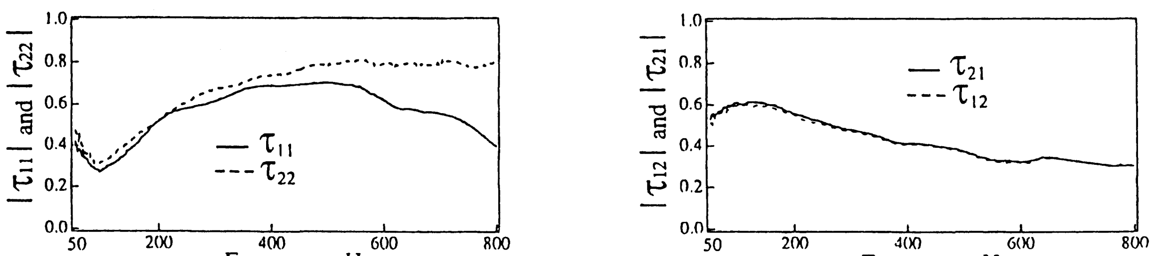
been given in the reference [1] for a two-port source. The complex coherence factor of the driving wave pressures between port K and L, $\mu_{KL}^{(f+)}$, are defined by

$$\mu_{KL}^{(f+)} \equiv \langle (f_K^+)^* f_L^+ \rangle / (|f_K^+||f_L^+|),\ \text{for } K=1,2,\ldots,M \text{ and } L(\neq K)=1,2,\ldots,M. \quad (19)$$

EXPERIMENTS

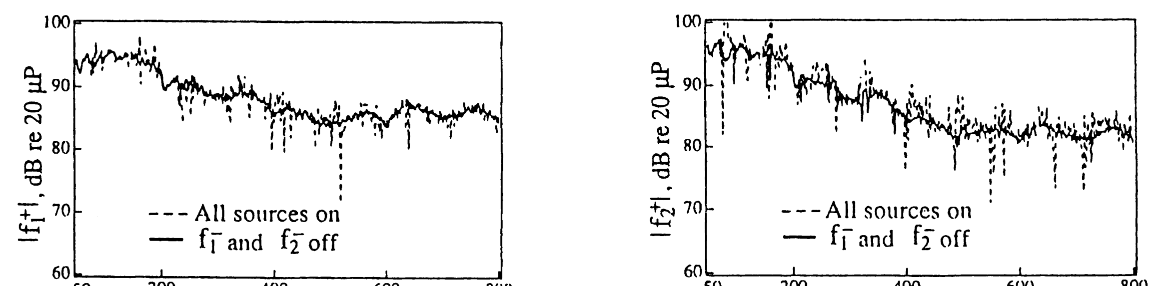
Experimental Conformation of Present Determination Method

Fig.2(a) illustrates the test arrangement to check the effectiveness of the external source rejection of the determination method of the acoustical properties for a two-port source. Fig.3(a) and (b) show the characteristic passive properties of the loudspeaker used for the primary source. The transmission factors τ_{12} and τ_{21} are reciprocal. Fig.3(c) through (f) show the driving wave pressure from each port of of the primary and external loudspeakers detected from the contaminated pressures by the other sources. Each agrees with that of direct measurement of the corresponding source only turn on. This confirms the effectiveness of the undesired noise rejection method.



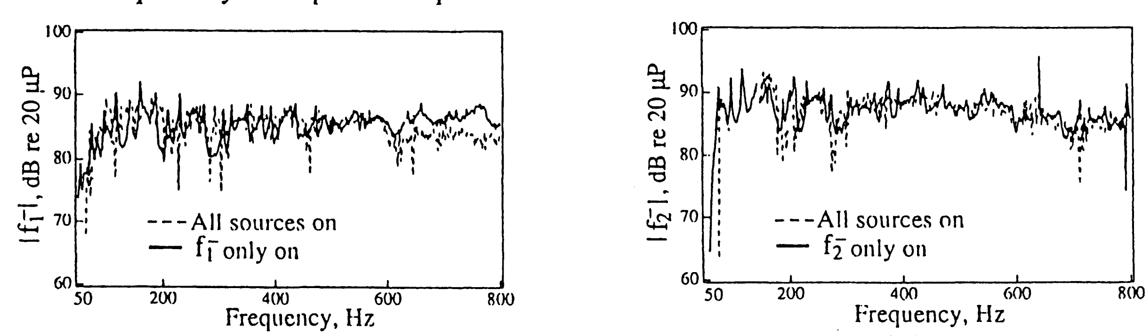
(a) Characteristic reflection factors of primary loudspeaker

(b) Characteristic transmission factors of primary loudspeaker



(c) Detection of driving wave pressure from primary loudspeaker to port 1

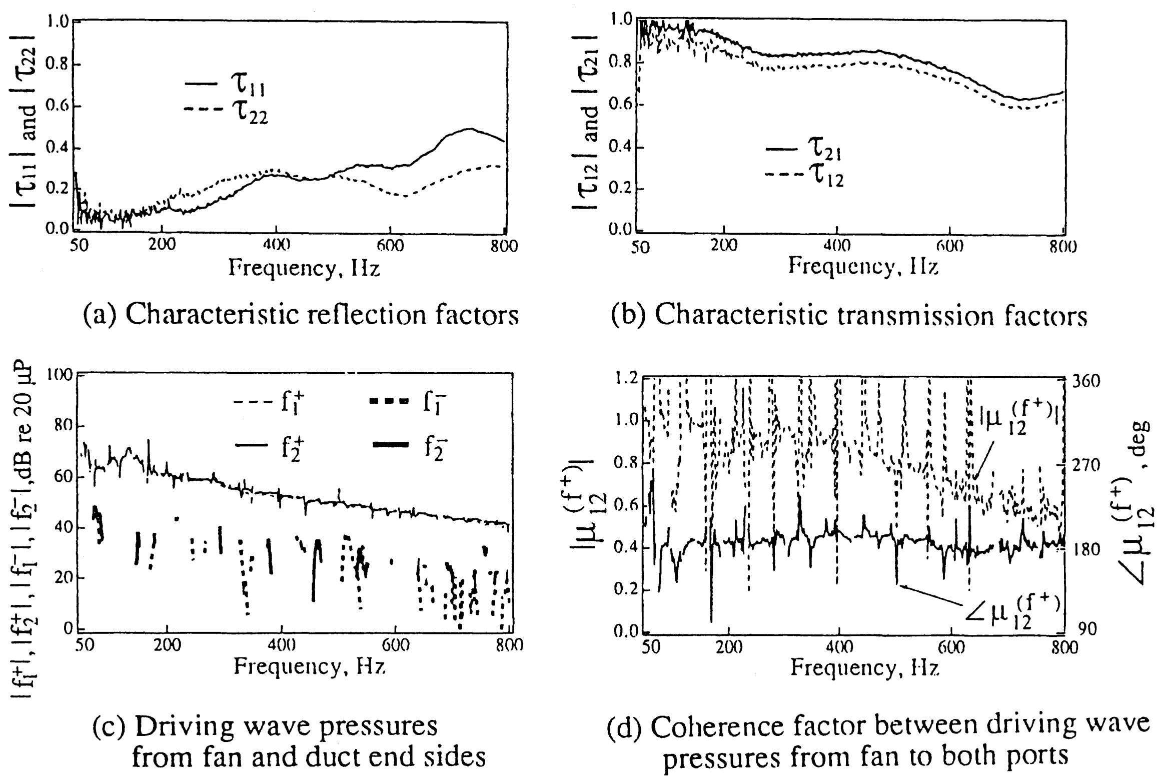
(d) Detection of driving wave pressure from primary loudspeaker to port 2



(e) Detection of driving wave pressure from external loudspeaker at port 1

(f) Detection of driving wave pressure from external loudspeaker at port 2

Fig.3 Test results of present acoustic characterization method



(a) Characteristic reflection factors

(b) Characteristic transmission factors

(c) Driving wave pressures from fan and duct end sides

(d) Coherence factor between driving wave pressures from fan to both ports

Fig.4 Results of application to acoustic characterization of a fan under operation

<u>Application to Acoustical Characterization of a Fan</u>

We applied this acoustical characterization method to an axial fan of resident use. The primary loudspeaker section was replaced by the fan section in the test duct arrangement as shown in Fig.2(b). An orifice was attached to the end of the discharge duct to control and to measure the air-flow rate.

Fig.4(a) and (b) show the passive properties of the fan under operation at Mach number of about 0.007. The transmission factor τ_{12} is somewhat less than that τ_{21} in magnitude. Fig.4(c) and (d) show the active properties. The driving wave pressure from the orifice was far less than those from the fan. The driving wave pressures from the fan towards both sides are, roughly speaking, similar in magnitude and out of phase, $f_1^+ \approx -f_2^+$, though partially coherent.

SUMMARY

A new determination method of the acoustical property of a HVAC duct component under operation with throttle noise rejection has been presented. The effectiveness of the method has been confirmed by a fundamental experiment. Its application to acoustical characterization of a fan has given some useful knowledge on the sound generation mechanism of fans.

REFERENCES

[1] M.Terao and H.Sekine, Proc. FAN NOISE, 343 (1992).
[2] M.Terao and H.Sekine, Proc. INTER-NOISE 89, 143 (1989).
[3] M. Abom, H. Boden and J. Lavrentjev, Proc. FAN NOISE, 359 (1992).
[4] ASTM, E1050 (1985).