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MEASUREMENT OF PLANE WAVE PRESSURES IN AIRFLOW DUCT BY THE TWO-MICROPHONE METHOD IN A SLIT-TUBE

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In order to measure the incident and reflected plane wave pressures in an HVAC duct, we have developed a four microphone method [1]. This requires additional two microphones for rejecting the flow induced microphone pressures besides the two microphones for detecting the traveling wave pressures [2]. As an alternative method to omit these additional microphones, we have been studying on a special probe which utilizes the slit-tubes [3]. This article focuses on the responses of the probe.

SLIT-TUBE MIDWAY MICROPHONE PROBE

A Handmade Probe and its Acoustical model

Figs. 1 and 2 illustrates a slit-tube midway probe under test and its acoustical model. The complex amplitudes of the local sound pressures in- and out-side of the slit-tube probe at the primary microphone location are denoted by m and a respectively. The complex pressures of the forward and backward traveling waves in- and out-side of the slit-tube are represented by m^+ and m^-, and by a^+ and a^-, respectively, which can be written as;

$$m^+ = D'_u a^+ + C'_u a^- + E_u m^- , \qquad (1a)$$

$$m^- = C'_d a^+ + D'_d a^- + E_d m^+ , \qquad (1b)$$

where C' and D' indicate the contribution factors of outside traveling waves to inside ones in the same and opposite directions, respectively, and E denotes the reflection factor from each of the slit-tubes at the primary microphone location. The subscript u and d are of the up- and down-stream side sections of the probe, respectively. Substituting m^- and m^+ of eqs. (1a) and (1b) each other, we have

$$\begin{bmatrix} m^+ \\ m^- \end{bmatrix} = \begin{bmatrix} D_u & C_u \\ C_d & D_d \end{bmatrix} \begin{bmatrix} a^+ \\ a^- \end{bmatrix}, \qquad (2)$$

where

$$C_u = (C'_u + E_u D'_d)/(1 - E_u E_d) ,$$

$$D_u = (D'_u + E_u C'_d)/(1 - E_u E_d) ,$$

$$C_d = (C'_d + E_d D'_u)/(1 - E_u E_d) ,$$

$$D_d = (D'_d + E_d C'_u)/(1 - E_u E_d) .$$

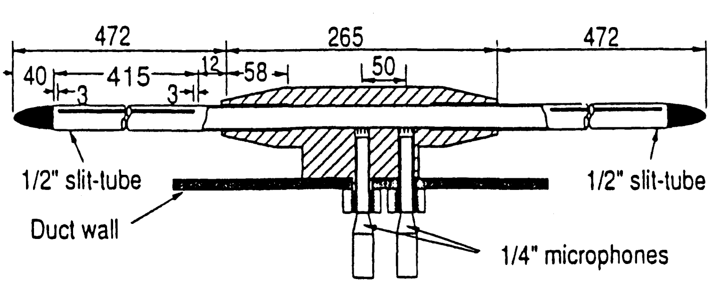


Fig.1 Hand made slit-tube midway probe. [Dimentions in mm]

Since the probe is made symmetrical with respect to the primary microphone, when the Mach number of wind is nearly zero, we can put $E_u = E_d = E$, $C'_u = C'_d$ and $D'_u = D'_d$. Then $C = C_u = C_d$ and $D = D_u = D_d$, and eq. (2) can be simplified as;

$$\begin{bmatrix} m^+ \\ m^- \end{bmatrix} = \begin{bmatrix} D & C \\ C & D \end{bmatrix} \begin{bmatrix} a^+ \\ a^- \end{bmatrix}. \quad (3)$$

Using this, we also have

$$m = m^+ + m^- = (C + D)(a^+ + a^-)$$

$$= (C + D)\, a = \Delta m\, a, \quad (4)$$

where $\Delta m = m / a = (C + D)$ is the probe response for the local sound pressure.

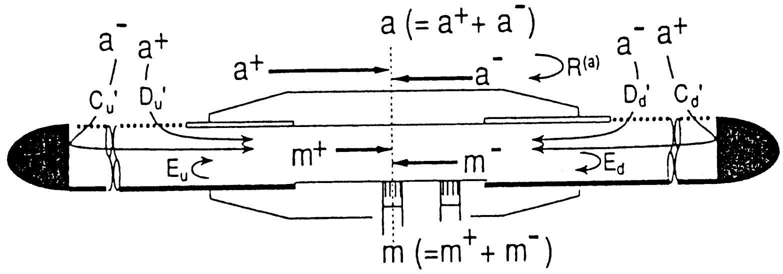


Fig.2 An acoustical model of the probe.

DETERMINATION OF THE PROBE RESPONSE

Determination Method and Test Setup of the Responses

At the first stage of the study, we start from the simplified model of eq. (3) and try to determine the responses C and D under no flow, though, in principle, we can determine the responses C_u, D_u, C_d and D_d of eq. (2) under airflow. Fig. 3 illustrates the air duct used for the tests. A loudspeaker was located just out of the one end of the duct. The other side was anechoically ended by inserting absorbent material in this response determination.

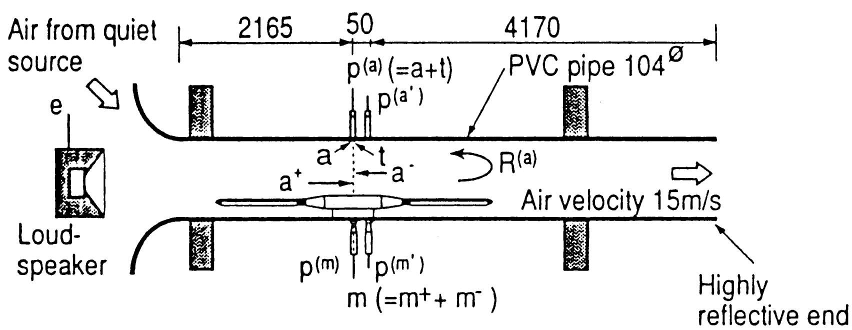


Fig.3 Test setup. [Dimentions in mm]

Measurement Method of the Sound Pressures

Instead of a, a', m and m' in eq. (3), each of the transfer functions, a_e, a'_e, m_e and m'_e, between the test signal, e, and each of the microphone pressures, $p^{(a)}$, $p^{(a')}$, $p^{(m)}$ and $p^{(m')}$, respectively, are measured in order to reject the flow induced pressure and/or ambient sound, t, independent of the test signal. Those transfer functions are written as;

$$a_e \equiv \langle e^* p^{(a)} \rangle / \langle e^* e \rangle = \langle e^* (a+t) \rangle / \langle e^* e \rangle = a/e, \quad a'_e \equiv \langle e^* p^{(a')} \rangle / \langle e^* e \rangle = a'/e, \quad (5a)$$

$$m_e \equiv \langle e^* p^{(m)} \rangle / \langle e^* e \rangle = m/e, \text{ and } m'_e \equiv \langle e^* p^{(m')} \rangle / \langle e^* e \rangle = m'/e. \quad (5b)$$

where * denotes complex conjugate and <> denotes ensemble average. The record length and the number of the records taken for the average are 0.5 second and 512, respectively. To detect the traveling waves, the relationships in the two microphone impedance measurement method [2] was used; i.e.,

$$a_e^+ = a_e / (1 - R^{(a)}), \quad a_e^- = R^{(a)} a_e^+ \quad (6a)$$

$$m_e^+ = m_e / (1 - R^{(m)}), \quad m_e^- = R^{(m)} m_e^+ \quad (6b)$$

The reflection factors in the duct and in the probe, $R^{(m)}$ and $R^{(a)}$, are

$$R^{(a)} \equiv a^-/a^+ = a_c^-/a_c^+ = (e^{-jks} - H_e^{(a)}) / (H_e^{(a)} - e^{jks}) , \quad (7a)$$

$$R^{(m)} \equiv m^-/m^+ = m_c^-/m_c^+ = (e^{-jks} - H_e^{(m)}) / (H_e^{(m)} - e^{jks}) , \quad (7b)$$

where k is the wave number, s is the space between the primary- and sub-microphones , $j = \sqrt{-1}$, and

$$H_e^{(a)} \equiv a_c' / a_e = a' / a , \quad (8a)$$

$$H_e^{(m)} \equiv m_e' / m_e = m' / m . \quad (8b)$$

Experimentally and Numerically Determined Responses

Fig. 4 shows the experimentally and numerically determined responses of the probe, Δm , C and D. In the numerical determination, we employed the substructure boundary element method (BEM) under no flow [4], and took unity for the normalized flow resistance of the slit covering, $R/\rho c$ [5]. Agreement in the responses between measurement and BEM is good except for the frequencies around 300 Hz and 650 Hz in the response C. The probable causes of these discrepancies are the resonances of the slit-tube and slit covering motions which were not considered in the BEM model.

SOUND PRESSURE MEASUREMENT IN AN AIR-FLOW DUCT

Sound Pressure Measurement Methods

Experiments were carried out at a fixed wind velocity of 15 m/s in the duct shown in Fig. 3. In the sound pressure measurement by the probe, instead of eqs. (5b) and (8b) the power spectrum of primary microphone, $|m|^2$, and the transfer function between the primary- and sub-microphones, $H^{(m)}$, were measured directly (without using the test signal, e) as;

$$|m|^2 = \langle (p^{(m)})^* p^{(m)} \rangle , \text{ and } H^{(m)} = \langle (p^{(m)})^* p^{(m')} \rangle / |m|^2 . \quad (9)$$

Taking the phases relative to the local pressure, m, we can write

$$m = |m| , \; m^+ = |m| / (1 - R^{(m)}) , \text{ and } m^- = R^{(m)} m^+ . \quad (10)$$

By using these pressures, the experimentally determined probe responses and eqs. (3) and (4), the duct sound pressures, a , a^+ and a^-, can be obtained. As the exact sound pressures in the duct, a , a^+ and a^-, to compare with those by the probe method, the coherent output pressure measurement method was employed; i.e., the transfer functions, a_e and a_e', of eq. (5a) and the power spectrum of the test signal, $|e|^2$, are measured. By using eqs. (7a) and (8a), and taking the phases relative to the local pressure, a, we have

$$a = |a| , \; |a|^2 = a_c^* a_c |e|^2 , \; a^+ = |a| / (1 - R^{(a)}) , \text{ and } a^- = R^{(a)} a^+ . \quad (11)$$

Test Results on the Sound Pressure Measurement

Fig. 5 shows the sound pressures measured at the flow speed of 15 m/s and for the duct end reflection factor of $R^{(a)} \cong 0.9$. As seen from the cases (H) where the acoustic pressures, a , a^+ and a^-, are superior to the flow induced pressure, t, the agreement between each of the sound pressures measured by the probe method and that by the exact (the coherent output pressure measurement) one is good. The limit of the flow induced pressure rejection by the slit-tube probe can be seen from the cases (L) where the acoustical

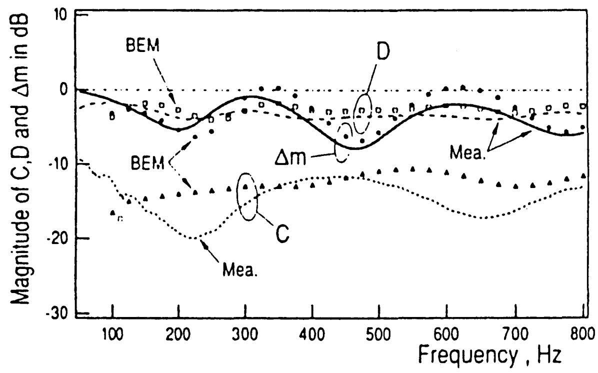
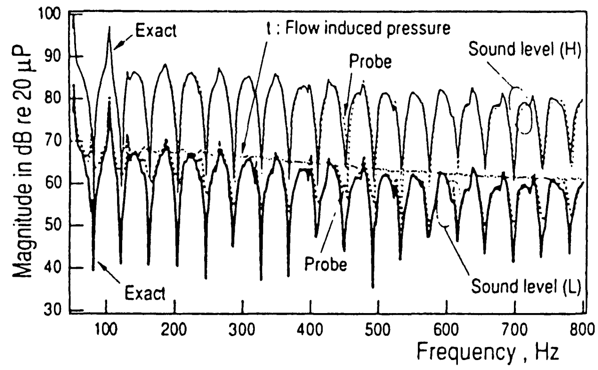
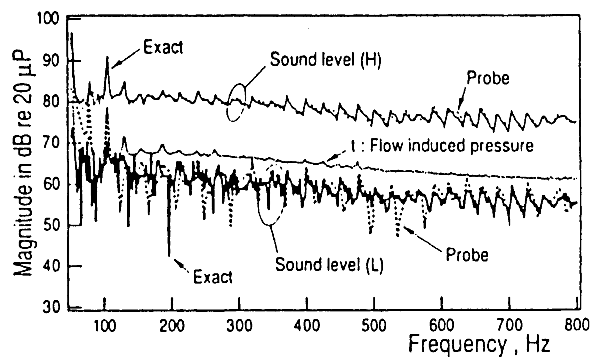


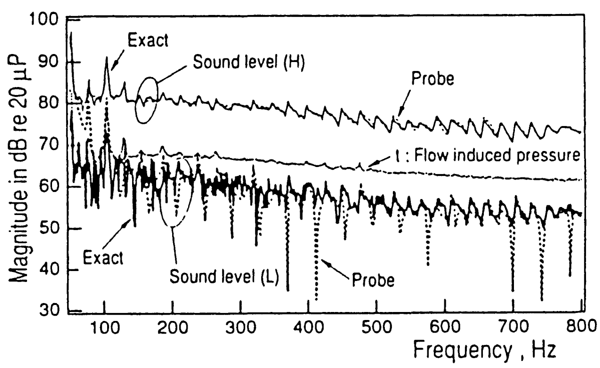
Fig.4 Probe responses determined in anechoically ended duct in still.



i) Local sound pressure a



ii) Incident wave pressure a^+



iii) Reflected wave pressure a^-

Fig.5 Sound pressures measured by the probe and exact methods. (For air velocity 15 m/s and duct reflection factor 0.9.)

pressures are inferior to the flow induced one. The probe method becomes inaccurate at frequencies where the sound pressure levels are about 10 dB or less than flow induced one especially for low frequency region, where the coherent output pressure method is inaccurate also.

SUMMARY

It has been confirmed that the slit-tube midway microphone probe rejects the flow induced microphone pressures and detects the traveling wave pressures as well as the local sound pressure with practical accuracy, unless the flow induced microphone pressure exceeds the sound pressures by about 10 dB or more except for very low frequency region. The probe responses determined by the simplest test under no flow in anechoically terminated duct are found to be effective even for one of the most strict cases probable in HVAC ducts such as the air stream velocity of 15m/s and a highest duct reflection factor of about 0.9.

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