EXPERIMENTAL MEASUREMENT OF THE TRANSMISSION OF NOISE THROUGH BRANCH JUNCTIONS OF AIR CIRCUITS

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ABSTRACT

An experimental study is presented on the characterization of the noise transmission properties of the duct junctions of ventilation and air-conditioning air circuits, assumed as three port acoustic systems. The procedure requires the measurement and post-processing of the transfer functions between the control signals of 3 loudspeakers, one at each branch, and the sound pressure signal recorded at 6 positions (two microphone technique). This paper describes the theoretical basis of the methodology and presents some of the results obtained for branch take-offs with three deviation angles and under different air flow conditions.

INTRODUCTION

Air circuits for ventilation or air-conditioning systems may conduct the noise generated at the fans or other sources towards the ventilated rooms. Usual regulations for thermal installations in buildings impose maximum background noise values for each room type, either in terms of overall noise levels (dBA) or referred to RC or NC indexes. In order to meet the noise specifications, many air circuits have to include silencers, either reactive or purely dissipative. Optimal selection of the silencers at the design stage of the system requires the previous calculation of the noise levels induced in the ventilated rooms.

The noise transmitted through air-circuits is usually calculated by means of empirical correlations for each element of the system, such as the formulas and tables indicated by ASHRAE [1]. In general these correlations give the attenuation or generation of sound energy through each element, depending on the geometrical characteristics, the frequency band and the air flow-rate. Calculations are performed by accumulating sound attenuations and sound re-generations along the air circuit. Since the sound can be partially reflected at some elements, like elbows or duct ends, the transmission of noise through each element has to be considered for all the different incidence directions [2,3]. Some elements such as elbows have well-established correlations. However, that is not the case of branch take-offs, due to the variety of geometrical configurations and sound incidence directions; for branch divisions, ASHRAE [1] suggests to estimate the exiting noise by dividing the incident sound energy in proportion to the cross-sections of the air outlet ducts, without considering the effect of the branch deviation angles, the effect of sound frequency nor the effect of the air flow-rate through the branch. Besides, the reflection of the incident sound is assumed small in general, and no guideline is provided to account for it.

This paper presents an experimental characterisation of the noise transmission properties for branch junctions with variation of the deviation angles and also of the air flow-rate distribution. The cross-section of the ducts was circular with 160 mm in diameter for all cases. Tests were

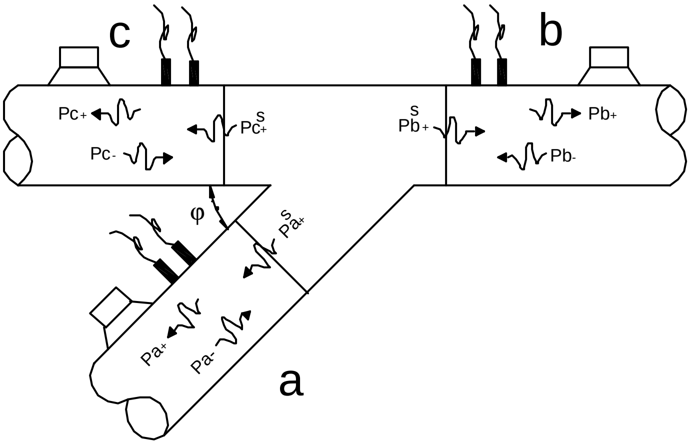

Figure 1. Schematics of a 3 port acoustic system, with sound pressure waves at each port.

performed by means of the two-microphone technique for each branch, under imposition of controlled acoustic loads with loudspeakers [3, 4]. Each branch was considered as a three-port system with two state variables for each port: the entering and the exiting pressure waves, assumed as plane waves. For such a system, the noise transmission properties are described with 9 complex transfer functions. The type of methodology has been previously applied to two-port elements such as fans or elbows [4, 5, 6]. This paper describes the theoretical basis of the study, the experimental set-up, the signal analysis methodology and the results obtained.

CHARACTERIZATION METHOD

If the elements under study are considered as invariant linear acoustic systems with 3 input/output ports, a, b and c, they can be fully described by means of 6 state-variables (2 for each port). Since the final purpose is the prediction of the sound transmitted along the air circuits, assumed as plane waves, the most convenient state-variables are the incident pressure waves (p_+) and the reflected pressure waves (p_-) at each port (figure 1). With these state variables, the equation that characterizes a 3 port acoustic element, i.e. a duct junction with 3 branches, can be expressed as:

$$\begin{pmatrix} p_{a+} \\ p_{b+} \\ p_{c+} \end{pmatrix} = \begin{pmatrix} R_a & T_{ba} & T_{ca} \\ T_{ab} & R_b & T_{cb} \\ T_{ac} & T_{bc} & R_c \end{pmatrix} \begin{pmatrix} p_{a-} \\ p_{b-} \\ p_{c-} \end{pmatrix} + \begin{pmatrix} p^s_a \\ p^s_b \\ p^s_c \end{pmatrix} = \mathbf{M} \begin{pmatrix} p_{a-} \\ p_{b-} \\ p_{c-} \end{pmatrix} + \mathbf{V} \qquad (1)$$

In equation (1), **M**, the dispersion matrix, collects the passive properties of noise reflection and transmission for the incoming sound from each branch side, and **V**, the source vector, represents the noise generated at the junction itself, mostly due to flow separation at the deviating branches and the corresponding turbulence production. The terms of the source vector **V** are not usually important except for high air velocities and great deviation angles. The present study has been focused on the noise transmission properties alone, i.e., on the determination of the dispersion matrix **M**. According to this model, the noise transmission properties of a branch junction are characterized by 9 complex parameters, which depend on the frequency as well as on the aerodynamic conditions. The module of these parameters represents the fraction of the amplitude of incident pressure at one port that becomes transmitted (or reflected) to any of the other ports of the branch junction (figure 2).

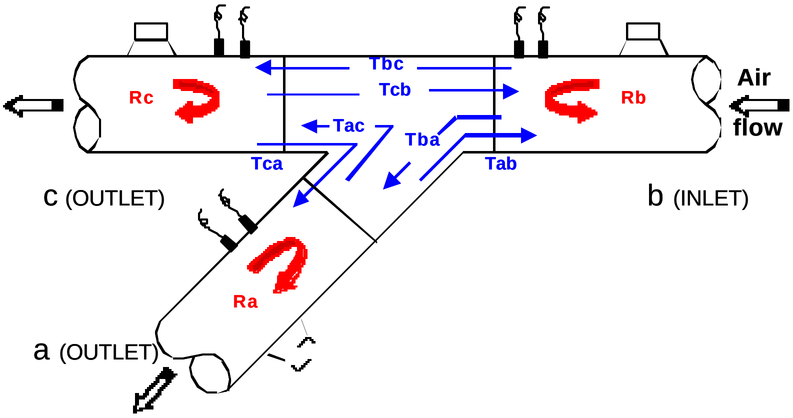

Figure 2. Coefficients of sound reflection and transmission for a 3 port acoustic system (elements of the dispersion matrix **M**).

In order to determine the dispersion matrix **M** with no disturbing influence from the source vector **V**, the technique derived by Lavrentjev et al. [4] has been used. The method, once adapted to the 3 port case, consists in applying three controlled acoustic states, by means of three loudspeakers, each at one side of the branch (the loudspeakers are to be mounted so that the air-flow is not significantly perturbed). Each acoustic state corresponds to one of the loudspeakers emitting sound while the other two are disconnected. The elements of **M** and **V** are not altered by the imposition of external acoustic loads. Hence, denoting each acoustic state with the super-index I, II or III, equation (1) may be extended to:

$$\begin{pmatrix} p^{I}_{a+} & p^{II}_{a+} & p^{III}_{a+} \\ p^{I}_{b+} & p^{II}_{b+} & p^{III}_{b+} \\ p^{I}_{c+} & p^{II}_{c+} & p^{III}_{c+} \end{pmatrix} = \begin{pmatrix} R_a & T_{ab} & T_{ac} \\ T_{ba} & R_b & T_{bc} \\ T_{ca} & T_{cb} & Rc \end{pmatrix} \begin{pmatrix} p^{I}_{a-} & p^{II}_{a-} & p^{III}_{a-} \\ p^{I}_{b-} & p^{II}_{b-} & p^{III}_{b-} \\ p^{I}_{c-} & p^{II}_{c-} & p^{III}_{c-} \end{pmatrix} + \begin{pmatrix} p^{s}_{a} \\ p^{s}_{b} \\ p^{s}_{c} \end{pmatrix} \tag{2}$$

Assuming that the loudspeaker noise is not correlated with the aerodynamic noise generated at the duct junction, the transfer functions between the electric signal driving the active loudspeaker and the sound pressures of the source vector **V** must be zero. In consequence, the source vector **V** can be eliminated from equation (2) by considering not the sound pressure waves but the transfer functions H_e between the loudspeaker electric signals and those sound pressure waves:

$$\begin{pmatrix} H^{I}_{ea+} & H^{II}_{ea+} & H^{III}_{ea+} \\ H^{I}_{eb+} & H^{II}_{eb+} & H^{III}_{eb+} \\ H^{I}_{ec+} & H^{II}_{ec+} & H^{III}_{ec+} \end{pmatrix} = \begin{pmatrix} R_a & T_{ab} & T_{ac} \\ T_{ba} & R_b & T_{bc} \\ T_{ca} & T_{cb} & Rc \end{pmatrix} \begin{pmatrix} H^{I}_{ea-} & H^{II}_{ea-} & H^{III}_{ea-} \\ H^{I}_{eb-} & H^{II}_{eb-} & H^{III}_{eb-} \\ H^{I}_{ec-} & H^{II}_{ec-} & H^{III}_{ec-} \end{pmatrix} \tag{3}$$

From this system of equations, a solution can be obtained for each of the elements of the dispersion matrix, in terms of the different transfer functions. As an example, the parameters Ra, Tab and Tac, that characterize how the sound pressure wave entering through port a is distributed to the other ports, can be expressed as:

$$\begin{cases} R_a = \dfrac{H^{I}_{ea+}\left(H^{II}_{eb-}H^{III}_{ec-} - H^{II}_{ec-}H^{III}_{eb-}\right) + H^{II}_{ea+}\left(H^{I}_{ec-}H^{III}_{eb-} - H^{I}_{eb-}H^{III}_{ec-}\right) + H^{III}_{ea+}\left(H^{I}_{eb-}H^{II}_{ec-} - H^{I}_{ec-}H^{II}_{eb-}\right)}{\det H_-} \\[2ex] T_{ab} = \dfrac{H^{I}_{ea+}\left(H^{II}_{ec-}H^{III}_{ea-} - H^{II}_{ea-}H^{III}_{ec-}\right) + H^{II}_{ea+}\left(H^{I}_{ea-}H^{III}_{ec-} - H^{I}_{ec-}H^{III}_{ea-}\right) + H^{III}_{ea+}\left(H^{I}_{ec-}H^{II}_{ea-} - H^{I}_{ea-}H^{II}_{ec-}\right)}{\det H_-} \\[2ex] T_{ac} = \dfrac{H^{I}_{ea+}\left(H^{II}_{ea-}H^{III}_{eb-} - H^{II}_{eb-}H^{III}_{ea-}\right) + H^{II}_{ea+}\left(H^{I}_{eb-}H^{III}_{ea-} - H^{I}_{ea-}H^{III}_{eb-}\right) + H^{III}_{ea+}\left(H^{I}_{ea-}H^{II}_{eb-} - H^{I}_{eb-}H^{II}_{ea-}\right)}{\det H_-} \end{cases} \tag{4}$$

where $\det H_-$ is:

$$\begin{aligned} \det H_- = {} & \left(H^{I}_{ea-}H^{II}_{eb-}H^{III}_{ec-} + H^{I}_{ec-}H^{II}_{ea-}H^{III}_{eb-} + H^{I}_{eb-}H^{II}_{ec-}H^{III}_{ea}\right) + \\ & +(-1)\cdot\left(H^{I}_{ec}H^{II}_{eb-}H^{III}_{ea-} + H^{I}_{eb-}H^{II}_{ea-}H^{III}_{ec-} + H^{I}_{ea-}H^{II}_{ec-}H^{III}_{eb-}\right) \end{aligned} \tag{5}$$

Similar formulations can be easily deduced for the other elements of the dispersion matrix **M**.

In order to use equations (4) and (5) in practice, the transfer functions of those equations must be referred to measurable magnitudes. However, a microphone does not capture the incident pressure waves (p_+) or the exiting ones (p_-), but the combination of both. This problem can be overcome by using two microphones for each of the branches a, b and c, at positions 1 and 2 (see figure 1). For each branch, the pressure waves that travel either in the positive or in the negative direction pass at those two positions with a phase delay that is proportional to the separation distance and to the sound wave number. If s_a, s_b and s_c are the separation distances of each microphone pair, k_{a-}, k_{b-} and k_{c-} are the wave numbers of the incident sound at each branch, and k_{a+}, k_{b+} and k_{c+} are the wave numbers of the exiting sound, the transfer functions of equations (4) and (5) can be referred to the measurable transfer functions by means of:

$$\begin{cases} H_{ea+} = \dfrac{H_{ea_2}e^{-ik_{a-}s_a} - H_{ea_1}}{e^{ik_{a-}s_a} - e^{-ik_{a+}s_a}} \\[2ex] H_{eb+} = \dfrac{H_{eb_2}e^{-ik_{b-}s_b} - H_{eb_1}}{e^{ik_{b-}s_a} - e^{-ik_{b+}s_b}} \\[2ex] H_{ec+} = \dfrac{H_{ec_2}e^{-ik_{c-}s_c} - H_{ec_1}}{e^{ik_{c-}s_c} - e^{-ik_{c+}s_c}} \end{cases} \qquad \begin{cases} H_{ea-} = \dfrac{-H_{ea_2}e^{-ik_{a+}s_a} + H_{ea_1}}{e^{ik_{a-}s_a} - e^{-ik_{a+}s_a}} \\[2ex] H_{eb-} = \dfrac{-H_{eb_2}e^{-ik_{b+}s_b} + H_{eb_1}}{e^{ik_{b-}s_a} - e^{-ik_{b+}s_b}} \\[2ex] H_{ec-} = \dfrac{-H_{ec_2}e^{-ik_{c+}s_c} + H_{ec_1}}{e^{ik_{c-}s_c} - e^{-ik_{c+}s_c}} \end{cases} \tag{6}$$

Equation (6) has to be applied for each of the three acoustic loads I, II and III (these super-indexes have been omitted in equation 6). The air velocity along each of the branches has to be introduced to obtain the effective sound speed and calculate the corresponding wave numbers. All this methodology can be further extended to obtain the elements of the source vector **V** as well, as described in references [4,5].

Equations (4-6) allow for the determination of the 9 complex elements of the dispersion matrix **M**, as a linear function of frequency. However, the common practice for noise transmision calculations in ventilation and air-conditioning circuits is to consider the sound power propagated for each octave or third of octave frequency bands [1]. The coefficients of sound power transmission or reflection for each frequency band can be estimated from the elements of the disperssion matrix **M**, as the average of the square of the modules for the frequencies of that band. Then they can be converted to sound attenuations expressed in dB.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The methodology described above was put into practice with a series of laboratory tests to determine the sound power transmission properties of several duct junctions, varying the deviation angles and the air flow conditions. Three PVC pipes with 160 mm in internal diameter were used for the branches of the test junction. At each pipe, at 2.5 m from the junction, a 6 inch loudspeaker was mounted on a lateral opening with an inclination of 45º, so that the air flow was not disturbed. One of the branches was connected to the air supply system, that consisted of a centrifugal fan with an oulet cross-section of 400 mm in diameter, a dissipative silencer with several annular sound absorbent chambers of increasing external diameter, and a transition duct to reduce the cross-section to the 160 mm diameter (figure 3). The loudspeakers were controlled from a white noise signal generator. The silencer was inserted to reduce the fan noise below the level of the loudspeakers. The air flow-rate through the circuit could be regulated with a variable restrictor at the end of the two exit ducts. The air velocity was measured with a turbine anemometer.

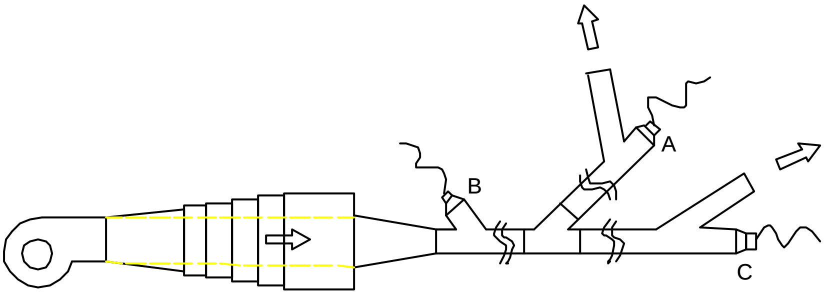

Figure 3. Experimental set-up: fan, silencer and test air circuit,
with duct junction and loudspeakers at the 3 branches.

On each of the three branches two ½inch microphones could be located flush-mounted, at 300 mm and 410 mm from the junction (positions 1 and 2 of microphones in figure 1). A 01dB Symphonie analizer was used to capture and process the sound pressure signals of the microphones and the electric signals of the loudspeakers. During each test the analyzer produced the transfer functions between the 3 loudspeakers and the 6 microphone signals, with a frequency span from 300 Hz to 1300 Hz. The sampling period for each of the transfer functions was at least 3 minutes. These 18 transfer functions were provided as input data for an especially designed calculation program. This program performed the calculations indicated in equations (4-6) of the preceeding section, to obtain the sound transmission coefficients of the dispersion matrix **M**.

EXPERIMENTAL RESULTS

Experiments were conducted on branch take-offs with nominal deviation angles φ=45º, 67º and 87º, relative to the direction of the inlet duct (figure 1). In all cases the designation of the branches is: a = branch take-off; b = air flow inlet; c = air flow outlet, lined with duct b (figures 1-3). Some examples of the transfer functions (module and argument) obtained between the loudspeaker and the microphone signals are shown in figure 4. The configuration for figure 4 was: φ=45º; active loudspeaker: at branch a; microphone signals: a1, b1 and c1; air mean velocity: 15 m/s at branches a and c.

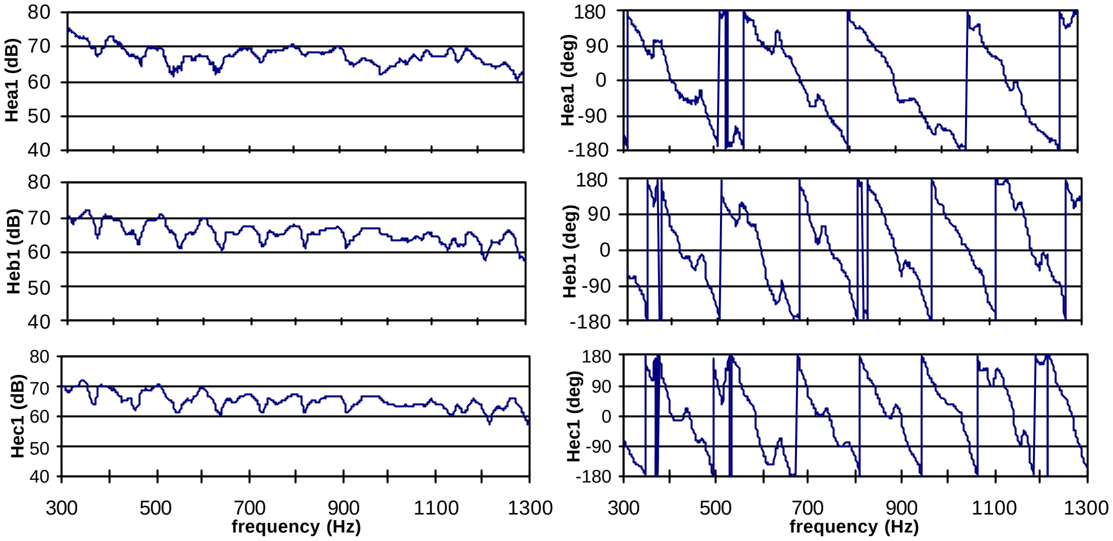

Figure 4. Transfer functions between loudspeaker signal (at branch a) and microphone signals (positions a1, b1 and c1), for φ=45º and air velocity of 15 m/s at branches a and c.

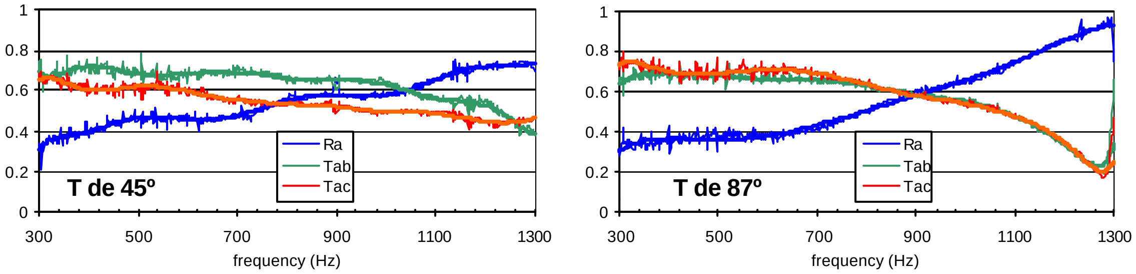

Figure 5. Transmission coefficients for incoming sound at branch a (flow-rate=0, φ=45º, φ=87º).

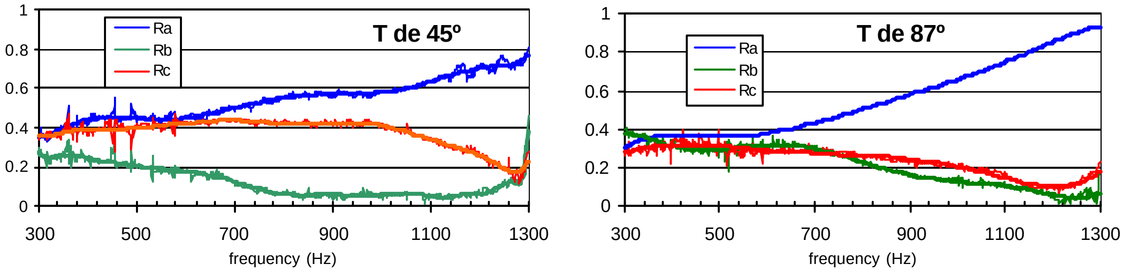

Figure 6. Sound reflection coefficients (flow-rate=0, φ=45º, φ=87º).

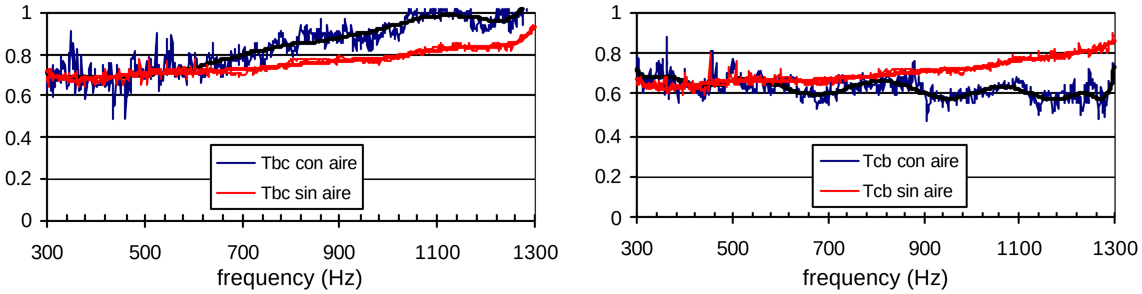

Figure 7. Sound transmission coefficients Tbc and Tcb for φ=45º, with no flow-rate and with an air velocity of 15 m/s (at branches a and c).

Figure 5 presents the sound transmission coefficients (module of the elements of **M**) for the sound entering through port a (i.e., Ra, Tab and Tac), for φ=45º and φ=87º, when there is no air flow. Figure 6 compares the reflection coefficients of the three branches, Ra, Rb and Rc, also for φ=45º and φ=87º, and with no air flow. These results clearly show that there is a remarkable dependence of these transmission coefficients with respect to the deviation angle φ of the branch take-off, to the directions of sound inlet and outlet, and, of course, to the sound frequency. However none of them is considered as a variable in the calculation guidelines for sound transmission through duct junctions given by ASHRAE [1]. Also in general the reflection coefficients appear to have the same order of magnitude of the other transmission coefficients, and hence the sound reflection should be considered in the calculations of noise propagation in order to obtain reliable predictions.

Figure 7 shows the transmission coefficients Tcb and Tbc for φ=45º, with no air flow and with an air velocity of 15 m/s at branches a and c. This figure shows that the effect of the air flow-rate is to shift the transmission coefficients towards higher or lower values depending on the sign of the air velocity with respect to the sound direction. However, this effect is important only for high frequencies.

CONCLUSIONS

An experimental study has been conducted to determine the sound transmission and reflection properties of branch take-offs in air-circuits, assumed as 3 port acoustic systems with plane wave sound propagation along the ducts. Experiments were conducted for three deviation angles and under different air-flow conditions. The results clearly indicate the great influence of the geometrical configuration, the incoming sound direction and the sound frequency on the sound transmission coefficients, though none of these factors is considered as a dependent variable in the ASHRAE recommendations for noise calculations in duct junctions of air circuits. Also, in general the fraction of reflected sound is comparable to the fraction of sound transmitted, and hence it is not negligible. On the contrary, the influence of the air flow-rate (up to air velocities of 15 m/s in the outlet branches) has been found to be small.

ACKNOWLEDGEMENT

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