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ATTENUATION AT SIDE OPENINGS IN AIR DUCTS

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INTRODUCTION

Noise propagating in and emanating from ventilation and air conditioning systems has been for many years a grave cause of concern for building services and mechanical engineers. Noise is both generated and attenuated in air ducts by various physical processes, and therefore the engineer will require information concerning levels of attenuation and generation in order to quantify the potential noise levels in the duct system and the necessary attenuation required to achieve the design criterion.

Various design guides have been produced containing information to assist the engineer, such as those of the Chartered Institution of Building Services Engineers (CIBSE)[1] and the American Society of Heating, Refrigeration and Airconditioning Engineers (ASHRAE)[2]. These guides include empirical formulae and tables of data which may be incorporated into the system design calculations. Most currently available commercial computer programs use data from one or other of the design guides, depending upon the country of origin, and both the computer software and the guides are extensively used by engineers who may have had little or no acoustic training.

A major criticism of design guides is that they present tables of data with no reference to the original source, making it impossible to determine whether the tables are valid in a particular application. Also, much of the data was collected many years ago (e.g. the CIBSE Guide concerning sound control was first published in 1972) and may not reflect current practice. Of more concern is that different guides give conflicting values for similar situations, as this is a frequent source of confusion to the building services engineer who often has no way of evaluating the most accurate solution.

An excellent illustration of the uncertainty that exists is provided by the treatment in various guides of the attenuation to be expected when sound energy is reflected from the ends of ducts, i.e. the so-called 'end reflection' attenuation. When a plane sound wave travelling along a duct sees a change in the acoustic impedance such as occurs at a room outlet, a proportion of the sound energy will be reflected back upstream, this proportion depending upon the frequency of the sound and the transverse dimensions of the duct. The greatest reflection effects, and hence attenuations, occur at low frequency and small duct dimensions, and are seen only below the cut-on frequency of the first cross mode of the duct. End reflection attenuation is useful to the engineer since it may provide high values at low frequencies which are otherwise difficult to obtain with conventional absorptive silencers and duct linings.

The data reproduced in design guides are based on empirical measurements of the reflection of sound at the open ends of circular cross section ducts, i.e. where the opening is normal to the direction of plane wave propagation. This raises three points when attempting to assess whether the data are likely to be applicable in a particular case.

Firstly, rectangular section ducts are frequently used in industry, and data obtained from tests on circular ducts may not be directly applicable here. The CIBSE Guide, which gives a graph of the data as functions of frequency and duct diameter, suggests that the equivalent diameter of a rectangular duct is 1.13 times the square root of the duct area, i.e. a simple area relationship. The ASHRAE Guide tabulates the data and refers to the 'mean duct width' without further explanation; this could account for some of the discrepancies between the CIBSE and ASHRAE data. The CIBSE and ASHRAE data are compared in Figure (1).

Secondly, the assumption that the opening is on the end of the duct is of limited value, since in practice any opening for a grille or diffuser is equally if not more likely to be in the side of the duct as on its end. Previous work by Osborne [3] suggested that the behaviour of sound at end and side openings is markedly different, and this has recently been enlarged upon by the present authors [4],[5]. The CIBSE Guide suggests that for side openings, half the value of end reflection attenuation for an open end should be applied, but gives no evidence to support the validity of this action. The ASHRAE Guide contains a note concerning the use of its tables for side openings quoting a report by Sandbakken et al [6] as the source. In essence this states that end reflection attenuation should not be applied to a side opening unless a spigot 3 to 5 duct diameters long precedes it.

Thirdly, all the values apply to openings that are not covered by any obstruction. This is not typical of current practice, where most openings are covered by grilles or diffusers either for air distribution purposes or simply for aesthetic reasons. CIBSE recommends the use of the usual table with the duct dimension established from the core area of the grille; ASHRAE is more reticent, acknowledging that the presence of an obstruction affects the value of attenuation, but failing to quantify this.

Failure of the methods suggested by the design guides and widely used in the building services industry to predict accurately duct noise levels will result in sound levels in the ventilated or air conditioned space being significantly in excess of design criteria. The reaction of many engineers will be to include a safety margin, which may result in increases in both capital and running costs of a system. The current investigation was therefore undertaken in order to assess the validity of published data in various situations.

The purpose of the investigation was initially to compare experimentally measured values of reflection coefficient for both end and side openings in rectangular ducts with those predicted by theory and to compare the resulting attenuation with published data. The second stage was to compare results for the different configurations when the openings were covered with a variety of grilles and diffusers. Previous work by the authors [4],[5] has shown that currently accepted theory does not apply to side openings. This paper confirms the findings of the previous studies and presents results for openings covered by obstructions.

EXPERIMENTAL PROCEDURE

Measurements were made using a variation of the simple impedance tube, this being a 2.4 metre length of 200 x 200 mm square section duct of rigid construction having a cut on frequency of about 850 Hz at room temperature. The sound signal was produced by a B&K Type 1022 beat frequency oscillator connected to a standard B&K Type 4002 impedance tube loudspeaker bolted to one end of the duct. Sound pressure level measurements were taken using a B&K Type 4146 12 mm microphone with probe tube connected to a B&K Type 2610 measuring amplifier and B&K Type 1615 third octave band pass filter set. Pure tone signals were used for all tests, and the sound radiated into semi-reverberant space.

The other end of the duct had an opening normal to plane wave propagation and an additional 200 x 200 mm opening cut in the side wall immediately adjacent to the end. Each opening was fitted with a cover plate which could be removed when the opening was under investigation. It should be noted that the configuration used in these tests, with the side opening immediately adjacent to the closed end, is not typical of the majority of outlets in practical systems, which of necessity will be more remote from the duct end; it does however occur frequently enough in practice to justify investigation. The experimental rig is shown diagrammatically in Figure (2).

Previous work having shown that results for the open end/closed side were completely different from those for the open side/closed end configuration, it was decided to extend the investigation to a comparison of results obtained when an opening is covered by some obstruction, as is typical in practice. The obstruction chosen for the present tests was a commercially produced 200 x 200 mm opposed blade volume control damper, as frequently used in industry. Measurements were made with the damper blades positioned both vertically and horizontally for both end and side openings. In all tests the volume control damper was fully open, i.e. the blades were parallel providing the maximum free area.

The pressure reflection coefficients were calculated from the measured maximum and minimum sound pressure levels in the duct for a range of frequencies from 150 Hz to 850 Hz, the latter being the cut on frequency of the first cross mode of the duct, and the former being chosen due to the wavelength restrictions of the 2.4 metre length of duct (i.e. the wavelength at 150 Hz is 2.3 metres). Phase differences between the incident and reflected pressure waves were also calculated for each of the frequencies used in the tests.

RESULTS

Figures (3) and (4) show the measured reflection coefficients for the two configurations compared with theoretical predictions for flanged and unflanged pipes for open ends and covered ends respectively. The theoretical curves were evaluated from the simplified theory of Kurze [7] which has been shown to be valid below the cut on frequency of the duct. The modulus of the reflection coefficient, R, is given by:

$$|R| = \left[\frac{1}{(2ka)^2 + 1} \right]^{\frac{1}{2}}$$

where $a = (S/\Omega)$ m, S being the duct cross sectional area and Ω being the solid angle into which the sound radiates, which will be 2π for a flanged duct and 4π for an unflanged duct. The transmission loss or attenuation may be expressed by:

$$\text{Attenuation} = 10 \log_{10} \frac{1}{1 - R^2} \quad \text{dB}$$

Results for the open ended duct agree closely with theory over the selected frequency range, and fall between the theoretical curves for flanged and unflanged pipes, approaching more closely the flanged condition particularly at higher frequency. Although the duct was considered to be unflanged, the presence of a small (40 mm wide) flange for fixing the end plate appears to have affected the results, and it is possible that adjacent surfaces (such as necessary supports) have also had some effect. Similar results have been previously obtained by Margetts and Gray [8].

Results for the end opening covered by the damper show lower values of reflection coefficient at low frequency (below about 350 Hz) than for the open condition, most of the data falling below the theoretical curve for a flanged pipe. At higher frequencies the values are higher than those observed for the simple open end, although the data all lie within the theoretical envelope. Comparison of the experimental data for horizontal and vertical damper blades reveals no significant difference between results.

Results for the open sided duct show no correlation with currently applied theory. At very low frequency the reflection coefficients approximate to the theoretical prediction, but at high frequency are much higher than predicted. In the frequency range 200 to 350 Hz a marked dip occurs where the reflection coefficients are much smaller than theory predicts, the lowest values occurring at around 250 Hz. Results for the covered side opening show similar patterns at low and high frequency, with values of reflection coefficient occurring in the region of the dip being slightly larger than those for the open side but still considerably smaller than those published in design guides. Again, no significant difference was noted between results for horizontal and vertical damper blades.

CONCLUSIONS

The measured results of sound pressure reflection coefficient for the open ended duct give good agreement with theory and also with the CIBSE design data. The latter gives slightly lower values, but it is possible that the CIBSE data includes the effects of a terminating grille since the present results for the end when covered by the damper show smaller reflection coefficients at low frequencies.

For an opening on the side of a duct current prediction methods do not appear to be applicable. At the lower frequencies, where the wavelengths of the sound are an order of magnitude greater than the dimensions of the opening, the open sided duct gives results agreeing fairly well with theory. Covering the opening with the damper does not appear to affect results at these frequencies.

At the higher frequencies, above about 500 Hz, where the wavelengths are small, the reflection coefficients are high and remain fairly constant with frequency. This is because the sound regards the duct as a closed tube at these frequencies, which implies that the plane wave does not see the side opening at all, and most of the sound energy is reflected back towards the source. With the damper in place, little difference was noted at these frequencies, apart from slightly higher reflection coefficients at frequencies above 700 Hz.

The dip in the mid-frequency range from 225 to 325 Hz cannot be simply explained. The low values of reflection coefficient show that most of the sound energy is emerging from the opening, which implies that the impedance seen by the sound at the opening matches that in the duct. This implies that the low impedance of the opening and the high impedance of the closed end combine to give a value similar to the duct impedance. Why this should be so is not yet clear, since the region of low reflection coefficient appears to be centred around the frequency where the dimension of the opening is about one-sixth of the wavelength of the sound, i.e. the wavelength is still relatively large compared with the dimension of the opening.

Figure (5) shows the phase relationships for the incident and reflected pressure waves for the covered openings. The curve for the end opening shows the phase difference gradually decreasing with frequency, as the impedance increases. The curve for the side opening shows interesting differences. At very low frequency where the impedance is low, the phase difference is large. At the higher frequencies, where the impedance is high due to the cover plate of the end opening, the phase difference approaches zero. In the mid-frequency range, there is a sharp change from large to small phase difference, which occurs in the region of the dip.

The application of published data to side openings could result in sound levels emitted at grilles being underestimated by around 3 dB at the lower frequencies for this size of duct. Overestimation of attenuation due to end reflection will result in room sound pressure levels being higher than predicted, and expensive remedial work may be necessary to achieve design criteria. It is therefore suggested that until further information is available no allowance should be made for end reflection attenuation where grilles are positioned on the side of ducts.

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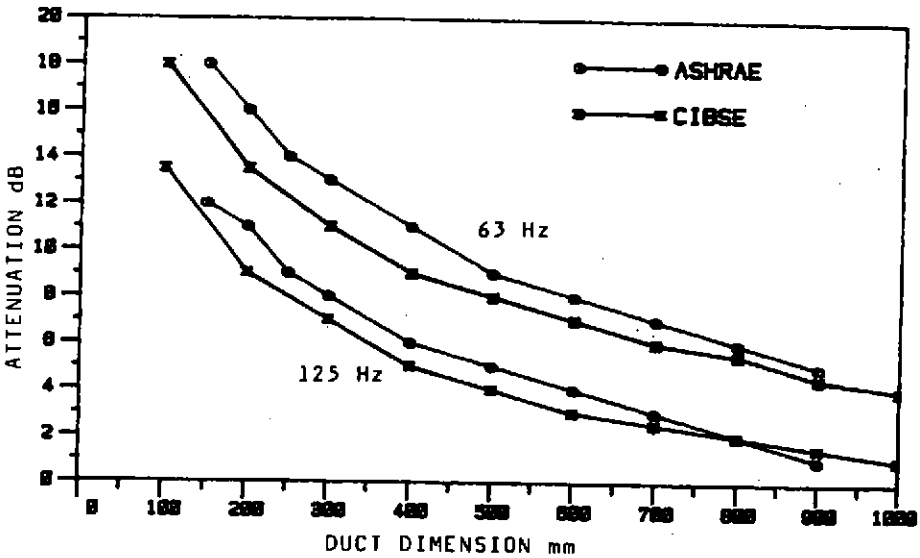

FIGURE 1 : COMPARISON OF CIBSE AND ASHRAE DATA

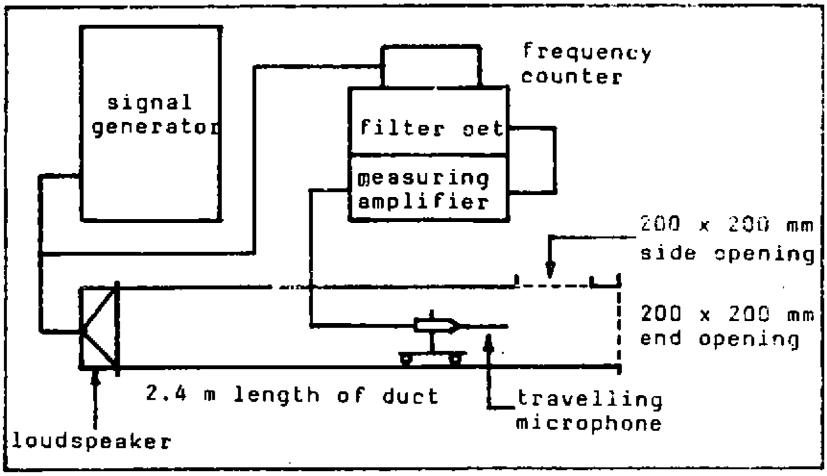

FIGURE 2 : TEST RIG AND MEASURING EQUIPMENT

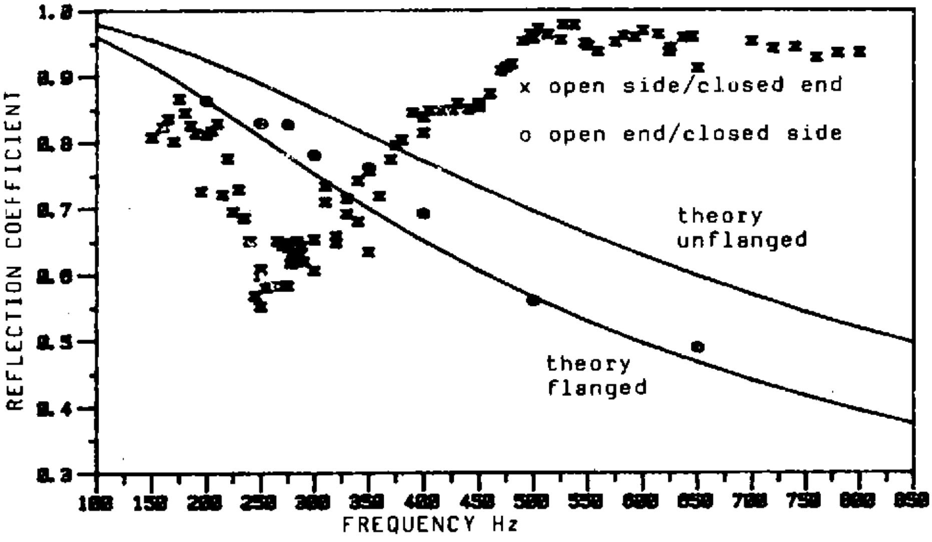

FIGURE 3 : REFLECTION COEFFICIENTS, OPEN

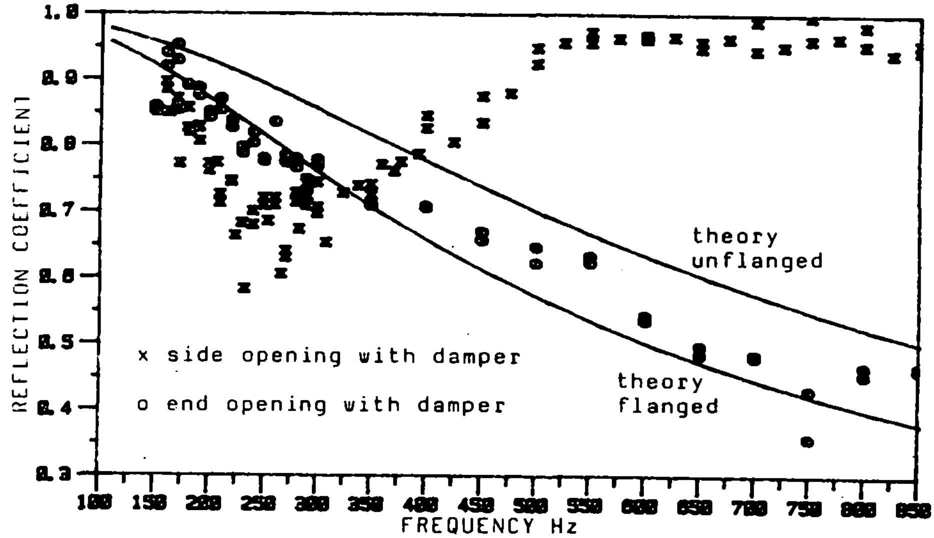

FIGURE 4 : REFLECTION COEFFICIENTS, WITH DAMPER

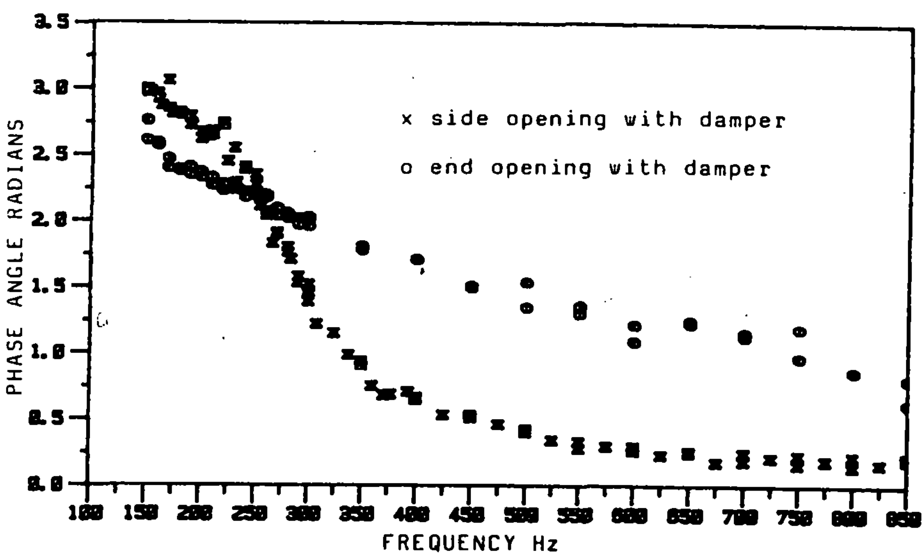

FIGURE 5 : PHASE RELATIONSHIP