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PRESSURE BASED TECHNIQUES FOR PREDICTING REGENERATED NOISE LEVELS

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High velocity ventilation systems are often plagued by excessively high noise levels as a result of interaction between the air flow and duct discontinuities. This regenerated noise would not be such a problem if it could be predicted at the design stage when suitable remedial treatment could be prescribed.

The ventilation system designer usually attempts to predict the level of regenerated noise using procedures laid down in such publications as the A.S.H.R.A.E. or CIBS Guides [1,2]. The information contained in these publications has been drawn from the published work of a number of investigators. These investigators usually worked on a limited range of in duct components and a limited range of duct sizes. Application of their results to systems often having very different configurations from those on which the original measurements were taken can produce dubious results.

A more attractive concept has been proposed by a number of researchers based upon the pressure loss caused by a particular flow spoiler. The attraction of this concept arises from the fact that the calculation of pressure drops across duct elements is commonly performed when designing a ventilation system. Thus if a pressure based technique for predicting regenerated levels noise can be evolved it would be possible to design the acoustics of a ventilation system alongside its aerodynamics.

PRESSURE BASED TECHNIQUES

A pressure based scheme for predicting the sound generated by the interaction of flow with a surface was first proposed by Iudin [3]. Iudin's work has been rather neglected and more interest has been aroused by the work of Gordon [4]. Gordon investigated the sound power generated by a variety of spoilers inserted close to the end of a pipe carrying high velocity air flow.

There are a number of reasons, however, why Gordon's work cannot be applied to predict regenerated noise in ventilation systems. They relate primarily to the experimental set up that he employed in his work. Gordon was interested in noise problems associated with aircraft engines and as a result worked at air velocities and with pressure drops across spoilers well in excess of those encountered in ventilation systems. He was also interested in the effect of a spoiler situated close to the end of a pipe i.e. close to the exhaust of a jet engine. A typical spoiler encountered in a ventilation system would be found immersed well inside a duct run.

Recently Nelson and Morfey have investigated aerodynamic sound production in low speed flow ducts [5]. In developing their theory Nelson and Morfey took into account the effect of the duct environment on the generation of noise.

The basis of the Nelson and Morfey theory is that the sound power radiated by an in-duct spoiler is related to the total fluctuating drag force acting on the spoiler. They further make the assumption that the fluctuating drag force is in direct proportion to the steady drag force. This is the same assumption that Gordon made in devising his theory and its validity has been confirmed by the experiments of Heller and Widnall [6]. The collapse of the experimental data into a generalised spectrum is achieved by the empirical evaluation of the constant of proportionality between the fluctuating and steady drag forces.

Nelson and Morfey give the following equations for the induct sound power level, SWL_D:

$$(f_c < f_o) \qquad 120 + 20 \log_{10} K(S_T) = SWL_D - 10 \log_{10} [\rho_o A \{\sigma^2(1-\sigma)\}^2 C_D^2 U_c^4 / 16 c_o] \qquad (1)$$

$$(f_c > f_o) \qquad 120 + 20 \log_{10} K(S_T) = SWL_D - 10 \log_{10} \rho_o \pi A^2 (S_T)^2 [\sigma^2(1-\sigma)]^2 C_D^2 U_c^6 / 24 c_o^3 d^2 - 10 \log_{10} 1 + (3\pi c_o / 4\omega_c)(A/(a+b) \qquad (2)$$

The Strouhal number, S_T, was determined by $S_T = f_c d/U_c$. The value of U_c used was determined from $U_c = (q/A_c)$ where q is the volume flow rate and A_c is the area of cross section of duct construction. The value of d used was always the spoiler width. C_D is the spoiler drag coefficient given by:

$$C_D = \bar{F}_3/(\tfrac{1}{2} \rho_o U_c^2 \sigma^2 A(1-\sigma)) \qquad (3)$$

where σ is the open area ratio A_c/A and A is the duct cross sectional area.

These equations formed the basis for the collapse of the experimental data of Nelson and Morfey. All terms on the right hand side of equations (1) and (2) are measurable variables or constants and the value of this expression can thus be evaluated to yield $20 \log_{10} K(S_T)$.

APPLICATION OF THE NELSON-MORFEY WORK TO OTHER SPOILER CONFIGURATIONS

The equations presented by Nelson and Morfey were developed from a rigorous analysis of the mechanisms of in-duct spoiler generated noise. The experimental results presented by Nelson and Morfey, however, were obtained using a very simple type of spoiler which cannot easily be related to typical elements found in real ventilation systems. The remainder of this paper describes an attempt made to assess the validity of the Nelson and Morfey equations when applied to spoiler configurations differing from those employed in their work.

Nelson and Morfey measured the sound power generated by flat plate flow spoilers. Some of the spoilers were vertical strips of plate placed centrally in the air stream and others consisted of plates protruding symmetrically from both sides of the duct leaving vertical strips of the ducts open. For their experiments they employed square section ductwork.

With an in-duct spoiler of this type the value of the open area ratio, σ, and the representative dimension, d, can be easily determined. The representative dimensions used by Nelson and Morfey was the spoiler width since the height was always equal to the duct height. In order to apply the theory of Nelson and Morfey to other duct obstructions, however, it is necessary to be able to determine the appropriate values of σ and d. For obstructions other than flat plate spoilers in a square duct or for any obstruction in a circular duct the values of σ and d cannot be determined from an inspection of the geometry of the situation.

Determination of the open area ratio

An approximate value of the open area ratio σ can be obtained from the measurement of the static pressure drop across the element.

Figure 1 shows a schematic of flow patterns in a duct containing a spoiler. For simplifying the problem the following assumptions can be made:

i) The spoiler may be considered to be a simple constriction in the duct (i.e. orifice)

ii) The static pressure at a plane sufficiently far upstream of the spoiler is constant across the duct (Plane 1; static pressure = P_1, flow area = A).

iii) The static pressure in a plane just downstream of the spoiler is constant across the duct (Plane 2, static pressure P_2, flow area A_c).

iv) Static pressure is recovered and that this recovery is represented by a static pressure P_3 constant over flow area A (plane 3).

From application of Bernoulli's equation and the law of conservation of momentum it can be shown that

$$\sigma = \frac{C_L - 1}{C_L - 1} \qquad (4)$$

The maximum effective velocity is given by

$$U_c = U/\sigma \qquad (5)$$

The static pressure loss can be determined from measuring the pressure difference between two points, one upstream of the spoiler and one downstream. Points should be selected at which the flow is not strongly affected by the spoiler. In this work pressure tapping points one duct diameter upstream and three duct diameter downstream fulfilled this criterion.

Determination of the representative dimension

In order to apply the Nelson and Morfey predictive technique to other in-duct elements it is necessary to be able to determine an appropriate value for the representative dimensions used to calculate the Strouhal Number.

Gordon [4] used the projected width of the flow spoiler (i.e. the wake thickness). The choice of this dimension arises from the simple configurations of spoilers that he employed and consideration of the well known relationship between Strouhal number, frequency of vortex formation, air velocity and diameter for a cylinder perpendicular to an air stream in free space. Similarly for the strip spoilers employed in Nelson and Morfey's experiments the value of d could be obtained by inspection [5].

In this work a value of d was estimated from an examination of the geometry of the situation and the simplified representation described in the previous section.

The first stage involved the classification of in-duct elements as either strip-like or orifice plate-like. For example, a damper would be considered strip-like whilst a bend would be considered orifice plate-like.

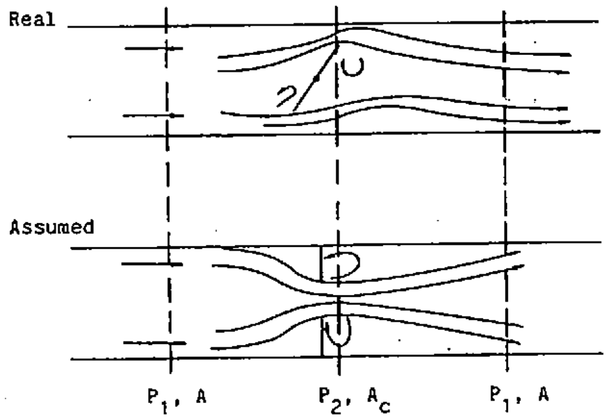

Fig. 1 The Flow Pattern

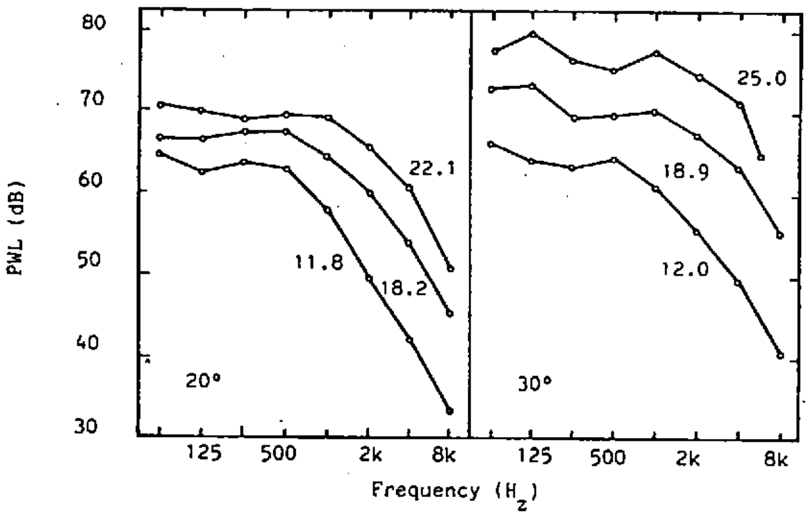

Fig. 2 Sound Power Spectra for different air velocities

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For a strip-like spoiler the representative dimension is given by:

$$d = A(1 - \sigma)/w \qquad (6)$$

where w is the duct width in the direction along which the spoiler lies.

For an orifice plate-like spoiler it is given by:

$$d = w(1 - \sigma^{\frac{1}{2}}) \qquad (7)$$

In this case w is the duct width in the direction other than that in which the flow is constricted for obstructions in which the constriction is primarily in one direction (e.g. bends). For obstructions in which the flow is constricted in both cross duct directions, w is the mean of the two directions.

EXPERIMENTAL PROCEDURE

The experimental rig

Air flow to the test spoiler was provided by a centrifugal fan and the flow rate was adjusted by a combination of flow adjusting damper and a branching duct. A novel feature of the rig was the use of a large anechoic chamber as a plenum silencer. The anechoic chamber was pressurised by the fan with air escaping via the test section of ductwork. The inlet to the test section consisted of a bell mouth followed by a section of egg crate flow straightener. This arrangement yielded a quiet, fully developed turbulent flow at the test piece which was situated approximately 5 metres from the duct entrance section.

The test duct extended through into a reverberation chamber and was terminated with an exponential horn to reduce the problem of sound reflection at the duct end. The reverberation chamber was provided with wide section outlet which allowed air to escape without the generation of noise.

The ductwork was circular in cross section having a diameter of 300 mm and manufactured from high density polypropylene. Circular ductwork was employed as this facilitated the alignment of sub-sections. Dense polypropylene was selected as the material from which the duct was constructed to reduce the problem of noise breakout from duct walls into the reverberation chamber.

In order that a large number of spoiler configurations could be studied over a reasonable period of time a single vane damper was employed as the spoiler. The configuration of this spoiler could be changed merely by altering the damper angle.

Measurements of airflow and pressure loss

The velocity of the air flowing through the duct was measured using a Setra pressure transducer and a digital voltmeter connected to a microcomputer via the IEEE 488 Bus. The pressure transducer measured the drop in static pressure across a 2 metre section of straight ductwork in a region where the flow was judged to be fully developed. The pressure transducer was calibrated by plotting its output voltage against the mean duct velocity obtained using a standard test procedure (BS 848 1966).

The static pressure drop across the spoilers was measured using an inclined manometer connected between an upstream and a downstream pressure tapping point. The pressure tapping points were selected so that they were not in the immediate pressure field of the spoiler. The pressure tapping points should not be so far apart, however, that the static pressure loss associated with the fluid friction at the walls of the duct is comparable to that across the

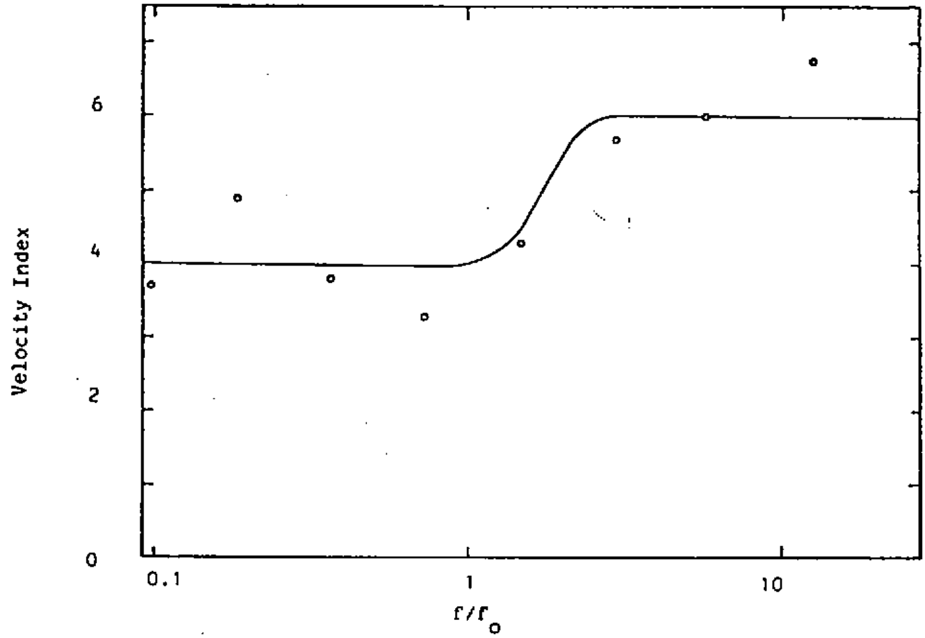

Fig. 3 Velocity Index

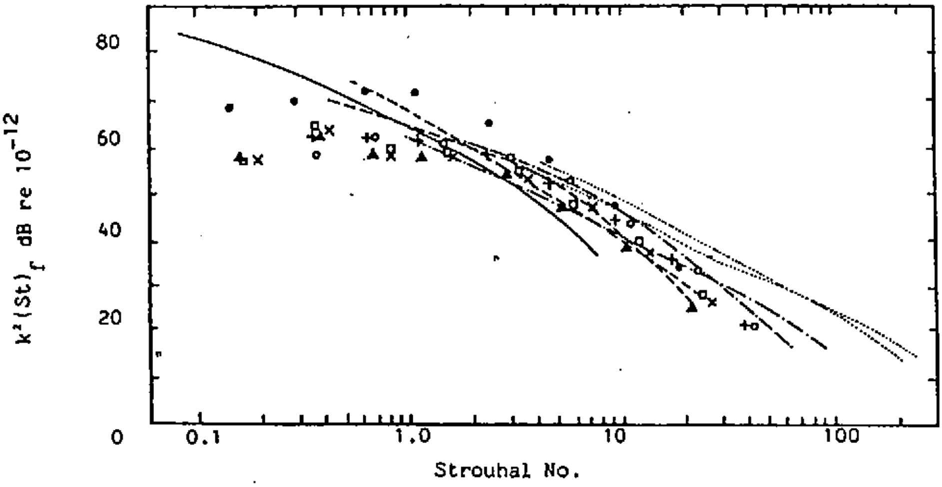

Fig. 4 Collapse of Data

spoiler. It was established by means of a series of measurements on different spoiler geometries that a tapping point situated one duct diameter upstream and a tapping point situated three duct diameters downstream of the spoiler yielded an accurate value of the static pressure loss due to the spoiler.

Acoustic measurements

The sound pressure level of the sound radiated from the duct exit was measured in a reverberation chamber of volume 214 m^3. The sound power radiated was calculated from the following relationship

$$SWL = SPL + 10 \log_{10} V - 10 \log_{10} T - 14 \qquad (8)$$

where V is the volume of the reverberation chamber, T is the reverberation time and SPL is the space averaged sound pressure level in the chamber.

The average sound pressure level was measured by reading the level at eight microphone positions in the room using a B&K Type 2131 Digital Frequency Analyser. This was connected to the same micro-computer as the pressure transducer DVM. With this arrangement the space averaged sound pressure level and duct air velocity could be rapidly determined. Each reading of sound pressure level was time averaged over an eight second integration period. The sound pressure level readings were then averaged and the mean and standard deviation calculated.

EXPERIMENTAL RESULTS

Dampers

Figure 2 shows the sound power level spectra measured for single vane dampers inclined at 20° and 30° for a range of air velocities. It can be seen from an examination of these figures that the shape of the spectra are similar.

The experimental points are the mean of eight readings and the "error bars" shown in the figures are ± one standard deviation.

Figure 3 shows a plot of the velocity index determined from the above data plotted against the ratio of octave band centre frequency to duct cut on frequency. The transition from a V^4 dependence of sound power below the cut on frequency to a V^6 dependance above the critical frequency can be clearly seen. This is in agreement with the theoretical predictions of both Nelson and Morfey [5] and Davies and Ffowcs-Williams [7].

Figure 4 shows a collapse of the experimental data on the basis of equations (1) and (2). Also shown in this figure are the trend lines given by Nelson and Morfey [5].

The majority of the data points obtained in the course of the experiments described in this work can be seen to lie within the range of trend lines given by Nelson and Morfey. There is a systematic deviation away from these trend lines for Strouhal numbers less than unity.

CONCLUSIONS

The predictive method given by Nelson and Morfey has been tested against measurements made on in-duct elements differing from those used in the course of their experiments and for ducts of circular cross section. In order to employ their predictive equations for in-duct elements other than simple strip spoilers it has been necessary to devise a method of estimating the duct clear area ratio in the vicinity of the spoiler and also the characteristic dimensions for use in the calculation of Strouhal Number. The collapse of the data obtained using dampers and as spoilers is similar to that observed by Nelson and Morfey with simple strip spoilers.

It is suggested that the trend lines reported in this work together with the method of determining values for clear area ratio and characteristic dimensions could provide the basis of a generalised predictive technique. Further work is now necessary to extend the study to duct elements such as bends and transition pieces.

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