THE APPLICATION OF ACOUSTIC TECHNIQUES TO THE COMMISSIONING AND CONTROL OF MECHANICAL VENTILATION SYSTEMS

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In-duct obstructions affect both the flow of air and the propagation of sound in a duct resulting in a loss of static pressure and the reflection of an acoustic wave travelling down the duct. In this paper the existence of a simple relationship between the pressure loss coefficient and the acoustic reflection coefficient is demonstrated. It is suggested that this relationship could form the basis of a technique for the commissioning and/or control of a mechanical ventilation system. It is shown that the acoustic reflection coefficient can be determined by computer modelling. Thus it may be possible to acquire the data base of acoustic characteristics of in-duct elements necessary for the application of this technique without the need for expensive physical measurements.

1. INTRODUCTION

Obstructions or other discontinuities in a duct affect both the flow of air and the propagation of sound along the duct. With regard to the effect on air flow, the obstruction will cause a loss of pressure. The larger the obstruction, the larger will be the drop in pressure. With regard to sound travelling along the duct, an obstruction or other discontinuity will be perceived as a change in acoustic impedance. An acoustic wave travelling along a duct will be partially reflected at an impedance boundary. The larger the obstruction, the larger will be the acoustic impedance change and the larger will be the fraction of sound energy that is reflected.

The determination of the relationship between acoustic impedance and pressure loss is the basis of the proposed technique. In the case of an element in which the degree of obstruction is varied to control air flow, the impedance will also vary for different settings. It is this variation of impedance with degree of obstruction which, in principle, means that an acoustic technique could form the basis of a technique of establishing static pressure losses in a ventilation system. This information could be used as the basis of commissioning and/or control techniques.

Commissioning (essentially balancing the airflow throughout the system) and testing for leaks of large ventilation systems is a tedious and time consuming task. Frequently this takes place towards the very end of the construction process under pressure of time and is rushed and often inadequately carried out [1-4]. An acoustic technique capable of rapidly establishing the pressure losses throughout the system from readings taken at a limited number of positions could save much time and effort.

Acoustic control could also be used to adapt the system to changing conditions. This would be especially important in variable air volume (VAV) systems where static pressure control via a PI element controls the fan. Such a control depends on selection of the control set point which designers and commissioning engineers determine empirically on site. Other methods, such as polling of individual boxes, is more complex and relies on feedback via BEM's outstations on local bus networks. This is expensive as many office buildings with VAV (ceiling or displacement) can have hundreds of boxes.

2. ACOUSTIC MONITORING OF THE DUCT SYSTEM

In order to monitor the state of the elements in a duct system it is necessary to measure continuously the impedance of each element. The basis of the proposed method is the determination of the impulse response of the system. The direct determination of the impulse response involves the generation of a short duration high intensity pulse and the recording of the time history at some point in the duct. The time history consists of a sequence of pulses resulting from reflections of the original pulse at duct discontinuities and the arrival time of a particular pulse depends upon the distance it has travelled and its shape is determined by the impedances of each discontinuity that it has encountered. An individual pulse can be "windowed" and fourier transformed in order to yield spectral information from which the acoustic impedance of the reflecting elements can be determined.

The same information can be obtained by injecting "white noise" (a pseudo random sequence) and by performing a cross correlation of the source signal and the signal picked up at a microphone in the duct. This technique has the advantage of being less intrusive than a true impulse as it is possible by time averaging to work with a low signal level even in the presence of noise.

3. EXPERIMENTAL DETERMINATION OF THE RELATIONSHIP BETWEEN THE PRESSURE LOSS AND ACOUSTIC IMPEDANCE

The first stage in this work was an investigation of the relationship between the pressure loss and acoustic impedance of in-duct elements for a variety of different duct components and configurations. An acoustic and ventilation rig was constructed and commissioned for the experimental work. Because of the limitations of laboratory space, the duct work system employed was of smaller section than that typically encountered in large ventilation systems so that the experimental work was essentially a scale model study. The scale factor was, however, relatively large (of the order of 1:4) and the relevant scaling law is very simple (the maintenance of a constant ratio of duct dimension to acoustic wavelength) so this presented no problems. At the frequencies employed the effect of excessive air absorption was not significant.

Initial work was concentrated on very simple in-duct elements such as orifice plates, dampers and strip spoilers. These simple elements were employed because they enabled a variety of configurations to be rapidly investigated The acoustic measurements were made using pseudo random noise and cross correlation employing a commercially available system (MLSSA) housed in a host PC to obtain the impulse response.

Figure 1 shows a typical time history and it can be seen that the pulses resulting from reflections at duct discontinuities can be clearly distinguished. The impulses due to reflection from a particular discontinuity were windowed, fourier transformed and compared with the fourier transform of the incident impulse to yield the acoustic reflection coefficient as a function of frequency.

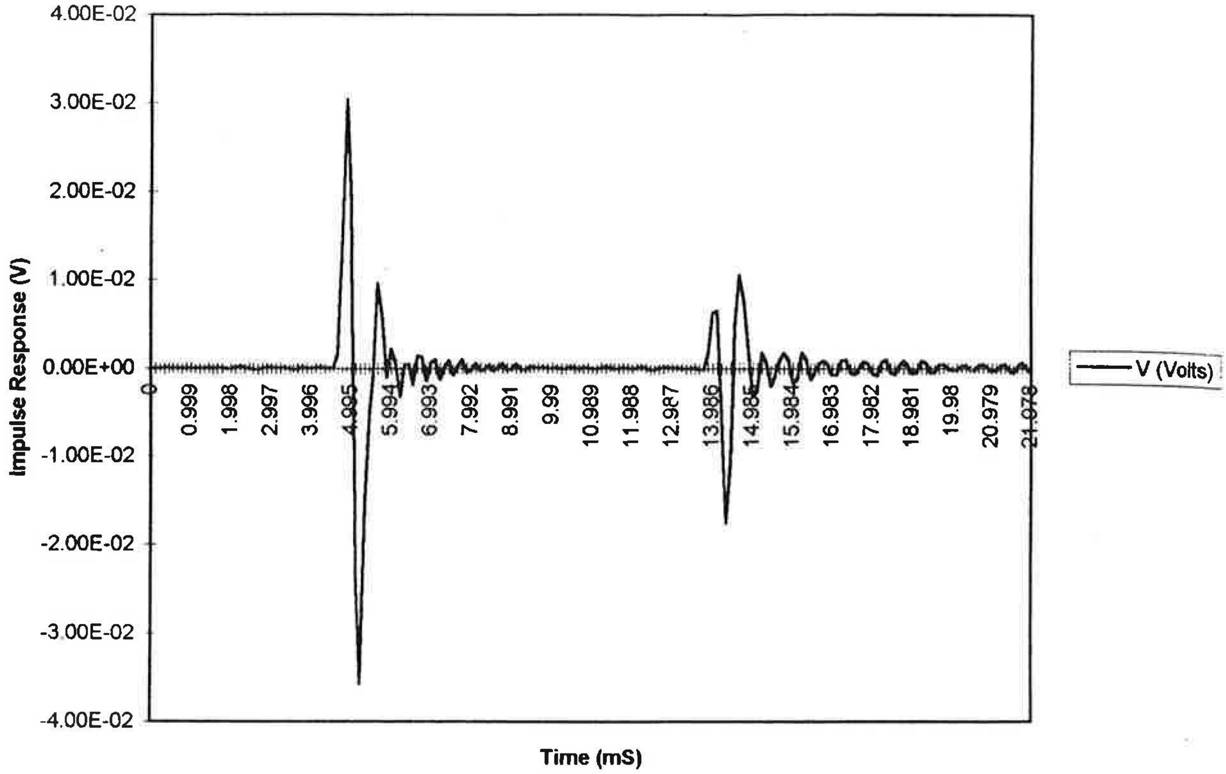

Figure 1 Impulse Response for Angled Spoiler in 100mm Diameter Circular Duct

Figure 2 shows the variation of the acoustic reflection coefficient of a simple damper as a function of frequency for different damper angles. It can be seen that the acoustic reflection coefficient at a given frequency increases with increasing damper angle.

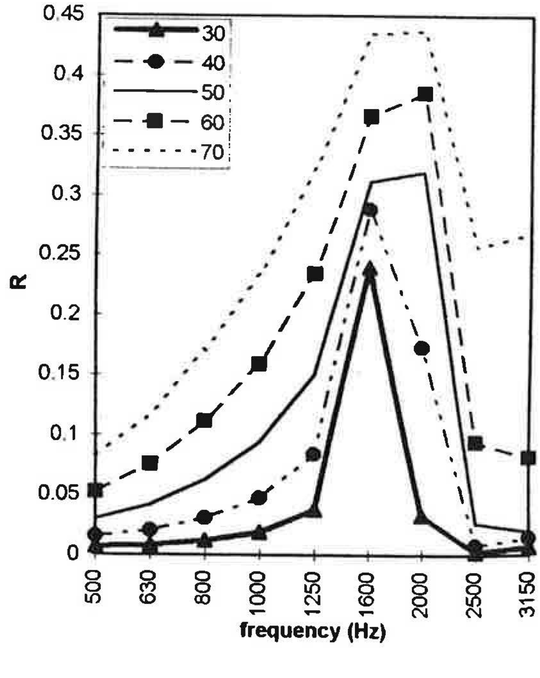

Figure 2 Reflection Coefficient of Angled Spoiler in 100mm Diameter Duct for Different Inclinations

Sound propagation in a duct is characterised by the cut on frequency. Below this frequency, which corresponds to that for which the duct cross sectional dimension is equal to one half wavelength, sound can only propagate in the form of a plane wave. Above this frequency sound can propagate via cross modes. For a particular damper angle, the acoustic reflection coefficient increases with frequency until the duct cut on frequency beyond which its magnitude decreases. This behavior was observed for all duct discontinuities investigated. This suggests that sufficient information regarding the state of a duct discontinuity can be obtained when working with frequencies below the duct cut on frequency.

Limiting the range of frequencies employed to those below the cut on frequency has a number of benefits for any proposed commissioning or control system. The first is that the problem of dispersion, resulting in a smearing of the acoustic pulse in the time domain, which would be experienced for frequencies above the cut on frequency is avoided. The second is that the positioning of a microphone in the duct is less critical. The third is that it will only be necessary to acquire data over a limited range of frequencies thus high frequency noise can be filtered out with a resulting improvement in the signal to noise ratio. Finally, any absorptive lining applied in the duct system will tend to reduce the high frequency sound rather than the low frequencies and will thus not appreciably reduce the amplitude of the measurement signal.

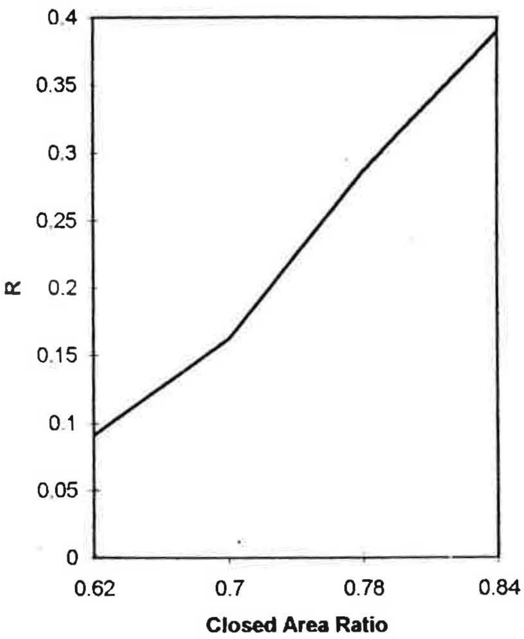

Figure 3 **Reflection Coefficient as a Function of Closed Area Ratio for Orifice Plates in 100 mm Diameter Duct**

Figure 3 shows the acoustic reflection coefficient plotted against the closed area ratio for orifice plates of different diameters. There is strong correlation between the two parameters over a range of values. For the inclined damper the sine of the angle of inclination determines the closed area ratio and good correlation was also observed when this parameter was plotted against acoustic reflection coefficient. This suggests that this technique could be employed to determine the blockage factor due to an in-duct obstruction.

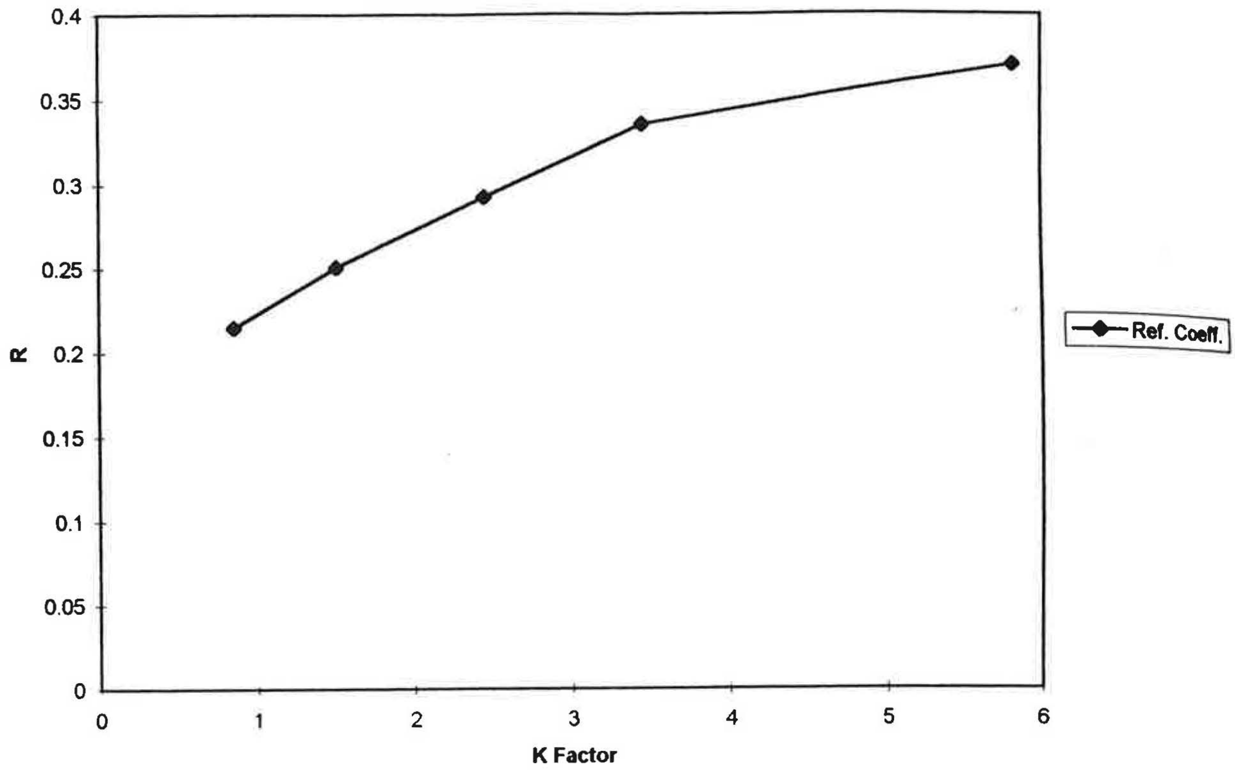

Figure 4 **Reflection Coefficient, R, as a Function of k Factor for Angled Spoiler in 100mm Duct**

Excellent correlation has been found between the acoustic reflection and pressure loss coefficients measured on the rig for a range of orifice plates and butterfly damper settings. Figure 4 shows the results obtained for the angled spoiler for a number of different angles of inclination.

In order to investigate the effect of factors likely to be encountered in real duct systems, the MLSSA measurements were repeated with varying levels of background noise injected into the duct and under conditions of airflow in the duct. It was important to establish the effect of these factors if the technique is to be employed for control purposes as both airflow and noise will be encountered in working systems. As expected background noise levels presented no problems that could not be overcome by increased averaging time. Perhaps more unexpectedly the effect of high velocity airflow in the duct had only a slight effect on the measured reflection coefficient of in duct elements.

4. DETERMINATION OF ACOUSTIC IMPEDANCE AND PRESSURE LOSS CHARACTERISTICS BY COMPUTER MODELLING

A completely experimental determination of the pressure losses and acoustic impedances of all duct elements would be impossible as it would require the construction of a large number of experimental rigs or measurements on existing systems. An investigation was therefore undertaken to establish if the acoustic reflection coefficient of typical duct elements could be determined using computer methods and thus avoid the need for expensive laboratory measurements.

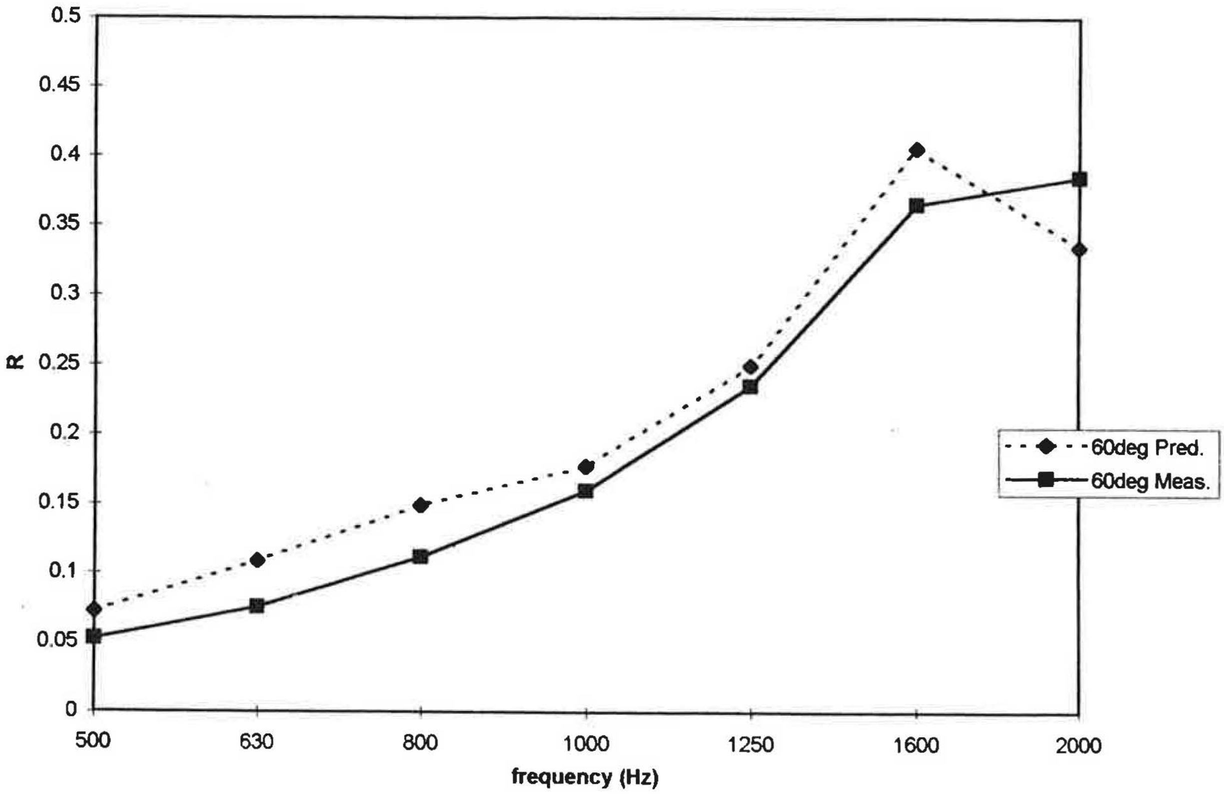

Figure 5 **Comparison of Predicted and Measured Reflection Coefficients for Angled Spoiler in 100mm Diameter Duct**

Good correlation has been observed between the measured acoustic reflection coefficient and that found by application of the SYSNOISE Boundary Element software package for a range of orifice plates and different damper settings. Figure 5 shows a comparison between measured acoustic reflection characteristics and those predicted using SYSNOISE. With regard to the pressure loss coefficient, a team at Nottingham University, under the direction of Professor Riffat, is engaged in a major study of employing computer methods for the determination of pressure loss coefficients of in duct elements and has published a number of papers which suggest that this is feasible [5].

5. CONCLUSIONS

The pilot project described in this paper has demonstrated the existence of good correlation between acoustic reflection and pressure loss coefficients. for a range of orifice plates and butterfly damper settings. The correlation is strongest for frequencies below the duct cut on frequency. The work with the Boundary Element software has demonstrated that this technique can be employed to determine acoustic reflection coefficients thus obviating the need for physical measurements. The work of Professor Riffat's team has established that the application of Computational Fluid Dynamics software can provide information on pressure loss coefficients without the need for aerodynamic measurements.

Further work is now needed to establish if the technique can be employed in practical systems in which the large number of reflections could result in overlapping pulses. It is thus necessary to investigate the efficiency of advanced signal processing techniques, such as cepstrum analysis, employed to separate overlapping acoustic pulses.

In order for the technique to be applied in control systems it would be necessary for the state of all variables to be continuously monitored. For control purposes a system is required which performs a moving average and continuously outputs the results so that the change in state of a variable can be determined. The response time of the measurement system to a change in state is critical to the performance of a control system. With regard to the proposed technique, the response time will be a function of the number of samples employed for the moving average and this will be determined by the level of noise in the system relative to the applied maximum length signal and the airflow in the system. There is thus the need for a systematic study of the effect of the above parameters on the response time.

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