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SENSOR POSITIONING IN ACTIVE DUCT SILENCERS

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INTRODUCTION

Splitter silencers for use in air-handling systems are known to be ineffective at attenuating low-frequency noise. As a consequence of this, a great deal of interest is now being shown in the development of active noise control (ANC) systems, which have the potential to provide substantial low-frequency attenuation without the cost, bulk and pressure losses associated with splitters.

When an active attenuator is installed in a duct, the position of the sensing microphone, which forms part of such a system, is critical in obtaining optimum performance. In this paper, two of the criteria affecting the choice of microphone position are examined. The first relates to the effects of the duct walls and of longitudinal reflections on the acoustic feedback path from the antisource loudspeaker to the sensing microphone. The second aspect concerns the generation of noise at the microphone due to local turbulent flow. Experiments have been carried out to determine the best microphone position in respect of the duct acoustics and the results have been critically assessed with regard to the criteria for minimum flow noise. The work was carried out on an ANC system of the monopole type [1], such as that illustrated in Figure 1.

OPEN AND CLOSED LOOP TRANSFER FUNCTIONS

The monopole attenuator can be represented by the block diagram of Figure 2, where:

- P_{in} is the acoustic pressure at the microphone due to the unwanted noise,
- P_{ls} is the acoustic pressure output from the antisource loudspeaker,
- $H(s)_f$ is the lumped forward ('straight') transfer function of the microphone, pre-amplifier, compensating network, inverting power amplifier and loudspeaker/duct combination.

The acoustic feedback path is a simple time delay of T seconds, being the propagation time for a plane wave travelling from the antisource to the microphone. It is assumed that the incident acoustic field has a negligible effect on the radiation properties of the loudspeaker.

The closed loop transfer function $H(s)_c$ is the ratio of output to input with the feedback loop closed:

$$H(s)_c = \frac{P_{ls}}{P_{in}} \qquad (1)$$

Complete cancellation of source noise is achieved when the magnitude of $H(s)_c$ is unity and its phase is 180°. It is not practical to directly measure $H(s)_c$, since the total acoustic pressure at the microphone is the sum of P_{ls} and P_{in}, but the open loop transfer function can easily be measured. However, because of the complexity of the transfer function of the loudspeaker/duct combination, the attenuation of the system cannot easily be predicted from the open loop transfer function. Nevertheless it does yield useful information concerning the stability of the system, and the optimum values of open loop gain and phase can be estimated for an attenuating system.

The requirement for the loop to remain stable at all frequencies is that the open loop gain $H(s)_f$ should be smaller than unity when the loop phase is 0° or a multiple of 360° (The Nyquist criterion). The feedback equation gives the relationship between open and closed loop transfer functions:

$$H(s)_c = \frac{H(s)_f}{1-H(s)_f \cdot e^{-sT}} \qquad (2)$$

The total acoustic pressure P_{out} downstream of the system is the sum of the incident noise and the output from the antisource, taking into account the time delay:

$$P_{out} = P_{ls} + P_{in} \cdot e^{-sT} \qquad (3)$$

Complete cancellation of the source noise occurs if $P_{out} = 0$. So for cancellation,

$$P_{ls} = -P_{in} \cdot e^{-sT} \qquad (4)$$

Then the closed loop transfer function becomes $H(s)_c = -e^{-sT}$ which substituted into equation (2) gives the open loop transfer function under conditions of complete cancellation

$$H(s)_f = \frac{1}{e^{-sT}-e^{sT}} \qquad (5)$$

This can be expanded using the MacLaurin series to give

$$H(s)_f = \frac{1-sT+s^2T^2/2! - \ldots}{-2sT+4s^2T^2/2! - \ldots} \qquad (6)$$

Then for a monopole system with the microphone close to the antisource [1], T tends to zero and the forward transfer function tends to $-\infty$. Thus the requirement for complete attenuation by such a monopole is that the forward gain should be infinite, hence that the forward phase should be 90° or −270°. Experimental results confirm that attenuation is obtained: 1) if the gain is high, for all values of phase in the first and second quadrants; 2) if the phase is close to 90°, for all non-zero values of gain.

ATTENUATION AS A FUNCTION OF LOOP GAIN

In practice, the gain in the feedback loop is limited by stability requirements. It is, however, possible to calculate the attenuation that can be obtained for a given value of gain for a monopole in which the time delay in the acoustic feedback path is zero.

The attenuation in decibels is defined as:

$$A = 20 \operatorname{Log}_{10} (P_{in}/P_{out}) \qquad (7)$$

where P_{out} is the sum of the incident noise and the acoustic output from the antisource loudspeaker,

SENSOR POSITIONING IN ACTIVE DUCT SILENCERS

$$P_{out} = P_{in} + P_{1s} \tag{8}$$

and from Figure 2

$$P_{1s} = H(s)_f(P_{1s} + P_{in}) \tag{9}$$

Combining equations (7),(8) and (9) and rearranging gives

$$A = 20 \log_{10}(1-H(s)_f) \tag{10}$$

A simplifying assumption has been made; $H(s)_f$ is a complex variable that can be regarded as consisting of a gain and phase angle for each frequency. If however we assume that the phase around the loop is 180° for all frequencies of interest, we can regard H as a real number and treat it as a product of a constant C (which, because of the phase inversion, must be negative) and of a real variable R which we will call the relative gain. To discover whether equation (10) can be applied to finite bandwidth systems, the constant C can be evaluated experimentally by measuring the attenuation as the relative gain R (in this case the gain of the power amplifier of Figure 1) is varied and then applying equation (10). It has been found that a consistent value of C exists for a large range of gains, demonstrating that equation (10) can be applied to broadband attenuating systems.

Figure 3 shows the attenuation as a function of gain, as calculated using equation (10). On this are superimposed experimentally determined values. It is clear that for good attenuation, the highest value of forward gain consistent with system stability is desirable. One factor that governs the gain available is the position of the sensing microphone, which must be chosen with regard to two criteria; flow noise and the duct acoustic.

FLOW NOISE

Airflow velocities in air-conditioning ducts are typically in the range 5-20 m/s, which for standard duct dimensions gives Reynolds numbers of the order of 10^5. Hence the flow is completely turbulent, and the microphone detects two pressure signals; the propagating acoustic signal to be cancelled and the flow noise caused by turbulent flow over the microphone. These two signals are indistinguishable to a single microphone, and unless then sensing microphone of an active attenuator is screened from flow the result is a serious deterioration in attenuator performance as the anti-source emits an amplified version of the flow noise.

Without a silent source of high-speed flow it has been found difficult to assess the effectiveness of flow screens in ducts [2]. However, it has been found that conventional wind screens and nose cones do not attenuate the flow noise sufficiently for this application. Turbulence screens of the sampling tube variety give greater flow noise rejection, but their dimensions are such that a sensing microphone thus screened would effectively become a distributed sensor, so making it unsuitable for active attenuation. Sampling tubes also have a significant effect on the sensitivity, phase response and directionality of microphones [3]; in particular, longitudinal modes inside the sampling tube can cause instability in the attenuator feedback loop.

Shepherd, Cabelli and LaFontaine have shown that the best active attenuation of a single frequency that can be achieved in ideal conditions is to 3 dB below the level of turbulent noise detected by the sensing microphone [4]. Research is currently being carried out to eliminate the turbulent noise using signal correlation techniques between several microphones. This is possible because turbulent signals detected by two microphones a small distance apart are uncorrelated, while acoustic components are correlated.

It should be noted that techniques such as those used for the determination of sound intensity in flow [5] cannot be used as these involve integration over a period of time, whereas an active attenuator relies on instantaneous information.

Preliminary experiments have indicated that a simple solution to the problem of turbulent flow noise exists and that attenuation can be achieved in a duct with airflow when the microphone is flush-mounted in the duct wall. The result of reference 4 would still apply however, and for a broadband system the minimum residual noise would still be governed by the flow noise at the microphone.

INFLUENCE OF DUCT ACOUSTICS

An oversimplified view is often taken of the behaviour of the duct acoustic below the lowest cut-on frequency. In this region, where ANC systems are most effective, sound propagation is normally assumed to be by axial plane waves only, but evanescent non-axial waves also exist below the cut-on frequency. These are attenuated exponentially with distance [6] so that their effect is negligible provided that the distance between antisource loudspeaker and the sensing microphone is significantly greater than the cross-sectional dimensions of the duct. When the sensing microphone is close to the loudspeaker however, these low frequency evanescent modes are significant and the three dimensional acoustic field must be considered.

Although ANC systems may be designed to operate at low frequencies, they are intrinsically broadband systems and so are affected by the duct acoustic at higher frequencies. In particular the cross modes cause large changes of phase and gain in the acoustic feedback path, and these can create problems of instability in the ANC system. The severity of these duct resonances can to some extent be reduced by introducing passive absorption close to the sensing microphone. This is not effective for low-frequency resonances, so it is also advantageous to position the microphone where it will be least affected by these.

A further complication is that longitudinal modes are set up between the ends of the duct, and between the antisource and each end of the duct. The antisource itself behaves as an open-ended duct termination for these modes [7] and further modes can exist due to bends, discontinuities or obstructions in the duct. These result in sharp irregularities in the forward transfer function of the system, which can cause the feedback loop to become unstable.

EXPERIMENTAL PROCEDURE

The duct used for the experiment had a square cross-section of side 35 cm. This gave degenerate cross-modes at 490 Hz and multiples thereof. The experiments were carried out without absorbent material in the duct, but the results are only shown between 0-2000 Hz, as in systems with passive absorption the gain would be below 0 dB above this frequency range.

Using the experimental apparatus shown in Figure 4, the open-loop transfer function of the system was measured for a number of positions of the sensing microphone. Prior to the measurements being taken, the system was set up to give optimum attenuation with the microphone at the centre of the duct; the system's amplifier and integrator settings being left unchanged for the other microphone positions. The results for some of the more interesting microphone positions assessed are described below.

RESULTS

Previous experiments had confirmed that in the absence of airflow, a monopole attenuator with the microphone at position 1 (Figure 5) gave the best attenuation. This is because the effect of non-axial waves is a minimum at the centre of the duct [7]. Conversely, a microphone at position 3 would be at a pressure maximum for all cross modes in both horizontal and vertical directions. However in this position it has the advantage of being more easily screened from flow induced noise.

Figure 6 shows the results for position 1. It is clear that the loop is stable, as the gain is below 0 dB at all frequencies at which the phase crosses zero. The only areas of high gain are below 200 Hz (where the system gave good attenuation) and at 1415 Hz. The latter is caused by the irregular free-field response of the antisource loudspeaker, but in this case occurs at a phase of 180° so that the system remains stable. It should however be remembered that in other ducts the phase may be different.

Figure 7 shows the open loop transfer function with the microphone in position 2, that is in the centre of the top surface of the duct. For ease of comparison, the corresponding result for position 1 is shown dotted. In this position, the microphone should detect all cross-modes in the vertical direction, but only the even-numbered ones in the horizontal direction. The graph shows a sharp change in phase and gain around 950 Hz, which corresponds to the second cross-mode, but there is no sign of the first cross-mode. This indicates that the first cross-mode is not generated in the vertical direction by the loudspeaker piston, which moves in the horizontal direction only.

It should also be noted that for this microphone position, the phase rolls off more slowly than for position 1. While this would normally be desirable, in this case it brings the phase to zero at 1415 Hz, at which point there is a peak in the gain. The gain available with the microphone in this position and with this particular antisource loudspeaker is therefore limited.

Figure 8 shows the result for position 3, in the corner of the duct. As expected, there is an area of high gain corresponding to the first cross-mode, and this would severely limit the available gain in a closed-loop system. The phase response is also erratic, and while there is still no evidence of the second cross-mode, it is clear that the performance of an attenuator using this microphone position would be severely limited. Similar results are obtained with the microphone in other corners of the duct.

CONCLUSIONS

The results show that the behaviour of the antisource loudspeaker and the acoustics of the duct both have a considerable effect on the stability of a monopole active attenuator. The position of the sensing microphone can be chosen to minimise the effect of non-axial waves, particularly the first cross-mode which cannot be damped effectively by passive means. This however requires the microphone to be placed at the centre of the duct, and in this position flow-induced noise at the microphone is highest. Conversely, to minimise the flow noise the microphone should be mounted in the duct wall, but there the effect of the cross-modes is generally greatest. A practical active attenuator requires a compromise between these two requirements. In this case such a compromise is presented by position 2 in the above results.

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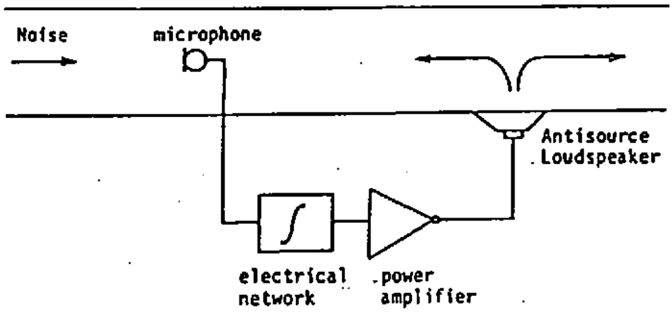

Figure 1

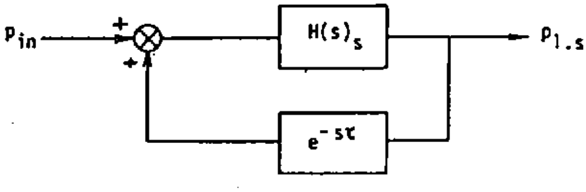

Figure 2

Schematic and block diagram of a monopole active attenuator in a duct

SENSOR POSITIONING IN ACTIVE DUCT SILENCERS

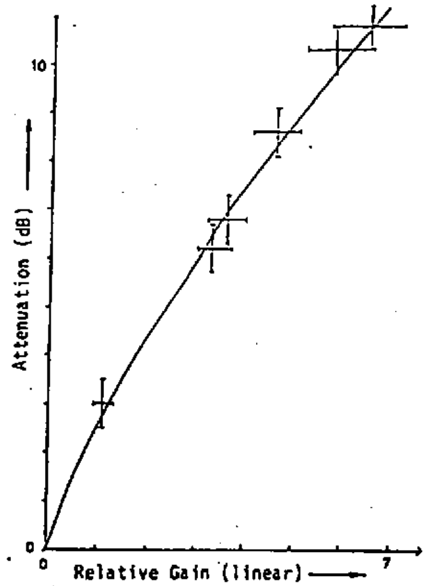

Figure 3
Attenuation by a monopole active attenuator as a function of relative gain

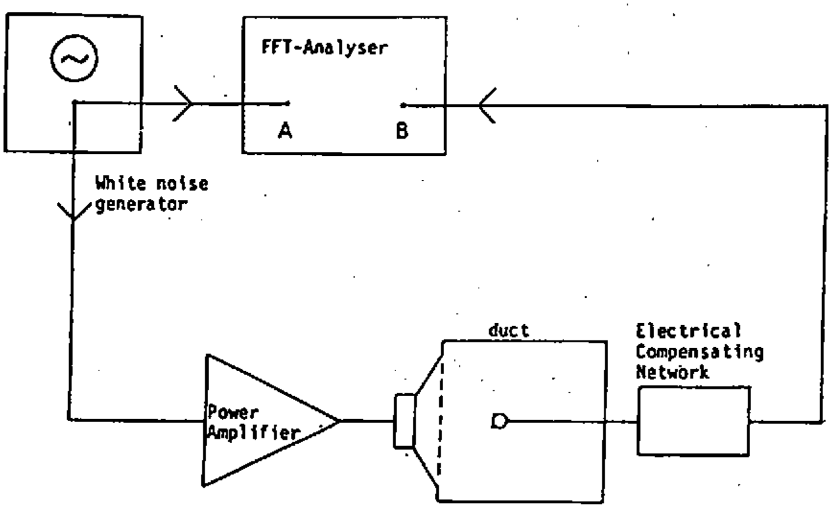

Figure 4
Apparatus for measuring the open loop transfer function of a monopole

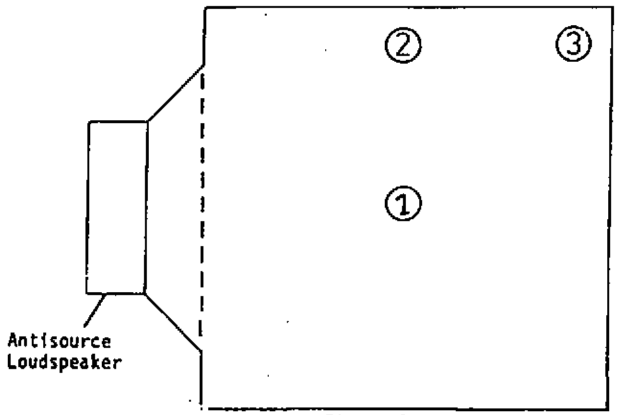

Figure 5
Cross-section of duct showing microphone positions described

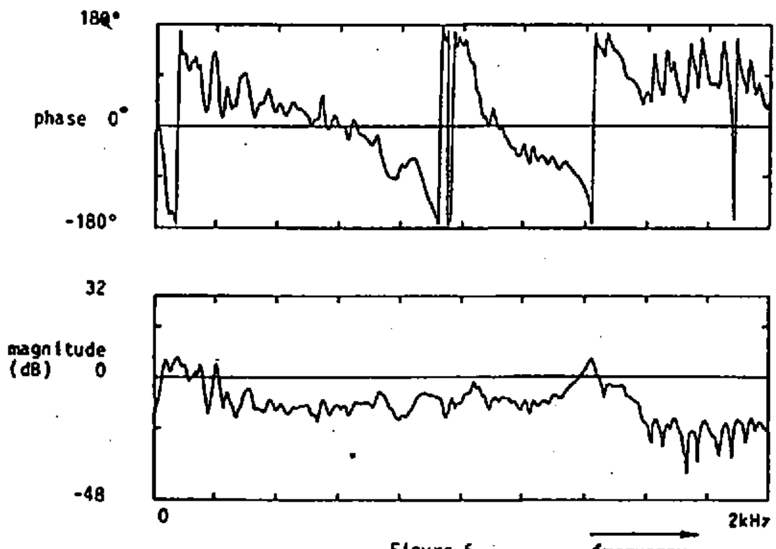

Figure 6
Open loop transfer function for microphone position 1

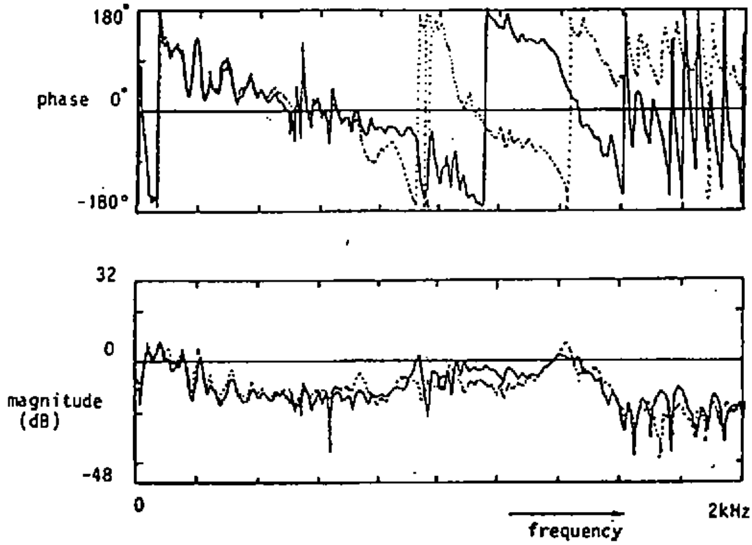

Figure 7
Open loop transfer function for position 2

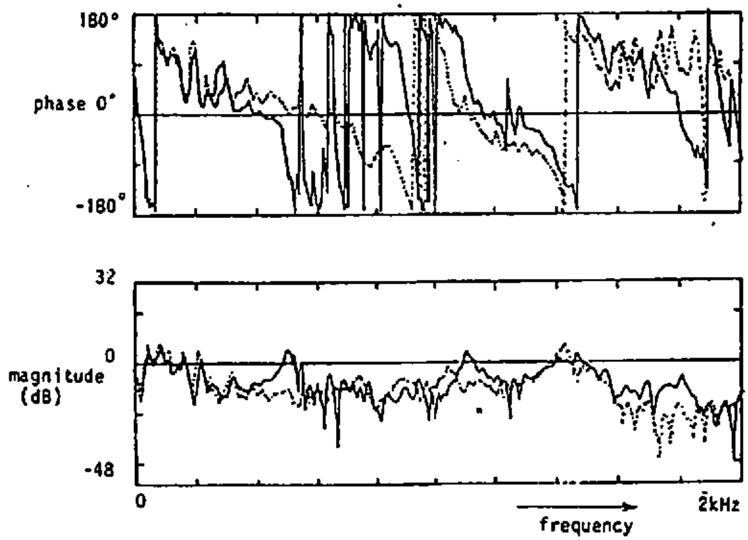

Figure 8
Open loop transfer function for position 3