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ACTIVE CONTROL OF MULTIPLE-SOURCE RANDOM SOUND IN ENCLOSURES

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1. INTRODUCTION

Active control techniques have successfully been applied to reduce the level of sound in enclosures where the sound is due to a single harmonic source, or to several harmonic sources at the same frequency. . Reductions of 10-15 dB or more have been reported for systems controlling engine-order noise in cars [1] and similar reductions have been achieved in aircraft [2]. This paper considers the feasibility of feedforward control of random noise in enclosures. In practical situations such noise often arises from a number of uncorrelated or partially correlated sources: road noise in cars is an example.

Using recordings of vibration and noise in a small hatchback car, the paper shows how the performance of an active control system can be calculated from measurements of the primary field and of reference signals related to the primary sources.

2. ACTIVE CONTROL OF RANDOM SOUND

2.1 Principle

Figure 1 shows the basic block diagram of a feedforward system for control of random sound. A set of reference signals **x** are passed through control filters **H** generating a set of signals **y** to loudspeakers inside the enclosure. The reference signals are chosen to represent the primary sources of the sound as closely as possible. The electroacoustics of the speakers, enclosure and microphones are represented in the diagram as a filter **C**. The primary sound sources (road and tyre noise, wind noise, *etc.*, in a car) give rise to signals **d** at the microphones. The signals $\hat{\mathbf{d}}$ at the microphones are due to the action of the control system. In a practical system the control filters **H** would be adapted continually to minimise the sum of the mean squared pressures $E\{\mathbf{e}^T\mathbf{e}\}$ at the microphones. However, road tests at steady speed have been used for this study, giving approximately stationary data so that fixed filters can be considered.

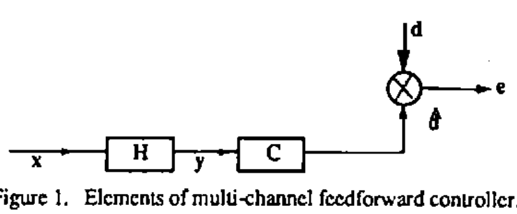

Figure 1. Elements of multi-channel feedforward controller.

2.2 Calculation of Optimal Filters

If the sound in the enclosure arises from stationary random sources then the optimal filters required for active control can be calculated from the Wiener equation, with appropriate modifications to cover the multiple-channel case. It is first necessary to derive a set of 'filtered reference signals' **r** by applying the reference signals **x** (*e.g.*, vibration measurements on the car body) to the filter matrix **C** which represents the electroacoustics of the path from the speakers to the microphones. Nelson *et al* [3] show how the filtered reference signals are calculated for the multiple-input case and go on to derive the optimal value of **H** from the matrix of cross-correlation functions between the filtered reference signals (S_{rr}) and the matrix of cross-correlation functions between the filtered reference signals and the primary field signals (S_{rd}). A computer program has been written to do this calculation and derive the coefficients of a set of FIR filters, **H**, of given length.

2.3 Prediction of Sound Reduction

Once the optimal filters **H** have been found from the given set of stationary data, it is a simple matter to apply the time-series of the measured reference signals to the **H** and **C** filters to predict the time series $\hat{\mathbf{d}}$ at the microphone. Adding this to the measured primary signal **d** gives a prediction **e** of the sound after cancellation. The spectra of **d** and **e** can then be compared to see what reductions would be available using the given reference signals. The results of this calculation are presented in Section 3.2 for a specific case.

3. VEHICLE SOUND AND VIBRATION MEASUREMENTS

3.1 Interior Noise Spectrum and Coherence

A Citroen AX11RE 3-door hatchback was driven at a steady speed of nominally 50 mph over a coarse-grained tarmac road surface. Six accelerometers were fitted to the underside of the car body. Four of the accelerometers were placed close to a suspension mounting point for each wheel, the others were on the vehicle centreline. Two microphones were placed inside the car, one next to the driver's headrest, the other at the rear of the car.

The spectrum of interior noise measured at the rear microphone is shown as the upper trace in Figure 2. The engine firing frequency and second harmonic are visible at 76 Hz and 151 Hz, while wheel rotation frequency, engine rigid body modes and other structural resonances give rise to a group of peaks below about 50 Hz.

Nelson *et al* [3] show that the multiple coherence γ^2_{xd} between several accelerometer signals **x** and one microphone signal **d** can be used to give a simple measure of the reduction which would be achieved by an unconstrained active control system using those accelerometers as reference signals. The reduction in the microphone spectrum at frequency ω in dB is given by

$$\Delta(\omega) = 10\log_{10}(1 - \gamma_{xd}^2(\omega)).$$

This represents a ceiling on the reduction which could be achieved by a real system, which would be constrained by the fact that the control filters must be causal and finite. 90% coherence corresponds to 10 dB reduction. Figure 3 shows the multiple coherence of the rear microphone with respect to (1) the four accelerometers adjacent to the wheels, and (2) all six accelerometers. The multiple coherence is high at the lowest frequencies, below 50 Hz, but a reduction in this frequency range will make very little difference to the A-weighted sound pressure level in the car. In the more useful range of 65-130 Hz, the multiple coherence with respect to all six accelerometers exceeds 80% for about half the range. 80% coherence corresponds to a potential reduction of 7 dB.

The multiple coherence provides a valuable tool in finding the best placing of the available reference accelerometers. Appropriate positions for the reference accelerometers can be expected to vary from car to car and work in this area is continuing.

3.2 Predicted Sound Reduction

The lower trace in Figure 2 shows the spectrum which could be expected using all six accelerometers as reference signals in an active control system with 125-point causal FIR control filters. The simulation shows reductions of around 5 dB in the range 65-130 Hz and larger reductions at the very low frequencies. Such a reduction would be perceptible but not dramatic. Table 1 compares the predicted reductions in mean squared pressure using 1, 2, 4 and 6 accelerometers.

No. of accelerometers	Reduction in mean squared pressure, dB
1	2.1
2	2.9
4	4.3
6	5.0

Table 1. Predicted reduction using 1,2, 4 and 6 accelerometers.

It is encouraging that the reductions predicted for finite, causal filters do not fall too far short of the ideal reductions for an unconstrained system. At 125 Hz, for example, the predicted reduction is 5.4 dB compared with a possible 7.4 dB for the unconstrained case.

3.3 Effect of Delays

Table 2 shows the effect of delaying the signals in the control chain (see Figure 1) by 5 ms, 10 ms and 25 ms. The calculations already include the effect of the acoustic delay path through the vehicle interior (about 4 ms) as this is incorporated in the C filter. A practical system would also include a further delay of around 4 ms due to anti-aliasing filters and processing time. The table shows that a 5 ms processing delay would cause the reduction in mean squared pressure to deteriorate from 5.0 to 4.5 dB. The effect of a delay is frequency-dependent and at 125 Hz the predicted reduction of 5.4 deteriorates to 3.3 dB.

Processing delay ms	Reduction in m.s. pressure dB
0	5.0
5	4.5
10	4.3
25	1.2

Table 2. Effect of delays in control chain.

These results show that any delays introduced by a practical random noise system would cause some deterioration in the response. Some improvement can be gained by placing the reference signals closer to the sources (*e.g.*, on the suspension) to give more time advantage. However, the nonlinearity of elements such as the vehicle suspension mountings will tend to reduce their coherence with the sound field inside the car.

4. CONCLUSIONS

Feedforward active control of random sound in an enclosure is feasible provided that reference signals can be found which are sufficiently coherent with the primary sources of the sound. In a specific example it is predicted that an overall reduction of around 5 dB can be expected in a small hatchback car using as reference signals six accelerometers attached to the underside of the body. Further work is required to identify a minimum set of reference signals to give high multiple coherence with respect to the measured sound inside the car.

ACKNOWLEDGEMENTS

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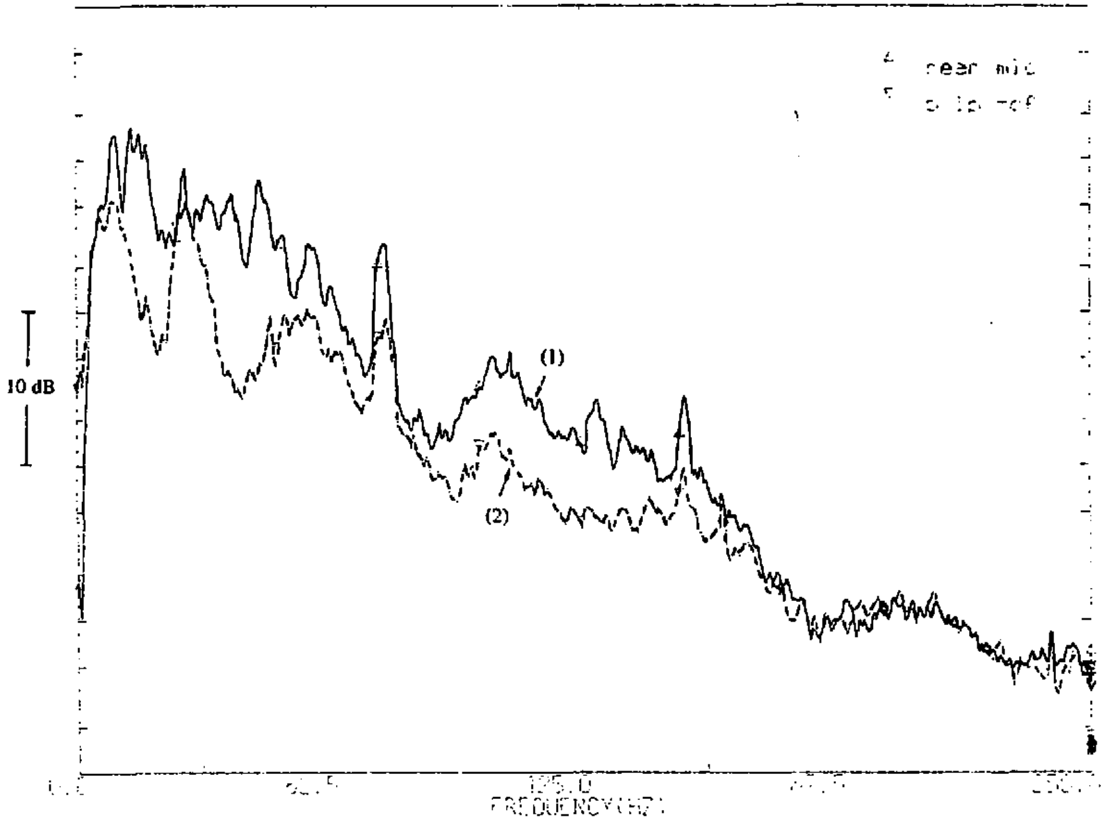

Figure 2: Vehicle Interior Noise Spectrum
(1) measured
(2) after cancellation using 6 reference accelerometers

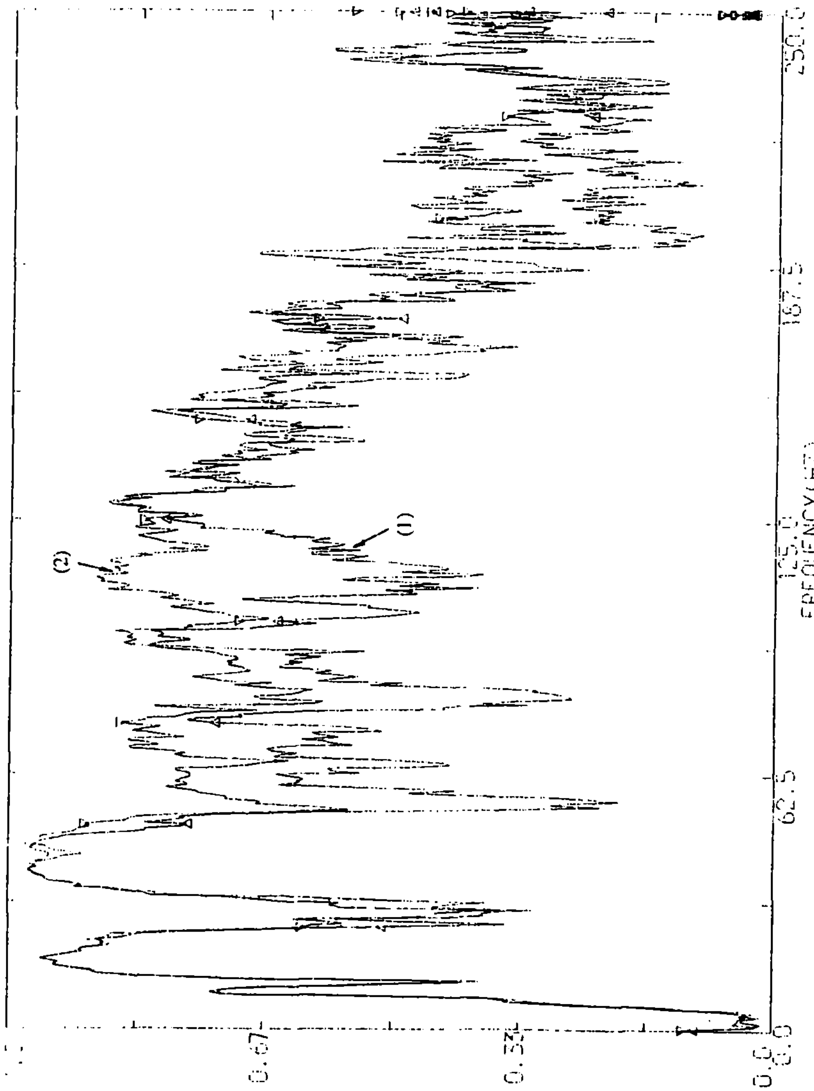

Figure 3: Multiple Coherence w.r.t. rear microphone:
(1) 4 accelerometers
(2) 6 accelerometers