ACTIVE CONTROL OF ACOUSTIC NOISE IN A SMALL ENCLOSURE

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INTRODUCTION

Any sound field can be thought of as the sum of propagating and reverberant fields. Much study has concerned the control of propagating fields; particularly in ducts. However, the control of the propagating field inside a room is much more complicated due to the multiple reflections involved and fundamentally requires that the control speakers be positioned in the line of the propagating field. Indeed, a propagating field is best controlled with a secondary source positioned as close as possible to the noise source. However, with multiple or large sources this may be difficult or impossible.

The principle of superposition can be applied to linear sound fields enabling the direct and reverberant fields to be considered separately. This paper is concerned with the active control of the low order modes of a reverberant field. In real situations the acoustic wave pattern of a reverberant field will be complicated, due to the shape of the enclosure and to objects and people within the enclosure, but a useful underastanding of the problem may be obatined by studying the simple stuation of a rectangular enclosure. A number of papers have been published concerning the active control of harmonic sound fields. Nelson [1] has shown that substantial reductions in the net acoustic power radiated can be achieved if the control sources are within half a wavelength of the noise source. Bullmore [2] has extended this theory to sound fields of low modal density by minimising the sum of the squared pressures at a number of different sensor locations and has shown that attenuation close to optimum can be achieved. It has also been shown how attenuation can be achieved with control sources separated from the noise source by distances of greater than half a wavelength. Little material has been published concerning experiments on the active control of broadband noise within an enclosure.

This paper describes the implementation of a system for the active control of the low order modes of the reverberant field in a small enclosure (where "small" infers that only a small number of acoustic modes dominate the field)

THEORY

In order to attenuate globally a sound field or produce a volume of attenuation it is necessary that the monitoring positions are chosen to be representative of the sound field throughout the volume of interest. In the case of a reverberant field it is necessary that the microphones pick up sufficient information about the dominant modes of the field. Let the sound field in an enclosure be dominated by n modes and the amplitude of the i'th mode be $A_i(t)$. Let the pressure in the enclosure be sensed by n sensors and the pressure at the j'th sensor be $P_j(t)$. Then the pressures at sensors 1 and 2 will be

$$P_1(t) = \Psi_{11} A_1(t) + \Psi_{21} A_2(t) + \ldots + \Psi_{n1} A_n(t)$$

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$$P_2(t) = \Psi_{12} A_1(t) + \Psi_{22} A_2(t) + \ldots + \Psi_{n2} A_n(t)$$

where Ψ_{ij} is the characteristic function of the i'th mode at the j'th sensor position. It represents the fraction of the standing wave present at a position: $\Psi = 0$ at a node and is a maximum at an antinode. The equations can be represented in matrix form:

$$P = \Psi A$$

and the modal pressures at a point obtained from the inverse equation

$$A = \Psi^{-1} P$$

Therefore in principle the characteristic functions (or eigenfunctions) of the modes need to be known in order to determine the modal pressures. Some knowledge of the mode shapes is also necessary when determining appropriate monitor positions. The important consideration in choosing the monitor positions is that the information present in the signals from the sensors is sufficient to define adequately all the modal amplitudes within the working range of the control system. Each monitor needs to be placed in an independent position from the others such that the simultaneous equations presented above can be solved.

An example will illustrate the meaning of the term independent. In practice it will be desirable to monitor a mode at or near an antinode to maximise the pressure detected. However, consider the case of monitoring the 1,0 and 0,1 modes in a 2-dimensional rectangular enclosure at positions in diagonally opposite corners. The matrix Ψ is then equal to $\begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix}$, and as this matrix is singular, i.e. the determinant is zero, it cannot be inverted and hence the modal pressures cannot be resolved. This has occured because the chosen monitor positions were not independent; each position detected the same component of each mode. Note, however, that it is not necessary for the monitors to determine the modal amplitudes completely, only that there is sufficient information about the modal amplitudes present in the signals to avoid its being swamped by interfering noise.

MULTICHANNEL CONTROL SYSTEM

An active system consisting of a number of detectors and sources capable of controlling the field at a number of monitor positions is shown in figure 1. The letters in the figure are matrices of frequency responses between the elements. It has been shown [3] how the responses of the controllers needed between the detectors and sources are given by

$$T = (C^H E F - C^H C)^{-1} C^H E$$

where T is the matrix of the transfer functions of the controller needed to give optimum attenuation at the monitors,

C is the matrix of the transfer functions between the control sources and the monitors,

F is the matrix of the transfer functions of the acoustic feedback paths between the control sources and the detectors,

A is the matrix of the transfer functions between the noise sources and the monitors,

B is the matrix of the transfer functions between the noise sources and the detectors, and

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E is the matrix of the transfer functions between the detectors and the monitors, and is equal to AB^{-1}.

Single Detector, Single Secondary Source, Two Monitors

Consider a controller consisting of one detector and one source controlling the field at two monitor positions . The required controller is given by

$$t = \left(\begin{bmatrix} c_1^* & c_2^* \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} f - \begin{bmatrix} c_1^* & c_2^* \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} \right)^{-1} \begin{bmatrix} c_1^* & c_2^* \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$$

where the matrices T, C, E and F have components t, c_1, c_2, e_1,e_2 and f. Multiplying out the matrices leads to

$$t = \frac{c_1^* e_1 + c_2^* e_2}{(c_1^* e_1 + c_2^* e_2) f - (c_1^* c_1 + c_2^* c_2)}$$

and extending this to a controller with n monitors gives

$$t = \frac{1}{f - \dfrac{\sum_{i=1}^{n} c_i^* c_i}{\sum_{i=1}^{n} c_i^* e_i}}$$

Simple control theory indicates that this can be implemented with a pair of electronic filters; one between the detector and the source in parallel with another cancelling the acoustic feedback from the source to the detector. Increasing the number of or moving the monitor microphones does not affect the acoustic feedback in the system. Hence designing a controller in this way, with independent feedback compensation, means that the monitors can be moved without altering the feedback incorporated in the controller.

Two Detectors, Two Secondary Sources

Consider the general arrangement of figure 2. The acoustic feedback paths add together at the detector microphone (actually the point of entry to the digital system). This feedback can be counteracted by modelling each acoustic path electronically and summing the electronic feedback paths at an equivalent position to the acoustic feedback paths. The success of the method lies in the simple topology of the multichannel controller, the simplicity is rendered by the positions where the feedback paths meet, namely *before* the signal splits to enter the separate feedforward paths to the speakers. The advantage of this configuration is that the electronic feedback filter has a simple response which only

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needs to model the acoustic feedback due to that channel alone. These paths are also causal ensuring that they can be adequately and simply modelled. The method also eases the extraction of the required feedforward filters from the matrix equation; under ideal conditions the feedback paths cancel exactly and the feedforward filters are given by the matrix equation $C^{-1}E$. This is a familiar expression; it is the matrix form of the one dimensional situation consisting of a single detector and single speaker controlling the field at a single monitor position.

Consider such a single channel controller (figure 3). It can be realised simply by just a pair of electronic filters; a feedback path modelling the acoustic feedback and a feedforward filter of transfer function *E/C*.

Multiple Detectors, Multiple Secondary Sources

Figure 2 indicates that a multichannel controller can be readily realised by repeatedly using a number of the filter pairs used in the single channel control system. The implementation of a single channel controller therefore tests the basic unit of a multichannel system. However, it can be seen that the number of filter pairs needed is equal to the square of the number of channels (where each channel consists of a detector-speaker pair) thereby limiting the number of channels that can be implemented practically.

PRACTICAL IMPLEMENTATION OF A SINGLE CHANNEL CONTROL SYSTEM

This section contains a description of the experimental results obtained from an implementation of a single channel broadband control system partially attenuating the reverberant field inside an enclosure. The filter pair required was implemented as two 128 point FIR filters realised using a Texas instruments TMS32020 microprocessor housed in a Ferranti PC860XT personal computer. A method is needed whereby the coefficients for the (digital) control filters described above can be obtained. The practical method used in these experiments consisted of a series of acoustical measurements on the control system. The same hardware was used both to record the various frequency responses of the system from which the digital filters were derived and also to implement the controller. This ensured an easy means whereby the electronic filter compensated for its own imperfections and ensured that the sampling rates used for the various measurements and for the subsequent filter implementation were all the same.

A suitable test enclosure (0.5 x 0.6 x 0.7m), practical apparatus and test conditions were configured to produce a situation in which a control system could be successful (figure 3). The first two modes of the enclosure had modal frequencies at about 240 and 290 Hz. Therefore the working range of the system was conditioned to be up to 350 Hz (determined by the cut off of the low pass filters at the entrance to and exit from the digital system). The sampling rate used was 1 kHz. Measurements were recorded by exciting the system with a swept frequency sine wave output from the digital system and capturing the response on the same digital system. The following measurements were recorded: a transient swept sine signal (x_2) was used to excite the noise source loudspeaker and re-

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sponses captured at the detector microphone monitor (y_{10}) and the monitor microphone (y_{30}); the signal y_{10} was used to excite the control speaker and the response captured at the monitor microphone (y_{32}); the transient swept sine signal was used to excite the control speaker and the response was captured at the detector microphone (y_{12}).

The feedback filter was derived from a deconvolution of the signals x_2 and y_{12}. The deconvolution was achieved with a least squared error FIR fit in the time domain. The feedforward filter was derived by deconvolving the signals y_{30} andy_{32}.

RESULTS

The results of the practical implementation of the control system operating in the enclosure are shown in figure 4. The noise source was driven with a pseudo-random signal from a Hewlett packard spectrum analyser. The signal from the monitor microphone was connected to the spectrum analyser to record the transfer function between the noise source signal and the signal at the monitor. The response with and without the control system in operation is shown. The control system was stable and attenuated the field to the same extent months after the system had been set up and the digital filters had been derived, demonstrating substantial stability over time.

CONCLUSIONS

A simple topology for the controllers for a multichannel control system has been presented. The method demonstrates how any multichannel controller can be realised by repeatedly using a number of the same type of filter pairs used in the single channel control system. A single channel broadband digital control system consisting of a single detector microphone and a single speaker attenuating the field at a single monitor position has been implemented. The active system successfully attenuated the first two modes of the reverberant field inside an enclosure.

ACKNOWLEDGMENTS

The work reported here was supported by an SERC CASE studentship in cooperation with Plessey Research (Caswell).

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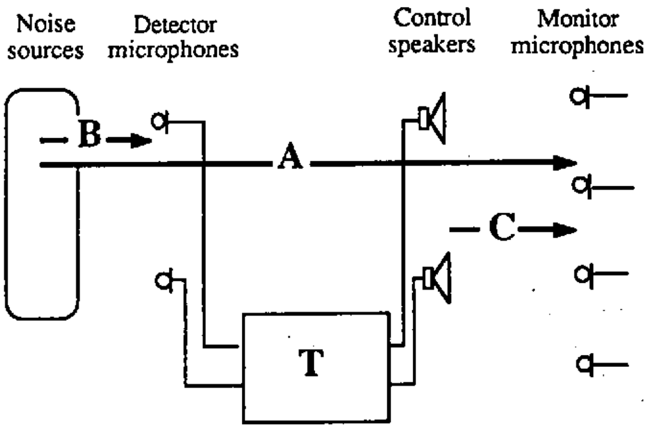
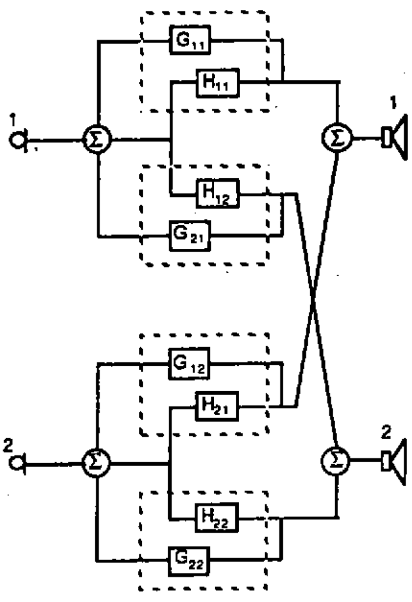


Figure 1. Two channel active noise control system



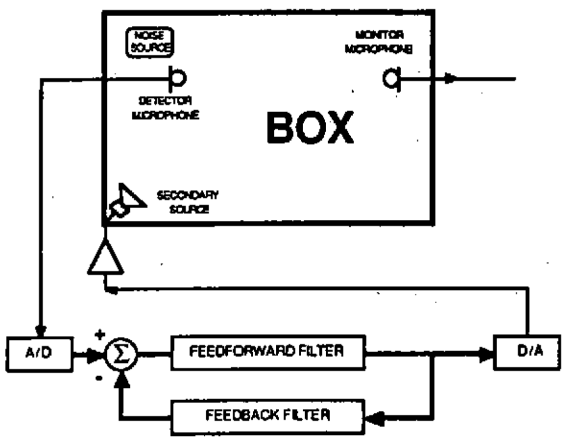


Figure 3. Single channel active noise control system in an enclosure

Figure 2. Two channel controller

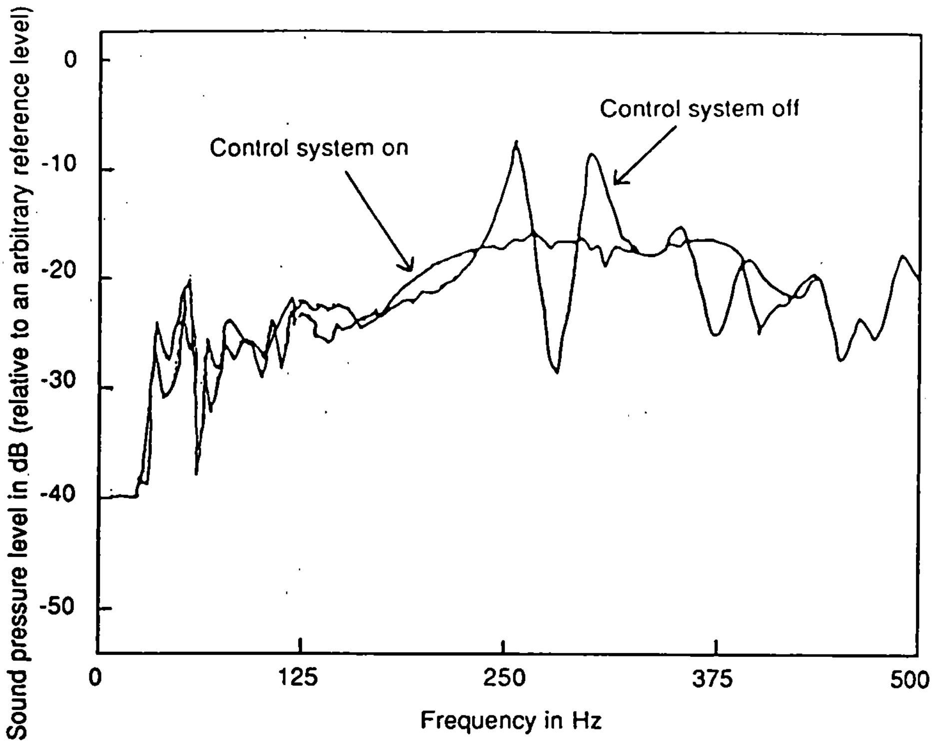


Figure 4. Amplitude spectra of the response at the monitor microphone with and without the control system operating.