Monograph:
Curtis, A.R.D., Nelson, P.A. and Elliott, S.J. (1990) Active Reduction of an Enclosed Sound Field: An Experimental Investigation. Research Report. Acse Report 381 . Dept of Automatic Control and System Engineering. University of Sheffield

Active reduction of an enclosed sound field: an experimental investigation

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Research Report No 381 January 1990

Introduction

Many experimental investigations into the active control of sound have concentrated on the simplest sound field, a one dimensional wave propagating along a duct, where a simple control strategy can be used because cancellation at one point guarantees cancellation downstream of that point. A simple controller can be implemented by measuring the sound upstream with a unidirectional sensor and using a feedforward controller with a delay and phase inversion to drive the cancelling source. The most common application of such techniques are installations such as air-conditioning ducts. There are many other applications, however, where control of an enclosed sound field is desirable, including the reduction of cabin noise in propeller driven aircraft and the reduction of engine noise in the passenger compartment of cars and lorries, and where the techniques of control developed for propagating sound fields are inappropriate. An enclosed sound field is composed of many waves reflected from the sides of the enclosure. There is no upstream location to measure and no downstream location to cancel the sound.

In this paper we study the simplest enclosed sound field, a duct with closed ends, and experimentally demonstrate that strategies developed for the control of sound in ducts do not perform as well as a strategy developed for the control of sound in enclosed spaces. The enclosed sound field has the simple structure of a standing wave composed of two propagating waves, an incident wave from the primary source and a reflected wave from the closed end. We investigate three control strategies for the reduction of this sound field, the acoustical virtual earth and the absorbing termination (both of which have been successfully used in ducts) and the strategy of minimzation of energy (developed for the control of sound in enclosed spaces). We experimentally implement and compare the performance of these three strategies in a test enclosure using single frequency excitation. Single frequency sound fields form an important class of practical applications including all those whose source is either rotat-

B. Absorbing Termination

Where the acoustical virtual earth prevents transmission of an incident sound wave by reflection, the absorbing termination acts so as to neither transmit nor reflect sound. It does not cancel the sound at just one location but cancels a whole propagating wave by complete absorption. A single source is sufficient to completely absorb a sound wave when used at one end of the duct but twin sources acting in conjunction are required when an absorbing termination used in the body of the duct.[1] Control systems of this type have been proposed for the control of sound in enclosed ducts by Guicking[3] and when placed in their twin source configuration have been successfully used by Swinbanks and others for the control of propagating sound in ducts.[4] The absorbing termination is the secondary source configuration which absorbs the maximum acoustic power from the primary sound field.

C. Minimization of Acoustic Energy

Where the aim of an active sound reduction system is to reduce the levels of sound in an appreciable volume both upstream and downstream of the secondary source then a reasonable measure of success is the reduction in the total acoustic energy in that volume. Neither the acoustical virtual earth nor the absorbing termination have the reduction of acoustic energy as their primary aim and do not minimize total acoustic energy when used in an enclosed space.[1] In order to minimize acoustic energy it first must be measured which, for an exact calculation, requires measurements at all locations in the sound field. An approximate measure of acoustic energy is obtained by measuring the sound field at several locations and summing the means of the squares of the sensor signals. We have called this measure J_p and have developed a technique for its minimization.[5]

II. Experimental Apparatus

The experimental sound field is enclosed by a 6m long duct constructed of high density chipboard with a cross section 0.234m by 0.533m. The duct was designed and built by Silcox[6] for experiments in the active reduction of propagating sound and is modified in these experiments by sealing both ends with chipboard panels to enclose the sound field. Two six inch diameter loudspeakers are housed in their own chipboard enclosures and, when required, are bolted onto the duct at three possible inlets in its top surface. When a source is not in use the inlet is closed by a chipboard panel. Loudspeaker L_0, at one end, is designated the primary source and loudspeakers L_1 at the other end is designated as a secondary source.

Three sets of sound sensors are used. For monitoring the entire sound field, a travelling microphone is attached to a small trolley which runs along the lower inside surface of the duct. For detecting propagating sound waves, two identical phase matched microphones are inserted into the mid- section of the duct and for measurement of the function J_p, eight piezo-electric microphones are inserted into the duct at evenly spaced intervals. The arrangement of the sources and sensors in the experimental duct is shown in figure 1.

The three control strategies are implemented using different controllers. In each case loudspeaker L0 is used as the primary source of sound and loudspeaker L1 as the secondary or controlling source, both driven by single frequency excitation signals. We shall describe each method of control in turn.

A. The Acoustical Virtual Earth

The excitation signals for the primary and secondary loudspeakers are obtained from the two channels of a variable phase oscillator. The sound field at the secondary loudspeaker L1 is monitored by placing the travelling microphone directly underneath it and the gain and phase of the secondary channel are manually adjusted until a sound pressure null is achieved at the travelling microphone.

B. The Absorbing Termination

When there is no reflected wave from the secondary source, the sound field in the duct is a wave propagating in one direction only, from primary source to secondary source. The propagating wave detector will then detect signals of the same magnitude but with phases which differ by an amount corresponding to the propagation of the wave between the pair of phase matched microphones. This phase lag should be $(d/\lambda) \times 360^\circ$ where d is the separation of the two microphones and λ is the wavelength of the sound. The condition of an absorbing termination is obtained by manually adjusting the gain and phase of the secondary channel until the signals from the two matched microphones are of equal amplitude and have the required phase difference. The sound field is then checked along its length by the travelling microphone to ensure the sound field is indeed composed of a single propagating wave.

C. Minimization of Acoustic Energy

The array of eight piezo-electric microphones gives an instantaneous measure of the distributed sound field and the function J_p can be calculated by summing the mean square values of these signals. This function is minimized on- line with respect to the secondary excitation signal by adapting a digital filter, driven by the same signal as the primary, according to a Filtered X-LMS algorithm. This technique is described by Elliott.[7]

III. The Suppression of a Resonance

To test the performance of the three control strategies, the primary loudspeaker is driven by a sinusoidal signal with an amplitude of 1.00V rms and a frequency of 107 Hz which is the frequency of the fourth acoustic resonance of the duct with four sound pressure nodes. This resonant sound field is controlled by each of the three controllers in turn. The sound field, both sound pressure amplitude and phase relative to the primary driving signal, is measured at 23 locations spaced by 0.25 m along the duct with the travelling microphone. The results are presented in figure 2 for the five cases:

1. Primary sound field, secondary source unmounted.
2. Primary sound field, secondary source mounted.
3. Controlled sound field, acoustical virtual earth.
4. Controlled sound field, absorbing termination.
5. Controlled sound field, minimization of acoustic energy.

A. Primary Sound Field

The four sound pressure nodes of the primary sound field can be clearly seen in the magnitude plot together with the $-\pi$ shifts in phase as the node is crossed. The maximum sound level is 89dB at a peak and the minimum 72dB at a node. The introduction of the secondary loudspeaker has a passive damping effect on the resonance, even though its input terminals are shorted, and the change in the reflection coefficient at that end of the duct is sufficient to reduce the amplitude of the peaks in sound pressure by around 3dB. The overall reduction in sound level as measured by the function J_{p23}, the sum of the squares of the sound pressures at the 23 measurement positions is 2.5dB. The structure of the resonance remains with the sound pressure nodes unchanged in amplitude and in the same location. The phase plot is almost unchanged and so is not shown.

B. The Acoustical Virtual Earth

The acoustical virtual earth disrupts the standing wave pattern of the resonant sound field by forcing a sound pressure node where previously there was an anti-node. The resulting sound field is the standing wave pattern of a duct with one end closed and the other open. This resonance would occur at a frequency of about 96Hz and although it is not strongly excited at 107Hz the pattern can be clearly seen in the four sound pressure nodes, one at the secondary source, and in the $-\pi$ phase shifts as these nodes are crossed. As the primary resonance has been disrupted the acoustic virtual earth succeeds in reducing the overall sound levels in the duct. The maximum sound level is now 82dB and the minimum less than 60dB at the virtual earth. The overall sound level J_{p23} is reduced by 6.9dB compared to the primary sound field.

C. The Absorbing Termination

The absorbing termination disrupts the standing wave pattern of the primary sound field by removing the reflected wave component. The resulting sound field magnitude is reasonably constant for the length of the duct and the phase decreases linearly with distance from the primary loudspeaker. This indicates that the resulting sound field is a wave propagating in one direction only, away from the primary source and so confirms that the control method has indeed removed the reflected wave component. The maximum sound level is 79dB, the minimum sound level 77dB and the overall sound level J_{p23} is reduced by 7.4dB compared to the primary sound field, an improvement of 3dB maximum and 0.5dB overall compared to the acoustical virtual earth.

D. The Minimization of Energy

This strategy disrupts the standing wave pattern of the primary sound field by a combination of absorption, as in the absorbing termination, and disruptive reflection, as in the acoustical virtual earth. A discussion of the physical mechanisms of the minimizing control is given in our previous paper.[1] The resulting sound field is the combination of a unidirectional propagating wave and a resonance of an open-closed duct. This can be seen in both the size and nodal structure of the sound pressure magnitude plot and in the 'rippled' phase transition. The maximum sound level is 79dB, comparable to that of the absorbing termination and the sound level exceeds that of the absorbing termination at only a few locations. However ,the minimum sound level is now 70dB and the reduction in overall sound level is 8.3dB.

In conclusion, all three strategies are successful in suppressing the acoustic resonances with the minimization of acoustic energy giving the best performance followed by the absorbing termination. The acoustic virtual earth, although successful in suppressing the resonance, has the worst performance in terms of both overall and maximum sound level reduction. When the same strategies are applied to a primary sound field excited at a frequency away from resonance the same pattern appears.

IV. The Control of an Anti-Resonance

We now investigate the performance of the three control schemes in controlling an anti-resonant sound field. A frequency of 96 Hz is chosen which lies between the third and fourth resonances and also corresponds to the fourth resonance of an open/closed duct, the residual resonance excited by the acoustical virtual earth above. Figure 3 shows the sound pressure and phase for the four cases.

1. Primary sound field, secondary source unmounted.
2. Controlled sound field, acoustical virtual earth.
3. Controlled sound field, absorbing termination.
4. Controlled sound field, minimization of acoustic energy.

A. Primary Sound Field

As is expected, the primary sound field of the anti- resonance is much reduced compared to that of the resonance. The maximum sound level is 81dB and the overall level is 6.8dB less than that at resonance. The structure of the open-closed resonance can be seen in the four sound pressure nodes and in the phase plot. Note that the open-end node occurs at the primary loudspeaker. There is an anti-resonance at this frequency because the primary source has great difficulty driving the sound field at this node. Mounting the secondary loudspeaker has very little effect on the anti-resonant sound field and so the sound field with the secondary source mounted is not shown.

B. The Acoustical Virtual Earth

The acoustical virtual earth forces a node at the secondary source where before there was an anti-node. The primary source now effectively acts in an open-closed duct with the primary at its closed end. It is now driving a sound pressure anti-node and as it is being driven at a resonant frequency of an open-closed duct, a resonance occurs. The maximum sound level is increased to 89dB and the overall sound level is increased by 7.2dB.

C. The Absorbing Termination

The absorbing termination removes one of the propagating wave components of the anti-resonant sound field. This disrupts the standing wave pattern, disrupts the sound pressure node at the primary source and allows the primary source to excite the sound field more efficiently. Although the peaks of the standing wave pattern of the anti-node are not increased in the resulting flat sound field, the troughs at the nodes are filled increasing the overall sound level by 0.6dB.

D. The Minimization of Energy

Both the acoustical virtual earth and the absorbing termination disrupt the standing wave pattern of the anti-resonance which leads to increases in overall sound level. In fact any control of an anti-resonant sound field by a secondary source will only increase its total acoustic energy. The minimization of energy control scheme therefore leaves an already quiet sound field well alone. The controlled sound field is little changed from the primary field; the peaks are a little reduced, the troughs a little filled. The overall sound level is reduced by 0.2dB.

V. Conclusions

The strategy of minimization of acoustic energy is recommended for the control of enclosed sound fields. Resulting sound fields have, by definition, the least acoustic energy, but also give good reductions in maximum sound level. Minimum sound levels are increased but this is rarely of concern. The strategy works for both resonant and anti-resonant sound fields and can be applied, as is shown elsewhere,[8] to sound fields with more complicated geometries.

The strategy of the absorbing termination succeeds in suppressing acoustic resonances in enclosed sound fields but also disrupts anti-resonances resulting in increased sound levels at those frequencies.

The strategy of the acoustical virtual earth is not recommended for enclosed sound fields. It forces new standing wave patterns in the sound field which result in new resonances and greatly increased sound levels at some frequencies.

References

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Figures

FIG. 1. The experimental sound field showing the arrangement of sources and sensors.

FIG. 2. The Control of a Resonant Sound Field: (a) Sound Pressure Level and (b) Relative Phase against duct position for the resonance at 107 Hz; comparison the control strategies. (—) Primary sound field, secondary source unmounted, (-···-) Primary sound field, secondary source mounted, (· · ·) Controlled sound field, acoustical virtual earth, (-··-) Controlled sound field, absorbing termination, (- - -) Controlled sound field, minimization of acoustic energy.

FIG. 3. The Control of an Anti-Resonant Sound Field: (a) Sound Pressure Level and (b) Relative Phase against duct position for the anti-resonance at 96 Hz; comparison the control strategies.

(—) Primary sound field, secondary source unmounted, (· · ·) Controlled sound field, acoustical virtual earth, (-··-) Controlled sound field, absorbing termination, (- - -) Controlled sound field, minimization of acoustic energy.

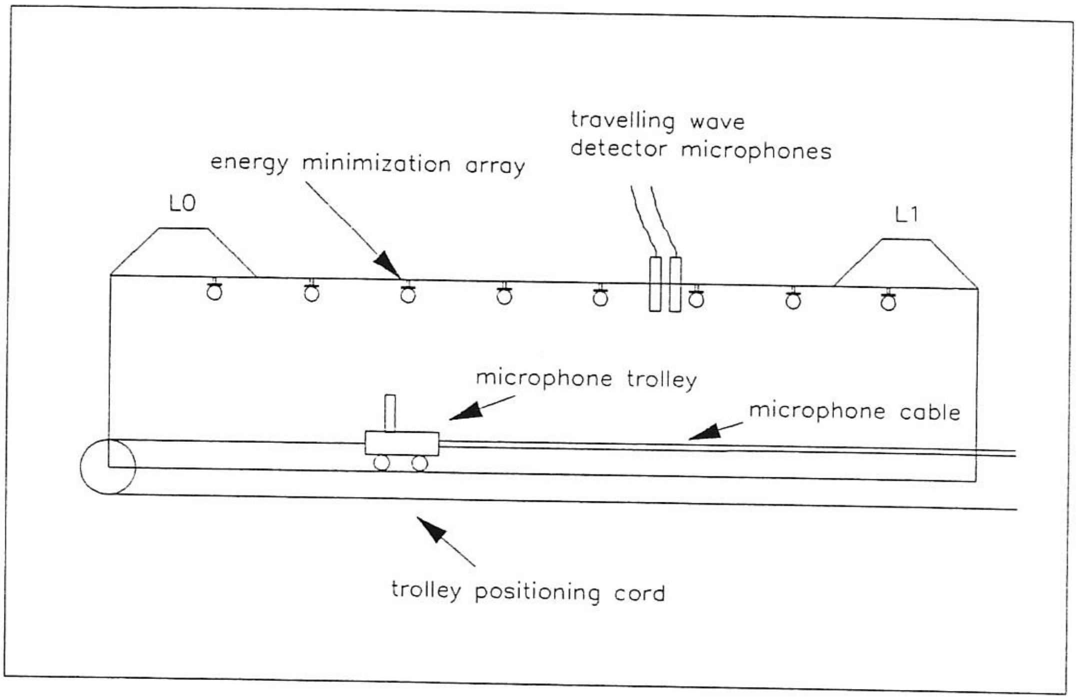
travelling wave
detector microphones
energy minimization array
L0
L1
microphone trolley
microphone cable
trolley positioning cord

Fig 1

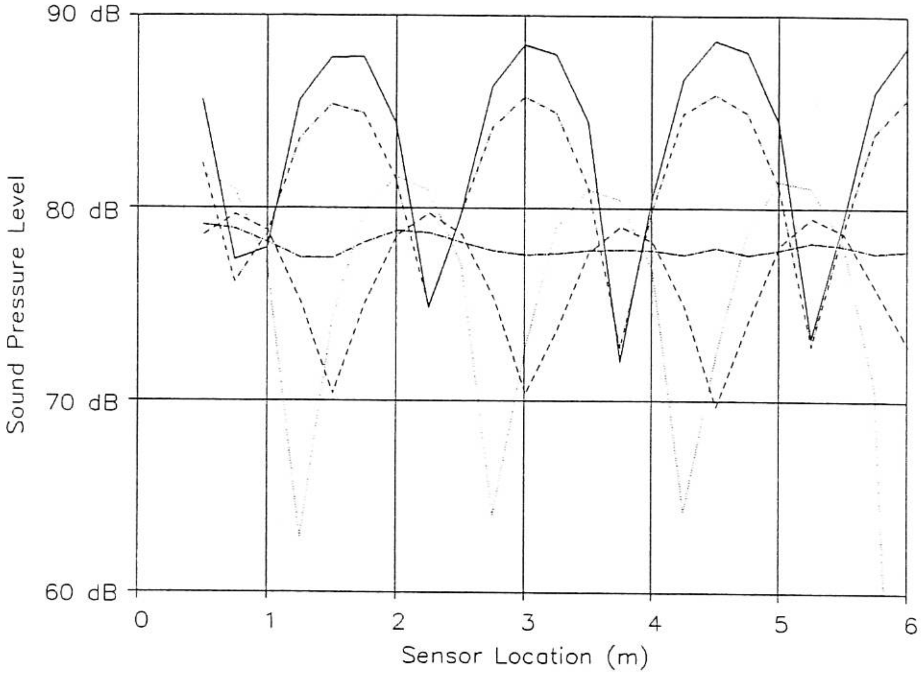
90 dB
80 dB
70 dB
60 dB
Sound Pressure Level
0
1
2
3
4
5
6
Sensor Location (m)

Fig 2a

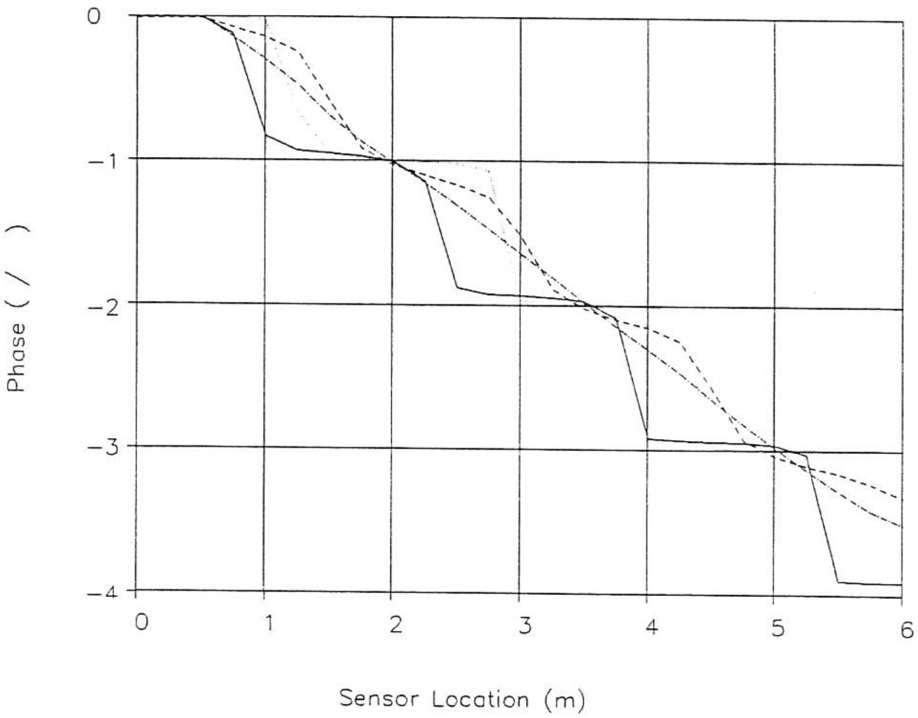

Fig 2b

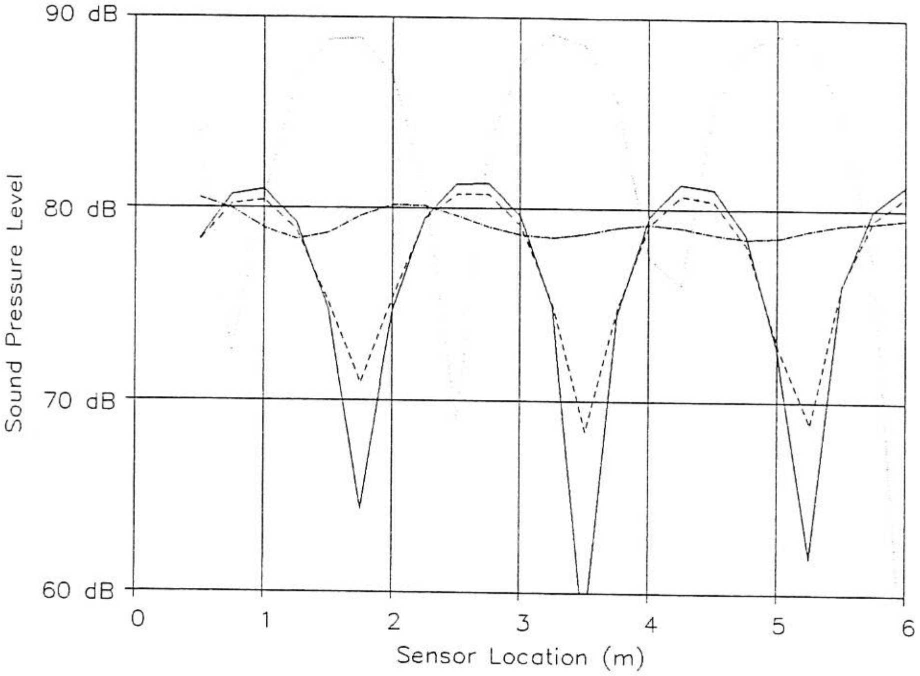
90 dB
80 dB
70 dB
60 dB
Sound Pressure Level
0
1
2
3
4
5
6
Sensor Location (m)

Fig 3a

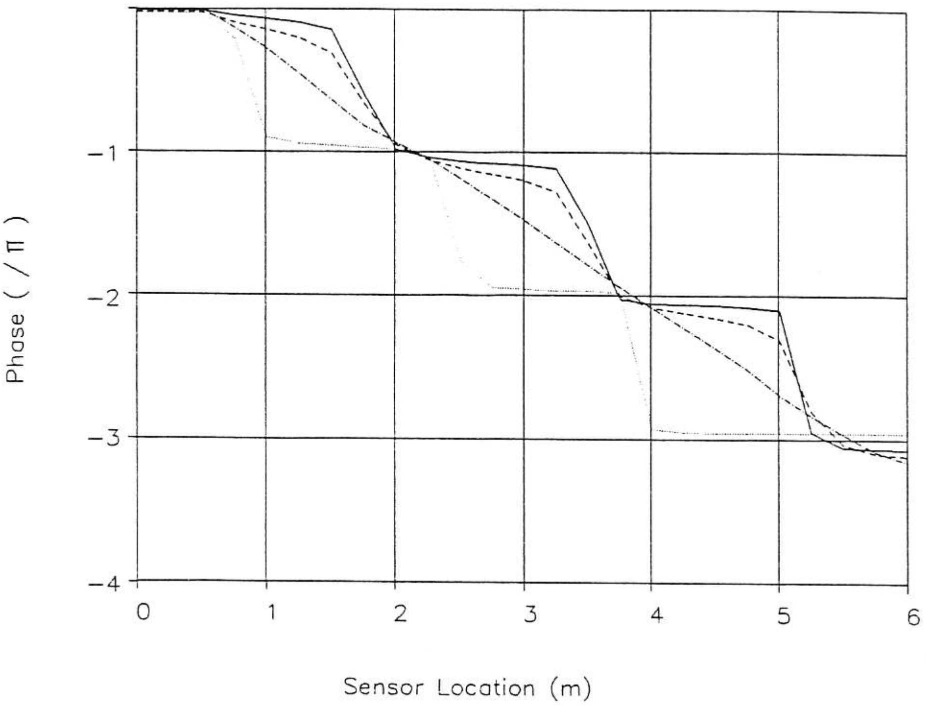

Fig 3b