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MODIFYING LOW FREQUENCY ROOM ACOUSTICS
2: GLOBAL CONTROL USING ACTIVE ABSORBERS

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ABSTRACT

The normal low frequency modes of small rooms may be controlled local to a defined listening point by arranging for secondary sources to produce sound which interferes destructively with the reverberant field at the control point. Unfortunately, despite perfect de-reverberation at one point, the total field within the remainder of the enclosure is still strongly influenced by the normal modes, both spatially and temporally. This paper describes how active devices can be used to suppress the normal modes of a room. By suppressing the modes a degree of de-reverberation is obtained over the entire enclosed volume, making the addition of absorbers an effective global control strategy.

INTRODUCTION

When sound is produced inside a bounded acoustic space, the walls of the space influence the dynamics of the sound sources and dictate the structure of the acoustic field within the space. Consequently, sound in a room can be very different to the sound that the same sources would produce in free field or in any other room.

The walls of a room introduce two significant effects to low frequency sound reproduced within it. Firstly, the presence of nearby walls can significantly influence the radiation load presented to a source. This "boundary effect" can be usefully exploited to enhance low frequency output from a small source [1] and it can equally cause unwanted disturbance of the frequency response if the source is further from the wall.

The second significant effect is the definition of normal modes of motion for the enclosed sound field. These modes present a frequency dependant radiation load to the loudspeakers, colour the steady state frequency response of the room, introduce a strong spatial dependence to the sound field and introduce significant colour to the impulse response of the room. All of these coupled consequences of normal modes are damaging to the perceived quality of reproduced sound at frequencies of low modal density.

Contemporary methods used to remove the damaging consequences of normal modes include good design practice in conventional architectural acoustics and equalization. The design of listening spaces is strongly constrained by the financial budget and architectural volume available. Both of these constraints strongly influence the low frequency performance of a room, explaining why even well designed spaces have imperfect low frequency acoustics. Coarse equalization, or accurately designed inverse filtering, can correct errors in the steady state low frequency response of a sound reproduction system at one listening position. However, the spatial effects of room modes and the influence of discrete modes on low frequency reverberation are not generally addressed by simple equalization.

Recent developments in active methods in acoustics motivate the evaluation of two other approaches to suppressing normal modes; local active de-reverberation and global active control. Active de-reverberation has been considered in the first part of this paper [2], where cancellation of the reverberant field at a listening point has been shown to be possible in principle. This strategy has some practical drawbacks, notably that monitoring microphones are needed in the field (at least at the listening point) and the de-reverberation fails remote from the designated listening position.

It is the purpose of the present paper to describe an alternative active control strategy, designed to globally suppress the low frequency normal modes of a built space. The strategy is designed to be implemented using self-contained active acoustic absorbers [3]. The theory will be introduced by considering various possible configurations of an active source in a simple resonant acoustic field.

A ONE-DIMENSIONAL ANALOGY

In order to develop the de-reverberation theory presented in [2] to a global control strategy, we shall first consider the simple case of a lossless one dimensional wave guide, of cross section S. The wave guide is closed by perfectly reflecting terminations at each end, x=0 and x=L, such that the normal modes of the enclosed soundfield are associated with the halfwave resonances at frequencies f_n:

$$f_n = \frac{nc}{2L} \tag{1}$$

where n is an integer and c is the speed of sound.

At one end of the system is a (constant velocity) source which emits plane waves of sound into the wave guide. This "primary" source will be used as an analogy for a loudspeaker exciting a room. At the opposite end of the wave guide is a "secondary" source of plane waves, which will be used to actively control the field - this source is analogous to an active "absorber" in a room.

De-Reverberation in the Waveguide

The direct sound caused by the primary source at a listening point x within the length of the system is simply the rightwards propagating plane wave:

$$p_{direct}(x) = \frac{\rho_0 c}{S} U_p \, e^{-jkx} \tag{2}$$

where U_p is the volume velocity of the primary source and other symbols have their usual meaning. The total pressure is associated with the direct fields of both primary and secondary sources and the reverberant field in the waveguide. The total pressure at the listening point x can be written as:

$$P_{total}(x) = \frac{\rho_0 c}{jS} \frac{1}{\sin(kL)} \left[U_p \cos(k[L-x]) + U_s \cos(kx)\right] \tag{3}$$

where U_s is the secondary source volume velocity. De-reverberation at point x amounts [2] to forcing the total pressure at x (3) to equal the direct pressure (2). This suppression of the reverberant field (and the direct field due to the secondary source) is achieved by designing the secondary velocity as a function of the primary velocity:

$$U_s = H(\omega) \; U_p \tag{4}$$

The control filter which achieves de-reverberation is defined by:

$$H(\omega) = \left[\frac{e^{-jkx} \, j \sin(kL) - \cos(k[L-x])}{\cos(kx)}\right] \tag{5}$$

which has solution:

$$H(\omega) = -e^{-jkL} \tag{6}$$

When the primary and secondary sources are related as defined by H (6), the system is perfectly de-reverberated at point x. However, the above solution is independent of the point x, such that de-reverberation at any one point in a waveguide means that the whole system has been de-reverberated - the strategy is globally controlling the normal modes of the system. This is in sharp contrast to the findings of de-reverberation in a room [2], which was a strictly local technique. We shall return to this de-reverberation strategy, presenting a different interpretation, after consideration of alternative methods of suppressing the modes of the waveguide.

Active Absorption in the Waveguide

The passive suppression of resonant modes in dynamic systems is usually achieved by adding damping. The addition of damping in the actively controlled waveguide system in achieved by arranging that the secondary source should absorb acoustic power. The secondary source will be absorbing power when the real part of the acoustic impedance at the end x=L has positive value.

The acoustic impedance at the secondary source can be actively controlled using the principles described in [3,4], such that, for example, the impedance may be forced to value:

$$Z_L = \frac{\alpha \rho_0 c}{S} \tag{7}$$

where α is a positive scalar. The power absorbed at the secondary source is then:

$$W_L \propto \frac{\alpha}{\alpha^2 \sin^2(kL) + \cos^2(kL)} \tag{8}$$

Maximum Power Absorption in the Waveguide

Intuition would suggest that in order to suppress the acoustic modes of an enclosure it is desirable to absorb the greatest possible power from the resonant modes. If this approach is used with an active absorber, implementing a real surface input impedance, then the control law suggested (by differentiating the power expression (8), equating to the derivative to zero and solving for optimum α) is:

$$\alpha_{optimum} = \left|\frac{1}{\tan(kL)}\right| \tag{9}$$

This configuration, of a resonant acoustic space excited by a constant velocity source (a reasonable first order model of an electrodynamic loudspeaker), with an active device configured to absorb maximum power from the field, has highly undesirable properties from the perspective of sound reproduction. Far from damping the resonant modes of the system, absorbing maximum possible acoustic power encourages existing modes and actually generates some new modes.

This is illustrated by Figure 1, which shows the total acoustic potential in the waveguide with no secondary source and with the secondary source configured to absorb maximum power. The total acoustic potential was calculated by summing the squared pressures at 100 equally spaced points along the length of the waveguide. When the secondary is off, the resonances at f_n (1) are clearly seen (they fall at $k_nL = n\pi$). When the maximum power absorber is implemented the original modes are still present but new modes are created, such that there are now modes when $k_nL = n\pi/2$. The active absorber has added resonances at the set of "quarterwave" frequencies by implementing extremely low acoustic impedance at these frequencies (making the pipe look "open" at x=L) whilst maintaining high impedance at the original halfwave frequencies.

In conventional passive damping treatments of a resonant space we never see this phenomenon as it is impossible to make a reflecting wall look like a pressure release point by adding passive damping.

Optimal Cancellation of the Field in a Resonant Waveguide

The absorption of maximum acoustic power from a resonant system excited by a constant velocity source has been shown to be unhelpful in suppressing acoustic resonance. An alternative strategy for controlling the sound in an enclosure by cancellation has been described by Nelson and Elliott [5]. In the system currently under consideration, adjusting the secondary source such that:

$$H(\omega) = -\cos\left(\frac{\omega L}{c}\right) \tag{10}$$

will give the best possible reduction of the acoustic potential within the waveguide. The effects of this cancellation, expressed in terms of the total acoustic potential within the waveguide for fixed excitation, are illustrated by Figure 2. Again, Figure 2 shows the forced response of the waveguide with no control, for reference. When the optimal canceller is turned on, the total acoustic potential in the duct is considerably flattened with respect to frequency. Unfortunately, the optimal canceller leaves two effects, which limit its utility as a controller for the modes of a room designed for the reproduction of sound.

Firstly, the optimal canceller is able to exert considerable control over the "zero'th" mode of the room, tending to subtract from the advantage a small loudspeaker experiences when driving a room as opposed to free field [1]. Secondly, although the acoustic potential in the system is considerably reduced, the pressure at a point is by no means independent of frequency and the radiation impedance presented to the primary source is strongly frequency dependant and reactive (potentially a problem for real loudspeakers).

Characteristic Termination of the Waveguide

If the secondary source is arranged to give an exactly anechoic termination to the waveguide, by forcing the acoustic impedance to :

$$Z_L = \frac{\rho_0 c}{S} \tag{11}$$

then the power absorbed is perfectly independent of frequency. This is because the characteristic termination has prevented the reflections of direct sound from the x=L end which cause standing wave interactions leading to the modes. The total acoustic potential in the characteristically terminated waveguide is illustrated in Figure 3, with the uncontrolled trace again shown for reference.

Since the impedance of the characteristic termination is known, we can use standard waveguide theory to relate the pressure at the termination to the primary velocity :

$$p_{total}(L) = \frac{\rho_0 c}{S} e^{-jkL} U_p \tag{12}$$

If this expression is substituted into the total pressure equation (3) a relationship between primary and secondary velocities for the characteristic termination results:

$$U_S = -U_p e^{-jkL} \tag{13}$$

Notice that this is exactly the same relationship as for de-reverberation in the duct (6).

ACTIVE GLOBAL CONTROL OF REVERBERATION IN ROOMS

The de-reverberation of constant cross section lossless waveguides, operating at frequencies below plane wave cut off, is simply achieved by characteristically terminating the waveguide. This approach cannot be directly applied in a room as the concept of characteristic termination is of no meaning in that context. Further, it is clear that the waveguide was easy to de-reverberate as the direct fields of the primary and secondary and the reverberant field were of the same plane wave form. It has been demonstrated in [2] that the different locations of the sources in a room, relative to the modes, makes global de-reverberation with a single secondary source impossible as the fields can only be matched at one point.

In spite of these difficulties, we shall attempt to generalise the characteristic impedance concept used in the one dimensional problem to define a surface impedance for an active absorber which achieves a measure of global control of room modes.

It is an established result that the impedance of an active absorber which is intended to absorb maximum power should be the negative conjugate of the radiation load presented to the absorber [5,6]. (This is not visible in the analysis of maximum power absorption from the waveguide, above, as the radiation load in that contrived situation is imaginary). Similarly, an optimal *canceller* should offer surface impedance of :

$$Z_{opt.cancel} = \frac{j\rho_0 c}{S} \tan(kL) \qquad (14)$$

which is the radiation impedance which the device would experience in an open pipe of length L. It is seen to be useful to characterise the various configurations possible for the active termination using radiation loads (not least because these can be measured automatically by an intelligent active system [4]).

If the *characteristic* termination (11) is interpreted in this way, it is seen to represent the negative (conjugate) of the radiation load which would be experienced in an infinitely long waveguide. This represents a one-dimensional "free-field" - the characteristic termination implements an impedance equal to the *negative conjugate of the free field radiation impedance.*

In a three dimensional application it is feasible to configure a small active acoustic absorber to implement the *negative conjugate of the radiation load it would experience in free field.* In practice the absorber would be mounted against a back wall, such that the radiation load considered should be that experienced when driving a half space. Such a configuration has been reported [3] and tested in the laboratory.

Figures 4 show a simulation of the pressure distribution in a room, excited by a constant velocity source near the centre of one wall. The source is driving the room at the frequency of the lowest normal mode. In Figure 4a the primary alone is operating; the clear halfwave resonance is seen. In Figure 4b a second source, near the centre of the opposite wall, is controlled such that its surface impedance is the negative conjugate of the radiation load the source would experience firing into half space; the analogy of the one-dimensional "characteristic termination". The pressure field shows a much smoother spatial dependence, indicating that the quality factor of the first mode has been significantly reduced. This damping of the mode is clearly visible in the steady state pressure response at a single point in the room, when a strong resonant peak is replaced by a smooth curve, as illustrated by Figure 5. Note that some of the higher modes of the space cannot be influenced by the secondary active source, as it is not coupled into these modes due to its position. This problem can usually be overcome by placing two devices in corners of the room.

CONCLUSIONS

It has been demonstrated that the acoustic modes of bounded acoustic spaces can be strongly influenced by the introduction of secondary active sources. If these sources are configured using conventional active control strategies, to cancel the enclosed field or absorb maximum power from the field, the consequences can be damaging to reproduced sound. It is, however, possible to configure an active source such that it exerts a useful degree of control over the low frequency acoustics of a room, reducing the spatial and temporal colorations introduced by discrete normal modes.

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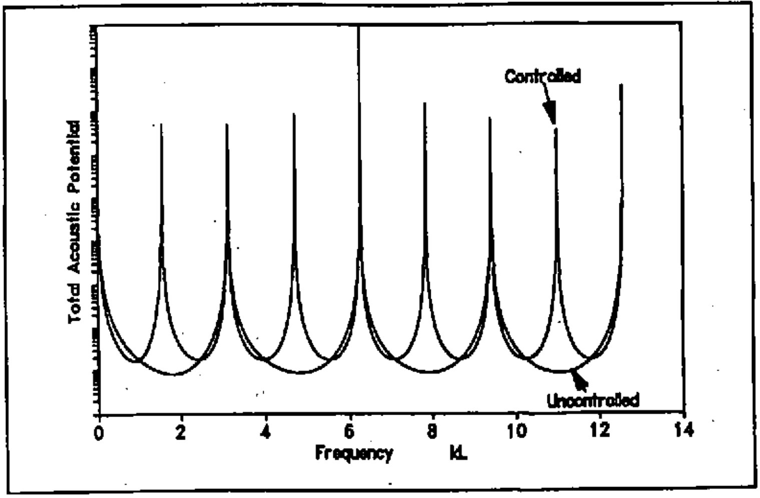

Figure 1 Total Acoustic Potential (arbitrary reference) in a waveguide with active controller configured for maximum absorption.

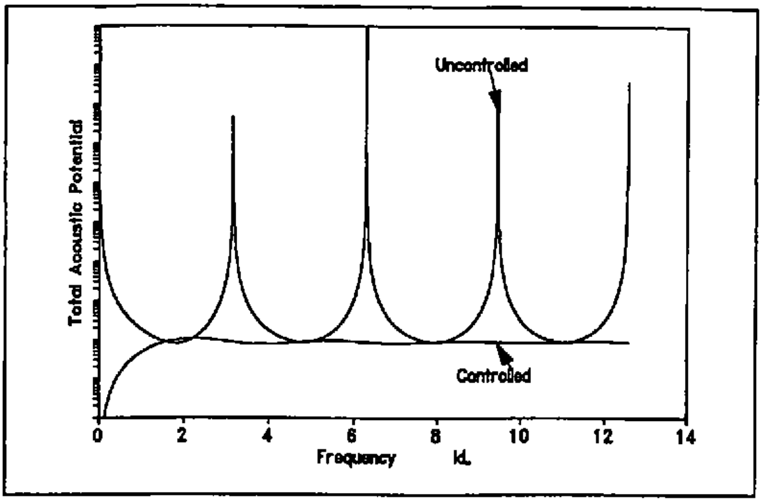

Figure 2 Total Acoustic Potential (arbitrary reference) in a waveguide with active termination configured for optimum cancellation.

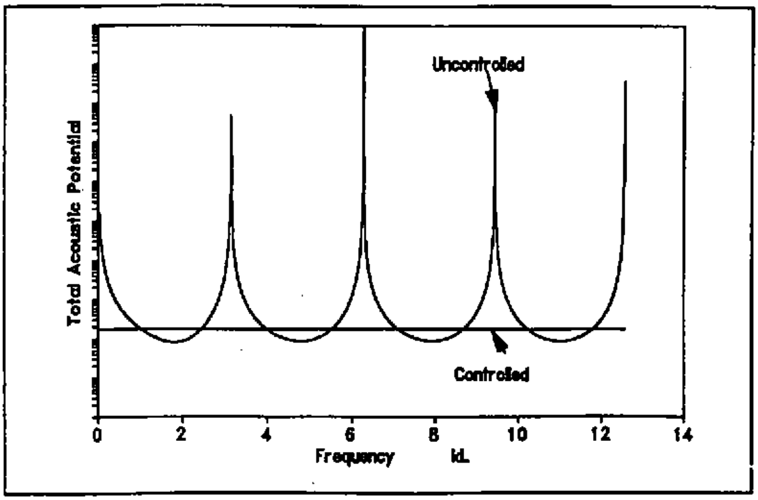

Figure 3 Total Acoustic Potential (arbitrary reference) in a waveguide with characteristic active termination.

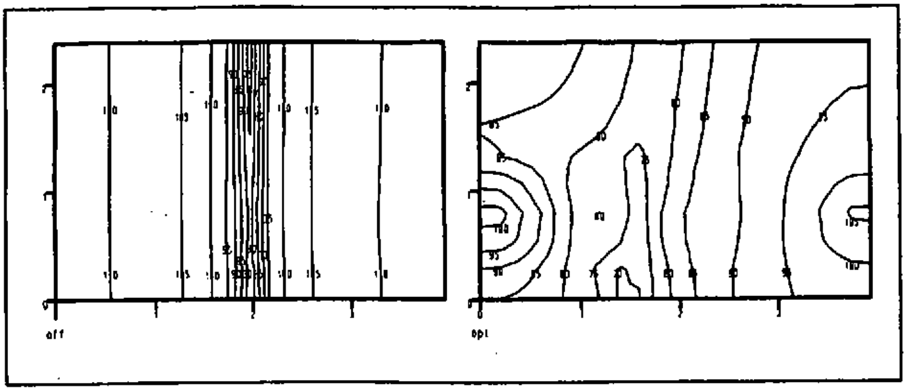

Figure 4 Pressure Distribution at the First Mode Frequency of a Room.

a) Uncontrolled
b) with Active Absorption

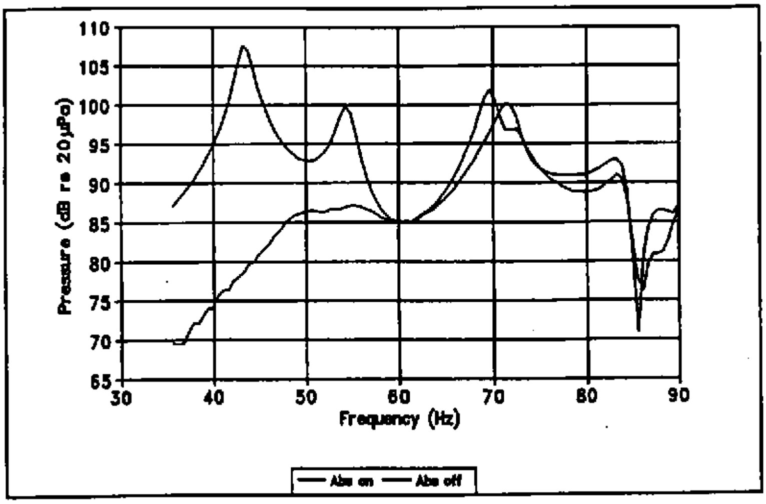

Figure 5 Magnitude Pressure Response at a Point in a Room, with and without Active Absorption.