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General introduction to the physics of sound in enclosures

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INTRODUCTION

The behaviour of sound in enclosures is not a straight forward subject. A reasonably simple theory (the reverberant field theory) does exist but the circumstances under which this simple theory may be safely applied are limited. Factors such as: the size of the room, the frequency of the sound waves and the time history of the sound are all relevant to the actual behaviour of the sound as contrasted with the behaviour that we predict from the reverberant field theory.

It must be stated that the reverberant field theory is not a physically correct theory of the behaviour of sound, such a correct theory is the modal theory. However the modal theory is not an easy theory to use and so in this talk I shall discuss mainly the former theory and shall try and show what allowances should be made for the modal theory and the time history effects.

Reverberant field theory

Sound may be regarded as a gas of particles that are produced by a source and these particles travel through a room at some 340 metres per second and bounce off the walls and so form a uniform, diffuse cloud of sound energy. The reverberant field is formed in most enclosures provided that the enclosure is not too 'dead' (has a lot of sound absorbing surfaces). The formation of the field implies that the loudness of a sound field throughout a room is independent of the position of the observer. You will be aware that this is not always so and in fact the reverberant field is not alone in a room there also exists the direct sound from sources in the room. Near a source this direct sound will predominate and the sound level will then obey the inverse square law. However at some distance from the source the level of the direct field will fall to equal the reverberant field level and beyond this 'Direct field radius' the reverberant sound will dominate.

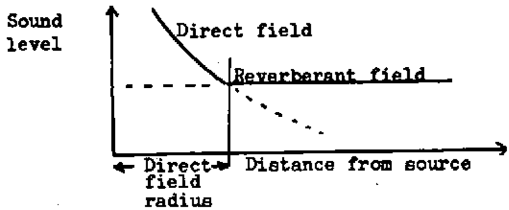

Fig 1. SOUND LEVEL IN A REVERBERANT ROOM NEAR A SOURCE.

Note that if 'The direct field radius' of a room exceeds the dimensions of the room then no dominant reverberant field will exist within the room and any noise problem within the room will have to be treated as if it were a free field problem and not a room acoustic problem at all.

Some relationships will now be stated concerning the behaviour of uniform diffuse fields.

First of all the energy density in a field E is found by considering the equilibrium between the sound power input to the room P from the source and the sound power lost from the room through absorbing processes. These processes are lumped together and given an effective area A (measured in sq.metre Sabins)

$E = 4P/CA$ $\qquad\qquad$ C = speed of sound

The factor C/4 is the effective speed of sound through the area A (see p.537 of ref (1))

When the source of sound is suddenly switched off the field will die away as the energy is absorbed by the area A. This does not happen instantaneously but is controlled by equation:

$$VE(t) = (C/4)AE(t)$$

which has solution

$$E(t) = E_o \exp(-CAt/4V)$$

Thus the sound energy decays exponentially, however the sound level in decibels is related to the logarithm of E(t) and this falls away linearly with time:

$$L(t) = 10 \log(E(t)/E_o) = -10\ CA \log(e)t/4V$$

The reverberation time Rt of the room is the time taken for the level L(t) to fall by 60 decibels and this is given by

$$Rt = (24V/CA \log e)$$

The reverberation time is an important acoustic parameter of a room, it is used as a guide to the quality of the room for purposes of speech, music entertainment. It can be seen that it is a function of the Volume of the room and the amount of sound absorbtion in the room

Purpose	Reverberation time (seconds)
Orchestral Music	1.8 - 3.2
Light music	0.9 - 3.2
Theatre/Cinemas	0.4 - 1.1
Domestic Environment, Offices	0.5 - 1.0

Direct field radius

The direct field energy density at radius r may be given by $P/4\pi r^2C$. By equating this to the reverberant field energy the direct field radius R may be found:

$$R = (A/16\pi)^{\frac{1}{2}}$$

or in terms of the reverberation time:

$$R = (3V/(2\log(e)\pi cRt))^{\frac{1}{2}}$$

This formula is a rough guide and should be used with care, it assumes an effective spherical radiator. R is increased when a source has a directional characteristic. For example for a source placed in a corner of a room, free to radiate over one octant the value of R will be increased by almost three.

Summary of Reverberant field theory

Sound in a room forms a reverberant field, this field is usually dominant except within the direct field radius of a source. The reverberant field is uniform and has a sound level controlled by the power of the source and the amount of sound absorbtion in the room. When the source is switched off the reverberant field dies away linearly with time. It is important to distinguish for any given noise problem whether the direct field or the reverberant field is involved. If the direct field is involved measures aimed at reducing the level of the reverberant field such as sound absorbing walls will not be effective in reducing the noise. In the reverberant field itself sound can be controlled by indirect means such as the addition of sound absorbing material.

The Effects of the Modal nature of sound fields

The simple theory given above is subject to two major inadequacies the first of these is the effects of discrete room modes. Within any room certain preferred patterns of sound waves exist. These preferred patterns (or modes) are analogous with the wave patterns preferred on a guitar string except that the 3 dimensional nature of the room makes them more complicated. Successive modes each have their own frequency which for a rectangular room are given by:

$$f = C/2((l/lx)^2 + (m/ly)^2 + (n)lz)^2)^{\frac{1}{2}}$$

where lx, ly and lz are the room dimensions C is the speed of sound and l, m, n are integers in the range 0→∞ each combination of values of l, m, n (except(0,0,0)) represents a mode. A typical distribution of modal frequencies is shown in the diagram:

Figure 2.

Mode density as a function of frequency

The modal density over a given frequency band increases as the square of the frequency and it is seen that at low frequencies only a small number of modes exists over a mode frequency range. The effect of this is that at high frequencies where numerous modes exist in a given frequency band the behaviour of the room tends to be the average of the individual mode behaviour. This average behaviour is similar to the reverberant room behaviour outlined above. At low frequencies however the response of the room is dominated by only a few modes and this leads to non uniform response and the sound in the room is a mixture of direct sound, echoes and modal resonances. When such modes occur coloration and reinforcement of sound occurs and it is necessary to introduce measures aimed specifically at controlling the offending mode itself. This involves identification of the mode and the placing of sound absorbing material at suitable points in order to damp out the mode. Echoes also need such individual attention.

Room shape effects

It is thought that irregular shaped rooms and the diffusion of sound and there is some truth in this in that irregular shape can spread the initial echoes to all parts of the room reducing initial delay time and increasing uniformity. However it has been clearly shown (2) that the irregularities in sound level produced by modal behaviour cannot be eliminated by this means. The mode shapes are made more complicated by the changed boundary conditions but the difference between the maximum and minimum sound levels remains unchanged. Room shape therefore, does not affect the reverberant field. It can effect echoes and initial delay times.

References

1)A. Wood 'Acoustics' (Blackie)

2)P. E. Doak, Acustica, Vol.9 1959 'Fluctuations of the sound pressure level in rooms'.