Proceedings of The Institute of Acoustics

SURFACE ABSORPTION AND SCATTERING IN ENCLOSURES

MURRAY HODGSON

DEPARTMENT OF ARCHITECTURE, UNIVERSITY OF CAMBRIDGE.

Introduction

In this paper the effects of surface absorption and sound scattering and their distributions on the reverberation time (RT) and sound propagation (SP) in various enclosures are discussed using theoretical results of Kuttruff and others supported by this author's experimental findings (particularly in the spoken presentation). Results are discussed in relation to proportionate enclosures (i.e. enclosures with the three dimensions similar - e.g. reverberation chambers, regular rooms, concert halls) and to disproportionate enclosures (e.g. factories, open-plan offices, corridors).

Sabine's or, more generally, Eyring's theories are commonly used to predict the RT and SP in enclosures. These theories assume that the enclosure is empty, proportionate and of uniform surface absorption. The mean free path (mfp) between surface reflections in the enclosure is 4 x volume/surface area (mfp = 4V/S) and the sound energy density and directional distribution are uniform throughout the enclosure - that is, the field is diffuse. The theories predict a sound decay decreasing exponentially with time (straight decay curve on logarithmic scale) and an RT proportional to the mfp and inversely proportional to the total surface absorption. Further, the sound level in the enclosure is the sum of a direct and a constant reverberant field.

Kuttruff /1/, on the basis of Monte-Carlo computer simulations of sound decays in enclosures which showed up short-comings of the classical theories, extended them to take into account the enclosure free-path distribution and of the distribution of surface absorption. The free-path distribution was described by its variance (γ^2) with increasing variance resulting in decreasing RT. The distribution of absorption was taken into account by considering the amount of energy incident on each absorbent surface.

According to the above theories, measurements of RT can be used to determine an average surface absorption and absorption coefficient for the enclosure. Most absorbent surfaces have an absorption which varies with incident angle. Measurement of their absorption in a diffuse field determines the diffuse-field absorption given by Paris' formula /1/. The absorption of such a surface in a non-diffuse field will be different and will result in a measured RT different from that predicted by Eyring's theory.

Empty enclosures with specularly reflecting walls and low, uniform surface absorption

a. Proportionate (e.g. empty rev chambers, regular rooms) - In such enclosures the mfp =4V/S and the field is diffuse /1/. Eyring's theory and its implications hold.

b. Disproportionate (e.g. large empty flat rooms, empty corridors, tunnels) - In these enclosures the mfp $\neq$ 4V/S /2/ and γ^2 increases with enclosure aspect ratio /1/. The field is non-diffuse and the sound decay is non-exponential. For example, in duct rooms (infinite length, height or width) and flat rooms (infinite length and width) sound decays according to $t^{-1}\exp(-k_1 t)$ and $t^{-2}\exp(-k_2 t)$ laws, respectively /2/. Use of Eyring's theory is not valid and it is difficult, though not impossible /2/, to derive an average surface absorption from a decay curve. Regarding SP, there is no constant reverberant field. Levels drop continuously with distance down any large dimension.

Empty enclosures with specularly reflecting walls and non-uniform surface absorption

The case of most interest and often considered theoretically is that of an enclosure with one surface highly absorbent.
a. Proportionate (e.g. rev chambers with absorbent sample, concert halls, regular rooms with carpets) - In rectangular enclosures with one surface highly absorbent sound decays according to a t^{-1} law. In rev chambers the walls can be splayed making the field more diffuse and resulting in exponential decays. However, in both cases, Eyring's formula can be very inaccurate, generally overestimating the RT (underestimating the absorption) /3/.
b. Disproportionate (e.g. empty factories with panel roofs, carpetted corridors)- In such enclosures the situation essentially is one of sound propagation over an absorbent surface. RTs and, especially, SP levels which are higher or, more commonly, lower than would be expected from the diffuse field absorption can occur. The field is highly non-diffuse and the sound decays non-exponentially. SP levels decrease at all source distances relative to the low absorption case. The decrease increases with absorption and source distance.

Sound scattering in enclosures

a. Surface scattering - this is realised by varying the shape or the acoustic impedence of the surfaces. For theoretical treatment scattering is assumed to occur according to Lambert's Law /1/. This is difficult to achieve in practice. On the other hand there is always some surface scattering in enclosures.
b. Volume scattering - this is realised in rev chambers by the use of suspended planar or solid diffusers. In factories the machines, stockpiles, barriers etc provide volume scattering. In open-plan offices scattering results from the presence of furniture and screens. For theoretical treatment /4/ scattering is assumed to be omnidirectional though, in fact, the details of scattering from any object are complicated. The scattering ability of volume scatterers is described by the total scattering cross-section per unit volume (Q). The mfp between scatters is Q^{-1}. Absorption by scatterers is described by the average scatterer absorption coefficient. In an unbounded region containing homogeneously distributed scatterers the impulse response is not a delta function. SP levels are higher near a source due to backscattering and lower far from a source than in a free field. Scatterer absorption has an effect on the sound field similar to that of volume (e.g. air) absorption.

Scatterers in enclosures increase the diffuseness of the sound field. Clearly this serves no useful purpose in proportionate enclosures with low surface absorption since their fields are already diffuse. However, it is worth noting here that the decrease of RT at low frequencies that commonly is observed in empty rev chambers when planar diffusers are introduced /5/ can only be caused by absorption of sound by the diffusers due to panel vibration.

In enclosures of any shape with diffusely reflecting walls the mfp is the same as with specularly reflecting walls. However γ^2 increases with aspect ratio. If the surface absorption is uniformly distributed the sound field is diffuse. A direct and constant reverberant field exists /1/.

<u>Scattering in enclosures with non-uniform absorption</u>
a. Diffusely reflecting walls /1/ - In such enclosures the scattering increases the diffuseness of the sound field resulting in exponential decays. The RT and the accuracy of the Eyring RT prediction depend on the amount and distribution of the absorption and the enclosure shape. In proportionate enclosures (e.g. some rev chambers with an absorbent sample) Eyring's prediction is accurate. In disproportionate enclosures with one surface highly absorbent the Eyring RT is lower (higher) than the actual RT if the absorption is on a small (large) surface. Schroeder and Hackman /6/ found that the RT in a two-dimensional disproportionate enclosure, containing an absorbent sample can vary up to 40% depending on the sample's position.
b. Volume scattering (e.g. rev chambers with an absorbent sample and diffusers, factories with panel roofs, open-plan offices, carpetted corridors with furniture)- The effect of volume scattering in an enclosure depends on the relative mfp's between wall and scatterer reflections. Volume scatterers do not change the mfp between wall reflections but greatly modify the free-path distribution, increasing γ^2 /1/. As has been shown theoretically by Kuttruff /7/ for rev chambers and Jovicic /8/ for flat and duct rooms and experimentally verified by Benedetto et. al. /5/ in rev chambers, increasing Q increases the diffuseness of the sound field causing more energy to be incident on the absorbent surfaces. The sound decay becomes more exponential /1/ and the RT decreases. That is, the total effective surface absorption increases. SP levels near a source remain approximately unchanged; the increase due to backscattering is cancelled by the decrease due to the greater effective absorption. Levels far from a source decrease sharply. The decrease of RT and of large-distance levels caused by the combination of scattering and absorption is significantly greater than the sum of the decreases caused by the absorption and scatterers individually! Kuttruff /7/ and Jovicic /8/ further showed that there is an optimum value of Q for maximum diffuseness and effective absorption. If Q is further increased sound energy becomes increasingly 'trapped' between the scatterers, decreasing the amount of sound incident on the absorbent surface and increasing the RT.

The figure shows the change of RT and of 1kHz octave SP measured in a factory of average dimension $45 \times 40 \times 4 m^3$ with a double-panel roof when first 25 and then a further 25 paper-roll-handling machines were introduced. The RT decreased by about 30% at all frequencies after introduction of each set of machines. The total decrease corresponded to an increase of third octave absorption of 520-900 m^2 - that is, $10-18 m^2$ per machine. The actual third-octave single machine absorption was measured to be about $1 m^2$. Further the SP level at 60m decreased by 16dB. Clearly reduction of RT and steady-state levels due to scattering can be considerable. This suggests great potential for the use of scattering in combination with absorption for noise reduction in factories and other enclosures.

<u>Influence of the volume scatterer distribution</u>
Measurements of RT were made in a 1:16 scale model of a factory of average dimensions $118 \times 45 \times 9 m^3$ with an absorbent roof and three distributions of volume scatterers. The model contained 140 cylindrical scatterers distributed homogeneously throughout the whole space, the lower half-space and over the floor. The RT did not vary significantly for the three distributions. This suggests that it is the amount of scattering and not its distribution that is important. One practical implication is that diffusers in a rev chamber can be suspended above head height, facilitating

working in the chamber, with no detrimental effects.

Conclusion

In empty enclosures with specularly reflecting surfaces the sound field is diffuse and Sabine/Eyring's theories hold only if the enclosure is proportionate and of uniform surface absorption. In disproportionate enclosures or enclosures with non-uniform surface absorption the field is non-diffuse and predictions using classical theories are inaccurate. Surface or volume scattering increases the diffuseness of a sound field and increases the effective absorption of any surface. The resulting decrease of RT or sound level can be considerable and suggests potential use of scattering in combination with absorption in enclosures; particularly factories.

References

/1/ H. KUTTRUFF, Room Acoustics, Applied Science Publishers Ltd., London 1973.

/2/ M.V. SERGEEV, Scattered sound and reverberation on city streets and in tunnels, Sov.Phys.Ac 25 (1979) 248-252.

/3/ M.R. SCHROEDER, Digital simulation of sound transmission in reverberant spaces, JASA 47 (1970) 424-431.

/4/ H. KUTTRUFF, Uber Nachhall in Medien mit unregel massig verteilten Streuzentren, insbesondere in Hallraumen mit aufgehangten Streuelementen, Acustica 18 (1967) 131-143.

/5/ G. BENEDETTO, E. BROSIO, R. SPAGNOLO, The effect of stationery diffusers in a reverberation room: an experimental study, Applied Acoustics 14 (1981) 49-63.

/6/ M.R. SCHROEDER, D. HACKMAN, Iterative calculation of reverberation time, Acustica 45 (1980) 269-273.

/7/ H. KUTTRUFF, Sound decay in reverberation chambers with diffusing elements, JASA 69 (1981) 1716-1723.

/8/ S. JOVICIC, Anleitung zur Vorausbestimmung des Schallpegels in Betriebsgebauden, Report for Minister fur Arbeit, Gesundheit und Soziales des Landes Nordrhein-Westfalen, 1979.

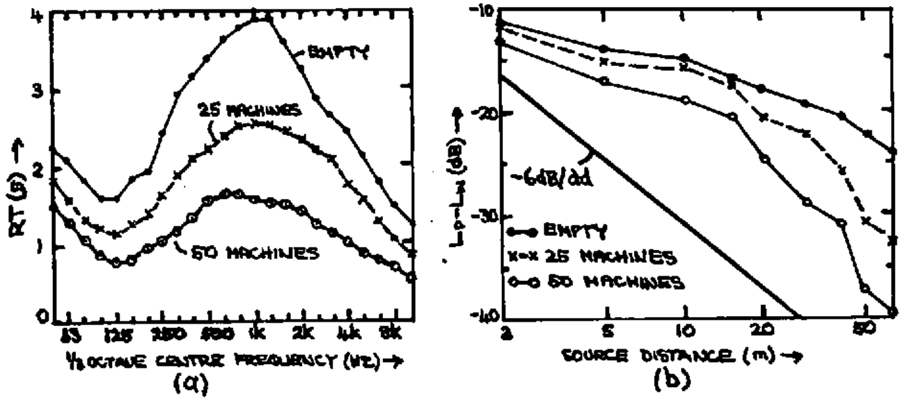

FIGURE - EFFECT OF MACHINES ON a) RT b) 1kHz OCTAVE SP IN A FACTORY.