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ACOUSTICS OF THE OPEN PLAN

PRIVACY IN LANDSCAPED OFFICES: THE EFFECT OF ATTENUATION RATE

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1. *SUMMARY OF SOME PROPAGATION MEASUREMENTS*

The propagation of sound in a landscaped office is characterised chiefly by the rate of attenuation of its energy as it radiates across the room; that is, by how quickly the noise level reduces as one moves away from the source. We have been concerned over the post three or four years with measurements of this attenuation rate.

Our earliest measurements were made on a rather simple model and revealed a behaviour somewhere between the uniform field of a fully reverberant rate near to the source. In subsequent measurements in a full size office the observations were largely borne out. An initial fall, at very short distances from the source, of dB for distance doubling was followed by a "plateau" where the attenuation reduced to about 3 dB for distance doubling. At greater distances the attenuation rate increased again, approaching 6 dB for distance doubling. The measurements were made with octave bands of noise in an attempt to blanket interference effects. At high frequencies the irregularities in the attenuation curve become less pronounced and attenuation close to inverse square law was observed at all distances.

Further measurements in another office showed attenuation rates in excess of 6 dB for distance doubling, beyond the edge of the "plateau". Similar results have been reported by other workers, in other offices. Since this phenomenon has a crucial bearing on the privacy of speech in landscaped offices, its origin has been the subject of intensive theoretical investigation.

2. *IMAGE THEORIES FOR THE SOUND FIELD IN LANDSCAPED OFFICES*

The wave approach to the consideration of the sound field in a landscaped office is ruled out by the complexity of the boundary conditions. For this reason attempts at theoretical study have been based on an image row concept in which the source and its images are taken to be imaged repeatedly in the floor (or working plane) and the ceiling, to form a line of sources of varying strength. The sound field at any point is then computed by summing the contributions of the images.

The simplest form of this concept is one in which energy only is considered (phase ignored), and the strength of the images is reduced by a constant reflection factor for each reflection involved in the formation of the image. The variation of reflection factor with angle is ignored at this stage. An image formed by no reflec-

tions is the ceiling and no reflections in the floor contributes to the total intensity at the point of observation, and intensity given by:

$$\Delta I = \frac{Wo.Rc^{nc}.R_f^{nf}}{4\pi D^2}$$

where Rc and R_f are the reflection factors for the ceiling and floor, and D is the distance to the point of observation from the imaginary position of the image. Calculations based on this simple approach give results which, for typical values of reflection factor, exhibit the main features of the earliest measurements, namely a plateau at mid-distances followed by more rapid attenuation, but which is never more than at a rate of 6 dB for distance doubling.

The inability of this approximation to predict the greater-than-inverse square law attenuation observed in some landscaped offices required us to refine our approach. One modification attempted was to improve the earlier assumption of a constant reflection factor by calculating the reflection factor appropriate to each image from the angle of reflection involved and on the assumption that the boundary surfaces were locally reacting. Thus the R_c and R_f of equation 1 were calculated for each image from assumed values for the impedances of the surfaces. Because, of the increase in absorption which occurs for a local reactor at about 60° angle of incidence that apparent strength of low order images falls at distances such that the angles of incidence are in this range. This leads to an increase in the observed rate of attenuation at these distances, as the contribution of the low order images is lost. However, while attenuation curves obtained on the basis of this calculation do show slopes a little greater than 6 dB for distance doubling, the sound level computed on this basis cannot fall below the level that would be obtained in free space, since the energy received direct from the source is unmodified.

In a few cases the intensity of the sound field in a landscaped office at a large distance from the source has been found to be less than would be expected in free space. That is to say, the attenuation has been found to be greater than inverse square law overall, rather than just in a restricted range. Neither of the preceeding theories can account for this. Unless we introduce scattering and diffraction from irregularities in the surface, such excess attenuation can only be explained on the basis of a bread band interference effect. To get this possibility into the image model it is necessary to move away from an intensity/source power approach and to consider the amplitude and phase of the contributions from the images. It now becomes necessary, for each point of observation, to sum the complex pressure amplitude $\tilde{p}n$ contributed by each image, where:

$$\tilde{p}n = \frac{po}{rn}./\tilde{R}c/^{nc}./R_f/^{nf}.e^{-ikrn}.e^{i\psi cnc}.e^{i\psi_f nf}$$

Here ψ is the argument of the complex pressure reflection coefficient $\tilde{R}$, r_n is the distance from the image under consideration, n is the number of reflections involved in the formation of the image and k is the wave number for the frequency considered. R_c or $_f$ will of course depend on the impedances of the surfaces, which we may assume to be locally reacting, and also on the angle of incidence involved in the reflections which form the image.

One would expect interference effects to produce constructive as well as destructive regions, but the rapidity with which these alternate in space decreases as the source/image distance becomes *small compared to the distance to the point of observation. Furthermore, the phase shift introduced on reflection at a locally reacting surface becomes increasingly negative at shallow angles of incidence. From this arises the possibility of offsetting the reduction of path difference between source and image, so as to keep their contributions to the total pressure out of phase.*

Calculations with this model require long periods of computer time since each summation, involving the calculation of amplitude and phase shift for large numbers of images, must be repeated a number of times for a range of frequencies in order to simulate bands of noise. It becomes difficult to retain an intuitive appreciation of the effect of varying surface impedances and ceiling height, but it is to be hoped that acquisition of results for a wide range of input data will eventually make this possible. This may then make possible the specification of acoustic properties required of a landscaped office ceiling to produce specific attenuation rates.

3. FACTORS AFFECTING PRIVACY IN LANDSCAPED OFFICES

The reason for the importance of the shape of the attenuation versus distance curve, and for wishing to be able to control it by design, lies in its effect on the privacy conditions in landscaped offices. In the first place, the attenuation curve will determine the noise level received at a point from each source in the room, and will consequently control the total noise level. A naive view might be that a large attenuation rate is to be preferred in so far as it will reduce the overall noise level.

If we consider an office in which, for simplicity, occupants are spaced at regular intervals and all have equal sound powers, the intensity level contributed at the point of observation by the occupants in a ring of radius R and width ΔR is given by:

$$IL_R = IL_o - 10X \log_{10} R + 10\log_{10} \frac{2\Pi R\Delta R}{A}$$

where IL_o is the intensity level generated by one occupant at unit distance, X is the exponent in the relationship determining the overall attenuation rate (e.g. 2 for inverse square law), and A is the area allowed per person. It will thus be seen that the total noise level (summing for all R) will depend on the strength of the individual sources IL, the density of occupation $^1/_A$, and the variation of attenuation exponent X with distance from the point of observation.

The degree to which the speech of the nearest individual is overheard in a landscaped office will depend partly on the loudness of received speech in the various octave bands, and again

$$IL_{overheard} = IL_o - 10X\log_{10} R_{nearest} \quad \text{for each band}$$

Thus if X and $R_{nearest}$ are both large the received intensity will be small. Since X will not vary much with frequency the spectrum of the received speech will not be modified, as it is when it passes through a wall. This means that there is no loss in intelligibility by frequency distortion of overheard speech in the landscaped office, as there is in partitioned offices. Notice also that the distance to the nearest neighbour $R_{nearest}$ will be proportional to $\sqrt{A}$.

The only other factor which can be used to control intelligibility is the amount of background (masking) noise. As we have seen above, this will depend on the value of X for larger distances, and on the denisty of occupation $1/A$. For privacy we require that the level of nearby speech should not exceed by too great a margin the background noise from the sum of distant sources. Expressing this mathematically:

$$\left\{ IL_o - 10X_1 \log_{10} R_{nearest} \right\} - \sum_N (IL_o - 10X_N \log_{10} R_N)$$

should not be too great in each frequency band. The summation indicates that background noise is made up of the combination of all the sources too far away to be perceived individually.

Two tentative conclusions can be drawn from this statement. First, if X is constant for all distances, an increase in A (area per person) will result in a greater fall in background noise ($\propto \log 1/A$) than in nearby speech level ($\propto \log 1/\sqrt{A}$) with a consequent <u>reduction</u> in privacy. Notice secondly, that if the attenuation rate X, is smaller for short distances (as with the plateau described above) than for large distances (and particularly if > 6 dB attenuation for distance doubling is obtained in the far field), there will be less privacy than if the converse were true. Greater privacy will result in rooms in which X is large initially, but less for distances greater than about 3m.

All the foregoing assumes that there is no "artificial" noise present. Electronic or air-conditioning sources can be used to provide masking noise if "natural" noise is inadequate, though there is obviously a limit to the extent to which masking noise will be tolerated. It should also be noted that screens which do not extend to full ceiling height may act to reduce privacy in that they may reduce background noise from distant sources to a greater extent than speech levels from neighbours.