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MODELLING AUDITORIUM ACOUSTICS WITH LIGHT

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1. INTRODUCTION

Successful acoustic design of auditoria for speech or music requires a modelling technique that is sufficiently detailed to include the relevant parameters, without being overly complex. Results from the model can then be applied to various objective measures of sound quality from which design choices could be made. These measures could be the distribution of sound energy within the auditorium, reverberation time, subjective spaciousness [1] and clarity index [1]. Two kinds of well-established models are used: the ray tracing technique [2,3] and small scale physical acoustic models [4]. The acoustic models require arduous modelling of the surface materials and can have problems at high frequencies for large auditoria because of the absorption of sound by the air. There can also be difficulties obtaining the correct directivities for the sound sources.

However, these high frequency problems with large auditoria are not experienced with small scale models in which light replaces sound. The aim here, therefore, is to introduce a small scale light modelling technique which provides more information than previous light models [5], giving the intensity, time delay and direction of reflections and reverberant background level. The method is similar in principle to the ray tracing technique and can be used to obtain the same objective sound quality parameters.

A finite light source is used within a mirrored enclosure. The light energy or luminance at an observation point is analagous to the sound energy at a point. The focused image of the light source and reflected image sources is the decomposition of the incident light into its directional components. From a photograph, the size and illuminance of each image source can be measured to give bòth the energy and time delay of each equivalent acoustic reflection following an impulse from which the clarity index could be obtained.

2. OPTICAL MODELLING THEORY

2.1 Neutral density filters

Neutral density filters [6] (used to model acoustically absorptive material) usually consist of black, colloidal carbon in a transparent, unsupported gelatine film. The filtering of light is only wavelength independent for visible light. The efficiency of the filter is described by the density D or transmittance τ which for normally incident light is,

$$D = \log_{10}\frac{\varepsilon_i}{\varepsilon_t} = \log_{10}\frac{1}{\tau} \qquad (1)$$

where ε_i, ε_t are the incident and transmitted irradiances (analagous to acoustic intensity).

2.2 Image source method

The perceived size and surface brightness of a light source and its reflected images can be calculated using the image source method, in which the multiple reflections of light from mirrored surfaces can be replaced by an infinite array of image sources. In Figure 1 a finite light source is located between two parallel mirrors. Also included in the figure are the first two pairs of image sources caused by the mirrors. The light reaching the observer from the real source travels a distance r_0, whereas the light from the n^{th} image source travels a distance r_n. Consider, for example, the light apparently emanating from the second image source, travelling the path SABO from the real source via two reflections. The path SABO has a length r_2 which also corresponds to the distance between the second image S2 and the observer.

Figure 2 gives the view seen by the observer in Figure 1. The real source in the centre appears to have a dimension d_0, while the second image source appears to have a smaller size d_2 on account of the greater path length r_2. In general, then, by the law of perspective the n^{th} image source will have a dimension d_n given as

$$d_n/d_o = r_o/r_n \qquad (2)$$

where r_n is the distance between the n^{th} image and the observer. The wave propagation times, t_o, t_n, from the two sources to the observer are therefore

$$t_n = d_o/d_n . t_o \quad . \qquad (3)$$

The illuminance of the image sources also decreases with increasing value n due to factors illustrated in Figure 3. An omni-directional source of radiant flux ϕ_e watts causes incident light of irradiance $E_e(r)$,

$$E_e(r) = \phi_e/4\pi r_n^2 \ , \qquad (4)$$

to fall upon a lens of area A at distance r_n. The flux passing through the lens ϕ_i is the product of the irradiance and the apparent lens area A cosθ.

$$\phi_i = \phi_e A \cos\theta/4\pi r_n^2 \qquad (5)$$

The lens focuses all the incident flux into the image of dimension d_n, giving an image illuminance I_n inversely proportional to the image area, i.e.

$$I_n \,\alpha\, \phi_i / d_n^2 = \phi_e A \cos\theta / \left(4\pi r_n^2 d_n^2\right) \tag{6}$$

However, from equation (2) the denominator is constant. Therefore, the illuminance I_n is simply proportional to $\cos\theta$, and independent of the distance to the observer of the real sources or any image source, i.e. for a perfect mirror the real sources and its images appear equally bright. In practice, the image sources will appear to grow dimmer with increasing order, but this is controlled by the number of reflections from the mirror. If the mirror has a reflectance of α then the n^{th} image source intensity I_n will be attenuated by n previous reflections, i.e.

$$I_n = \alpha^n I_o \tag{7}$$

where I_o is the real source illuminance in the image plane.

In the centre of Figure 2 is the rectangular image of the real source. This particular field of view is sufficient only to include four image sources and background. The total luminance ϕ received is simply equal to the sum of image luminance $A_n I_n$ of the image sources and the background.

$$\phi = \sum_{n=0} A_n I_n + A_b I_b \tag{8}$$

where $A_b I_b$ is the background luminance. The background luminance depends on the amount of diffuse light reflection within the enclosure, or reverberant sound in an acoustic analogy. The total luminance ϕ could equally be measured with a light meter of the same field of view.

The clarity index, C, in an acoustical context, is 10 $\log_{10}$ ratio of the sound energy arriving up to 80 ms after the direct sound arrival (including the direct sound energy), to the sound energy arriving after that time. This can be measured directly from Figure 3 as

$$C = 10 \log \frac{\sum_{n=0}^{m} A_n I_n}{\sum_{n=m}^{\infty} A_n I_n + A_B I_B}, \tag{9}$$

m is the image number giving a time delay corresponding to 80 ms. The images n < m will be larger than m^{th} image (i.e., the images are ordered by size).

3. OPTICAL MODELLING OF AN AUDITORIUM

The objective of optical modelling of an auditorium is to obtain images in the form of Figure 2 from which the luminance of the sources and background can be measured. The images are controlled by three parameters; the geometry, the surfaces and the light sources, which are discussed here in the context of a particular optical model of a rectangular enclosure. A simple geometry was selected to permit comparison of theoretical and measured results.

Figure 4 is a diagram of the model. Four 3 mm thick front silvered mirror walls with 3 mm hardboard backing were supported vertically on moveable right-angle stands. The wall lengths and angles were variable although most measurements used a 0.3 m × 1 m rectangular plan. Various ceilings were used. The camera used in the experiments was a Canon AE-1, the film was a black and white ILFORD FP4-125 35 mm of recommended meter setting ISO 125/22°.

The mirrored walls were covered with a variety of materials to give combinations of absorption, specular and diffuse reflection.

Front silvered mirrors were used to obtain specular reflections in the manner of a smooth hard wall in the acoustic analogy. Standard mirrors have reflectances of about 0.95; unfortunately, the mirrors used here were of poor quality with uneven reflectance due to uneven silvering.

Combinations of absorption and diffusion are obtained using paper with calibrated grey tones ranging between white and black. Neutral density filters placed over the mirror wall give different combinations of specular reflection and absorption, i.e. producing a dim image. White net fabric placed over the mirror wall gives a mixture of diffuse and specular reflection to model the acoustic case of a hard surface with a roughness approaching the sound wavelength.

The light source, a monopole in plan, consisted of a half cylindrical shell of white diffusing paper illuminated from the rear. The diffusing shell was set in a mirrored front wall so that only half a source need be constructed. The shape of the shell controls the light directivity pattern to model the chosen acoustic source, a flat rectangular membrane, gives a cosine directivity pattern in both planes corresponding to that of a dipole.

4. EXPERIMENTAL TECHNIQUE

Photographs were taken of the real source and image sources as seen in Figures 2 and 4. These photographs were developed, and the negatives projected onto a translucent screen.

Dimensions and illuminance of the image sources were measured from the rear of the screen. The image illuminance measurements were made using a photodiode light meter and equation (2).

The illuminance I_n of each image source is related to the density D_n of the negative.

$$D_n = \gamma \log_{10} H \qquad (10)$$

The density is plotted against 'exposure' H, where H is

$$H = At \, . \, I_n \qquad (11)$$

A is the camera aperture area, t is the exposure time. γ was measured to be 0.53 for the film used.

5. EXPERIMENTS

A set of experiments was carried out to test the feasibility of both the modelling techniques and the measurement procedures. Experiments 1 and 2 were used for clarity index measurements on a plane rectangular enclosure. Experiments 3, 4 and 5 tested various wall covering materials.

In experiment 1 the floor and ceiling were black, in experiment 2 the floor and ceiling were white. With consideration of Figure 1 the real source and first nineteen image sources to the right were photographed. In Figure 5 the real source is on the left, and the second and third to the right. Image sources four to nineteen are seen in Figure 6. Using the image heights, d_n, the predicted distances between the observer and image sources r_n were calculated from equation (2) and compared with the true distances. The errors were less than 5%, illustrating the potential of this method for obtaining time delay information.

The measured luminance of each image source (the illuminance, area product $I_n A_n$) was plotted as function of time or reflection number in Figure 7. This curve corresponds to the decay of energy of a rectangular enclosure of length r_0 = 10 m, following an impulse. Also plotted in Figure 7 is the decay of energy obtained using the average values of reflectance for each mirror, α, β.

The clarity index can be obtained using equation (9). Figure 7 gives the luminance $A_n I_n$ for the terms appearing in the numerator before 80 ms. The denominator is largely controlled by the diffuse background illuminance I_B and area A_B. With the black floor and ceiling the background illuminance I_b was 3.9×10^{-4} relative to the real source, giving a clarity index for the 10 m room of 4, indicating good speech clarity. When the white floor and ceiling were added the background illuminance increased to 2.5 $\times 10^{-3}$ or 8 dB, indicating an 8 dB increase in reverberant sound level. The clarity index then dropped to – 4, indicative of poor speech intelligibility.

Another parameter that could easily be measured from the optical data is the subjective spaciousness which could be obtained using the directions of the early reflections.

Figure 8 shows the image sources when fine white net fabric was covering the side walls. The floor and ceiling were white card. The diffuse reflections cause a high reverberent background level into which the image sources swiftly sink, after only five reflections. The background contribution, reducing the clarity index, would be very high as seen from the noticeably grey tone.

6. CONCLUSIONS AND RECOMMENDATIONS

(1) Optical modelling can be used to visualize the sound field within an enclosure giving the intensity and time delay of reflections and the magnitude of the reverberant background level.

(2) The strength and directivity of various idealized sound sources can be modelled, as can wall surfaces giving specular or diffuse reflection with absorption.

(3) Objective measurements can be made of loudness, subjective spaciousness and clarity index.

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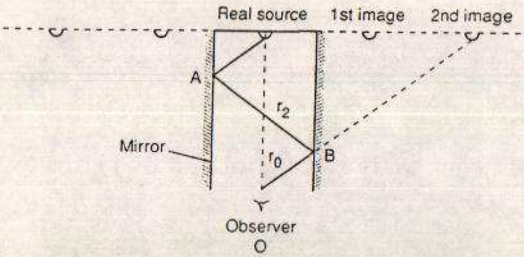

Figure 1 Image source model of parallel sided enclosure.

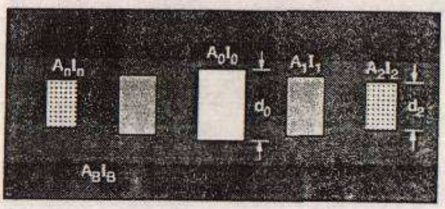

Figure 2 Image source and background contributions to the total intensity.

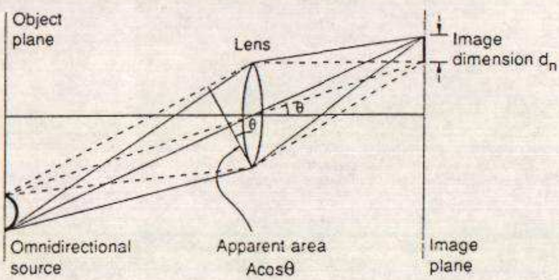

Figure 3 Factors determining image intensity.

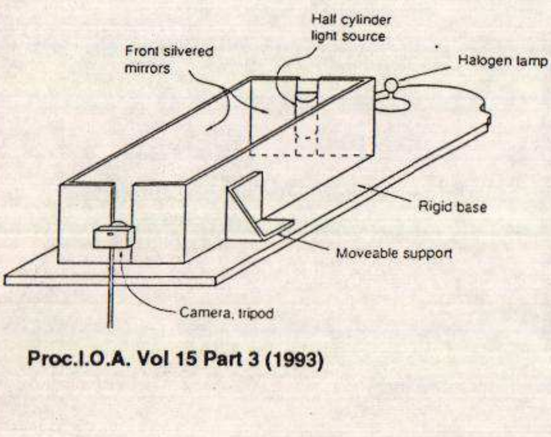

Figure 4 Diagram of the model.

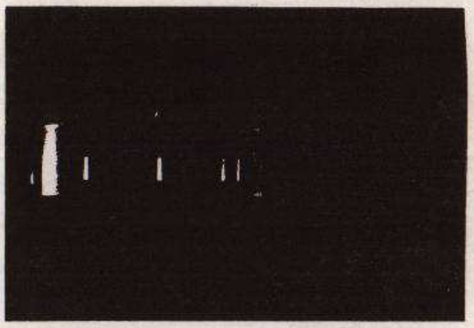

Figure 5 Real, first and second image sources, experiment 2, 2 sec at f/16, paper print 5 sec at f/16.

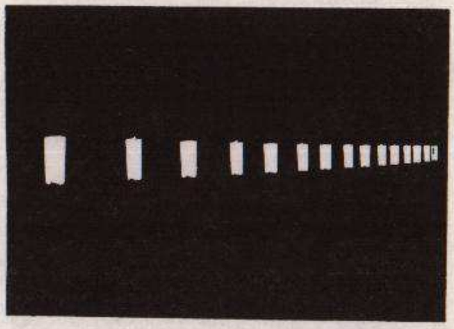

Figure 6 Fourth to nineteenth image sources, experiment 1, 2 sec at f/4, paper print 3.5 sec at f/16.

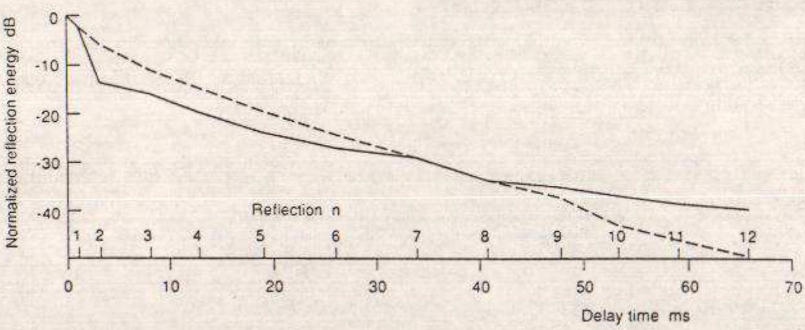

Figure 7 Impulse response of a room (r_o = 10 m); measured —— ; theory, α = 0.53, β = 0.39 - - - - .

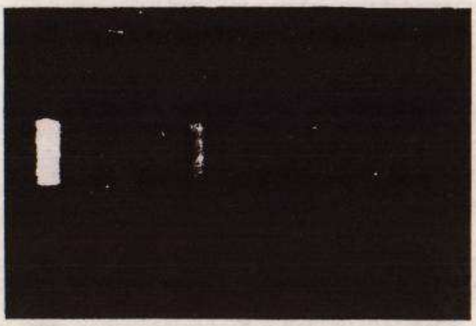

Figure 8 Second to fifth image sources, white net side walls, white floor and ceiling, 2 sec at f/4, paper print 0.5 sec at f/16.