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RESEARCH INTO THEATRE ACOUSTICS

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Introduction

In auditorium acoustics there are two basic aspects to be considered – the physical acoustic aspect of the sound field created by the sound source, and the subjective aspect of how the ears interpret this information. In the case of music the subjective problems generally dominate discussion and command research effort. But with speech the subjective aspects are relatively well understood even if not universally accepted. The physical acoustic aspects appear however to be less well documented and work in acoustic models in Cambridge has provided the opportunity to quantify the requirements more closely.

Subjective requirements

The subjective problem relates primarily to an objective measure well correlated with intelligibility. In theatres one criterion which is not very helpful is that of reverberation time. The well-known graph of speech intelligibility against reverberation time may be relevant to uniform diffuse spaces but theatres are not generally in this category. It is obvious in many rooms that intelligibility is also a function of position. The recommended reverberation time for theatres of about 1 sec. is as much a matter of ambience as intelligibility. The principal other measures that have been proposed are the 50 ms energy fraction by Thiele (1), Lochner and Burger's criterion (2) and the Modulation Transfer Function of Houtgast and Steeneken (3). Each of these probably has its shortcomings but each provides good correlation with intelligibility. The influence of background noise can also be incorporated in the measures but will not be considered here.

For our studies we have principally used the simplest of these, the 50 ms energy fraction. As well as being relatively easy to measure, it is easy to visualise the room acoustic behaviour in terms of an early and a late sound component. The late sound component is not only a function of the reverberation time but also a function of the total acoustic absorption. Our experience suggests that for satisfactory intelligibility in a theatre a value for the 50 ms energy fraction of greater than 0.5 is required.

Physical acoustic requirements

The problem is thus to achieve at least as much early energy within 50 ms of the direct sound as late energy after 50 ms. What can be said about the behaviour of the 50 ms energy fraction in the theatre situation?

In a small regular auditorium, the early energy fraction is generally independent of position at distances significantly greater than the reverberation radius. This will not however be the case in a large auditorium as the reflection situation within 50 ms of the direct sound is not uniform. A useful starting point is to consider the well-known diagram indicating the variation in sound level in a room as a function of distance from a point source. The reverberant or reflected sound level is constant and the direct sound level decreases 6dB for every doubling of distance. The two are equal at the reverberation radius. If the direct energy is "increased" by being followed by an equal energy reflection, the "reverberation" radius is increased by a factor of 1.4.

In a large theatre the early sound will consist of a few (e.g. 2 - 3) reflections in addition to the direct sound, whereas the reverberant or reflected component will be less than 4 W/A (for a sound power of W, and total acoustic absorption A) as we are only concerned with the energy after 50 ms. For an omni-directional source, the reverberation radius for a large theatre is typically about 6m. The limiting distance for intelligibility in a large theatre is thus larger than this.

A human speaker is directional however, and relative to an omni-directional source the limiting distance will be larger when the speaker faces the listener and smaller when the speaker faces away. An acoustic model enables one to analyse the components of early and late sound in a theatre and to investigate the influence of the orientation of a directional source.

Model research

An acoustic scale model has the potential to reproduce perfectly the acoustic sound field at scaled-up frequencies. In an eighth-scale model one works at eight times normal frequencies. The absorption of the air can be scaled accurately by reducing the humidity level in the model to around 2% relative humidity, which proves to be a realisable level. The problems of modelling remain principally those of transducer design.

For a theatre model, the principal requirement is for a source covering the speech frequency band with the directionality of a human speaker. We have succeeded in building a model source which fulfils most of the requirements. It is hoped to give details of its construction at a later I.o.A. meeting. Basically it consists of a tweeter loudspeaker attached to an inverted horn, so that the sound is emitted from a 6 mm aperture well separated from the magnet assembly of the loudspeaker. With this source we are able to conduct subjective tests in the model; that is, play speeded-up speech through the model and listen to the signal recorded in the model at normal frequencies. The source can also be used for objective measurements to measure the early energy fraction with an impulsive signal.

We can therefore investigate the intelligibility in the model both subjectively and objectively. One of the great virtues of model work is the facility for making modifications to the model and being able to determine their effect on intelligibility.

From the work so far, the following relevant points have emerged:

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1. With good sight-line design the direct sound is basically determined by inverse-square law behaviour. So in general, attenuation at grazing incidence is not a contributory factor.
2. A stage reflection assists actors except when they are at the front or edge of the stage.
3. Early reflections are necessary for seats more than a certain distance from the stage. The number of reflections required depends on what orientations are used by actors.
4. The ceiling is likely to be the surface over which the acoustical consultant can have the most control. The acoustic requirements are likely to be in conflict with stage lighting requirements. Seats which are the most remote from walls or ceilings are likely to be the most difficult to cater for.
5. As well as discrete reflections there is a diffracted energy component in the early sound, presumably scattered from seating and room surfaces. For seats more than 10 m from the stage front values of 30 - 50% of the direct sound energy appear to be typical.
6. The late reverberant sound level appears to be relatively constant with regard to seat position and speaker orientation (unless there are deep balcony overhangs).

<u>A theoretical approach</u>

The direct sound component is calculated on the basis of the inverse square law together with data for the directionality of a speaker. Although objective directionality data is available, which we have been able to confirm, further subjective measurements appear desirable to clarify the situation of a speaker turning away.

The early sound component is the sum of the direct sound and the early reflections (with a small additional diffracted component). Early reflections can frequently be determined from drawings.

The theoretical late sound component in a diffuse field is given (in reference (4)) by:

$$I_t = 312\,\frac{T}{V}\,.\,e^{-13\cdot 82t/T}\,.\,I_o r_o^2 \qquad (1)$$

where T is the reverberation time, V is the auditorium volume, I_o is the direct sound intensity at distance r_o from the source, and t is the transit time from the source to the receiver plus 50 ms. The origin of this equation is the expression 4 W/A for the reverberant sound component with an exponential decay component. A correction can be readily introduced to account for late energy dissipated in the flytower.

In a theatre in which we have conducted measurements, the late sound energy approximates closely to the theoretical value given by equation (1). Until measurements have been made in other theatres we shall not know to what extent design influences this component.

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With the approach described it is possible to derive contour maps of the early energy fraction given an assumption about the early reflections (e.g. one reflection at 30 ms, or early reflection energy equal to direct sound energy). Such a map **based on the latter assumption will be** shown. It indicates satisfactory conditions up to 22 m from the source for straight ahead of the speaker, 11 m at 90° to the speaker and only 7.2 m directly behind.

Conclusions

Given a limiting distance of 20 m from the stage front to the rear-most seat, intelligibility is unlikely to be a problem in a proscenium-type theatre in which the actors face the audience. The development of the thrust-type stage, in which members of the audience can be sitting behind the actor, has introduced a situation in which careful acoustic design is required. The theoretical framework described above indicates the nature of the problem. It is hoped to conduct measurements in several British theatres to be able to derive design guides of a more architectural nature. Small scale (e.g. 1:50) acoustical models may however also be able to assist in theatre design.

References

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