PRACTICAL CONSIDERATIONS IN ACOUSTIC MODELLING OF AUDITORIA

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1. Introduction

There are now many commercially available computer programmes (albeit of widely varying technical standards) for modelling acoustics. For large auditoria and high-profile projects, acoustic testing of physical scale models is also still widespread, often assisted by computer processing of the results. Many papers have been written about individual methodologies, but few if any about the fundamental advantages and limitations of these tools. This paper addresses the last of these subjects from the point of view of the consultant in auditorium acoustic design. Auralisation is not discussed in this paper.

The historical background and development of physical scale model testing are discussed in Barron's paper at this conference [1], and Meynial et al have written a useful summary of the principles and applications [2]. There are many publications on the development of computer modelling, of which some of the better overviews come from the acoustics group at Chalmers University [7,13].

2. Technical Considerations

2.1 Absorption coefficients

In physical models, the need to find materials with the required absorption coefficients at the scaled frequency is at first sight a serious problem. In fact for most fibrous absorbers, reasonable approximations should be possible, although requiring extensive measurement of absorption coefficients for many materials. Standing wave tubes are of some use for this, but of course only measure the absorption coefficient at normal incidence. The absorption coefficients can be measured directly in the scaled model.

In theory, it should also be possible to design scaled models of panel absorbers and to measure their absorption coefficients in the same way. In practice, panel absorbers are not often intentionally used in concert halls, and to best of the author's knowledge scale modelling of panel absorbers is not an active area of research.

Physical models may require better representation of absorption coefficients for a given level of accuracy than computer models. Once a physical model is built, there are relatively few possible adjustments and acoustic absorption is adjustable only by changing the material itself. In addition, the properties of the scaled material are inextricably linked; it is unlikely that a scaled material can accurately reproduce both the diffusing and absorbing characteristics of a complex surface such as an audience in raked seating. In the computer model, of course, the two are easily separable at each frequency.

For neither type of model is the choice of absorption coefficients straightforward. Different publications report widely different absorption coefficients for similar materials. Reverberation chamber measurements can not be taken at face value, not least because the basic assumptions on which Sabine's formula depends are clearly not met in reverberation chambers with acoustic material on part of one surface only. Any methodology which regularly returns absorption coefficients in excess of 100% (normally due to edge effects) clearly has to be treated with caution. For measurements on seating, the standard method requires the edges of the sample to be boxed in, but it is perhaps more realistic to use absorption coefficients derived from measurements in real auditoria. Some seat manufacturers now supply such data.

It has been considered [4] that gross errors in concert hall design are rarely due to use of the wrong absorption coefficients, as most of the materials used are highly reflective. Accurate values are required, however, for surfaces close to the sources, for the principal sources of absorption (seats and audience) and for panel absorbers. An illustration of this is the Royal Festival Hall in London, where the designers seriously underestimated both panel and fibrous absorption in spite of exhaustive reverberation chamber tests.

2.2 Air absorption

The absorption of the propagation medium has to model that of air in the full-sized hall. This is a function of temperature and humidity. These parameters are easily adjusted in a computer model, but in physical models it was originally necessary either to dry out the air in the model to very low values of relative humidity or to fill the models with another gas such as helium - both rather cumbersome procedures. Proposals to eliminate air absorption altogether by carrying out the tests in a vacuum have proved unrealistic. Fortunately it is now possible to measure in air at normal humidity and temperature, adjusting the measured results by use of a computer program [2].

2.3 Diffusion and diffraction

In theory even a small-scale physical model should, if accurately scaled, reproduce diffusion and diffraction effects. Meynial quotes the required accuracy as typically 0.5 mm in the dimensions of a typical small-scale (e.g. 1:50) model [2]. It is difficult to model curved reflectors and complex shapes to this level of accuracy, so large scale models are needed for reliable results. Even on these, modelling of complex surfaces such as diffusing balcony fronts or suspended reflectors has to be very accurate. In addition, as discussed above, a material chosen to have the right absorbing properties at the scale required may have very different surface diffusion properties. Procedures for measuring and characterising diffusion are being addressed by a workgroup in the AES. [15].

Many papers have been written on ways of modelling diffusion within geometric computer models. Dalenbäck, Kleiner and Svensson's informed and readable review of the subject [7] lists no fewer than 42 references, at least 10 of which are required reading for a good grasp of the subject.

A few key points bear repetition here :

i) The choice of diffusing factors can have more effect on the results than the choice of absorption coefficients;

ii) Over a large number of reflections the assumption of totally diffuse reflections is generally more realistic than the assumption of totally specular reflections [11];

iii) In spite of the above, many currently available prediction and auralisation methods do not treat diffusion adequately. In Vorlaender's round-robin test on 19 modelling systems [12], 6 did not model diffusion in early reflections and a further 5 ignored diffusion altogether [13]. None of these models performed well in the test;

Diffraction of waves also occurs at the edge of each surface, and when the surface dimensions are not very much larger than the wavelength. This can be modelled by including an edge diffraction function, but in general the modelling of many surfaces smaller than the typical wavelengths concerned is counter-productive.

2.4 Sources and receivers

For physical models, there are obvious problems in miniaturising real sources such as musical instruments or the human voice. Short pulses are normally used, being generated either by a spark gap or a small loudspeaker. This limits the use of the model to measurement of impulse response, which theoretically should allow us to derive a full acoustic description of the room. In practice, signal processing is required to compensate for the lack of low frequencies in impulse responses [2] and the further signal processing required to "auralise" the model is similar in complexity to that required for computer models. For auralisation a miniature dummy head containing two microphone capsules is required to give a binaural output [5]. This dummy head should be located in an array of similar heads to simulate the diffraction and absorption effects of the surrounding audience.

In any model, many receiver positions are needed to determine the variation in acoustic conditions both on stage and in the seating area. Ideally we should have receivers in a 1 metre grid. This is easily achieved in computer models, which can also show these as coloured "maps" (Figure 1) but is not normally practical for physical models, for which Meynial suggests a minimum of three source positions and 7 receiver positions to give statistically significant results [2]. This will of course depend on the size of the hall and the seating layout - asymmetric and "vineyard" halls will require more receiver positions than simple rectangular halls, and modelling canopies or orchestra shells will require more source locations. A traditional opera house, with sources on stage and in the pit and the audience in vertically-stacked boxes, would require very many measurements.

2.5 Prediction of early and late parameters.

At first sight, it is surprising that in most concert halls reverberation time can be predicted even approximately using the Sabine or Norris-Eyring formulae, as these assume a diffuse sound field with evenly distributed absorption. In concert halls in particular, the absorption is almost entirely limited to the audience and seating. In fact these statistical methods will generally be inaccurate for early reflections, where the sound field is not diffuse, but once a diffuse field is established we can expect them to give reasonable results for the late part of the decay.

Another way of considering this is to recall that measurements in real auditoria will generally show some difference in the slope of the early and late parts of the decay. This is commonly characterised by the difference between early decay time and RT60 reverberation time. Statistical reverberation time calculations will generally predict the gradient of the late decay, but not the early part or indeed the starting point. Early decay time in particular can vary significantly with source and measurement positions in a real hall because it relies only on a few reflections.

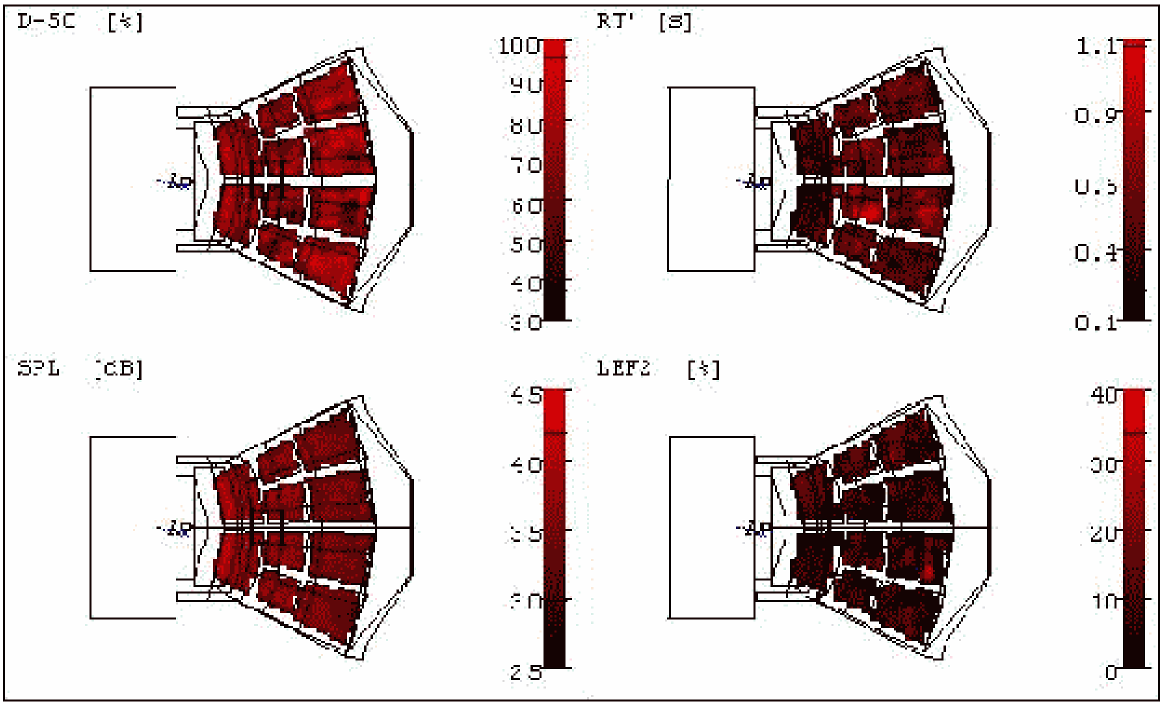

Figure 1 - Overview of acoustic parameters using CATT-Acoustic model

The early reflections dominate all of the important room parameters other than reverberation time, and also affect the ensemble of orchestral musicians. These are all strongly affected by diffusion. All models must therefore deal with diffusion in the first few reflections (typically the first 3 to 5 orders) in a technically correct manner.

2.6 Geometrical acoustics and phase information

The term “geometric acoustics” is often confused with ray tracing, and indeed some computer models rely entirely on ray tracing for prediction. It has long been established however [14] that the only method capable of giving great accuracy in early reflections is is an Image Source Method, and it is significant that in Vorlaender’s evaluation of models [12] the only consistently accurate predictions of early parameters used this method.(Note that although these programs allow interactive ray tracing for visualisation of reflected paths, they are not ray tracing models in the widely understood meaning of the word).

ISM models obviously can not deal directly with curved surfaces, which are therefore split into a number of smaller flat surfaces. For convex surfaces, which have a diffusing effect in any case, very fine sub-division into many small planes is not necessary provided that these surfaces are allocated realistic diffusing coefficients. Large reflective concave surfaces are not normally found in good auditoria, but the above approach (provided that the surface is modelled symmetrically) will also show any focusing effects.

Another confusing assumption is that any geometric method must cause the loss of all phase information. In fact, as the model must record the time of arrival of each “ray” after its emission from a given source, so that the distance travelled by the ray is known. The relative phase is therefore easily calculated for any frequency, and indeed for auralisation a phase function can be synthesised for each reflection path. There is, however, some loss of accuracy from the averaging of absorption and diffusion effects over octave bands.

2.7 Modes, standing waves, flutter echoes and late reflections

While phase information can be recovered and used for auralisation, modal behaviour is a different matter. An accurate physical model will detect the presence of modes, if not always their strength. Computer models can not do this, but an experienced acoustician should not need a model to calculate room modes in halls of the relatively simple shapes where they are likely to be significant. Similarly, the physical model will detect the presence of unwanted late reflections but not their cause. Echogram and interactive “ray history plots” (Figure 2) are extremely useful tools in a computer model for tracing individual reflections.

2.8 Frequency range

Most computer models present results in octave bands, normally from 125 Hz to 4 kHz. This is merely a matter of convention and convenience. With improvements in calculation methods and increases in processor speeds, there is no reason why a commercial model should not provide third-octave or finer analysis, provided that the input data are available. An intrinsic limitation on predictions at lower frequencies is the ratio of surface size to wavelength, although to some extent this limitation is reduced by allowing a reasonable amount of surface and edge diffusion at low frequencies as discussed above. Computer models therefore share with all other acoustic measurement and prediction methods the characteristic that they are less accurate at low frequencies.

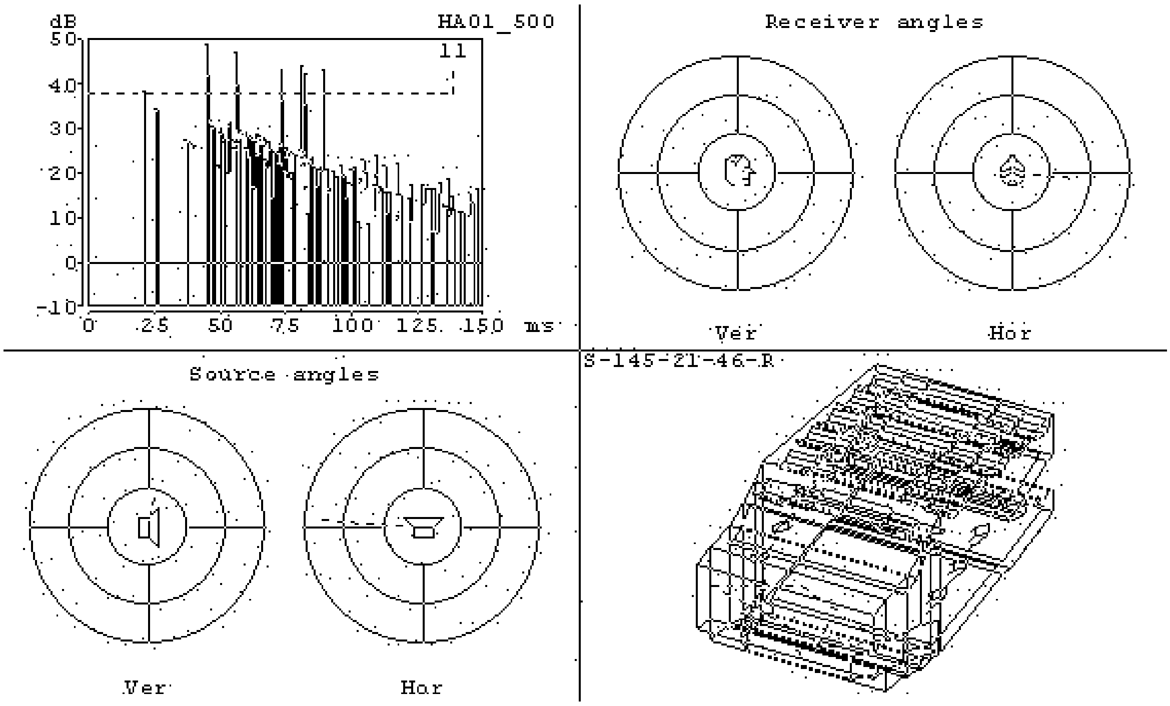

Figure 2 - Echogram and ray tracing for early reflections on a concert hall stage

3. Calibrating the Model

Acoustic alterations to existing halls provide a valuable opportunity for us to test the accuracy of our modelling techniques. We can measure many acoustic parameters and record impulse responses and known sources, all for different combinations of source and receiver positions in the existing hall - the ideal 1:1 physical scale model. Ideally, these would be measured under a variety of acoustic conditions, such as with the use of additional reflectors on stage.

The data acquired can then be used to “calibrate” a physical or computer model. If the model correctly predicts either absolute values or trends for a wide range of conditions in the real hall, it can then be used with considerable confidence to predict the effects of changes to that hall.

This approach is applicable to either computer or physical models. The physical model is here at a disadvantage, because it is difficult to adjust parameters independently to reflect the reality as represented by measurements in the hall. It is better suited to computer models, as agreement of a model’s calculations with measured data in the existing hall should overcome all of the objections to computer models. In practice, this “calibration” process is likely to revolve largely around the selection of individual absorption and diffraction coefficients.

The above technique requires a clear understanding of the relations between measured and predicted parameters, which in turn requires a detailed knowledge how one's measurement and calculation systems work. These may vary from the different ways in which Lateral Energy Fraction is calculated [3] to the sampling rate of the measurement system. It is not enough to treat these systems as "black box" technology, taking note only of the end results. To provide the power and flexibility required, these tools allow adjustment of a wide range of parameters and hence, in the hands of those who do not understand them, they can give plausible but incorrect answers.

4. Non-Technical Considerations

No model is of practical use to a project unless the acoustician can persuade his client to act on the results. Historically, the results of physical scale modelling have not always been perceived to be as helpful as they might, although in many cases the responsibility for this appears to lie, not with the acousticians concerned, but with their clients who did not act on the results [3,4]. One reason for this, however, may be that the time required to create and test a physical scale model reduces the technique's usefulness at the outline design stage, so that reliable results are only available once a design is well advanced. At this stage it is less likely that substantial alterations to the shape, layout or volume of the hall will be countenanced by the design team.

There is also the appeal of a tangible, physical scale model to the client [2,6]. A scale model has a certain cachet that no amount of computer modelling can give. Their use in press and public relations should not be overlooked in a climate when these have such an important role in generating support and funding for arts building projects, at least in the UK. There is no doubt that scale models look better in exhibitions and on television than computer models. We have, however, found wide acceptance among clients and architects for the use of computer modelling at all stages of outline design.

The time required to create, test and amend physical scale models is substantially greater than that for the equivalent exercise on a large-scale computing model, with an inevitable effect on cost. The model shown in Figure 2 took some 30 hours to create from scratch, and by using variables for some dimensions, is very quickly changed to model, for example, different reflector heights or the use of an orchestra pit. It can model inputs from many sources, each with its own directivity and time delay, and will map the results to show variation of each parameter at every seat if required. Typically a full set of results requires 2-3 hours of computing time on a standard desktop computer.

The cost of creating, testing and altering models can been reduced by joint ventures with university departments, at the risk of students spending many hours of research time making models to support fee-earning consultancies. Historically, scale modelling has had a valuable role in teaching acoustics [2], although to an extent they have to be treated as "Black box systems" in which alterations are made until the desired result is achieved, without necessarily knowing why. Computer models have the advantage that the effects on the acoustics of changing individual parameters are much more easily seen, and the principles involved are available in the program itself. It is undeniable that the research required to develop computer models has increased enormously our understanding of the mechanisms involved.

5. The Future - Models to Solve the Wave Equation?

Finite element or other wave-related models have not to date been considered feasible for auditorium modelling [8]. Claims have recently been advanced for finite element methods in acoustic design, largely related to modelling loudspeaker response in rooms [9]. Models which rely on solving the wave equation are regularly used in the analysis of vibration and groundborne noise propagation, and are now being applied to room acoustics [10]. Large amounts of processing power are required to apply such models to the long decay times typical of concert halls, but these are by no means out of the consultant's reach. A more substantial problem is the mathematical representation of reflecting and diffusing surfaces, which effectively form the boundary conditions for the wave equation in these models. The problems are complex, but probably no more intractable than those faced a decade ago by the researchers who have developed successful prediction and auralisation programmes using geometric methods.

6. Conclusions

Computer modelling has, in the past, been dismissed by advocates of physical models on the grounds that physical models reliably provide all of the acoustic data required (although published results to support this view are scarce). There is a natural perception that physical models must give the right answers because sound propagates in the same way in the model as in the auditorium. The above discussion shows that physical scale modelling is not necessarily the automatically correct technique that it is often claimed to be, and in practical applications computer modelling should be capable of more accurate results - particularly where this can be calibrated against a real auditorium.

The consultant should be aware that of the many computer modelling packages currently available, very few appear to have all of the characteristics required to give realistic results over a wide range of conditions. No system should be used without being aware of the basic principles used and of its technical limitations.

7. References

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