

Proceedings of the Institute of Acoustics

21 YEARS OF ACOUSTIC SCALE MODEL TESTING

M Barron

School of Architecture and Civil Engineering, University of Bath, BATH BA2 7AY
Fleming & Barron, Combe Royal Cottage, Bathwick Hill, BATH BA2 6EQ

1. INTRODUCTION

Models have long been valued as a way of visualising or investigating the complex behaviour of sound in enclosures. As long ago as 1843 Scott Russell experimented with 2D water wave models [1]. The more precise 2D air-wave models were first photographed by W.C. Sabine using the Schlieren technique in 1912 [2]. Acoustic scale modelling also has a long history [3], being first used by Spandöck in the 1930s. Considerable experience has been built up in scale modelling but computer modelling now presents a challenge, with the convenience of requiring no more than a computer to generate not only objective results but also auralisation (aural simulations of music or speech as would be heard in the space).

The principle behind acoustic scale modelling is actually simple. The complex behaviour of sound when it meets finite size surfaces or obstacles depends on the relationship between the size of the surface and the wavelength. If this ratio is kept constant, acoustic behaviour is reproduced in miniature. From reference to the fundamental equation: $\text{Speed of sound} = \text{Frequency} \times \text{Wavelength}$, we see that if the wavelength is reduced the frequency must be increased. The propagation medium in the model is the same as at full size, so for a 1:10 scale model we need to increase frequency ten times.

Thus scale modelling takes care of the complexities of wave behaviour. Computer models on the other hand are based on tracing sound rays; wave behaviour is only incorporated with difficulty. Computer models also need to find ways of dealing with reflection off diffusing surfaces and some method for handling the enormous quantity of sound rays which make up the reverberation. Techniques for dealing with these various complications will take time to optimise and require very careful validation.

2. SCALE MODELLING IN PRACTICE

Because acoustic modelling involves high frequencies, one issue which needs to be confronted is air absorption. By using either dehumidified air (around 2% r.h.) or bottled nitrogen, the so-called molecular component of air absorption can be all but eliminated. In fact at 1:8 or 1:10 scale, the air absorption can be almost perfectly modelled in this way [3]; at smaller scales air absorption can be easily corrected for when tests are made with dry air or nitrogen. The Midas software system [4] allows corrections to be made to measurements in atmospheric air; the penalty to pay for this is reduced dynamic range.

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Hard materials can be simulated by varnished timber or sheet plastic. Absorbing materials need to be selected for models, usually on the basis of a trial-and-error method. Absorption is generally measured in a model reverberation chamber using the standard technique. In auditoria audience seating, or audience, constitute the major absorbing surface. Because these elements also scatter incident sound, it is important to reproduce their physical shape as well as their absorption coefficient.

For microphones, 1/4" and 1/8" capacitor microphones are almost ubiquitous. Source transducers often require some ingenuity. Loudspeakers tend to have the problem that even if they can generate the required frequency, they are often highly directional and their magnets can produce a serious acoustic shadow. An array of electro-static transducers can be used for the high frequencies.

For objective measurements spark sources are very attractive because they produce a short impulse from a very small volume. The duration of the spark, and hence the frequency of maximum energy, is determined by the energy discharged in the spark [5]. At 1:50 scale only 4mJ of electrical energy can be dissipated yet this is sufficient for a decay of 50dB in a model of a large concert hall, Figure 1. (The decay in Figure 1 is produced by implementing the Schroeder integral with correction for the background noise [6].)

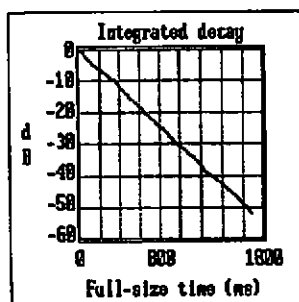


Figure 1. Integrated decay of response to a spark source in a 1:50 scale model of the Glasgow Royal Concert Hall

3. ANALOGUE VERSUS DIGITAL SIGNAL PROCESSING

During 21 years, analysis has switched from being almost completely analogue to almost wholly digital. It is interesting to compare the two. For both approaches though it is important to bandpass filter microphone signals to avoid signals being swamped by irrelevant noise.

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Analogue techniques involved many boxes and some fairly bulky equipment. The most bulky was a multiple speed 4 track tape recorder with the facility for simultaneous playback and recording. This recorder was used to implement the interrupted noise method for reverberation time measurement with the decay traces plotted out on a traditional level recorder. The tape recorder was also used for subjective testing of models with music or speech.

Many objective quantities involve integrated energy. A purpose-built analogue squarer and integrator was used for this. However if a spark source is used, no two spark signatures are the same and a digital store for impulse responses is invaluable. To measure the ratio of early-to-late energy could involve as many as 12 boxes of equipment; the operator had a choice of about 40 knobs he could adjust!

For digital analysis, only a microphone amplifier, bandpass filter and storage oscilloscope are necessary. The sophistication comes in the writing of the software with a flexibility way beyond the opportunities of analogue solutions. For instance, the dynamic range of the decay in Figure 1 was extended by about 5dB by first subtracting the background noise intensity and then starting the integration with the energy of the extrapolated decay. With digital analysis considerable time is required to develop the software, but the end result is a rapid measuring system which involves less operator involvement.

4. 1:8 SCALE MODELLING

In 1974 Professor Peter Parkin initiated a research project into acoustic scale modelling at the Building Research Station, Watford. This project moved to Cambridge University in 1975 when I was asked to join, shortly to be followed by Raf Orlowski. The chosen scale was 1:8 and we had two models: the Barbican Concert Hall and the Olivier Theatre in the National Theatre, both in London. The models were both built of varnished timber and were connected up to a continuous drying plant.

The choice of 1:8 scale is convenient because it is a whole number of octaves. The other point in its favour is that reel-to-reel tape recorder speeds traditionally vary by multiples of two. The models were tested both objectively and subjectively with music and speech, as appropriate. With both models the experience was very instructive.

4.1 Barbican Concert Hall, London

In the case of the Barbican Concert Hall, the model was tested before completion of the real hall [7]. The primary aim was to investigate the value of a series of diffusing spheres which had been proposed for the ceiling space. It was concluded that the spheres were performing a useful role in improving acoustic uniformity throughout the space.

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The acoustics of the Barbican Concert Hall have had their fair share of criticism since the hall opened in 1982. Commenting on the acoustics is complicated by the fact that there is not one but several faults. The most obvious problems in the real hall concerned reverberation time; these were independent of the model exercise. The hall volume is too small for a satisfactory mid-frequency reverberation time. But this is compounded by a short low frequency reverberation time, the most likely cause of this appears to be excessive low-frequency absorption by the audience seating. The 2000 diffusing spheres were removed from the hall in an early effort to increase the reverberation time at 125Hz.

Objective assessment of the model also used the newer measures related to the impulse response, such as the early-to-late sound energy ratio. It is now clear that there was a lot more to learn about interpreting these measures. From measurements in the completed hall [8] it is also apparent that in this hall the objective measures underestimate the criticisms of listeners. It is possible that the acoustics here are more sensitive than elsewhere to the presence of an audience.

A subjective testing system was developed for music at 1:8 scale, along the lines of the system developed by the BBC [9]. The listening system was rather crude, consisting of a pair of 1/4" microphones separated by a head. The recordings are instructive to listen to but it was clear that they were suitable only for detecting differences between recordings, not for making an overall judgement of the acoustic quality. Subsequently a 1:10 scale model head with scaled outer ears has been developed by Xiang and Blauert at Bochum [10], which enables much truer recordings to be made. Does this then allow overall acoustic judgements to be made? I would question such a judgement. For example even with true reproduction of the listening process, there is the very serious problem of reproducing an orchestra with its complex directivity characteristics.

4.2 Olivier Theatre, National Theatre, London

This model was not tested during the design process but was pressed into urgent service once the theatre was about to open in 1976. There were clearly acoustic difficulties and the first question concerned the nature of the problem: were the problems due to echoes or associated with the impulse response? Echoes are an obvious fault and the theatre had some examples which could be tracked down in the model. Yet echoes proved to be more a symptom of the fundamental problem rather than the cause. Experience with the Olivier model formed the foundation of an understanding of theatre acoustics, which was confirmed in the Acoustic Survey of British Auditoria [8].

Twenty years previously in 1953 the concept of the early energy fraction had been proposed as a correlate of speech intelligibility [11]. It just remained to establish what influenced the fraction in a drama theatre. In theatres with intelligibility problems there are usually insufficient early reflections, though a reverberation time shorter than 1 second is also desirable. The directional

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nature of the source is crucial as well and poor intelligibility is normally restricted to situations where the actor is facing away from the listener.

To conduct full sets of tests at 1:8 scale, a model directional speech source was developed by Orlowski [12]. This was also used for subjective tests and produced persuasive recordings of the effect of the actor turning round, for instance.

5. 1:50 SCALE MODELLING

While models at 1:8 or 1:10 can be very accurate and offer the opportunity for subjective testing, they have practical limitations as design aids. They are expensive and require spaces with more than normal ceiling height to house the models. Perhaps even more important than these is the problem of the time it takes to construct the model, which means that the model cannot get fully integrated in the design process. A more flexible model is required in which major geometrical modifications are possible. These considerations led to investigation of the feasibility of testing at 1:50 scale. In physical terms this scale implies models of concert halls, for instance, which are around 1m long and can be carried easily by two people.

Preliminary experiments at 1:50 scale were conducted with a simple rectangular box [13]. Soon after in 1977, we were extremely lucky to be lent a 1:50 scale architectural model of the Cambridge University Music School auditorium by the architects Sir Leslie Martin, Colen Lumley and Ivor Richards. With access both to the model and the full-size building, we were able to develop and validate the testing techniques. The investigation of small scale modelling had to consider source transducers and microphones, gas/air absorption and model materials [14]. Spark sources are predominantly used with 1/8th inch microphones. The model is flushed with nitrogen. Models are now built of acrylic (perspex) with the seating being reproduced geometrically with a carefully chosen fabric to match the absorption of the full-size article. While some measurements can be made in the 100kHz octave (2kHz full-size), most measurements are limited to a maximum frequency of the 50kHz octave (1kHz full-size) up to which the directivity of the microphone is only a minor problem.

Seventeen auditoria have now been tested at 1:50 scale as part of the design process including concert halls, drama theatres, opera houses and a lecture theatre. The testing process is divided into two parts. In the first part only the reverberation time (and early decay time) are measured, while the model seating and other absorbing materials are added to the model. Subsequently impulse response measurements are undertaken as well as measurements of level distribution. Impulse responses can also be replayed at a scaled down speed through a loudspeaker, which can prove very valuable for studying echoes.

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5.1 Concert hall models at 1:50 scale

No sooner had we advertised in 1977 that model testing at 1:50 scale was viable than a model at that scale of **St. David's Hall, Cardiff**, "arrived" for us to test from the consultants Sandy Brown Associates. At that time all the analysis equipment was analogue. Measurements had to be made in 1/3rd octaves and for impulsive measurements it was necessary to take the average of say 10 spark responses for each measured value - overall a rather tedious process. The models then were of varnished timber (and we had some difficulties with sawdust occluding the microphone!).

We had reasonable confidence in the modelling process. Later this could be confirmed by comparison with the full-size concert hall; Figure 2 shows comparison of the model with full-size for the case of the early-to-late energy ratio. (Results in this figure have been corrected for the small differences in reverberation time between the model and the full-size hall.) But the biggest problem we faced was how to interpret the results. In the case of the early-to-late ratio or index (C_{80}), we had recommendations by Reichardt *et al.* [15] for music of the Classical and Romantic eras. The total range considered acceptable for both these musical styles was 6dB, but was this appropriate? For a 2000 seat concert hall should we perhaps just be applying the criterion for Romantic music? And what frequency range should we be applying this to? Should we take the mean over 5 octave frequencies 125 - 2000Hz, as used for Figure 2, or a smaller frequency range?

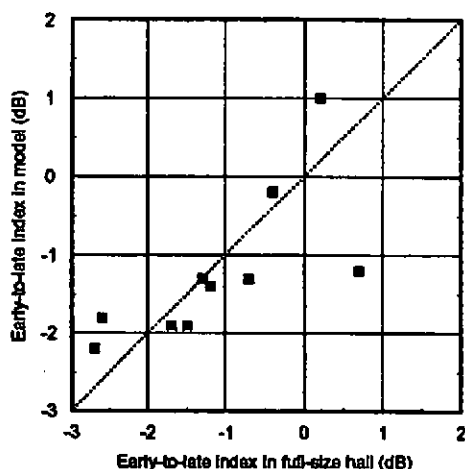


Figure 2 Comparison of measured values of the early-to-late sound index in the 1:50 model and full-size St. David's Hall, Cardiff.

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On the other hand, there is a predicted value for the ratio based on an exponential decay: $C_{80} = 10 \log(e^{1.11/T} - 1)$. For a 2s reverberation time, the predicted value is -1.3dB. If we measure values significantly different from this, should we be concerned?

It has taken a while to resolve these issues. Musical clarity, which is thought to be related to the early-to-late ratio, is now considered to be linked to just the mid-frequencies, 500 - 2000Hz. (The low frequency ratio is influenced by attenuation at grazing incidence, also known as the seat dip effect, which presumably has little bearing on perceived clarity.) For this mid-frequency ratio, measured values in halls with satisfactory clarity generally fall in the region of ± 2 dB [8, p.61]. As far as agreement with predicted values is concerned, a strong direct sound or strong early reflections will produce early-to-late ratios higher than the value predicted for a simple exponential decay. An improved prediction scheme has been proposed, called revised theory [16].

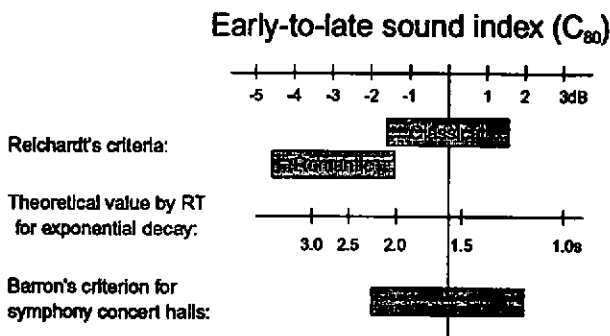


Figure 3. Alternative criteria for the early-to-late sound index (C_{80})

Returning to the model testing of St. David's Hall, a major concern at the time was that sound behaviour should be sufficiently diffuse. In most auditoria the major absorbing surface is the audience and this is located only on the floor. With absorbing material on only one of the six principal surfaces, diffuse conditions are far from guaranteed. In a model the state of diffusion can be checked as absorbing materials are introduced to the model, by comparing the measured change in reverberation time with predictions. A further check can be made by quantitatively assessing the linearity of decays. The ratio of the early decay time (EDT) to reverberation time (RT) is useful for this; Table 1 shows the ratio of mean EDT to RT in the model and full-size St. David's Hall. The agreement between model and full-size is very good. The fact that the ratio is so close to unity and that the standard deviation of EDT values throughout the hall is small corroborates the observation that this hall offers diffuse acoustics. This is surely a consequence of having a subdivided audience separated by reflective surfaces and a highly diffusing ceiling.

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Octave Frequency (Hz):	125	250	500	1000	2000
Mean EDT/RT: Model	1.03	1.00	1.00	1.04	-
Mean EDT/RT: Full size	0.94	1.05	1.01	1.00	1.01

Table 1 Comparison of the ratio of mean early decay time to reverberation time in the model and full-size St. David's Hall, Cardiff.

During the testing programme for this hall, several modifications were tested. One of the salutary lessons of modelling was that many modifications produce negligible acoustic effect. It is possible that many of the things which acousticians fight vociferously over make no difference at all! On the other hand, gross aspects such as in this hall the subdivided audience are the decisive ones for acoustic quality.

The next major concert hall model to be tested was for the new concert hall for Glasgow, eventually to open in 1990 as the 2450 seat Glasgow Royal Concert Hall. Three models of this hall were tested between 1985 and 1988 [17]. The first had the plan form of an elongated hexagon. One characteristic picked up in the model was a triple reflection off ceiling surfaces tangential to an ellipsoid, Figure 4. Since the delay of these reflections was 160-180ms, they would have been heard as a disturbing echo. The second model had a suspended ceiling which proved to be insufficiently transparent.

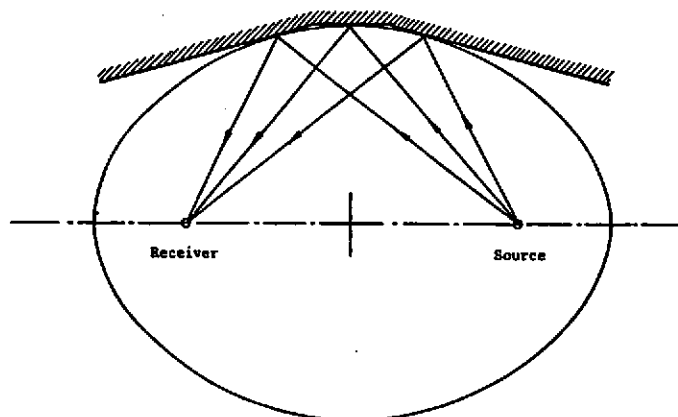


Figure 4. Reflection paths off high level surfaces in the first model of the Glasgow Royal Concert Hall.

The final design had reflectors at high level to compensate for the fact that the hall width at that point reaches 44.5m. The reflectors were tested in several forms, including the Quadratic Residue

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Diffusers which were finally used. In the full-size concert hall these reflectors contributed towards one of the highest fractions in concert halls for the early energy arriving laterally at listeners.

The Waterfront Hall, Belfast, was tested twice at model scale in 1992. In design terms this hall is a fairly direct descendent of the much praised St. David's Hall but the two halls differ in terms of the situation at the ceiling level. In St. David's Hall the roof structure and some ventilation ducts are included within the acoustic volume above an acoustically transparent suspended ceiling. The Waterfront Hall contains suspended elements but being less "random" these surfaces may perhaps not promote the same degree of diffusion.

The description here will highlight the problems which were encountered in the first model and how they were resolved in design terms. The account at this meeting by the acoustic consultants, Sandy Brown Associates [18], deals with the final design, which matches closely the second model tested.

While the reverberation time behaved as expected as model seating was added to the first model, it was a surprise to find that the early decay time (EDT) was significantly shorter than the reverberation time. At mid-frequencies the ratio for the mean EDT/RT was 85%; this is in the bottom quartile for measured values in 21 large concert halls. While low values for the ratio are found in halls with reflecting surfaces which direct first reflections onto seating, this is not obviously the case in this hall.

Three further deficiencies were found in the first model:

- 1) inadequate early reflections to seats at the rear of the Stalls seating area.
- 2) a low level of late reverberant energy at seats furthest from the stage at the highest level (the behaviour was akin to that found under a low overhang).
- 3) echoes at positions opposite the stage about $\frac{3}{4}$ of the way back, Figure 5.

Octave frequency (Hz):	125	250	500	1000
Mean EDT/RT: Model 1	-	-	0.82	0.87
Mean EDT/RT: Model 2	1.02	1.00	0.91	0.98

Table 2. Ratio of the mean early decay time to reverberation time in the two models of the Waterfront Hall, Belfast

The changes made for the second model were a) to bring some seating blocks closer to the stage, b) to rotate some surfaces in plan in the Stalls to provide more reflections to rear Stalls positions and c) a substantial redesign of the ceiling and suspended elements, with in particular a raised soffit at the rear of the hall opposite the stage. The effect of these changes on the EDT was to

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increase values so that they were now closer to the reverberation time, Table 2. This demonstrated that the acoustics were now more diffuse, almost as diffuse as St. David's Hall, which has ratios of mean EDT/RT close to unity, Table 1.

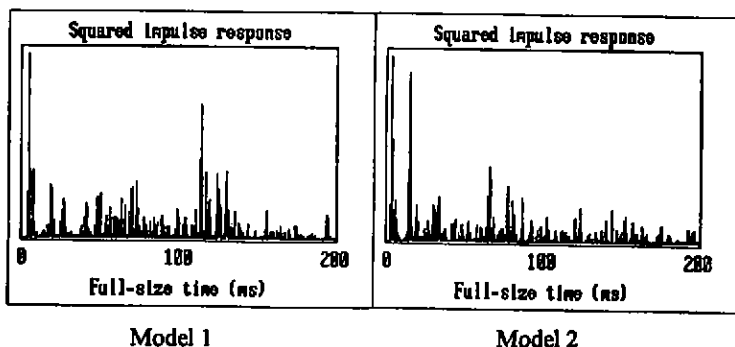


Figure 5. Impulse responses at the same seat position in models the Waterfront Hall.

Modification (b) improved conditions at the rear Stalls (problem 1), while the raising of the soffit at the rear (modification c) resolved problem (2) for seating at the highest level. The echo paths (problem 3) involved reflection off the cornice between the walls and ceiling; these paths were obscured in the redesign of the ceiling. Figure 6 shows squared impulse responses at the same position (front of highest balcony opposite the stage) for the first and second models. In the first model the echoes, delayed around 120ms, are clear, while in the second model the impulse response follows the preferred "fir tree" criterion [1, p.421].

Model testing of the Waterfront Hall demonstrated very clearly how testing at 1:50 scale can be fully integrated within the design programme and influence the design in major ways.

5.2 Drama theatre models at 1:50 scale

In 1978 we were asked by Sound Research Laboratories to test a model of the future Theatre Royal, Plymouth. This produced several interesting results [14, mentioned as "Theatre model results"]. Mention has already been made of the modelling procedure whereby the reverberation time of the auditorium is measured as absorbing materials are progressively added. In a proscenium theatre, there is the problem of what to do with the proscenium opening. This has generally been handled by placing an absorbing screen over the opening while the seating is being installed and then opening up the proscenium to check that sufficient absorbing material has been placed in the stage house. (In practice, the reverberation time of theatres can be influenced by the amount of absorbing material placed in the stage house; we have tended to test with the condition of high absorption in the stage house.)

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The absorption coefficient of the model seating was measured in a model reverberation chamber and compared with the effective coefficient measured in the model auditorium. It was found that at mid-frequencies the seating was absorbing only 83% of the energy absorbed in a diffuse sound field. This was attributed to screening by balcony overhangs, and would mean that the reverberation time in the full-size building could be expected to be slightly higher than calculated by standard formulae.

Most measurements were devoted to ensuring adequate speech intelligibility, with emphasis on testing the situation with the actor facing across stage and listeners in the half of the auditorium behind the speaker. Inadequate intelligibility (based on the 50ms early energy fraction) was discovered at the highest level of seating and improved by redesign of the suspended ceiling. The full-size theatre which opened in 1982 with 1270 seats achieved satisfactory intelligibility for all locations [8].

Model testing for good speech conditions appears to be a reliable exercise both at large and small model scales. At least in the case of speech there is no ambiguity about the relevant objective measure to study.

5.3 Opera house models at 1:50 scale

Four models have been tested for use for opera. Whereas the measurements developed for speech and music can be expected to be applicable for opera houses, there was no tradition of standard measurements for opera beyond reverberation time. If other measured quantities were to be considered, what criteria would be appropriate? The situation is of course complicated by having two sound sources: the singers on stage and the orchestra in the pit. Experience both in models and from measurements in full-size opera houses has led to proposals to consider intelligibility for the singers and clarity and envelopment for the orchestral sound [8]. But perhaps most important are the sound levels generated by each sound source and crucially the balance between the singer's level and the orchestra.

The first model tested in 1980 was of an opera house for La Plata in Argentina (consultants Bickerdike Allen Partners). This is also the largest house tested so far with a capacity of 2180 in an auditorium volume of 15,500m³ with three main levels of balcony and three further lines of boxes along the side walls. This model was pivotal in understanding the acoustic effects of balcony overhangs. In several spaces it had been observed that the early-to-late index was larger under overhangs than in the main body of the auditorium. But this difference under overhangs was particularly marked in this model. Was this a peculiarity of this design or a characteristic of most opera houses with overhangs?

A large value of the early-to-late index will either be caused by a high value of the early sound or a low value of the late (or perhaps a combination of the two). Measurements were made of the

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early and late sound levels, which established beyond doubt that there was deficient late sound energy under these overhangs. To test whether the especially low values for the late sound were caused by poor diffusion, panels were hung in the main volume, but with minimal effect. It gradually became clear that audience under an overhang cannot receive late sound from many surfaces, and if the proscenium opening is essentially absorbing acoustically, this would explain why the problem is more severe in opera houses than spaces such as concert halls (for the same balcony geometry), Figure 6. By blocking off the top half the proscenium opening it was possible to find evidence to support this theory, since this physical change caused the late sound levels to increase under the overhangs.

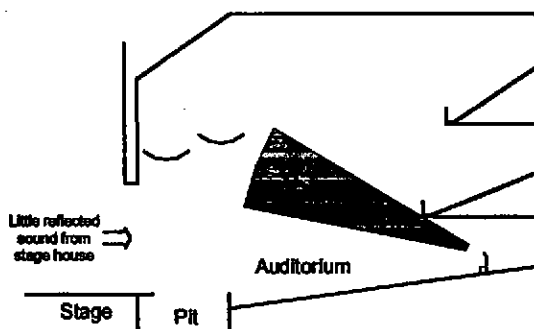


Figure 6. Long section of an opera house, showing the small angle from which later sound can arrive at seats beneath an overhang.

Impulse response measurements also highlighted problems associated with the high ceiling in this house and focusing by concave surfaces. A diffusing ceiling was proposed as well as replacement of the curved surfaces. The importance of using the splays to the side and above the proscenium opening for acoustic reflections also became clear from the model tests. Construction of the full-size opera house has been rather protracted.

6. CONCLUSIONS

The experience of testing models at various scales has been especially rewarding in reaching an understanding of the behaviour of sound in auditoria and appreciating the acoustic contribution of the various elements in a design. Indeed speaking personally I have probably learnt as much from model testing as other sources of experience combined. Models have provided pointers for what to look for in full-size auditoria. Since most of the modelling relies on objective measures, the testing has stimulated an understanding of acceptable values for the newer measures and what aspects of the design are important. Various publications owe their inception to model results:

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concerning energy behaviour in concert halls [16], behaviour under balcony overhangs [19], speech in theatres [8] and assessment of EDT results [20].

Testing models demands a range of skills. At the practical level it is important to understand the physical and electronic system being used and know for instance when a microphone is misbehaving. The measurements generate a series of objective results and an understanding of each measure is essential. And based on these results, decisions have to be made when to propose major changes to the design. The roles of technician and engineer have to be combined with that of the acoustic designer.

For our testing at 1:50 scale, it was fortunate that the first two models we tested (St. David's Hall, Cardiff and the Theatre Royal, Plymouth) were each good basic designs! With time, we have developed greater understanding and confidence. In the last few years, radical changes have been proposed to several designs we have tested and a second series of tests undertaken on a modified model.

Acoustic scale modelling now has a history of over 60 years, though in the early years it was a case of developing and validating techniques rather than as an active influence on design. Computer models have a clear advantage in terms of convenience and cost, but they have yet to demonstrate that they can cope with the complexities of diffraction and cope with the transition between the early and reverberant sound. Computer models require a good description of the acoustic character of surfaces; this has led recently, for instance, to work on the diffusion coefficient for surfaces [21]. For complex geometries, it is likely that diffusion properties of surfaces may need to be measured at model scale in any case! The position of acoustic scale modelling looks secure for yet a while as a design aid for major concert halls, opera houses and drama theatres.

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