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THE ACOUSTIC DESIGN OF THE GLYNDEBOURNE OPERA HOUSE

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1 INTRODUCTION

The first performance in the 'new' Glyndebourne Opera House took place in May 1994 on the 60th anniversary of the opening of the original theatre, with the same opera, *The Marriage of Figaro*.

Privately funded, and set within the grounds of an English country house, the new auditorium has a capacity of 1200 seats plus 42 standing places and 12 wheelchair positions, compared with 830 seats in the previous opera house.

The history, design and construction of the opera house have been well documented [1], [2], [3]. This paper describes the realisation of the client's acoustic brief, discussing the analysis techniques used, the resultant design elements and the achieved results.

2 THE BRIEF

The project was relatively unusual in that an excellent acoustic was required for a sole, clearly defined purpose, the performance of opera. Glyndebourne is particularly well known for its Mozart productions, but the first season also typically included operas by Birtwhistle, Britten and Tchaikovsky.

The client's brief was simple and direct: to combine the renowned clarity of the old house with a 'resonance' that would flatter the orchestra and singers. Throughout the history of opera there has been debate over the primacy of words or music. The resolution of this dichotomy, ie the achievement of both high vocal clarity and a full and exciting orchestral sound, was the basis of the acoustic design.

Table 1 includes the criteria set by Arup Acoustics to help achieve the requirement of the brief.

The mid- and low frequency RT criteria are of particular interest. The old house had an occupied RT of only 0.8s, shorter than almost all other opera auditoria and considered far too dry.

It was a presumption of the acoustic design strategy that a significantly longer RT, resulting in a greatly improved orchestral sound, could be achieved provided that strong early reflections could also be realised to balance the early and late sound, ie to ensure appropriate values for C_{80} and D_{50}. It was further decided to design for an increase in the low frequency RT relative to the mid frequencies. This is of course the norm for concert halls, ensuring a rich low strong sound and firm bass line, but does not concur with orthodoxy for opera houses. Again it was predicted that the provision of strong early reflections of the singers voices, particularly in the singers' upper formant frequency ranges, would counter any upward masking effects from low frequency orchestral sounds. Hence the thin sound and weak bass line which can occur with a linear RT frequency characteristic could be avoided.

3 THE AUDITORIUM CONCEPT

Another client requirement was for theatrical and acoustic intimacy. The architects ensured this by adopting the classical horseshoe form, but within an overall circular drum geometry, as shown in Figure 1. This form, with 3 levels of seating, as shown in Figure 2, minimises the average distance of the audience to the performers.

Further, the balcony fronts of the circles reduce the effective acoustic width of the auditorium, providing early reflections to the stalls which enhance clarity and vocal intelligibility. At the same time, a concave plan form introduces obvious dangers of undesirable sound focusing, or even echoes. In traditional houses extensive areas of drapes, carpet, etc absorb sound and extensive ornamentation diffuses sound, mitigating these dangers. However, neither the client nor the architect at Glyndebourne (nor indeed the acoustician) were interested in a 'plush and velour' house. The challenge, therefore, was to provide an unfocused acoustic within a visually circular geometry.

4 ACOUSTIC MODELLING

Because of the basic concave geometry of the auditorium, the use of a ray-tracing/image source computer model was not considered appropriate. The main modelling tool was therefore a 1:50 scale acoustic model. This scale of model is preferred by Arup Acoustics as it is relatively inexpensive, portable and can be quickly updated in response to design changes and to test design options [4].

The model was constructed in perspex of appropriate thickness to model masonry and concrete. The scale absorption coefficients of the surfaces, including the model seating, were verified using Arup Acoustics' 1:50 scale reverberation chamber. The impulse modelling technique was conventional, with a spark source and ⅛" microphone controlled by MIDAS software [5].

Modelling was carried out for the rehearsal (unoccupied) condition. The model predictions for RT and EDT were compared with full-scale measurements in the completed auditorium, for 4 locations in the stalls, circle and upper circle. Good correlation was found: RT average error +0.1s (error range +0.05s to +0.2s), EDT average error +0.1s (error range -0.2s to +0.35s). The model was found to consistently underestimate the clarity index (C_{80}): average error -1.85dB (error range -0.9dB to -2.85dB). It is considered that this may be partially caused by the fact that the side balcony fronts in the model were modelled as diffusing, whereas in the final design they were shaped to optimise the early reflection pattern.

The architects original concept was for a domed ceiling to the auditorium. This was the first roof profile tested. Using a simple form of auralisation, that is reproducing the spark impulses at 1/50 speed, the acoustician was able to dramatically demonstrate the resultant echoes at certain locations. Two further roof geometries were subsequently evaluated in the model, including the final solution.

In addition to impulse testing the model was used for optical investigation of first reflections using mirrored surfaces, a directable source mirror system and a laser. Volume estimation was also carried out in the scale model using the bead infill technique.

5 AUDITORIUM GEOMETRY

The auditorium contains a variety of acoustic elements to provide a good distribution of sound, enhancing clarity and preventing image shifts or perceptible late reflections caused by concave form focusing. These elements are principally diffusive:

- structural ribs and fins semi-exposed in the flat disc of the central ceiling, combining architectural, structural and acoustic functions.
- the vertical upper wall surface at ceiling level (Figure 2), which is circular in plan, is modulated by moulding the pre-cast concrete panels with a convex profile.
- convex timber diffusing panels and seat box elements to obscure the concave drum wall.
- large diameter circular ducts are exposed within the auditorium.

Sound absorptive panels, consisting of slatted timber backed with mineral wool, are installed only where space did not permit the use of (deeper) diffusion, for example at certain exit ways.

The balcony fronts are constructed in timber segments. The vertical profiles change around the curve, providing lateral reflections from the straight sides and diffusion from the curved sections. Significant lengths of the concave balustrades are acoustically-transparent, both to avoid focusing and to maximise the sound level at overhung seats.

The auditorium surfaces are all self-finished materials which meet the requirements of both the architect and the acoustician: timber, concrete, steel and glass.

The seats were purpose designed by the architect, with a velour fabric covering foam on a plywood frame. During a programme of both impedance tube and reverberation room testing, the constructions were iteratively modified to meet the acoustic absorption requirements, both occupied and unoccupied. The underside of the seat pans are slotted to expose the seat squab and increase the absorption in the unoccupied condition.

There is a tradition at Glyndebourne to encourage young singers. To achieve the delicate balance between stage sound and pit sound the pit is partially overhung with a (removable) forestage. The 'open' distance dimension between the orchestra rail and forestage edge is 4m, the overhang dimension is around 3.7m. A total area of $112m^2$ is available, with a maximum clear height also around 3.7m.

The orchestra rail is designed to be acoustically-transparent or reflective, in modular sections. For the first season the conductors and music staff opted for transparency to enhance the upper string sound within the stalls.

6 ACHIEVED RESULTS

An acoustic test rehearsal day, with a capacity audience, full orchestra, singers and a typical box stage set enabled objective measurements and subjective assessments to be made with the auditorium both occupied and unoccupied (without audience and orchestra) on the same day.

Table 1 summarises the key parameters. All have been achieved except for the original RT target value and the EDT/RT ratio. The RT target value was reduced when it was apparent that the target volume/seat of $7m^3$ was not quite achievable. Of particular interest is that the average occupied RT of 1.25s corresponds exactly to the final volume/seat of $6.25m^3$ using the 'rule of thumb' rule of $0.2s/m^3$.

Table 2 may also be of interest to auditorium designers, in that it compares the average measured RT values with conventional Sabine and Eyring calculations, using spreadsheet software. The normally-found increase in over-prediction at lower frequencies and the greater accuracy of the Eyring formula for this type of space are apparent in both occupied and unoccupied conditions. At low frequencies the predictions are more accurate for the occupied state, at high frequencies the predictions are more accurate for the unoccupied state. The average error in prediction exceeds that for the acoustic scale model in both cases.

Analysis of the measured impulse responses showed almost textbook forms in most locations, with good early energy arrival patterns.

Subjectively, Sir George Christie (the client), Bernard Haitink and Andrew Davis (the regular conductors), the London Philharmonic Orchestra (the resident orchestra), singers and press have all praised the acoustic.

7 NOISE CONTROL

Glyndebourne is a quiet setting for an opera house, but the site is affected by aircraft overflights.

The auditorium drum is constructed of a twin fair face brick wall with specialist resilient wall ties. In addition to optimising airborne sound insulation, the resilient break along this circumferential gridline provides protection against noise from footfall impacts on the hard foyer surfaces.

The auditorium roof is a twin construction (Figure 2) with a concrete inner and a lead-covered outer layer. The flytower roof is concrete; smoke extract is via an attenuated duct system, eliminating the inevitable weakness caused by a stage lantern. The flytower walls are external lead-covered panels and inner pre-cast concrete panels or dense blockwork walls, depending upon location.

The stage and backstage are separated by 3 massive power-operated acoustic/fire doors, the central door operating vertically. The doors achieve the specified average sound level difference requirement (average 63Hz to 8kHz) of 45dB. A further 10m x 4m hinged acoustic door, thought to be one of the largest of this type installed in Europe, protects the rehearsal stage from the backstage. This door achieves the required average sound level difference of 40dB.

Major noise and vibration producing plant items, namely the chiller, boilers and emergency generator, are located remote from the main building in a converted stable block. The air condenser unit is also remote.

Conditioned air is supplied from air handling units located in the basement below the backstage area, via large ducts and primary, secondary and tertiary attenuators. The air enters the auditorium through individual underseat air supply units at very low velocity (0.1m/s). The selected units, supplied by Krantz, form the seat pedestals. These were acoustically tested to ensure that each did not contribute more than PNC 15 - 34dB to the overall noise level (ie PNC 15 - 3dB - 10log 1200dB).

The (hydraulic) front of house lift is immediately adjacent to the auditorium drum (Figures 1 and 2). It was constructed with a self-supporting inner concrete shaft on an isolated foundation, not connected to the outer brickwork shaft.

Particular attention was paid to noise control from lighting, including the transformers for the low voltage houselighting fittings and the noise from colour scrollers on production lanterns.

8 DESIGN TEAM

Architect:	Michael Hopkins & Partners
Structural and Services Engineers:	Ove Arup & Partners
Theatre Consultants:	Theatre Projects Consultants
Acoustic Consultants:	Arup Acoustics

9 REFERENCES

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[4] R ORLOWSKI 'Acoustic Scale Modelling of Sabine and non-Sabine spaces: past, present and future', Proc. ASA Sabine Centennial Symposium on Architectural Acoustics, Cambridge, MA, USA, June 1994

[5] X MEYNIAL, G DODD, J-D POLLACK & A H MARSHALL: 'All-scale model measurements: the MIDAS system', 121st ASA meeting, Baltimore, USA (1991) J. Acoust. Soc. Am. 89 (4,2) 4AA2

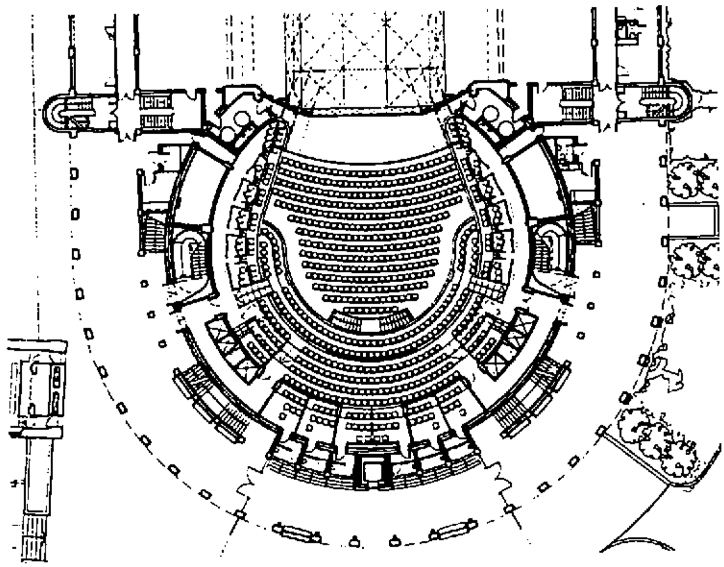

FIGURE 1: Plan of auditorium at stalls level

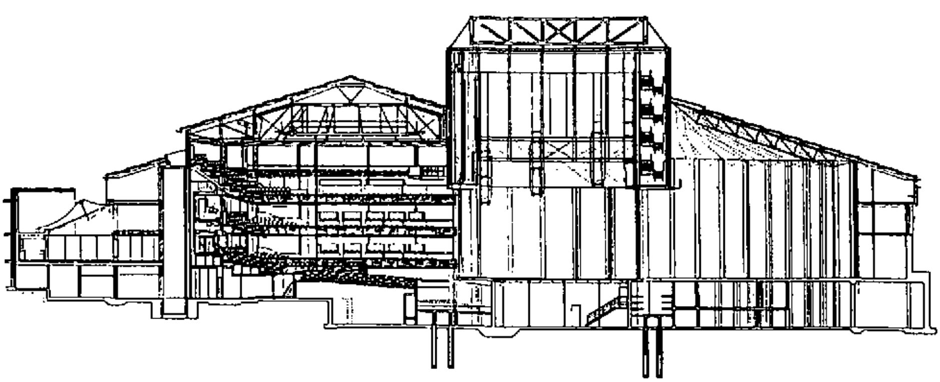

FIGURE 2: Long section showing auditorium, stage and backstage

Parameter	Occupied		Unoccupied	
	Criterion	Achieved	Criterion	Achieved
Mid-frequency RT (500Hz/1kHz)	1.4s	1.25s	≤1.55s	1.45s
Low frequency RT (125Hz)	≤1.75s	1.65s	≤1.95s	1.95s
RT difference, occupied to unoccupied (mid frequency)	≤0.2s	0.2s	-	-
RT difference, occupied to unoccupied (low frequency)	≤0.25s	0.25s	-	-
EDT	-	0.95s	-	1.15s
EDT as %RT	≈90%	76%	≈90%	76%
C_{80}	>0dB	3.3dB	>0dB	4.0dB
L_T	0dB < L_T <5dB	1.25dB - 4.6dB	-	-
STI	≥0.6	0.63	≥0.6	0.63
Volume/seat	($7m^3$)	$6.2m^3$	-	-
Furthest seat to stage	30m	29m	-	-
Balcony overhang depth/height	≤2	2	-	-
Maximum stalls width	18m	16.2m	-	-
Background noise level	PNC 15	PNC 15	PNC 15	PNC 15

TABLE 1: Acoustic design parameters

Note: All RT and EDT values rounded to nearest 0.05s from base data, C_{80} and L_T values to nearest 0.1dB, STI values to nearest 0.1

Condition		Octave Band Centre Frequency, Hz						
		125	250	500	1k	2k	4k	Av
Occupied:	Sabine	+0.25	+0.5	+0.45	+0.35	+0.3	+0.2	+0.25
	Eyring	+0.1	+0.35	+0.3	+0.2	+0.15	+0.15	+0.15
Unoccupied:	Sabine	+1.05	+0.6	+0.35	+0.25	+0.05	+0.05	+0.4
	Eyring	+0.95	+0.45	+0.2	+0.1	-0.05	-0.05	+0.25

TABLE 2: Prediction errors of classical RT formulae, s