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SOME ASPECTS OF OPERA HOUSE ACOUSTICS

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INTRODUCTION

The acoustical requirements for rooms in which musical productions are staged are considerably more complex than those for concert halls. Without diminishing the importance of the orchestral sound the impressions of the singer should be given the highest priority. Thus the bel-canto-passages require sufficient reverberation perhaps even a certain amount of spaciousness to give the voice a voluminous richness and the melody line a sound cohesion. The singer also likes to feel a certain "resonance" of the room which not only gives assurance in the production of the voice, but also security in participation in ensemble.

On the other hand a considerable amount of clarity if required to ensure an adequate intelligibility. Particularly in the fast parlando-passages or recitativo it is of importance to the listener that the articulation of the singer is enhanced by early reflexions in the higher frequencies. In the great arias or e.g. in richly orchestrated scenes of the Wagnerian Opera the main problem in understanding the text arises from the masking of the singer by the orchestra.

Thus each Opera house has individual and very different requirements according to the type of performance and the respective strength of the appropriate orchestra. Therefore it might be of interest to compare the acoustical data of some historical and new Opera houses and the size of the orchestra playing in them, in order to get some information on the balance between singer and orchestra.

ACOUSTICAL DATA OF A FEW OPERA HOUSES AND ORCHESTRAS

For the sound level impression of orchestras the statistical sound field is mainly responsible since the direct sound of an orchestra playing in a pit is masked in most of the listener seats. For this reason it is relevant to determine the statistical energy density level L_E of the orchestra's forte sound in a room, which is known to be:

$$L_E = L_w - 10 \lg V/V_o + 10 \lg T/T_o + 14 \text{ dB} = L_w - L_A$$

where L_w is the sound power level of the orchestra, V the room volume, $V_o = 1 \text{ m}^3$, T the reverberation time, and $T_o = 1$ s. The characteristic quantity for the room attenuation is then L_A. As can be seen in the upper diagram of Fig. 1, these values are largely determined by the volume. They are less influenced by the reverberation time which varies between 1.0 and 1.1 s for the theatres of Mozart's time, and between 1.1 s and 1.3 s for the most Opera houses of the 19th and 20th century. For the rebuilt Semper-Opera in Dresden, it has the extreme value of 1.85 s /1/. So the values of L_A are in the range of 20 dB for the old theatres, and 25 dB for the modern theatres. This means that an orchestr with the same number of players was louder by about 5 dB in the old theatres. It is remarkable, too, that the difference between the

Semper Opera and the large Teatro Regio is no more than 3 dB.

The size of orchestras which played in the named historical Opera houses during Mozarts time is known. Of special interest is the numerical strength of the string players compared with those of the wind instruments. The latter were played only in singles and were arranged accordingly to the individual piece. The size of the orchestra can be applied to determine the radiated sound power which of course depends on the musical dynamics. As the dynamic range which is the most critical for the singer is the orchestra's forte, the sound power of the single instruments /2/ playing forte, has been summed up for some sizes of orchestras: the three original sizes of Mozarts orchestras, a small present day Opera house orchestra "A" (8 first violins etc.) and an orchestra specified by Verdi at the Scala "V" (12 first violins etc.). The middle diagram of Fig. 1 shows the corresponding sound power levels of an all string ensemble as well as the combination of a string ensemble with the two wind variations. At the historical theatres these variations are not taken into account since the wind ensembles were only small.

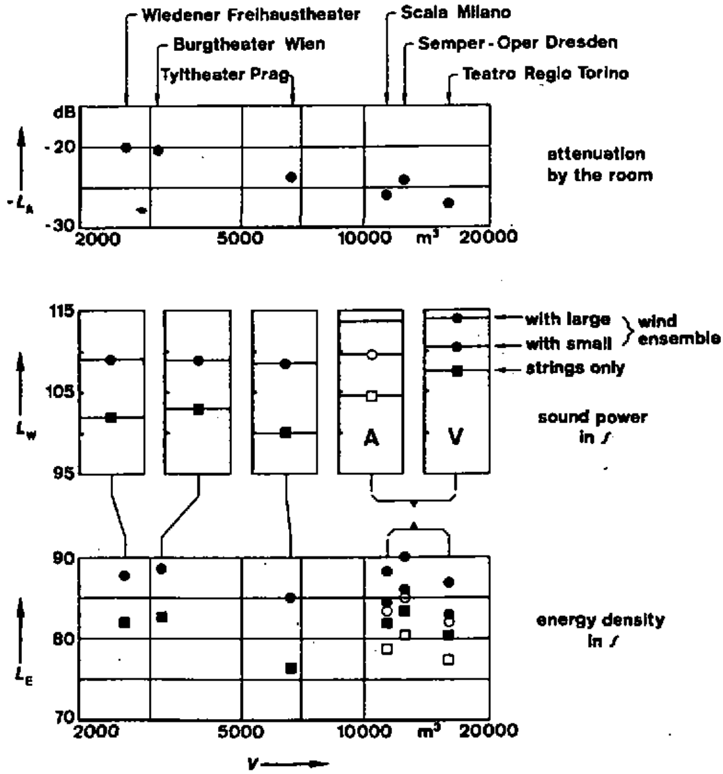

Fig. 1 Attenuation by the room absorption, sound power level of orchestras and energy density level in some Opera houses

The values of the energy density level for strings and full orchestra are shown in the lower diagram of Fig. 1. Looking at the levels of an all string ensemble it is noticeable that the relatively small ensembles in the historical Viennese Theatres achieve values which are achieved only with effort by the relative large orchestras in the "V" seating format in the newer Opera houses. Inspite of this, in these Opera houses one comes across pieces of Mozart's time in which the ensemble corresponds to seating arrangement "A", causing a further downgrading of 1.5 dB of the string sound. With a smaller wind ensemble the effect of size in the newer Opera houses shows clearly, since the number of wind instruments can not be adjusted to the acoustical environment. Therefore it must be expected that the wind ensemble typical for many Mozart passages achieved the same levels in the old Viennese Theatres as the large ensembles achieve in the newer Opera houses.

Added to this is the fact that for the listeners seated in the stalls, the direct sound is screened by its bending on the balustrade of the orchestra pit. Fig. 2 shows this effect in a few typical situations. The values are calculated according to /3/ and indicate the level attenuation which occurs in addition to the geometrical attenuation. The upper row of the diagram refers to raked rows of seats and the lower one to a flat arrangement. The left and right-hand diagrams refer to seating at a distance of 3 m and 10 m from the orchestra pit, respectively. The solid and dotted curves refer to an orchestra pit at a depth of 2 m or 1 m respectively below the level of the stalls. Finally, each field contains a curve for a musician seated at a distance of 1 m from the balustrade of the orchestra pit, and one for a musician at a distance of 4 m.

As can be seen, the screening increases strongly with rising frequency. With the orchestra seated at the lower position, at very high frequencies the attenuation may be more than 20 dB. When the orchestra is not seated so low, the attenuation is weaker by between 5 and 10 dB, which is particularly noticeable

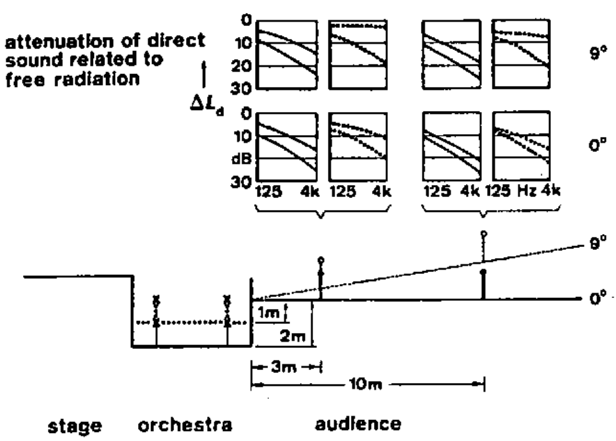

Fig. 2 Attenuation by bending of the orchestra's sound

at higher frequencies; the sound of the orchestra is lighter in timbre and clearer in articulation, but of course, also rather louder. The differences in the positions of the musicians are also greater, i.e. the instruments closer to the stage gain more in brilliancy than those closer to the public.

THE BALANCE BETWEEN SINGER AND ORCHESTRA

The balance between singer and orchestra sensed by the listener depends, of course, to a very great extent on the sound power ratios between these sound sources, though the spectral energy distribution is also important. Finally, the unimpeded sound radiation in the auditorium is also to the singer's advantage. Since there is no reliable data for the sound power of singers to be found in literature, Spelda's dynamic measurements /4/ may be taken as a basis for the comparison of the sound power radiated by singers and by other instruments. From this results a sound power level of 102 dB for the average forte of a singer. The peak values of the fortissimo may be from 15 dB to 20 dB above this. With regard to the balance between the singer and the orchestra, the sound power of the singer in forte thus corresponds approximately to that of the historical string group and by comparison, the wind group's forte approximates the peak values of the singer's sound power.

For the carrying power and dominance of the singing voice vis-a-vis the orchestra the so-called singer's formant in the region of 3000 Hz is important. Its strength depends to a considerable degree on the degree of voice training and only insignificantly on the pitch level but is noticeable influenced by the dynamic, with an increase in the overall level of 10 dB it can rise to 16 dB /5/. With good singing voices the level of the singer's formant in forte can be within 10 dB of the level of the strongest tonal components - the fundamental formants of the sung vowels. As to be seen in Fig. 3, this fact is even more remarkable since in the sound power spectrum of most orchestral instruments playing forte the spectral components at 3000 Hz are already about

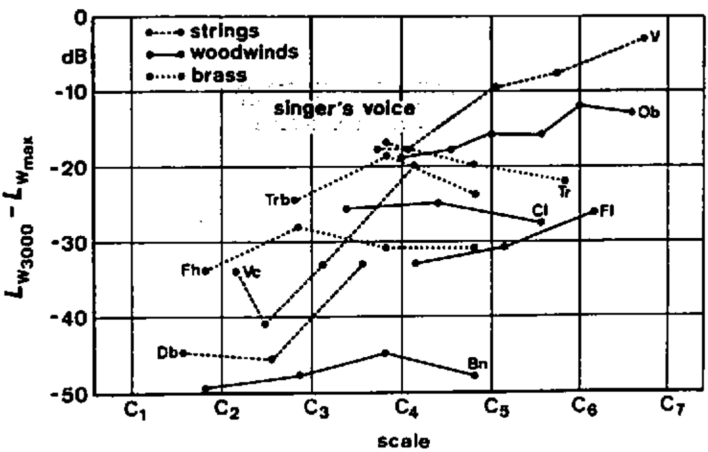

Fig. 3 Sound power level of the 3000 Hz components in relation to the strongest components, when playing forte

20 Hz below the strongest components and for the deep instruments this gap is up to 30 dB. An exception is the oboe where the 3000 Hz components are about 12 dB below the strongest spectral region. In the high and medium pitch range of the violins the gap is only 6 to 10 dB. All values are for forte sounds. With lower dynamic levels (with exception of the strings) the 3000 Hz components decrease faster than the lower frequencies components.

Without the singer's formant which at 3000 Hz can clearly exceed the sound power level of the orchestra, as above mentioned values show, the singer could succeed only with great effort. Although violins and oboes produce substantial sound in this frequency band the direct radiation of these components is weakened by the orchestra's position deep in the pit. On the other hand the singer on stage has the advantage of uninterrupted voice directivity.

THE DIRECTIVITY OF SINGERS

The directivity of the sound radiation of singers /6/ is caused partly by the shading of the head and partly by the geometry of the mouth and its airflow. The latter causes the directivity among different vowels to vary. The direction of the strongest radiation is not necessarily to the front of the singers; in fact double maxima to the side can occur. These influences are most obvious in the frequency range of 1000 Hz to 2000 Hz. The dynamics and pitch - apart from the highest notes - have no significant influence on the directivity.

A 20^{o} downwards maximum which is most prominent in the frequency range of 2000 Hz is typical for the trained voice. It recurs in a weakened form in all octave bands and is most developed in the dark vowels. The vertical radiation is weaker than sideways in all bands. To the back the level decreases continuously and at 4000 Hz reaches a value of -20 dB referred to the radiation to the front of the singer. Altogether, it can be assumed that when the singer turns by an angle of 40^{o}, there is a perceptible change in the timbre of his voice, and that from about 80^{o}, this change has a negative effect.

To be able to assess the voice's clarity in a room, it is of interest to know the voice's reverberation radius. This depends on the volume and reverberation time of the room and also on the voice's directivity. In Fig. 4, therefore, the statistical directivity factor is given, that is, the factor by which at

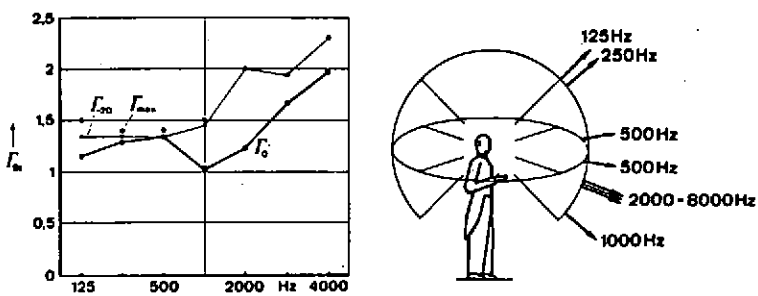

Fig. 4 Statistical directivity factor and directions of strongest sound radiation of a singer

a certain point the sound pressure of the directed source is distinguished from the sound pressure of an omnidirectional sound source of the same power. The directions of the strongest sound radiation for each octave range are also given.

In Fig. 5 the reverberation radius relevant for the singer's formant are shown in the outlines of the old "Burgtheater" in Vienna and the Semper Opera in Dresden; it is assumed that the singer is standing 2.5 m behind the stage's edge. Also shown are complementary curves for 3 x the reverberation radius, i.e. the distance at which the direct sound is 10 dB below the statistical field; at this distance, based on the 'law of the first wave front' an unambiguous localisation of the source is still possible. It is amazing how well this curve conforms with the Semper Opera whereas in the longer room of the 'Burgtheater' the back seats are already outside of it. Opera houses of today's common size achieve at 4000 Hz values of approximately 6 m; it follows that with a statistical directivity factor of 1.65 a value of 30 m results for 3 x the reverberation radius and that must be regarded as the limiting distance for separation of source and listener.

However this limiting value should not be considered too dogmatically if the direct sound can be supported with early reflections. The best surface to generate these would be the floor area 2 to 5 m in front of the singer as the particularly strong sound components from the singer's downward directed maxima arrive there; they are relatively flat, i.e. they are reflected into the room at angles up to about 45°. A balance is thus created by means of these reflections when the singer stands more to the back of the stage, so the "permissible limit" for the distance between stage and back rows may be calculated from the front area of the stage. Also wall reflections from the proscenium area can be very effective since the radiation to the ceiling is not so strong.

THE SINGER AND THE ROOM'S "FEEDBACK"

It is known from old experience that singers feel very comfortable in some Opera houses because of feeling a stimulating effect from the room reverberation on their own voice whereas in other Opera houses they find singing much harder and perhaps have more difficulty adjusting to the ensemble. The temporal and spatial structure of the feed-back of sound energy from the auditorium to the singer is relevant here.

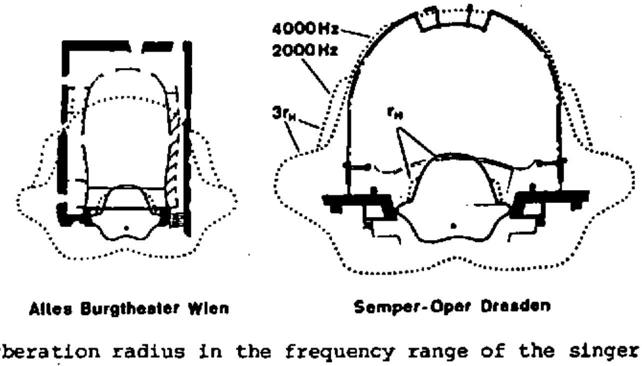

Fig. 5 Reverberation radius in the frequency range of the singer's formant

OPERA HOUSE ACOUSTICS

Experiments with synthetic sound fields /6/ however showed that for the singers - contrary to the instrumental players - it is not the early reflections but the reverberation which plays the greatest role. The length of the reverberation time in the range of approx. 1 - 3 s doesn't affect the singer's acoustic assessment as long as there are no strong single reflections in the early phase. If the reflections forming the reverberation begin at a transit time of about 80 ms one or two early single reflections are desirable. The preferable time range has a transit time of 15 to 35 ms, i.e. equivalent to the reflection surfaces 2.5 to 6 m from the singer. Circle balustrades and balcony fronts close to the stage and also the stage decoration are such surfaces. From the singer's point of view, however, reflections coming from the same direction as the greater part of the reverberation energy are more to his advantage.

Early reflections which are too strong can disturb the balance between his own voice and the orchestra for the singer. The sound pressure level at the singer's ear is 5 to 10 dB below the sound power level of his voice. As Fig. 1 illustrates, the sound pressure level produced by the orchestra at the singer's ear is 20 dB below the sound power level of the orchestra in old theatres and about 25 dB below it in new theatres. According to Sundberg /7/ for the sound to which he must adjust his intonation, a singer needs a level (at the ear) in the range of from 5 dB above his voice up to 15 dB below it. Assuming that the sound power of singer and orchestra is approximately the same, in a modern Opera house the singer is only just able to hear the orchestra sufficiently well.

Early reflections of the sound of his own voice would therefore change the balance to such an extent that the singer's intonation would be impeded. On the other hand, reflections of the orchestra's sound caused by the balustrade of the pit can enhance the direct sound and improve the ensemble feeling of the singer. Fig. 6 shows different profiles of the balustrade and their influence on the direction of the sound reflections; the small circles above the stage mark the height of the singer's head. If the pit is rather flat, a vertical balustrade seems to be favourable concerning all instruments. A reflect-

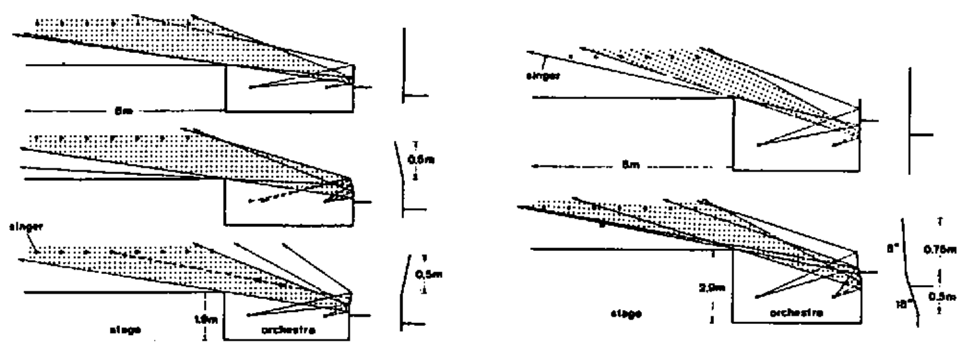

Fig. 6 Sound reflections caused by different kinds of orchestra pit balustrades

ing area declined towards the stage amplifies only the instruments situated close to the balustrade, and an area declined towards the audience results a reflection from the singer's sound back to the stage, without reflecting the sound of the instruments positioned close to the stage. If the pit is rather deep, a specially folded balustrade is more favourable, especially for singers standing more distant on the stage.

An important influence on the room sound on stage are the circle seats arranged in boxes /8/. If the partition walls between the individual boxes reach from the boxes' floor up to the ceiling, i.e. below the next circle, angles are formed between the backwall, ceiling and the partition wall of the boxes which reflect the sound back to the stage giving the singer a feeling of creating a voluminous sound in the auditorium. It is however essential that the boxes are not too deep and that the balcony fronts and the storey height leave a large enough space open so that the ceiling as well as the backwall of the boxes can be seen from the stage. Otherwise the angular (billiard-shot) reflection cannot work. In view of this, one must be aware when restoring or building new Opera houses that the elimination of the box arrangement in the circles creates a problem unless an alternative for reflection surfaces from the auditorium is found.

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THE BRITTEN OPERA THEATRE: ACOUSTIC DESIGN

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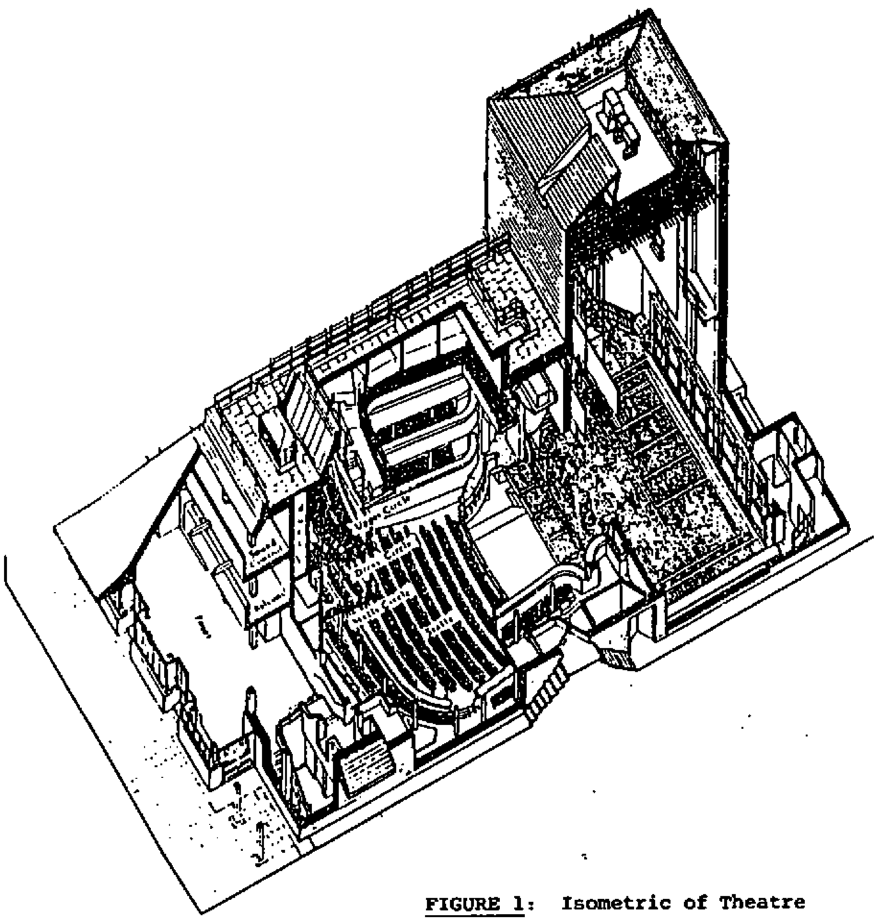


FIGURE 1: Isometric of Theatre

INTRODUCTION

The Britten Opera Theatre at the Royal College of Music (RCM) in London was opened by Her Majesty the Queen in November 1986. The acoustic design is of interest in that the theatre was designed specifically as a teaching opera house, and was built on a very constrained site within the College.

BRITTEN OPERA THEATRE

The background and precedents which resulted in the basic design concepts have been discussed previously [1]. This paper presents more prosaic data which it is hoped will prove of interest to acoustic consultants and theatre designers; basic design data are listed at the end of the text.

THE AUDITORIUM ACOUSTIC

The theatre is primarily for the teaching of young singers and musicians. It was therefore determined that the design should ensure that relatively weak voices were not overwhelmed by (perhaps sometimes overloud) players. Also the acoustic should not be too "flattering" to the singers, who must train their voices to sing in auditoria with volumes from 3,000m³ to 15,000m³ or more, without being so dry and analytical as to discourage the performers.

Site and planning limits dictated a compact auditorium with a volume of around 2,000m³. The modest dimensions, with traditional horseshoe form, shallow balcony overhangs (3 rows of seats below) and a raked stalls floor, made realisation of high clarity, immediacy and intimacy possible in all seats.

The design aim was for a mid frequency (500Hz - 1kHz) reverberation time (RT) of 1.25s with the theatre full, rising to not more than 1.4s under rehearsal conditions. It was decided that a controlled rise at low frequencies was desirable, with the inevitable fall at high frequencies to be minimised. Initial RT predictions showed the original design volume to be too low, and the roof height was increased by 3m.

Strand Seating 'Horizon' seats, with wool upholstery (but reflective backs and seat undersides) were selected to minimise the difference between rehearsal and performance conditions. Studded rubber flooring was installed in lieu of carpet; the only absorptive finishes apart from the seating were the upholstered balcony resters and the stage drapes. Figure 2 shows the final measured RT's (gunshot source), with 1.2s (full) achieved at 500Hz. Note the small change with occupancy. The seats were tested in accordance with the 'boundary screening' method in ISO 354: 1985[2]. Figure 3 compares the predicted (full) RT characteristic after the seat tests with the final times. Whilst care must be taken in this comparison (other factors changing as the design developed) it appears that this method, based on a relatively small number of seats, may still slightly overestimate the overall absorption of the seating.

The geometry of the theatre ensures a strong early reflection pattern. A convex 'scroll' profiling was adopted for the balcony fronts, together with surface modelling, to (1) provide useful lateral reflections, (2) introduce limited diffusion and (3) prevent echoes or undesirable focussing from surfaces of concave plan form (no echoes are audible).

The brief requirement for a maximum of 84 players (a large number for a 400 seat theatre), plus the need to maintain a balance slightly in favour of the singers, dictated a relatively deep semi-covered pit. The inevitable problem of excessive sound levels within the covered section was anticipated and addressed by the provision of adjustable drapes on the rear and side walls, and the installation of mineral fibre tiles on the soffit at the rear of the stage overhang. An orchestra lift and rostra are provided for adjustment of section levels.

The maple stage is semi sprung using TICO pads, to ensure that the stage is both resilient for ballet and quiet for opera. The flytower soffit is finished with woodwool panels to control the reverberant decay in the flytower, particularly when only a limited area of soft material is being flown.

The theatre foyer is often used for rehearsal. The floor is timber and the ceiling and walls are generally reflective, sound absorption being provided by carpet on the circulation areas and panels of fibrous absorption on the balcony soffits.

SOUND INSULATION

The Britten Theatre occupies a former courtyard within the main body of the RCM and Imperial College, immediately adjacent to the concert hall (with pipe organ) and surrounded by music practice rooms and teaching spaces. The following measures were adopted to limit external noise intrusion:

- independent building foundations and superstructure, with resilient inserts and structural discontinuities at all potential bridging points (link corridors, escape stairwells, etc)
- diaphragm masony walls (225mm/50mm cavity/150mm), plastered internally, with all cavities kept clear during construction
- concrete roof slab with paved finish; multi-layer boarding on pitched roofs
- lobbied access with sealed, solid core doors at all access points
- 'self-protecting' stage lantern geometry (see Figure 1).

Statistical measurements of external noise break-in indicated that only occasional peaks exceed NR15 within the auditorium.

All internal auditorium access is via carpeted lobbies, with absorptive ceilings and solid core doors with thick glass vision panels. The doors are fitted with neoprene perimeter and centre rebate seals and are close cut to the carpet at the threshold. As is often the case, building movement and use were found to reduce the effectiveness of the seals. It is of interest to compare the measured level differences shown on Figure 4: the upper curve (average 40dB, 63Hz - 8kHz) is for a lobby with 'perfect' seals (gaps sealed with several layers of tape), and a plan dimension of 3.6m between the two doorsets, the lower curve (average 34dB) is with the doors and seals as found, with a smaller distance of 1.8m between the doors. The combination of increased separation and improved seals can be seen to provide a significant improvement in overall performance.

Large access doors (1.3m wide by 6m high) were required between the stage and the existing workshop. Two heavy hinged doors were custom-designed; each

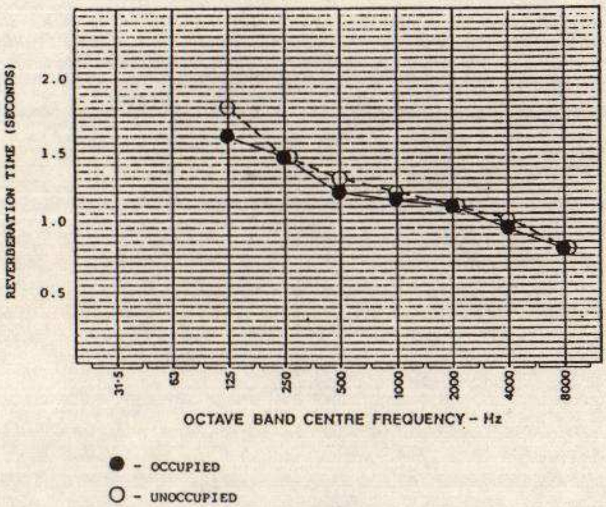


FIGURE 2 : Final measured reverberation times

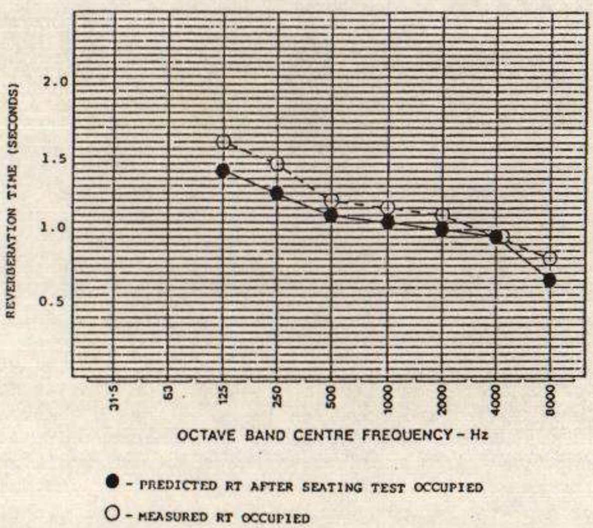


FIGURE 3: Comparison of final (full) RT with RT predicted after seating absorption tests

consists of a steel frame with 19mm ply panels each side of a 50mm core of high density mineral wool. Neoprene perimeter compression seals and automatic drop threshold seals are fitted, the lobby plan separation between the doors is 1.8m. The measured level difference of 52dB (average, 63Hz - 8kHz) was limited by flanking via an adjacent temporary access.

SERVICES NOISE

The theatre is mechanically ventilated but not air-conditioned. The air handling plantroom is beneath the stalls, and the fans were installed within specialist acoustic enclosures fitted with integral primary attenuators, secondary attenuators being installed before the ducts penetrate the auditorium. Supply diffusers are mostly of the Jetflo type. As an additional safeguard against noise intrusion from the plant, the rear stalls floor is isolated using a floated slab on TICO pads. No plantroom break-in is measurable. All rotating plant and associated pipework is isolated with high deflection spring mounts.

A design target limit of NR20 was set for the auditorium and stage. As shown in Figure 5, levels of between NR21 and NR23 were achieved in all but a few seats, (where an inaccessible control damper in a main supply duct resulted in a slight excess due to regenerated noise). The lowest level measured was NR19. Noise in the lighting control room meets NR25.

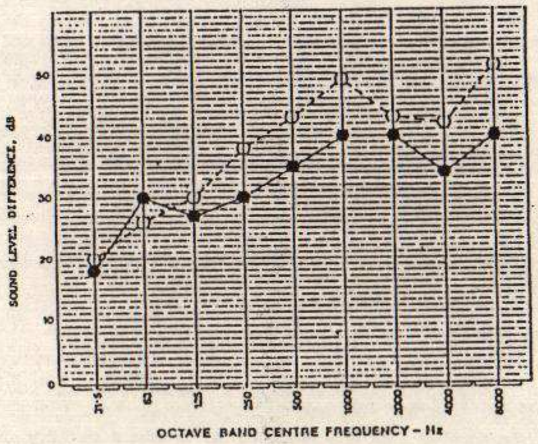
The dimmer room, fitted wtih 120 Strand Lighting dimmers, is also located below the stage. Table 1 presents measured noise levels from the dimmer racks.

Dimmer load	dB(A)	Octave Band Centre Frequency, Hz							
		63	125	250	500	1k	2k	4k	8k
0%	56	63	62	57	52	49	50	45	34
75%	57	55	62	55	51	50	50	46	48

TABLE 1: Measured dimmer room noise levels (approximately 0.75m from dimmer rack, room volume $54m^3$, all surfaces reflective), dB.

SOUND SYSTEMS

The design team did not encompass a theatre specialist, and hence the acoustic consultant advised on the provision of sound facilities. The use of sound in opera is not highly developed at the RCM, but 44 microphone lines (18 in the pit), 16 tie-lines and 23 loudspeaker lines have been installed for future use. To overcome the familiar visual intrusion of proscenium loudspeakers, three acoustically-transparent but visually-unobtrusive panels were installed each side of the proscenium arch, at stalls, dress and upper circle levels, with loudspeaker supports behind. With this arrangement the College can locate effects loudspeakers, etc, in accordance with the particular spatial requirements of the production. Allowance has also been



● - Seals as found, 1.8m door separation

○ - Fully sealed, 3.6m door separation

FIGURE 4: Level differences across typical door lobbies

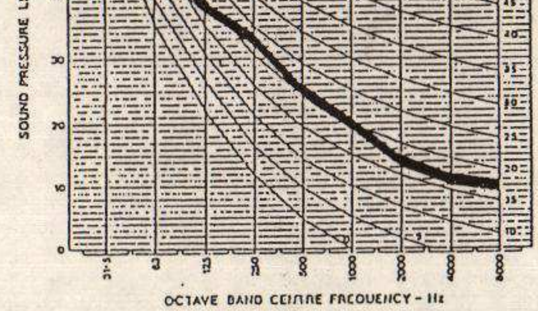


FIGURE 5: Measured services noise levels in theatre

made for on-stage foldback loudspeakers. The building budget did not allow for a fitted sound control room but distribution routes have been provided for the possible future use of a room at the upper circle level.

Basic show relay/paging and twin channel ring intercom systems have been installed, as well as CCTV.

The previous Parry opera theatre, located below the concert hall, is being converted for use as a recording studio suite, to be linked by multiple audio cables to a patchfield located below the stage.

DESIGN DATA

Volume:	2146m^3
No. of Seats:	405
Pit Capacity:	80
Auditorium height:	10.2m
Seating area width:	13.5m
Seating area length: (pit to rear of stage circle)	10m
Overall width:	16.5m
Proscenium width:	9m
Stage depth:	9.8m
Further seat from stage:	16.4m

CREDITS

Client:	Royal College of Music
Architect:	Casson Conder Partnership
Structural Engineer:	Ove Arup & Partners
Services Engineer:	John Bradley Associates
Acoustic Consultant:	Arup Acoustics
Main Contractor:	John Laing

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