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Acoustical Design Considerations of the Sydney Opera House

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Abstract – The Opera House, which is now completed (inauguration October, 1973) has a unique history of construction. While actual construction started in 1959, a subsequent change in administration led to a complete reprogramming and redesign of the interior spaces including the acoustical designs.

The large halls were tested with the aid of models during both periods. The results of the model tests are compared with the results obtained from tests of the completed halls.

Other features of the designs such as the smaller halls and sound isolation are reported too.

[*Compiler's Note: All illustrations in the original are reproduced here. Click on thumbnails to view figures and diagrams at full scale*]

1. Introduction

A time period of more than sixteen years lies between the very first design of the complex and the actual completion of the Sydney Opera House. Construction of interior shapes and spaces began four years ago.

No wonder that this unique situation has involved several major changes of the general design, and also corresponding changes of the acoustical design of the interiors.

Design changes occurred frequently in the early period (the Utzon period) as consequences of the changing concepts of the architect. Changes in design in the later period (the Peter Hall period) were motivated mainly by the complete change of the whole programme for the uses of the building, although some changes also occurred as a result of the acoustical model testing of the large halls.

It may therefore be well worth the effort to give an account of this "acoustical design development", thus exposing some of the problems encountered during the whole period. Most of these problems refer to the two larger halls, but the design of the smaller halls and the aspects of sound isolation are included.

2. The First Programme and the First Design

The main emphasis of the first programme was assigned to the two large halls, "Major Hall" and "Minor Hall", although requirements for an experimental theatre, an orchestra rehearsal room and a chamber music room were also included.

Several uses of the Major Hall were listed, but most important was "symphony concerts" (approx. 2,800 seats), closely followed by "grand opera" (approx. 1,800 seats). It has never been queried that this dual purpose could be achieved with reasonably good acoustical quality for both uses of the hall, provided that the general design was adapted in accordance with acoustical requirements. It is obvious, however, that a dual purpose hall may never reach that level of perfection which a single purpose hall can aim at and probably achieve. This is particularly true of the Opera House design by Utzon, where the boundaries of the shells and the areas encompassed by the shells define, to a large extent, a specific category of interior shape which is only remotely associated with acoustical requirements of large halls. It must be admitted, however, that these requirements, generally speaking, are much better known today than they were sixteen years ago.

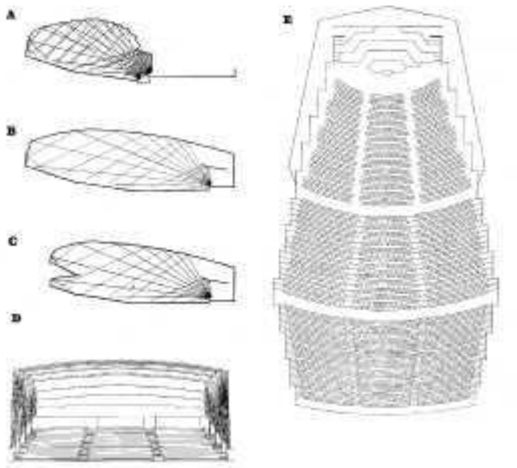


Figure 1—First design of Major Hall.

The first design of the Major Hall is shown in Figure 1 (two alternatives with and without balcony) in long section as well as in plan (Utzon, 1958). The ceiling shape was influenced by the idea of an even distribution of ceiling reflection from the stage, whereas the shape in the plan expressed the thinking that parallel side walls (in sections) were advantageous in order to obtain multiple reflections crosswise. The same thinking influenced the nearly vertical side walls.

(A) Longitudinal section(case of "Grand Opera").
(B) Longitudinal section(case of Concert Hall alt.1).
(C) Longitudinal section(case of Concert Hall alt.2).
(D) Cross-section at rear.
(E) Plan, seating.

It should be noted, however, that at this early stage of the design it was not fully realized that the near vertical side walls would actually pierce through the limiting boundaries of the shell system. The design was unrealistic.

With regard to the uses of the Minor Hall, the first programme indicated two main purposes: (1) drama, and (2) intimate opera, with a seating capacity of about 1,000-1,100.

The first design proposals of the Minor Hall were very sketchy and did not really attack the problems of acoustics. At this stage, in 1958, it was agreed that a prejudgment of the acoustics of both halls should be aimed at, not only by calculations of reverberation time (RT) and geometric constructions of reflections, but by acoustical model testing. It may very well be argued that at the time scientific evidence of the validity of acoustical testing on scaled models was only about to be established and also that there hardly existed quantitatively defined criteria (other than RT) which could be measured, either in halls or in models.

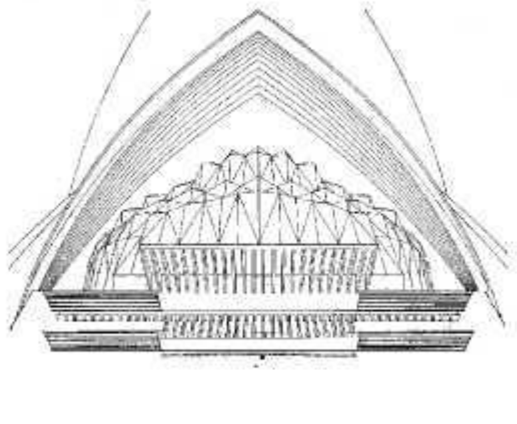
However, the importance of the acoustical design for the Opera House overshadowed these hesitations and it was recommended and decided to start off with a model of the Major Hall at a scale of 1:10. The design in plan was as shown, whereas the ceiling design had been changed to a stepping ceiling with horizontally oriented sections.

The choice of the scale factor (1:10) was guided by the fact that the influence of sound absorption in the air increases rapidly with frequency, so that model frequencies in excess of 30-40 kHz would not permit a reasonably good simulation of the acoustical properties without including a complicated dehumidifying procedure of the air inside the model. The instrumentation for model testing included a high quality tape recorder with a speed relationship of 1:10, thus making it possible to obtain direct listening tests as well as objective testing. A reasonably good agreement between absorption of the model boundaries and the expected wall and ceiling panelling of the hall (wooden panels) at corresponding frequencies was achieved by shaping the model of hard fibre boards (varnished on the inside). To simulate an audience absorption at model frequencies blankets of fibre glass material of 4 in. thickness were applied. This crude approximation was later to be refined in several steps. The similarity of the model to the projected hall was checked by measurements of RT in the model and by comparing the measured values with the calculated values of RT in the hall.

The problem of establishing quantitative criteria had previously been approached by the author in another context. The Concert Studio in the Radiohus and the Tivoli Concert Hall in Copenhagen had been used as objects for a study of the so-called "Rise Time" (Jordan, 1959). A similar method was adopted for the model testing of the Major Hall model, but the loudspeaker instrumentation was a limiting factor at the time. Elecrtostatic speakers with twelve membranes mounted on a sphere were not sufficiently uniform in radiation pattern at model frequencies to give reliable readings for the building-up process of pulses of random noise.

3. Major Hall and Minor Hall,Several Alternatives

Figure 2—Second design of Major Hall. North elevation.



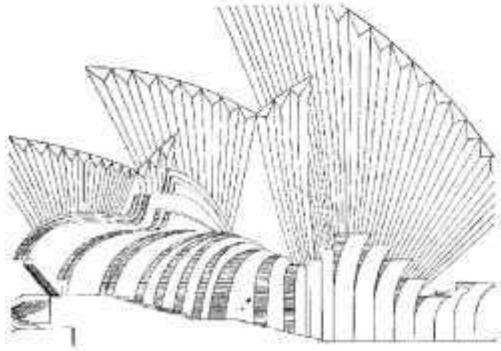


Figure 3—Second design of Minor Hall. Longitudinal section (showing interior elevation).

The model of the Major Hall became outdated when the architect introduced quite different concepts for both halls. The Major Hall in the second design had a " diamond " ceiling, no doubt with a high degree of sounddiffusing capacity, but it also had extremely low side walls which certainly had the advantage that they would not pierce through the shells (Figure 2) (Utzon *et al.*, 1962). The Minor Hall in this design had a vault-like ceiling shape which had little relation to the acoustical design (Figure 3). Neither of these designs was tested acoustically by model testing.

The third and final phase of the Utzon design period showed still another approach to the interior design of the two large halls. Here the Major Hall design became radically changed compared with previous attempts. The original idea used the stage area proper for the seating of no less than 1,000 persons during concert performances, the remaining 1,800 seats being located in the auditorium proper, while when used for opera the 1,000 seats on the stage should disappear.

This concept made it necessary, in case of concerts, to establish a very large reflecting ceiling to shield off the stage loft. The mechanics of introducing an immense movable ceiling were never really attacked. The new design tried to avoid this problem altogether by moving all seats (even in the case of concerts) out in front of the proscenium frame, thus changing the stage into a normal theatre stage with an orchestra shell for housing the orchestra.

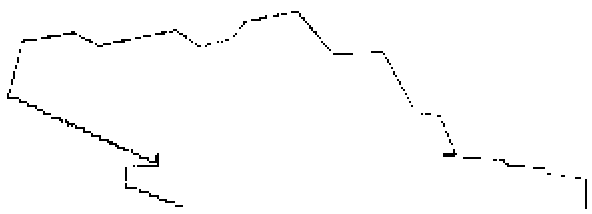


Figure 4 (A) Third design of Major Hall: Longitudinal section and plan. [Note from Compiler. *This is **not** a thumbnail. The original published figure was of insufficient quality to be copied satisfactorily*]

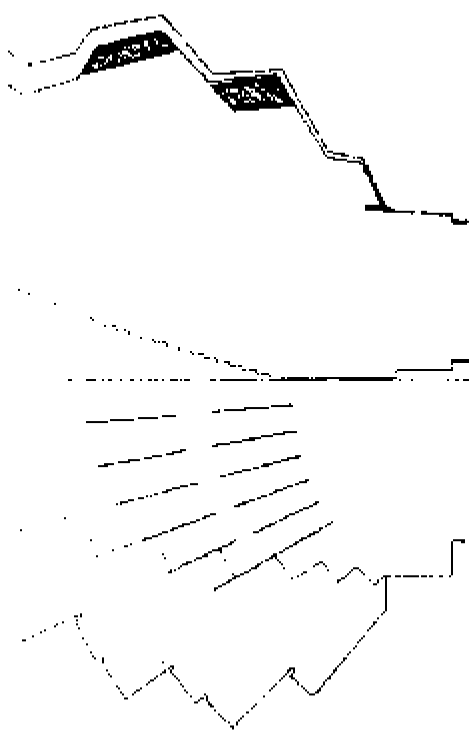


Figure 4 (B) shows long section and plan of this model with the suspended baffles indicated. [Note from Compiler. *This is **not** a thumbnail. The original published figure was of insufficient quality to be copied satisfactorily*]

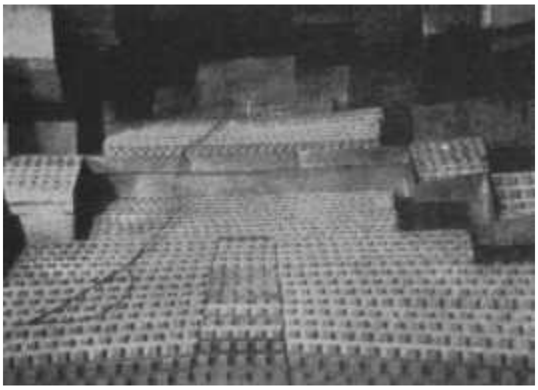


Figure 4(C) View of the model towards the rear

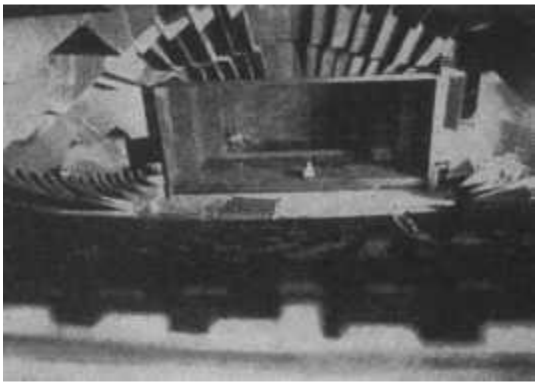


Figure 4(D) View of the model towards the stage (podium)

For this purpose the auditorium had to be widened with side terraces and the seats had to be closed up. Nevertheless the seating would still fall short of the design goal of 2,800 seats by several hundred.

The shape of the ceiling of the Major Hall was changed once more, this time into strips of saw-toothed profiles in the long section (Figure 4 (A)). The side walls became elements of focal oriented planes interrupted by radial concave segments.

The method had been tried out in another case, the New York State Theater (completed in 1964), of which a 1:10 scale model had been tested in Gevninge, Denmark (Jordan, 1964). Results obtained on this model had been compared with results later obtained in the completed theatre auditorium, and the agreement was found to be reasonably good.

Whether the suspension of vertically oriented baffles along the ceiling profiles could be used to improve measured values of steepness at certain locations in the auditorium, especially in the centre locations of the orchestra level, represented a special problem of model testing in this third design of the Major Hall. The model tests indicated that this might be feasible (Jordan, 1965).

It is worth noting that in this model the audience plus seats simulation had been improved compared with previous models. The individual persons were simulated by small blocks of neoprene and the seat-backs by continuous strips of fibre board. Two views of the model are shown in Figure 4 (C) and (D).

The Minor Hall design, too, was a radical departure from previous attempts. It was characterized by ceiling profiles of large, convex elements oriented along radii from a focal point on the stage. This design was tested in a 1:10 model at Professor Cremer's institute in West Berlin. Oscilloscopic pictures of short pulses in different locations were applied to evaluate the influence of the various reflections from the ceiling and the walls. Subsequently, minor corrective measures were suggested (Cremer, 1965).

Although acoustical model research was applied to evaluate this final Utzon design of the Major and Minor Halls, the results of these tests did not adequately support the design which at least partly had been adopted for aesthetical reasons. Moreover, other aspects (e.g. such as the available volume of the Major Hall auditorium per seat) indicated that the value of RT with capacity audience would be rather low for a concert hall of this size.

However, at this stage events quite irrelevant to any of the acoustical problems led to a complete change of the administration of the project. During the year 1966 a new team of architects had taken over the responsibility of completing the design and construction of the Opera House. Since most of the exterior design had been completed and constructed, this responsibility concerned mainly the interior design. In fact, there appears to be a rather clear cut between the two design periods: while the exterior design was almost exclusively founded on Utzon's concepts, the interior design subsequently developed into something absolutely different.

4. Reprogramming and Redesign

The new Design Architect, Peter Hall, assisted by the late Theatre Architect, Ben Schlanger, and the author formed a small study group in order to take a new look at the problems, starting with the following question: Given the empty spaces below the shells, what does the City of Sydney most urgently need to accommodate in its arts centre?

What should the programme of the building be like? About ten years had elapsed since the original programme was edited, did it need a thorough revision? The answer was yes, and out of the discussions and considerations the following main items evolved:

(1) The Major Hall to be the Concert Hall (approx. 2,800 seats).
(2) The Minor Hall to be the Opera Theatre (approx. 1,600 seats).
(3) The empty "under stage" below the previous Major Hall to be the Orchestra Rehearsal and Recording Studio.
(4) The Experimental Theatre to be the Drama Theatre (approx. 550 seats).
(5) Empty workshop space to be the Chamber Music/Cinema and the Exhibition Area.
(6) The space previously intended to house the Chamber Music Room to be the Recital Hall.

Out of a session in London during mid-1967, the first redesign of the Major Hall developed (Called now the Concert Hall). To integrate completely the volume under the main A-shells, the stage and the auditorium were merged and the ceiling was pushed upwards to increase the total volume. The gross shape in plan became essentially a double spade, which has certain inherent acoustical merits. The orchestra stage, originally intended to be at the extreme end of the hall, was moved towards the centre, thereby creating seating behind the orchestra not only for a choir but for an audience as well. The complete wall behind this seating was to be the organ facade. Never before in the design development had there been a solution to the problem where to locate an organ when a theatre stage had to be included. The seating in front of the orchestra stage consisted now of the orchestra level, the first and second terraces, and side-boxes along the periphery to the left and right.

The shape of the ceiling in Peter Hall's first design showed faint reminiscences of Utzon's latest design of the Minor Hall: large convex surfaces in a kind of catenary succession. The side walls represented a problem: how to obtain the benefit of vertical elements to give side reflections and at the same time adapt them to the shape of the shells. The result became a staircase arrangement where the horizontal steps defined the catenaries of the ceiling (in the direction of the long axis) (Figure 5 (A), (B) and (C)).

Figure 5—First design of the Concert Hall

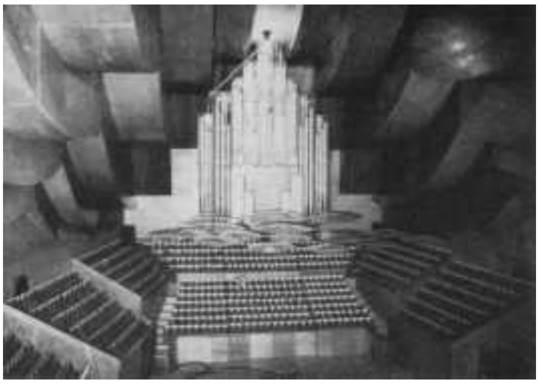


Figure 5A View of the model towards the organ

Figure 5B View of the model towards the rear

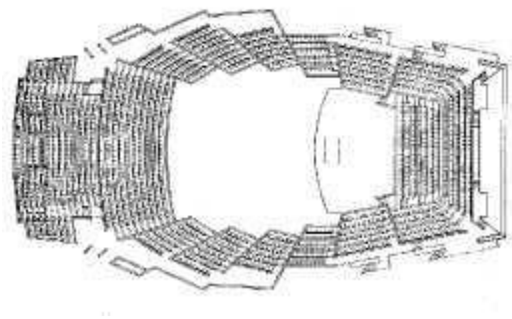


Figure 5C Plan of the outlay and seating (terrace level)

5. Model Research of the Concert Hall and the Opera Theatre

The idea of evaluating the acoustics of large halls by pretesting models was still maintained, and it was decided to build 1:10 scale models of the Concert Hall and the Opera Theatre. This time the models would be located at the Opera House site in an empty rehearsal space in the basement.

The models were built of thick plywood and varnished on the interior surfaces. Further progress in audience simulation had been developed for use in other models. The seats were made of continuous strips of neoprene, while persons were represented by individual neoprene blocks topped with small squares of cardboard simulating the heads.

The instrumentation, too, had advanced. Pulses were now generated by a high-tension spark source which radiated sound pulses of very short duration. The signal was picked up by small condenser microphones with lin. diameter and recorded on high-speed tape recorders. The tapes were later analysed in the author's laboratories in Gevninge, Denmark.

The method of applying short pulses to test the acoustics of a room had been developed by applying M. R. Schroeder's theory (Schroeder, 1965) and had been used in a 1:10 model of the New Metropolitan Opera House, Lincoln Center, New York) (Jordan, 1969, 1970).

The early criteria of "rise time" and "steepness" were gradually being replaced by a new criterion, "Early Decay Time" (EDT). This criterion was known to be correlated with subjective impressions of reverberation as found in the investigation undertaken by M. R. Schroeder and his co-workers (Atal *et al.*, 1965). Furthermore, a working hypothesis was developed on the assumption that values of EDT should not be much lower than values of statistical RT (no more than 10-20% lower). This would be applied to individual locations throughout a model or a hall.

Averaging values of EDT, measured in the audience area and comparing it with the average value of EDT measured on the orchestra stage, produces a coefficient termed "Inversion Index". This index should never be less than 1.0, i.e., the EDT should be at a higher level in the audience area than the average level in the stage area. This hypothesis has developed with the different criteria starting with rise time, which preferably should be shorter on the stage than in the auditorium, followed by steepness, which preferably should have higher values on the stage than in the auditorium. Incidentally, a certain relationship of reciprocity exists between steepness and EDT, as became evident from the considerations of 1M. R. Schroeder (Schroeder, 1966).

A complete survey and evaluation of modern acoustical criteria has been given by W. Reichardt (Reichardt, 1970).

The results of the model testing for the first design of the Concert Hall were reported upon early in 1968 and were followed by subsequent reports, including the testing of the Opera Theatre model, 1968-69 (Jordan, 1968-69).

In accordance with the working hypothesis mentioned above, the measured values of EDT were compared with the average value of RT for different locations in the model. The inversion index was calculated for two different cases: (*a*) with the circular, convex reflectors of plexiglass suspended above the orchestra stage; (*b*) with the reflectors removed. A definite indication of higher values of inversion index was observed with the reflectors above the orchestra platform.

Generally speaking, deficiencies in EDT values were observed in the orchestra level seating. Certain improvements, e.g. increasing the ceiling height to some extent above the terrace area, did not result in any considerable overall improvement of these deficiencies.

Obviously, only a quite radical departure from this first design could improve conditions at the orchestra level. An improvement could only be obtained if side reflections were increased in strength compared to reflections from the ceiling. One way of decreasing the dominance of ceiling reflections would be to move the ceiling further up and to straighten it out. Furthermore, if at the same time the side walls lost their step-like arrangement and were brought closer together the side reflections would take more dominance. An arrangement with side boxes meant that the side walls above the boxes could come closer together and the boxes would become as recessed into these walls. The ceiling design resulted in a crown piece above the stage and a beam-like structure, above the main body of the hall, radiating from the crown (Figure 6 (A) and (B)).

These changes were subsequently carried out on the model and a new test series was undertaken. The values of EDT in the orchestra level seating increased quite considerably due to the changes, while the inversion index still showed adequate values.

Figure 6—Second (and final) design of the Concert Hall

(A) View of the model towards the organ

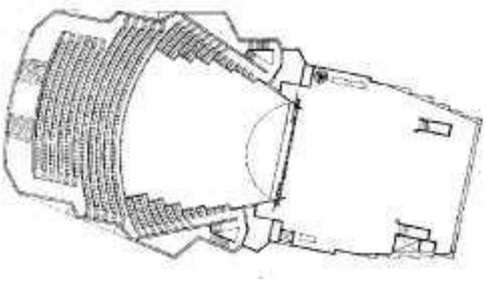
(B) View of the model towards the rear

This design became adopted as the final design for the Concert Hall. Certain modifications of the crown above the stage and of diffusing boxes along the ceiling beams were included without too noticeable effects on the main results. The fact that the reflectors improved the general conditions was repeatedly experienced.

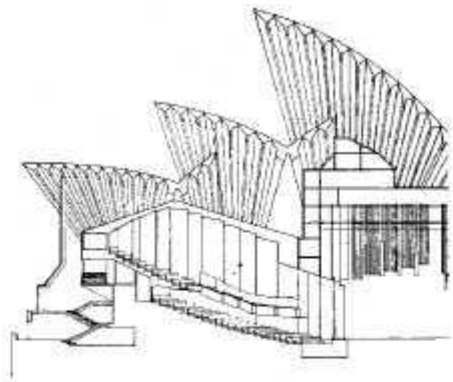
In most of the test series only one octave band (16 kHz octave) had been tested, but in the final test series the octave bands 2 and 8 kHz were included. It was noted that at 2 kHz the values of EDT in the orchestra level seating were lower, which was interpreted as due to a not quite sufficient ceiling diffusion. It was recommended to include more of the diffusing boxes in the final design of the hall itself.

The first design of the Opera Theatre was ready for testing early in 1969. This design (shown in Figure 7) had a relatively low flat ceiling (Hall, Todd and Littlemore, 1968).

Figure 7—First design of the Opera Theatre



(A) Plan



(B) Longitudinal section

In the model of the Opera Theatre the sound source (spark gap) had to be located alternatively in the orchestra pit and upon the stage or forestage, so that EDT values at different microphone locations could be measured in both cases. In addition to the evaluation already explained, the closeness of the values of the inversion index in these two cases was now included as a specific characteristic of the Opera Theatre design.

All the test series undertaken in the Opera Theatre model have shown values of EDT in excess of the values of the statistical RT. The calculated values of the inversion index, however, showed considerable spacing between the pit case and the stage case, the pit values being highest, the stage values actually being below 1.0. In subsequent designs of this model the ceiling of the auditorium was gradually moved upwards, the tests indicating each time an improvement in values of the inversion index. In the final design the ceiling was moved upwards as far as the shell structure permitted.

Figure 8 shows a picture of the model of this design. Testing of the final design showed better agreement between the values of the inversion index for the two cases, both having values exceeding 1.0.

Figure 8—Final design of the Opera Theatre. View of the model towards the rear.

This design was finally adopted for the Opera Theatre with minor alterations such as the placing of suspended reflectors above the orchestra seating area.

6. Various other Design Features of the Opera House

6.1. The Chamber Music/Cinema

The Reception Hall was in the first design period known as the Chamber Music Room. The seating capacity of 250 seats, however, was found insufficient and at the time of reprogramming a separate area, adjacent to the Central Passage, was preferred for housing a Chamber Music Hall of 400 seats. However, it was also felt that the Arts Centre of Sydney would need an arts cinema, and therefore the difficult combination of Chamber Music and Cinema was proposed. After struggling for a number of years with the problems inherent in such a dual purpose hall (variable acoustics, movable stage, etc.), the following recommendation was made—this hall should be exclusively an arts cinema and chamber music should be played in the other halls (Concert Hall, Opera Theatre and Drama Theatre). This recommendation was accepted, but unfortunately a certain ambiguity in terms, lingered on and the term "Chamber Music/Cinema" was even used in pre-publications, although the design and construction of a hall exclusively for cinema use proceeded.

At a far too late stage the authority which eventually had to run the complex (the Opera House Trust) requested a compromise to be made. The feasible, but not very significant increase of reverberation was implemented and a musician's platform was designed and constructed.

The hall has now received its name: “ The Music Room”, a somewhat dubious choice of name for what will remain in the future a last-minute compromise solution.

6.2. The Drama Theatre

This area, originally the space for the Experimental Theatre of the Utzon period, has a seating capacity of 550 seats and a reverberation time close to 0.9 sec which must be considered ideal for a drama theatre of this size. No problems of dual purpose have troubled the design of this addition to the original programme.

6.3. The RehearsalIRecording Studio (RIR)

Figure 9—View of the completed Rehearsal/Recording Studio

Due to the reprogramming, the immense understage of the previous Major Hall was changed into a sizeable Orchestra Rehearsal Hall (Figure 9) which has a volume of approx. 5,200 m^3 and a reverberation time of 2.0 sec. Incidentally, this value of RT brings R/R on to the same level as the Concert Hall, which has RT close to 2. 1 sec.

The much discussed variation of RT with frequency has not been of too great concern. A slight increase of RT towards low frequencies is strongly advocated by some authorities, and has in fact been aimed at, although the author does not share this opinion.

Far more important, in th eopinion of the author, is the frequency dependence of the medium frequencies to the higher frequencies. It has often been experienced that a certain suppression of the range between 400 and 1,000hz (and a corresponding emphasis of the range above 1,000 hz) has decidedly a merit for studios and concert halls (Jordan, 1947).

In the case of the R/R, a special type of panelling (thick, slot-perforated plywood with backing of mineral wood) has been used to obtain this particular RT dependence of frequency. Figure 10 shows the RT *v.* frequency characteristic measured in one-third octave steps.

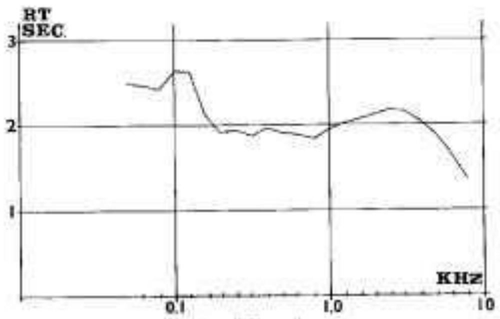


Figure 10—Reverberation time (RT) *v* Frequency (0.063–8kHz) for Rehearsal/Recording Studio. ½ octave values.

For the benefit of using this area for television production, curtain tracks along the periphery of the balcony fronts have been installed in order to achieve a lower value of RT.

6.4. Examples of Sound Isolation Design

The problem of excluding exterior noise, especially from the large halls, has been a constant worry throughout the design period. The large halls have large areas exposed to the exterior, directly at the shells, indirectly at the glass facades and at the louvre walls.

In the first design period it was attempted to arrive at an acceptable if not ideal solution to this problem. Inner ceiling constructions were thought of as sandwich combinations of two layers of plywood with an intervening layer of mineral wool. On account of the revision of the programme and design it became possible to redesign the ceiling also with regard to sound isolation. An interior "cocoon" of saprayed concrete on a supported steeel mesh (under the shells) forms a separate sound isolating barrier on the inside of which the actual panelling (a plaster/ply combination) is mounted. Several glass constructions were tested for the large glass walls and finally a laminated construction with two layers, totalling ¾ in. thickness, was selected.

Actual testing of noise isolation from exterior noise by means of a helicopter hovering at a constant level of 200 ft above sea-level has shown that the interiors of the halls are very well protected from noise. Figure 11 shows a diagram to support this statement.

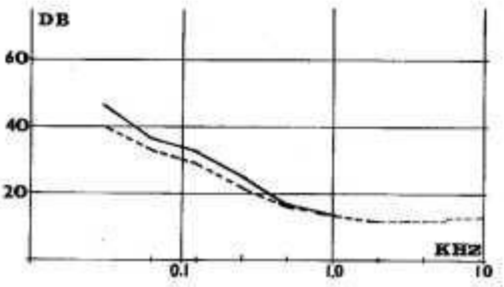


Figure 11—Noise levels in the Concert Hall due to helicopter outside the building (200 ft above sea level). [Continuous line] Helicopter present [Broken line] Ambient noise

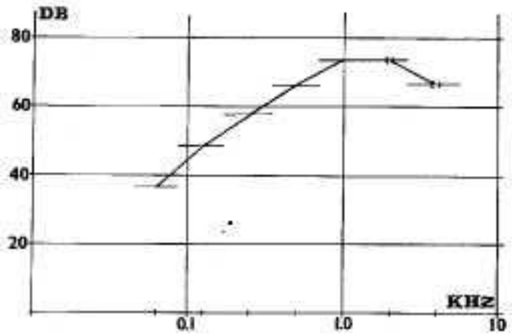


Figure 12—Transmission loss between Rehearsal/Recording Studio and Concert Hall. (Value in brackets influenced by ambient noise level. True values greater than or equal.)

Sound isolation between various areas inside the complex have received much attention. Especially worth mentioning is the difficult case of separating the Concert Hall from the Rehearsal Hall underneath. Double slabs of heavy concrete isolated mutually by neoprene pads were used in conjunction with separate isolated walls of the Rehearsal Hall. Figure 12 shows a diagram of the results obtained.

6.5 Electro-acoustical System (E.L.A.)

The design of the electro-acoustical system has developed considerably since the first design period, especially when it was decided to include Simultaneous Interpretation (SI) and to integrate this system with the ELA system.

Only a few features need to be mentioned here: those which are related to the acoustical design problems of the large halls (the Concert Hall and the Opera Theatre).

To incorporate a loudsp[eaker system in the concert hall with a reverberation time of 2.1 sec entails certain well-known difficulties, e.g. a narrow margin between feedback level and maximum permissible speech level.

The ways to overcome these difficulties, and in the case of the Concert Hall it was decided to use a centrally located speaker system with very highly directional sound columns. A thorough investigation of large sound columns led to the following two different solutions. Suspended above the state in the Concert Hall, both were tried out with prototypes, one with acoustically tapered speakers and another with electrically tapered speakers.

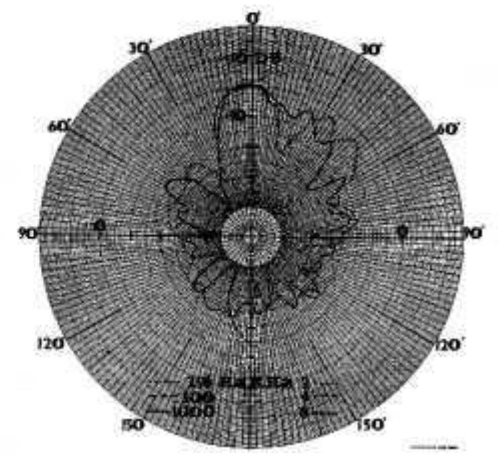


Figure 13—Diagram of vertical polar pattern of the electrically tapered 13' column. (Applied in the Concert Hall.)

A diagram of polar patterns is shown in Figure 13. The second system was finally adopted after testing it for announcements at the second test concert.

The Opera Theatre system of speakers is inserted into the proscenium frame as shorter sound columns, right, centre and left, following the profile of the proscenium. Additional speakers in the ceiling may be used for special effects, e.g. delays or reverberation. Under the balcony soffit delayed speakers assist in increasing the sound level of the spoken word.

These speaker systems are of course not used for voice or music amplification, but only for auxiliary purposes.

7. Testing of the Completed Large Halls

During a special testing session (at New Year, 1972-73) including actual musical performances in the presence of an audience, the acoustical results were measured and later evaluated.

Pictures of the completed Concert Hall and Opera Theatre are shown in Figures 14 (A) and (B) and 15.

Two different testing methods were applied:

(1) To measure statistical RT: The music from the very first bars of the Beethoven *Coriolanus* overture, played by the Sydney Symphony Orchestra, were recorded on tape at a number of locations in the Concert Hall. The locations corresponded to those used in the model of the Concert Hall during the model testing. Later the tapes were analysed by filtering through 1/3 octave or 1/1 octave filters and recording on a level recorder. This method is only reliable in the case of very precise playing, which was obtained due to the skill of the conductor (Sir Bernard Heinze) and the Sydney Symphony Orchestra.
Incidentally, this method has some historical background. It was used for the first time in 1934-35 to test the RT of the old Philharmonic Hall of Berlin (now destroyed) (Meyer and Jordan, 1935).

(2) The method, previously used to measure statistical RT as well as EDT, was also used for the testing of the halls. Instead of the high-voltage spark (used in the models as a sound source) a pistol or a shotgun was fired (using blanks) from the stage of the Concert Hall as well as from the stage and the pit of the Opera Theatre. The shots were recorded at the

same locations as used in the models.

Figure 14—Views of the completed Concert Hall

(A) View towards the organ. (B) View towards the rear.

Figure 15—Views of the completed Opera Theatre. View towards the stage.

The tapes were later analysed by filtering, reverse recording of the tape, and by integrating the signal. The integrated signal was fed to a level recorder and the values of EDT measured from the curves recorded. The same method, minus the integration, was used to obtain the vaJues of RT.

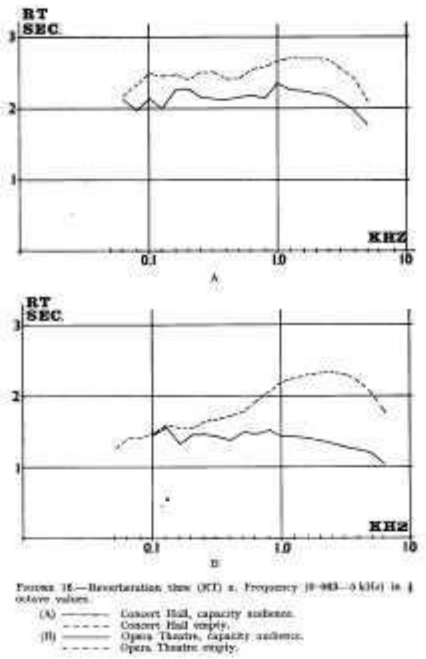


Figure 16—Reverberation time (RT) *v* Frequency (0.063–5kHz) in ½ octave values.
(A) [cont. line] Concert Hall, capacity audience
[discont. line] Concert Hall empty.
(B) [cont. line] Opera Theatre, capacity audience.
[discont. line] Opera Theatre empty.

Both methods were used in the empty halls as well as in the halls with near capacity audiences present; in the Concert Hall test concerts were held on 17th December, 1972, and 21st January, 1973; in the Opera Theatre one test concert was held on 21st January, 1973. The results cannot be recorded in detail here, but examples of RT characteristics are shown in Figure 16 (A) and (B). Further, it should be mentioned that the detailed analysis of EDT values has shown, a general consistency with values measured in the model, although some individual locations may show discrepancies. A few locations in the Concert Hall have values of EDT which at low frequencies fall a little short of the RT value. This, however, varies with the elevation of the reflectors above the stage. The shape of the reflectors in the final design has been changed from circular (spherical) to toroldal for two reasons: to reduce the area and to achieve more diffusion in the horizontal direction.

None of the locations in the Opera Theatre have values of EDT short of the average RT value.

Most interesting results have been obtained by calculating the inversion index for the different cases and a quite convincirig agreement between model values and hall values can be seen in Tables 1 and 2.

Table1
Inversion Index for the Concert Hall

	16 kHz octave	Average Value 2-8-16 kHz	
Model, first design:			
Reflectors at sidebox soffit level	1.10	--	
Without reflectors	1.01	--	
Model, second design:			
Reflectors at sidebox soffit level	1.19	1.11	
Reflectors just below the crown	1.13	1.09	
	2kHz Octave	Average Values	
		125-4000	500-4000
Hall empty:			
Reflectors at sidebox soffit level	1.14	1.14	1.18
Reflectors just below the crown	1.10	1.09	1.11
Hall capacity audience:			
Reflectors at sidebox soffit level	1.00	0.97	0.99
Reflectors just below the crown	1.04	1.05	1.05
Reflectors at 34 ft above the stage	1.10	--	1.11

From the values for the Concert Hall it seems legitimate to conclude that the intermediate position of the reflectors has the greatest merit. Why the sense of variation of inversion index with the elevation of the reflectors is reversed in the hall with capacity audience is not readily explainable. Maybe the lack of orchestra musicians simulation in the model can explain this result.

Table 2
Inversion Index for the Opera Theatre

Model	16 kHz Octave		Average Value 8-16 kHz	
With sound source at . . .	Pit	Stage	Pit	Stage
Flat ceiling design . . .	1,15	0,90	--	--
Stepped ceiling . . .	1,13	0,97	--	--

High ceiling, balconies . . .	1,26	1,15	1.17	1.11
			Average value 2-4-5-16 kHz	
Final design . . .	1,27	1,10	1.22	1.13

Opera Theatre	2 kHz, Octave		Average value 125-4000 Hz	
With sound source at . . .	Pit	Stage	Pit	Stage
Capacity audience . . .	1,28	1,15	1.22	1.10

For the various model designs of the Opera Theatre it is seen that the values of inversion index for the pit and the stage series approach each other as the design advanced.

The values of inversion index of the Opera Theatre with capacity audience are very close to values of the final design model. Average values and values at one of the highest octaves used do not seem to disagree very much.

As for the musical judgments of all auditoria, the author wishes to refrain from citing any cgmments. Let the results speak for themselves.

8. Acknowledgements

The documentation exposed in Jørn Utzon's two reports ("the red book" of 1958 and "the white book" of 1962) has been used repeatedly to reproduce the designs of "Major Hall" and Minor Hall - of the Utzon period (1957-66).

For the account of the early model testing during the same period the author has used his own files, in a single instance supplemented with information from an unpublished report by Lothar Cremer.

The later adopted method of pulse testing, which became vital in testing of models as well as of completed halls, is based on the general theory of M. R. Schroeder.

The development of acoustical criteria over the whole period is only partly exposed in this article, but interested readers can gain much supplementary information from the references given. Especially, the survey of W. Reichardt is most valuable in this respect.

The documentation relating to the second design period (the Peter Hall period, 1966-73) is based on pictures and drawings of models and designs available to the author due to his close co-operation with the architects, Peter Hall, Lionel Todd and David Littlemore.

A considerable part of the instrumentation for the model testing was put at the author's disposal through the cooperation of the Project Officer, Philip Taylor (of the Public Works Department).

The actual construction of the very exact plywood models was undertaken by Hornibrooks Ltd. (in charge of model teams: Frank Daniels).

During the model testing Peter Knowland assisted the author in extended investigations.

Never shall the author forget the co-operation with Peter Hall and the late Ben Schlanger during the period of reprogramming, the outcome of which became the basis for all subsequent interior designs of the Opera House. A majority of the joint recommendations were accepted and were closely followed up by the redesign of the interior.

The former Minister for Public Works, Davis Hughes, took a vivid interest in the acoustical design problems of the Opera House during these seven years.

As professional architect, Lionel Todd supported the author strongly in aiming at the very best solution to the problems of sound isolation, especially of the large halls.

The excellent preparation of the test concerts was due to the co-operation of several organizations in a special committee.

It is appropriate to emphasize the contribution of Sam Hoare and his co-workers of Hornibrooks who were responsible for all practical arrangements. The acoustical testing team was organized by Niels Jordan, who manned the taping locations with volunteers.

The Sydney Symphony Orchestra, conducted by Sir Bernard Heinze, performed at the very first concert given in the Concert Hall. For the benefit of the acoustical tests they patiently repeated the first bars of the *Coriolanus* several times.

The ABC National Training Orchestra, conducted by Robert Miller, together with the soloists Elizabeth Fretwell and Donald Smith, all performed at the subsequent test concert in the Concert Hall and in the Opera Theatre.

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