THE ACOUSTIC DESIGN OF THE OPERAEN COPENHAGEN

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1 INTRODUCTION

Exactly to schedule, the new Copenhagen Opera House was handed over to the people of Denmark on 1 October 2004. The gala opening was in January 2005 and the first opera performances, starring Roberto Alagna as Ramades in Aida, took place in January 2005. The most remarkable aspect of the project was that it went from concept to completion in less than 4 years, an incredibly short period for an opera house project. (By comparison, the Nytt Operahus i Oslo, which is a very similar waterside project, began planning in 2000 and will not open until 2008).

This paper describes the acoustically important areas of the building and the acoustic design concepts that were applied.

2 THE BUILDING

The Operaen was a gift to the people of Denmark from Mr Møller, the head of the AP Møller Foundation and the owner of the Maersk. Maersk is the largest shipping line in the world, owns a commercial airline and shipyards and has extensive oil and gas and industrial assets.

The site for the gift is one of the mort important in Copenhagen. The centerline of the main auditorium and stage is directly on the axis which runs from St. Frederick's Church through the Amelienborg (Royal) Palace.

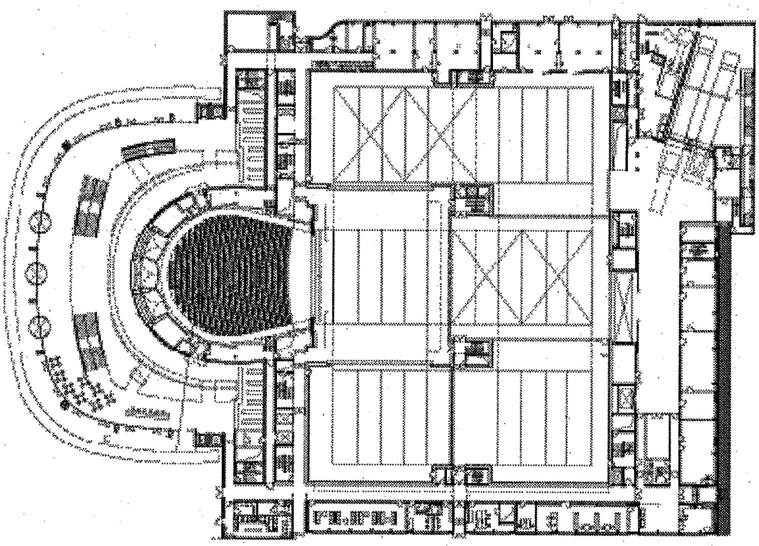

Figure 1: Stage level plan of the Operaen Copenhagen

As shown in Figures 1 and 2, the main auditorium is a conventional opera horseshoe variant. It is served by a standard configuration of a main stage and 5 ancillary stages, one of which is a rehearsal stage. The full-size orchestral rehearsal room is directly below the main auditorium. At Level 4 there are major opera, chorus and ballet rehearsal rooms, plus smaller warm-up and practice rooms. The Operaen also benefits from a sound studio and associated control room.

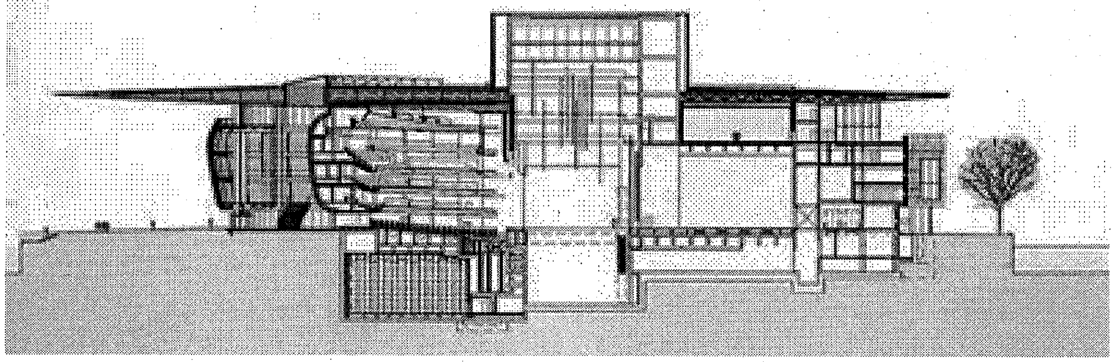

Figure 2: Longitudinal section through the auditorium centreline, Operaen Copenhagen

3 THE MAIN AUDITORIUM

3.1 The Room Acoustic

3.1.1 The design philosophy

Successful opera house design balances different requirements:

- Between the architecture, the acoustics and the theatricality / functionality
- Between reverberance and clarity
- Between the singers and the orchestra
- Between spaciousness and accuracy of source location
- Between sound systems (in production support roles only) and the natural acoustics
- Between audience capacity and the acoustics and visual intimacy

There are opera houses with great architecture and poor acoustics and others with great acoustics but a poor appearance. The truly great opera houses are both visually and acoustically impressive.

Design teams are comprised of people. To balance sight, sound and function it helps if the strength of character of the lead designers is also matched, so that the design progresses co-operatively. The author believes that this balance was achieved during the design of the Operaen.

The balance between reverberance and clarity relates to a central ambiguity of opera: the balance of the words and the music. Both are vital, but unless expertly crafted one can obscure the other.

Similar obscuration can occur between reverberance and clarity. Southern European opera houses (in which the audience generally understands the language the opera is sung in) tend to favour clarity, ie an understanding of the words, over a more reverberant, concert hall type orchestral sound. The opposite is true of most North American and some Northern European opera houses. For Copenhagen the client considered clarity to be important.

A complication in opera house design, not found in concert halls or drama theatres, is the need to balance the loudness of the singers and the orchestra.

Some opera houses, particularly the more reverberant theatres, tend have strong spatial sound fields, with the reverberant sound 'filling' the space. The author does not favour this approach, because opera is an illusionary art and the sound field should come from the stage, alongside the visual experience. This philosophy has been followed in Copenhagen.

Another balance is between the inclinations of the acoustic designer, (which is not purely objective, the designer has choice in what he or she helps create, within overall limits) and the expressed sound requirements of the client and the musical director. This process is complicated in that musicians and acousticians speak similar but different languages.

The author does not believe in the use of electronics and sound systems for direct reinforcement or amplification of the performers in new opera theatres. The opera audience attends to hear great voices soar past the pit to their ears. If loudspeakers reinforce the sound this experience is lost. Sound systems are widely used in opera – for sound effects, to balance offstage performers, to help singers performing inside a glass box, to add reverberance to a voice of a god and for foldback sound to the performers. Some opera houses use electroacoustic enhancement systems to overcome serious defects in their acoustic response. In this case a judgment is necessary – why be precise philosophically if the sound could be significantly improved? New opera houses should be designed for 100% 'natural' sound. (There is of course a school of thought that suggests that a loudspeaker is no less natural than a wall or ceiling).

The opera house designer is always under pressure to include more seats. As well as increasing revenue for the operating companies, if all seats are sold (as in Copenhagen) then of course more people should be given the opportunity to attend. As the audience capacity increases, however, acoustic and visual intimacy reduces and the sound becomes quieter, less exciting and powerful. Few singers can fill the New York Metropolitan Opera (3816 seats) with sound. A count of ~1450, as in Copenhagen, is better acoustically and allows for successful performances by more singers.

3.1.2 The room geometry and materials

The room is based on the conventional horseshoe form that has proven architecturally, acoustically and theatrically successful for opera performance. The normal capacity is 1471 plus 56 standing. With the largest pit the seating capacity is 1439, with no pit it is 1650. The main finish is timber.

The floor is timber and board, 60 mm thick. The seats are fully velour covered, but have relatively thin back and seat cushions. Sound reflecting velour covers the proscenium return surfaces, which are important for singer sound reflections.

The wall elements are multiple layers of timber bonded to gypsum board, total surface mass ~ 65 kg/m^2. This construction provides a fine timbral balance, with a good bass response. The elements are angled to provide an even distribution of early sound through the seating areas. This results in an unusually but pleasingly strong vocal sound at the rear of the stalls. The walls feature high frequency scattering incisions to avoid acoustic glare and reduce image shifting.

The balcony fronts are angled in the front part of the room but are convex where concave in plan. The angled sections direct high frequency sound from the stage: the 1st balcony to the stalls, the 2nd to the 2nd and 3rd tiers. The 3rd balcony and the technical gallery are not angled but curved and hence gently sound scattering. The architectural lighting design provides high frequency sound scattering, inspired by the plaster modeling on traditional balcony fronts. The balcony fronts are sculpted out of solid timber, 25 mm - 75 mm thick.

Between the balcony fronts and the outer wall auditorium are the 'box fronts'. Close to the proscenium, these are full height wall elements that reduce the acoustic width of the auditorium. The surfaces closest to the proscenium create a shallow balcony overhang, providing important early reflections and maintaining the propagation of sound into the main body of the room. The box fronts are constructed of 38 mm timber and are textured with a smaller and shallower variant of the high-frequency sound scattering 'L-shapes' found on the outer walls.

The tier soffits are 15 mm 'Nesporex' panels (18 kg/m^2), bent across a framework of timber noggins with semi-random spacing to vary the resonant frequency of the construction and avoid excessive low frequency absorption. The design philosophy was to provide sound scattering on necessary parts of the vertical planes, with the horizontal surfaces generally smooth. Some small grooves in the soffits provide very limited high frequency scattering. The front part of the soffits beneath the 2nd and 3rd tiers is near horizontal, providing useful early reflection to the front rows at the rear and cue-ball reflections at the sides closer to the proscenium. The soffit above the 3rd tier under the technical gallery and follow spot room is 30 kg/m^2 and provides mid- and high frequency sound scattering in an aesthetically sensitive way.

The balcony overhangs balance acoustics with capacity; acoustically there is one too many rows in the 2nd tier.

The technical gallery above the audience tiers is acoustically-transparent, to avoid interruption of useful early sound reflections to the audience high in the room.

The suspended ceiling above the stalls is of multiple board construction, with a surface mass of 40 kg/m^2. It is convex in both planes, to provide gentle sound scattering. Instead of sound-losing lighting bridges, the front of house luminaires are mounted in individual ceiling slots. These ceiling slots are semi-enclosed in the ceiling voids, to further reduce sound energy loss from the main volume. The surface mass of the over-pit reflector is 30 kg/m^2. The roof of the auditorium, which is exposed around the ceiling, is painted concrete.

An acoustic reflector is provided above the pit, 13 m above stage level. The primary function of this reflector is to reflect sound from upstage singers to the audience. It also provides ensemble reflections between the sections of the orchestra.

The auditorium has with a motorised variable sound absorption, with pre-sets software controlled at the stage manager's desk. Large area fabric banners can be lowered to reduce the room response (maximum mid-frequency RT reduction 0.17 s) for electronic operas, musicals and ballet with amplified soundtracks.

3.2 The orchestra pit

The orchestra pit is one of the largest in the world and has a very flexible configuration.

The dimension between the pit rail on the centreline and the stage front can be selected to be 3.4, 6.4 or 7.3 m, according to the repertoire requirements. The maximum playing area is 165 m^2, including an overhang below the stage of 1.5 m. This can be reduced or eliminated by a system of tracking acoustic panels. Each panel can be rotated to present a (mid and high frequency) absorbing or reflecting face to the sound field. Tracking panels also adjust the width of the playing area.

There are 3 pit elevators, corresponding to the 3 open pit dimensions, allowing the floor to be set according to the wishes of the musical director. The elevator platform floors are 45 mm of plywood sheets pinned together, supported by joists at different, 450 – 650 mm centres. The pit is ventilated through low velocity grilles in the elevator platforms.

The pit rail is modular, allowing acoustic transparency or solidity in sections.

3.2.1 The design parameters and achieved values

Table 1 presents some of the design targets adopted. Also shown are the spatially averaged values of these parameters predicted by the ODEON v5.02 computer simulation and by the 1:25 scale model (shown in Figure 3) and the measured values.

Parameter	Target	Predicted ODEON	Predicted 1:25 scale	Measured
RT	1.5 s	1.55 s	1.85 s	1.4 s
RT, 125 Hz	1.7 s	1.85 s	3.2 s	1.65 s
D_{50}, stage source	0.5	0.56	0.57	0.62
C_{80}, pit source	> -2 dB, < 2 dB	1.3 dB	-0.3 dB	2.1 dB
Gstage – Gpit (both omni, unoccupied)	0 dB	-1.2 dB	-	0 dB

Table 1: Acoustic parameters, average of 500 & 1 kHz octave bands, spatially averaged, 100% occupied with orchestra and stage set (models with typical stage set, measured with Turandot large scenic elements), except as indicated. Targets are minima except where indicated.

Table 1 shows that both the computer and the scale models over-estimated the RT. In fact the best correlation was achieved by the simplistic predictor Occupied RT (s) = 0.2(Volume/Number of seats); V/N is 7.1 m^3. The author has found this to be true also for Glyndebourne opera house (V/N = 6.25 m^3, RT = 1.25 s) and the Wales Millennium Centre opera theatre (V/N = 6.9 m^3, RT = 1.4 s). The relationship may be invalid for RT >> 1.4 s. The mid frequency RT unoccupied is 1.55 s.

3.3 The Drama of Silence – Absence of Noise

3.3.1 The design philosophy

Some of the most dramatic moments in an opera performance are the rare, short periods of complete silence (as when Jenufa realises that her child is dead). Maximum drama occurs only in a complete absence of noise. Opera is an illusionary art; noise can dispel the bond of belief between performers and the audience. Absence of noise provides the conductor and performers with the maximum possible dynamic range. Hence noise should be inaudible during opera performances.

The continuous building services noise limit was PNC15, so noise from outside the room was limited to L_1 = PNC 15 – 5 dB.

3.3.2 Sound insulation

The absence of services noise demands high sound insulation to ensure no disturbance from nearby noisy activities. This is achieved by sound absorbing lobbies and circulation spaces that wrap around the auditorium. There is a deep roof void above the auditorium ceiling slab.

The sound control room has a sound-isolating openable window. A sheet of 12 mm glass slides vertically and is sealed with pneumatic seals.

The fire curtain and the vertical-action side and rear stage doors each achieve D_w45.

3.3.3 Theatrical systems noise control

Arup Acoustics' extensive opera house design experience was applied to set and help engineer appropriate noise limits for stage engineering components. A wagon system moves sets and scenic elements of sets between the 6 stages. The wagons move on casters, driven by toothed wheels. These rise through openings in the compensating elevators over which the wagons run. Wagon movements are in audible to the audience (40 dBL_{Aeq} at 1.2 m directly above a moving wagon).

There are 4 main stage elevators, each 4 m x 16 m in plan. Their motors are installed on massive concrete inertia bases on vibration isolators. The motors and control cabinets are enclosed by plasterboard constructions in rooms three floors below stage level. The elevators are probably the quietest in the world, achieving 25-30 dBL_{Aeq} when raised or lowered, measured at the conductor's head position.

The power flying system is also quiet, 26 dBL_{Aeq} at the conductor for 3 bars flying in or out at a typical operating speed. The design criterion of 20 dBL_{Aeq} (achieved elsewhere by AAc, eg in the Royal Opera House London) was however exceeded by noise generation where the flying wires pass over the head pulleys. The wagon system generates a similar low noise level and together, the theatre machinery maintains the magical illusion of noiseless movement.

Noise from the house and fire curtains and the side and rear stage acoustic doors was also controlled.

The dramatic impact of major but silent set movements, employed to great theatrical effect in the opening gala and the opening production of Aida, is a major success.

No luminaires, colour scrollers or accessories with fans are installed in the auditorium.

3.3.4 Building Services Noise Control

There is no building services noise in the auditorium. Sound pressure levels meet (an inaudible) PNC 6. The ventilation supply is at low velocity from beneath the seats. The Lindab underseat displacement units supply air at 11 - 12 l/s.

The house lighting uses low noise LED sources in the balcony fronts and fibre-optic sources for the balconies. The fibre-optic sources are mainly located outside the auditorium volume to exclude their cooling fan noise. Special fanless engines are installed where cable lengths preclude external engine locations. Quiet Source 4 downlighters are located in the convex ceiling and on the technical balcony.

4 THE TAKELLOFTET

The studio theatre, called the Takelloftet (the 'sail loft') is an isolated 'box-in-box' construction, to control noise from the nearby get in lift and deliveries and trash compaction in the bay beneath, and the kitchen / canteen above. The space is 23 m x 17 m in plan. Seating up to 200, it is a flexible space for performances including chamber music recitals, small scale opera, ballet and modern dance and jazz. To provide sufficient room volume to provide sufficient reverberance for music, whilst retaining a useful early ceiling reflection, the room is 10 m high. An acoustically-transparent tensioned wire grid is provided 7 m above the floor. Retractable seating and movable towers that are movable allow space reconfiguration to accommodate the various uses. The lower parts of the outer walls have angled panels to avoid flutter in the flat floor configuration (with no towers). The panels also provide low frequency control. The movable towers provide galleries for seating or, when rotated, become sound reflecting elements around the stage, eg for chamber music recitals. Vertical tower surfaces are angled to scatter sound.

The acoustic for a particular event is partially determined by the performance area settings, eg theatrical drapes, arranged on a by production basis. There are also 2 systems for varying the acoustic response. Firstly theatrical serge curtains on each long side of the room. These extend out of enclosures along the full length of the room above the tensioned wire grid. Secondly fabric - wrapped mineral fibre panels that extend down the 2 long side walls from their stores at high level. The achievable range of mid-frequency RT in the unoccupied space (as set up for chamber music) is between 1.35 s - 1.65 s.

Air is supplied via high level jet nozzles and is also extracted at high level. The services noise level is PNC 19.

5 THE REHEARSAL ROOMS

5.1 The Orchestral Rehearsal Room

Figure 3: The Orchestral Rehearsal Room

The orchestral rehearsal room, which measures 22 m x 20 m x 10 m, is located 12 m below water level, directly beneath the auditorium. To reduce noise from ships and to provide maximum sound isolation from the auditorium, the room has a vibration-isolated 'box-in-box' construction. The pre-cast concrete walls and floor are supported on elastomeric (Sylomer) pads with a system natural frequency of ~ 12 Hz.

On the walls and the ceiling there is a modular arrangement of tuned low frequency sound absorbers, convex sound scatterers and broadband sound absorbers. Motorised, vertically moving sound absorbing panels adjust the room acoustic for different ensemble sizes. The vertical panels are moved using a simple rotating spindle system provided by Crawford in the unoccupied room is flat across the frequency bands, giving a slight low frequency rise (10%) when occupied. The movable panels allow variation of the mid frequency RT from 1.4 s to 1.1s. The system has 4 programmable pre-set configurations. The complex system of acoustic components on the walls and ceiling is visually screened by an acoustically-tested wall lining of slotted mdf panels and a feature wavy ceiling created from timber strips, creating a fine working space for the orchestra and choir.

Exceptionally low noise levels from the ventilation (via 'jet' nozzles) and lighting (total PNC 12) and the high level of sound insulation from adjacent spaces make the room highly suitable for recording as well as rehearsal. Separated from the rehearsal room by deep cavity double glazing is a control room that can be used for recording and monitoring without noise intrusion from the rehearsal room or the surrounding musicians' lounge.

5.2 The Rehearsal Stage, Opera Rehearsal Room and Chorus Room

The rehearsal stage is separated from the rear stage by two 11 m high operable walls, 1.5 m apart. Each operable wall is rated at R_w 51 dB. Careful detailing (especially regarding the compensating elevators below the walls) and high quality installation have resulted in an overall weighted sound level difference between the rear stage and the rehearsal stage of D_w 63 dB. Noisy activities can be carried out in the rear stage without disturbing rehearsals in the rehearsal stage. The side and rear stages all have sound absorption pin-fixed to their concrete soffits to limit noise build-up. The rehearsal stage also has sound absorption on 2 adjacent walls, installed as horizontal panels between solid strips that are used for resting scenery against. The 2 m of the walls above floor level are sound reflecting, but are angled between the strips to prevent flutter echoes. The mid-frequency unoccupied RT is 1.15 s.

The opera rehearsal room is typical of the rehearsal rooms, many of which are constructed as a plasterboard 'room within a room' on an isolated concrete slab, to minimise noise intrusion. Structurally isolated double-glazing helps to maintain the sound insulation. The high quality Danish craftsmanship has enabled unusually high standards of sound insulation to be achieved. Noise from building services is well controlled at PNC 20.

The slatted architectural finish to the walls and ceiling hides the distributed sound absorption and services installations. Reverberance is closely controlled. Sound scattering walls (to reduce flutter echoes and perpendicular room modes) are expressed in a zig-zag form.

The chorus room has fixed timber tiering and adjustable curtains on the wall facing the chorus.

5.3 The Ballet Rehearsal Rooms

The ballet rehearsal rooms have sound absorption above the mirrors and on non-mirrored walls. Vertically angled glass panels, architecturally integrated with the glazed walls, reduce flutter echo formation between the glazing and the parallel mirrors.

6 SUMMARY

In the Copenhagen Operaen the complex acoustic requirements have been rationally integrated into the design such that the acoustic elements appear to be intrinsic to the architecture. The result is a technically complex but beautiful building, crafted to provide world class facilities to the highest acoustic standards.

7 THE TEAM

Client: AP Møller Foundation (Ib Kruse, Bo Wildfang, Peter Poulsen)
Architect: Henning Larsens Tegnestue (Henning Larsens, Peer Jeppersen, Dominic Balmforth, Helle Basse Larsen)
Acoustic Consultant: Arup Acoustics (Rob Harris, Jeremy Newton, Ben Cox, Judith Ruttle, Angus Deuchars, Thomas Wulfrank, Lee Kirby)
Theatre Consultant: Theatreplan (Richard Brett, Neil Morton, Liam Hennessey, Charles Wass, John Whittaker)
Engineer: Rambøll (Finn Gjorrett, Flemming Koch)
Contractor: Pihl (Jørgen Lassen, Claus Wiegand Larsen)
User: Det Kongelige Teater (Michael Christensen, Claus Due, Michael Schønwandt, Kasper Holten)