FLEXIBLE ACOUSTICS AND SOUND SYSTEM DESIGN TO ACCOMMODATE PROGRAMMING INSIDE AND OUTSIDE THE VENUE SPACES

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1 INTRODUCTION

Opened in 2017, the new Stavros Niarchos Foundation Cultural Center (SNFCC) is one of the largest cultural projects recently realized in Europe. The vast and ambitious development is a cornerstone of continued urban renewal and regeneration, as well as a progressive 21st Century investment in cultural infrastructure for Greece to share knowledge, culture, and the presentation of the performing arts. Its success is in many ways a symbol of the revitalization of the country after its period of crisis, playing a major role in the economic, cultural and sociological development of Athens and of the country.

As a multipurpose cultural facility, flexibility is essential to the programmatic success. While celebrating the historic art of opera, accommodating a wide variety of arts programs supports the SNFCC mission of ‘access for all’. This article will summarize the design of physical elements that allow for acoustic flexibility as well as the audiovisual systems and infrastructure that supports high-fidelity / high-definition experiences and connectivity throughout the SNFCC campus.

2 ORCHESTRA PIT

Many have evaluated the acoustic challenges of the orchestra pit and studied solutions that have resulted in positive feedback surrounding the challenges musicians face[3,4,5]. The size, depth and shaping of the orchestra pit are all factors to be considered during design that not only influence the acoustic quality within the orchestra pit but within the opera theater as well. Past studies have illustrated there is not a singular solution to address the acoustic challenges within the orchestra pit for musicians. The acoustic quality of an orchestra pit is very subjective but important to help enhance the working environment – particularly related to health and safety – for musicians.

2.1 Opera Theater

The orchestra pit within the opera theater includes a series of variable acoustic panels as follows:

- Moveable panels that can track forwards / backwards along a rail and rotate to provide a sound absorbing or sound reflecting (with high frequency diffusion) finish
- A pit rail with removable panels to provide acoustic transparency of sound reflecting finishes
- Removable sound absorbing panels that can be installed in the soffit of the orchestra pit soffit / stage overhang
- All sound absorbing finishes are 50mm thick (45 – 60 kg/m^3) mineral wool with perforated metal facing (open area ≥ 70%)

These elements allow the musicians and the conductor to adjust their acoustic environment to control loudness and low frequency energy buildup.

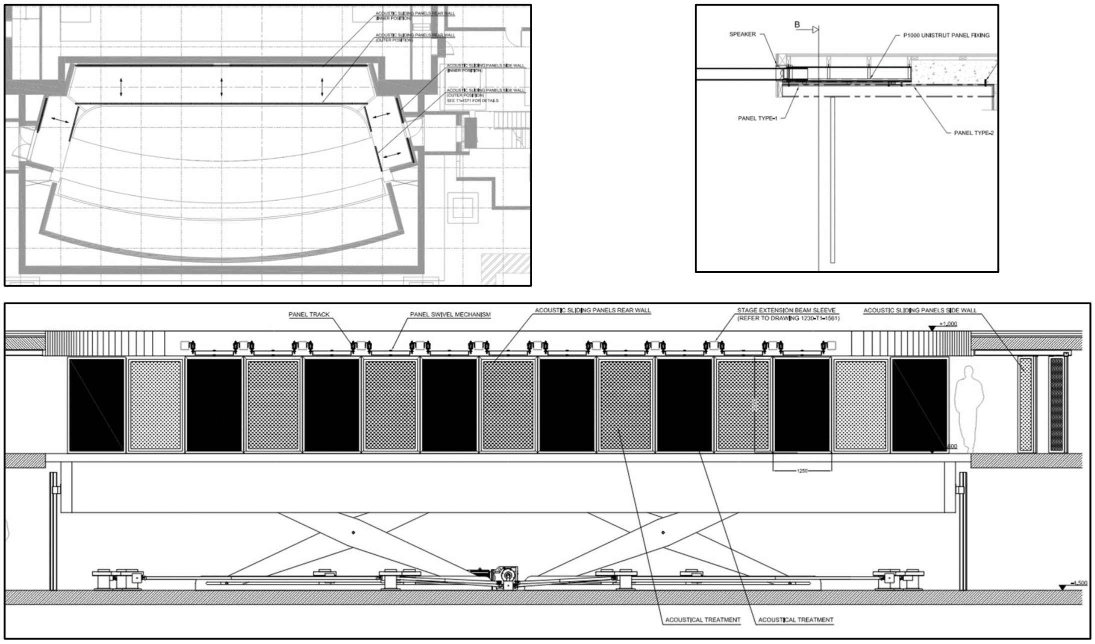

Figure 1: Design drawings of orchestra pit panel system in opera theater. Plan diagram (upper left), rear wall elevation (bottom), and detail of stage overhang panel (upper right).

Figure 2: Opera theater orchestra pit with tracking panels that can rotate to be sound absorbing or sound reflecting with high frequency diffusion (left) and orchestra pit rails that are sound reflecting or acoustically transparent (right)

2.2 Alternative Stage

An open orchestra pit is included in the alternative stage with a fixed height of 1.6m. Temporary sound absorbing panels of the same construction as the opera theater can be added to the front and rear walls of the orchestra pit.

Figure 3: Alternative Stage orchestra pit with sound absorbing panels on front and rear wall.

3 ACOUSTIC CURTAIN SYSTEMS

The use of sound absorbing curtains is commonly used throughout the performance and rehearsal spaces at SNFCC to adjust the room acoustic.

Within each space the variable acoustic curtain construction consists of two layers of serge wool (400 g/m^2 per layer) stitched together with 50% fullness and typically hang 120mm away from the wall. A summary of the acoustic curtain coverage area and performance is provided in the following table.

Space	Total Area / Location	Room Acoustic Results	
Opera Theater	98.6 m^2 / Catwalk 153.6 m^2 / 4th Balcony 91.8 m^2 / 3rd Balcony 70 m^2 / 2nd Balcony	$RT_{unoccupied}$ $RT_{occupied}$ $RT_{unoccupied\ Ac.\ Curtains}$ $RT_{occupied\ Ac.\ Curtains}$	2.00s 1.80s 1.65s 1.30s
Alternative Stage	73.6 m^2 / 1st Balcony 118.2 m^2 / 2nd Balcony 143.5 m^2 / Catwalk	$RT_{unoccupied}$ $RT_{occupied}$ $RT_{unoccupied\ Ac.\ Curtains}$	1.68s 1.36s 1.00s
Orchestra Rehearsal Room	214.5 m^2 / Lower 348.6 m^2 / Upper 24.8 m^2 / Storage Pocket Wall	$RT_{unoccupied}$ $RT_{unoccupied\ Ac.\ Curtains}$	2.20s 0.90s
Chorus Rehearsal Room	75m^2 / Front Wall	$RT_{unoccupied}$ $RT_{unoccupied\ Ac.\ Curtains}$	1.30s 1.18s (estimated)

Table 1: Summary of variable acoustic curtain coverage and room acoustic mid-frequency reverberation time results (RT) for various modes.

Figure 4: Variable acoustic curtains in opera theater (upper left), alternative stage (upper right), orchestra rehearsal room (lower left), and chorus rehearsal room (lower right).

The following sections summarize the distribution, control and storage of the variable acoustic curtains within key spaces.

3.1 Opera Theater

All elements are electronically controlled within the opera theater via motorized systems. Each zone can be individually controlled and presets can be established with multiple zones. When retracted, the storage areas are fully closed with hinged panels.

3.2 Alternative Stage

All elements are manually operated within the alternative stage. At the 1st and 2nd balconies, the curtains can store in pockets behind the wood acoustic panels at the rear corners. The catwalk level curtains do not have storage but can be split into two and bunched.

3.3 Orchestra Rehearsal Room

The variable acoustic curtains are split into an upper zone and lower zone. The lower zone is manually operated and consists of 13 curtains, each 5m long and 3.3m high. A single curtain in front of the storage pocket can cover the room finishes but does not store away.

The upper zone is electronically controlled via motorized systems and consists of two curtains that cover the extent of the upper wall zone (4.6m high).

3.4 Chorus Rehearsal Room

The variable acoustic curtains are manually operated and cover a portion of the front wall. The limited area of variable acoustic curtains is provided as some of the wall finishes are fixed sound absorbers (perforated wood with sound absorbing treatment in the cavity)[1]. The curtains store in an open pocket.

4 AUDIOVISUAL SYSTEMS

Modern performance facilities deploy technology throughout to support productions and the SNFCC is designed to leverage technology at nearly every location on the 50-acre campus. This allows for the creation of new stages for performance and temporary spaces for broadcast / simulcast. While there are many audiovisual systems throughout the SNFCC, this section will focus on the principles of the audiovisual systems and the opera theater system in hopes that that reader will realize key lessons in flexibility, design planning and team collaboration to realize performance excellence and be future ready.

4.1 Benchmark Facilities

Prior to the SNFCC, recent new opera houses have incorporated robust performance sound, video and communication (PSVC) infrastructure to support goals similar to SNFCC – accommodate a wide range of program and provide a flexible technology backbone for audiovisual media that supports artistic composition and productions.

Key benchmarks for the SNFCC PSVC systems were Oslo and Copenhagen opera houses. Each facility includes a combination of analogue and structured cabling that “future-proof” technical systems through a flexible infrastructure that can adapt to the changing specifics of technology. They also feature sound reinforcement systems that are integrated into the performance spaces and can be leveraged for various programs outside of standard opera repertoire.

4.2 Infrastructure Architecture

PSVC technology infrastructure is prevalent throughout SNFCC. The infrastructure was designed in close coordination with the IT systems consultant as it leverages CAT6 structured cabling and fiber. Signal distribution and routing is architected around four levels of connectivity:

- **Local:** Routing and connection of technical systems within each space mainly through analog connectivity.
- **Intra-Building:** Utilization of structured cabling tie-lines for connectivity between physical spaces within a building (e.g. rehearsal and performance spaces)
- **Inter-Building:** Technical systems connectivity between buildings and/or building and outdoor spaces via the use of single-mode fiber cabling.
- **Broadcast:** Tieline panels and routes for temporary cabling to support broadcast events from the performance spaces.

While the infrastructure was designed to be extensive, it also needed to be mindful of the high-quality finish and aesthetic throughout the facility. Extensive collaboration between the design team and builder realized great results to integrate and conceal the PSVC infrastructure within the architecture while allowing for ease of access and cable routing when in use. Some examples include performance loudspeakers within the proscenium arch and cheek walls of the opera theater, PSVC panels within the opera theater and alternative stage. Mock-ups were conducted through the construction process to confirm that tight tolerances could be achieved by the various tradespersons and so that operation of the systems – including acoustic performance – was not compromised due to limited field coordination.

Figure 5: Mock-ups of PSVC elements. Mock-up of opera theater central loudspeaker cluster with proscenium arch and sound absorbing treatment in cavity (upper left and upper middle). Opera theater balcony PSVC panel mock-up within balcony front cavity (lower left and lower middle). PSVC infrastructure in alternative stage, concealed behind acoustic wood wall panels (upper right and lower right)

4.3 Opera Theater Sound Reinforcement System

4.3.1 Overview

The opera theater sound system is comprised of the following components:

- A main left-right-center system integrated inside the proscenium for main floor seating coverage (Figure 6-1)
- Cheek wall loudspeakers located to the left and right of the proscenium opening at parterre and 1st balcony levels for image localization for the middle of the stalls seating (Figure 6-2)
- Stage lip loudspeakers integrated into the stage front for image localization for the front seating rows (Figure 6-3)
- Underbalcony recessed ceiling loudspeakers individually zoned to be used as a sound-mapped array or surround sound configuration (Figure 6-4)
- Stage left and right cardiod subwoofers to supplement the audio system with low frequency coverage (Figure 6-5)
- Loudspeakers mounted on the adjustable torm to provide foldback audio coverage on the stage
- Voice alarm loudspeakers located to the left and right of the proscenium opening (Figure 6-6)

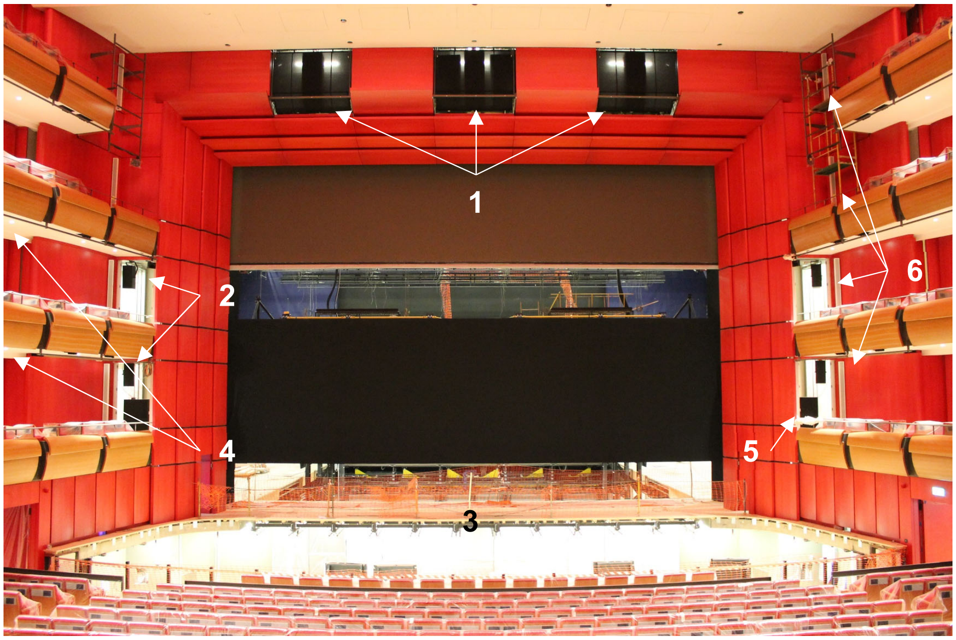

Figure 6: Primary sound system features of the opera theater.

The following sections summarize the design approach, analysis, and revisions that occurred through the course of the project for the opera theater sound system.

4.3.2 Design Approach and Analysis

In evaluating loudspeaker strategies the following parameters were considered early in the design process:

- Physical space would be limited to incorporate a high-fidelity system within the architecture of the proscenium arch
- A wide vertical coverage pattern would be required to achieve coverage at all seating levels from the left/center/right clusters so a rotatable horn feature would be needed.
- Control of low-frequency directivity from the main loudspeakers would be important to limit excitation of the proscenium arch cavity.

The Renkus Heinz STX series (3-way arrayable cabinets) was selected to achieve these goals along with Tannoy CMS ceiling loudspeakers for underbalcony areas.

Design coordination revealed that the upper part of the proscenium arch interfered with the electroacoustic coverage from the left/center/right loudspeakers. To resolve the acoustic shadowing, the first panel of the proscenium arch was motorized to retract when the sound system would be used.

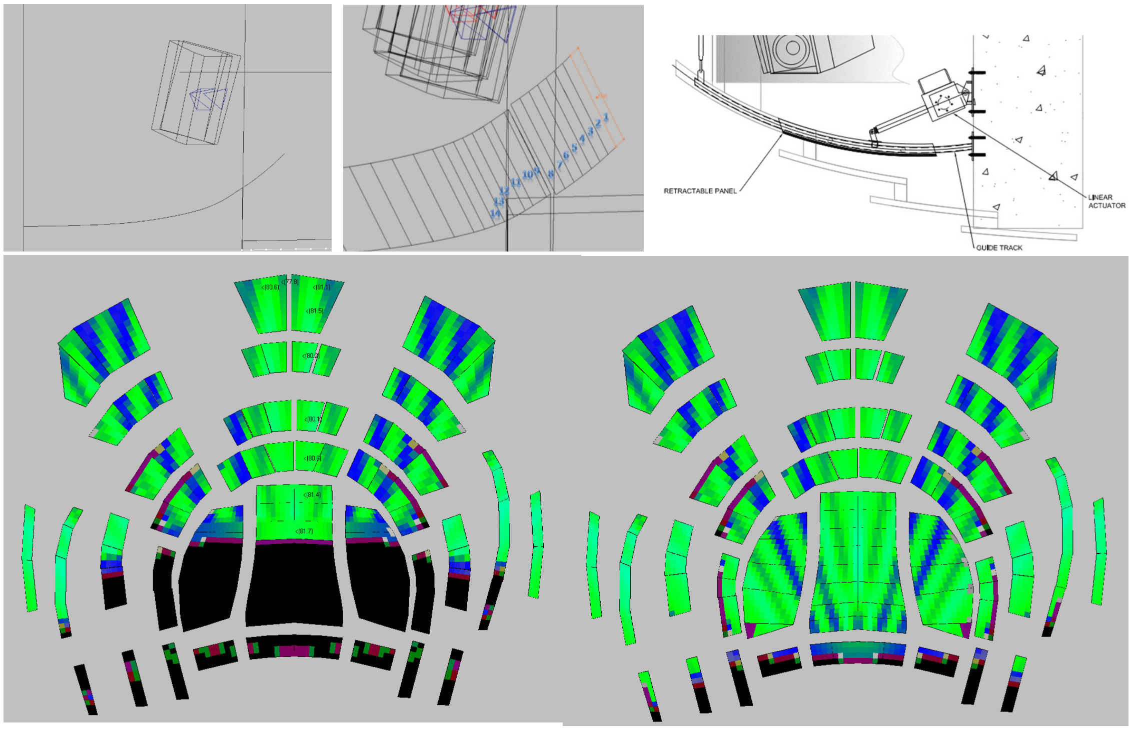

Figure 7: A 3D electroacoustic model placed the loudspeaker above and slightly behind the proscenium arch (upper left). The reflector was segmented (upper middle) and elements were removed one-by-one to evaluate acoustic shadowing of direct sound. For the center cluster with all elements in place, significant acoustic shadowing occurred – the black area of false color map – in the main stalls (lower left). With the first full panel of the proscenium arch retracted, there was minor acoustic shadowing at the front of the stalls and balconies (lower right) where stage lip and underbalcony loudspeakers would provide coverage. Design drawing of the linear actuator solution is shown (upper right).

4.3.3 Design Revisions

Following the mock-up of the loudspeaker cluster, proscenium arch, and ceiling it was determined that the acoustically transparent face of the proscenium arch was not aesthetically desirable. A similar approach was to be implemented for the cheek walls where the performance loudspeakers and voice alarm loudspeakers were to be concealed behind the black acoustically transparent loudspeaker cloth fabric. This posed challenges for maintaining the performance criteria established of the sound reinforcement and voice alarm systems.

At the cheek wall locations, the solution was simple – move the voice alarm loudspeakers to be surface mounted and create manually operable wood doors that would be conceal the performance loudspeakers when not in use and opened when required.

Figure 8: Cheek wall loudspeaker and subwoofer locations with manually operated millwork doors closed (left) and open (right) prior to installation of acoustically transparent cloth. Voice alarm loudspeakers were surface mounted within the opera theater.

In the proscenium arch, motorized doors would be added to open/close the areas in front of the left/center/right clusters as well as retract the first 'lip' of the proscenium arch from the previous design evaluation. Electroacoustic analysis was conducted to evaluate the width of the door required so there would be no acoustic shadowing of direct sound. The analysis revealed that without reverting back to the original design, an ample width could not be achieved that eliminated shadowing as well as acoustic energy on the back of the proscenium arch.

It was determined that the modelled results could be under representing these issues and they may not be easily resolved during system commissioning 'tuning'. The limiting factor was primarily the physical size of the loudspeaker cabinet and cluster in comparison to the architectural constraints. Given that there was a desire to maintain the revised aesthetic, an alternative solution was required to mitigate this risk.

When the design documents were issued for tender, compact line array technology had not been readily available in the market. At this juncture in the project construction, compact line array technology had made significant advancements and been implemented in many fixed installations, including at another local venue in Athens. These advances allowed for three options to be considered – all with significantly smaller physical footprints.

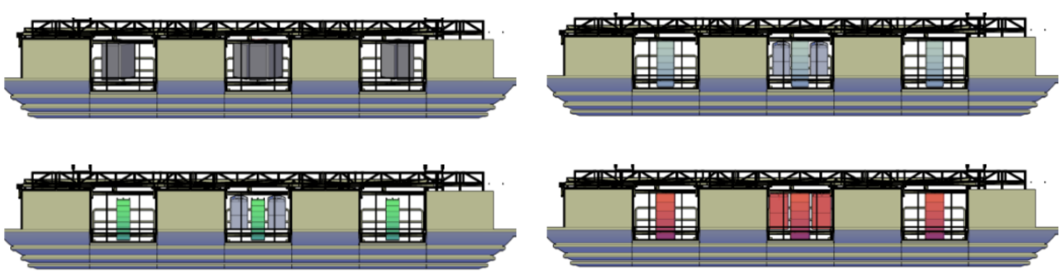

Figure 9: Elevation views of proscenium loudspeaker clusters. Basis of design Renkus Heinz STX9 (upper left) and alternative options – d&b T-Series with center Yi-sub array (lower left), d&b Y-Series with center Yi-Sub array (upper right), and d&b V Series with center Vi-Sub array (lower right)[11].

Various performance improvements could be realized with the compact line array technology and subwoofer arrays:

- With the smaller physical size, direct sound energy shadowing by the proscenium is eliminated with 2.5m wide door openings (original aesthetic design intent) and retraction of the first proscenium panel in the 2.5m zone.
- Subwoofers from the 1st balcony cheek wall locations could be moved into the proscenium arch as part of the subwoofer array to provide interference free and uniform low frequency coverage to the opera theater. This design strategy also slightly reduced low frequency energy on the back side of the proscenium.
- Advanced DSP processing could be implemented to enhance fidelity and coverage uniformity. In addition, sections of the opera theater sound system can be 'turned off' to limit electroacoustic energy distribution.

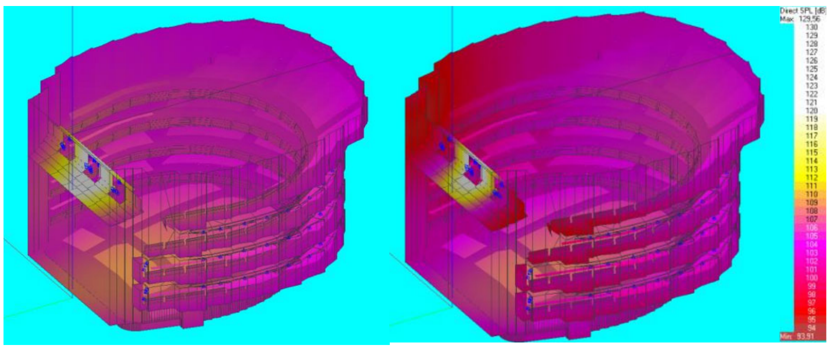

Figure 10: Direct SPL of low-frequency energy (100 Hz 1/3rd octave) from basis of design loudspeaker clusters (left) and subwoofer array (right)[11].

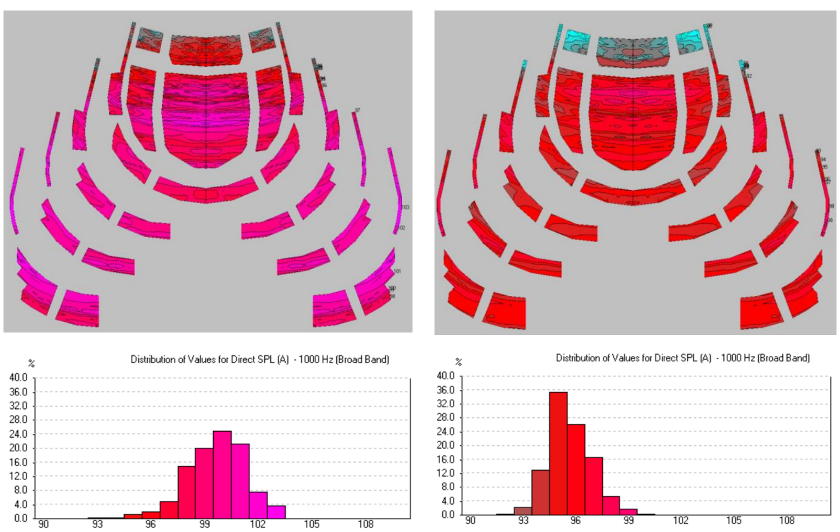

Figure 11: Direct SPL of compact line array (1kHz, A-Weighted) under normal operation (left) and with advanced DSP processing (right)[11].

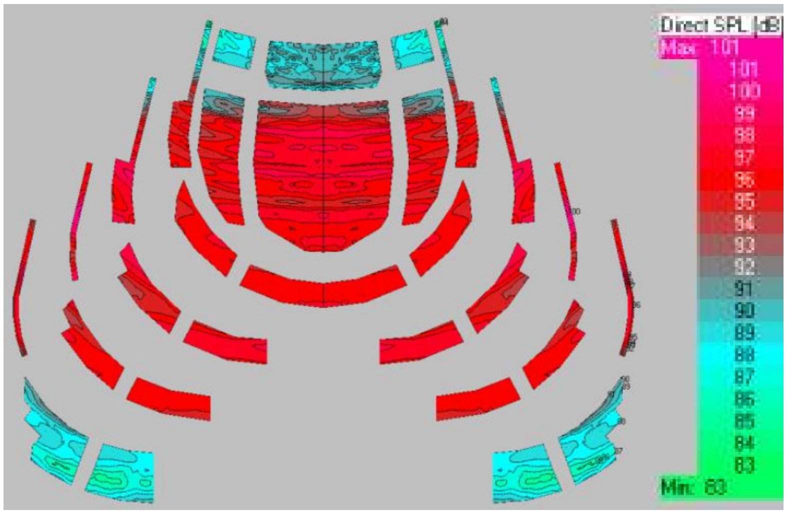

Figure 12: Direct SPL of compact line array (1kHz, A-Weighted) using advanced DSP processing to 'turn off' coverage to the 4th balcony[11].

Similarly, the underbalcony loudspeakers specified were no longer available at the time of installation. The Tannoy CMS603 was utilized with two loudspeakers per amplifier / DSP channel. The revised configuration allowed for more precise time delay, fill above shadowed areas with greater accuracy, and more effects channels to use in the circumference of the balconies.

4.3.4 Installed System

The final installed sound system loudspeakers included:

- 14 d&b Yi8, 7 d&b Yi12, and 4 Vi-SUB loudspeakers for the left/center/right clusters
- 4 d&b Vi7P loudspeakers for the left and right cheek walls
- 4 d&b Vi-GSUB subwoofers for the left and right cheek walls
- 6 d&b E6 loudspeakers for the stage lip
- 2 d&b E8 loudspeakers for the adjustable torm for stage foldback monitoring
- 12 d&B E8 loudspeakers for portable effects
- 69 Tannoy CMS603 recessed ceiling loudspeakers for underbalcony coverage and surround effects

5 FUTURE DESIGN – THE INTERSECTION OF NATURAL ACOUSTICS AND AMPLIFIED SOUND

Design of the SNFCC highlights the challenges and tensions that exist between the 'traditional' elements for a quality natural acoustic and technologies which support modern performance and new patron experiences. With care of design, quality of craftsmanship by tradespersons, and extensive collaboration a quality natural acoustic can be achieved with these traditional elements. Variable components honor the craftsmanship of the traditional approach while supporting program flexibility. However, are we limiting the acoustic flexibility through the exclusive use of physical elements? These components require substantial space that provides a limited range of acoustic variability, are costly and have logistical limitations.

Acoustic enhancement systems have been available on the market for over 50 years but have had limited application in performance venues[7]. In recent years we have seen advances in audio DSP power, reduced cost of high-quality audio equipment, and a newfound investment in spatial audio by pro audio manufacturers. Complemented with immersive visuals and other performance technologies, audiences are experiencing and seeking more immersive events. With greater accessibility to hardware and software, the next generation of performers and technicians are increasingly comfortable with advanced audio technologies and are implementing it in their productions – whether 'home-built' or a purchases product / system. For example, wave field synthesis (WFS) technology was applied in the 2017 production of Andrew Schneider's *AFTER* using a 372 channel array fabricated and programmed by sound designer Bobby McElver[8]. At commercial scale, Holoplot offers WFS loudspeaker technology which will be the source of the immersive audio experience at the MSG Sphere venue in Las Vegas, NV opening in Fall 2023[9].

Ultimately these audio technologies are another tool for a production to use in the storytelling process – the crux of the opera art form. Given the prevalence and access of spatial amplified audio, some composers have argued it should be used regularly in opera composition. As well, it is a tool that can enhance the connection with younger audiences who are excited by low frequency energy from subwoofers and often are listening with a smaller scale of immersive audio – through earphones[10].

The design of the SNFCC highlights the need for early evaluation in the design process where the natural acoustic and amplified sound intersect in a venue that supports traditional and new compositions. Detailed analysis, flexibility and some foresight to future technologies are needed to integrate these elements with success.

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