SOUND ISOLATION AND HVAC NOISE CONTROL: DESIGN VERSUS PRACTICAL CHALLENGES AND CONSTRUCTIBILITY

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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.

The opera house building facility is a compact building, which includes challenging adjacencies between loud and noise sensitive performance and rehearsal spaces, that resulted in innovative noise and vibration control mitigations. In this paper, we aim to present practical and constructability challenges for sound isolation and HVAC noise control through two case-studies developed for the 480-seat Alternative Stage. The first addresses the feasibility of constructing the full concrete box-in-box around the Alternative Stage, and offers practical solutions through early contractor engagement, and an understanding of construction sequencing. The second investigates the role of aerodynamics and materiality through testing, in order to achieve a low background noise in the space with high diffuser face velocity.

1. Concrete Box-in-Box: The main challenge in this space was the question of how and when to pour the concrete roof slabs of a box-in-box in a cast-in-situ building. On one hand, accessing the formwork of the outer box is impossible if the roof slab of inner box is already in place. On the other hand, it is not possible to pour the roof slab of the inner box, if the outer box slab has already been poured. Early contractor engagement, clear mapping of the construction sequencing, and close collaboration with the structural engineer resulted in a hybrid metal deck / flat slab solution ensuring the feasibility and integrity of the box-in-box for the Alternative Stage.
2. Air-Distribution and Low Background Noise: Design guidance and standard practice for low noise ventilation systems require extremely low air velocity throughout the system. However, in cases requiring long-air-throws, low diffuser face-velocity is not possible. Turning the attention to aerodynamics, materiality, and diffuser wall friction made it possible to achieve the specified low background noise with excessively high diffuser face velocity.

2 CASE-STUDY #1: CONCRETE BOX-IN-BOX

2.1 Criteria & Design Challenges

Not surprisingly, given its proximity to the Opera Theatre, the Dance School, and Rehearsal Spaces, the Alternative Stage at SNFCC required a full box-in-box construction. However, design constraints, spatial limitations, and overall technical systems required a rethinking of the typical box-in-box construction, and a close collaboration with the Project's Structural Engineers. The box-in-box structure had to accommodate for the following, while maintaining the integrity of the sound isolation:

1. Catwalks and performance equipment trusses, all suspended from the ceiling.
2. Wrap-around gantries and two balcony levels, accommodating close to a third of the overall audience capacity, supported off the walls.

While the outer box was namely cast-in-situ concrete, the inner box was comprised of the following separate components, (illustrations on Figure 1 and 2):

1. **Floating concrete floor:** A 200-mm normal weight concrete slab on top of 6-mm deflection neoprene pucks. The concrete floor floated within an independently isolated perimeter concrete beam.
2. **Isolated perimeter concrete beams:** 400x340-mm concrete beams on 25-mm continuous neoprene pads, running the entire perimeter of the Alternative Stage, separated from the outer box by a 50-mm continuous neoprene pad, and separated from the floating concrete floor by a 50-mm acoustically-sealed isolation joint.
3. **Inner box steel structure:** A steel structure comprising of steel columns, cross-bracing, and beams sat onto of the isolated perimeter beams, 90-mm away from the outer box with neoprene bracing.
4. **Concrete loaded metal deck:** A corrugated metal deck topped with 150-mm concrete.
5. **Inner CMU block walls:** 120-mm 75% solid CMU block walls were built on top of the concrete perimeter beam in front of the inner box steel structure.

This design approach allowed for a fully contained, fully independent, box-in-box with little compromise. The **inner box steel box** and the **isolated perimeter concrete beams** were designed specifically to carry entire load of the Alternative Stage, including the walls, ceiling, balconies and gantries, catwalks, and the performance equipment trusses. By incorporating the perimeter concrete beams and inner steel structure into the design, we were able to free the floating concrete floor from excessive perimeter loads, and eliminate inner ceiling / wall penetrations for structural loading.

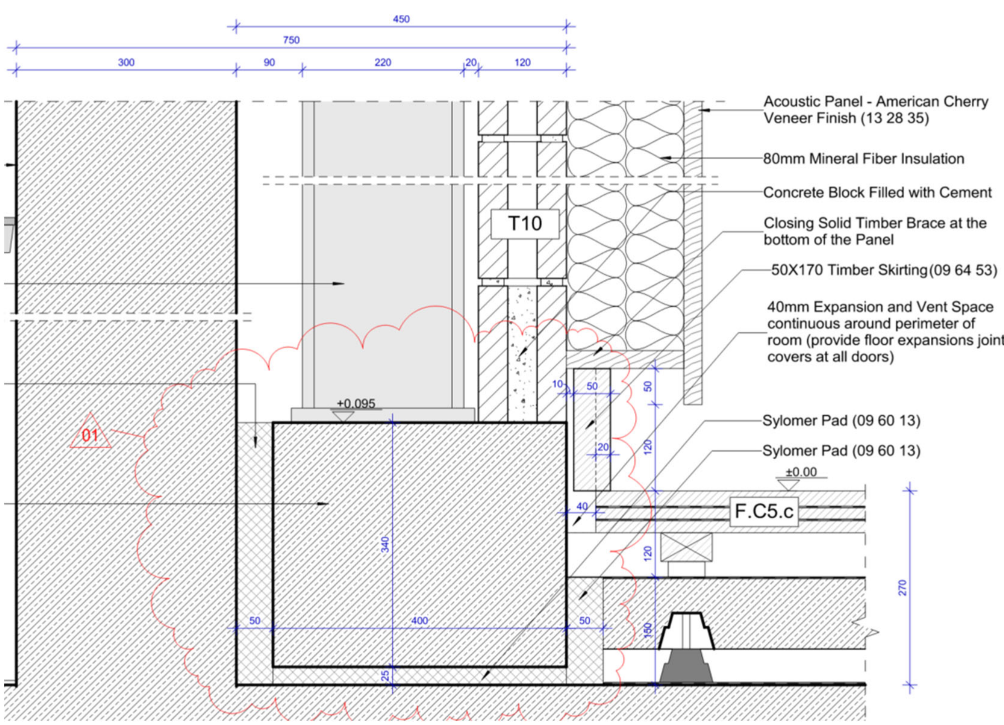


Figure 1 - Floating Floor and Perimeter Beam Detail

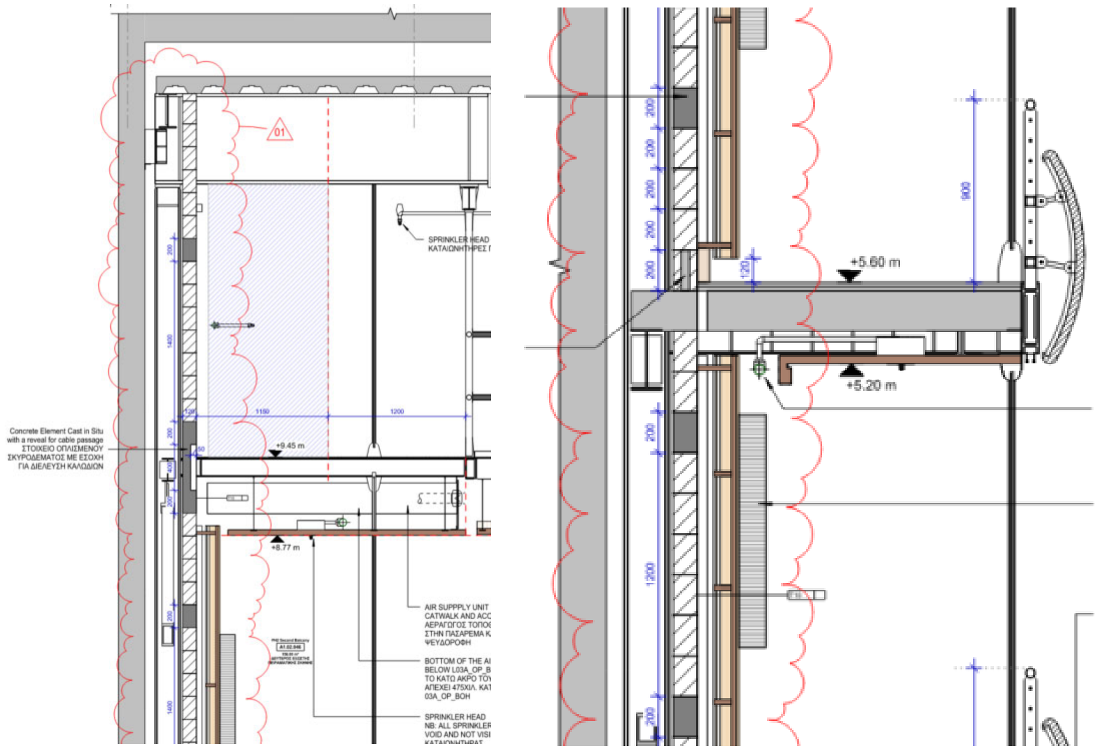


Figure 2 - Details of steel structure loading and inner box ceiling

2.3 Site Challenges & Contractor Collaboration

Given the design described above and its various components, successful execution onsite required the contractor to fully embrace the design, work with us collaboratively to overcome site challenges, and most importantly to outline a clear construction sequence and methodology in which the various components can be built/installed. One key challenge with regards to sequence of construction was the question of the inner ceiling: *how and when to pour the concrete roof slabs of a box-in-box in a cast-in-situ building?*

Even as part of the tendering process, we raised this question to each of the contractors and challenged them to include a clear method statement in their respective bids and their final presentations. In raising this question as part of the tendering process, we wanted to achieve the following:

1. Stress the importance of sound isolation in the overall design from the onset.
2. Invite the contractor to embrace the overall acoustic criteria.
3. Lay the groundwork for contractor collaboration and engagement, as well as give space for contractor contribution to finding creative solutions.

During the tendering presentation by the different contractors, each contractor presented their own methodology and sequence for building the box-in-box, with one creating full animation showing their sequence step by step. The methods and sequences varied between contractors, which is an indication of the importance of bringing contractors early on into the design conversation. Each presented method proved valuable in its own right to ensuring the design criteria is met, and provided us with a better understanding of the challenges contractors face during implementation.

The results were three different sequences and methods:

1. The first contractor called for completing the construction of the outer box and the slab above while leaving openings, in order to pour concrete atop the metal deck for the inner box.

2. The second contractor called for completing the inner box first, including the metal deck concrete, and modifying the design, in order to provide enough vertical space between the inner and outer box in order to retrieve the formwork once the slab of the outer box was completed.
3. The third contractor, called for the use of precast concrete for the outer box slab. Although this differed from all other areas of the building, this by far seemed the simplest and easiest of all methods.

Once again, it is important to stress that the above approaches were presented by competing contractors during the bidding stage of the Project. In the end, the second method was selected for a variety of reasons.

As can be seen from the site photos presented below, the final sequence was:

1. Inner Box: Isolated perimeter concrete beam.
2. Inner Box: steel structure and metal deck (no concrete).
3. Outer Box: Main beams
4. Inner Box: Concrete atop the metal deck.
5. Inner Box: CMU block walls.
6. Inner Box: Concrete floating floor.
7. Outer Box: Concrete Roof slab

The outer slab above the Alternative Stage was poured in small sections, and the vertical gap between the inner box and outer box was increased enough to allow for the construction team to retrieve the formwork as they worked their way from front to back of the space.

Figure 3 - Step 1. Isolated Perimeter Beam

Figure 4 - Step 3. Inner beam, steel and deck. Outer beams/wall (sway brace)

3 CASE-STUDY #2: AIR DISTRIBUTION

3.1 Criteria & Design Challenges

Given the program and different performance anticipated in the Alternative Stage, the set criterion for background noise was PNC 20. Following all design standards and best practice, achieving PNC 20 requires at a minimum the followings:

1. Low air-stream velocity throughout as per the table below:

   Table 1 - PNC 20 Maximum Duct Velocities

Mechanical Room	Riser duct	Last 4 diameters	At terminal
6.0 m/s	3.75 m/s	2.0 m/s	1.25 m/s

2. Very low diffuser air velocity with NO elements in the airstream.
3. No dampers within the space.

However, a combination of spatial limitations, technical design requirements, and variability in program usage and capacity, resulted in the air-supply being located along the two long sides of the venue under the second balcony. This had a series of knock-on effects on the overall design of the system, which deemed all the typical “tried and tested” methods for noise control impossible, as described below:

1. When supplying air from the sides of the space from up high, jet nozzles with high air velocity were required so that the air would reach the center of the space before dropping, to ensure even coverage and minimize draft.
2. The variability in occupancy, usage, and orientation required variable air volume supply, which resulted in variable air volume boxes and dampers within the airstream.
3. The use of the main ceiling within the space for theatre equipment, rigging, trusses, and other equipment limited any possibility of placing additional overhead diffusers.

A close collaboration with the entire project team, especially the architects and mechanical engineers during design, and the contractor and suppliers during construction, allowed for the design of a full system that enabled us to achieve the background noise criterion within the above limitations as described in the section below.

3.2 Design - Air Handling and Acoustics

Working closely with the mechanical engineer, we turned our main focus to the high airstream velocity as the key challenge that needed to be addressed, from air handling unit to diffuser and everything in between. We worked to ensure any potential for turbulence was addressed throughout the system, and specified system components that were acoustically optimized to minimize turbulence and self-noise. Lastly, together with the contractor, we ensure that the designed system was mocked-up and tested in advance.

1. **Air handling units (AHUs):** The AHUs serving the Alternative Stage are equipped with multiple fans that come online at 4 different speeds, depending on the occupancy and load. Through the automated control system, each speed setting triggers a number of multileaf dampers, (see 6 below), to be fully open or fully closed, but never partially open. This approach, together with the self-balancing ducts, (see 5 below), minimized any potential for turbulence in the airstream resulting from the use of typical dampers with various adjustments located within the space.
2. **Self-balancing ducts**: Two self-balancing header ducts run on both of the long sides of the Alternative Stage supplied by different air handling units. The self-balancing enabled us to rid

the main branches of any typical dampers, which would result in turbulence in the airstream, and allowed us to tolerate higher airstream velocity.

3. **Multileaf dampers:** Seven (7) multileaf dampers located within the main branches of the header ducts. These mutlileaf dampers are designed and controlled to operate in 2 positions only - either fully open, or fully closed based on the fan setting within the air-handling system as described in point 1 above.
4. **Secondary silencers:** There is a silencer after each of the multileaf damper.
5. **Plenum boxes:** Each silencer feeds into a plenum box in order to slow the air down, further reduce low frequency noise, and allow for laminar air-flow into the final run towards to the diffuser.
6. **Final run and diffuser:** From each of the plenum boxes, three circular ducts run straight under the second balcony with an air-stream velocity >3.0 m/sec. Each of these circular ducts terminates with a fixed jet nozzle diffuser with acoustically optimized contours. The selected diffuser is 15 dB lower than more traditional jet nozzle diffusers by the same manufacturer. The nozzle diffusers are specifically located at the end of the duct inline with the airstream to ensure minimize turbulence.

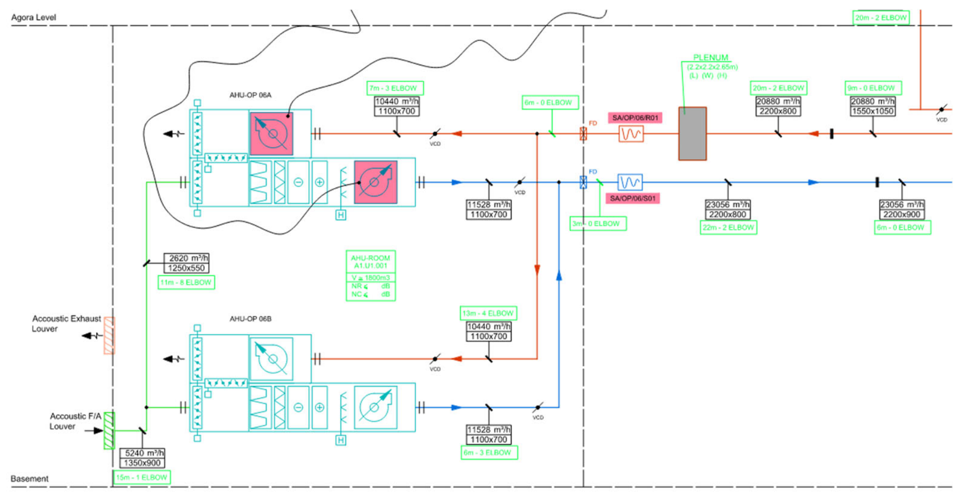


Figure 5 - Duct path from AHU

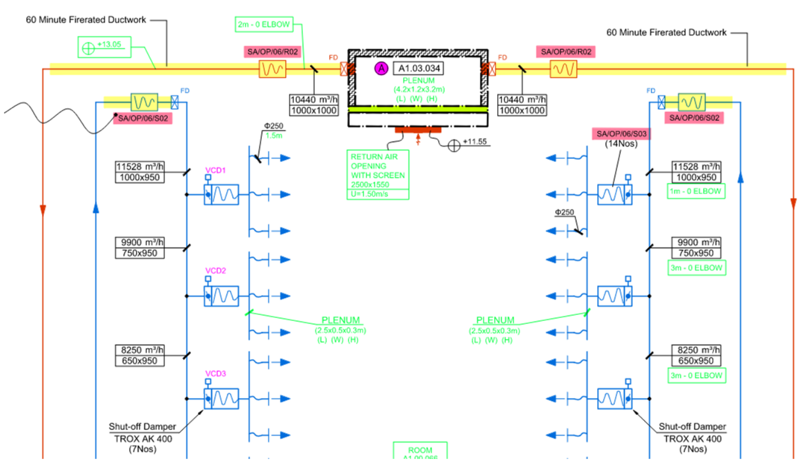
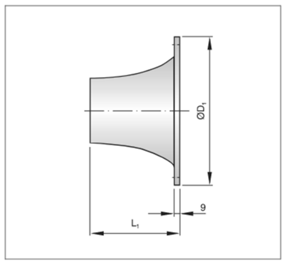
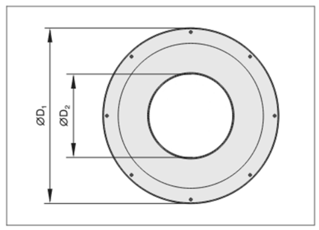


Figure 6 - Duct path final runout





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Nominal size	$ØD_1$	$ØD_2$	A_{eff}
	mm	mm	m^2
100	138	50	0.00174
125	161	64	0.00277
160	225	82	0.00469
200	265	108	0.00813
250	315	136	0.01289
315	400	174	0.02110
400	485	230	0.03683

Figure 7 - Selected diffuser dimensions

3.3 Mock-up and Testing

Working closely with the Mechanical Engineer, Contractor and the Systems Supplier, we developed a mock-up for testing at the Labs of the suppliers in Germany. The mock-up comprised of the one full branch, constructed to scale, and connected to a fan supplying 1650 cubic meters per hour, as per the final design.

- Airstream velocity in each of 3 final runs was > 3m/sec.
- Diffuser face velocity was >10m/sec.

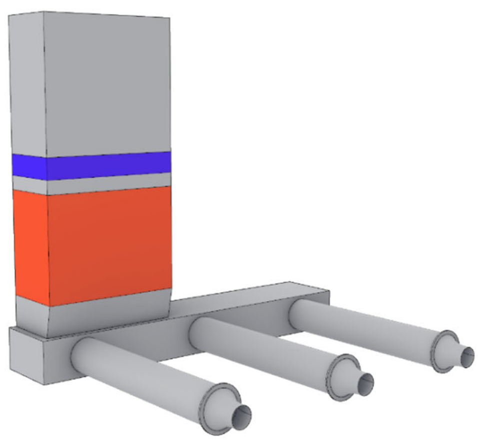

Figure 8 - Test Duct/Diffuser configuration

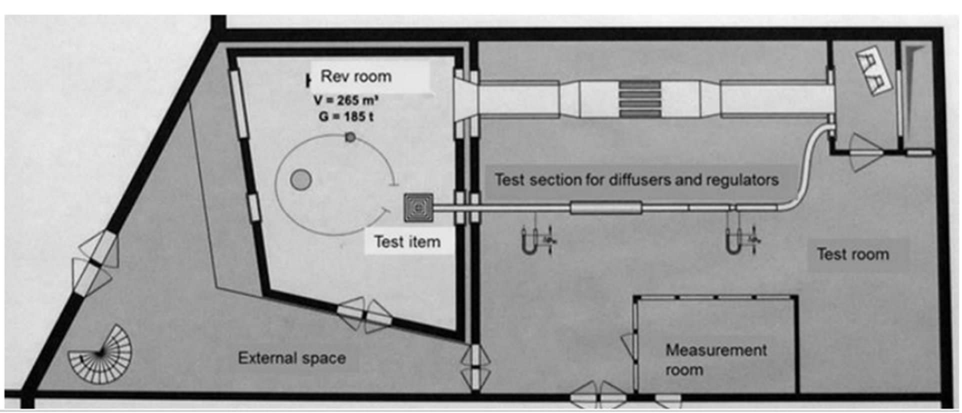

Figure 9 - Trox Test Chamber

Initially, two different tests were conducted.

1. A smoke test in order to confirm the air-throw is inline with the design.
2. PWL test within the test chamber.

Figure 10 - Mockup testing

The test allowed us to test further design concepts, such as including perforated sheets within the plenum boxes to ensure the air is distributed evenly across all 3 final runs. However, none of these were deemed to be useful or to have a noticeable effect.

Table 2 - Measured PWL of nozzle mockup

		Octave band Frequency in Hz							
	dB(A)	63	125	250	500	1k	2k	4k	8k
Target Supply PWL for a single diffuser predicted to achieve PNC 20	**30**	46	39	32	26	20	15	13	13
Measured Supply PWL with single branch, no nozzle	**13**	31	19	16	8	-2	-6	-3	8
Measured Supply PWL with single branch, with nozzle	**25**	35	24	23	21	19	17	14	8

3.4 Installation and Final Testing

Although the diffuser face velocity exceeds 10 m/sec, the overall design of the system from AHU fans selection to the jet nozzles and every element in-between, as well as the control system, allowed for achieving the specified PNC 20 background noise level throughout the Alternative Stage.

Figure 11 - Installation (progress shot) of ductwork in venue

4 CONCLUSION

The design of Alternative Stage included significant challenges in finding solutions to meet the target criteria for sound isolation and HVAC noise levels. The success of these solutions relied heavily on early and continuous collaboration with vendors and contractors along with the design team. Due to our ability to work closely with these partners during construction in developing unique installation sequences and mockup testing protocols, we were able to achieve criteria using methods that do not appear to follow the traditional rules-of-thumb. We hope that the examples in this paper can highlight the value of collaboration throughout the construction process, in order to support the vision of the overall team rather than adhering inflexibly to established methods at the cost of holistic design.

5 REFERENCES

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5. SMACNA HVAC Systems Duct Design