A new method to predict and measure the noise control performance of a performing arts centre displacement system

by J O'Keefe

Abstract

The re-emergence of HVAC displacement systems is a fairly recent phenomenon and one that the noise control industry is still responding to. A typical displacement system for a performing arts auditorium has a room or chamber below the audience area. The floor of the audience is then perforated with a series holes, allowing the supply air to slowly ventilate upwards. A new method has been developed to predict and quantify the combined behaviour of the chamber and the holes in the floor. It is based on a concept of near and far field components, combined in the same way that one might study direct and reverberant sound fields. Measurements have been performed in three auditoria, two with acoustically lined chambers and one without. The chamber and floor openings, combined, introduce approximately 20 to 30 dB of noise control isolation, although there are some pipe resonance issues around 200 to 400 Hz. The new method was first implemented on Toronto's Four Seasons Centre for the Performing Arts, with encouraging results.

Measurements indicate that the latter is more important, insofar as noise control is concerned. There is good agreement between the proposed prediction method and measurements, although the number of measurements, to date, is limited. We encourage others to perform similar measurements and share them with the community.

A new method to predict and measure the noise control performance of a performing arts centre displacement system.

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1 INTRODUCTION

The foundation of good acoustics is a quiet room. Nothing is more fundamental. A quiet room will reveal all the acoustical nuances of Reverberation, Clarity and Warmth that a noisy room covers up. It also gives the performers on stage a more powerful presence. Nothing is more dramatic than an actor or musician who can hold hundreds of people on the edge of their seats in perfect silence.

Most of the background noise generated in a theatre or concert hall – or any room for that matter – comes from the Heating Ventilation and Air Conditioning (HVAC) system. In recent years, performing arts venues are increasingly being designed with so-called "Displacement Systems", instead of the conventional "top down" HVAC system.

1.1 Displacement Systems

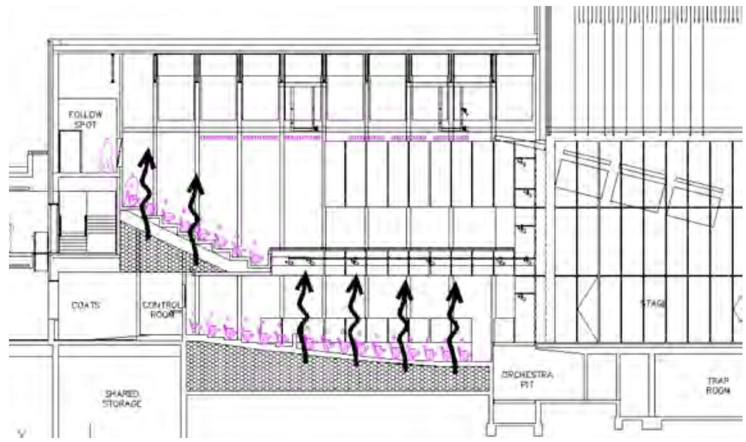

Figure 1. Longitudinal section showing the displacement system at The Esplanade, Medicine Hat, Alberta. Air is supplied through holes in the floor and returns through ductwork located in the ceiling space.

A displacement system ventilates a room by doing just that, by displacing the air in it. In a typical system, a large plenum is built underneath the auditorium and the floor of the auditorium is perforated with a series of 150 mm (6”) holes, typically one per seat. Please see Figure 1. Air is then supplied into the plenum through a series of distribution ducts. Once the plenum is pressurized, the air slowly flows up through the holes, into the auditorium, typically at a velocity of about 0.5 m/s (100 ft/min). Return air is extracted through ductwork in the ceiling space above the auditorium. These very low velocities, typically chosen by the ventilation engineer to prevent drafts on patron’s ankles, match perfectly with the acoustical engineer’s concern about turbulence induced noise.

1.2 Historical Context

For most of the 20th century, theatres and concert halls have been ventilated with overhead supply systems. Noise control engineering, a discipline that emerged around the middle of the 20th century, developed design and calculation procedures accordingly. The re-emergence of displacement systems is a fairly recent phenomenon and the noise control industry is still responding to it.

So, how does one calculate the noise attenuation of a typical displacement system plenum? There has been little public discussion on the matter and there is little, if any, information in the literature to guide designers. Current industry standard calculations such as those published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) do have calculation procedures for plena but not of the kind considered here. For example, the ASHRAE routine assumes that air is supplied through a duct connected to the side of a box. In a typical displacement system for a performing arts centre, the air is supplied through ductwork inside a room.

The analysis of plenum noise control presents a dilemma. Each hole in the floor is an aperture into the plenum and can thus be considered a noise source. Good sight lines make for good sound paths. With that in mind, should we concern ourselves with all these noise sources or just the few that can be “seen” by a listener sitting in his or her seat? And, if we take this “line of sight” approach how many noise sources are we actually dealing with? A microphone located in the orchestra level, for example, can “see” only four or five noise sources. On the other hand, in a typical performing arts venue, a microphone located on the catwalk might be able to “see” hundreds of noise sources. An appropriate analysis, of course, must consider both scenarios. But how?

To answer that, we should remember how sound in a room is predicted and analysed. At the beginning of the 20th century, the concept of "Direct" and "Reverberant" sound fields was developed. Sound pressure levels in a room can be accurately predicted by breaking the analysis down into these two components. The Direct Field is the sound that comes from the sound source and nothing else. It is deterministic and attenuates according to spherical divergence, i.e. a distance squared (r^2) relation. The Reverberant field consists of the hundreds, or sometimes thousands of reflections that bounce around the room immediately after it has been insonified. Originally thought to be ergodic, recent studies suggest that the Reverberant Field may be chaotic. In either case, it is easily and accurately described by statistical analysis.

To summarise, when one stands inside a room and considers the sound there are two salient components: the Direct Sound, coming from a sound source that you can point your finger at, and the Reverberant Sound, something which comes from everywhere, from all surfaces in the room.

The displacement noise problem does not fit quite so neatly into these categories of Direct and Reverberant sound. But, in a sense, it doesn't have to. The concept of two separate fields is more important than the content of those fields. This shines a new light on the analysis. Recalling the dilemma described above, it can be seen that the microphone on the orchestra level is always close to the noise sources while the microphone on the catwalk is always far away. Thus, the analysis can be conveniently broken down into Near and Reverberant Field solutions, similar to but not quite the same as the Direct and Reverberant field solution of traditional room acoustics theory. This distils the analysis into two manageable components that can be easily predicted before construction and easily measured afterwards.

2. CONCEPT

In noise control engineering, the most important noise is the loudest noise. That statement seems self-evident but it is often underappreciated and can, at times, be hard to grapple with. The plenum noise question is a case in point. How does one know beforehand which noise is going to be the loudest? In the conceptual framework that has been developed, is it the Near Field or the Reverberant Field?

The Near Field might be the prime candidate. Take a worst case scenario where one of the distribution ducts in the plenum terminates right underneath an opening in the floor slab. There will be an audience member sitting directly above with a pair of ears approximately 1 m above that hole in the slab. The opening through which the air (and the sound) flows is modeled acoustically as a partially blocked pipe. As such it will display resonances. Are those resonances important?

Perhaps it's the Reverberant Field that is the louder component. Unlike the Near Field, where we're dealing with one or two noise sources, the Reverberant Field has hundreds. But, in a typical performing arts centre of 1,000 seats or more, should we consider all of those "sources"? If we did, the calculation would suggest that the Reverberant Field is very much louder than the Near Field. Is that accurate? Perhaps not.

The discussion up to now has been treating each opening in the floor as a noise source on top of the floor, as if there were hundreds of small loudspeakers underneath the seats. This follows Huygen's Principle and, although it is perfectly valid, it does, as demonstrated, lead to confusion. A subtle but important refinement of the concept is to re-locate the noise source(s) from above the floor in the auditorium down into the plenum below. To compensate, we then consider the Noise Reduction across the slab, where the Noise Reduction of the common partition is calculated as an area ratio combining the concrete floor and the partially blocked pipe. This reduces the discussion about hundreds of noise sources to the simple propagation of sound between two rooms; something every modern acoustical engineer deals with on a daily basis. In other words, the conceptual framework has moved from a rather difficult 17th century physics of acoustics discussion to a much simpler mid 20th century noise control engineering paradigm.

3. MEASUREMENTS

The concept described above was informed and confirmed by measurements in three recently opened venues: the Mississauga Living Arts Centre in Mississauga, Ontario (MLAC), The Esplanade Arts and Heritage Centre in Medicine Hat, Alberta and the Four Seasons Centre for the Performing Arts (FSCPA) in Toronto. Data on the three rooms is shown below in Table 1.

Table 1

Building	City	Volume (m^3)	Type of Diffuser	Plenum lining
The Esplanade	Medicine Hat	5,450	Mushroom	None
MLAC	Mississauga	approx. 13,000	Seat pedestal	100 mm
FSCPA	Toronto	14,000	Seat pedestal	50 mm

3.1 Near Field

The Near Field measurements were performed as follows: a white or pink noise source was

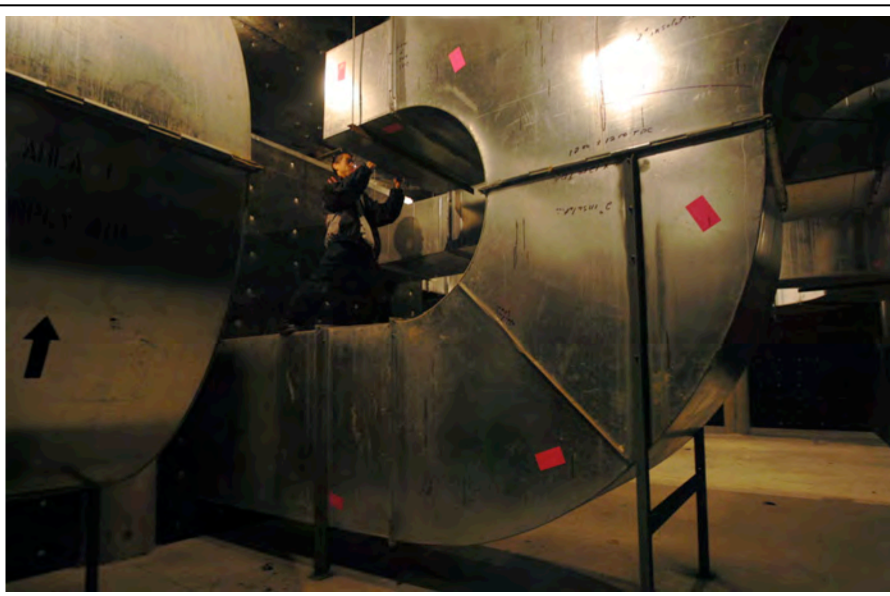

Figure 2. Kiyoshi Kuroiwa performing acoustic measurements in the plenum underneath Hammerson Hall at the Mississauga Living Arts Centre. Mr. Kuroiwa is holding a sound level meter but it is blocked from this view by the duct.

placed either inside or on top of one of the distribution ducts in the plenum, typically about 400 to 500 mm from the slab hole under test. A single measurement was performed on the source side, i.e. on the plenum side of the hole, approximately 75 to 100 mm from the opening. Care was taken not to occlude the hole. A photograph of in-situ measurements is shown in Figure 2.

Three sets of measurements were then performed in the auditorium:

(i) A single measurement at floor level within 25 mm of the slab opening. This is for scientific interest, giving us the clearest description of the physical behaviour of the slab hole, e.g. resonances and the like.

(ii) A single measurement at ear level taken in an occupied seat directly above the slab opening. This is for practical interest as it most closely reflects the conditions experienced by an audience patron.

(iii) A series of measurements throughout the auditorium at progressively further distances from the hole under test. These measurements were used to develop acoustic contour maps.

In all cases, the sound levels measured in the plenum are subtracted from those in the auditorium to give the Noise Reduction between the two rooms.

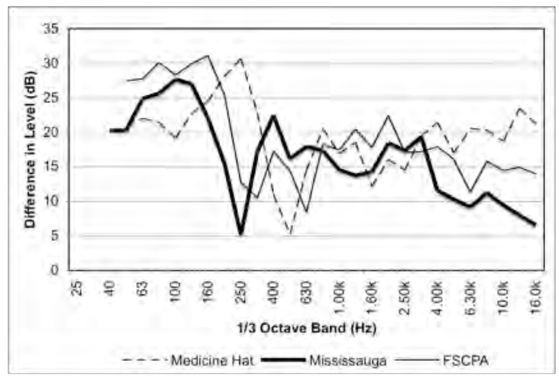

Figure 3. Measured Near Field Noise Reduction from the underside of a slab hole to the diffuser at the floor level immediately above.

Figure 3, Figure 4 and Figure 5 show the results of measurement sets (i) to (iii) respectively. In Figure 3 we see clear signs of pipe resonances, e.g. the dips at 250 Hz, 500 Hz and 630 Hz. In Figure 4, i.e. at the same source location, only at ear level in the seat immediately above, the pipe resonances are still evident but so are the higher frequency barrier effects created by the chairs. Mapping software was developed for measurement set 3, partial results of which are shown in Figure 5.

3.2 Reverberant Field

Reverberant Field measurements were performed as one might perform an in-situ Noise Reduction measurement of a wall or floor. Procedures for this type of measurement are well documented, for example in ASTM E-336 *Standard Test Method for Measurement of Airborne Sound Insulation in Buildings*. The white or pink noise source was placed on the floor of the plenum. Six or more “reverberant field” measurements were performed in the plenum, then again in the auditorium above. The results are shown in Figure 6.

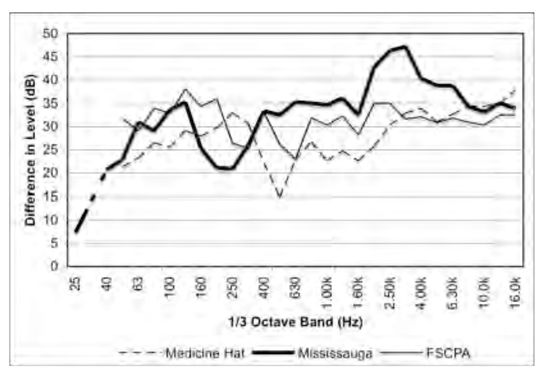

Figure 4. Measured Near Field Noise Reduction between the underside of a slab hole and ear level in the seat directly above.

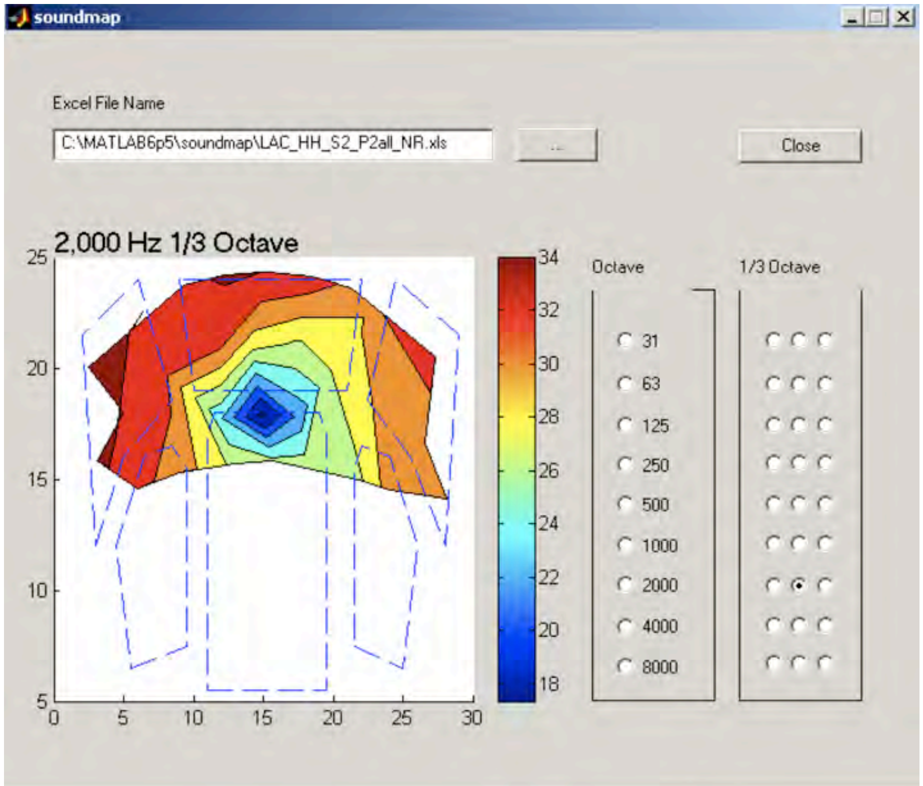

Figure 5. Contour map of Near Field Noise Reduction measurements at the Mississauga Living Arts Centre. The dashed lines indicate the location of seats and aisles on the orchestra level.

3.3 Near vs. Reverberant Field

So which is louder, the Near Field or the Reverberant Field? Measurements to date consistently suggest the latter. Typical results are shown in Figure 7 and Figure 8. At most frequencies, the Noise Reduction (or Difference in Level) for the Reverberant Field is lower than the Near Field. This means that the Reverberant Field will be louder inside the auditorium. The only exceptions occur at what we suspect to be the pipe resonance frequencies. This exception however, is limited in effect and it is a safe 1st order approximation to assume that the prediction algorithm can be limited to the Reverberant Field. This is fortunate because of the two, the Reverberant Field is much easier to calculate.

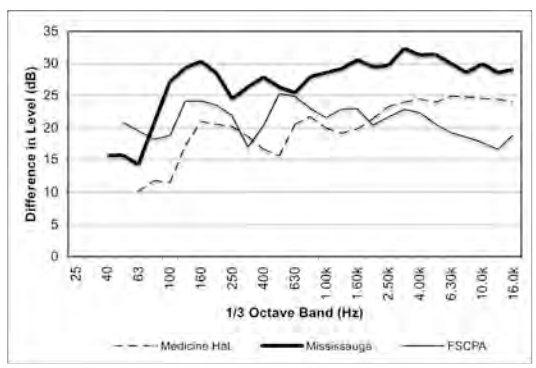

Figure 6. Measured Reverberant Field Noise Reduction between the plenum and the orchestra level.

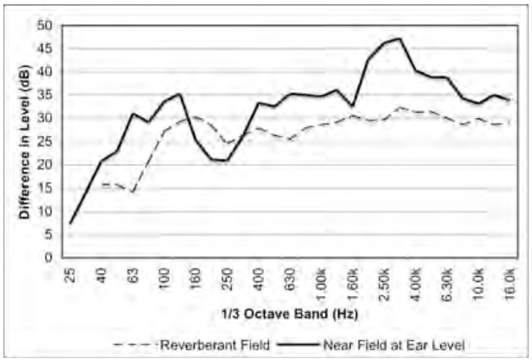

Figure 7. A comparison of Near and Reverberant Field Noise Reduction at the Mississauga Living Arts Centre.

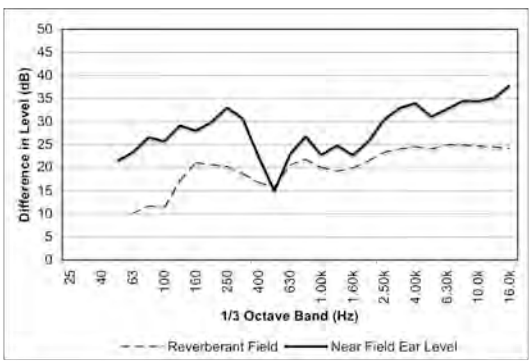

Figure 8. The same comparison as Figure 7, this time in The Esplanade.

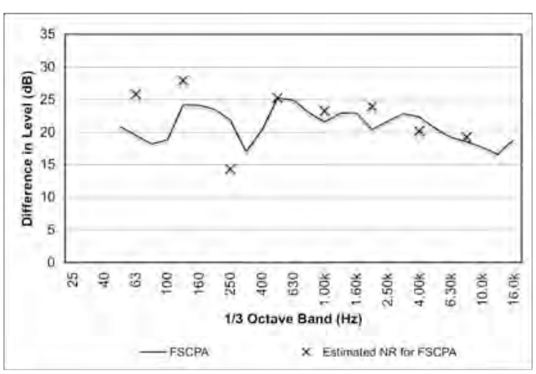

Figure 9. Calculated (X) and measured (–) Reverberant Field Noise Reduction at the Four Seasons Centre for the Performing Arts.

4. VALIDATION

Figure 9 shows a comparison between the calculation procedure described in Section 2 and measurements from Toronto's Four Seasons Centre for Performing Arts. Using the MLAC near field measurements at the diffuser (seen in Figure 3), an area ratio Noise Reduction calculation was performed. The calculation (shown with X's) indicates good agreement with the measurements except at low frequencies, where attenuation is somewhat over-estimated. We suspect that the discrepancies are related to pipe resonances, something we hoping to refine in the next few years.

5. CONCLUSION

A new procedure to both predict and measure the noise control performance of a performing arts centre displacement system has been developed. Two components of the sound field have been considered, which we have called the Near and Reverberant Fields. Measurements indicate that the latter is more important, insofar as noise control is concerned.

There is good agreement between the proposed prediction method and measurements, although the number of measurements, to date, is limited. We encourage others to perform similar measurements and share them with the community.

6. ACKNOWLEDGEMENTS

I would like to thank Bob Essert, who participated in the plenum measurements at the Four Seasons Centre for the Performing Arts. His sage advice on the topic of building noise control and N1 is also greatly appreciated. Kiyoshi Kuroiwa helped out with the measurements at the Mississauga Living Arts Centre and his hard work is, as always, appreciated.