Objective and subjective analysis of acoustical response in newly renovated Palais Moncalm, Quebec City, Canada

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To celebrate 75th anniversary of Palais Montcalm, the building has been almost entirely rebuilt and transformed into the *House of Music*. The main room, named *Salle Raoul-Jobin*, has been designed specifically for the resident chamber orchestra: the *Violons du Roy*. Collaboration between acoustical consultant, Larry S. King, and architect Jacques Plante of MUSE consortium results in a 979 seats concert hall with variable acoustic to accommodate different kinds of musical events. Since reopening in March 2007, the acoustic performance has been enthusiastically acclaimed by professionals, by world known musicians, and by public. Principal reason of this study is to characterize acoustical response of the hall with various adjustments of wall curtains and motorized canopy. Acoustical objective parameters, such as reverberation time, early decay time, impulse response or C80 index will be analyzed and compared to musical subjective perception of few instruments played at multiple positions on stage and for different listening locations.

1 Introduction

In 2003, after an architectural competition, Quebec City administration chose to renovate the *Raoul-Jobin* hall for the special use of classical concerts, which would satisfy needs of resident chamber music orchestra: the *Violons du Roy*. This old Art Deco style theatre has been totally transformed by a group of architects named the MUSE Consortium, composed of three firms, *L'Architecte Jacques Plante*, *Les Architectes Bernard & Cloutier*, and *St-Gelais-Montminy Architectes*, with the support of Larry S. King as acoustical consultant from *JaffeHolden*. The new hall is around 36m long, 23m wide, and 17m high, resulting into a total volume of 11800m^3. The interior height is 3m greater than before reconstruction. This has been made possible by lowering the whole floor, allowing a direct access from the foyer to the back of new stalls. Instead of its large unique and less satisfactory balcony, now the room has two short balconies at the rear and one row of lateral boxes on each of the three levels. The new hall hosts 979 seats, 534 at orchestra level, and 83 in the gallery located behind the stage. This results into a quite large per seat volume of 12m^3. The volume of the room is reduced by the presence of a heavy canopy, whose height can be adjusted between 11.5 and 15.0m above the semicircular stage [1].

To host variety shows and different kinds of classical music, variable acoustic is very helpful. As it can be seen on figures 1 and 2, in addition to the canopy adjustments, heavy velvet curtains can cover most reflective and diffusing walls. Finishes are made of high-density maple veneer, with backspace filled with volcanic sand. The overall appearance of the new hall is particularly successful and harmonizes nicely with the color of stringed instruments.

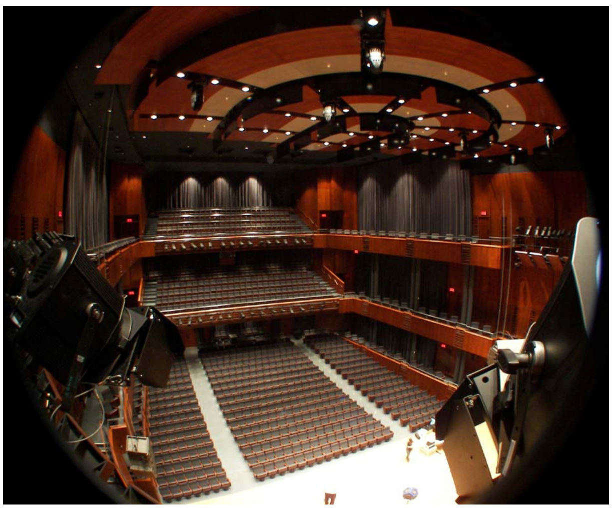

FIG. 1 Picture of the *Raoul-Jobin* hall (configuration #5).

2 Acoustical measurements and instruments

Four days were necessary to complete data acquisitions for the following evaluation criteria:

- Reverberation time, 1/3 octave RT_{60}, 9 measured points, for 5 configurations of the hall (parameters RT_{60} and EDT).
- Impulse response, all pass and 500/1k/2k/4kHz octave bands, 6 measured points for 2 configurations (C80 index and ITDG)
- Pressure distribution, in 1/3 octave and dB(A), 27 measured points for 3 configurations (G_{global} and G_{mid})
- Polar measurements with hypercardioid microphone and TEF program, 500/1k/2kHz octave bands, 5 measured points for 2 configurations (3D patterns and LF).
- Speech transmission index STI, in octave bands (9 measured points for 2 configurations).
- Background noise measurement, in 1/3 octave bands and dB(A), 4 measured points.

Following instruments have been used for acoustical measurements:

- Omnidirectional noise source consisting in a dodecahedron with large band Hi-Fi 8" speakers, 300W_{RMS}, located in the center of the stage (calibrated in laboratory and at 1m in the hall, equalized for linearity control);

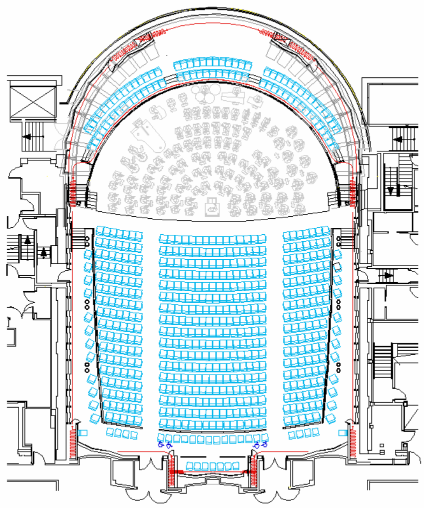

FIG. 2 Plan of orchestra and gallery levels, with movable curtains in red.

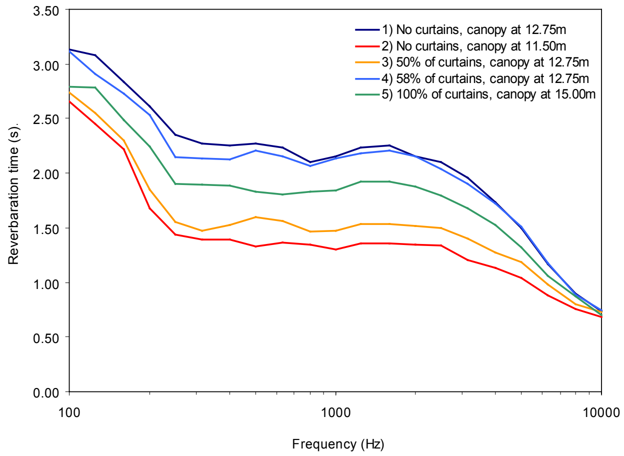

FIG. 3 Average reverberation time spectrums of 5 different configurations.

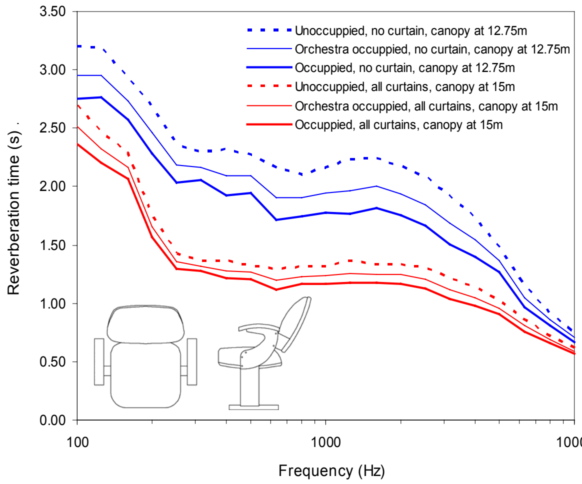

FIG. 4 Reverberation time spectrums depending on occupancy, with 2 configurations. (based on seats absorption)

- Dual channel analyzer from Brüel & Kjaer, model 2133 (1/3 octave spectrums, 1/3 octave RT and impulse responses), with two 1/2" Brüel & Kjaer microphones;
- Brüel & Kjaer sound level meter, model 2260 (1/3 octave spectrum, software for 1/3 octave RT);
- Rion sound level meter, model NL-28 (1/3 octave spectrum);
- TEF-20 analyzer with RT and PET softwares (1/2" microphones, standard and hypercardioid);
- 1/3 octave dual channel filter and generator from Norwegian Electronics, model 719;
- Artificial head with two 1/2" microphones and Fostex VF-16 digital recorder (for binaural recordings).

3 Reverberation analysis

Figure 3 shows RT_{60} obtained in the empty room by 1/3 octave, for 5 configurations of movable curtains coverage and height of canopy, as described in table 1.

Reverberation time is very homogeneous in the hall. For example in configuration 1, maximal standard deviation is only 0.17s in lowest frequencies, and 0.09s on whole spectrum.

Considering that seats are not designed to have the same absorption when occupied or empty, it is possible to calculate the occupancy's impact on reverberation times by a precise determination of the difference between absorption coefficients in laboratory conditions. A sample of 6 seats, disposed as in the hall, has been tested in a reverberant room, occupied or not by students.

TABLE I. Description of 5 different configurations of the hall, with their $RT_{60,\ mid}$ and EDT_{mid}.

Configu-ration	Hall uses	Curtains coverage	Canopy height (m)	RT60 (s)	EDT (s)
1	*"Violons du Roy"*	0 %	12,75	2,20	1,59
2	Small orchestras	0 %	11,50	2,14	1,62
3	Partially occupied	50 % *	12,75	1,85	1,27
4	Amplified sound	57 % **	12,75	1,52	1,14
5	Variety shows	100 %	15,00	1,33	0,92

* Curtains behind stage and all 2nd balcony level.
** Curtains at the back of the hall and all 2nd balcony level.

Figure 4 shows the reverberation time estimated when only orchestra section is occupied or when the hall is fully occupied, with two different configurations (#1 and 5) [16]. Moreover, the real occupied RT is planned to be evaluated in a future study.

Bass ratio has been determined to 1.25, which corresponds to Beranek's recommended values [5].

4 Impulse response

On figure 5, it is possible to observe that in the middle of orchestra, reverberation is very sustained and homogeneous, even if ITDG (initial time delay gap) is relatively long (36ms) [7].

Clarity factor for 80ms (C80) has been calculated from impulse responses in 500 to 2kHz octave bands, for 6 points in the hall, and 2 configurations (values were also positively compared to TEF analyzer results). In configuration #1, which is preferred by the *Violons du Roy*, ITDG = 37.7ms, and mid frequencies C80 = -0.70, while in configuration #5, which is used for variety shows, ITDG = 35.8 ms and mid frequency C80 = -0.14 [6].

Impulse responses have also been used to analyze particular reflections at different positions in the hall, specially at first rows of stalls. Fig. 6 is given as an example at the first row.

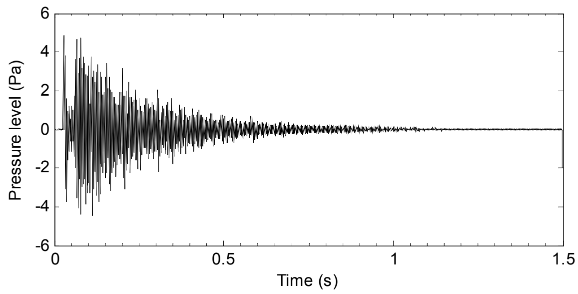

FIG. 5 Impulse response at seat K1 of orchestra, with configuration #3. (all pass)

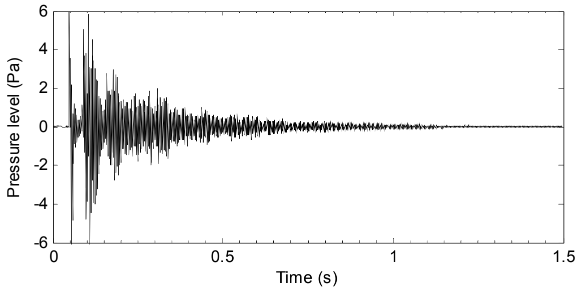

FIG. 6 Impulse response at seat A1 of orchestra, with configuration #1. (all pass)

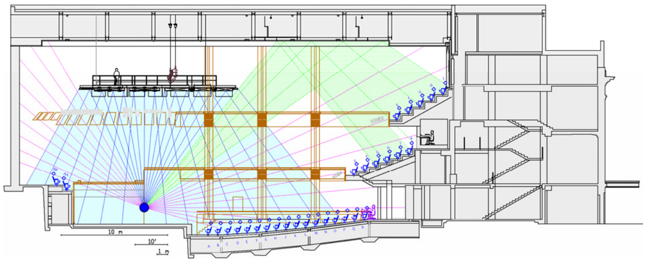

FIG. 7 Cross section of the concert hall, with sound source in the middle of the stage, and with configuration #1.

As it can be seen on the reflectogram of fig. 6 and vertical section of fig. 7, pressure variations happen at this point and match with a first reflection, followed by others, between the horizontal canopy at 12.75m and stage's floor (acoustical propagation distances of 24, 48 and 72m).

5 Sound Pressure distribution

Sound pressure levels have been recorded at 27 points of the hall, for 3 configurations (#1, 2, and 5).

Figure 8 shows the attenuation as a function of the distance from the omnidirectional source, for measured points in the principal axe of the room in configuration #1 (reference level at 1m from source). The attenuation distribution is mapped for two configurations (#1 and 5) on fig. 9.

As it can be noticed without deployed curtains, sound propagation is quite axial, especially near the stage. This will also be confirmed by polar measurements.

If a ratio is made with the free field propagation of the sound source, the strength factor in mid frequencies (G_{mid}) is determined to 5.8dB in configuration #1, and to 2.5dB in configuration #5.

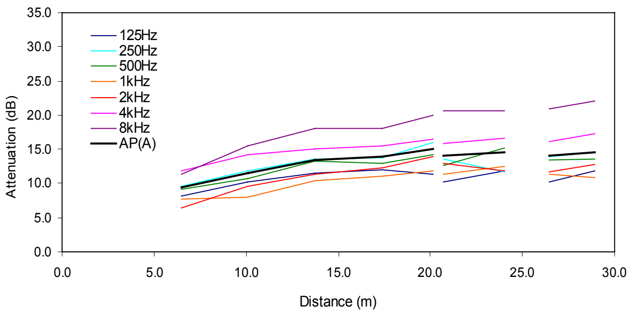

FIG. 8 Attenuation level as a function of distance from the source, for octave bands, in configuration #1.

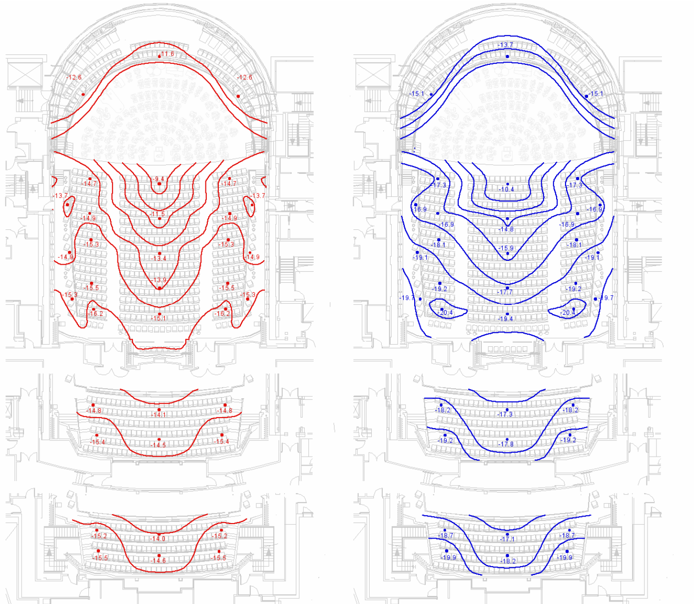

FIG. 9 Attenuation maps in dB(A) (in red for configuration #1, and in blue for #5).

A relation can be established between this value of G_{mid} and the ratio of early decay time to the cubic volume of the hall multiplied by a million ($EDT/V \cdot 10^6$), which equals 134.7. As it can be seen in the literature, the *Palais Montcalm* compares favorably to values of famous concert halls [9].

6 Polar measurements

Polar analyses have been obtained in octave bands (500, 1k, 2k, and 4kHz) with a hypercardioid microphone oriented in 6 orthogonal directions, and compiled with the TEF program, for 5 locations and 2 configurations (#1 and 5). Figure 10 shows an example of three-dimensional pattern obtained in the front of the stalls (seat B1).

Following the decay limit chosen for the computation, the number of reflections identified on the polar plot can be selected. It is possible to read the azimuth and the distance of reflections' origins in addition to their corresponding pressure levels. When the polar plot is rotated, it is also possible to see the axial aspect of the propagation, especially for this location (at seat B1).

Those polar measurements also allow to evaluate average values of lateral fraction (LF), in mid frequencies octave bands [10, 15]. In configuration #1, the average LF is 0.14, while it is 0.07 in configuration #5.

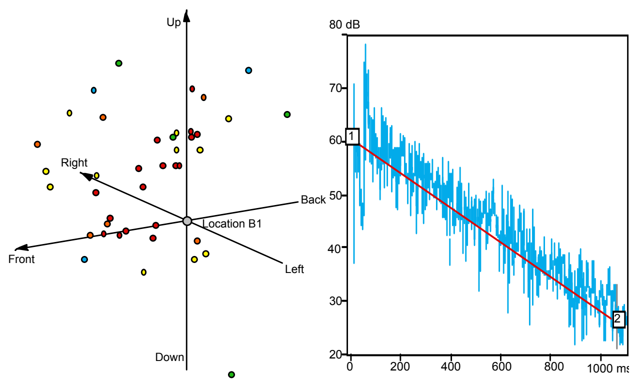

FIG. 10 Polar sound pattern and its corresponding decay computed at seat B1, in configuration #1.

7 Background noise and STI

The background noise has not been considered before because of its very low level, which reaches only an average value of 18.2 dB(A), with 4 measurement points. That is widely under the reference curve of NCB-10 recommended by Beranek [8]. This deep silence level provides an exceptional dynamic, as it is mentioned in concert listening comments.

Speech transmission index (STI) have been measured in octave bands, for 9 positions, and 2 configurations (#1 and 5). This parameter is not usually applied for concert hall analysis, especially with the use of an omnidirectional source. However, obtained values in different points of the hall are partially representative of perceived clarity and intimacy [18]. The average STI results are 0.54 in configuration #1, and 0.60 in configuration #5.

8 Subjective musical evaluation

FIG. 11 Picture of the hall during subjective tests.

In addition to the objectives measurements, a subjective evaluation has allowed to get statistical results of appreciation, accordingly to 9 subjective parameters. This evaluation also revealed preferences about seating positions. Twenty briefed participants compiled their impressions about clarity, reverberation, envelopment, intimacy, loudness, brilliance, warmth, dynamic and their overall impression on 7 steps scales [3]. They heard different music at 8 listening seats. This music consisted in 9 minutes of Bach's Partita nº2 and parts of his Prelude's work, played on a Steinway located center stage. Then, 7 minutes of chamber music's extracts, Beethoven's violin concerto, Marcello's oboe concerto and Bach's harp concerto. Subjective evaluation of background noise wasn't part of the questionnaire because the hall appears to be very quiet without any sound sources.

The most significant results, loudness, intimacy, clarity, and envelopment, appears in fig. 12. Reverberation and warmth aren't shown because the results were very good for these parameters, without significant differences between listening seats. Figure 13 also shows favorites and the less appreciated seats as chosen by the participants. Artificial head recordings were also performed at each listening positions to preserve musical data for further analyses.

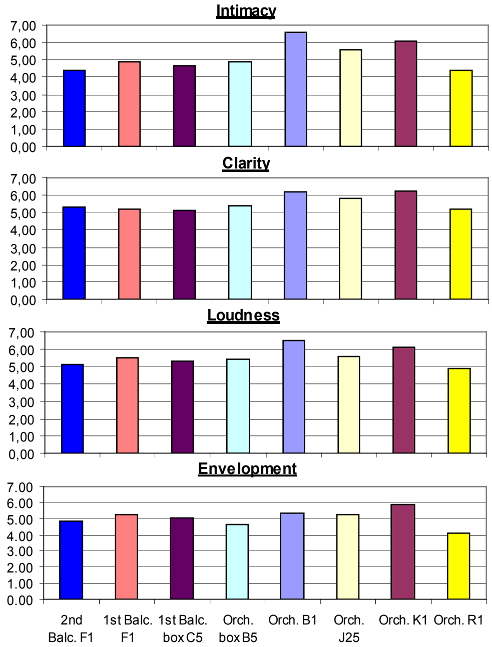

FIG. 12 Results of subjective survey about acoustical quality of the hall, in configuration #3.

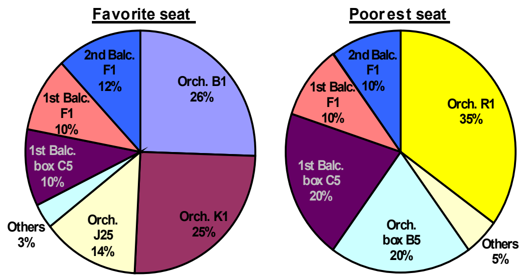

FIG. 13 Results of subjective survey about global appreciation of seats, in configuration #3.

9 Concert listening comments

An extended subjective evaluation, achieved during the actual concert season, allows the compilation of many impressions about the acoustical performances of the hall.

Bela Bartok's Divertimento, 2nd mvt., Molto adagio, 24 musicians, (seat: orch. K10). "Slow basses very agreeable, revealing the whole hall's contribution. This work couldn't be played so brilliantly without the exceptional dynamic allowed by the hall".

Bela Bartok's work for strings, percussion and celesta, 3rd mvt., Adagio, 24 musicians, (seat: orch. K10). "Great clarity. Solo instrument's details well heard because of the hall's dynamic. Grained music".

Franz Schubert's men's choir (16 voices) and string quintet, D714, 2nd mvt, Molto adagio, 24 musicians, (seat: balcony H26). "Nice warmth for low frequencies with unison voices, cellos and bass. Strong presence despite distance. Great hall's reaction about this work. Wonderful sound balance between strings and voices. Nice dynamic, with *ppp* string's soli. Reverberation seems lightly shorter because it was a sold out concert".

Claude Debussy's string quartet, 3rd mvt., Andantino, by *Quatuor Élysée* (seat: orch. box B2). "Interesting exchanges between violins and alto because the precision of the source's recognition. During alto and cello soli, strong merging impression with the hall".

Rachmaninov's Quartet nº2, G minor, 2nd mvt., Andante molto sostenuoto (seat: orch. box B2). "Interesting resonances in the 2nd movement beginning with the impression of listening more than a string quartet, exceptionally powerful hall response" (half occupied hall, lowest position of the canopy).

Mendelssohn's Quartet opº13, A minor, (seat: orch. S4). "Orchestra subjective image more focused with distancing effect. Relative fullness and envelopment of the low frequencies (less exceptional than in the front of the hall)".

Robert Schuman's A minor string quartet, orchestra version by Bernard Labadie, 16 musicians (seat: orch. box B1). "Very nice Andante with large and long reverberation but without echo from the hall's back. Exceptional orchestra ensemble during Scherzo. In the Adagio, the orchestra seems to occupy the entire width of the stage. During the Presto finale, the hall procures its own life to the music. It is easy to share the enthusiasm of Maestro Labadie".

10 Conclusion

Reverberation times measured in the *Raoul-Jobin* hall are very homogeneous in all parts of the hall and their mid values can be adjusted between 1.3 to 2.2 seconds. This is remarkable for a very simple curtains adjustment system. *Violons du Roy*'s concerts are generally given with the longest reverberation time (configuration #1). It can be noted that in this condition mid RT value decrease to 1.8s when the hall is fully occupied. This point has already been mentioned in musical comments. The hall is warm with a good support for the low frequencies, certainly in relation with the construction quality of the reflecting wood panels. The listener envelope is very interesting and clearly perceived, while leaving enough clarity and intimacy perceptions (C80 values are quite acceptable).

For most locations impulse responses are very clean, especially in the middle of the stalls. ITDG index meets standard values, but could be a little bit shorter with more first reflections effect.

Subjective tests conducted for 8 different locations with short musical samples have given very interesting results. They indicate great coherence in the evaluation of suggested performance parameters, and a clear classification of the different locations in the hall, except erratic opinions concerning lateral boxes.

Finally, after one season of concerts, musical comments confirm the acoustical qualities of the hall for different kinds of music: piano solo, small chamber ensembles, voices, or more important orchestra, with various instruments and percussions.

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