Acoustical analysis of a variable roof configuration concert hall: The São Paulo hall

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The Sala São Paulo (Sao Paulo Hall) is recognized by musicians and musical critics in general by its good acoustical quality. It has a variable acoustics due to its movable roof, which is employed by musicians to tune the room according to the musical style, in an *ad hoc* procedure. This work addresses the acoustical quality of Sala São Paulo and its dependence on the roof configuration. Impulse responses for one source, eight microphone and two dummy head positions, using the sweep sine technique with pre-emphasis, were obtained for seven roof configurations. Some details of the measurement procedure to ensure good accuracy are discussed. The measurement results were then used to compute the main room acoustical quality parameters, for each octave band between 63 Hz and 8 kHz. The spatial average and deviation of these data are presented as a function of the frequency band. The influence of the roof configurations on the obtained acoustical parameters is also discussed. Furthermore, comparative plots among Sala São Paulo and two representative halls from the classical and romantic periods are reported and discussed.

1 Introduction

Built with geometrical dimensions similar to that of some famous concert halls of the romantic period, the Sala São Paulo (SSP) possesses the characteristics of good sound diffusion due to its ornamentation, plenty of columns, niches, balconies and other diffusion elements, as can be seen in Fig. 1. It is considered by critics, musicians, and other music appraisers as a hall with excellent acoustics, as expressed by the conductor Alceo Bocchino: "...if you want to know which is the best acoustics that I have experienced, I will tell you: One of it was that of the Concertgebouw, in Amsterdam, where you can hear the breath of the world greatest flautist ... and the other one was that of the Sala São Paulo, an excellent acoustics..." [1].

The SSP is architectonically conceived with an essentially rectangular geometry, with 48.5 m length, 21.0 m wide and 24.5 m maximum height, occupying an area of 1100 m^2. There are 1509 seats distributed among the main floor, several balconies and choir, the last ones depending on the kind of performance. The fundamental project's technical aspect — for the objective of this work — was the designer's decision to provide the hall with a movable roof, allowing to modify its shape, volume, and acoustical characteristics. The roof consists of 45 rectangular plates organized in a matrix of 5×9 with each group of three plates moving independently. Since there are 15 roof elements that can be displaced in a range of 20 meters, a great diversity of volumes and forms are available to tune the room according to the musical performance options.

The musical performance experience in SSP has shown that this feature is commonly employed, in an *ad hoc* process, following the musicians feeling — with some success — instead of any "scientific" methodology. This work intends to verify how effective the change in the acoustical parameters are with the different roof configurations, trying to put into acoustical terms what has been done in practice at Sala São Paulo.

Figure 1: The Sala São Paulo stage with OSESP. Observe the movable roof plates.

2 Roof configurations

Seven roof configurations, called here as A, B, C, D, E, F, and M were studied. They can be divided into three groups. The first group (roof configurations A, B, and F), features configurations that — as far as we know — have never been used in concert situations in SSP. It includes the maximum room volume (A) and the minimum room volume (F), among other possible configurations. These configurations were predetermined by the authors. The second group (C, D, and E) includes intermediary roof configurations that have been used recently in the roof for different styles of music performances. The movable roof has a numerical control system and all musical performance and corresponding roof configuration are stored in the computer data bank. The third group consists of roof configuration M, which was used to measure the binaural impulse response at the seat used by SSP artistic director when he is not conducting the orchestra by himself. The configurations choice, made in a somewhat *ad hoc* process by the authors, provides a reasonable spread of situations among the almost infinite possibilities offered by SSP.

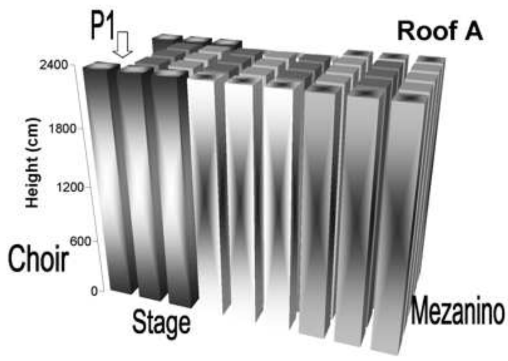

Figure 2: Roof configuration A

Figure 2 illustrates the available space in the room for the roof configuration A. The vertical bars indicate the air volume over the audience, under each movable plate. In this configuration, the overall room volume is maximum. The roof surface is plane and horizontal, at a height of 23.7 m over the stage. The only exception is the group of three plates P1 (at left, in the figure) that, due to a mechanical restriction, is limited to a level of 20.1 m.

3 Acoustical measurements

The measurement procedure worked, shortly, as follows. Once the sound source had been positioned — on stage, near to the stage center, at the point maked with the letter F on Fig. 3 — and microphones and the dummy head were put at previously selected seats, the room was excited three times with a pre-emphasized sweep sine signal [2], to later perform a synchronous average. Then, the microphone positions were changed, until all

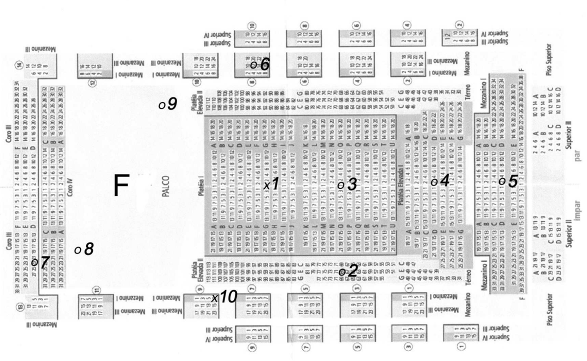

Figure 3: Diagram of the ten measurement positions. Points marked with 'X' are dummy head positions.

positions shown in Fig. 3 were covered. In total, eight microphone and two dummy head positions were evaluated, as shown. The microphone height corresponded to that of the pinna of a seated person. The impulse responses obtained were then stored for post processing and determination of decay curves and room acoustic parameters computation: T_{30}, EDT, C_{80}, CT and BR, following the ISO 3382 standard [3]. Binaural impulse response were also recorded at the dummy head positions. The procedure was repeated for each one of the tested roof configurations.

3.1 Choice of excitation signal type

The desire to use the captured binaural RIRs in posterior convolutions made the use of sweeps as excitation signal indispensable. As has been revealed before [4], they allow the elimination of harmonic distortion products from the RIR which are always present and caused by the non-linearities of the measurement loudspeaker. In contrast, if the stimulus is a pseudo-random noise signal, such as an MLS, the distortion products are homogeneously distributed over the entire IR period [5]. At calm sites, the noise floor induced by distortion artifacts can easily dominate the overall noise floor and limit the SNR of real-world RIR measurements with pseudo-noise signals to something in the range of 60-70 dB. In measurements with sweeps as the excitation signal, the obtainable SNR almost exclusively depends on the real interfering noise level. Since all harmonic distortion products can be completely excluded from the IR, the sweep level can approach the maximum that can be tolerated by the loudspeaker.

3.2 Measurement techniques

To obtain the RIRs, a circular deconvolution was applied. While a linear deconvolution is more adequate for non-periodic sweep measurements because it allows for easier elimination of the distortion artifacts, the circular deconvolution is equally well suited if the sweep length is considerably longer than the RT.

The necessary reference spectrum of FFT order 19 has been created together with the excitation sweep. Its modulus consists of the inverse pre-emphasis curve, while its group delay takes the opposite course of the excitation sweeps' group delay. Additionally, a band-pass filter has been applied to defeat noise outside the sweep's frequency range, resulting in the reference spectrum response. During the measurements, this reference spectrum is multiplied with the FFT of the captured sweep response, resulting in the room transfer function. An IFFT finally yields the RIR, from which noise and distortion artifacts can be removed.

3.3 Measurement equipment

The measurement system was the ModulITA, conceived by the Institute of Technical Acoustics at the University of Aachen. It is a remote-controlled modular 4 channel ADC/DAC rack system with integrated preamplifiers, transducer supplies, power amplifier and PC interface for full duplex audio data transfer. The receivers were a dummy head [6] made by the same institution, equipped with phantom-powered 1/2" condenser microphone capsules (Schoeps), and two diffuse-field compensated 1/2" condenser microphones from Larson-Davis, type 2559. The subwoofer, composed of a Selenium WPU1205 12" PA driver, was fed from an external power amplifier.

At each combination of microphone positions, three to six sweeps were emitted and each response stored to disk. Later, the results were summed up (by complex addition of the room transfer functions). Separately recording each sweep response made it possible to exclude from the averaging process those whose SNR was lower due to railway traffic in the nearby station or other transient noise sources. In contrast, performing synchronous averaging already in the data acquisition phase would have meant that many measurements would have to be interrupted and discarded when sudden transient noise appeared.

The typical SNR was about 75 dB for a single measurement. For most positions, three shots were used and summed up in the post-processing, yielding around 80 dB of SNR.

4 Main findings

The first aspect to bring to evidence is the dependence of the obtained results, for some roof configuration, with respect to the seat position, that means, its spatial deviation. Then, the influence of roof configurations on the spatial average of some acoustical parameters is presented.

4.1 Spatial Deviation

Figures 4 to 7 show the acoustical parameters T_{30}, EDT, C_{80}, and CT, obtained from the IR's filtered in octave bands from 63 Hz to 8 kHz, at six microphone positions, for the roof configuration C. The results of the spatial deviation are very similar to those for other roof configurations. A curve indicating the spatial average is also presented.

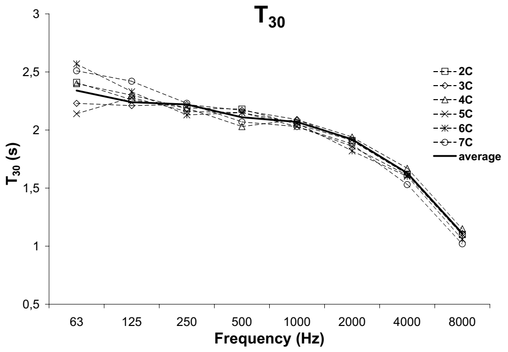

Figure 4: T_{30} for several mic. positions at roof C.

The plot of T_{30} versus frequency for six different microphone positions, Fig. 4, shows a small spatial deviation for all frequency bands, except for 63 Hz, which indicates a rather good sound diffusion in the hall. In the 63 Hz octave band, diverging results were expected since the room modal characteristics prevail at this frequency and the reverberation time is strongly dependent on the hearing position [7].

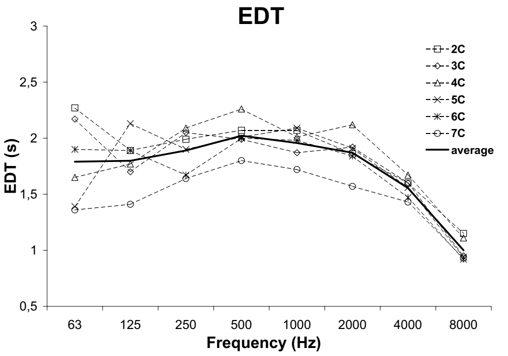

Figure 5: EDT for several mic. positions at roof C.

Looking at the plot of EDT at different microphone positions, Fig. 5, it can be noted that a greater dispersion was obtained due to the influence of the first reflections at each seat position [8]. In fact, an EDT value of 1.8 s at mic. 7 (choir position) and 2.3 s at mic. 4 (elevated audience position) has been measured in the 500 Hz octave band. A similar behavior, for T_{30} and EDT parameters, was found for the other roof configurations.

Figure 6 shows the plot of C_{80}. It can be observed that the variation with frequency is rather small, except at the very high end, but there is a strong dependence on the seat position. The maximum clarity index at 1 kHz was 1.0 dB, at seat 12 in box 8 (mic. 6) and the minimum value at the same frequency was −2.2 dB, at

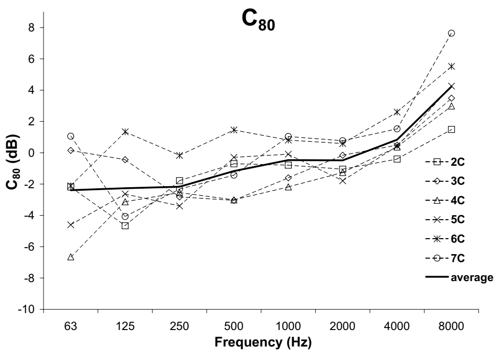

Figure 6: C_{80} for several mic. positions at roof C.

seat 2D, in the elevated part of the audience (mic. 4).

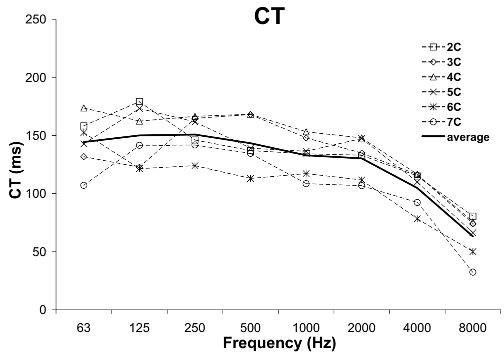

Figure 7: CT for several mic. positions at roof C.

The CT plot, on Fig. 7, corroborates the fact that microphone positions 6 and 7, with high clarity index, are those that present the smallest value of CT, as usual. As can be seen, there is significant dispersion of the values obtained.

4.2 Roof Configuration Dependence

The most important aspect to be considered in this work is the dependence of the parameters spatial average with regard to the roof configuration.

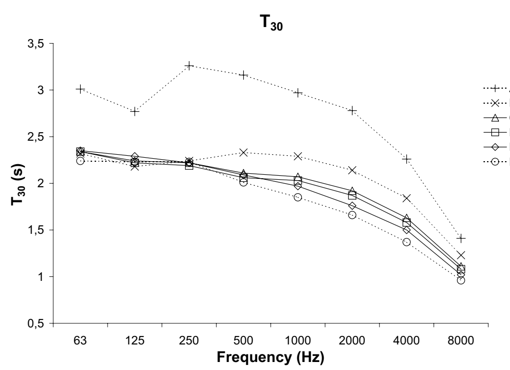

Figure 8: Spatial average of T_{30} for several roof configurations, as a function of frequency.

Figure 8 shows the plot of T_{30} for the chosen roof configurations (A–F) as a function of frequency. In the octave band of 250 Hz, for instance, a reverberation time

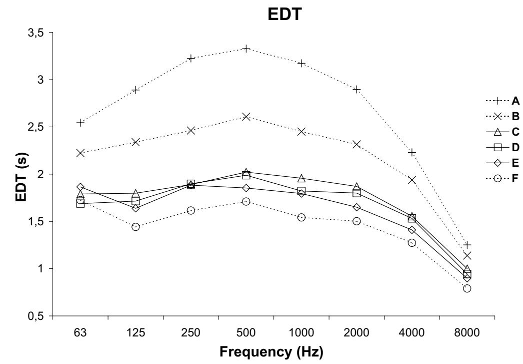

Figure 9: Spatial average of EDT for several roof configurations, as a function of frequency.

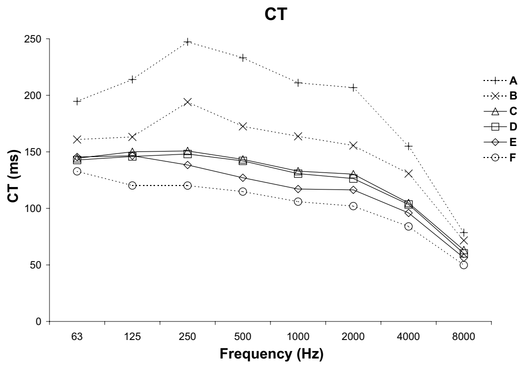

Figure 11: Spatial average of centertime for several roof configurations, as a function of frequency.

of 3.3 s has been detected for roof configuration A, constituting the highest volume. For 1 kHz, a value of 2.4 s was found for roof configuration B, the second highest in volume. It is worth noting that, except for configuration A, the plots are close one to another, mainly at the lower frequency range. This means that — except for roof configuration A — there is only a small sensibility of reverberation time with respect to the roof configurations.

As can be seen in Fig. 9, the EDT parameter is much more sensitive to the roof configurations. For 500 Hz, for instance, the following EDT values, in seconds, were obtained: A, 3.4; B, 2.5; C and D, 2.1; E, 1.8; and F, 1.6. Since the EDT is an important parameter for subjective musical appreciation [9], this sensibility seems to be the main responsible for the efficacy of Sala São Paulo tuning by using the movable roof.

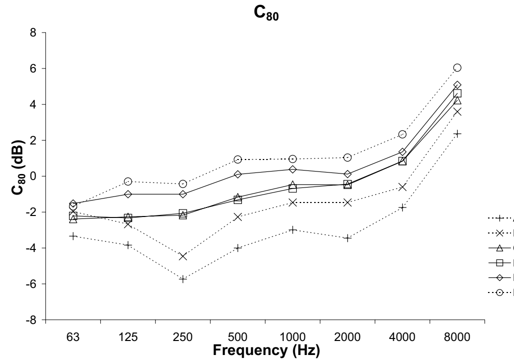

Figure 10: Spatial average of C_{80} for several roof configurations, as a function of frequency.

The comparative values for the clarity index, C_{80}, are presented in Fig. 10. Again, the room presents a good sensibility of the parameter with respect to changes of roof configuration. For instance, at 500 Hz, the differences are higher than 4 dB. The curves follow, consistently, the room volume reduction, presenting more clarity for small volumes, as expected.

The results for the center time, CT, are show in Fig. 11. It can be seen that, at 1 kHz, the values remain between 106 ms (F) and 211 ms (A), a relationship of almost 2:1. As happens with the other parameters, the center time accompanies the room volume variation.

The values obtained for the bass ratio, BR, for the six roof configurations are show in Fig. 12. Except for roof B, the bass ratio varies inversely with the room volume. For intermediary configurations, used in concerts, BR stays around 1.1.

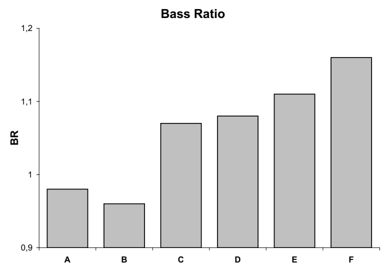

Figure 12: Bass ratio for several roof configurations, as a function of frequency.

As can be noted in Figs. 4–12, except for T_{30}, all acoustical parameters (its spatial average) present a good and consistent variability with respect to changes of roof configuration, meaning that this feature is indeed efficient to modify the room acoustics characteristics, making the Sala São Paulo suitable for distinct musical interpretative options.

5 Comparative results

The musical appreciation in the 20^{th} century pointed to the romantic production as the greatest in quality level. As a consequence, rooms for music performance built in this century take the romantic concert halls as a model to be pursued. However, these rooms could be not ideal, for instance, to perform other interpretative options or even musical compositions from the classical or baroque period. It is thus of interest to verify the range of variation of the acoustical attributes of Sala São Paulo and compare them at least to a representative hall from the classical period and another from the romantic one.

The plot on Fig. 13 shows that the values of T_{30} obtained for roof A are very close to those of the romantic hall. Its acoustical parameters are a standard goal pursued in the design and construction of contemporary concert halls [10]. For the other roof configurations the curves are located between those of the romantic and classical halls, approaching the last one — but never reaching it — when the room volume decreases.

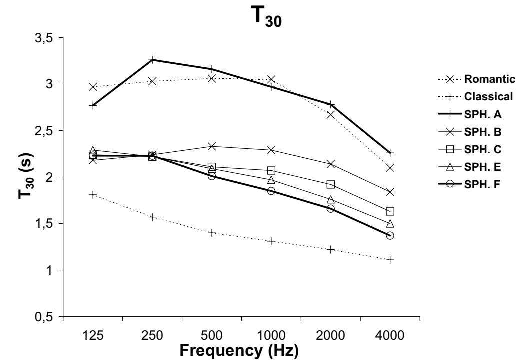

Figure 13: Comparison of T_{30} for Sala São Paulo at five roof configurations and halls of the classical and romantic periods, as a function of frequency.

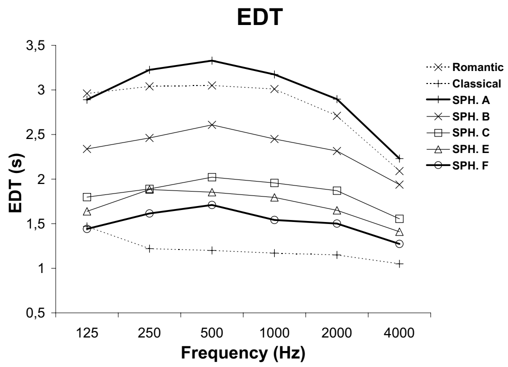

Figure 14: Comparison of EDT for Sala São Paulo at five roof configurations and halls of the classical and romantic periods, as a function of frequency.

The wider range of values observed in the EDT plot, Fig. 14, puts in evidence the versatility of Sala São Paulo. As a matter of fact, the values of roof configuration A are all higher than those of the romantic hall, while in the other roof configurations the parameter decreases, with the values for roof F closer to the classical hall curve. This result let us conclude that tuning this hall for different music styles or even musical interpretation by moving the roof is quite effective.

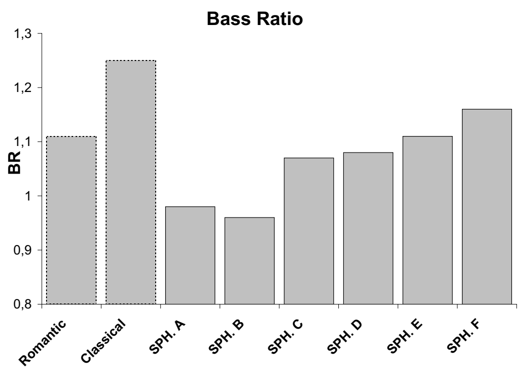

Figure 15: Comparison of BR for sala São Paulo and halls of the classical and romantic periods.

In the Bass Ratio plot, presented in Fig. 15, it is shown, differently from the other presented results, that for this parameter, the roof configurations used in concerts (C, D and E) are those that yield values closer to the one of the romantic hall. With these three roof conditions, the BR values are near to 1.1, the same value presented by the romantic hall. The classical hall shows a higher value for this parameter, 1.25, which none of the tested roof configuration of Sala São Paulo reaches. This acoustical parameter is associated with the subjective attribute of warmth, due to the stronger hall response at lower frequencies. The roof configuration F presents a BR value closer to the classical hall, just under 1.2.

6 Conclusions

In comparison with other recognized halls, built in two different musical periods, the versatility of Sala São Paulo to supply the required acoustical characteristics for distinct musical interpretation styles was verified. Depending on the roof configuration, the hall can assume acoustical parameters very close to the ones of romantic halls, as well as to approximate, although not so close, classical ones.

The movable roof of Sala São Paulo is an important facility to tune the hall in a very efficient way. The authors believe that, at present time, musicians experience with this feature is still insufficient to extract all possibilities from the hall. Many other roof configurations will be certainly tested and we hope that this research can offer aid for the success of musical performance at the Sala São Paulo.

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