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Practical and accurate room acoustical measurements in large indoor multipurpose halls and measures to optimize acoustics

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ABSTRACT

This paper presents practical ways to perform accurate room acoustical measurements, particularly of echoes in large indoor multipurpose halls, and describes provisions to obtain good acoustics. It is based on recent experience acquired at the “Palais des Sports Paris-Bercy”, POPB, and similar European stadiums.

POPB is one of Europe's major indoor stadiums with a seating capacity of about 17 000 persons. After 30 years of use, a major renovation takes place. This multipurpose hall is home to a wide range of activities such as music concerts, sports events (tennis, motocross, ice skating, basketball, etc.), and political rallies.

The paper focuses on the acoustical characteristics of the main hall of the POPB. Different acoustical measurements (reverberation time, background noise level, quasi-impulse responses with a highly directional speaker) have been performed in order to investigate the existing characteristics. Solutions to improve acoustics in the design phase are presented.

The acoustical characteristics encountered at POPB being typical of large indoor multipurpose halls, the measurement method and the acoustical treatments can be applied in similar halls.

1. INTRODUCTION

Through different renovation projects, an approach for improving acoustics in large indoor halls has been developed. This approach consists firstly in assessing the reverberation time and secondly, in investigating reflections by use of a highly directive speaker and a quasi-impulse signal. The details of this approach and the results in the case of the POPB are presented hereafter.

The major renovation of the POPB stadium includes substantial changes of the main hall. All seats will be renewed, parts of the tiered seats will be lifted for better angle of view and new rooms will be built within the volume of the hall.

The POPB stadium has large dimensions: length 135 m, width 95 m, volume ca. 245 000 m^3. A permanent electro-acoustic system is used for Public Address while music events use their own

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sound system. In order to maximize the intelligibility of speech and quality of music, the influence of the hall on the produced sound signal should be as little as possible. Hence, optimal distribution of sound reflections is necessary as well as elimination of echoes. Large amounts of sound absorption are therefore required, with the consequence that the reverberation time is limited in the same time.

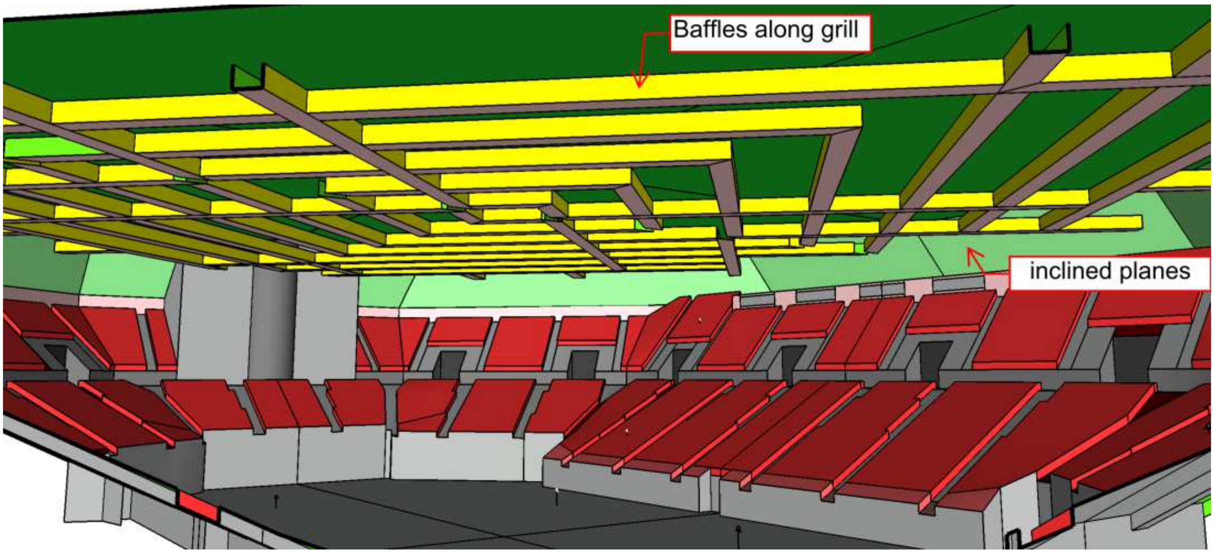

Figure 1 - Sound absorbing (in color) and reflecting surfaces (in gray)

The actual hall already has extensive sound absorbing surfaces: the corrugated steel roof is perforated, the inclined planes are entirely covered with mineral wool back perforated sheet and a considerable quantity of baffles is mounted in the grill.

The first step of the investigation consisted in measuring the reverberation time in unseated condition. As large halls often have strong late reflections, measurements using a highly directive sound source radiating a quasi-impulse signal were performed in order to detect the possible presence of echoes and their origins. The advantage of using a directional source is to be able to aim at possible echo-generating surfaces to test, where echoic reflections occur.

Echoes could be observed subjectively. Therefore, an analysis of room responses to the quasi-impulses was performed to obtain better knowledge of their amount, intensity and origin. As a result, measures to eliminate the echoes were dimensioned and included as far as possible in the new design of the main hall.

2. MEASURING REVERBERATION TIME

The reverberation time was measured as T_{30} at several positions and spatially averaged in the unseated situation and on stage in a typical concert set-up.

These reverberation times have a rather flat characteristic at around 2.7 seconds in the octave bands 125 Hz to 2000 Hz with a steep drop in frequency bands above 2000 Hz, as shown in Fig. 1.

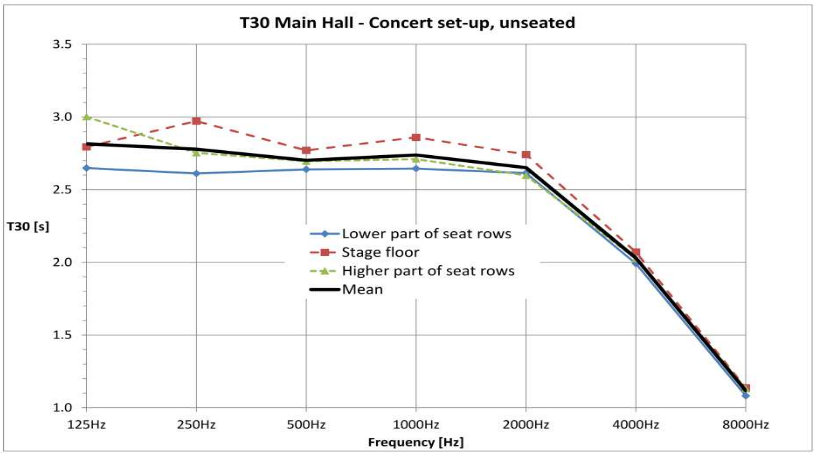

Figure 2 – Measured T_{30} (unseated, concert set-up)

At a first glance, acoustical conditions for amplified music seem to be fair with a flat reverberation time over a comparatively wide frequency range.

According to Lautenbach et al. [1], the optimal reverberation time in large indoor halls in unseated situation can be roughly estimated by:

$$T_{60} = 0.038V^{0.325}$$

The background of this formula is, that first order reflections must be reduced by 10 dB at least to avoid echoes from far surfaces.

With a volume of ca. 245 000 m^3, the main hall should have a reverberation time around 2.1 seconds according to this formula. Hence, the measured reverberation time is about a third above the optimum value for good acoustics.

From the reverberation time point of view, one can therefore conclude that the main hall offers in unseated state fair acoustical conditions already before additional measures.

Obtaining optimal acoustical conditions in terms of reverberation time by reaching a value of ca. 2.1 s in the frequency bands 125 Hz – 2000 Hz in unseated state would require extra absorption of ca. 4200 m^2 “open window” (Sabins) in the hall. Absorption is frequency-dependent. Taking 0.7 as a practically reachable absorption factor for 125 Hz, shortening the reverberation time in the lower frequency range, which is desirable for amplified music, would represent ca. 6000 m^2 of additional low frequency sound absorbing material in the hall. Reducing reverberation time further appears then to be definitely a large scale affair, in terms of material and costs.

In seated state, the reverberation time will exhibit an extra decrease above ca. 250 Hz. The importance of the slope will vary accordingly with the size of the audience.

3. MEASURING ECHOES

Because of their dimensions, reflections in large halls have mostly long delay times. Often such large halls suffer from strong late reflections that reduce clarity of music and speech intelligibility. The main hall of the POPB was therefore investigated for the presence of such adverse reflections in unseated state.

For measuring possible echoes a quasi-impulse signal was sent out with a highly directive speaker at specific source locations towards different directions. The quasi-impulse technique allows subjectively to detect audible echoes on-site at once, given the time delay between the direct and the reflected sound is sufficiently long. The high directivity of the chosen speaker enables, to a certain degree, to select the surfaces that are especially causing strong reflections and to check whether these excite echoes.

3.1 Directivity of the speaker

The speaker used for the echo detection measurements is a horn driver Paso UT-60 with a large-format (1.2 m long) exponential horn and circularly symmetrical bell (0.55 m diameter), having consequently a rotationally symmetric directivity pattern. The directivity of this speaker is determined using “MLSSA” (based on Maximum Length Sequence approach) with the set-up shown in the figure below (left). The obtained directivity pattern is presented in the polar plot in the same figure (right). For the calculation of the directivity, the impulse responses were evaluated until the moment the first surface reflection arrived.

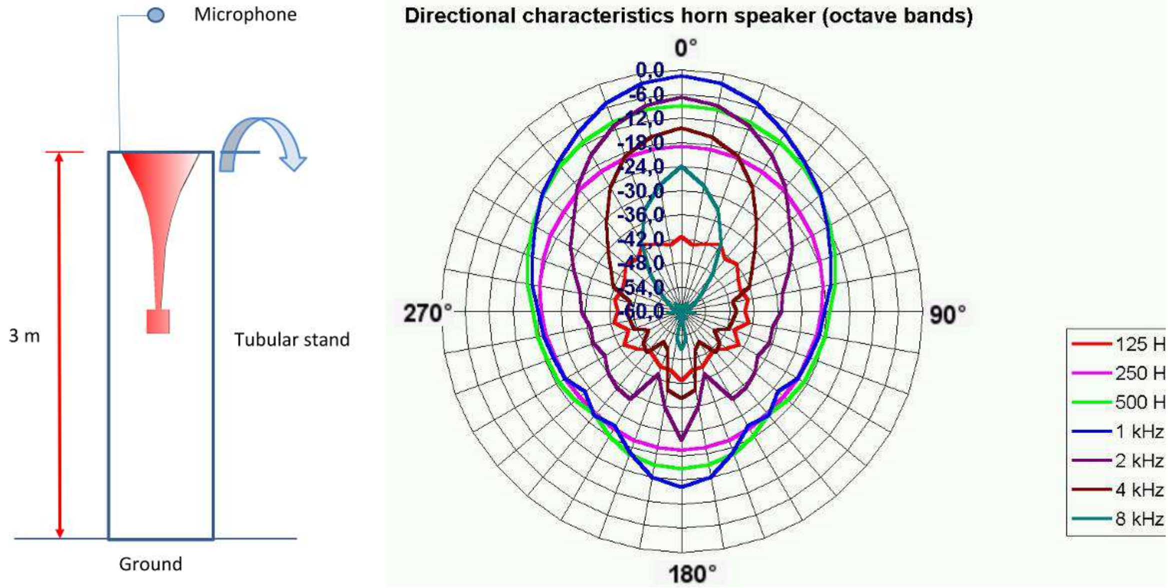

Figure 3 – Schematic set-up of directivity measurements and polar plot of directivity pattern

The resulting directivity pattern exhibits a strong longitudinal directivity of ca. 45° (-6 dB) with a side damping of ca. 20 dB and a rear lobe of ca. -22 dB, resulting in a Q-factor of 17 and a directivity index (DI) of approximately 12 dB at 1 kHz. The frequency spectrum of the horn speaker covers the range from ca. 200 – 10 000 Hz (+/- 6 dB).

3.2 Characteristics of the stimulus: quasi-impulse room response excitation signal

As stimulus to excite and to subjectively detect possible echoes in a room, a signal is needed which fulfills the following demands:

1) it is a transient signal, repeated with a periodicity larger than the reverberation time of the room,
2) that is short enough not to blur the possible echo (i.e. ≤ 5 ms),
3) but at the same time carries enough power,
4) and covers a broad frequency band.
5) Finally, it should be possible to feed this signal with maximum possible amplitude through power amplifier and directional source without being in danger to spoil the waveform seriously due to clipping effects or damage amplifier or speaker.

For this purpose a ‘click’ generator Alphaton PC 100 was used. Its quasi-impulse signal (‘click’) was sampled and normalized to a level 0 dB re. full-scale. The waveform of this quasi-impulse signal basically consists of a single square pulse concentrating the sound energy within a time interval of 5 ms, followed by a longer low-level double settling pattern (resulting from the analogue generating circuit). Its time response and spectral content are shown in figure 4, exhibiting a global 6 dB/octave spectral decay.

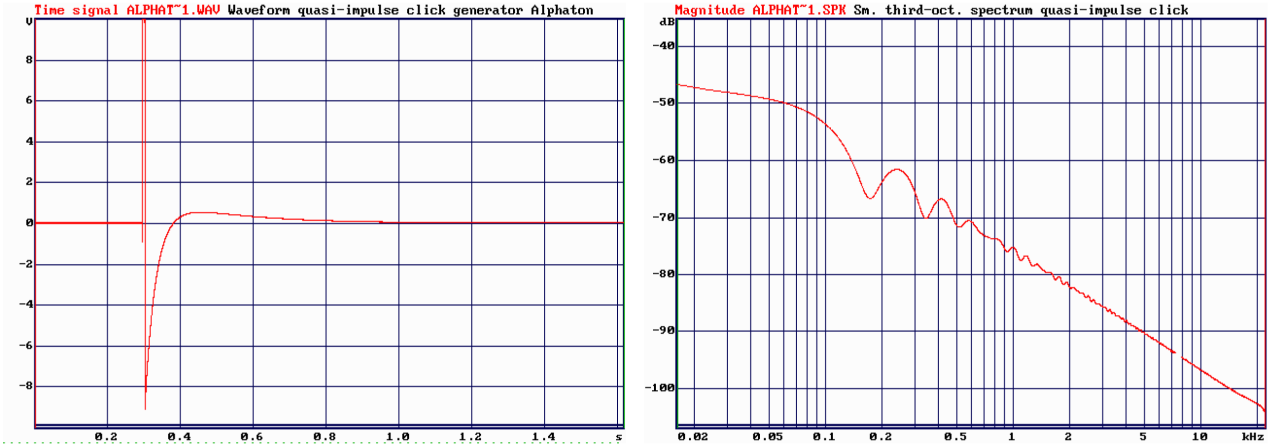

Figure 4 – Echo stimulus: waveform (left) and smoothed third octave band spectrum (right)

3.3 Measurement set-up

The directional speaker should be positioned in order to simulate the situation to investigate. In the case of POPB, it was decided to examine the concert situation with the stage at one end of the stadium. The quasi-impulse stimulus was fed to the directional speaker via the power amplifier Alesis RA 150 with maximum possible level and measured at different receiver positions. The horn speaker was placed horizontally where the left line array normally is positioned, and vertically approximately at the middle of the height of the array at the same time. It was aimed at different surfaces by modifying the pointing angle to:

1. The roof (90°): No echoes were audible, which is valuable information.
2. The tiered seats (ca. 45° to 120°): Hundreds of reflections could be heard and measured, but no isolated strong reflection or single strong echo was observed.
3. The end pillar and flat surfaces beside: echoes became clearly audible. These surfaces, being made of steel sandwich panels, are highly reflective for a wide range of frequencies.

The directional speaker was kept in position 3, pointing toward the pillar and the flat surfaces for the subsequent measurements.

An omni-directional pressure microphone was placed at the sound engineer's position (FOH, point 1) and at the middle position of the stage where usually the singer is located (point 2). These positions had been indicated by the sound engineers as "*difficult to get tight bass*" and "*too much return from the hall*". Four other positions in the tiered seats were chosen by walking around in the hall while subjectively listening to the impulse signal and the reflections, see figures 5 and 6.

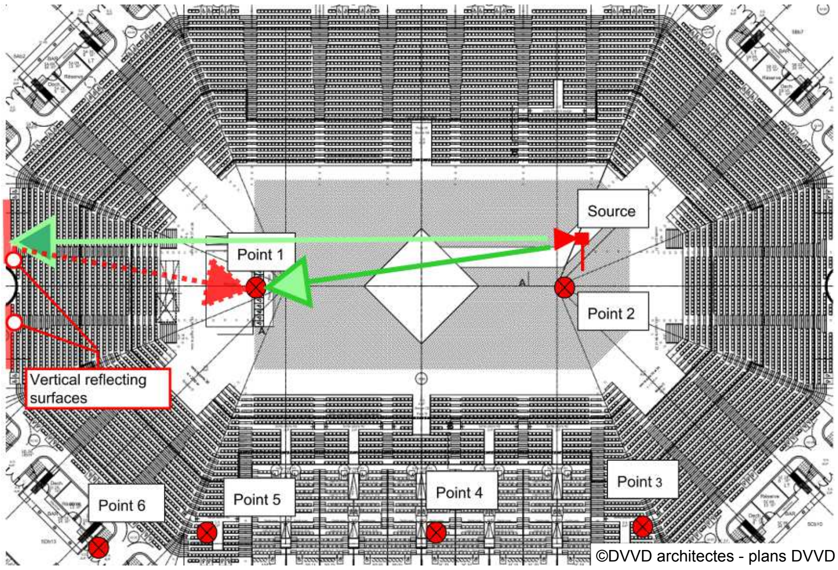

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Figure 5 – Source and microphone positions for measurements

Figure 6 – Speaker and reflecting surfaces

3.4 Analysis of the quasi-impulse measurements

A rough broad-band identification of echo effects is possible by subjectively listening to the wav-files. A first broad-band time delay analysis is possible in the oscillogram view of e.g. audio edit software packages. In figure 7 the identified echoes (level and delay) are plotted against a threshold curve.

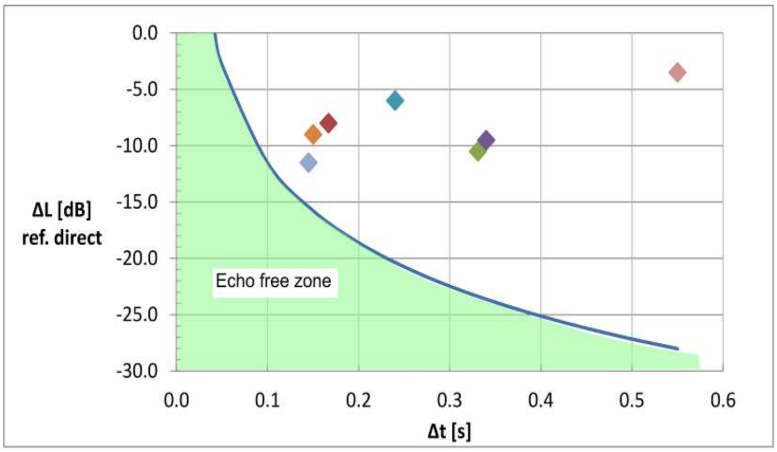

Figure 7 – Identified echoes vs. threshold curve

It is obvious that audible and potentially disturbing echoes are present. This rough method, however, does not reveal the spectral aspect of the echoes nor their strength relative to the surrounding level of smoothed ETC. For a more accurate analysis of echoes, one can use Yamamoto's method on the smoothed ETCs (sudden jumps in smoothed ETC > +6 dB) and the echo-criterion $E_K(\tau)$ by Dietsch [2].

These methods have been applied in an analysis of the quasi-impulse measurements done at POPB. Only the results for the sound engineer’s position are presented and discussed further.

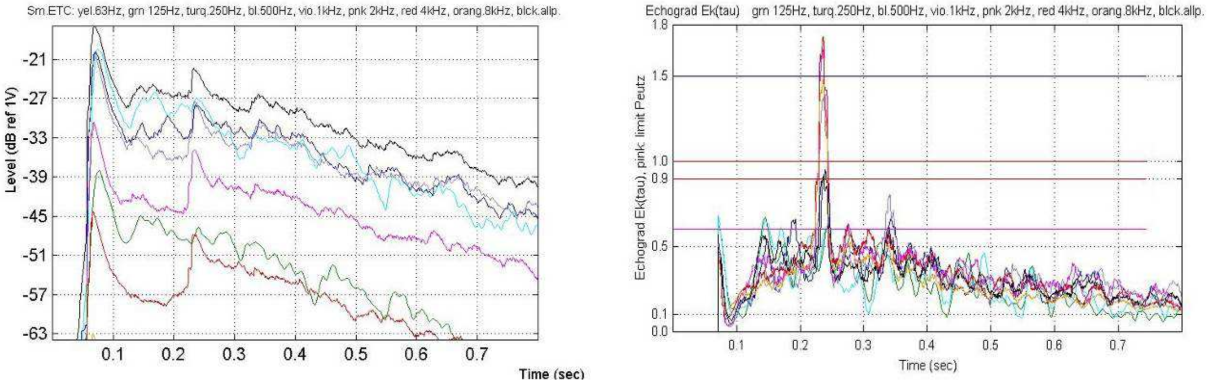

Figure 8 – Octave band ETCs and Echograd $E_K(\tau)$ of quasi-impulse response at example position FOH

The analysis shows a distinct echo with time delay of ca. 167 ms after the direct sound at point 1 (FOH) position in the octave bands above 500 Hz. Looking at the geometry, the extra path for the sound to travel past the sound engineer’s position, reach the reflecting surface and bounce back to this same position is $\Delta d = \Delta t * c = 167 \text{ ms} * 340 \text{ m/s} \approx 57 \text{ m}$. Thus, the suspected origin of the echoes at FOH was confirmed as the following geometry: flat surfaces on both sides of the pillar.

The directivity of the speaker reduces the number of possible surfaces generating echoes, making the identification easier and possible on location. Assessing the origins of the echoes would be more difficult with an omni-directional source as the number of reflections would increase. Echoes encountered in concert situation are generated usually by directional speakers like line-arrays, too.

4. SOLUTIONS

The evaluation of the measurement results has shown that efforts to improve the acoustics of the hall should primarily focus on controlling the echo phenomena. Measures for improvement consist therefore in applying highly effective absorption and diffusion at specific areas to eliminate detrimental reflections rather than pure addition of widespread sound absorption as one would apply to reduce the reverberation time. In order to eliminate late isolated strong reflections, absorption coefficients of ≥ 0.9 in the interesting frequency range are needed.

In the new version of the hall, a new set of tiered seats will be installed on both end pillars for increasing the seating capacity. This will considerably reduce the area of the vertical reflecting surfaces. The rest of the surfaces above will be treated with mineral wool, exhibiting high sound absorption over a wide range of frequencies of $\alpha_w > 0.9$ (conform EN ISO 11654). Given the diffraction created by the new tiered seats and the high absorption on the flat surfaces is supposed to suppress the echoes from these surfaces sufficiently.

Figure 9– Vertical areas (each side pillar) after the project

A walkway circles the main hall at midlevel, creating a 2 m high wall that is highly reflective in the original situation (ceramic tiles on concrete). This wall will be partly covered with micro-perforated OSB-panels placed at different angles as shown in the figure below. The panels have a sound absorption coefficient α_w between 0.6 and 0.8 depending on the air cavity behind, which is many times more than the actual ceramic tiles (evaluated α_w of ca. 0.05). The added absorption will therefore considerably reduce the strength of the sound reflections. The irregular pattern of the panels will reduce the area reflecting sound at any given angle, thus diffuse the reflections and contribute to reduce their strength.

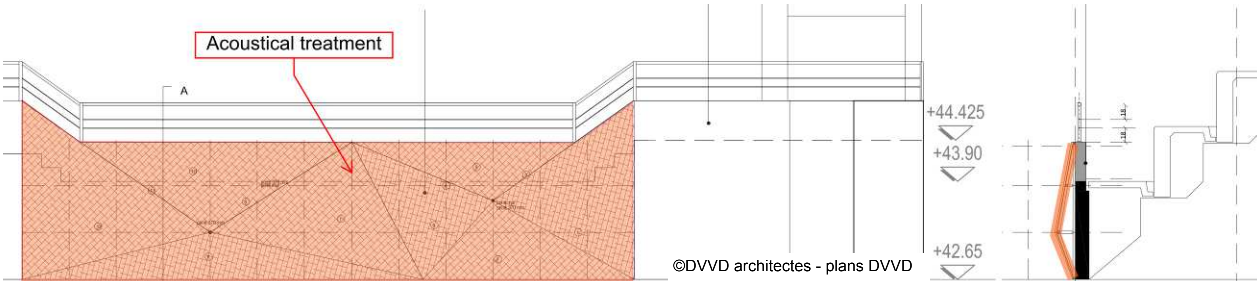

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Figure 10 – Acoustical treatment on the walkway

Since all the seats will be changed, great care is taken to insure that the new seats will offer at least the same amount of absorption, more than the existing ones. A comparative test will be performed in laboratory on existing and new seats.

Compared to the present situation, about 500 m^2 of supplementary absorbing surfaces will be introduced, i.e. about roughly an eighth of the necessary extra sound absorption to reduce the reverberation time by 0.6 seconds as estimated in chapter 2. The global reverberation time after the renovation project will be slightly reduced.

The costs of supplementary absorption to shorten the reverberation time to optimum values are not feasible within the budget of the project.

5. CONCLUSIONS

The use of a quasi-impulse signal allows a clear auditive perception of echoic reflections. Measurements with a highly directive speaker allows to reduce the number of surfaces and reflections involved, making the identification of echoes and their origins easier. This paper suggests therefore the use of a quasi-impulse signal with a highly directive speaker as an efficient way to detect, measure and identify echo-generating surfaces in large venues, prior to a more detailed examination of reflections.

Acoustical characteristics of large halls with fair reverberation times but suffering from adverse echoes can be improved in efficiently by highly absorptive finishing materials at selected surfaces attenuating specific strong late sound reflections. Sufficient attenuation of the echo phenomena must always be achieved prior to additional sound absorption aiming to shorten the reverberation time.

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