Large scale in situ acoustic reflection measurements in a theatre

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Introduction

The acoustic reflection properties of material used in a theatre are a major concern, both in the initial design stage and during renovation. The PU surface impedance method allows the simultaneous measurement of both sound pressure and acoustic particle velocity, providing the opportunity to measure materials as they are installed on seats, floors, walls and ceilings, assessing their sensitivity to both normal an oblique angles of sound wave incidence. Using portable equipment, the actual testing time is short, allowing large scale testing. The method was applied at the Musis Sacrum theatre in Arnhem, the Netherlands.

PU in situ surface impedance method

The PU free field surface impedance technique makes use of a Microflown velocity sensor and a sound pressure microphone. Both sensors are mounted in one probe that is positioned close to the material and a sound source is positioned at a certain distance. The impedance can be derived from the ratio of pressure and velocity [1]-[11]. From this, material reflection and absorption can be calculated.

Measurements in the free field can be difficult because plane waves are practically impossible to create in a broad frequency range. Therefore an image source model is used that takes into account the spherical waves, that are present because of the point source that is used. It is assumed that the spherical reflection coefficient, after correction, equals the planar reflection coefficient. It shows to give almost identical results for higher frequencies (f>200Hz) [4],[6]. With that the reflection coefficient can be derived with equation (1).

$$R = \frac{\dfrac{Z_{measure}}{Z_{ff}} - 1}{\dfrac{Z_{measure}}{Z_{ff}}\left(\dfrac{h_s - h}{h_s + h}\right)\left(\dfrac{ik(h_s+h)+1}{ik(h_s-h)+1}\right)+1}\,\frac{h_s+h}{h_s-h}e^{ik2h} \qquad (1)$$

With k the wave number and R the planer reflection coefficient. When the measured impedance at the material ($Z_{measure}$) and measured impedance in the free field (Z_{ff}) are measured close after each other, all amplifier settings, AD settings, calibration of the microphone and microphone etc. are likely to be unchanged. Also the temperature, and thus the characteristic impedance of air, is assumed to be the same during both measurements. As long as these conditions are met, the values do not have to be known as they will vanish in the ratio $Z_{measure}/Z_{ff}$. The distance between the probe and source h_s is kept at a constant 23cm. A probe-sample distance h of 5mm to 20mm is normally used.

The probe is able to measure in the whole audible range but the lower frequency limit of the method at this moment is 100~300Hz. This is due to the low sound pressure emission from the loudspeaker at low frequencies (and the limited dimensions of the samples). Also close to a fully reflecting plane the particle velocity is practically zero.

The measurement set up that is used (Figure 1) consists of a spherically shaped loudspeaker. The radiation impedance of such a loudspeaker is studied in [12]. The radiation impedance in front of the loudspeaker is quite similar to a monopole. The loudspeaker is mounted to a grip and mechanically decoupled from the structure that holds the PU probe.

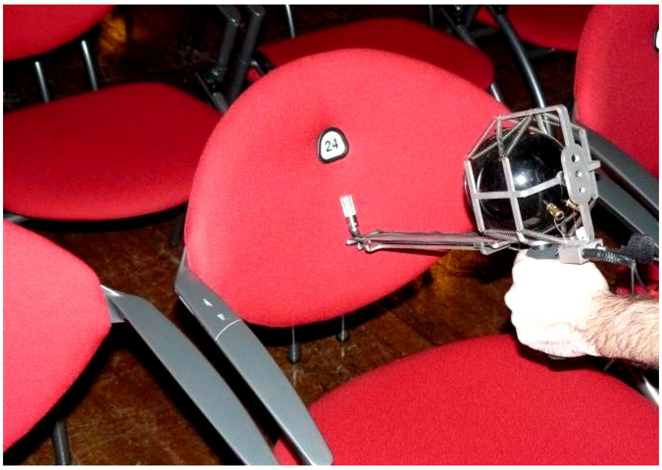

Figure 1: PU in situ impedance setup

Because with this method, the impedance is measured directly in one spot and close to the material, it is possible to measure while having little disturbance from most room reflections. The distance between the probe and the source is only 26cm, so reflections at some distance are less dominant than the signal from the direct source. The method has already been applied several times inside a car [7],[8].

A moving average in the frequency domain many times gives a result similar to an anechoic measurement. A time windowing technique could also be used but the moving average is more robust [9]. When there are many random reflections the smoothed result should follow the actual impedance. However when the actual impedance has a sharp change this averaging should not be applied, so some care is required. Also when there is one dominant reflection (e.g. from one wall only) the moving average should not be used. This problem will be further discussed in the next chapter.

Measurements

The in situ impedance is measured inside the concert hall of the Musis Sacrum theatre in Arnhem, the Netherlands (see Figure 2). In three hours 65 measurements were done. This theatre is used for several purposes, such as opera and theatre performances, so there are different reverberation time specifications for different user moments. For instance, before the rehearsals of the local orchestra, the main hall is filled with seats in an attempt to reduce the reverberation time. The impedance measurements give a better insight of the individual contribution of these seats.

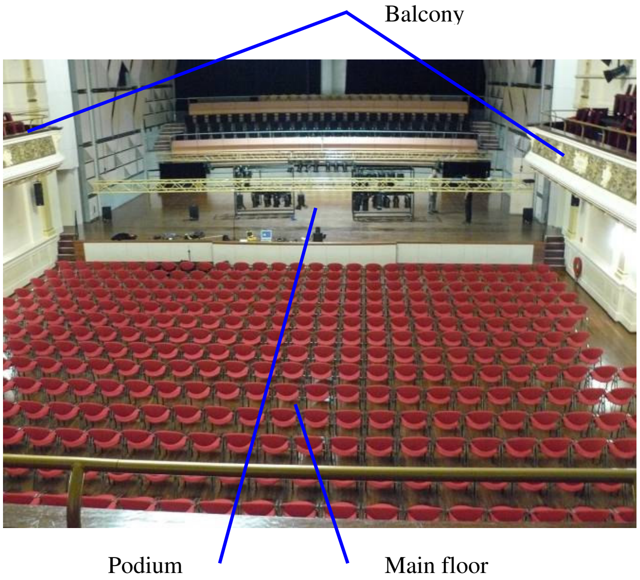

Figure 2: The concert hall of the Musis Sacrum theatre

The reflection coefficient is studied here instead of the absorption, because there is no fully reflective plate behind many objects under test. The sound can go partially through the material as well, and it is therefore difficult to determine the actual absorption by the material itself.

Because the impedance is measured very close to the material, there is a high spatial resolution. To obtain the effective reflection of a larger area, the probe is scanned along the surface, or the average impedance is calculated out of several measurement points [9],[10].

Reflection measurements

In Figure 3 the reflection of several different seats is plotted. While there is little sound reflected from the balcony seats or the red seats on the ground floor, the podium seats reflect most sound below to 1kHz, which contributes to the fact that most sound generated at the stage is reflected into the hall. The reflection from different seats or different parts of the seat is varying, but there is little variation between different seats of the same kind. Also the reflection coefficient of a closed balcony seat is almost equal to an open seat.

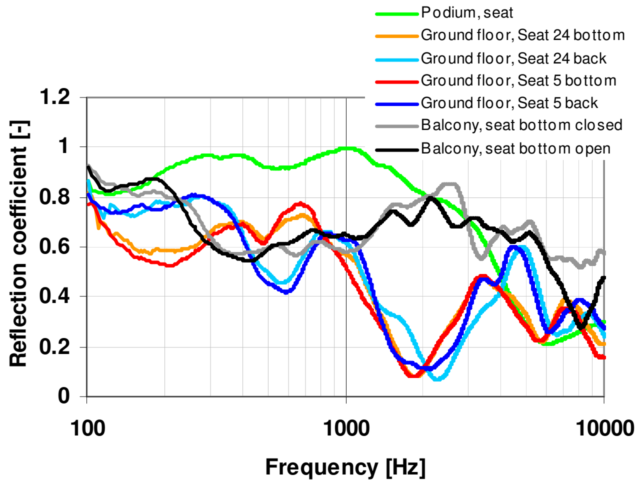

Figure 3: In situ reflection of various seats

On many points the floor was measured, but it is almost 100% reflecting at all frequencies, except for the balcony floor, where is less reflection above 6kHz (Figure 4). Most walls and ornaments in the hall that have a high reflection, but there are some panels on the podium that are less reflective. For instance some panels on either side of the stage have cavities with a much lower reflection coefficient than panels without cavities (Figure 4 red and green line, Figure 5).

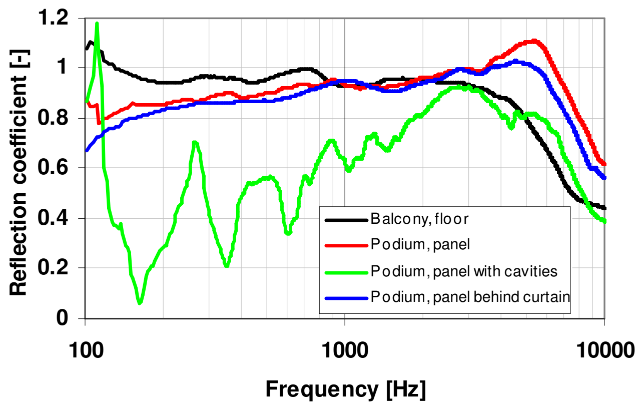

Figure 4: Reflection of the balcony floor and some wall panels

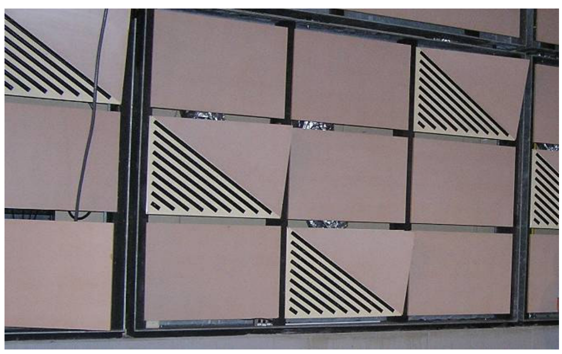

Figure 5: Panels with cavities on the podium

A perfect measurement environment for the in situ impedance setup would be an anechoic condition (all reflections are only be caused by the sample itself). Measurements in more reverberant environments are also possible, if e.g. a moving average in the frequency domain is take, or if a time windowing technique is used. In fact, for the moving average principle a situation with a more reflections (from objects at different distances from the setup) is preferable because then the many reflections cancel each other.

Reflecting surfaces far from the setup will have smaller amplitudes compared to the direct source, and the influence is minimal. Also, if a strong reflecting plate is positioned a few centimeters from the probe there can be little distortion [11]. The position from the direct source and the mirror source to the probe is almost equal and the reflection from the side plate will only add up to the direct source. The difference in path length is minimal and therefore there will only be interference at (very) high frequencies.

However, when a single reflecting plane is positioned a little further from the setup, at some frequencies a strong interference with the direct source can be present. This was first observed by the RWTH [8]. Here such a measurement is repeated. A steel plate is placed 30cm from the setup (Figure 6). The reflection coefficient is very different for the frequencies where the direct source is in anti-phase with the reflections from the steel plate at the probe position, see Figure 7.

Figure 6: One hard reflecting plate next to the setup

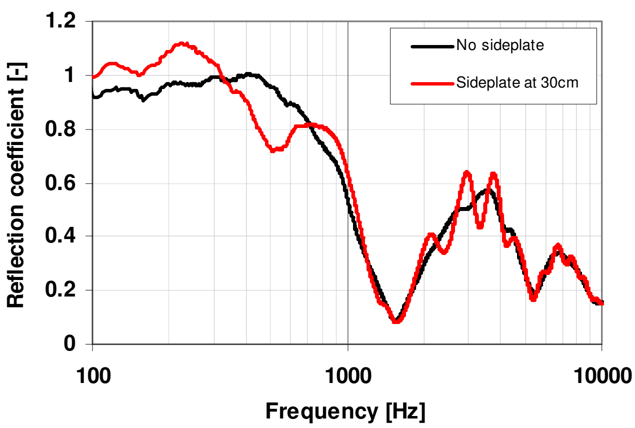

Figure 7: Distortion of the reflection coefficient due to a fully reflective plate on the side

If a moving average in the frequency domain is used, this distortion does not disappear because the amplitude of the unwanted mirror source are significantly large compared to the direct source. Because signal from the direct source and reflections from the material will be measured slightly earlier than the reflections from the steel plate a time window could be used to get rid of these reflections. A disadvantage of such a time window is that the length of the window should be longer to be able measure the lower frequencies correctly, but then there is some overlap with the reflection from the steel plate.

An idea is to use not only the velocity signal normal to the surface, but also the lateral velocity. If there is a mirror source that is positioned not normal to the surface there is an interference with the direct source that affects both the pressure and the normal particle velocity. The lateral velocity depends only on the lateral component of this mirror source (Figure 8). Therefore the lateral velocity might be used in the future to get rid of the unwanted mirror source component in the pressure and normal velocity signal.

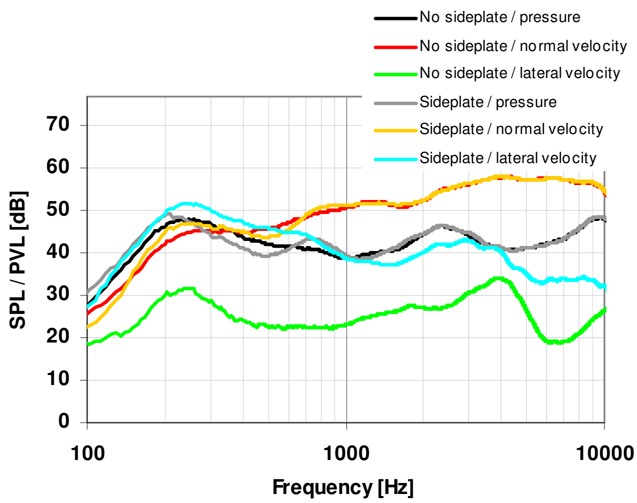

Figure 8: Pressure and velocity response close to an absorbing surface, with and without reflective plate on the side

During the measurement in the theatre the influence of one (or more) dominant reflections was avoided by making sure there were no walls next to the sample. The influence of unwanted reflections from neighboring walls can be measured because they depend on the location. By measuring at different positions and on different samples (e.g. many seats) one can separate from the reflections from the sample itself.

Conclusion

The free field in PU surface impedance technique was used in a theater setting to characterize the sound reflecting properties of individual materials and equipment. In three hours 65 measurements were done with a portable setup on different types of seats, wall panels and floors.

Some acoustic environments e.g. a single dominant reflective plane close by make the measurement difficult. The additional measurement of the lateral particle velocity may solve the effect of this.

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