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Technical Note

Acoustic Characterization of a Room: Study Case Between Simulation and a Portable Method

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Large venues and auditoriums are commonly associated with their astounding architecture. Their acoustic quality is an essential factor in its qualification as a great and functional, or a badly designed place. However, acoustics is often overlooked during the design stage of a building due to the complexity and high cost of the measurements involved. For this reason, it is important to explore more accessible ways to implement acoustics evaluations. The aim of this work is to compare typical experimental measuring methods and the use of mobile devices to assess the acoustic quality of a room. These measurements are contrasted with the software simulation of the same acoustical space. The results show that the mobile system can be used for professional measurements with low restrictions in the frequency range of interest of this study (90 Hz to 4000 Hz).

Keywords: architectural acoustics; acoustical parameters of room; room acoustics; mobile devices.

1. Introduction

Environmental sound affects the human being in several ways: physiological, psychological, cognitive and behavioral (Cowan, 2016). Therefore, it is important to study spaces where human activities take place. Architectural and building acoustics concerns improvement of sound in rooms and it is critical for spaces ranging from recording studios to theatres and concert halls. The particular case of rooms dedicated to educational uses, such as classrooms, libraries, auditoriums, conference rooms, also requires an adequate acoustic design.

Learning spaces are places where children and young people spend a large part of their daytime. For this reason, it is very important to evaluate acoustic conditions in classrooms, libraries and school auditoriums (Zannin, 2009; Hodgson, 1999; Escobar, Morillas, 2015). Several studies have been conducted to assess acoustic conditions in classrooms, some of them have been conducted to analyze the effect of reverberation time (Nowoświat *et al.*, 2016; Nowoświat, Olechowska, 2017). Other studies have been focused on speech intelligibility measuring (Choi, 2017).

In a study by Nowoświat and Olechowska (2017), reverberation time measurements were carried out in five different poorly dampened classrooms They estimated reverberation time using the residual minimization method (MMR) (Nowoświat, Olechowska, 2016) and compared it with measurement data and numerical simulations.

Choi (2017) carried out the impulse response measurements in 12 university classrooms. These measurements were used to determine the modulation transfer function for the Speech Transmission Index (STI) calculation. Also, U_{50} values were determined from both signal-to-noise ratios (SNR) and C_{50} values. His results illustrate that useful-to-detrimental sound ratios can be used to measure the combined effects of room acoustics and SNR values on speech intelligibility in classrooms essentially as accurately as STI values. Choi (2018) experimentally investigated the effect of the distribution of occupants in partially occupied classrooms.

In order to evaluate comfort in classrooms, other important aspects besides acoustic conditions have been analyzed. Bluyssen *et al.* (2018) studied the relations between classroom characteristics and health and comfort of school children. This study was conducted in 54 classrooms of 21 primary school buildings in the Netherlands. Data were collected through physical measurements, questionnaires applied to children and teachers, and checklists for classroom and school building. Their results show that, among all different aspects considered in the study, noise is the most common annoyance for primary school children in the Netherlands; more than 85% of children reported that they were bothered by noise in their classrooms.

The present study has two main aims. The first was to compare different experimental methods to assess the acoustic quality of a room. The second aim was to explore the use of mobile devices in the architectural acoustics field. The remainder of this paper is organized as follows. Section 2 describes a summary of studies that have made comparisons between different techniques and using different equipment to assess the acoustic quality in a room and acoustics measurements with mobile devices. Section 3 describes the measurement methodology. The results are then presented in Sec. 4 and discussion in Sec. 5. Finally, Sec. 6 presents the summary and conclusions.

2. Related work

2.1. Comparison of different experimental methods

Acoustic characterization of rooms consists in determining the acoustic quality on a specific space and can be carried out using different experimental methods. Generally, the methodology used in room acoustic analysis is based on acoustic measurements in accordance with the International Organization for Standardization (ISO 3382-2009), as well as on acoustic simulation. An acoustic measurement setup includes specialized measurements equipment such as a sound level meter or sound analyzer, sound sources, microphones and acoustic calibrator. On the other hand, acoustic simulation concerns the assessment of a room, where the sound can be analyzed through virtual acoustic modeling. There are several commercial options available (Catt Acoustics; Software EASE; ODEON).

Fausti and Farina (2000) compared acoustical parameters in opera houses using different measurement techniques and equipment. The following measurement techniques were compared in their research: technique based on the use of a real-time analyzer, technique based on the digital recording of the impulse response generated by impulsive sources and its subsequent analysis, impulsive technique based on the deconvolution of a steady pseudo-random test signal (Maximum Length Sequence – MLS) and impulsive technique based on the deconvolution of an exponentially sweeping sine wave as a test signal. Their results showed that the differences obtained between different measurement techniques and equipment were not significant. However, regarding the recording technique, a difference was found between monaural and binaural measurement. Also, slight differences were found between impulsive sources as pistol shots or balloons, and omnidirectional loudspeaker.

D'orazio *et al.* (2018) evaluated the influence of equipment and techniques in the measurement of speech intelligibility in an open-plan office. In situ measurements were done using omnidirectional and directional sound sources with different sound power levels. Their results show that different techniques and equipment influence the measurement of the speech intelligibility; also, the presence of high background noise levels may introduce uncertainty in STI calculation.

Dick and Vigeant (2016) compared some room acoustics metrics when obtained from room impulse responses measured with a conventional microphone configuration, an omnidirectional and figure-8 pair, to those measured with a spherical microphone array. The metric considered in the study were: reverberation time (T_{30}), early decay time (EDT), clarity index (C_{80}), strength (G) lateral energy fraction and late lateral energy level. Their results show that spherical microphone arrays can be used to obtain valid room impulse responses measurements.

2.2. Acoustic measurement with mobile devices

A wide spectrum of applications is possible due to recent mobile technology developments. These developments include an increase in its usage and computational capabilities, its Internet connectivity, integrated microphones, cameras, motion sensors, GPS, etc. Mobile phone applications have been developed in different areas, such as:

1) health: cardiac health monitoring (Rubel *et al.*, 2005; Scherr, 2006; Scully *et al.*, 2012; Nam *et al.*, 2016) and personal health monitoring (Reddy *et al.*, 2007);
2) sensing environmental conditions: air quality monitoring (Dutta *et al.*, 2009; Devarakonda *et al.*, 2013) and noise pollution monitoring (Rana *et al.*, 2010; Kanjo, 2010; Maisonneuve *et al.*, 2009; iHEARu; SoundPrint; SoundCity);
3) education, in order to measure some physical phenomena in a classroom or in a laboratory (Kuhn, Vogt, 2013; González, González, 2016; Sans *et al.*, 2013; Gómez-Tejedor *et al.*, 2014; Klein *et al.*, 2014) and medical education (Ventola, 2014).

A large number of existing studies in the literature have examined the use of mobile devices in different acoustic measurements. For instance, in the study conducted by Brown and Evans (2011) sound pressure level from various sources and reverberation time were measured with an Apple iPhone$^{\text{TM}}$ 3GS. A hand-held analyzer (Brüel & Kjaer Type 2250) was used for the purposes of comparison. To measure sound pressure level, SignalScope Pro application was used; whereas to measure reverberation time the Impulse Response module of the Audio Tools package by Studio Six Digital was used. The results showed that the internal microphone has a limited frequency range and limited dynamic range; however, considering measurements of noise levels above to 40 dB(A) and below to 80 dB(A) useful results can be obtained. For reverberation time measurements, the results showed that the smartphone provided comparable and repeatable results to a reference sound level meter.

Rizzi *et al.* (2015) developed a smartphone application to obtain some room acoustical parameters: T_{20}, T_{30}, C_{50}, D_{50}, EDT. They carried out measurements in mid-sized and large rooms, using simple impulsive sources like balloon burst, hand claps or wooden claps. For the acoustic measurements, the internal microphone of two iPhone models was employed. Similar results were obtained above 250 Hz for reverberation time measurements compared to a reference system. For clarity index estimation useful information can be extracted observing the parameter sign trend which was found to be reliable.

The measurement of the sound pressure level in noisy outdoor environments with mobile devices is an important research topic that has been studied extensively. For instance, Aumond and his collaborators (2017) investigated the accuracy of mobile devices to measure urban noise pollution. A total of 3409 environmental noise measurements were made by 60 volunteers using an application based on NoiseTube at 28 previously selected points in Paris. In parallel, measurements were made at fixed stations for environmental noise monitoring and a sound level meter. Their results showed that the noise levels measured with previously calibrated mobile phones correlate strongly with those measured in the fixed station and sound level meter. However, it is important to notice that their research was performed on Android-based devices only (HTC-One X).

The use of mobile devices in education has increased enormously. For physics or engineering students, mobile devices have also become useful experimental tools. For instance, to analyze the Doppler effect (Gómez-Tejedor *et al.*, 2014; Saba, Rosa, 2003), to measure and visualize directivity of a sound source (Hawley, McClain, 2016) and to analyze soundscape by means of sound pressure level measurements and the creation of sound maps (Satoh *et al.*, 2016; Aumond *et al.*, 2017).

3. Measurements methodology

The present study has two main aims. The first was to compare different experimental methods for measuring different acoustical parameters. The different experimental methods considered were:

1) acoustic measurement with reference equipment,
2) acoustic measurement using a mobile device, and
3) acoustic simulation based on EASE software.

The second aim was to explore the use of mobile devices in the architectural acoustics field. All measurements were carried out according to the international standard ISO 3382 (2009). The sound source was in the front area of the auditorium, and the sound receiver positions were chosen in the main seating area (see Fig. 1). The microphones were located far away from the sound source to avoid a strong influence of the direct sound, according with ISO 3382 – Sec. 4.3. Room acoustical quantities were determined from the measured impulse responses in an empty auditorium with a capacity for 140 people.

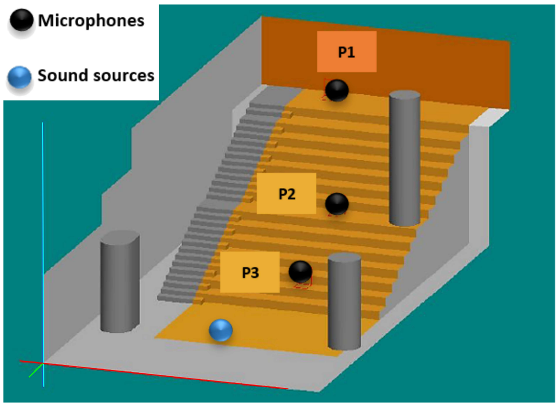

Fig. 1. Positions of microphones and sound source during the acoustic measurements.

3.1. Auditorium description

An auditorium was investigated as a case study. The auditorium has an area of 1137.27 m^2, a height of 11.3 m in the highest part, and a total volume of 1304.26 m^3. The auditorium is part of the library building located in Tecnologico de Monterrey, in Monterrey City. The library building has 17 300 m^2 of construction and is made up of six levels with a configuration of spaces. The distribution allows the accommodation of a wide variety of environments to improve the learning experience, as including new teaching laboratories, study spaces for individuals and collaborative study spaces, reading rooms and research spaces. The building is capable of accomodating 2500 people. The library was awarded for the best interior design of an academic library in the Library Interior Design Awards, awarded by the International Interior Design Association (IIDA) and the American Library Association (ALA). Also, this project is pursuing LEED Gold certification. Library building at Tecnológico de Monterrey is shown in Fig. 2.

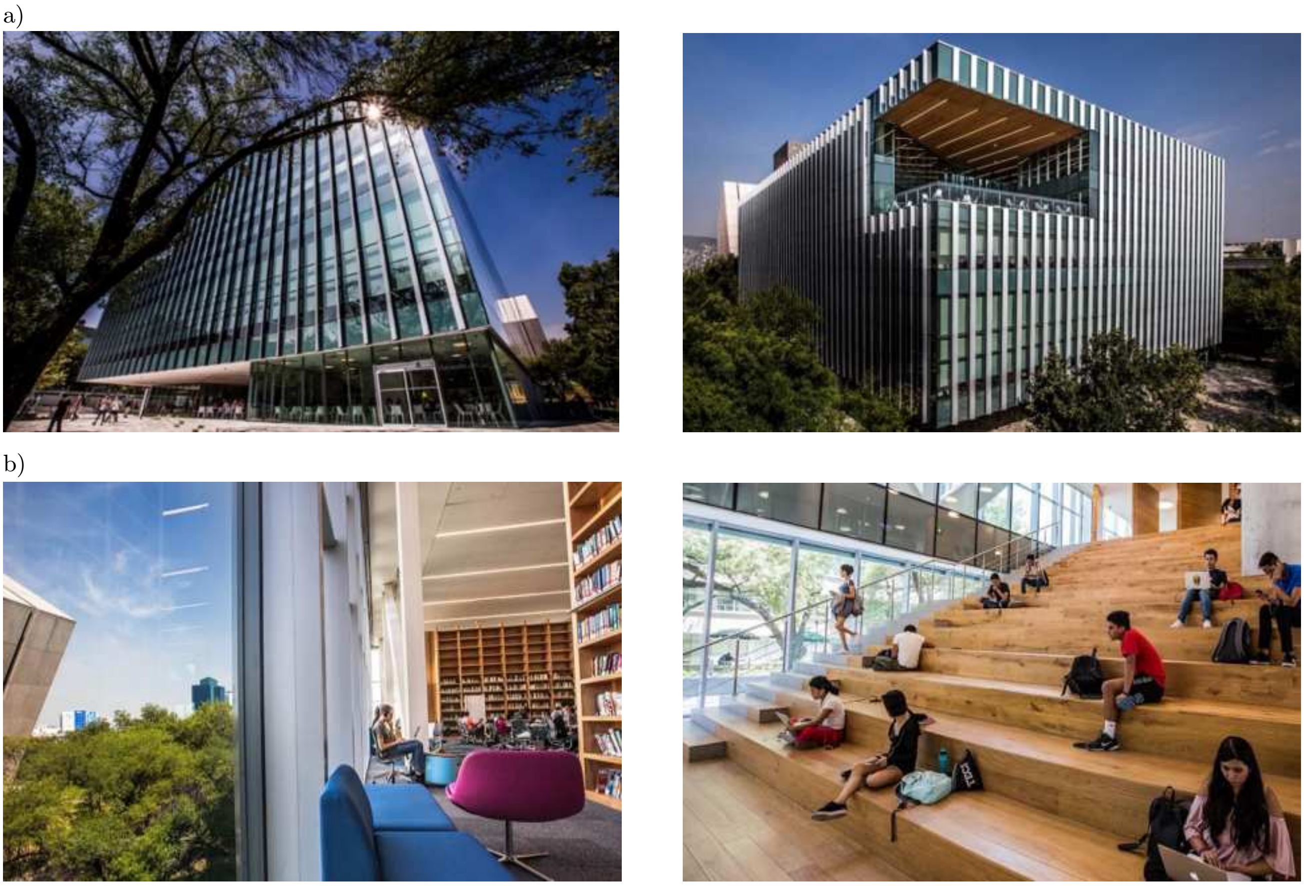

Fig. 2. Library building at Tecnológico de Monterrey campus Monterrey: a) exterior view, b) interior view.

3.2. Acoustic measurement with reference equipment

3.2.1. Impulse response measurement

In order to measure the impulse response, a random Maximum-Length Sequences (MLS) signal was used as the source signal and was radiated into the room from an omnidirectional loudspeaker, with an operating frequency range from 40 Hz to 18 kHz (Ibarra *et al.*, 2018). Measurements were made at three receiver positions (see Fig. 1) using an omnidirectional microphone (RTA-M; dbx by Harman, South Jordan, UT). The sound source and receivers were managed by a National Instrument USB-6211 data acquisition card. The digital signal processing was done with Matlab software. In every location the measurement was performed three times and its mean value was taken into consideration.

In order to obtain the reverberation time, the Schroeder's backward integration method was used. Schroeder (1965) has shown that the reverberation curve can be measured with increased precision by backwards integration of the impulse response, $h(t)$, as follows:

$$R(t) = \int_{t}^{\infty} h^2(t)\,\mathrm{d}t = \int_{0}^{\infty} h^2(t)\,\mathrm{d}t - \int_{0}^{t} h^2(t)\,\mathrm{d}t. \qquad (1)$$

In which $R(t)$ is equivalent to the decay of the squared pressure decay.

3.3. Acoustic measurement with mobile devices

3.3.1. Impulse response measurement

For the acoustic measurements with mobile devices a mobile phone HTC, model M9 was used. The excitation signal was manually generated using a balloon. A notable mobile application such as WaveEditor for Android$^{\mathrm{TM}}$ was used as recorder. The Automatic Gain Control (AGC) was deactivated, in order to the impulse response record was not falsified and so the input gain was adjusted according to the level of background noise and the level of impulse response of the room.

The procedure for calibrating the mobile device is outlined below. The experimental setup for mobile system calibration is shown in Fig. 3. The reference microphone and a sound level meter (Brüel & Kjaer Type 2270) were located at 1 m from the omnidirectional loudspeaker.

A random MLS signal was generated by Matlab software, data acquisition was through a data acquisition card of National Instruments NI USB-6211 in order to characterize the mobile phone microphone via comparative transfer function, where Fast Fourier

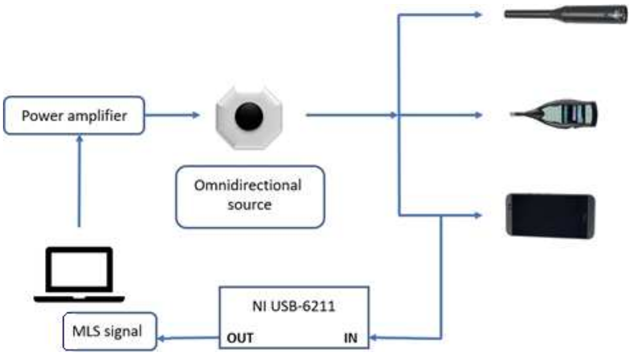

Fig. 3. Experimental setup for mobile system calibration.

Transform (FFT) is applied to impulse response of each transducer. The sound level meter is settled at the same distance to measure the sound pressure level for calibrating the microphones. The dbx reference microphone, the sound level meter and the HTC mobile are placed as Fig. 3 indicates, the impulse response between omnidirectional loudspeaker and receivers are measured, and 1 m is the distance between them. If FFT is applied to the impulse response, then the corresponding transfer function is obtained. Figure 4 shows $H_{\text{ref}}(f)$ transfer function.

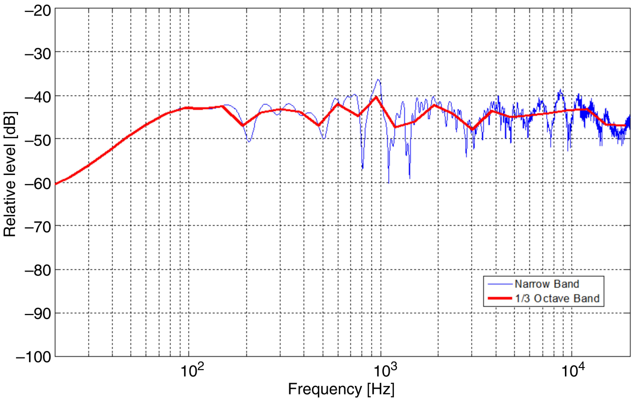

Fig. 4. Transfer function between omnidirectional loudspeaker and dbx microphone.

The transfer function between the omnidirectional loudspeaker and dbx reference microphone, H_{ref} is

$$H_{\text{ref}}(f) = H_{\text{omn}}(f) \cdot H_{\text{amp}}(f) \cdot H_{\text{dbx}}(f) \cdot H_{\text{int}}, \qquad (2)$$

where $H_{\text{omn}}(f)$ is the omnidirectional loudspeaker transfer function, $H_{\text{amp}}(f)$ is the power amplifier transfer function, $H_{\text{dbx}}(f)$ is the microphone transfer function and $H_{\text{int}}(f)$ is the interface transfer function.

Now, the reference dbx microphone is replaced by HTC microphone, and the transfer function is measured, calculating $H_{\text{mob}}(f)$, Fig. 5, being

$$H_{\text{mob}}(f) = H_{\text{omn}}(f) \cdot H_{\text{amp}}(f) \cdot H_{\text{HTC}}(f) \cdot H_{\text{int}}(f), \qquad (3)$$

where $H_{\text{HTC}}(f)$ is the HTC microphone transfer function.

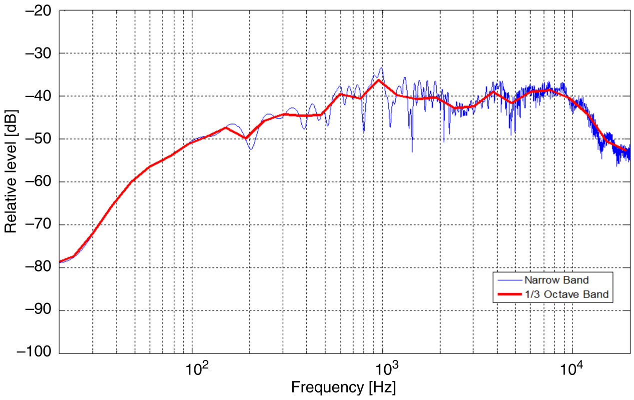

Fig. 5. Transfer Function between omnidirectional loudspeaker and HTC microphone.

It can be seen in Figs 4 and 5, the two transfer functions, one between omnidirectional speaker and dbx microphone and the other between omnidirectional speaker and HTC mobile, first transfer function has a nearly flat frequency response and the frequency response of the second one is less flat.

The ratio between Eqs (2) and (3) gives

$$\frac{H_{\text{mob}}(f)}{H_{\text{ref}}(f)} = \frac{H_{\text{omn}}(f) \cdot H_{\text{amp}}(f) \cdot H_{\text{HTC}}(f) \cdot H_{\text{int}}(f)}{H_{\text{omn}}(f) \cdot H_{\text{amp}}(f) \cdot H_{\text{dbx}}(f) \cdot H_{\text{int}}(f)}. \qquad (4)$$

That is, the transfer function of the HTC mobile microphone is:

$$H_{\text{HTC}}(f) = H_{\text{dbx}}(f) \cdot \frac{H_{\text{mob}}(f)}{H_{\text{ref}}(f)}. \qquad (5)$$

Logarithmic scale is used, just with subtraction of $H_{\text{mob}}(f) - H_{\text{ref}}(f)$ (with the assumption of frequency response of reference microphone is flat, as its specification says) the frequency response of HTC mobile microphone is obtained (Fig. 6). The frequency response is almost flat from 400 Hz until 10 kHz; subsequently it decays about 10 dB/oct.

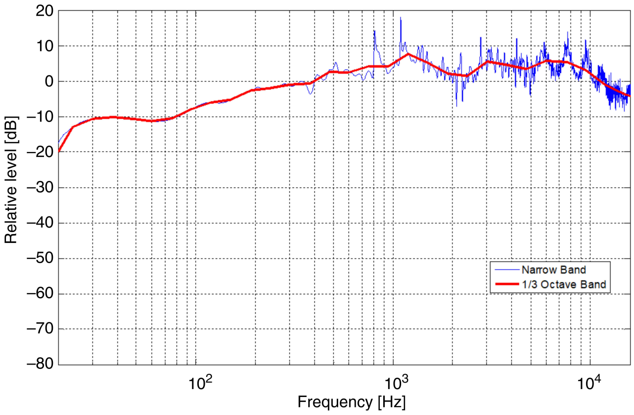

Fig. 6. Frequency response of HTC mobile microphone.

Table 1. The algorithm implemented in Matlab.

Code	Description
`decay = 10*log10(flipud(cumsum(flipud(out(:,1).^2))));`	`% Schroeder reverse integration`
`decay = decay - max(decay);`	`% find IR max`
`Tstart = find(decay <= −5, 1, ’first’);`	`% −5 dB`
`T20end = find(decay <= −25, 1, ’first’);`	`% −25 dB`
`T30end = find(decay <= −35, 1, ’first’);`	`% −35 dB`
`p=polyfit((Tstart:T20end)’,decay(Tstart:T20end),1;`	`% linear regression`
`T20 = 3*((p(2)−25)/p(1)−(p(2)−5)/p(1))/Fs;`	`% reverberation time, T20`
`q=polyfit((Tstart:T30end)’,decay(Tstart:T30end),1;`	`% linear regression`
`T30 = 2*((q(2)−35)/q(1)−(q(2)−5)/q(1))/Fs;`	`% reverberation time, T20`
`IRstart = find(decay <0, 1, ’first’);`	`% direct sound`
`C50=10*log10(1−10^(decay(IRstart+0.05*Fs))/10)−decay(IRstart+0.05*Fs);`	`% clarity index,` C_{50}

3.4. Impulse response calculation

An algorithm was implemented in Matlab to obtain the reverberation time and Clarity C_{50}. The algorithm was based on Schroeder integration. The algorithm implemented in Matlab are shown in Table 1.

The algorithm shown in Table 1 was applied for the reference system and mobile device, in order to obtain Figs 8 and 9 presented in Sec. 4. The impulse response is plotted in Figs 8a and 9a, the inverse integrated level is displayed in Figs 8b and 9b, the frequency response of the system-room is shown in Figs 8c and 9c.

3.5. Acoustic simulation based on EASE software

The EASE 4.3 software was used to simulate the auditorium and obtain the simulated values for different acoustical parameters. The 3D model of the room was made in Sketchup software and then exported to EASE 4.3 to perform the necessary simulations. The acoustic materials that were used for the simulation were the closest to real ones according to the software database and the absorption coefficient (see Fig. 7). For the floor, wooden parquet $\alpha = 0.07$ was fixed, for the walls glass window $\alpha = 0.17$ was used and for the ceiling gypsum board $\alpha = 0.1$ was fitted.

4. Results

The impulse response, decay curve and frequency response are shown in Figs 8 and 9, measured at point 1 with reference equipment and with a mobile device, respectively. From these results, it can be observed that the excitation signal is quite different between two experimental methods. The impulse response measured with the reference system has a higher noise-signal ratio compared to the measurement with the mobile device.

Table 2 shows the comparison between the values of reverberation time obtained with three techniques: simulation, measurement with reference equipment and measurement with a mobile device. The results obtained with three techniques do not indicate significant differences. The differences are less than 0.7 seconds in the frequency range of interest. Also, the Mean Squared Error (MSE) between the simulation and experimental measurements are shown.

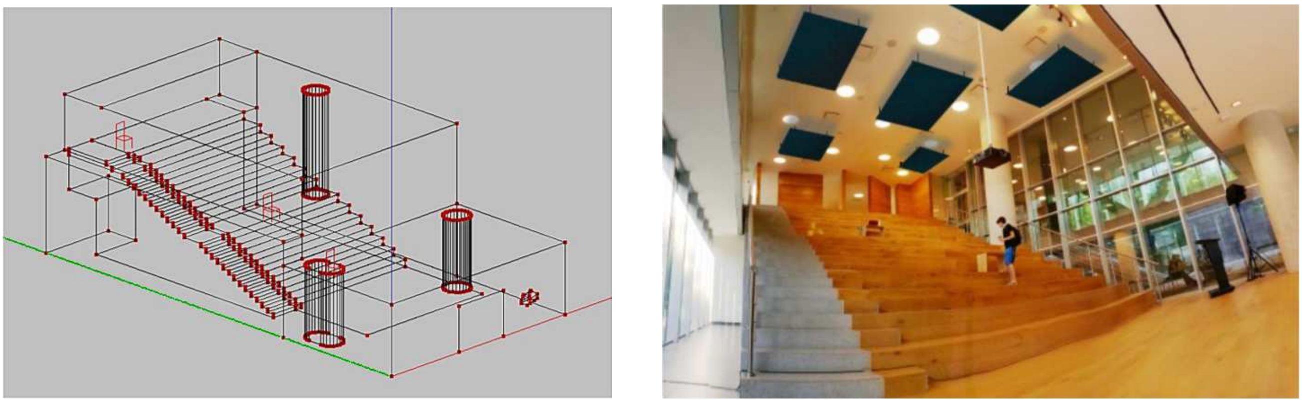

Fig. 7. 3D model library auditorium.

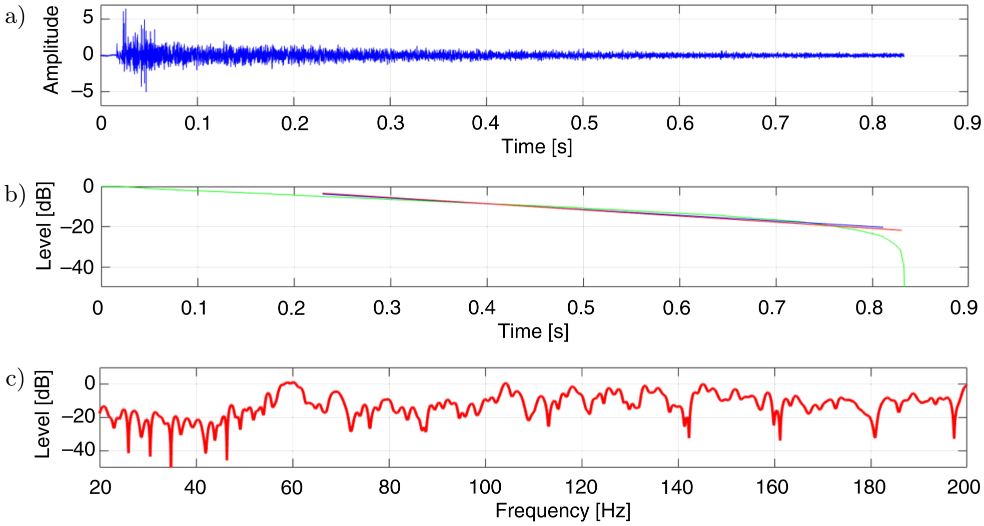

Fig. 8. a) Impulse response, b) decay curve, c) frequency response obtained with reference equipment at point 1.

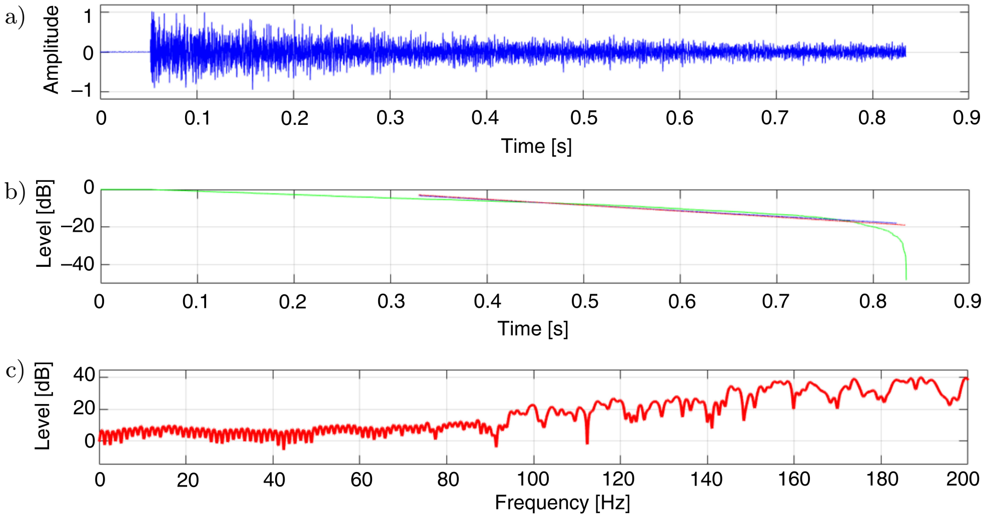

Fig. 9. a) Impulse response, b) decay curve, c) frequency response obtained with mobile device at point 1.

Table 2. Comparison between the values of reverberation time obtained with different techniques.

Frequency [Hz]	Simulation [s]	Reference [s]	$\lvert\Delta T\rvert$/MSE	Mobile [s]	$\lvert\Delta T\rvert$/MSE
125	1.3	1.4	0.1/0.47	1.1	0.2/0.40
250	1.6	1.3	0.3/0.51	1.2	0.4/0.43
500	2.0	1.3	0.7/0.55	1.5	0.5/0.44
1000	2.2	1.7	0.5/0.50	2.2	0.0/0.42
2000	2.3	1.8	0.5/0.50	2.1	0.2/0.51
4000	2.2	1.7	0.5/0.50	1.5	0.7/0.70

The values of C_{50} indices were determined from the impulse response. Impulse response was measured with the use of MLS signal reproduced through an omnidirectional sound source. Table 3 shows the comparison between the values of clarity C_{50} obtained with the two different techniques: simulation and measurement with a reference equipment has shown average difference of up to 2.35 dB.

Finally, in Table 4, the vibration modes of the room are shown, the vibration mode (0, 1, 3) in the frequency response of the measurements can be seen in Fig. 10. There is a good matching between two experimental measurements and the simulation acoustic. However, the measurements with the mobile device are limited due to the frequency response of the balloon; it does not respond at frequencies lower than 90 Hz.

Table 3. Values of the clarity (C_{50}).

Frequency [Hz]	Reference	Simulation	|ΔdB|/MSE
125	–0.3	–1.5	1.2/2.4
250	–0.2	–2.0	1.8/2.6
500	0.1	–2.4	2.5/2.7
1000	0.5	–2.8	3.3/2.8
2000	0.4	–2.4	2.8/2.6
4000	0.5	–2.0	2.5/2.5

Table 4. Modes vibration.

Mode	Theoretical [Hz]	Reference [Hz]	|ΔHz|/MSE	Mobile device [Hz]	|ΔHz|/MSE
3, 0, 1	57	57.6	0.6/0.54	NA	NA
0, 4, 1	64	64	0/0.58	NA	NA
4, 1, 1	75	75	0/0.71	NA	NA
2, 0, 2	80.5	80	0.5/0.76	NA	NA
2, 4, 0	81.6	82	0.4/0.79	85	3.4/2.66
0, 4, 2	103	104	1/0.80	100	–3/2.28
4, 4, 0	111.2	112	0.8/1.77	107	–4.2/1.92
0, 1, 3	118	119	1/1.74	119	1/0.87
0, 2, 3	127.7	127	0.7/1.74	126	–1.7/1.45
1, 1, 3	132.7	132	0.7/1.72	132	–0.7/1.31
1, 2, 3	142.5	142	0.5/1.85	142	–0.5/1.40
3, 2, 4	147	151	4/2.0	147	0/1.55
1, 3, 3	158.8	159	0.2/0.58	158.8	0/1.79
4, 1, 3	177	176	1/0.70	174	–3/2.19
1, 4, 3	181	181	0/0	181.8	0.8/0.8

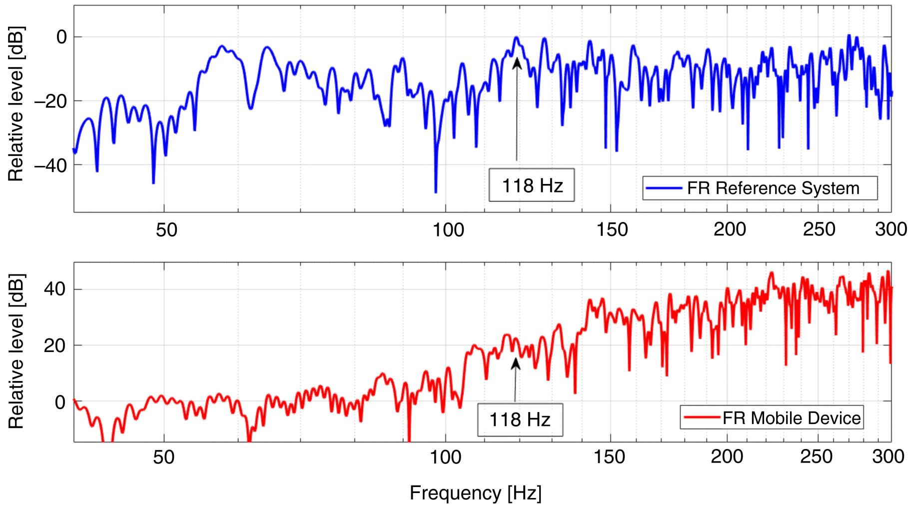

Fig. 10. Vibration mode (0, 1, 3) of the library auditorium.

5. Discussion

Table 2 shows the results obtained from the acoustic simulation, the reference system and the mobile device. The differences between simulation and experimental techniques were up to 0.7 seconds, with the simulation tending to calculate higher reverberation times than the reference system, principally at higher frequencies. A possible explication of the difference between the results is the frequency range of the sound sources employed. The omnidirectional loudspeaker operates within a frequency range of 40 Hz to

18 kHz, whereas that frequency response of the balloon starts at 90 Hz. These results agree with Fausti and Farina (2000) who found slight differences between impulsive sources as balloons and omnidirectional loudspeakers, in their acoustic measurements.

Table 3 shows the results of C_{50} indices obtained with the experiments are in roughly agreement with results of sound clarity obtained with the simulation method. These values are below the minimum recommended value (2 dB) which is indicative that the speech intelligibility of and the loudness are not very good. The uncertainty of the exact positions of the sources and receivers in the experimental processes and their impossible exact replication in the simulation, plus the complexity of the models, can be the difference between the measured and the simulated values, it could also be due to several factors, such as the atmospheric conditions.

In general, the differences between acoustic simulation and experimental techniques may be due to the impossibility of modeling exactly the complex form of some objects in the room. For example, circles were approximated by hexagons. Also, the acoustic materials used for the simulation were the closest to real ones, according to the software database.

In acoustical measurements, one of the main limitations of mobile devices is the microphone. The use of these microphones is intended for speech signals, whose frequency range is between 250 and 4000 Hz, which can have implications on the quality of acoustical measurements.

Finally, further analysis with different geometrical shapes and sizes of rooms is required.

6. Summary and conclusions

The aim of this work is to compare typical experimental measuring methods and the use of mobile devices to assess the acoustic quality of a room. These measurements are contrasted with the software simulation of the same acoustical space. A set of room impulse responses was measured, then some acoustic parameters from these responses were obtained. The room impulse responses were measured using different equipment: a reference equipment, a calibrated mobile device and an acoustic software simulation. The reference equipment setup consisted of an omnidirectional loudspeaker and an omnidirectional microphone; another measurement setup consisted of a mobile phone to record the signal and a balloon as a signal excitation, in both cases Matlab was used for digital signal processing.

The results show that there are no significant differences between the values obtained by the measurements with reference equipment and the mobile device setup, at least in the frequency range of interest of this study, from 100 Hz to 4 kHz.

On the other hand, it is important to point out that although mobile devices have become a useful tool in different areas in the acoustics field: measurement of urban noise, teaching acoustics, among others, the users always should be aware of the limitations of these devices.

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