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ACOUSTIC DECISION SUPPORT SMARTPHONE APPLICATION FOR BUILDING STAKEHOLDERS

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Acoustic comfort is a very important feature when designing a room used by many people such as a gymnasium, a concert hall, a conference room or an office. It is mainly related to reverberation time and other characteristics of the room. Building and construction stakeholders (architects, contractor, designers, developers, etc.) usually work with acoustic consultants to optimize room acoustics. However, they do not have a simple decision support tool, which provides both guidance and recommendations to make preliminary decisions regarding acoustics, therefore saving time and money. A smartphone application (ClapReverb) was designed to measure and compute reverberation time in the medium range frequency domain. The user needs to produce a few handclaps while following instructions on the screen. This method does not require additional hardware because the sound is recorded using the inboard microphone of the smartphone. The upcoming results provide the room's reverberation time and recommendations on acoustic comfort. Thus, two main concerns were addressed in this study: 1) defining the range of validity of the measurement through handclaps and the smartphone microphone, 2) developing an ergonomic application useful for building and construction stakeholders. A parametric study has been conducted to develop a robust process to measure reverberation time and to define the range of validity of the measurement in terms of frequency, reverberation time error, room volume, ambient noise, handclap type, etc. Measurements were compared to a reference method, which was wooden clapping device impulses recorded with a class-1 microphone and analyzed with a Scilab analysis program that complied with ISO-3382 Standard. Overall reverberation time results showed a mean absolute error of 0.09 s computed by ClapReverb (mean relative error of 6.0 %). ClapReverb provides reliable results with ambient noise up to 60 dBA, and is therefore a promising easy-to-use smartphone application which democratizes acoustics and helps stakeholders to optimize room acoustics.

Keywords: room acoustics, reverberation time, measurement, smartphone application, building stakeholders.

1. Introduction and related work

Within the last century, acoustic comfort has become an important parameter for a wider range of rooms, such as libraries, bars, restaurants, halls, conference rooms, swimming pools, gymnasiums, art galleries, museums, or offices. Reverberation Time (RT) is a parameter that is easy to measure and especially useful to describe room acoustics and optimize the acoustic comfort. RT is mainly related to the room volume and the amount of sound absorbing materials. To assess the optimum RT, room acoustic measurements and numeric simulations are usually made. Then, two main parameters are considered to provide useful recommendations: the room size and its intended use[1].

Building stakeholders don't often take into account the acoustic scope of a project and when they want to, they don't have a useful and easy tool to carry out a first analysis. Moreover, there is often a confusion between sound absorption and sound insulation when communicating with building stakeholders. Because of this confusion, inappropriate architecture practices and incorrect assembly during the construction phase of the building can affect the room's acoustic comfort and result in huge expenses to implement corrective solutions.

To measure RT, several commonly used methods are available. MLS, interrupted noise and swept-sine techniques have two major disadvantages: they require bulky and expensive equipment (loudspeaker and amplifier), and sometimes a specific software to process the collected data. This constitutes a significant limitation for building stakeholders, who do not always have the time and resources to get preliminary recommendations and quick results. In opposition, impulse methods have the advantage of requiring lightweight hardware. To generate the impulses, pistol shots [2], balloons [3][4], firecrackers [4], wooden clapping devices [5], and handclaps [6][7] can be used. Among those impulse sources, the more convenient and easily available is definitely the handclap. In a previous research, Griesinger and Seetharaman et al. concluded that handclaps measured with professional audio recorder can be a reliable impulse source to measure some room acoustic characteristics such as the RT above 250 Hz.

Nowadays, smartphones are widely spread. The fact that they all include inboard microphones that are used to record voices and videos makes them a convenient device to perform room acoustic measurements. However, smartphones have some hardware and software limitations. Firstly, the inboard microphone has some disadvantages compared to class-1 microphones, such as calibration, microphone directivity, and frequency response[8]. Secondly, smartphones such as Apple iPhone have kernel software processing that makes the use of the raw signal digitized by the analog-to-digital converter impossible. However, it has been shown that smartphones can still provide fairly accurate results compared to professional hardware [9] [10], and are therefore a promising tool to perform acoustic measurements on RT. Seetharaman et al. developed an iPhone application to compute the RT in a room using handclaps [11]. However, in their previous research, handclaps measurements were made in only three rooms with a professional audio recorder [7] and the application's results are not easily understandable and interpretable for novices.

In this study, an acoustic decision support tool (ClapReverb) was developed to democratize room acoustics. It provides an easy-to-use method to measure RT and gives tips for a better control of room acoustics. The user just needs to produce a few handclaps while following the instructions on the application. This method does not require any additional hardware since the sound is recorded using the inboard microphone of the smartphone. Once the claps are done, an algorithm complying with ISO-3382 Standard [12] automatically computes the RT, and recommendations on the acoustic comfort of the room are given. Measurements were taken in 58 rooms with a diversity of features. The application's results were compared to a reference method at three frequency bands. Furthermore, the robustness of the measurement method and the algorithm against ambient noise was assessed.

2. Materials

2.1 Experimental protocol

Impulse sounds were recorded with two devices simultaneously: 1) the internal microphone of an iPhone 5 with ClapReverb installed, and 2) a class-1 microphone with a *.wav* recording system. Both microphones showed a suitable frequency response in the octave bands of interest (500 Hz, 1000 Hz, 2000 Hz). Both microphones were located very close to each other. Ambient noise was measured with a class-1 microphone. Two types of impulse were generated: a) handclaps from the same person, and b) a Wooden Clapping Device (WCD) to get referential RT values.

Both measurement devices were located at a strategic position in the room, or at several positions if the room had a complex volume. The devices were located at least one (1) meter away from reflecting surfaces (except the floor). Five (5) claps were executed all around the room, at a distance ranging from 1 to 5 meters from the device. The tests were conducted in mostly silent environments, with minimal ambient noise to avoid irregularities in the measurements. Two identical tests were done in the same conditions to generate the impulse: one using hands and one using a WCD.

Measurements were made in 58 rooms with a variety of usage, volume, shape, ambient noise, and RT. A total of 10 rooms were removed from the analysis because of circumstantial abnormalities, such as external noise or technical difficulties.

2.2 Rooms database analysis

Table 1 lists RT, ambient noise level and volume that were encountered in the tested rooms. Some of these rooms were studios, offices, conference rooms, amphitheaters, theaters, gymnasiums, swimming pool, and a basilica.

Table 1: Room database features with average, mean deviation (MD), minimum and maximum values for 48 rooms. A wide range of reverberation time, ambient noise level and volume were measured in a variety of rooms.

	Average	MD	Min	Max
Reverberation time at 1000 Hz (s)	1,50	0,97	0,15	4,29
Ambient noise level (dBA)	40	7	25	60
Volume (m^3)	5196	6860	17	49000

3. Method

3.1 Bias identification and preliminary tests

Many parameters were tested regarding the clapping method and the microphone location in the room in order to analyze and minimize the measurement method's bias. Two types of clap were tested; one with flat hands, and one with domed hands. Moreover, a variety of smartphone dispositions was tried, such as on a tripod, on the floor, on a hollow bench, or on a soft surface. Lastly, since an iPhone 5 has more than one internal microphone, the directivity of the top and bottom ones was tested with the smartphone's screen facing upward.

3.2 ClapReverb validation

ClapReverb validation was performed in three steps: 1) reliability of handclaps, 2) reliability of iPhone's internal microphone and computation algorithm, and 3) validation of ClapReverb's computation algorithm with handclaps measured with the iPhone's internal microphone. The reference method consisted of impulses of the WCD measured with the class-1 device and analyzed by a Scilab program following ISO-3382 Standard.

Firstly, to ensure the reliability of the handclaps, the measurements recorded with the class-1 device from both the handclaps and the WCD were analyzed with the Scilab program. Comparing the two clapping methods ensured that the impulses created by hand are reliable enough to provide satisfying results. Secondly, to verify the reliability of the iPhone's internal microphone and the RT computation algorithm, the measurements of WCD impulses recorded simultaneously by the class-1 device and the iPhone's internal microphone were analyzed. RT results between ClapReverb's algorithm (internal iPhone's microphone data) and the Scilab program (class-1 device data) were compared.

Finally, to validate ClapReverb's calculation method and to ensure that it can provide reliable results with handclaps, the measurements of handclaps recorded by the iPhone's internal microphone and those of the WCD impulses recorded by the class-1 device were analyzed. RT results between ClapReverb's algorithm (internal iPhone's microphone data) and the Scilab program (class-1 device data) were compared.

To compare the methods and to validate ClapReverb, the Mean Absolute Error (MAE) for the three frequency bands for all rooms was computed with Equation 1, where Ref_i is the RT value computed by the reference method, x_i is the RT value computed by the method to validate (step 1 to 3) and N is the number of values. Also, the Mean Relative Error was defined by the difference in percentage between the reference values and the values of the validation method.

$$MAE = \frac{\sum |Ref_i - x_i|}{N} \tag{1}$$

3.3 ClapReverb robustness to ambient noise

In order to have a good estimate of the RT of a room, the handclaps must be significantly louder than the ambient noise level to have reliable data to extrapolate an accurate curve. But there is a certain limit to the sound level that can be produced by handclaps. Different sensibility thresholds can be selected on the application when conducting the measurement according to the ambient noise level in the room. To establish the limit at which the application can provide reliable data, an ambient noise robustness test was performed in a homogeneous acoustic field. The ambient noise level was increased from 35 dBA to 75 dBA while running the application and executing the handclaps. At each increment of 5 dBA, fifteen (15) handclaps measurements were done at a single position 3 meters away from the ClapReverb iPhone. The sensibility threshold was adapted for the application to recognize the claps. Then, the results were compared to the reference RT value of the room to identify the limit where the results stop being reliable.

3.4 Application's algorithm for computing reverberation time

Clapverb's procedure consisted of recording ambient noise and impulses. The user created 5 impulses that were detected automatically and recorded separately. The embedded algorithm to compute RT was coded using the AudioKit library [13]. First, recorded audio signals were downsampled to 6300 Hz to reduce processing time, by applying a low-pass filter and removing samples to reduce the sampling rate. Octave band-pass filters were applied at 500 Hz, 1000 Hz and 2000 Hz. For each impulse and each frequency band, the processing described below is applied, which complies with ISO-3382 Standard.

Automatic detection was performed to find the beginning and the end of the impulse, which is close to the intersection between the sound decay curve and the value of the ambient noise. Then, Schroder's integration was computed and a linear regression was applied to compute the slope of Schroder's integration to deduce the RT_{60} value. An error handling function could exclude RT values having an incorrect slope or time index. For successful computations, the RT is averaged with 3 of the 5 values (maxima and minima removed). If there were one or more errors, the RT is averaged with all values. An information message is shown on the screen to inform the user of the measurement and computation succeed status.

4. Results

4.1 Bias identification and preliminary tests

Clapping with domed hands gives optimal results compared to flat hands since it generates lower frequencies. Realiable RT values were measured at 250 Hz and above with domed hands. Consequently, 500, 1000 and 2000 Hz frequency bands were chosen. These frequencies are accurate enough for ClapReverb's purpose to democratize acoustic within the construction industry. It was also determined that, for practical purposes, placing the device directly on the floor is the best option, although locating it on a chair or a table does not significantly affect the results, and neither does the softness of the surface. The WCD shows steadier and more regular claps as well as providing even lower frequencies than the domed handclaps. Finally, the iPhone's top microphone showed a better performance in a wide range of angles.

4.2 ClapReverb validation

Mean Absolute and Relative Errors (MAE and MRE) for the validation of steps 1) and 2) are summarized in Table 2. Three more rooms were excluded because of high errors that occured with RT less than 0.25 s (MRE of 72.0 % for those rooms with individual relative errors up to 287.7 %).

To validate step 3), two sets of identical tests were compared: one with handclaps and reverberation time computed by ClapReverb's algorithm, and another one with the reference method. The few extreme values that occurred when the RT was below 0.25 s boosted the overall error. The MAE and MRE between ClapReverb and reference method are shown in Table 3. The MAE are respectively 0.11 s, 0.09 s and 0.08 s for 500 Hz, 1000 Hz and 2000 Hz (MRE of 6.8 %, 6.0 % and 6.8 %). Figure 1 displays the ClapReverb error in relation to the RT of the room measured with the reference method as a Bland-Altman plot. The mean difference estimate is 0.001 s (0.2 %) with a 95 % Limit of Agreement (LoA) interval of -0.26 s to 0.27 s (-16.4 % to 16.9 %). Figure 2 is a plot of the RT error in relation to the volume of the room.

Table 2: Mean Absolute and Relative Errors of reverberation time, showing the reliability of handclaps compared to wooden clapping device (step 1), and the reliability of iPhone's hardware and ClapReverb's algorithm with wooden clapping device impulses compared to the reference measurement method and analysis (step 2). Thre rooms with a RT < 0.25 s were excluded.

Handclaps (step 1)		iPhone's hardware and algorithm (step 2)	
MAE (s)	MRE (%)	MAE (s)	MRE (%)
0,06	3,9	0,08	6,0

Table 3: Mean Absolute and Relative Errors of reverberation time, showing the reliability of handclaps measured and computed with ClapReverb compared to the reference measurement method and analysis (step 3).

Including RT < 0.25 s		Excluding RT < 0.25 s	
MAE (s)	MRE (%)	MAE (s)	MRE (%)
0,10	10,5	0,09	6,0

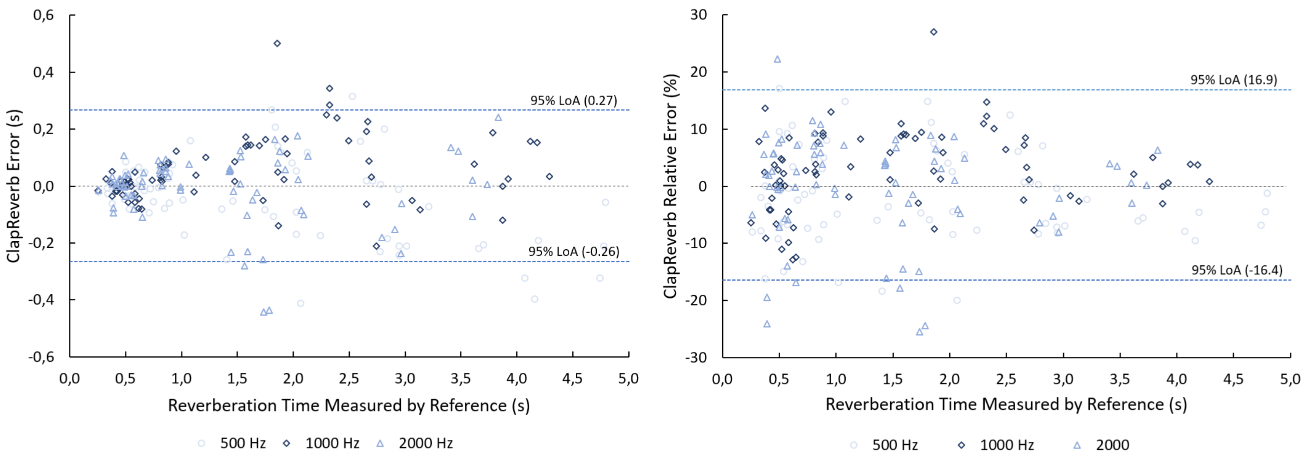

Figure 1: Reverberation time error computed by ClapReverb for all rooms excepted room with RT < 0.25 s, in relation to the reverberation time measured by the reference method (step 3).

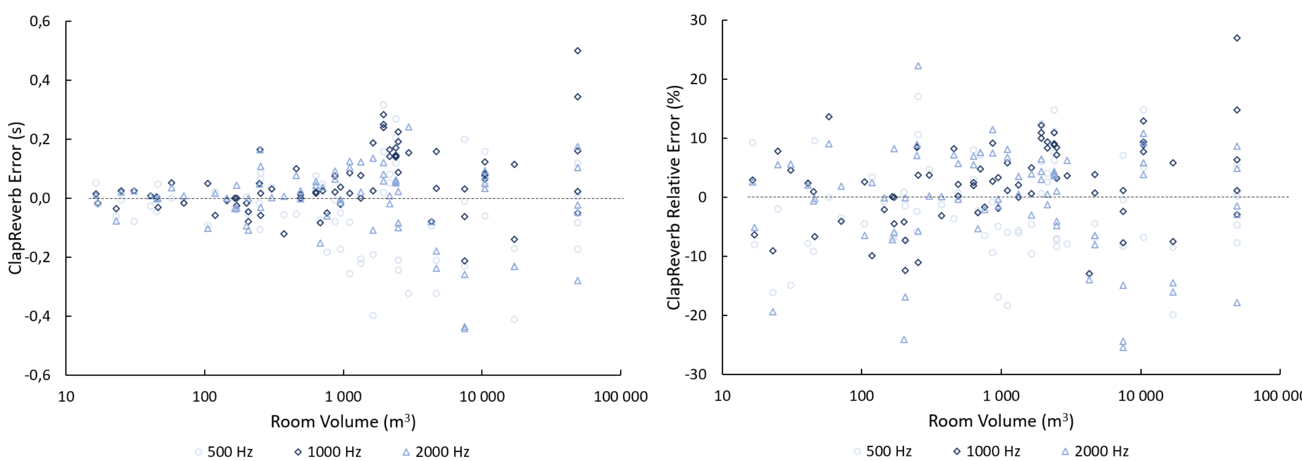

Figure 2: Reverberation time error computed by ClapReverb for all rooms excepted room with RT < 0.25 s, in relation to the volume of the room (step 3).

4.3 Robustness to ambient noise

The reference values were taken with the reference method at the lowest ambient noise level achievable in the room (35 dBA). Experimental results showed an accurate performance of the application below 60 dBA (MRE of 6.1%), except for the 500 Hz frequency band. At 65 dBA, the relative errors are 124 % at 500 Hz, 13 % at 1000 Hz, and 18 % at 2000 Hz, which are too high to provide reliable results. Above 70 dBA, the error varied but was still too high to provide reliable results. Handclaps were not dectected with ambient noise greater than or equal to 80 dBA.

5. Discussion

5.1 ClapReverb validation

Preliminary tests have defined a validation method for conducting the measurements in optimal conditions. The validation of step 1 showed that the handclap impulse method is a valid one at 500, 1000 and 2000 Hz frequency bands even if the handclaps were inconsistent and could differ from one another. ClapReverb is considered as a reliable analysis method with WCD impulses.

For ClapReverb's validation (step 3), there is a 0.09 s MAE (6.0 % MRE) compared to the reference method. When the room RT increases, the error in seconds tends to increase, whereas the relative errors tends to decrease. When the room volume increases, the error in seconds tends to be higher, whereas the relative errors are more consistent. The measurement precision for RT less than 0.25 s is not a major concern. Indeed, it is mainly important for building stakeholders to know if the designed room (studio, movie theater) has a RT value that is low enough for that usage. The application can just inform the user that the RT is less than 0.25 s.

Most errors are caused by the processing, which automatically selects the portion of the recorded signal that will be analyzed to compute the RT. On the other hand, the Scilab program requires a manual selection of the intersection point between the end of the decay curve and the ambient noise level, and so uses different time indexes of the signal to compute the slope. Since the reverberation time slope is not linear, a slight shift in the time boundaries can induce a change in the resulting RT value. The RT values below 0.25 s were unreliable, since the selected portion of the signal was too short to properly extrapolate the RT of the room. Moreover, even if the collected data was measured in optimal conditions, real-life circumstances during measurements induced some errors, such as low-level handclap, low Signal to Noise Ratio (SNR) between handclap and ambient noise, unwanted noise events, or furniture between handclap and microphones. Lastly, part of the errors was probably caused by the quality of the iPhone's microphone, which is not a class-1 microphone, and the kernel software processing that can't be removed.

To conclude, the current version of ClapReverb is a reliable RT determination tool if the RT of the room is above 0.25 s.The room volume and absorption do not have a considerable impact on the result precision. Moreover, the application's performance does not differ significantly between the three studied frequency bands.

5.2 Robustness to ambient noise

The ambient noise in a room can influence the application's results. The errors at 60 dBA are greater at 500 Hz because higher frequencies stand out more from the ambient noise level. As the ambient noise was increased, the trigger level of the application to detect the claps was adjusted. Since there is a maximum power that handclaps can reasonably attain without harming the hands, it is hard to obtain a SNR that provides enough data to extrapolate a valid RT when there is a high ambient noise. Impulse peak levels of at least 20 dBA above the ambient noise level provide reliable results.

6. Conclusion

An easy-to-use smartphone application (ClapReverb) was developed to democratize acoustic and raise awareness of the acoustic domain among the construction industry. Building stakeholders could use it to measure reverberation time and the application gives them tips to better understand room acoustics in their projects. This method does not require any additional hardware since the handclap impulses are recorded using the inboard microphone of the smartphone. This application was tested in 48 rooms with a variety of usage, volume, shape, ambient noise, and reverberation time. Impulses from a wooden clap device were recorded with a class-1 microphone as a reference. The robustness to ambient noise was assessed and showed that the current application provides reliable results for ambient noise below 60 dBA. Overall results showed a mean absolute error of 0.09 s (mean relative error of 6.0 %), which makes the application a promising tool for building stakeholders to support them to make first decisions regarding room acoustics.

ClapReverb is available on the Apple Store. Future work should focus on including the definition D50 criteria, developing the Android application and adding an easy-to-use acoustic material first sizing module.

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