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Room Acoustic measurements with logarithmic sine sweeps on Android phones

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ABSTRACT

An application for room acoustics measurements has been developed for Android devices: its novelty represents the use of the logarithmic sine sweep method which is better than typical direct methods used so far. The article describes the main points of the design phase and stresses the instrument on-site testing results in common use rooms. The testing of this Android instrument gives insights on small-room acoustics and on acoustical parameters measurement quality.

1 Introduction

An accurate measurement of acoustical parameters must follow ISO 3382 [1] standard, this sets the technology and the methods to be used.
Often it is not practical to use the full professional measurement apparatus: in the professional life sometimes it is sufficient to carry out a rapid first survey of the room's acoustics data, with a lower precision grade.
With small projects it can be convenient to use economic instrumentation to obtain first estimates, especially at 500 and 1000 Hz.
For this purpose, an Android and iOS Application "APM Tool" has been developed, starting the project with Redaelli [2] in 2014 and using the direct method to obtain room impulse responses. The application records and analyses the room response to an impulsive signal, produced with a clapper, a balloon pop or even an handclap (this last with a lower quality).
The APM Tool measurement performances are limited partially by the hardware/software characteristics (MEMS, AGC), but also from the modest precision of the direct method itself, which is sufficient for RT measurements at mid and high frequencies but less so for other acoustical parameters. Generally, the generated impulse is always different (poor repeatability), it doesn't energize the spectrum uniformly and it has a bias in the time domain.
For these reasons we developed "APM Sweep", a new software version that integrates the logarithmic sine sweep method to obtain better impulse responses. This indirect measurement method (ISO 18233/2006) requires the use of an external sound source to reproduce the sine-sweep: this source should be omnidirectional to properly excite the room sound-field.
This method allows to shorten the quality gap with professional instrumentation. It allows to bypass the clipping problems and the AGC software limitations that burdens the direct measures of impulses on mobile devices.

2 Logarithmic sine sweep

Logarithmic sine sweep is a sinusoidal signal with exponentially increasing frequency.
If ω_1 e ω_2 are the starting and finishing angular frequencies, the sweep duration is T in seconds, the signal is defined as [3]:

$$x(t) = \sin\left[\frac{\omega_1 \cdot T}{\ln\left(\frac{\omega_2}{\omega_1}\right)} \cdot \left(e^{\frac{t}{T}\cdot \ln\left(\frac{\omega_2}{\omega_1}\right)} - 1\right)\right] \qquad (1)$$

In the frequency domain it has a pink spectrum, decreasing by -3dB/octave. It is possible to calculate an inverse filter, given by the time-mirrored version of x(t). At the inverse filter i(t) is applied an amplitude modulation function [4]:

$$A(t) = C \cdot \frac{\omega(t)}{\omega_0} \qquad (2)$$

Where ω(t) is the inverse filter angular frequency at time t, ω_0 is the angular frequency at the initial time, C is a regularization parameter. After this amplitude modulation the inverse filter ha a +3dB/octave increasing spectrum.
It is demonstrated [3] that by convolving the sine sweep with its inverse filter a pure impulse is generated:

$$x(t) \otimes i(t) = \delta(t) \qquad (3)$$

Every room acoustic behaviour can be modeled via a LTI system, reproducing a sine sweep signal x(t) we can record the room's response modified signal in y(t).
The room's response in time is defined as h(t), its dual in frequency H(f).
From signal elaboration theory we know that the LTI response to a signal x(t) is the convolution of the input signal with the system's impulse response:

$$y(t) = x(t) \otimes h(t) = h(t) \otimes x(t) \qquad (4)$$

Basic signal elaboration theory says that any signal convoluted to a pure Dirac impulse is that signal itself.
By combining this two laws we obtain:

$$y(t) \otimes i(t) = h(t) \otimes x(t) \otimes i(t) = h(t) \otimes \delta(t) = h(t) \qquad (5)$$

Equation (5) demonstrates as by deconvolving the recorded sine sweep y(t) and the calculated inverse filter we obtain the room's impulse response h(t).

3 Schroeder frequency

A well-known acoustic phenomenon within closed spaces is the presence of resonance modes. The resonance modes, or standing waves, are related to the room dimensions. The modal density (i.e. the distribution of resonance modes in the audible spectrum) increases with frequency. Particularly the modal density increases with the square of the frequency. Above a specific frequency, called *Schroeder cutoff frequency*, the sum over modes indices can be approximated by an integral and normal modes can be regarded as a continuum distribution. In this range of frequencies, they should be treated from a statistical point of view (Sabinian sound field) and the impact of individual modes can be neglected. The formula to compute *Schroeder cutoff frequency* is the following:

$$f \approx 2000\sqrt{\frac{T_R}{V}} \qquad (6)$$

where V is the room volume and T_R is the measured reverberation time of the room. Note that *Schroeder cutoff frequency* is inversely proportional to the square root of the room volume, so for small-rooms the effect of normal modes on the frequency response is more relevant.

4 Implementation of the new application

The deconvolutiom procedure we showed has been implemented relying on the "APM Tool" original structure as an alternative to the direct measurement method. The starting and ending point of the user experience is the same in "APM Sweep": a parallel workflow has been added to the original one of the direct measurement method (base on direct impulse response acquisition). In "APM Sweep" the user can choose which measurement method to execute; if logarithmic sine sweep is chosen, the user can now set sweep duration (from a 1s minimum to an 8s maximum) as well as the initial and final frequencies.
Setting long sine sweep durations leads to more accurate measurements but requires more memory and CPU workload.
The new software features allow also to discard some measurement sessions if any disturbing event (i.e. impulses) has occurred during the signal acquisition.

The possibility of keeping track of multiple measurement positions has been maintained in logarithmic sine sweep software procedures.

The application generates the logarithmic sine sweep and computes its inverse filter. The sweep signal is reproduced by means of an external audio connected to the smart device and simultaneously recording the room response.

Hence from this deconvolved impulse response the *EDT*, T_{20}, T_{30}, D_{50}, C_{50}, C_{80} acoustic parameters are calculated by the structures that already exist in "APM Tool", after performing the deconvolution of the room impulse response from the recording of the sweep reproduced in the room and its inverse filter.

These operations are done in memory and require a short elaboration time, based on the hardware-software features of the specific devices.

Frequency-dependent values of the acoustical parameters derived from the deconvolved impulse response are reported both in textual and graphical manner, with possibility to permanently store results in device mass memory and optionally export them in a CSV file. This ensure compatibility with results visualization format and storage structure of APM Tool measurements.

5 MEMS Microphones

Measurement performances of both "APM Tool" and "APM Sweep" have been tested because of hardware characteristics of MEMS microphones integrated on smart devices.

The above-mentioned microphones offer a frequency response that is not linear at the frequency range ends due to their structural and geometric characteristics.

Moreover, their position next to the other electronic components inside the device package modifies the MEMS polar diagram making it not-always omni-directional.

These two hardware limits give a measurement error of acoustic parameters compared with reference values measured with professional devices.

Besides, the actual Leq = 35 - 85 dBA MEMS dynamic range requires a strict control on clipping and the signal gain, which is managed by each producer with their own AGC algorithm [2].

6 Field-test: ordinary room

Several filed-tests have been performed in order to verify the quality of the results given by APM Sweep compared to a professional measurement setup.

As an example, the case study of a 42 m^3 volume ordinary room is proposed here. Three different setups have been compared:

1. professional measurement system with dodecahedron loudspeaker and omnidirectional measurement microphone. The generation of sine sweep signal and the calculation of acoustical parameters from the obtained h(t) has been performed with "Aurora" plugin suite for Audacity [6];
2. "APM Sweep" installed on a LG Nexus 5 device using a dodecahedron loudspeaker as source;
3. "APM Sweep" installed on a LG Nexus 5 device using a commercial 2" Bluetooth loudspeaker as source.

For each setup 5 loudspeaker positions and 3 microphone positions have been used, for an overall combination of 15 different source-receiver positions.

7 Reverberation time T_{20} results

Figure 1 shows the results for reverberation time measurement.

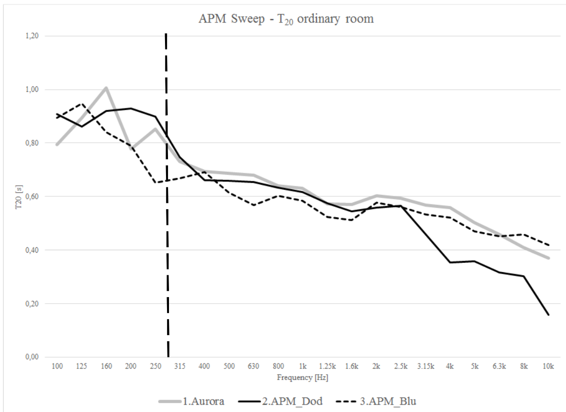

Figure 1. T_{20} results on ordinary room.

As can be seen on Figure 1 the measurement results for reverberation time T_{20} obtained with the professional setup (grey line) are correctly

represented by APM Sweep, both for dodecahedron loudspeaker setup (black continuous line) and for Bluetooth loudspeaker one (black dotted line). The best result quality is obtained from 315 to 2500 Hz.
The vertical dotted line is located on the theoretical position of the *Schroeder cutoff frequency.* Note that below that frequency the difference between the three setup is more relevant: this is due to the influence of resonance modes (different room behavior with small displacement of measurement instruments – not Sabinian sound field).
In Figure 2 is represented the RSD analysis of the 15 reverberation time measurements.

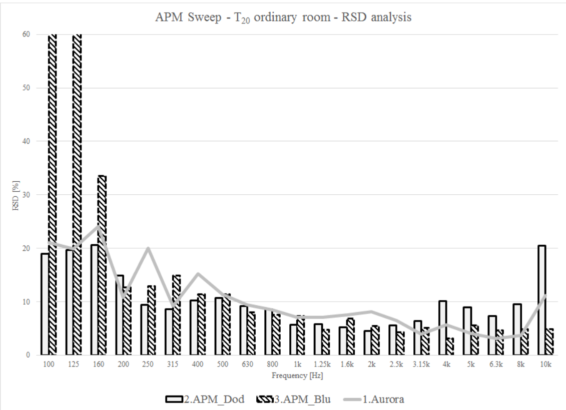

Figure 2. RSD analysis for T_{20} measurement

The RSD (relative standard deviation) is given by the formula:

$$RSD = \frac{\sigma}{\mu} \cdot 100 \quad [\%] \qquad (7)$$

where σ is the standard deviation and μ is the average of the 15 different combinations of source and receiver positions, taken for each setup.
The RSD trend with respect to frequency usually reflects the degree of Sabinianity of the enclosure: if the room is quite Sabinian, an approximately uniform RSD value is expected in the whole frequency range; otherwise, in a case of a non-Sabinian enclosure, a higher RSD at low frequencies is expected and the peaks in that range may be likely attributable to the normal modes distribution. Figure 3 shows that inside a non-Sabinian room, the RSD both APM sweep setup is comparable to professional one in the range 315 to 2500 Hz. Using the small Bluetooth speaker as a source, the RSD values are higher in the low end, due to speaker physical dimensions and restricted bandwith.

8 Clarity indices C_{50} and C_{80} results

Figure 3 shows the results for Clarity Index C_{50} while Figure 4 shows the results for C_{80}.

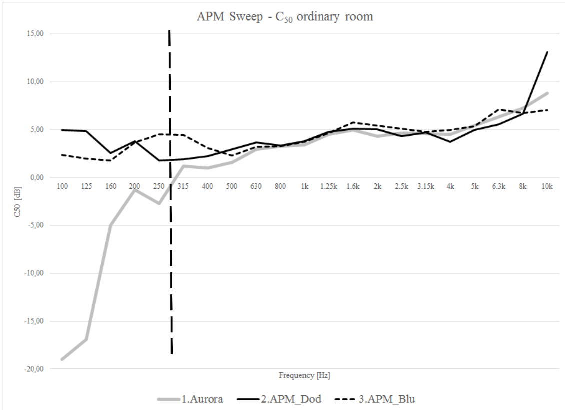

Figure 3. C_{50} results on ordinary room.

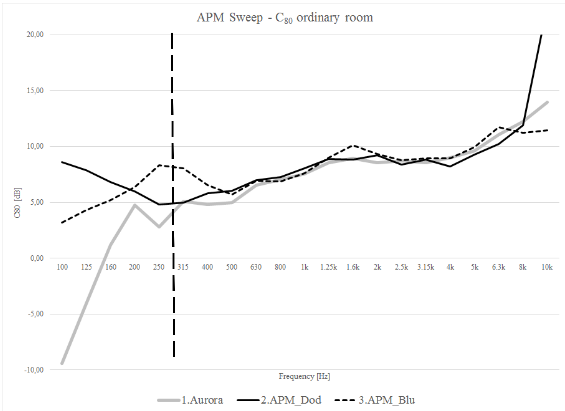

Figure 4. C_{80} results on ordinary room.

As it can be seen in the previous figures, in the range from 315/400 Hz up to 8 kHz, both the setups used with APM Sweep app, show results that are comparable to the ones obtained with professional measurement setup. But the low frequency definition of Clarity should be verified.

9 Field-tests – RT measurement error

Several field tests performed in different acoustic environments showed that (in spite of the hardware limitations illustrated), the implemented logarithmic sine sweep procedure allows a clearly inferior measurement error compared to the direct method with reference to the values measured with professional instruments.

In particular the new procedure allows important reduction of measurement error on parameters of reverberating time at low and medium frequency (under 1000 Hz).

Besides, taking measurements by means of sine sweep easily avoids clipping and AGC interference that is strong on Android devices. These procedural difficulties mainly happen either in small rooms or when powerful impulses are being used.

As a result, D_{50}, C_{50}, C_{80} parameter measurements are also by far more accurate through the sine sweep indirect measurement technique as can be seen on Figure 4 and 5.

For the sake of brevity, we shall now report the graphics of the evaluation error on T_{20} for the tested room. In order to be compared with the RSD of the professional measurement setup, the error for both "APM Sweep" setup has been calculated as showed by the following formula:

$$e(f) = \frac{|v_{ref}(f) - v_{mes}(f)|}{v_{ref}(f)} \% \tag{8}$$

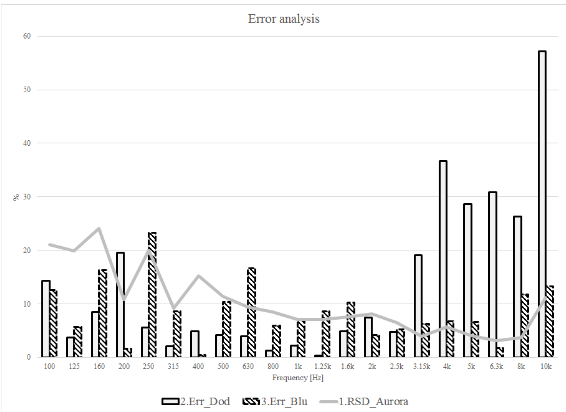

Figure 5. Error analysis.

Figure 5 confirms that the error is often well below the high quality measurement RSD: APM Sweep gives a good measurement error in the range from 250 to 2500 Hz using the dodecahedron and from 800 Hz up to 6200 Hz using the Bluetooth source .

10 Conclusions

By developing the "APM Sweep" application we demonstrated that the indirect measurement technique by means of a logarithmic sine sweep can be efficiently implemented on smart devices, in spite of the hardware limitations inherent in the electronic components (mainly MEMS microphones).

The measurement results for an ordinary room showed that the acoustical parameters evaluated by "APM Sweep" are comparable with the ones obtained with a professional setup, especially above the room's *Schroeder cutoff frequency* and up to 2500 Hz. The use of a very small Bluetooth loudspeaker still allows fair measurement quality at high frequencies.

References

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[6] http://www.angelofarina.it/Public/Aurora-for-Audacity/