PRACTICAL ASPECTS OF THE ISO PROCEDURE FOR MEASURING THE SCATTERING COEFFICIENT IN A REAL-SCALE EXPERIMENT

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ABSTRACT

The procedure for measuring the random-incidence scattering coefficient of surfaces according to the ISO draft ISO/CD 17497 has been tested in real scale experiments. Some practical problems raised by real scale experiments are presented, together with the solutions that have been adopted to solve them. These problems are mainly bound to the great size and weight of the sample (at least 3m diameter), to the stability of the propagation medium inside the test room and to the great number of measurements required.

1. INTRODUCTION

The ISO (International Organization for Standardization) technical committee ISO/TC43/SC2/WG25 is presently working on the publication of a recommendation for the measurement of the random-incidence scattering coefficient of (rough) surfaces [1]. This procedure is based on the measurement of two coefficients :

- the random-incidence absorption coefficient α_s of the surface sample, which is obtained by the usual method in a reverberation room;
- and the random-incidence specular absorption coefficient α_{spec} of the same surface sample, which depends on its scattering properties.

This second coefficient is obtained by placing the sample on a (circular) turntable, in the reverberation room. The impulse response of the room is then measured for several orientations of the sample, while the table is rotating. Phase-locked averaging of all these impulse responses is supposed to eliminate (or at least attenuate) the diffuse components, leaving only the specular contributions in the average impulse response. Finally, backward integration of this response gives the reverberation time associated with the specular component only, and then the absorption coefficient α_{spec} [1].

The two coefficients α_s and α_{spec} are introduced in a simple formula which gives the random-incidence scattering coefficient (s) of the surface sample.

This measurement technique has been mainly tested in (reduced) scale reverberation rooms [2]. This communication reports on full-scale experiments.

2. DESCRIPTION OF THE TEST SET-UP AT THE UNIVERSITY OF LIEGE

The 190m^3 reverberation room looks roughly like a truncated pyramid in which none of the walls are parallel to another. No diffusers are present in this room, so the volume is completely empty. Typical values of the reverberation time (T30) measured in the empty room are :

Octave band :	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
T30 (s) – empty room	18	13.8	11.3	8.3	4.8	2.4
T30 (s) – with turntable	9.3	8.9	8.1	6.2	4.2	2.3

The circular turntable has a diameter of 3 meter. The plate is made of agglomerate wood (16mm thick) on top of which is a thin foil of white laminated wood.

The first practical problem is that the only entrance to the reverberation room is about 2m high. It is therefore impossible to bring a 3m diameter circular sample into this room without cutting it in two (or more) pieces. These pieces must then be assembled inside, in such a way that the resulting gaps or slits between them are as small as possible. This is particularly true for the base plate of the turntable which should be (ideally) plane. Any resulting gap or slit between the pieces may create unwanted scattering at high frequencies. In our experiments, we have tried to minimize this effect by filling the slits with pasta or covering them with a band of sticky paper. As will be explained later, none of these actions had significant effect on the scattering coefficient of the base plate.

Another aspect to be considered is the flatness of the re-assembled plate. Bending or misalignment at the dividing line should be avoided, for example by the use of suitable fastening between the pieces of the table.

One loudspeaker is used as a sound source, its bandwidth covering our frequency domain of interest (i.e. 125 Hz to 10 kHz). No particular care has been taken concerning its omnidirectional character (that's perhaps a point that we should analyze in the future). One or two microphones can be simultaneously connected to our measurement system. The location of the loudspeaker and the microphones are chosen according to the recommendations specified in the ISO draft [1].

The measurement system has been described in a recent publication [3]. The impulse response is here obtained by a logarithmic sine sweep technique. The choice between MLS and log sine sweep has been made for practical reasons, mainly because our system is not able to generate sufficiently long MLS sequences for such a highly reverberant room.

The parameters of the sweep signal have been fixed after the following considerations :

- the frequency domain we are interested in comprises the octave bands between 250 Hz to 8 kHz. The sweep will therefore be generated between 100 Hz and 22 kHz;
- the sweep duration should be long enough, in order to obtain a good separation on the time axis between the linear impulse response and the second-order distorsions [3]. Our tests indicated that at least 15s should be used for the sweep;
- the duration of the silence after the sweep should be long enough, in order to avoid significant truncation errors in the tail of the impulse response. Our tests indicated that at least 10s of silence should be used.

Further reductions in the total emitted signal duration have been adopted. Indeed, it must be remembered that the whole process requires the evaluation of several impulse responses, at least 72 if step-by-step measurements are performed [1]. This is of course a very long process, and every possible time reduction is welcome. Our first experiments have shown that the measured reverberation times are not significantly affected if the logarithmic sine sweep signal has a duration of 12s followed by a silence of 6s.

3. PHASE-LOCKED AVERAGING OF THE IMPULSE RESPONSES

The impulse responses (IRs) are derived from the deconvolution of the signal measured at the microphone, i.e. the response of the reverberation room (including the turntable and the sample) to the log sine sweep signal. The calculations required by the deconvolution can take one or two minutes with our measurement system, for such long impulse responses. The calculation of 72 IRs would therefore last more than two hours, during which the stability of the propagation medium is not guaranteed (see later).

Again, to save time, a phase-locked averaging **of the (72) measured signals** is performed, and only one deconvolution is needed at the end of the process. If the reverberation room is assumed to be a linear and time-invariant system, this is justified (but see discussion below).

Phase-locked averaging of the measured signals is performed by sending, some seconds before the sweep signal, a tone burst consisting of 5 periods of a sine signal at 1kHz (fig. 1). The distances between the loudspeaker, the sample, the walls and the microphone are chosen such that the direct sound is clearly identified in the measured signal. Phase-locking then requires numerical processing of the measured signal : initial time “t=0” is associated with the third crossing point of the direct part of the tone burst with the time axis. Then, the tone burst and its reverberation tail are removed (from “t=0” to the beginning of the sweep) from the measured signal, before averaging.

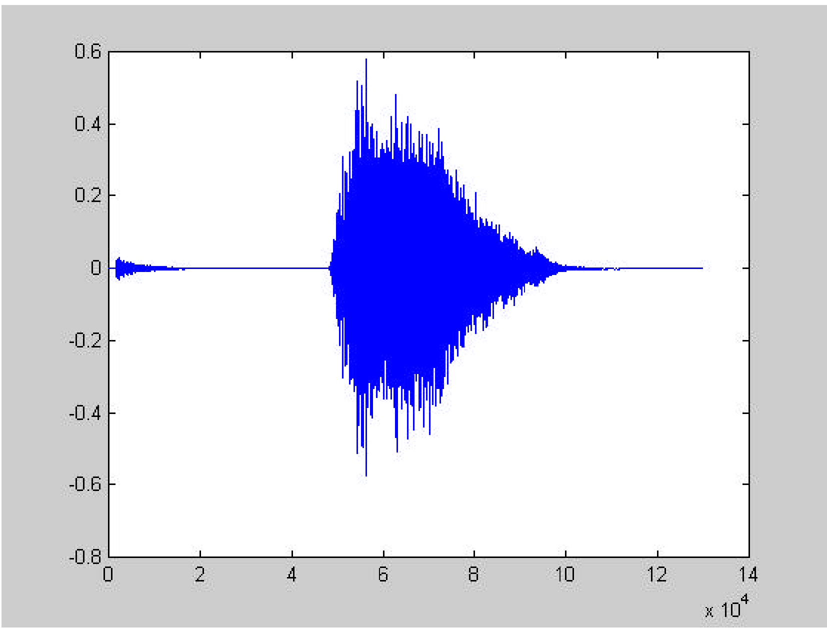

Figure 1 : Sound pressure signal (arbitrary units) measured at one microphone position, showing the 5 periods tone burst followed by its reverberation tail, a silence of some seconds and, finally, the log sine sweep signal (+ reverberation). On the horizontal axis, one unit represents 10 samples.

This technique of phase-locking has been compared during several experiments with the direct phase-locked averaging of the IRs. Only in few cases have we found **small** differences with the reverberation times obtained from the averaged IR. These few cases have been identified as situations where the propagation medium was particularly unstable (for example, during very cold winter days, when cold air from outside could penetrate by accident in the reverberation room). It could be that small variations in air temperature induce small differences in sound speed. Therefore, for a given distance between loudspeaker and microphone, the delay between the tone burst and the beginning of the sweep signal could slightly change. What was indeed observed in these cases is that some individual IRs, computed from their corresponding phase-locked sweep signals, are (by accident) delayed for some few samples at 44.1kHz, by comparison with their expected position on the time axis.

This analysis suggests that the stability of the propagation medium is an important parameter to consider, particularly in full-scale measurements (see also later).

4. BACKWARD INTEGRATION OF THE AVERAGE IMPULSE RESPONSE

This operation has been done according to the ISO draft [1]. In particular, the reverberation times are computed from the slope of the decay curves estimated between –5dB and –20dB (initial decay). Also, the non-linear parts of the average IR (which are inherent to the log sine sweep technique) are removed before integration.

5. ROTATION OF THE TURNTABLE

It was first decided to rotate the base plate step-by-step, and to perform IR measurements for example every 5 or 10 degrees. This decision was initially motivated by our intention to avoid the problem of finding a sufficiently silent motor which could be used in a continuous rotation measurement. But, once this decision was made, the question was "how to rotate the table?".

The first idea was that the operator would himself open the door of the reverberation room after a sweep measurement, manually rotate the table and then quit the room (closing the door) for the next sweep measurement. However, experiments have shown that the cycles of opening/closing the door could significantly affect the measured reverberation times (RT). This can be shown by measuring several times the RT during one or two hours, with or without opening/closing the door. In the first case (WITH), significant differences in RT (more than 0.1s) are observed.

The problem is even more serious when the measured IRs are averaged (**remember that, in our case, the sweeps rather than the IRs are averaged, but the following conclusions are the same**). In that case, the slight variations between the individual IRs are averaged as "near-to-zero", leading to significantly shorter average IR and, thus, significantly shorter RT. This would be erroneously interpreted in the ISO method as "scattering by the sample". The following table shows several RT measured in the reverberation room WITHOUT rotating the base plate (Δt is the waiting time between two individual IR measurements). This table illustrates the effect of opening/closing the door between each IR measurement.

RT (seconds)	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
One IR	11.80	10.62	9.27	6.30	4.12	2.19
Average of 6 IRs - door closed/Δt=1min	11.80	10.61	9.25	6.27	4.08	2.17
Average of 6 IRs - door closed/Δt=4min	11.79	10.59	9.21	6.21	4.04	2.15
Average of 6 IRs - open/close the door	11.76	10.51	8.98	5.95	3.79	2.04

The ISO draft recommends to wait at least 15 minutes (after closing the door) before starting a new measurement. This condition is here clearly violated, **but it is not sure that respecting this waiting time will solve the problem**, since even with the door closed, some slight variations are observed at high frequencies, due to the medium instability. Moreover, 72 measurements at 15 minutes interval would lead to 18 hours for the whole procedure !

These variations between the individual IRs are illustrated by the figure 2, which shows parts of two IRs measured for the same base plate orientation, but at different instants after opening/closing the door. The two IRs are perfectly in phase for the first samples (not shown). The figure shows the delays of about 3 samples observed 1.3 second after the direct sound.

Moreover, it could be shown that this delay increases proportionally with the time measured after the direct sound. This effect can be explained by a slight variation in the speed of sound of some millimeters/sec, or by slight temperature variations of some 0.01°C.

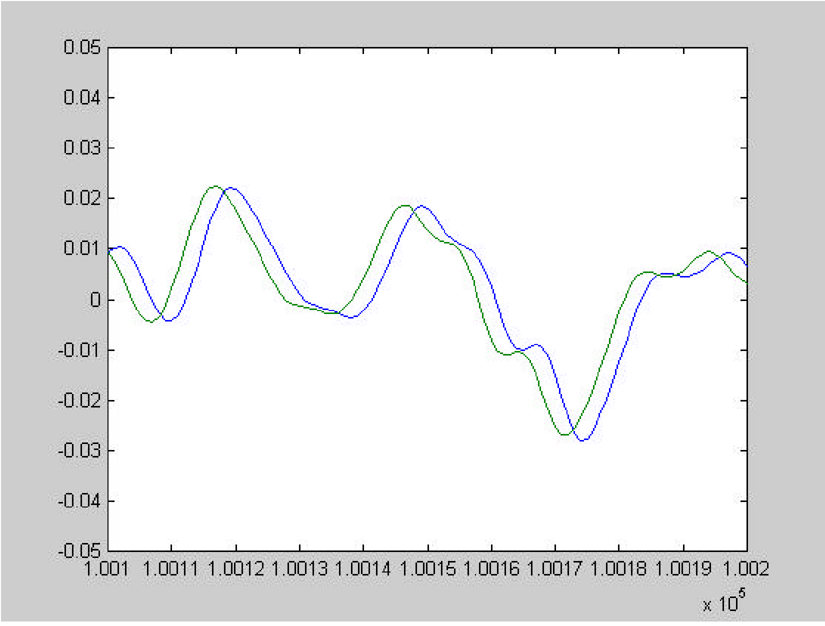

Figure 2 : Parts of two IRs (about 1s after direct sound) showing the delay introduced by opening/closing the door. The two IRs are phase-locked for their first samples (not shown). Horizontal scale is a count of the signal samples.

The second idea for rotating the table was to keep the door closed, but a second operator inside the reverberation room is in charge of rotating the turntable. A simple communication system was installed between the two operators. This idea has rapidly been dismissed, because it lead to still worse results : even with the operator and the table motionless were the RT significantly reduced after averaging.

The final solution was to motorize the turntable. This operation will not be described in this paper, but it can be mentioned that it is not so easy to find a step motor and a rotating system which is able to move such a heavy weight ! So now, with this new procedure, the operator is standing outside the reverberation room with the computer controlling the measurement system **and** the automatic (step-by-step) rotation of the base plate.

6. SCATTERING COEFFICIENT OF THE BASE PLATE

This coefficient should be theoretically zero. In practice, the scattering coefficient s_{base} must be less than a certain limit value which is specified in the ISO draft as a function of frequency (fig.3). The first measurements of s_{base} showed too high values above 2 kHz. These were identified as an effect of (mainly) diffusion (asymmetry) of the base plate. Indeed, the analysis of the IRs measured at different angles revealed more "erratic" differences than in fig.2, which were clearly interpreted as diffusion. However, this diffusion could be created by air movements resulting from the rotation of the base plate. Therefore, we repeated the experiment with the same number of measured IRs, but this time the table was moved back and forth (with an azimuth increment of 12 degrees) such that the IRs were always measured for the same table position. In that case, the equivalent "s_{base}" was found to be close to zero, indicating that the table movements do not seem to create diffusion in the medium.

The base plate symmetry was then checked. Stiffness was improved, bending at the edge was corrected as far as possible. Slits were filled with pasta. But, as already reported, these actions had little influence on the scattering coefficient of the base plate.

Finally, a significant operation was to put down blocs of concrete all around the circular table, to close the cavity between the base plate and the floor. We indeed observed that the only significant asymmetry of our turntable was introduced by a rotating support, situated below the base plate, and whose shape was rectangular instead of circular. With the concrete blocs belt around the turntable, it was intended to prevent sound waves to propagate in the cavity under the base plate and to be reflected by this asymmetric structure.

This operation had a significant influence on the reduction of the coefficient s_{base} which is now below the ISO limit. There still remains an uncertainty on the physical interpretation, but the fact is that it works ! Figure 3 gives a summary of several measurements of the base plate scattering coefficient.

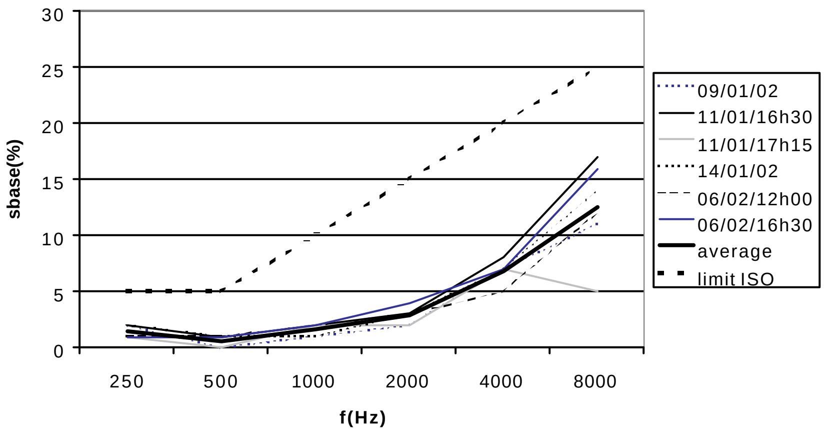

Figure 3 : Results of several measurements of the base plate scattering coefficient, compared with the ISO limit.

Further measurements have been performed for a fiber cement sine shape surface. These results will be reported in another publication.

7. REFERENCES

[1] Draft ISO/DIS 17497-1 : Acoustics - Measurement of the sound scattering properties of surfaces – Part 1 : Measurement of the random-incidence scattering coefficient in a reverberation room.

[2] M. Vorländer and E. Mommertz, Definition and measurement of random-incidence scattering coefficients, *Applied Acoustics* **60** (2000), 187-199.

[3] G.-B. Stan, J.J. Embrechts and D. Archambeau, Comparison of different impulse response measurement techniques, *accepted for publication in the Journal of AES* (scheduled for april 2002).