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# On the use of geometrical acoustic models of a reverberant chamber to improve the reliability of sound absorption measurements

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## ABSTRACT

Measuring sound absorption in reverberant chambers, even when complying with ISO 354 standard, may often return results affected by significant uncertainty, while repeatability is also a well known issue when different laboratories are involved. When considering results from a single laboratory, obtained from a specific chamber, several elements contribute to the quality of the measurement, some of them are more evident (like the diffusers), while others are more difficult to account (like the sample position, mounting, and sealings). With reference to the diffusers, one effect typically attributed to insufficient diffusion is the fact that calculated absorption coefficients are higher than unity. The present paper investigates how these effects may be better understood by means of geometrical acoustic modelling, analyzing the variations in reverberation time (and hence in absorption coefficients), resulting from different positioning of diffusers, as well as locations of sample, sources and receivers in real rooms and comparing them with simulated values.

Keywords: Sound absorption; reverberant chamber; ISO 354

## 1. INTRODUCTION

Sound absorption coefficients of materials and surfaces are normally measured using small samples mounted in a standing wave tube according to ISO 10354-2 standard (1). The method is known to be accurate, but it is limited to normal incidence, and it clearly fails in reproducing real world mounting conditions of larger samples. Under such conditions a measurement in a reverberant chamber, (according to ISO 354 standard (2)), is typically preferred because it also returns the diffuse field behavior of the material and allows measuring sound absorption of objects and materials which require more complex supporting structures (like ceilings, etc.). However, even this method is not immune from criticism. In fact, it is known to return results that are not as accurate and repeatable as desired (3). In fact, the method relies on the measurement of reverberation times with and without the sample to be tested, and on the subsequent calculation of the sound absorption based on the classical Sabine's formula. As it is an indirect measure, the accuracy of the method largely depends on the correctness of the formula used to relate absorption and reverberation time, which normally means that the room must be ergodic, mixing and weakly absorbing to ensure the sound field to be sufficiently diffuse(4,5). For the same reason sample dimension should not be too large to avoid further increasing uneven sound propagation. When one, or more, of the above requirements are not met, use of classical diffuse-field formulas may result in large discrepancies between measured and predicted reverberation time, consequently inducing significant inaccuracy in sound absorption determination.

In order to prevent such measurement problems, qualification tests are usually required by standards. ISO standard 354:2003 (2) poses no limitations to reverberation time variances, but a minimum number of diffusers must be installed so that the measured absorption coefficient reaches a maximum and then remains stable. The recommended area of diffusers is between 15% and 25% of the total surface area, and the panels should have different sizes from 0.8 $m^2$ to 3 $m^2$. Conversely, ASTM C423-17 (6) requires the relative variation of decay rates with microphone position (to be moved in at least five positions) to be smaller than a maximum limit, when the room is empty. The relative variation is expressed as the ratio of the standard deviation between decay rate measurements and their mean value. However, both the qualification procedures fail in some way, considering that a number of round-robin tests (7,8) pointed out significant repeatability issues.

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However, although not recognized by any standard, the effects of room geometry, its diffuseness, and sample placement may be investigated by means of computerized geometrical acoustic (GA) simulation tools. This idea was first introduced by Benedetto and Spagnolo (9) who suggested that, even in a standard reverberant chamber, sound absorption coefficients of materials could be more accurately determined by properly modelling the test room, and obtaining the absorption coefficients of the material by matching the measured and simulated reverberation time. This procedure, like all GA methods, is effective in medium-high frequency range and has been successfully tested in several occasions (10,11), receiving an even more refined treatment based on an iterative least-mean squares optimization (12). The latter approach, if properly applied first to the empty room, and then to the room with the added sample, is expected to provide more accurate absorption coefficients for use in simulation models. In the present paper, taking advantage of a series of measurements carried out in the reverberant chamber of the Laboratory of Building Physics of the Politecnico di Bari, several configurations were investigated, changing diffusers positions and adding sound absorbing patches. The effects of such changes on measured sound absorption coefficients were first discussed. Then, the same configurations were analyzed in the GA simulation tool.

## 2. METHODS

### 2.1 Laboratory measurements

The reverberant room is a 200 $m^3$ space, with a surface area of 208 $m^2$, having six non-parallel walls and a splayed ceiling to aid diffusion. The floor is finished in marble, while walls and ceiling are plastered with a very smooth finishing coated with enamel varnish. Six curved diffusers made of Plexiglas having different shapes and a total two-sided area of 20 $m^2$ are randomly suspended from the ceiling. The area of diffusers corresponded to 10% of the total surface area, thus slightly below the minimum recommended value (2) of 15%. Two loudspeaker positions and six microphone positions were used to obtain average reverberation time values. Sabine's formula was used to calculate absorption coefficients. Air temperature and relative humidity were continuously recorded in order to compensate for air absorption variations throughout each test. Corrections were made according to ISO 9613-1 (13). A 10.8 $m^2$ polyester fiber mat, 2 cm thick was used as test sample.

The measurement equipment included two omni-directional sound sources (Look-Line D301 and B&K 4295), two random incidence microphones (GRAS 40-AR), and a 24 bit/48 kHz sound card (Echo Layla 24). Reverberation time was calculated from impulse responses obtained by exciting the room with a 19 s logarithmic sine sweep.

The chamber configuration was changed as follows.

a) <u>Config. A:</u> Reference configuration; with diffusers suspended to the ceiling, one source position on the corner and one at 1.5 m distance from reflecting surfaces (Figure 1a);
b) <u>Config. B:</u> Damped; same as before, with three polyester fiber panels (10 cm thick, 0.6 m by 1.2 m) located vertically at three corners so to create a varying depth air gap (bass trap mounting);
c) <u>Config. C:</u> Damped with modified diffusers; same as reference with only two polyester fiber panels located at opposite corners (Figure 1b), one of the ceiling diffusers (1.61 $m^2$ area) was mounted vertically on the floor, and one extra wooden diffuser (0.6 m by 0.5 m) was located in a corner. Both source positions were located on the floor close to corners.

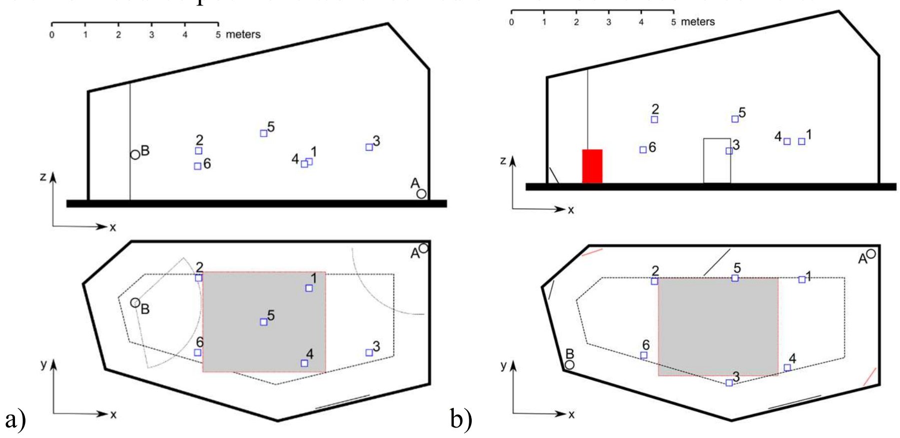


Figure 1 – Plan and cross section of the reverberant chamber under a) config. A, b) config. C

## 2.2 Geometrical acoustic model

The geometrical acoustic model of the reverberant chamber was made using the commercial software CATT Acoustic, with the TUCT v. 1.0 engine (14). This tool provides different algorithms to compute impulse responses, mostly differing in terms of treatment of diffuse reflections. Algorithm 1 always treats first-order reflections deterministically, meaning that each ray is split into a part that is reflected according to the laws of GA and one that is scattered. Conversely, higher order reflections are not split, but are treated randomly depending on the scattering coefficient of the surface (e.g. if the latter is 0.1, 9 reflection out of 10 will be reflected specularly, while the others will be reflected randomly). A more refined method, named Algorithm 2, uses a first degree of actual ray split-up for all reflection orders where all specular-specular and all specular-diffuse reflections are deterministic, while remaining reflection combinations are treated randomly. This algorithm is computationally more demanding and is recommended for room with critical conditions. In the present case, given the very low scattering coefficients used for large flat surfaces, no significant differences were expected between the two methods, so the simpler and computationally efficient Algorithm 1 was used.

The geometrical model used for calculations was dimensionally identical to the real room (Figure 2), with a volume of 200 m$^3$, a floor surface of 45 m$^2$, and an overall surface of 208 m$^2$ excluding diffusers and other movable elements. Sources and receivers were located in the same positions used during the measurements and the sources were assumed to be omni-directional. Calculations were run using the recommended number of ray which was about 37000, and truncation time (i.e. the length of the simulated impulse response, was set to equal the longest measured reverberation time under the same configuration). The Schroeder frequency varied between 430 Hz under empty conditions, and 360 Hz when the sample is in place. Thus, results in the lowest two bands are unreliable and other prediction tools should be used (15). The effect of air absorption was taken into account by properly setting temperature and relative humidity as measured during the on-site survey, so that the software could calculate the appropriate coefficients according to ISO 9613-1.

Absorption and scattering coefficients of the different surfaces were assigned starting from literature values, and subsequently refining them in order to obtain the best match with measured results under the same conditions. Given the nature of the simulation, a maximum difference between measured and predicted values of 1% was considered as acceptable. Reverberation times (T30) measured under the different conditions as listed in Table 1, as well as under no-diffusers conditions, were used as reference. The resulting absorption coefficients are given in Table 2.

With reference to scattering coefficients, given the smooth nature of the surfaces, the values were assumed to be independent of frequency and very low. The typical value which is recommended for flat surfaces is 0.1, but, for the above reasons, all the calculations were carried out assuming also a value of 0.05. No significant variations as a function of scattering coefficients appeared for the empty room, thus suggesting that diffuse conditions are met in the model even when the lowest scattering coefficients are used. For diffusers, the “automatic edge diffusion” option was activated to take into account the diffraction effects at the borders of the panels.

Table 1. Reverberation times measured under the different configurations

| *Room configuration* | *Octave band [Hz]* | *125* | *250* | *500* | *1000* | *2000* | *4000* |
|---|---|---|---|---|---|---|---|
| Empty room | | 10.79 | 11.05 | 10.30 | 8.35 | 6.35 | 4.02 |
| Empty room with diffusers | | 8.68 | 9.64 | 8.87 | 7.83 | 6.15 | 4.05 |
| Empty room with diffusers and dampers | | 5.11 | 4.06 | 2.93 | 2.23 | 1.86 | 1.51 |

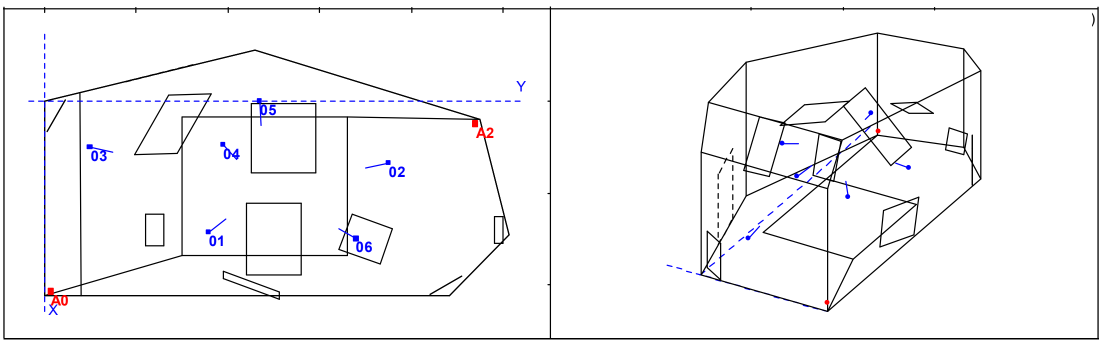


Figure 2 – Plan and 3D view of the GA model of the reverberant chamber

Table 2. Absorption coefficients used in the simulation

| *Material* *Octave band [Hz]* | *125* | *250* | *500* | *1000* | *2000* | *4000* |
|---|---|---|---|---|---|---|
| Marble floor | 0.013 | 0.013 | 0.015 | 0.02 | 0.02 | 0.020 |
| Plastered surfaces finished with enamel varnish | 0.010 | 0.011 | 0.011 | 0.011 | 0.014 | 0.014 |
| Simple door | 0.200 | 0.120 | 0.100 | 0.080 | 0.060 | 0.040 |
| Plexiglas diffusers | 0.033 | 0.020 | 0.020 | 0.015 | 0.012 | 0.010 |
| Polyester fiber panel | 0.600 | 0.840 | 0.940 | 0.950 | 0.920 | 0.960 |

## 3. Results

### 3.1 Measurements

First of all, the results of the measurements of reverberation time (T30) in the empty chamber under the different conditions are presented (Figure 3a). Results show quite impressive variations, particularly when the damping panels are added to the room, showing nearly halved values under config. B and slightly longer T30 values under config. C. As expected, T30 values drop at the highest frequencies as a consequence of the air absorption. In fact, calculation of the total equivalent absorbing area (Figure 3b) in which air absorption is subtracted, shows a rather flat response as a function of frequency. In all the cases total equivalent absorbing area falls below the maximum limit prescribed by ISO 354 standard (2). Thanks to the corner mounting, the polyester fiber panels provided a relatively flat increase to absorbing area, allowing a smooth control of the room conditions without the sample installed.

The absorption coefficients of the test panel were calculated with reference to one-third octave bands (Figure 4a) and octave bands (Figure 4b). Results showed that both configurations B and C provided similar results, while config. A yielded lower absorption values, particularly in the high frequency range, where an underestimation of about 10% appeared.

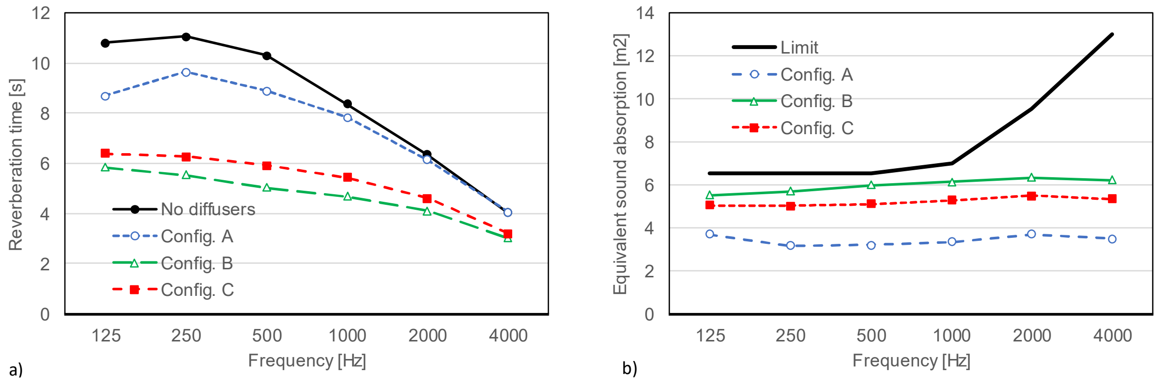


Figure 3 – Plot of a) average reverberation time (T30) and b) equivalent sound absorption as a function of different configurations including ISO 354 limits

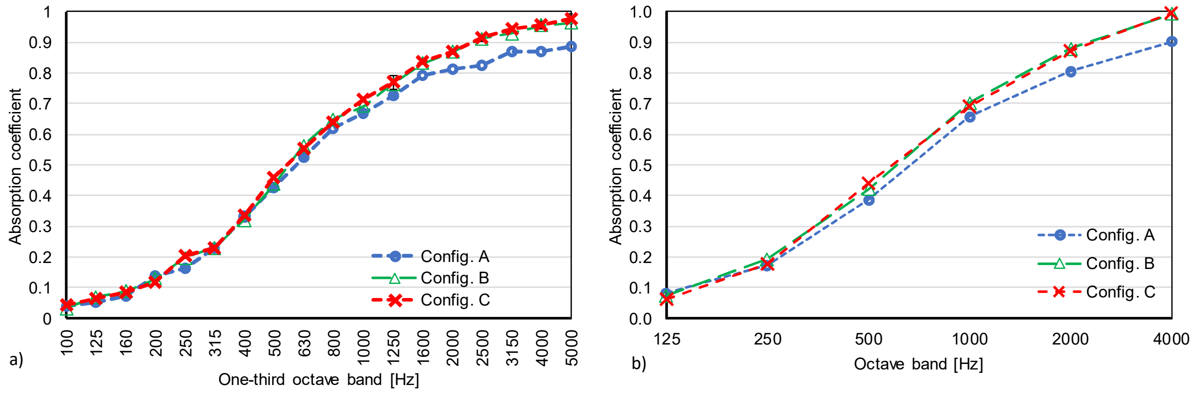


Figure 4 – Plot of ISO 354 absorption coefficients as a function of frequency and of different configurations in a) one-third octave bands and b) octave bands

This behavior could be explained as a consequence of the position of the sample on the floor surface and of the fact that all lateral walls were vertical and without any scattering element, so that slowly decaying reflection paths moving at grazing incidence over the floor, could barely interact with the sample to be tested. Conversely, the presence of sound absorbers and of additional diffusing elements along the vertical surfaces close to the floor contributed to dampen that slowly decaying paths. Thus, the location of damping or diffusing elements close to the floor but on vertical surfaces, a portion of the space which is typically left untreated to ease sample placement and source and receiver movement, actually proved to be effective in obtaining more diffuse conditions and more reliable results.

### 3.2 GA models

Taking into account the above results, the GA model was used in order to answer the following questions:

1) Is it possible to better explain the differences between config. A and the others?
2) Does the GA model respond correctly to changes in room configuration?
3) How could GA models help to improve measurement accuracy?

With reference to the first question, starting from the calibrated model of config. A, the absorption coefficients of the test sample were iteratively changed until the lowest possible difference (below 1%) was found between measured and simulated values. The results of the iterative adjustment procedure were shown in Table 3, suggesting that when the scattering coefficient of the flat surfaces was set to 0.05 an error below 1% was obtained adopting sound absorption values that were in close agreement with those obtained from measurements under config. B and C. If the scattering coefficient assigned to flat surfaces was increased to 0.10 (the default value) a slight decrease in the absorption coefficients of the sample was observed, but they remained fairly close to those measured in configs. B and C, confirming that GA modelling may provide more reliable results than just using Sabine's formula. Finally, in order to define a unique scattering coefficient to be used in the subsequent calculations, the absorption coefficients measured under config. C were used to feed the GA model, and the scattering was changed until a good match between predictions and measurements was found. A value of 0.07 at frequencies from 500 Hz to 1 kHz, and of 0.06 at the remaining bands, was finally assigned. Low frequencies were not included in the optimization and a default value of 0.10 was assigned.

Table 3. Comparison between measured and simulated reverberation times under config. A

| *Material*   *Octave band [Hz]* | *125* | *250* | *500* | *1000* | *2000* | *4000* |
|---|---|---|---|---|---|---|
| Measured T30 | 6.97 | 6.14 | 4.08 | 2.83 | 2.28 | 1.80 |
| Predicted T30 (scattering coefficient set to 0.05) | 6.93 | 6.11 | 4.08 | 2.81 | 2.26 | 1.79 |
| % Error | -0.5% | -0.5% | 0.0% | -0.6% | -0.7% | -0.3% |
| *Sample absorption coefficient* | *0.10* | *0.19* | *0.41* | *0.71* | *0.88* | *0.99* |
| Predicted T30 (scattering coefficient set to 0.10) | 6.92 | 6.09 | 4.04 | 2.81 | 2.25 | 1.78 |
| % Error | -0.6% | -0.8% | -1.0% | -0.6% | -0.9% | -0.9% |
| *Sample absorption coefficient* | *0.10* | *0.19* | *0.41* | *0.69* | *0.85* | *0.96* |

To answer question 2, starting from the calibrated model (including measured absorption coefficients of the sample, and optimized scattering coefficients), reverberation times referred to configurations B and C without and with samples were analyzed and the respective errors calculated. Results, summarized in Table 4, showed that for all the configurations, at frequencies above Schroeder's limit, the errors were typically very small (around 1%) with some exceptions in which errors never exceeded 2.5%. No systematic behavior could be seen in these errors, as they had different signs, took place at different frequencies in different configurations. However, on average, in presence of the sample, slightly larger errors were found, even though they were mostly at lower frequencies, where diffusers are less effective and modal behavior affects measurements. At high frequencies, where the largest variations in measured absorption coefficients were found, with respect to the different analyzed configurations, results were very good. This was an important result, also considering uncertainties related to air absorption, which in the software is computed according to ISO 9613-1 (13) based on actual values of temperature and relative humidity. So, after all, the GA model proved to be a reliable approximation of the room behavior above Schroeder's frequency.

Table 4. Comparison between measured and simulated reverberation times under config. B and C

| *Material Octave band [Hz]* | *125* | *250* | *500* | *1000* | *2000* | *4000* |
|---|---|---|---|---|---|---|
| Measured T30 (Config. B, empty) | 5.84 | 5.53 | 5.03 | 4.69 | 4.09 | 3.02 |
| Predicted T30 (Config. B, empty) | 5.87 | 5.52 | 5.04 | 4.64 | 4.04 | 2.97 |
| Error (%) | 0.51% | -0.18% | 0.20% | -1.07% | -1.22% | -1.66% |
| Measured T30 (Config. B, full) | 5.11 | 4.06 | 2.94 | 2.23 | 1.86 | 1.51 |
| Predicted T30 (Config. B, full) | 5.30 | 4.18 | 2.94 | 2.17 | 1.85 | 1.51 |
| Error (%) | 3.72% | 2.96% | 0.00% | -2.69% | -0.54% | 0.00% |
| Measured T30 (Config. C, empty) | 6.38 | 6.25 | 5.90 | 5.42 | 4.60 | 3.19 |
| Predicted T30 (Config. C, empty) | 6.57 | 6.45 | 5.91 | 5.47 | 4.57 | 3.14 |
| Error (%) | 2.98% | 3.20% | 0.17% | 0.92% | -0.65% | -1.57% |
| Measured T30 (Config. C, full) | 5.62 | 4.57 | 3.18 | 2.42 | 1.97 | 1.55 |
| Predicted T30 (Config. C, full) | 5.90 | 4.69 | 3.26 | 2.40 | 1.95 | 1.53 |
| Error (%) | 4.98% | 2.63% | 2.52% | -0.83% | -1.02% | -1.29% |

In order to answer the last question there are several aspects that could be considered. First of all, it is possible to take advantage of the potential offered by the GA modelling tool to visualize the sound field and, in particular, the position of the image sources (up to the 9$^{th}$ order). Figure 5 compares the distribution pertaining to configurations A and C, as a function of source positions. In all the cases there is a large number of image sources that lay close to the horizontal plane, but in case A their number is larger than in case C, confirming the important role played by grazing sound, and that of the elements that may contribute to absorb or break those paths. The position of the source on the floor also seems to contribute significantly to reduce the spatial distribution of the image sources, while the position off the floor (Figure 5c) makes a much more scattered cloud of image sources, but the concentration of sources along planes parallel to the floor remains and is even more evident (and doubled because of floor reflections).

So, as the increase in scattering coefficient of flat surfaces clearly shortened the reverberation time under fully occupied room, while the empty room proved to be immune as the lengthy reverberation contributed to further diffuse the reflections, a possible use of the GA model could be that of optimizing the distribution of reflectors/diffusers, so to improve diffuse field conditions.

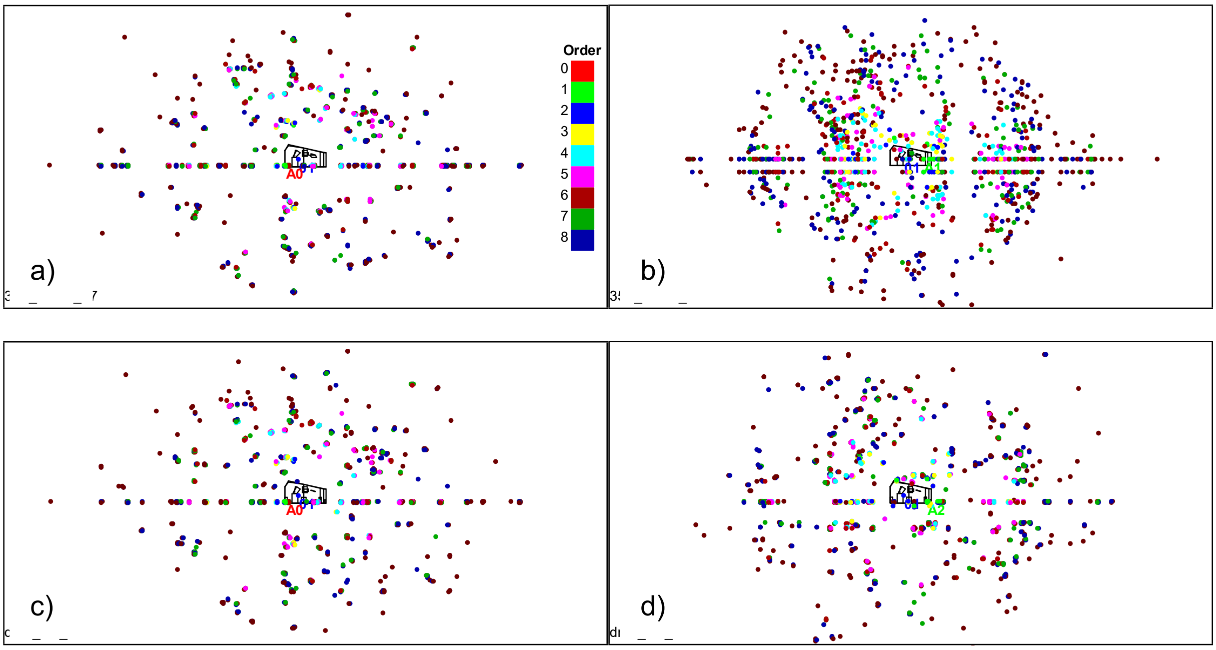


Figure 5 – Plot of the image source distribution as a function of source position and different room configuration: a) Config. A, S-A; b) Config. A, S-B; c) Config. C, S-A; d) Config. C, S-B

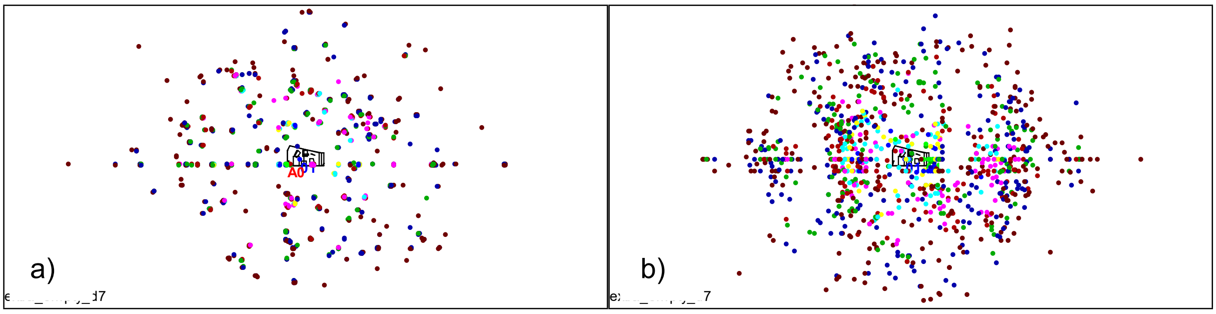


Figure 6 – Plot of the image source distribution (up to 9th order) as a function of source position for the configuration with alternate diffuser placement: a) S-A; b) S-B.

Table 5. Comparison between measured and simulated reverberation times under the optimized diffusers configuration

| *Material* *Octave band [Hz]* | *125* | *250* | *500* | *1000* | *2000* | *4000* |
|---|---|---|---|---|---|---|
| Predicted T30 (empty) | 8.22 | 9.27 | 8.67 | 7.82 | 6.07 | 3.82 |
| Predicted T30 (full) | 7.19 | 6.1 | 4.04 | 2.83 | 2.23 | 1.71 |
| Absorption coeff. (calculated from Sabine) | 0.05 | 0.17 | 0.40 | 0.68 | 0.86 | 0.98 |

As an example, two more 1.3 m square diffusers have been added on the walls located at 0 and 0.65 m from the floor in order to intercept and disrupt persistent and nearly-horizontal paths. The plot of the image source distribution (Figure 6) shows a significant improvement, with a more even distribution of the points and a reduction of those laying on the same plane. In terms of predicted reverberation times, they show in both empty and full configuration an almost perfect agreement with those calculated using Sabine's formula and the resulting absorption coefficients (Table 5) are almost coincident with those used in the model (which are those resulting from measurements in config. B and C). So, controlling reflection paths, without adding any damping material, it was possible to overcome the limitations observed when configuration A was adopted.

## 4. CONCLUSIONS

Geometrical acoustic simulation can be a valid help to support and complement measurements of sound absorption coefficient in a reverberant chamber according to ISO 354 standard. In fact, sound diffusers are typically mounted far from the areas where the sample to be tested must be located, in order to avoid interferences with sources, microphones and operators. However, this leaves room to persistent horizontal reflection paths which may result in an underestimation of the absorption coefficient in certain situations (e.g. when the sample is very thin). Adoption of damping and scattering elements located along the plane parallel to the floor prove to be beneficial to obtaining more accurate measurements. A comparison between the results obtained using different room arrangements and those obtained by geometrical acoustic simulation showed that the latter contributed to immediately obtain the correct sound absorption coefficient even when the results of the less diffuse configuration were used to feed the model. Conversely, using the absorption coefficients resulting from the more diffusing configurations to feed the geometrical acoustic model resulted in very accurate reverberation time prediction under all the analyzed combinations. Finally, taking advantage of the good performance shown by the method, it was used to propose alternative configurations capable of overcoming the observed limitations without the use of damping elements. Further investigations are under way in order to take into account different and thicker samples.

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