Bibliographical reference

Sound Absorption Measurements under Strongly Non-Diffuse Conditions: The Case of the Pastrana Tapestries at Meadows Museum in Dallas, Lisa Pon, Scott C. Douglas and Francesco Martellotta, Acta Acustica **vol. 102** (Number 5), 2016, pp. 955-962

DOI

https://doi.org/10.3813/AAA.919010

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 102 (2016) 955 – 962

DOI 10.3813/AAA.919010

Sound Absorption Measurements under Strongly Non-Diffuse Conditions: The Case of the Pastrana Tapestries at Meadows Museum in Dallas

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Summary
Tapestries have long been considered as alternate means to decorate walls, often combining refined craftsmanship with the use of expensive materials like silk and gold. However, besides their decorative function, tapestries often contributed improvements to indoor conditions, and particularly room acoustics thanks to their sound absorption. The acoustic properties of such materials, although predictable with relative accuracy depending on their physical characteristics, are rarely measured in the literature. Taking advantage of the temporary installation of the Pastrana tapestries at Meadows Museum (Dallas), the reverberation time with and without the tapestries was measured. Despite the non-diffuse conditions observed in the room, the results of the measurements were used to explore the possibility to derive absorption coefficients by means of an indirect approach based on the use of a geometrical acoustic model. Results obtained with this method proved more reliable than those obtained using classical formulas, and they were in agreement with theoretical values derived for thin porous materials of similar characteristics.

PACS no. 43.55.Br, 43.55.Ev, 43.55.Ka

1. Introduction

Medieval and Renaissance tapestries contributed to the magnificence of noble palaces through their designs (at times by famous artists), the labor-intensive weaving techniques they required, and the expensive materials they used (hand-dyed silks and wools, at times wrapped in gold and silver foil). Furthermore, tapestries could contribute to thermal comfort (by increasing surface temperature and thus reducing unwanted heat exchange from occupants' body), as well as to acoustic comfort (by increasing sound absorption and reducing reverberation, thus yielding better conditions for speech intelligibility). Some evidences suggest that occupants were aware of the effects of tapestries. In fact, it was common practice to remove them during the warmer seasons to benefit of a cooler feel from bare walls. From the acoustical point of view, recent investigations also suggest a significant degree of awareness of the better acoustic conditions resulting from addition of tapestries and other ephemeral installations [1, 2, 3, 4, 5].

Acoustical behavior of tapestries can be studied assuming them as thin porous sound absorbing materials whose properties are well known and understood [6, 7]. Their sound absorption mostly depends on surface mass and flow resistivity, which is a measure of how easily air can enter the pores. Their theoretical behavior can be predicted with relative ease under simplified boundary conditions (i.e. normal incidence of sound waves, fixed distance from back wall), but things get more complicated when real world conditions apply. The effect of draping, incidence from various angles, different tensile levels due to hanging conditions may often prevent any simple generalization. Probably for the same reasons, it is not so simple to find experimental acoustic data, that are more frequently collected for simple curtains close to walls, or draped, and much less frequently for tapestries and paintings [8]. The variables affecting the final result may prevent generalization, but considering the very limited literature dealing with acoustic characterization of artistic artifacts [9], any additional contribution may be useful to broaden knowledge about their actual contribution to room acoustics. For the above reasons, the present paper took advantage of the temporary exhibition of four "Pastrana Tapestries" held in

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Received 26 May 2016,
accepted 8 July 2016.

SMU Meadows Museum in 2012 [10], to determine their acoustic properties.

Absorption coefficients of textile materials are normally measured using small samples mounted in a standing wave tube (according to ISO 10354-2 standard [11]). 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 [12]), may be more appropriate as it also returns the diffuse field behavior of the material. In this case the test room volume should be between 200 and 500 m^3, and the sample dimension should be between 10 and 12 m^2. If the room is larger than the conventional 200 m^3, the sample area should be increased by a factor $(V/200)^{2/3}$. 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 [13]. A third option, particularly interesting when the object of the measurement is very large or difficult to move into a reverberant chamber, might be represented by measuring absorption characteristics directly on-site [14, 15], but even these methods present a number of limitations, particularly when used indoors. So, the lack of a "perfect" approach explains why reverberation chamber measurements are still preferred to characterize sound absorption.

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 [16, 17]. For the same purpose 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, as in the present case, 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. So, a fourth option may be considered. In fact, availability of computerized geometrical acoustic simulation tools allows modeling sound propagation in rooms by taking into account their actual behavior and the effect of the sample to be tested. So, Benedetto and Spagnolo [18] suggested that, even in a standard reverberant chamber, sound absorption coefficients of materials could be determined with better accuracy by properly modelling the test room, and obtaining the absorption coefficients of the material by properly matching the measured and simulated reverberation time. This procedure has been successfully tested in several occasions [2, 19], and it has received an even more refined treatment based on an iterative least-mean squares optimization [20]. So, taking advantage of the opportunity offered by the geometrical acoustic approach, and considering the almost unique occasion to acoustically characterize a historically relevant piece of tapestry, the results of the measurements and the relative elaborations are presented and discussed below.

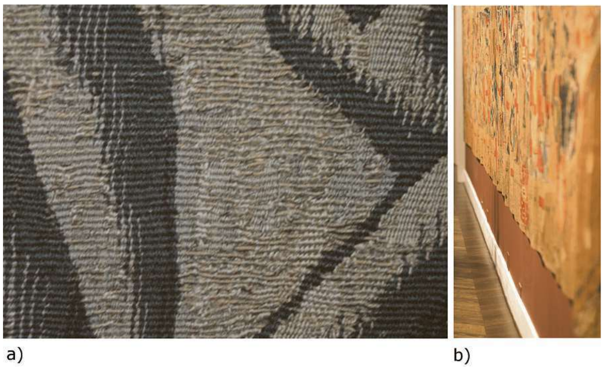

Figure 1. a) Detail of the tapestry (Courtesy of Fundación Carlos Amberes, Madrid); b) View of one of the tapestries hung in the Meadows Museum.

2. Methods

2.1. The tapestries

The four Pastrana Tapestries, approximately 11 m by 3.5 m each, were commissioned by Portugal's King Alfonso V (1432–1481) to celebrate and commemorate his conquests of Asilah and Tangier in the summer of 1471. The tapestries were woven in Tournai workshops in the late 1400s. Their original intended location is now unknown, though one scholar plausibly suggested Lisbon's Paço dos Estaus, built around 1450 to house the visiting foreign dignitaries who would have been the natural audience for the tapestries' political message [21]. In 1664, the tapestries were donated to the Collegiate Church of Our Lady of the Assumption in Pastrana (Spain), where they are now displayed in the church's sacristy, which has become the *Museo Parroquial de Tapices de Pastrana*.

Between 2008 and 2009 the tapestries were carefully restored (as can be seen in Figure 1a) and prepared for exhibition and travel by the firm De Wit and Sons, in Belgium [10]. Each tapestry was cleaned, backed with a linen lining, and fastened by means of velcro strips (fixed to its top border) to a strip 30 cm high and 1.25 cm-thick, made of medium density overlay, covering the whole length of the tapestry and attached to the gallery wall. This technique of using a continuous Velcro strip adheres to modern standards of conservation, avoiding the "scalloping" of a tapestry's top edge caused by the stress from rings attached to the textile and suspended from hooks on the wall, the method most likely used historically. Whichever hanging technique is used, as the tapestries' yarns stretch and contract at different rates and to different extents, there is a fair amount of undulation, so that distance from the wall likely ranged between 0 and 5 cm (Figure 1b).

Figure 2. The installation of the Pastrana tapestries in the gallery at Meadows Museum.

2.2. The room

After the restoration work, the tapestries were shown in several temporary exhibitions located in Europe and United States. One of these exhibitions was held in Meadows Museum in Dallas, which is part of the home institution of two of the authors, thus offering a unique occasion to carry out the measurements. Tapestries were installed each one on a different wall of a 17.7 m square gallery having a 5.38 m ceiling (Figures 2 and 3). The walls are 2 cm plywood behind 1.5 cm plasterboard and 1.5 cm sheetrock. The floors are 1.25 cm wood tiles. The ceiling is made of mineral fiber panels (USG Premier Nubby), 25 mm thick. During measurement sessions all the doors were closed, temperature was 21 °C and relative humidity was 46%. No significant variations appeared between the sessions with and without the tapestries installed. The overall room volume is 1685 m^3, with a floor surface of 313 m^2.

2.3. Measurement method

Measurements of the reverberation time of the room were carried out according to ISO 3382-2 standard [22], using the survey method which is stated to be appropriate for the assessment of the amount of the room absorption. A computer-generated noise burst was emitted using two Adam A7 speakers set 2.7 m apart and roughly 0.6 m in front of a wall. The loudspeakers are not omni-directional, but for the survey method this is not a mandatory requirement. All recordings were made using omnidirectional microphones placed in front of the loudspeakers, beyond the minimum distance required by the standard. Repeated measurements were carried out and the resulting reverberation time (T_{20}) was calculated.

2.4. Determination of absorption coefficients

Under diffuse field conditions, determination of absorption coefficients can be carried out using the standard approach, by means of classical Sabine's and Eyring's formulas. They can all be written in the form

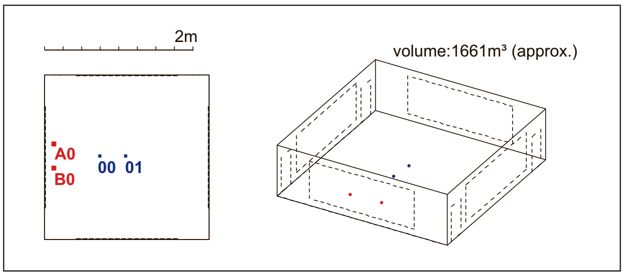

Figure 3. Source (A0,B0) and receiver placement in the gallery at Meadows Museum.

$$T = 0.161 \frac{V}{S\alpha + 4mV}, \tag{1}$$

where V and S are the volume and the total surface area of the room, respectively, m is the sound attenuation constant of the air (which can be estimated using ISO standard 9613-1 [23]), and α is the "absorption exponent".

Different absorption exponents can be used according to the formulas to be applied. The most widely used formula is that defined by Sabine, for which the absorption exponent is simply the average absorption coefficient given by

$$\alpha_{Sab} = \frac{1}{S} \sum \alpha_i S_i. \tag{2}$$

An alternative formulation was proposed by Eyring, according to which the reverberation time had to become zero when the absorption exponent was set to unity, resulting in the relation

$$\alpha_{Eyr} = -ln(1 - \alpha_{Sab}). \tag{3}$$

This formula is often used in the presence of high absorption (ideally when α_{Sab} is larger than 0.1). Further variations of such formulas were proposed by other researchers in the effort to better fit the actual conditions found in rooms, particularly when dealing with non-uniform distribution of sound absorption [24]. The formula has been re-arranged also to fit a two-dimensional case, when one surface is markedly more absorbing than others [25]. However, one of the best performing variations [26] was proposed by Arau-Purchades [27], according to which the absorption exponent is given by

$$\alpha_{ArP} = \left[-ln(1-\alpha_x)\right]^{S_x/S} \cdot \left[-ln(1-\alpha_y)\right]^{S_y/S} \cdot [-ln(1-\alpha_z)]^{S_z/S}, \qquad (4)$$

where S_x is the ceiling plus the floor surface area, S_y is the surface area of both side walls, and S_z is the surface area of both end walls. In addition, α_x, α_y, and α_z are the mean absorption coefficients of the surface areas S_x, S_y and S_z.

In order to derive absorption coefficients according to classical formulas, the absorption exponent is determined for both the conditions with and without the sample (the tapestries, in this case). The latter is used to obtain the residual absorption (i.e. the absorption pertaining to the room). The first, including the contribution of the sample, is used to retrieve its absorption coefficient.

2.5. Determination of absorption coefficients using a geometrical acoustic model of the room

As anticipated, in the present case the room could hardly be considered as a reverberant test room, having a larger volume, a regular shape, and a large sound absorbing ceiling, causing uneven distribution of sound absorption under empty conditions. Under these conditions an indirect estimation of the absorption coefficients based on the Benedetto and Spagnolo [18] method is the only possibility to get a reasonably accurate estimation of the absorption coefficients.

The method takes advantage of the potential offered by computerized acoustic simulation carried out through geometrical acoustic (GA) models and requires a first calibration of the “empty room” model, during which all the acoustic parameters pertaining to room surfaces must be defined. During this step, absorption and scattering coefficients of surfaces must be adjusted so that the predicted reverberation time matches the measured one. Once this step is completed, the “sample” to be measured is added to the model and its absorption and scattering coefficients are adjusted until the predicted reverberation time matches the one measured in the actual room with the samples inside. Clearly, in order to be effective, the method requires an accurate modelling of the actual room behaviour. The more refined procedure proposed by Pelzer and Vorländer [20] could not be implemented because it required measured impulse responses (which were not available because the room was excited by noise bursts), and because the geometrical acoustic tool did not provide access to the requested information.

In the present case the commercial software CATT Acoustic was used and the simulation was run using the TUCT v. 1.0 engine [28]. Given the expected non-diffuse behavior of the room, the so-called “Algorithm 2” was used, as it ensured more accurate predictions of acoustic parameters under critical conditions (mostly at the expense of computation speed), and a significant drop in run-to-run fluctuations due to random processes.

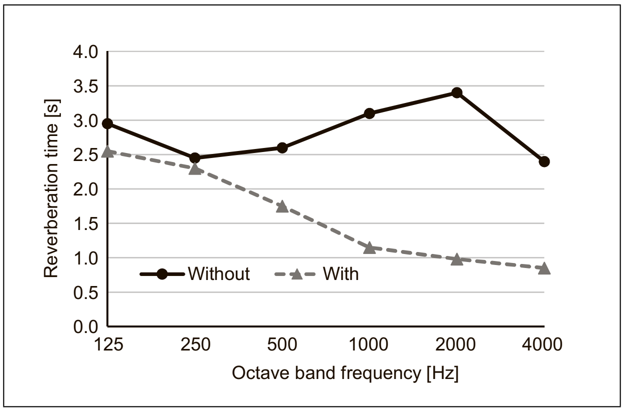

Figure 4. Reverberation times (T_{20}) measured in the room with and without tapestries.

3. Results

3.1. Application of classical formulas

Results of the T_{20} measurements for both the empty room and the one with tapestries are given in Figure 4. Significant differences appeared in the high frequency range, while at low frequencies T_{20} values with and without tapestries were more similar. In the empty room, despite the large amount of absorbing materials located on the ceiling the reverberation time remained rather long, confirming that lack of diffusion made that treatment largely ineffective in agreement with the findings of Nilsson [29]. Application of the tapestries on the walls determined a more even distribution of sound absorption, and an increased diffusion due to scattering effects close to borders. As a result, at high frequencies, a dramatic drop in T_{20} appeared.

Following the above observations, the calculation of absorption coefficients according to classical formulas given in Section 2.4 was carried out. Considering that textiles are mostly transparent to sound at low frequencies (so that the wall contributes to absorption even if covered), and that at high frequency their absorption coefficient is certainly larger than that of the underlying wall, α values were given with no correction for the covered area. The resulting Sabine's absorption coefficients (α_{Sab}), were given in Figure 5, and were very low below 500 Hz and then rapidly rose to 1.2 at 2 kHz and above. At all frequencies, absorption values were higher than expected. At low frequencies this might depend on the transmission through tapestries which was not negligible in that frequency range. At high frequencies, values of α_{Sab} greater than one appeared. This characteristic usually happens when objects and samples have exposed borders (like chairs and thick panels), but in this case it was clearly a consequence of the non-diffuse acoustic conditions as it will be demonstrated below.

As the tapestries covered a large area and, together with the ceiling, introduced significant absorption in the room, Eyring's formula might be more appropriate to perform calculations. In fact, the corresponding absorption coefficients were lower than those previously calculated, but they still remained rather high for a tapestry hung straight close to a wall. So, a final calculation was carried out using Arau-Purchades formula which should be able, at least in principle, to account for inhomogeneous distribution of sound absorption. In this case, the formula requires three different absorption coefficients, one for each Cartesian axis. Anyway, due to geometrical symmetry, in the present case they reduced to two, one for the z-axis, including floor and ceiling for which absorption coefficients were taken for granted (see Table I and next Section for details), and one for vertical walls, for which α was derived from the measured T_{20}. The resulting values were similar to those previously obtained at low frequencies, while they were lower in the higher frequency range. So, among the three formulas considered, Arau-Purchades' formula at least managed to provide more realistic results, proving its usefulness in environments with uneven distribution of sound absorbing materials.

3.2. Application of the alternative method

Finally, the indirect method based on the GA simulation was used, according to the procedure outlined in Section 2.5. The finishing and materials of the different surfaces were carefully analyzed in order to assign the most suitable absorption coefficients during the simulation. The absorption coefficients of the ceiling (which includes lighting and air conditioning inlets), were derived from the technical specification of the product. The floor and the doors were rather conventional and were consequently assigned typical values taken from the literature [6], with minimum adjustment to account for specific features (and ease model calibration). The whole set of data is given in Table I. Finally, walls had a multi-layer composition, resulting in a 5 cm thick panel which was assigned literature values of absorption coefficients corresponding to a 5 cm thick wood, slightly reduced in the high frequency range due to smooth finishing. However, absorption and scattering coefficients of walls played a major role in determining the acoustics of the room under unoccupied conditions, and required a careful fine-tuning to avoid errors.

Initially, only absorption coefficients were modified, while scattering coefficients were kept to 0.1 for all surfaces as it is typically recommended for flat surfaces[28]. However, a proper match with measured reverberation times proved impossible even by minimizing absorption coefficients at high frequencies. Conversely, at low frequencies even using the initial literature values the agreement was rather good. Thus, considering that previous experience with the same tool and with simplified geometries showed that scattering coefficients as low as 0.1 were sufficient to build up a diffuse field under evenly distributed absorption conditions [30], it was concluded that scattering coefficients lower than 0.1 might be needed to take into account the flat and scarcely diffusing behavior of the walls. In fact, as shown in Figure 6, increasing scattering coefficients to 0.15 further emphasized the effect of the ceiling and caused T_{20} to systematically decrease, although by a small amount. Clearly, under such conditions even assuming perfectly rigid walls ($\alpha = 0$), it was again impossible to match measured values. Conversely, when scattering coefficients were lowered to 0.05 over all frequencies, a much larger increase was observed in T_{20}, with a good agreement at high frequencies, while things worsened in the low and medium frequency range.

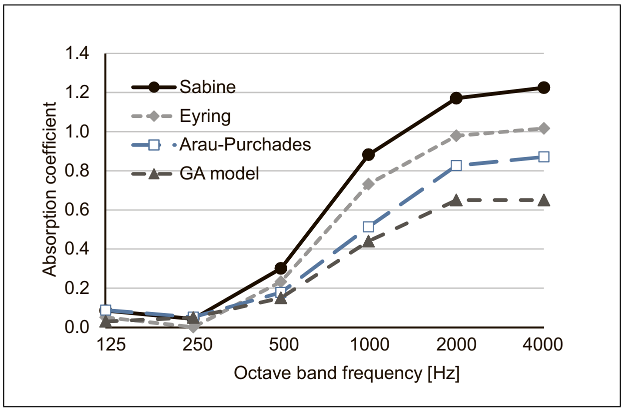

Figure 5. Absorption coefficients calculated according to different methods.

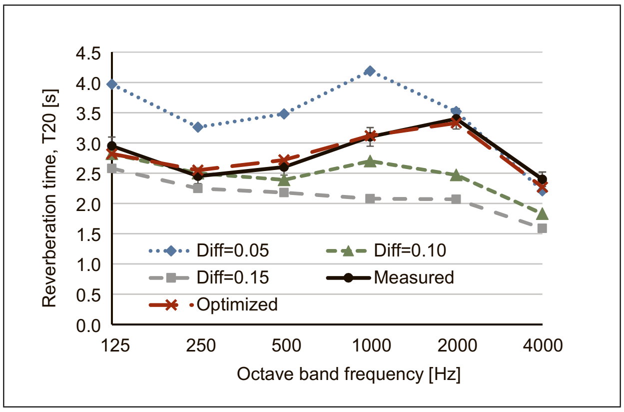

Figure 6. Reverberation times (T_{20}) measured and simulated in the room under bare walls conditions and using different scattering coefficients for the walls. Error bars on measured values correspond to JND.

Now, at low frequencies the smaller vertical dimensions of the room, combined with the presence of the doors, increased diffraction effects (and consequently scattering coefficients), while such effects become less effective as the frequency grows as the walls are large compared to wavelength. A similar transition from a more diffuse behavior at low frequencies and a more "bidimensional" behavior is also considered by Tohiama and Suzuki [25]. So, the above considerations combined with the results shown in Figure 6, suggested to use scattering coefficients that decreased from 0.10 in the lowest bands (125 and 250 Hz) to 0.08 at medium frequencies, and finally to 0.05 at high frequencies. The resulting agreement between measured and

Table I. Summary of the absorption coefficients assigned to room surfaces based on their characteristics. [1]: Reference [6], with small adjustments (±0.02) to calibrate the model. [2]: USG Ceiling System Catalog; values equal or greater than 1 were limited to 0.99.

	Area [m^2]	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Floor (wooden planks)[1]	313	0.04	0.04	0.03	0.03	0.03	0.02
Walls (5 cm wood)[1]	350	0.03	0.05	0.05	0.04	0.03	0.03
Wooden doors[1]	24	0.14	0.10	0.08	0.08	0.08	0.08
Ceiling[2]	313	0.54	0.53	0.91	0.99	0.99	0.99

simulated T_{20} is shown in Figure 6, with differences well below JND.

When tapestries were added to the model, to keep into account diffraction effects at borders of the tapestries and the undulation of their surface, the corresponding scattering coefficients were set to 0.10 at all frequencies. The resulting absorption coefficients (Figure 5) were in good agreement with those calculated using classical formulas at low frequencies, while they decreased significantly at high frequencies in agreement with the expectations related to the non-diffuse behavior of the room under “empty” conditions. In fact, reverberation was dominated by the slowly decaying reflections bouncing between vertical walls, while reflections impinging on the absorbing ceiling vanished rapidly. Conversely, when walls were covered by tapestries, the evenly distributed absorption made the sound propagate according to more diffuse conditions. So, in the light of the above considerations, taking into account all the limitations that affected the measurements, and in comparison with values obtained from classical formulas, absorption coefficients resulting from the GA model could be considered as the best approximation of real values.

4. Comparison between measured and theoretical absorption values

In order to validate the results of the absorption coefficients obtained by means GA modelling, having no “reference” measured values, it was interesting to compare them at least with theoretical values. In fact, tapestries are porous materials whose acoustic behavior can be predicted with reasonable accuracy at least under ideal conditions (no drapes, constant distance from wall, etc.). A summary of the theory used to get such values can be found in [6, 7]. It can be reminded here that according to Kuttruff [7] for very thin layers of porous absorbers, like curtains, when the fabric has a finite mass and can be supposed to vibrate as a whole, its characteristic impedance can be expressed as a simple function of flow resistance (σ_s), surface mass (m), and angular frequency ($\omega = 2\pi f$),

$$Z_r = \left(\frac{1}{\sigma_s} + \frac{1}{\mathrm{j}\omega m}\right)^{-1}. \tag{5}$$

However, for curtains and textiles, the largest contribution to sound absorption derives from the air gap between the material and the rigid wall behind it. In this case the impedance of the air gap depends on its thickness (d), on the wave number in air ($k = \omega/c_0$), and on characteristic impedance of air ($Z_0 = \rho c_0$), with c_0 being sound speed in air and ρ its density,

$$Z' = -\mathrm{j}Z_0 \cot\left(kd\right). \tag{6}$$

The resulting impedance Z_s is consequently obtained as the sum of the above terms, taking into account that in case of oblique incidence a dependence on the angle also appears. Once the impedance of the layer has been determined its reflection factor can be calculated as

$$R = \frac{Z_s - Z_0}{Z_s + Z_0}, \tag{7}$$

and the absorption coefficient is finally given by $\alpha = 1 - R^2$. Given the angular dependence, under diffuse field conditions an average over all the possible incidence angles is needed.

In the present case the tapestries have an average thickness of about 3 mm, with small variations due to weaving. Their surface mass and flow resistance were not directly measurable, so they were estimated by comparison from visual inspection of the samples and consultations with textile conservators, and assumed respectively equal to 800 g/m^2 and 600 Pa·s/m. In order to take into account the uncertainties resulting from this estimation, absorption coefficients were calculated for all the possible combinations of the above parameters assuming variations of ±20%. Figure 7a shows the absorption coefficients calculated using different distances from the wall under a perfectly diffuse sound field. Variations due to uncertainties were larger at higher frequencies and smaller distances from walls, with absolute differences rarely exceeding 0.05. However, the largest differences appeared as a function of distance from wall, with values estimated using GA model closer to the curves corresponding to farthest distances, and particularly to the values at 2 cm. When predicted values were averaged over the different distances from the wall (Figure 7b), the measured values obtained from the GA model were in good agreement with the both the averages calculated over the largest distances, with absolute differences usually below 0.05.

Considering the approximations introduced in the theoretical model due to limited knowledge about the actual characteristics of the Pastrana tapestries (the effect of the back lining was not taken into account at this stage), the

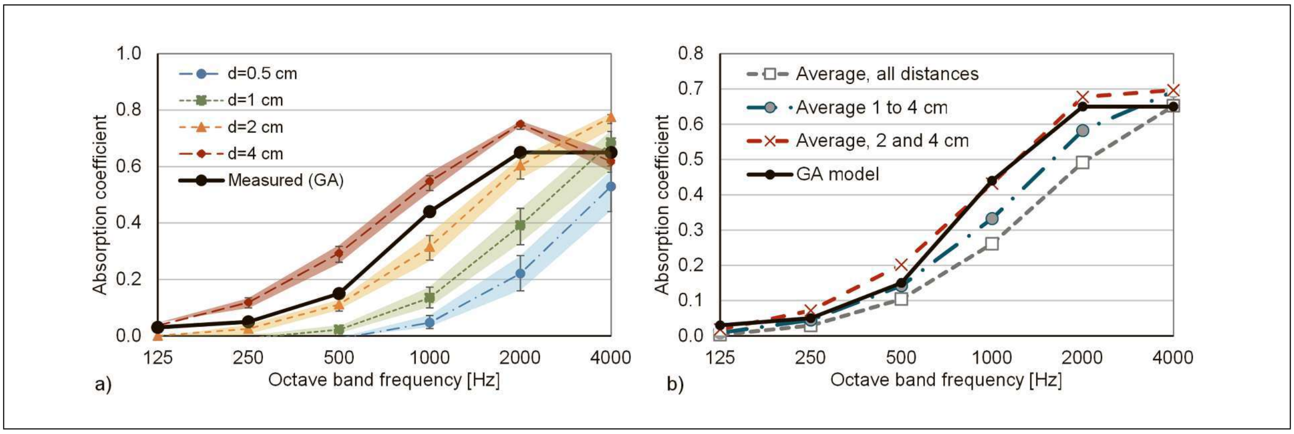

Figure 7. Absorption coefficients measured and predicted according to theoretical model. a) Theoretical values calculated for diffuse sound field as a function of different distances from wall. Shaded areas correspond to variations due to a ±20% uncertainty in input parameters. b) Theoretical values calculated for diffuse sound field averaged over different distances from wall.

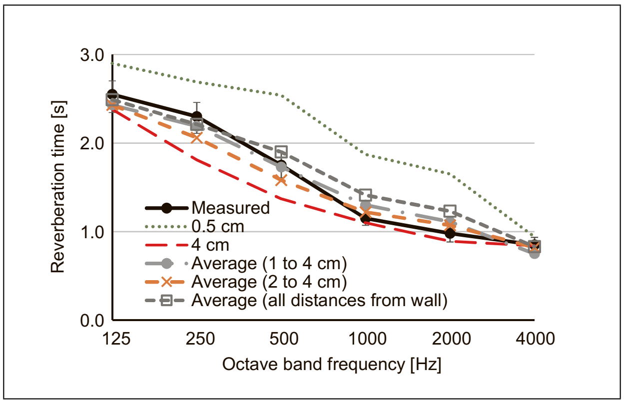

Figure 8. Reverberation times (T_{20}) measured and simulated in the room using different combinations of theoretically determined absorption coefficients (as given in Figure 7). Error bars on measured values correspond to JND.

above results showed significant agreement with those derived from GA model. This suggests, on one side, that despite the difficult environment the use of GA model allows overcoming most of the limitations related to using classical formulas, yielding values that are consistent with theoretical values. On the other side, when the measured absorption coefficients are not available, but the physical properties of the tapestries and their mounting conditions are known with sufficient detail, theoretical models may offer a good alternative to using experimental values which may not fit the actual characteristics, with drapes and mounting conditions representing the main source for discrepancies.

In order to perform a final check of this latter hypothesis, the reverberation times of the room were recalculated using the same GA model and assigning the tapestries the absorption coefficients obtained from theoretical models and shown in Figure 7. The results are given in Figure 8 and confirmed that the use of specific values of the distance between absorbent material and wall generally determined large errors. In particular, assuming a distance of just 0.5 cm resulted in a significant overestimation of the values over all the frequency bands. Conversely, assuming a distance of 4 cm resulted in underestimation at low frequencies, while performance was good in other octave bands. Averaging the absorption coefficients calculated at different distances yielded the best results, particularly when the values at 0.5 cm were not included in the average. In such cases the maximum error never exceeded 10%, which can be considered an acceptable result in a blind test without any calibration. So, in order to get a reasonable estimate of absorption coefficients and, hence, of reverberation times, when using prediction formulae, even the amount and shape of the drapes (and consequently the distance from wall) needs to be determined with good accuracy. In any case, averaging the absorption coefficients calculated at different distances from rigid wall helps minimizing the errors.

5. Conclusions

The paper took into account a set of measurements of reverberation time in the same room with and without the unique “Pastrana” tapestries, exploring the possibility to determine their absorption coefficients despite the fact that the measurements were carried out in a room that was far from ideal for standardized procedures. In fact, use of classical formulas yielded clearly inaccurate results because of the non diffuse behavior of the empty room. However, absorption coefficients derived from a GA model showed more realistic values. As it was not possible to compare such values with more accurately determined experimental data, theoretical values were determined based on physical characteristics of the tapestries, showing substantial agreement. Thus, use of a GA model to indirectly determine absorption coefficients proved effective to overcome the significant limitations of the room used for the measurements. In addition, if the room characteristics are properly modelled this method allows the user to actually get the absorption coefficient of the sample to be tested, minimizing the room effect and hence generalize the results. Finally, this approach may be very useful when measuring absorption coefficients of samples that could hardly be moved to a standard test room or cut into pieces to fit into a standing wave tube.

Acknowledgements

The authors are grateful to Charlie Guijarro for his help in finding the ceiling specifications, and to Julia Burke, Head of Textile Conservation, National Gallery of Art, Washington D.C., for fruitful discussion about tapestry characteristics.

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