The Acoustics of The Holy Family Church in Salerno

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Résumé

L'église de la Sainte Famille de Salerne (Italie) construite en 1971 a radicalement révolutionné la structure spatiale de la conception des bâtiments préconciliaires. La géométrie circulaire du toit a nécessité un travail complexe avec l'emploi d'ouvriers de chantier naval pour aboutir à une géométrie unique. Cependant, des géométries futuristes telles que celle-ci entrainent des conditions acoustique complexe, comme cela est apparue une fois la construction achevée. Dans cet article, les résultats des mesures de la distribution spatiale des caractéristiques acoustiques dans ce grand espace sont rapportés. L'analyse des valeurs des paramètres acoustiques confirme les mauvaises conditions acoustiques pour l'écoute de la parole et de la musique. A l'aide de la modélisation, les auteurs ont étudié des solutions possibles pour la correction acoustique de cette architecture moderne. Cet article rend compte des conclusions d'une telle étude.

Mots clefs : église, mesures acoustiques, acoustique de culte, diffusion sonore, temps de réverbération

Abstract

The church of the Holy Family in Salerno (Italy) built in 1971 radically revolutionized the spatial structure of pre-conciliar church building design. The circular stepped geometry of the roof required a complex work with the employment of shipyard workers to come out with a unique geometry. However, such futuristic geometry also resulted in challenging conditions for its acoustics, as they emerged when the construction was completed. In this paper, the results of measurements of the spatial distribution of the acoustic characteristics in this large space are reported. The analysis of the acoustic parameter values confirms the poor acoustic conditions for speech and music listening. With the help of modelling, the authors have investigated possible solutions for the acoustic correction of this modern architecture. This paper reports the conclusions of such a study.

Keywords: church, acoustic measurements, worship acoustics, sound diffusion, reverberation time

1 Introduction

Churches are complex acoustic places due to their shape and large size, along with the presence of side chapels, vaults, and domes that represent focusing geometries and coupled volumes [1, 2]. Moreover, the typical use of acoustically reflecting materials such as marbles contributes to the formation of highly reverberant conditions in these large spaces [3, 4]. It is worth noting how the absence of acoustically absorbing materials inside the church leads to several problems such as the increase in reverberation time values with the increase in volume [5, 6]. As well as a significant sound absorption generated by the presence of the congregation in the central area which determines considerable changes in the acoustic conditions as the number of people occupying the pews changes. Thus, often churches that have poor sound characteristics especially when they only partially occupied. The long reverberation that develops in churches enhances listening to the music played on organs, Gregorian chants and different types of the choir. The reverberation, generated by the repeated reflections of the sound waves on the walls, increases the sense of participation of the congregation. Churches are currently used for two different activities, that in some ways are opposing when considered from an acoustic point of view: verbal communication with the congregation, recitation of psalms and prayers, explanations and comments of sacred texts [7]. Usually, all activities require a short reverberation, while the optimal listening of choirs and sacred music requires a long reverberation time. In many churches, there are conditions in which the congregation must pay close attention to understand the spoken word. To remedy these problems, expensive and sound amplification systems are adopted which, if they are not installed properly, can worsen listening and thus worsen the comprehension of speech. During the celebration of liturgy, different types of sound messages coexist, each of which requires different acoustically optimal conditions. Organ music requires an optimal reverberation of about 2 to 3 seconds to encourage a sense of congregation participation; music from musical instruments requires an optimal reverberation of 1.5 seconds. Whereas, sermon readings or the homily require a short sound tail with an optimal reverberation time of about 1.0 seconds to obtain good speech intelligibility. To have acoustics suitable for all the elements of the liturgy, a church should be transformed into a room with variable acoustics. In the Middle Ages, the acoustic correction in some churches was obtained by inserting amphorae in the sidewalls, which exploited the principle of Helmholtz resonators.

Moreover, small stages were sometimes made in the centre of the aisles where the speaker stood and modulated

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his own voice thus being understood by the congregation. Another solution was to create large screens behind the ambos, where the priest stood to give the homily, in order to focus the sound on the congregation. An analysis of the size of church volumes according to the architectural style shows an evolution characterized by a progressive growth of dimensions culminating in the large volumes of the Gothic and Renaissance period, in which the dimensions of the churches had to reflect the political power of the civil communities or nuns who had built them. Today, the size of churches has become smaller, but the use of concrete has led to a worsening of the acoustic conditions. It is useful to mention that the acoustic characteristics are not always the same in the whole area of the considered environment; they depend on the actual shape of the environment. The reverberation is almost independent of the shape as well as the particular position of the receiver, while the clarity and intelligibility of the speech depend on the distance from the sound source to the receiver, its visibility and the possibility of receiving the reflections that reinforce the components of the direct sound.

2 Church Architecture

Located in the neighborhood of Fratte in Salerno, a popular district of the city, the Church of the Holy Family is a significant work of contemporary architecture. Designed in 1968 by the architect Paolo Portoghesi, in partnership with the engineer Vittorio Gigliotti, it was built between 1971 and 1974 [8-10]. The church is one of the first Italian buildings of worship built entirely of reinforced concrete, whose construction required skilled workers, including teams experienced in shipbuilding, given the particular curvature of the structures. The idea was to create a space for listening with the centrality of the altar and where there was no longer a separation between the celebrant and assembly, but a unity of participation. Space was assumed as a symbolic quality of transcendence, represented by six large circles that, connected with each other, represented unity within the Holy Trinity. The six circles came, with a substantial variation, from the church of "*Sant'Ivo alla Sapienza*"; along with the dome that reinterprets the model of the church of Borromini and rests on walls with irregular and jagged surfaces. In the church of Borromini, the starting spatial figure is based on an equilateral triangle and is the result of a geometric scheme in which the six circles intersect with a triangle. While in the church of Salerno the six circles, instead of being combined according to the equilateral triangle, are combined according to a rotation principle that tries to represent growth geometrically. Therefore, continuity and organicity to express in the architecture the processes of the creation of life [9]. Figures 1 shows the plant and the section of the church, while Figure 2 shows an internal view. The building has a very complex circular structure, which can be described organically as the fusion of three giant trees that with their branches full of leaves circumscribe and define a space: a church that wants to renew the Catholic liturgy at its roots, expressing in the form the indications resulting from the Vatican Council. The

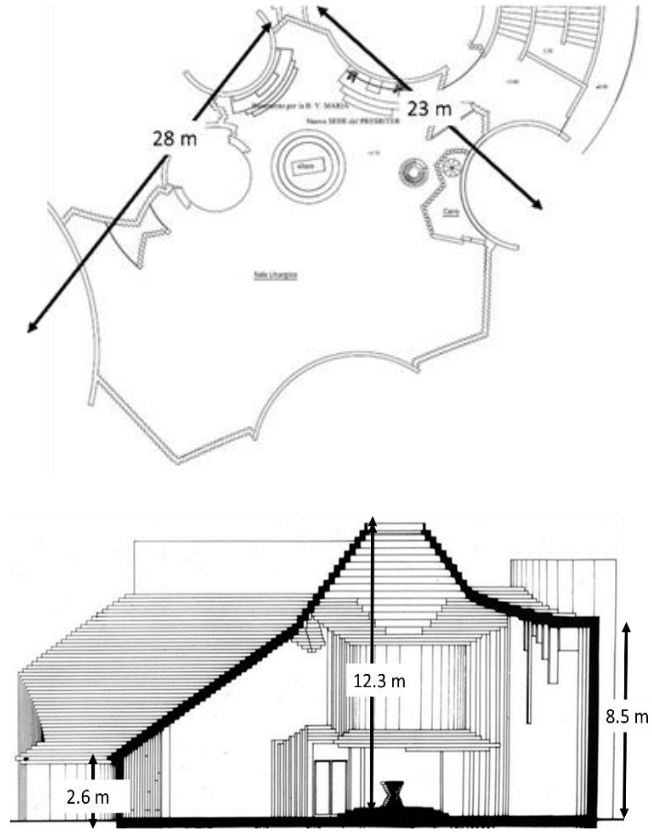

Figure 1: Plant and Section of the church.

Figure 2: Internal view of the church.

Figure 3: Central concave stepped dome.

circle is the inspiring element of the entire work. The church is structurally composed of six centres contained in three concentric circles. The idea was to create a building that expressed, through the choice of curved shapes, the concepts of unity and centrality of the divine. A "sacred" space carefully designed to create an active, full and fruitful of the people of God in the sacred celebration through a liturgical form Christocentric, a central space around the altar, and which opposes the longitudinal spatial forms and shows clerical anti conciliar. Where the altar that acquires a deep meaning strength (located, as the focus of the sacred space – centre not purely geometrical – on three circular steps in marble and an Hourglass concrete base) and where the assembly's attention converges. The ambo is in a decentralized position: it recalls the hourglass style and the material of the altar: the marble pedestal and the concrete structure. The tabernacle is lateral to the altar, in a space adjacent to the sacred hall and clearly visible to the congregation, so as to create, in its silence, the best contemplative atmosphere of adoration and individual prayer. The geometric essentiality of the tubular structures is similar to the burning flames that heat the worshippers and orient them upwards, where the circular openings invite direct contact with God, traditionally imagined in the skies above. The concave steps of the roof of the sacred building, which symbolically evoke the theme of the assembly, exalt the enunciation of another archetypal motif like the amphitheatre [11]. The different colours of the windows symbolize the necessary dialogue between human nature (in the blue-green colour) and the divine nature, in the yellow-white colour. With its stepped roof, with a riser of 0.25 m, derived from the evolution of the concentric irradiance of the spatiality of the six external centres mentioned above (or rather, the spatial fields of the six centres, “enclosed” in geometric circles, expanding in concentric waves, “describe” space in a fluid movement of internal convexities). With the convex vertical extensions of the wall elements, to which the geometric cuts are inscribed for the openings of the coloured windows and with its central concave stepped dome (Figure 3), generated by the crossing of three big vaults above the altar. This convexity of the three times iconography refers to the three divine persons of the Trinity, underlines the great moment of the liturgy: the passion and resurrection of Christ.

3 Acoustic measurements

In order to analyses the acoustic characteristics of the dome, acoustic measurements were carried out using an impulsive sound source located on the altar. The sound source was maintained fixed at 1.5 m from the floor. A BRAHMA digital recorder was used to record the impulse responses in 20 different receivers located in fixed positions and with one source positions, one in the ambo where the homily is officiated.

To reduce any background noise, the measurements were taken without any visitors, so that the impulse responses were recorded under empty conditions. During the acoustic measurements, the background noise was lower than 40 dBA. Figure 4 shows the plan of the church with an indication of position of the sound source on the ambo and the receiver microphone points in the audience area. The recorded impulse responses were elaborated with the Dirac 4.0 software, with several acoustic parameters being analyzed as defined in the ISO 3382-1 [12], such as reverberation time (T30), Early Decay Time (EDT), clarity (C80), definition (D50) and sound transmission index for speech intelligibility (STI) [13]. Figures 5, 6, 7 and 8 show, respectively, the average values and relative standard deviations of the acoustic parameters measured (T30, EDT, C80 and D50), with the sound source on the ambo. The acoustic measurements of the characteristics of the church in its current condition show an excessive length of the reverberation, which is manifested by a reverberation time (T30) with an average value equal to 7 s; an average EDT value equal to 7 s.

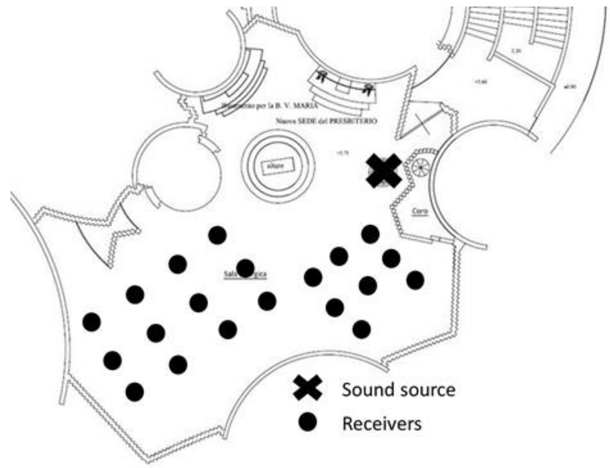

Figure 4: Plan of the church with an indication of the position of the sound source on the ambo and the microphone points in the audience area.

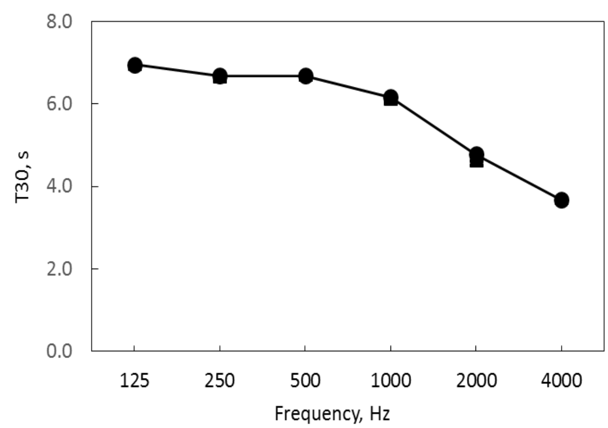

Figure 5: Average measured values of T30 and relative standard deviations.

The clarity average value C80 is equal to -8 dB and the definition average value of D50 is equal to 0.10. The values of the standard deviation for C80 and D50 show substantial differences, due to the fact that the measured acoustic parameters vary significantly from point to point. In this configuration, the acoustic measurements of the characteristics of the church in its current condition show an excessive length of the reverberation. With the sound source on the ambo the reverberation time values T30 and EDT are constant in the frequency range between 125 Hz and 1000 Hz, and thereafter are reduced to 4.0 s at 2000 Hz and 3.0 s at 4000 Hz. Furthermore, the values of the average characteristic acoustic measured when compared with the optimal recommended ones, indicate that in the church, there is not a good speech under-

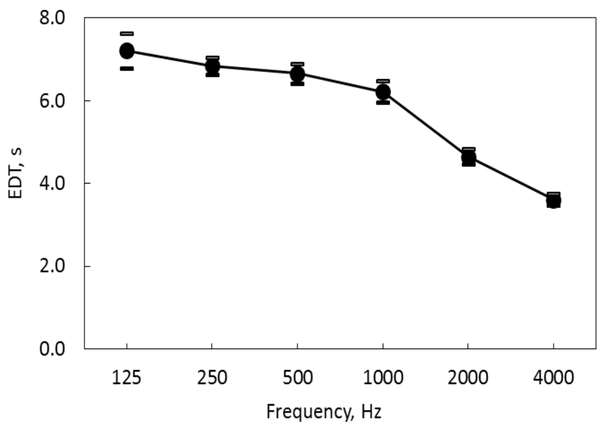

Figure 6: Average measured values of EDT and relative standard deviations.

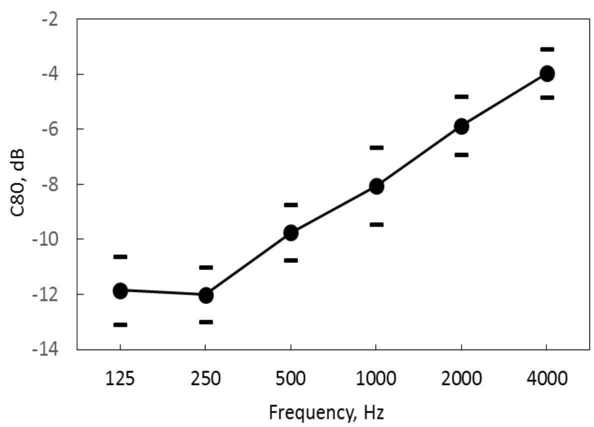

Figure 7: Average measured values of C80 and relative standard deviations

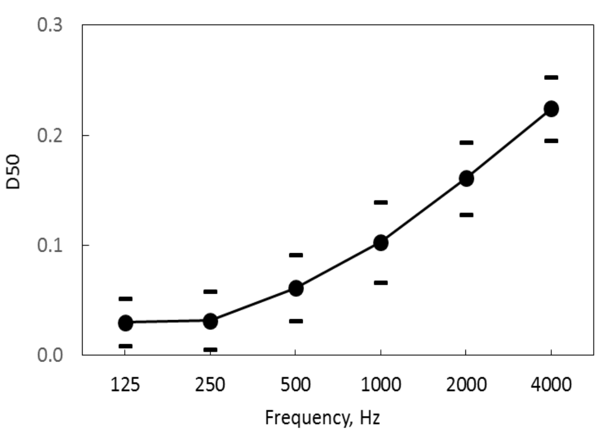

Figure 8: Average measured values of D50 and relative standard deviations

standing and listening to musical performances is not satisfactory. To better understand the acoustic characteristic of the church the spatial average distribution of the acoustic parameters in the area where the congregation sits (audience area) were analysed. The values of T30 and C80, as well as the value of the STI (index of speech comprehension), were reported at the frequency of 1000 Hz. Figure 9 shows the spatial distribution of the parameter T30 at the frequency of 1000 Hz, in which it is possible to notice that T30 assumes a value equal to 6.5 s. These values are uniform within the church but are such as to exceed the recommended values for the correct listening of musical performances, as reported in current literature. Figure 10 also shows the spatial distribution of parameter C80 at the frequency of 1000 Hz, in which it is possible to notice that C80 assumes a value equal to -8 dB for points near the sound source, and then decreases to -10 dB for points far from the sound source. These values indicate that musical performances in the church are not perceived in a suitable way because the C80 values are not included in the optimal range reported in the literature.

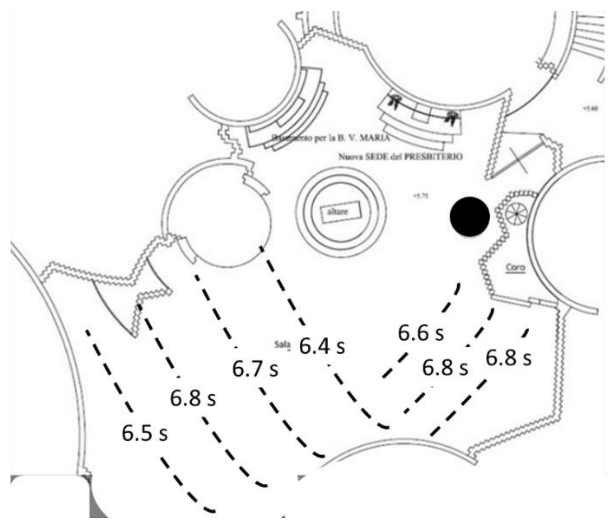

Figure 9: Spatial distribution of parameter T30 at the frequency of 1000 Hz

Figure 11 shows the spatial distribution of the STI parameter, in which it is possible to notice that STI assumes a value equal to 0.3 for the points near the sound source, and then slowly decreases to 0.26 for points far from the sound source. In the area near the ambo where the sound source is located, the value of the STI is equal to 0.38 and then decreases to 0.34. The value of the STI in every point of the church is an indication of the low comprehension of the spoken word. The church in the current state does not meet the criteria of good listening for music and speech.

For the position of the sound source, the reverberation times EDT and T30 measured in the absence of public are high due to the presence of poorly sound-absorbing surfaces. The remarkable articulation of the surfaces of the roof with the stepped section, with the 0.25 m riser, produce diffusive effects for a wide frequency range. Diffusion produces a spatial homogenization of the temporal decay of the sound field that is highlighted by a modest standard deviation of EDT and T30.

Figure 10: Spatial distribution of parameter C80 at the frequency of 1000 Hz

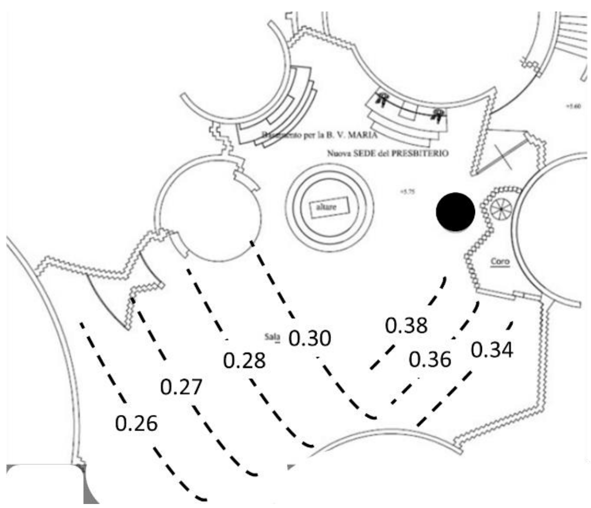

Figure 11: Spatial distribution of parameter STI.

A computer simulations with the software Odeon were carried out to study the effect of sound absorbing systems that can be adopted in the respect of the original architecture of the venue. Odeon uses a hybrid method of images plus ray-tracing. Figure 12 shows the Odeon virtual simulation model of the church. The first step consists in the calibration procedure, it consists in the comparison of measured quantities with analogous calculated ones. If the difference is unsatisfactory, a suitable calibration of the acoustic model is to be carried out in order to reduce the difference to a reasonnably low value. When a virtual model has been obtained which represents adequately the observed state of a room, desired changes or insertions can be considered.

To calibrate the acoustic model, measured averaged values of T30 were compared with the corresponding values calculated with Odeon for each octave band. An iterative procedure was used to reduce the difference between the measured and calculated values of T30. This implied little adjustments of the sound absorption coefficients (α) and the scattering coefficients (s) [14-16]. The interventions for the

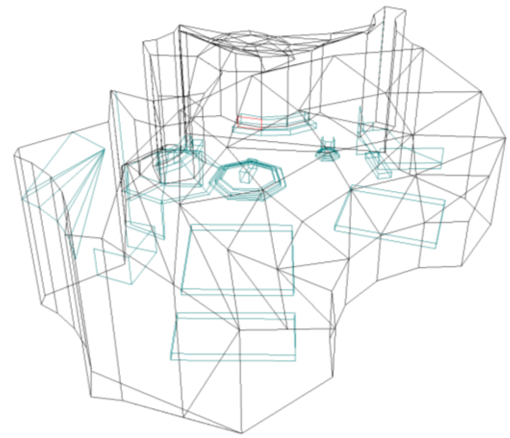

Figure 12: Odeon virtual simulation model of the church.

acoustic correction in the churches subject to constraint can be exclusively of the reversible type and must not alter the existing surface finishes. The structures must be temporary and therefore easy to place and remove to preserve the beauty of the environment, or positioned in particular areas in order not to affect the aesthetics of the structure. In the current configuration inside the church, the measured values of the reverberation time and of the other acoustic parameters are excessive compared to those required for a good understanding of speech. The solutions that allow you to respect the constraints imposed are the insertion on the side windows of transparent micro-perforated sheets (*Barrisol type*) and the insertion of sound-absorbing cushions under the benches. The evaluation of the goodness of the acoustic correction was carried out with the help of the Odeon software for architectural acoustics. Table 1 shows the sound absorption coefficient values of the materials used in the numerical simulation

Table 1: Sound absorption coefficient values of the materials used in the numerical simulation

Frequency, Hz	125	250	500	1 k	2 k	4 k
sheets	0.1	0.2	0.7	0.8	0.6	0.6
cushions	0.4	0.7	0.75	0.8	0.8	0.8

It was hypothesized to cover the side windows with transparent micro-perforated sheets for a surface of 134 m^2 of transparent acoustic sheet. Furthermore, it was decided to intervene on the assembly benches present inside the church as they are complex elements, built in wood and are therefore acoustically reflective elements. The use of benches covered with cushions of sound-absorbing material allows to obtain a good acoustic correction. For these reasons, simulations were carried out by inserting 100 m^2 of sound absorbing material under the benches. The acoustic correction with the insertion of sound-absorbing sheets and sound-absorbing cushions leads to a reduction in the reverberation time, so as to obtain an optimal value for the C80, but not for the D50. Figures 13, 4, 15, and 16 shows the average values of the acoustic characteristics (T30, EDT, C80 and D50) of the church in its current state, with the windows covered with transparent acoustic sheets and with the benches covered with soundproofing cushions.

4 Conclusion

The church presents problems for the understanding of speech due to the large volume and presence of reflective materials. The acoustic measurements with the empty church have provided an average reverberation time (T30) of about 7 s. The church is not suitable for the understanding of speech or listening to musical performances. However, a good speech understanding inside churches has become necessary due to the type of religious service, based on a vocal message after the Vatican II Council. For the church to be used correctly to listen to the speech an appropriate acoustic correction should be carried out inside. Panels of sound-absorbing materials should not be used since they are not suitable for churches, transparent micro-perforated sheets withe absorbent cushions should be used instead. Micro-perforated sheets and cushions under the benches have good acoustic characteristics. The use of the transparent sheet means that the walls of the church are visible and cushions under the benches so the aesthetics values are safeguarded.

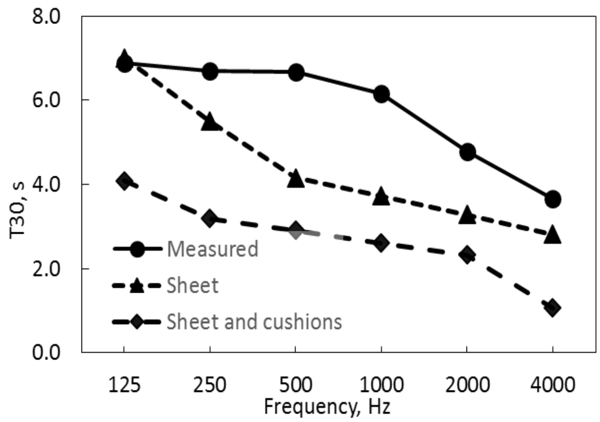

Figure 13: T30 average values.

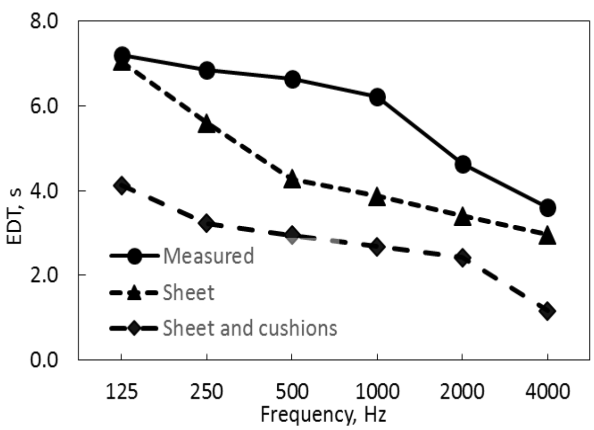

Figure 14: EDT average values

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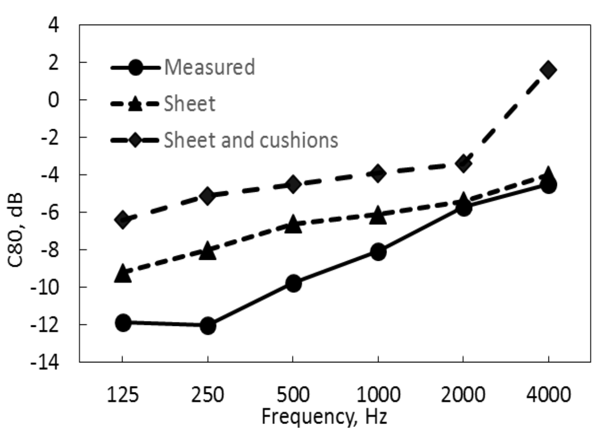

Figure 15: C80 average values

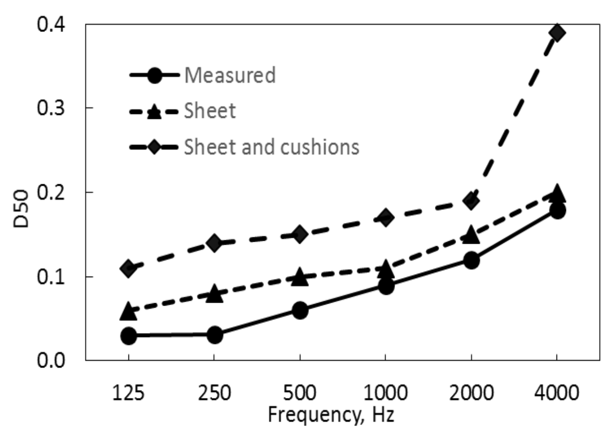

Figure 16: D50 average values

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