Cistercian Monastery of S. Bento de Cástris, Évora, Portugal: Acoustic measurements under ORFEUS Project

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***Abstract*—The Church of the Monastery of S. Bento de Cástris in Évora (13th- 19th centuries) presents an unusual space setting which seems to favour different positions for coral groups supporting liturgical and musical expression activities. These options are possibly of an empirical nature, since the scientific knowledge in the field of building physics and in particular of building acoustics are relatively recent. It is important to explore, with on-site measurements, the actual conditions of acoustic behaviour and in particular meet the reverberation times. Consequently, results obtained must be compared with the current recommendation for this type of space. This article characterises the Church in terms of its conception and its most relevant constructive aspects. The interest in measuring reverberation time, in this type of enclosed space, is also discussed. Such results of reverberation time measurements are presented and analysed for the different spaces of the Church. Finally, the findings of the study are presented as well as some hypotheses for future work in terms of acoustic analysis of Cistercian spaces and for a better understanding of the architecture and music relationship, in its different expressions.**

***Index Terms* — Acoustics, Cistercian Architecture, Reverberation, S. Bento de Cástris.**

I. Introduction

In spaces destined to hold religious celebrations, it is essential to hear pleasant sounds with appropriate level and quality along with an environment conducive for silence, reflection, search of inner identity and hearing of sacred music and the sacred word. The acoustic design of a space intended for religious activities can be carried out and optimized with use of computer applications for modelling and simulation or through measurements on reduced models. In this sense, it defines the best organization and configuration of space as well as the most appropriate volumetry and selection of surface coatings which provide the desired conditions. The study and acoustic treatment of existing spaces, often in buildings of historical or patrimonial interest present some complexity, since it is not always possible to change existing situations due to distribution, configuration and volumetry of those spaces as well as different types of coatings and ornamentation of the interior surfaces.

The chaotic stream of sound waves in an enclosed and particularly reverberant space always causes issues regarding word intelligibility consequently making spaces unpleasant for users. These spaces can be conveniently studied and problems can be solved by using acoustic corrections. For this purpose, it is necessary to explore, with on-site measurements, the actual conditions of the acoustic behaviour and in particular meet the reverberation times and compare the results obtained with the current recommendations for this type of space.

The Church of the Monastery of S. Bento de Cástris in Évora (13th -19th centuries) presents an unusual space setting; thus, two different positions are contemplated for the supporting choir and for the liturgical activities of the religious community: the higher choir on the extension of the Church nave placed at a level higher than the assembly, and the lower choir on the side of the main chapel. The question that arises and which is to be analysed is whether this configuration was aimed to favour different positions of choral groups and other forms of musical expression.

The acoustics of older religious spaces was probably developed through means of an empirical nature since scientific knowledge in the field of building physics and in particular of building acoustics are relatively recent. It was only in the late 19th century that scientific studies were conducted to allow, for instance, the description of the reverberation phenomenon for different sound frequencies in indoor spaces. In fact, in 1895 authorities from Harvard University requested Wallace Clement Sabine to study and propose amendments to resolve serious acoustic problems of the Conference Room in the Fogg Art Museum. These studies were carried out for approximately two years and allowed Sabine to come up with the well-known formula to determine reverberation time. Nevertheless, the article "Collected Papers on Acoustics" was only published in 1922 by Harvard University Press [1] but the formula proposed by Sabine, is still in use today.

More recently, the acoustic behaviour of churches has been a subject of study, which has allowed to identify new areas of research regarding different aspects of knowledge and

Manuscript received December 30, 2014. Cistercian Monastery of S. Bento de Cástris, Évora, Portugal: Acoustic measurements under ORFEUS Project

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development [2,3,4,5]. Main concerns focus on the audience, which should be able to hear clearly the words uttered by clerics or sung by the supporting chorus. To improve intelligibility of sounds, it is necessary to reduce the reverberation to acceptable levels and ensure an even distribution of sound in the room, especially in the nave of the Church [6].

When assessing acoustic auditoriums different parameters can be used nevertheless, as mentioned previously, the most important is the reverberation time. This article explores the acoustics of the Church of the Monastery of S. Bento de Cástris, in Évora using onsite measurements and withdrawing conclusions regarding the existing situation.

II. THE ORFEUS PROJECT

This study is the result of work carried out for the FCT EXPL/EPH-PAT/2253/2013 Project. The ORFEUS Project – “A Reforma tridentina e a música no silêncio claustral: o Mosteiro de S. Bento de Cástris” (The Tridentine Reform and music in the cloistral silence: the Monastery of S. Bento de Cástris) – is financed by the Foundation for Science and Technology (FCT) with community co-financing through the COMPETE program “Programa Operacional Factores de Competitividade” (Operational Program Factors of Competitiveness), of QREN and the European Union (FEDER). The University of Évora was the proponent institution through the Interdisciplinary Centre of History, Cultures and Societies (CIDEHUS), and the University of Beira Interior is one of the partner institutions together with the University of Minho and the University of the Azores.

The ORFEUS Project is based on a multidisciplinary approach around the Tridentine Reform reflexes in the musical Cistercian feminine matrix between the 16th and 18th centuries. This research, guaranteed by historians, architects, engineers, musicologists, organologists, will make it possible to achieve the proposed results. To know the particularity of S. Bento de de Castris is required a selection of its legacy to be analysed, taking into account previous studies, and a comparative perspective (especially with the monasteries of the same order, the same historical time and with different female orders) and think that the occupied spaces, to play or sing, in monastic structures also moved in the considered chronological framework.

The project aims to establish, from the selected books, the permanence and the ruptures not only at a liturgical level but also regarding other levels as musicological and iconographic-codicological that the Council of Trent implied. It is intended to study and identify the possibility of various networks linked not only to music and singing as well as its teaching and performing, privileging the relation with the city of Évora (Portugal) and the music school of the Cathedral of Évora.

The aim of this article provides the team with information on the actual acoustics of this space and tries to establish knowledge regarding the architecture of the Church of the Monastery of S. Bento de Castris and the duality of its choirs (one higher at the end of the nave and another lower and lateral to the apse).

III. FEATURES OF THE STUDIED CHURCH

The Monastery of S. Bento de Cástris has been a National Monument since 1922 and it is located in the Alentejo region, to be precise on “Alto de São Bento” São Bento hill, about two kilometres from the city of Évora (Fig.1and Fig.2).

Fig. 1.Aerial view of the Monastery of S. Bento de Cástris

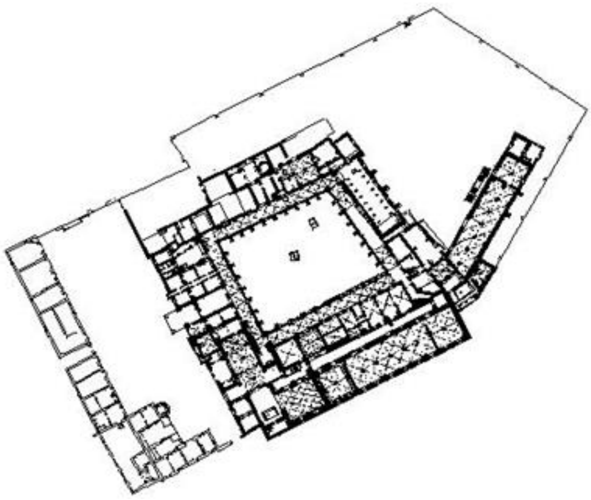

Fig. 2. Plan of the Monastery of S. Bento de Cástris (no scale).

The building, while Cistercian Monastery, dates back to the 13th century if we consider it in full exercise of its functions and with complete construction of the Church, the chapter house, the Nuns’ ward and all other facilities supporting community livelihood such as refectory and kitchen [7]. The monastic building that remains today presents architectural features that fit within a period between late 15th century and early 16th century, traces of final Gothic may be found as well as mudéjar (which are stylistic mixtures between Cristian and Islamic Art in some Portuguese regions under Islamic influence before and during the Christian Reconquest). These artistic and architectonical influences were always reconciled with Cistercian requirements. The Church of the Monastery possesses characteristics from the 1500’s, being worth to highlight the Manueline ribbed masonry vault as well as the the arch formeret and discharging arch which finish in half columns [7]. The decentring of the transept in relation to the nave of the Church suggests traces of a previous building.

The Church has a biaxial latin cross plan, showing a single nave and transept (Fig. 3 and Fig. 4). The nave has three sections, the first two (corresponding to the transept and the intermediate section) 5.70 m x 6.80 m and the third 5.70 m x 3.50 m [7]. The last section and part of the following is occupied by the higher choir (Fig. 5) with noticeable Gothic traces. The lateral choir appears in the 16th century which consists of an unusually low vault down on which a coating of lozenge boxes is placed (Fig. 6).

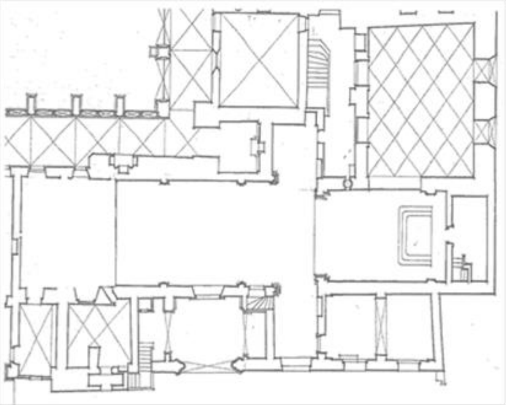

Fig. 3. Church plan (no scale).

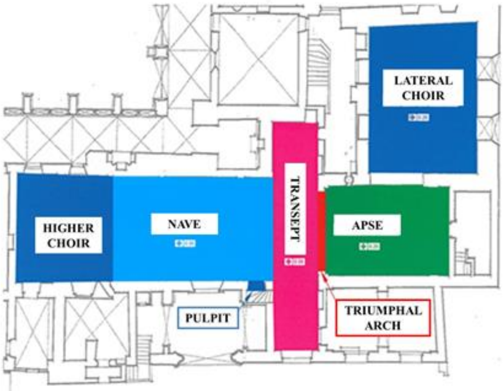

Fig. 4. Identification of the spaces.

Fig. 5. Higher choir viewed from the nave.

Fig. 6. Lateral choir (access through the apse).

The access to the Church is made laterally to the nave, as it would happen in female monasteries, part of it would open to the secular community so as not to disturb or break cloistered life. The sacristy would remain south in relation to the apse allowing the chaplain's access when celebrating the Eucharist. The southern arm of the transept gives access to the sacristy and the pulpit. The opposite arm of the transept has a confessional booth and a pathway which would give access to the nuns' ward and which is now sealed.

Through time alterations, to the building, occurred in order to adapt it to new realities and requirements. During the 18th century new alterations appeared in the Church especially in terms of decorations where a rococo style is noticeable in gilt carvings, stucco and tiles (Fig. 7). After the extinction of Religious Orders, in Portugal, in 1834, these buildings acquired new usages.

The last Cistercian Nun of the Monastery of S. Bento de Cástris died in 1890 thus, the monastery became extinct and the building suitable for other uses in accordance with the Decree of 1834. After 1941 the building becomes part of the DGEMN (Direção Geral de Edifícios e Monumentos Nacionais) "General Directorate of Buildings and National Monuments" and in 1937 conservation works started on the referred building [8]. The Monastery of S. Bento de Cástris was used as Casa Pia of Évora - Section Baptista Rolo, which was a former orphanage, until 2004 and after its abandonment, in 2006, there was an attempt to host the National Museum of Music by the Ministry of Culture [8].

In what refers to coatings of different interior surfaces that compose the enclosed space and contribute to characteristics of acoustic behaviour inside the Church, the existence of different materials must be taken into account.

In this way it is important to refer the walls of the nave which are plastered masonry and ornamented by ashlars of tiles that around the Church nave as well as sealed openings that exists on the north side of the Church and that feature a wooden grid and some gilt vegetal decorations.

The access openings to the Church are closed by wooden doors where an iron grid in the lateral choir stands out separating this side from the apse. The openings that allow lighting in the Church are also carried out by means of wooden frames and simple glass. There are two large windows on the south wall of the Church, one on the southern arm of the transept and two on the main chapel to which an eastern additional opening is added at the top of the apse.

The Church roof is ribbed and vaulted and composed of masonry covered with stucco. A triumphal arch, composed by a perfect round arch, marks the nave of the main chapel. This demarcation is also achieved through a two-step elevation of the apse in relation to the nave's floor level. The apse features an altarpiece (three steps higher in relation to the floor of the main chapel) and an 18th century throne, in gilt, as well as an altar in the same material.

The floor of the nave is of marble and the floor of the apse a combination of marble and granite, which was carpeted in the late 20th century. In what regards floorings of lateral and higher choirs, both consist of marble. Currently there are wooden benches on the nave. Considering the movable heritage, both the high choir and the side choir had wooden chairs. In the SIPA/DGEMN archives, photos of rows of wooden chairs, with multi-coloured paintings in canvas or wood, can be seen in the higher choir [5]. In the lateral choir, due to the unique flatness, the backrest of the chairs would reach the cornice. Currently these chairs no longer exist and only plastered walls and ashlar tiles of a random pattern can be seen (possibly where the Abbess's chair existed). Towards east, on the cornice, two circular openings with wooden frames and simple glass can be seen.

Fig. 7. Nave viewed from the higher choir.

Fig. 8. Ceramic tiles portraying scenes from St. Bernard’s life.

Nuns would follow the requirements imposed by cloistered life hence being separated by iron grids and curtains both on the high and lateral lower choir (the grid of the higher choir no longer exists, having been replaced by a wooden balustrade). This prevented visual contact between the religious and secular community without, however, disturbing the hearing.

In the 18th century, substantial parts of the nave’s walls and transept were covered with blue and white ceramic tiles, and a polychrome frame, portraying scenes from St. Bernard’s life (Fig. 8). This coating material does not absorb very well sound waves and, when compared to the behaviour of the traditional stucco coating, it is verified that it contributed towards the increase of reverberation in the room and towards alteration of the original acoustic characteristics. The same happened with changes in dimensional characteristics of the higher choir with the consequent decrease in its volume

IV. Determination of Reverberation Times

A. Reverberation and intelligibility of sound

Reverberation can be explained as the persistence of sound in an enclosed space due to successive reflections of sound waves on surfaces of the enclosed space. When it comes to performing acoustic measurements, the consideration falls upon the persistence of the sound field established by the sound source beyond the moment when it ceases to emit. The reverberation time, *Tr*, is considered the primary objective parameter to translate human subjective perception of reverberation and, it is defined as the time interval required for the energy density of a sound field in an enclosed space to be reduced a millionth time [9], or, in other words, the time corresponding to 60 dB decay of the sound level.

The reverberation time can be evaluated onsite using acoustic measurements or estimated by using empirical formulas; the best-known example is the formula proposed by Sabine. According to Sabine’s formula, the reverberation time depends on the frequency of the sound, the internal volume of the space and the sound absorption of surfaces and objects in the space.

The measurement of reverberation time is done based on the European Standard EN ISO 3382-2 [10]. The methodology recommended in this standard consists of direct registration of sound pressure level decay after stimulation of the compartment with a wide band frequency signal or signal from frequency bands previously defined. In terms of time, the decay curve is therefore the graphical representation of the sound pressure level decay in a compartment, after the sound source is interrupted (Fig. 9).

Fig. 9. Graphical representation of the sound pressure level decay experimentally measured.

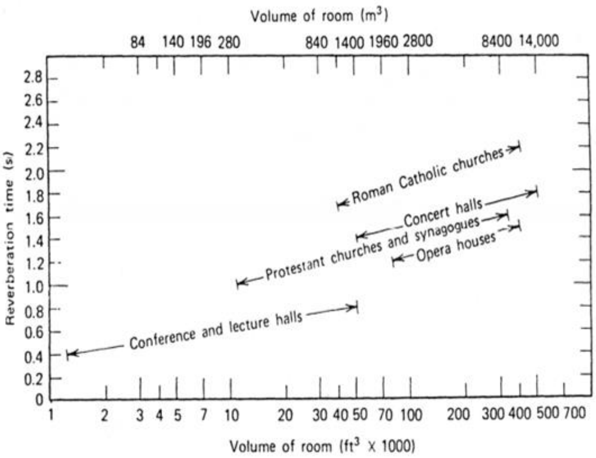

Fig. 10. Ideal reverberation time [11].

Different values for reverberation time, *Tr* are recommended for different indoor activities involving the use of word or musical activity with different volumes and sound frequencies. In many publications the original sources of proposals for recommended values are not identified so, this information must be used with some caution.

Two reference examples with some connection to religious activities are presented in this article as well as values foreseen in the national regulation [9]. The first reference is an abacus (Fig. 10) proposed by Rigden (1985) in the publication "Physics and the Sound of Music" [11] which propose reverberation times depending on the volume of the space and the type of activity planned.

In the second reference [12] ideal reverberation times are proposed based on the planned activity and applicable to Christian areas (Table 1).

TABLE 1: VALUE OF IDEAL *TR* FOR DIFFERENT ACTIVITIES

Activity	Ideal *Tr*
Choral Music	1,8 – 2,5
Congregational Chantic	1,8 – 2,5
Organ Music	2,0 – 3,5
Orchestral Music	1,8 – 2,5
Contemporary Music / Rhythmic	0,5 – 1,0
Speech / Theatre	0,7 – 1,8

Portuguese legislation [9] establishes that spaces mainly intended for oratory, including auditoriums, conference rooms, multipurpose rooms and cinemas, must comply with reverberation time requirements. In such buildings, the regulation stipulates that the average reverberation time, *Tr*, in frequency bands of 500, 1000 and 2000 Hz, must satisfy the following conditions, when furnished normally and without occupation, where *V* represents the internal volume of the space in cubic metres.

i) $Tr \leq 0{,}12\ V^{1/3}$, if $V < 250$ m^3

ii) $Tr \leq 0{,}32 + 0{,}17 \log V$, if $250 \leq V < 9000$ m^3

iii) $Tr \leq 0{,}05\ V^{1/3}$, if $V \geq 9000$ m^3;

The referred regulation also foresees that the project of acoustic conditioning of these spaces should include a specific study in order to ensure a proper reverberation feature in the remaining frequency spectrum and good word intelligibility in the various locations of that space [9].

B. *Stages and equipment used in the study development*

The application of the EN ISO 3382-2 [10] to the case study, contemplated the reverberation time measurement, the interpretation of the results and verification of result conformity obtained with the predicted values in reference publications. The measurement of the reverberation time was carried out with the support of a set of acoustic measurement equipment provided by the Health Laboratory of Building (LABSED) in UBIMedical. This equipment includes an omnidirectional sound source, receiver and supporting software with the following main features:

a) Sound source composed of an omnidirectional loudspeaker Cesva BP012 and noise generator/amplifier Cesva AP601 - Directivity diagram totally Omnidirectional, 123 dB of sound power level, white noise generator, pink and pink filtered, 1/3 octave bands of 50-5000 Hz, cable control, remote control or Bluetooth airway transmission (included in AP601) and forced-air refrigeration system erasing the fan automatically (for measurement of background noise).

b) Sound level meter integrator and real-time Spectrum Analyser Cesva SC 310, Class 1, spectral analyser by bands of thirds of octaves and octaves. Measures all parameters simultaneously with frequency considerations A, C and Z. Unique scale and amplification modules: reverberation time measurement and expanded spectral analysis as well as vibration measurement and module dosimeter to assess noise in the workplace.

c) CMA support Software - Cesva Measuring Assistant and software for calculating and reporting CIS - Cesva Insulation Studio reports. The support software measurement has several functions. Before measurement it allows the import of plans, selection of measurement points and to check surrounding conditions (distances between measuring points, devices, and space limits). During the measurement procedure, it manages automatically the devices (noise sources and receiver) and guides the operator in carrying out the measurements (placement of the equipment and connection of the noise source, for example). This way it is possible to check, in real time, the results of different measurements (background noise, measured spectrums, etc.) and repeat the acquisition of data in case of need. After carrying out measurements, these interact with the CIS software in order to obtain the final report of the onsite measurement.

C. *Methodology adopted in case study*

For spaces with an area greater than 50 m^2, the European Standard EN ISO 3382-2 [10] foresees for the determination of the reverberation time process, two positions for the sound source and six positions for the receiver, with two decay measurements at each position and a total of twelve decays. Accordingly, to evaluate the reverberation time in the Church of the Monastery of S. Bento de Cástris, which has an area much greater than 50 m^2, two positions for the sound source and six positions for the receiver would be enough to comply the EN standards. However, it was considered appropriate to densify the number of readings in the attempt to explore in greater detail the acoustic characteristics of the Church. Consequently, were defined seven positions for the sound source (from F01 to F07) and fourteen positions for the receiver (from R01 to R14), as shown in Figure 11.

The positions of the sound source were determined in consideration with the main features of space usage: F01 (altar), F02 (opposite the altar after Vatican Council II), F03 (lateral choir), F04 (pulpit), F05 (nave), F06 (nave) and F07 (higher choir). As illustrated in Figure 11, the positions of the receivers were evenly distributed throughout different usable spaces of the Church trying to measure detailed features form the reverberation time in the Church. Figure 12 illustrates a measurement image with the sound source position on F05 and the receiver on position R02, while Figure 13 illustrates the sound source on position F04 and the receiver on position R01.

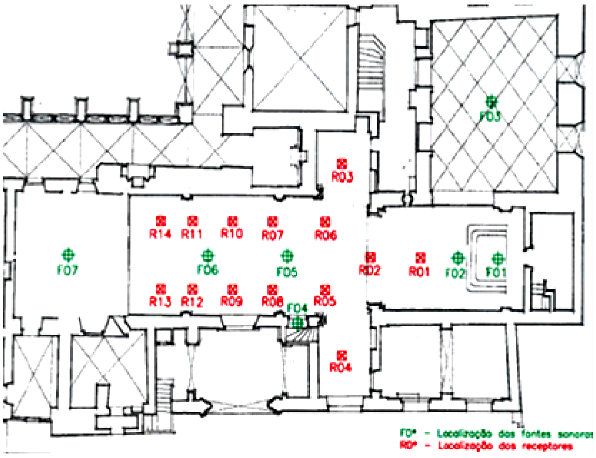

Fig. 11. Scheme of the positioning of the sound sources (in green) and receivers (in red).

Fig. 12. The sound source on position F05 and the receiver on position R02.

Fig. 13. The sound source on position F04 and the receiver on position R01.

When positioning measuring equipment there was also the concern to prevent surrounding surfaces from interfering in the readings. Thus, there was a minimum distance of 1m from walls and floors, a minimum distance of 2 m between measuring sites, a sound source height of 1.5 m above the floor and a sound-level meter height of 1.2 m above the floor.

The reverberation time measurement work on the Church of the Monastery of S. Bento de Cástris was carried out continuously on July 30, 2014, with an inside temperature of 29 °C and a relative humidity of 48%. The total number of measurements was 196 (from a combination of 7 sound source positions, 14 sound level meter positions of 2 readings at each measurement site).

The measurement methodology consisted of the following main steps; a more detailed description can be found in reference [13]: 1) equipment calibration according to temperature and humidity conditions; 2) stabilization of the background noise level; 3) sound emission; 4) extinction of the projected sound (demanding absolute silence to operators in order to avoid interference in the measurements); 5) registration of the decay and 6) repetition of the process, by making another measurement or by moving the receiver .

V. Analysis and Discussion of the Results

Through these measurements it was possible to obtain values of the reverberation time for different frequency bands and different combinations between the position of the sound source and the receiver. In general, results show that different locations of the Church feature average reverberation times, *Tr*, in octave bands centred in frequencies of 500, 1000 and 2000 Hz, with values close to 3.5 s (Fig. 14).

If only records in the 500 Hz frequency are considered, an average value of 3.80 s is obtained (Fig. 15), and if frequencies of 500, 1000 and 2000 Hz are considered, as recommended in RRAE [9], the average value of *Tr* is 3.32 s (Fig. 16). This means that the equivalent sound absorption area of the space is superior for higher frequency sounds.

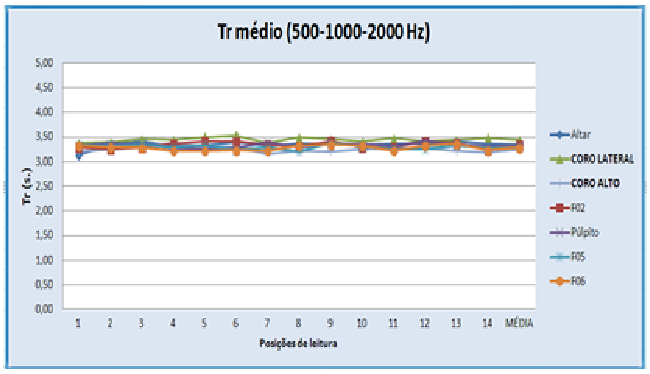

Fig. 14. Average value of *Tr* for frequencies of 500, 1000 and 2000 Hz.

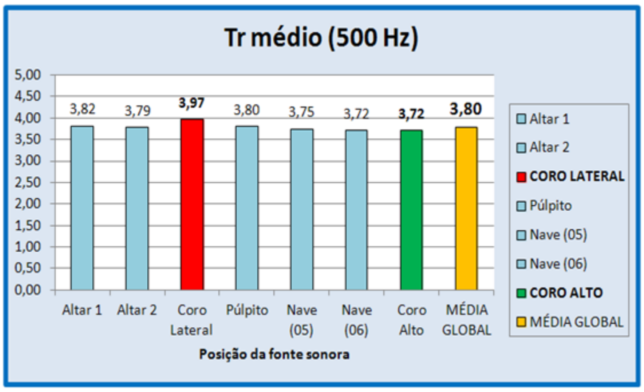

Fig. 15. Average value of *Tr* at 500 Hz for different positions of the sound source.

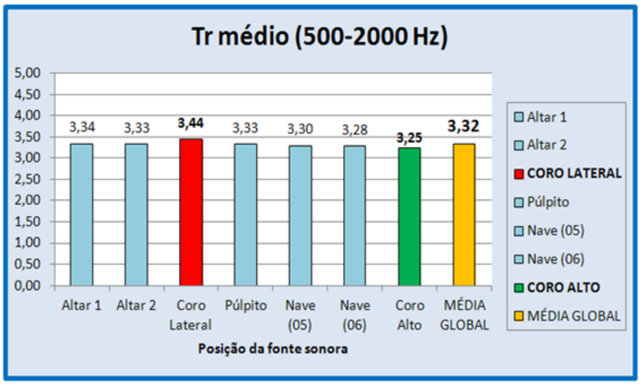

Fig. 16. Average value of *Tr* at frequencies from 500 through 2000 Hz for different positions of the sound source.

Through the analysis of figures 15 and 16 it was possible to verify that the highest values of the reverberation time were obtained with the sound source placed in the lateral choir (3.97 s and 3.44 s, respectively). On the contrary, the lowest values of the reverberation time were recorded when the sound source was placed in the higher choir (3.72 s and 3.25 s, respectively). These findings highlight some advantage of the higher choir in relation to the lateral choir in what refers to reverberation times.

The reverberation time perceived in the nave of the Church (generally occupied by the assistants of the activities) was analysed for different positions of the sound sources (Fig. 17). Usually the sound comes from four different sources, two for the priest (altar and pulpit) and two for the choir (lateral or higher choir). This study will allow evaluating the actual conditions of the acoustic behaviour of the Church, in which concerns to reverberation time perceived by the audience.

The analysis of the average *Tr* on frequency 500 Hz has shown a clear distinction between sounds emitted from the lateral choir and the higher choir (Fig. 18). Similar distinction was found when the analysis was carried out for frequencies of 500, 1000 and 2000 Hz (Fig. 19).The analysis of figures 18 and 19 show that the measured reverberation times were very close to each other and were almost constant for the examined frequency range when the sound sources were placed on the altar and the pulpit, which favours and distinguishes the communicative expression of the priest during liturgy and while preaching from choir and church music activities.

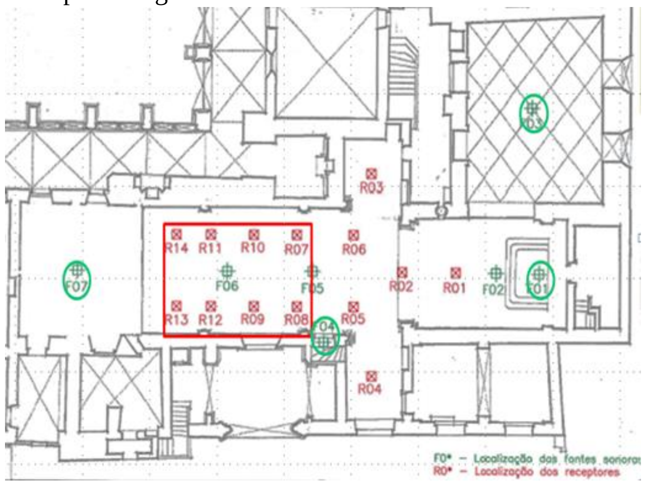

Fig. 17. Measuring positions in the nave: the receivers (in red) and the sound sources (in green).

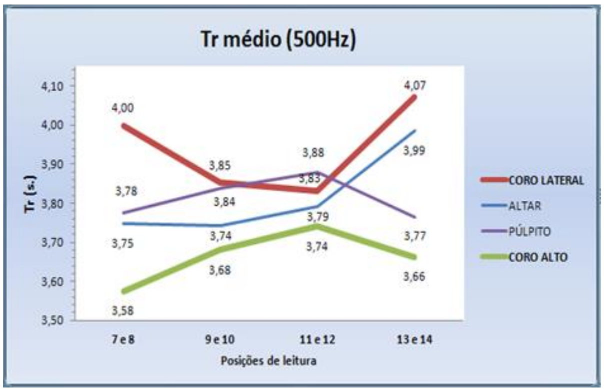

Fig. 18. Average value of *Tr* at the nave for the frequency of 500Hz

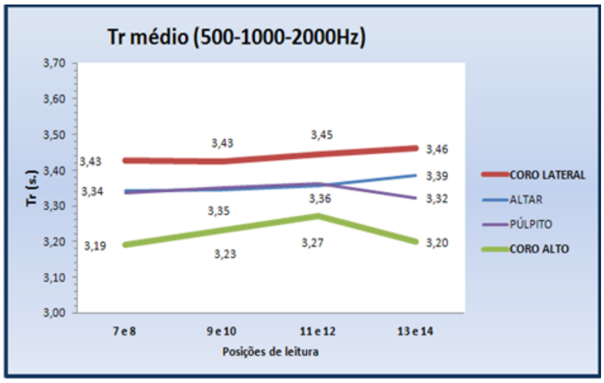

Fig. 19. Average value of *Tr* at the nave for the frequencies of 500, 1000 and 2000 Hz.

While comparing ideal values shown in Fig. 10 it is possible to conclude that the measured values are almost always higher than those recommended. For this reason the Church would have to undergo acoustic correction study in order to fulfil the objectives intended for the liturgical activity or any other required activity. However, taking into account the indicative values of reverberation time suggested by Segler and Bradley [12] and shown in Table 1, there seem to be appropriate conditions in terms of space for concerts of organ music. This aspect in particular deserves some attention, since a 19th century organ still exists in this Church, in the northern arm of the transept (Fig. 20 and 21). This organ, or more specifically this small model organ, was awarded in one of the great 19th century universal exhibitions (Fig. 22).

There are references to contributions, in compliance with functions carried out in the choir and in musical instruments, made by several Nuns such as Isabel Moreira and Maria Moreira (1660), organist and violist, or Isabel Cecilia de S. Bernardo (1678), organist, [14] certifying the use of such instruments in the Church of the Monastery of S. Bento de Cástris.

Fig. 20. Organ still in use by one of the ORFEUS Team members.

Fig. 21. Organ located in the northern arm of the transept.

Fig. 22. Gold Medal at world competition in Universal Exhibition (19th century).

VI. Future Work

This study is in no way considered complete, taking into consideration other important acoustic characteristics to be verified in churches, at least those used for religious worship. In the specific case of reverberation time, it would be important to complete the work now started by studying, for example, churches of other Cistercian Monasteries, of other construction eras, with different types of interior organisation, or which have used different materials in its construction, or coating and ornament of the referred spaces thus, to verify similar features of acoustic behaviour.

Another aspect considered of interest would be to explore and look further into this study by using ideal features of acoustic measurements in architectural spaces and different types of musical activities, whether performed by choirs or instruments.

VII. Conclusion

This work confirmed the interest and up to date content of the acoustic study of interior spaces namely destined for liturgical activities, especially in spaces used by the Cistercian Order throughout times. Acoustic comfort levels must be guaranteed in all usable spaces in order to optimize the transmission of sounds and listening conditions which are essential for all audience members; therefore, such studies should be continued.

In the particular case of the Church of the Monastery of S. Bento de Cástris in Évora, measurements carried out in order to find reverberation times in different spaces, with different locations for the sound source, have shown that their values are high enough to be able to influence and disrupt communication activities. In this sense, actions must be taken in order to correct this situation, nevertheless with respect for the existing heritage characteristics, in particular with regard to some types of coatings and ornaments which should be preserved.

Acknowledgment and Notes

The achievement of this work was only possible due to equipment provided by the Health Laboratory in Building (LABSED) of UBIMedical belonging to the University of Beira Interior.

The funding for the research which results are now presented on this paper at the 1st International Conference on New Music Concepts (ICNMC 2015) was possible with the financial support of the FCT EXPL/EPH-PAT/2253/2013 Project ORFEUS “A Reforma tridentina e a música no silêncio claustral: o mosteiro de S. Bento de Cástris” (The Tridentine Reform and music in the cloistral silence: the Monastery of S. Bento de Cástris), financed by the Foundation for Science and Technology (FCT) with community co-financing through the COMPETE program “Programa Operacional Factores de Competitividade” Operational Program Factors of Competitiveness, of QREN and the European Union (FEDER).

A last word of appreciation must go to Maria Antónia Fialho Conde, Assistant Professor at the University of Évora (Portugal) and Researcher of CIDEHUS – Interdisciplinary Centre of History, Cultures and Societies of the University of

Évora (Portugal), as the main researcher and coordinator of the the FCT EXPL/EPH-PAT/2253/2013 Project ORFEUS "A Reforma tridentina e a música no silêncio claustral: o mosteiro de S. Bento de Cástris" (The Tridentine Reform and music in the cloistral silence: the Monastery of S. Bento de Cástris), who always supported and encouraged this specific research.

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