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Acoustical reconstruction of San Petronio Basilica in Bologna during the Baroque period: the effect of festive decorations

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The Basilica of San Petronio in Bologna (Italy) is a large Gothic church characterized by three naves divided by cluster piers made of brick and flanked by square chapels. It is 130 m long, 60 m wide and 44 m high, developing a volume of 170000 m³. The widespread use of smooth plaster and the substantial lack of decoration give rise to a reverberation time (in unoccupied conditions) which varies from about 13 s at 125 Hz to 5 s at 4 kHz, with an average of 10.7 s at mid frequencies. In occupied conditions the expected mid-frequency reverberation time should lower to about 6.5 s. Nonetheless, these acoustic conditions appear scarcely compatible with the characteristics of the Baroque music which was composed for the “Cappella musicale” during the 17th century. However, historical research pointed out how, in that period, rich draping and curtains were often used during the major religious and civil celebrations. The analysis of the acoustic consequences of such temporary installations was performed by means of acoustic simulation based on historical records calibrated on the current configuration of the church. The paper presents the results of such reconstruction.

1 Introduction

The history of music presents several examples of musicians who composed their works having in their minds the very specific place where those works had to be performed. Famous examples are J.S. Bach’s compositions for the Thomaskirche in Leipzig [1] and Gabrieli’s works for St. Mark Basilica in Venice. However, less known examples may be found exploring the musical literature. One of such examples is the music of the composers that worked for the “cappella musicale” of the Basilica of San Petronio in Bologna [2-3] and in particular of Giacomo Antonio Perti who directed the “cappella” for a long period from 1696 to 1756, composing several masses and other sacred works [4]. Many hypothesis have been made on the possible relationships between the compositions and the specific acoustics of the Basilica which was (and still is) characterized by long reverberation exceeding 10 s in empty conditions. Such difficult acoustic conditions raise another interesting issue about the possible attempts made to improve them.

In fact, during the major holidays it was common practice to adorn the church with rich draperies covering balustrades and columns. During special occasions, such as the festivities for the patron saint, draperies were also hung as curtains in the top of the vaults between the columns and sometimes between the bays and between nave and aisles. Iconographic material and archival sources give evidences of large amounts of such materials being used, therefore it is likely that the acoustic effect, although limited by the simultaneous presence of large congregations, might be significant.

The present work summarizes a research aimed at investigating the acoustic consequences of using draperies and decorations in San Petronio Basilica and the possible influences that the resulting acoustics had on the musical work deliberately composed for this place.

2 Description of the church

The Basilica of San Petronio (Fig. 1) was built by the civil authorities who wanted to show the power of the city with a sign of devotion towards the patron saint. The first stone was laid in 1390 when the architect Antonio di Vincenzo (1350-1401) was entrusted to build a Gothic cathedral bigger than the original St. Peter’s Basilica in Rome. However, the Pope halted such majestic project imposing a

shift to a less impressive project. The church as it is today is the fifth biggest church of the world and was completed (at least in the interior part) in 1659 when G. Rainaldi (1570-1655) built the vaults.

The interior shows its Gothic layout. The three naves of the basilican plan are divided by ten cluster columns made of bricks, supporting pointed arches and ribbed groin vaults. The walls and the vaults are finished in white plaster, while arches and ribs are made of red bricks emphasizing the regular subdivision of the nave in square spans. Each side aisle is flanked by eleven square chapels corresponding to one quarter of the main module.

The chancel is characterized by the high ciborium (a work by J. Barozzi da Vignola), by the wooden choir (made in 15th century by Agostino de’ Marchi), and by the massive organ which occupies two sides of the area, substantially creating an acoustic volume well separated from the main volume of the church.

The church dimensions are simply impressive, with a total length of 130 m, a width of 60 m, and an height of 44 m, developing a volume of about 170000 m³.



Fig.1 Interior of the Basilica

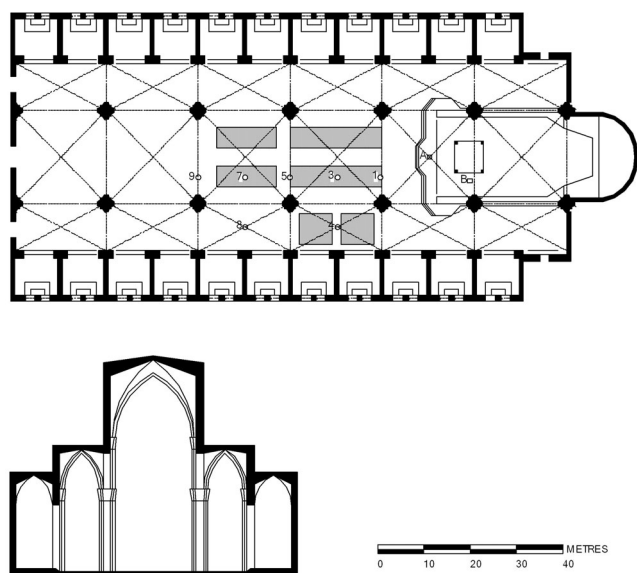


Fig. 2 Plan and section of the Basilica with source and receiver placement

3 Acoustic measurements

A set of acoustic measurements was carried out in unoccupied conditions, complying with the ISO 3382 standard [5]. An omni-directional sound source made of twelve 120 mm loudspeakers (with a frequency response from 100 Hz to 16 kHz) mounted on a dodecahedron, together with an additional sub-woofer to cover the frequencies below 100 Hz, was used. High-quality impulse responses were collected by using a B-format microphone (Soundfield MkV) and a binaural head and torso (B&K 4100D). The signal used to excite the rooms was a constant envelope equalized sine sweep generated with MATLAB according to Müller and Massarani [6] so that the spectrum of the radiated sound was substantially flat from the 50 Hz to 16 kHz third-octave bands. The room responses were recorded at a sampling rate of 48 kHz and 24 bit depth, to obtain, after deconvolution, impulse responses with very low noise (the signal to noise ratio was generally higher than 60 dB even at the lowest frequencies).

Sound sources were located (Fig. 2) in front of the altar and on the side of the ciborium inside the chancel. Strict time limitations prevented using more than seven receivers which were distributed in the main nave and in one aisle assuming geometric and acoustic symmetry. The source and the microphones were 1.5 m and 1.2 m from the floor surface, respectively. The B-format microphone pointed with the X axis toward the sound source, while the binaural head was placed on the seat facing the altar (with no head rotation).

The whole set of IRs collected in this way was later used to calculate the most important acoustical parameters according to the ISO 3382 standard [5]. A summary of the most significant acoustic results is reported in Table 1 and in Figure 3. Measured reverberation times are markedly lower (about 2 s) than those measured in a previous survey [7], however this discrepancy may be the result of either

different interior configurations (due to restoration works in a small area of the side aisle during the most recent measurements), or different measurement techniques, or a combination of them. In both cases T30 shows the typical decreasing trend as a function of frequency, depending on the significant effect of air absorption.

Taking into account the results of the last survey a virtual acoustic model (Fig. 4) was developed using the software CATT-Acoustics v. 8.0d. Absorption coefficients of different surfaces were assigned using literature values, especially for the huge plaster and brick surfaces. For surfaces where accurate estimation could not be made the absorption coefficients were determined iteratively in order to obtain a good match on T30. Resulting values of the acoustic parameters showed good agreement with those measured, with mean errors within just noticeable difference limits [8].

| | | |
|----------------------|------------------------|-----------------------|
| $RT_{mid} = 10.7$ s | $RT_{low} = 12.5$ s | $BR = 1.17$ |
| $EDT_{mid} = 10.2$ s | | $TR = 0.56$ |
| $G = 2.0$ dB | $G_{min} = 0.7$ dB | $G_{max} = 4.8$ dB |
| $C80 = -10.5$ dB | $C80_{min} = -13.3$ dB | $C80_{max} = -3.1$ dB |
| $LF_{nave} = 11\%$ | $LF_{aisle} = 24\%$ | |

Table 1 – Main results of the acoustic measurements

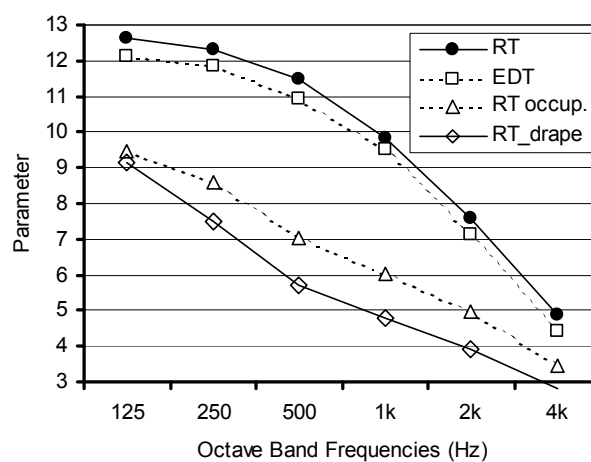


Fig. 3 – Measured reverberation times vs. frequency compared with simulated values

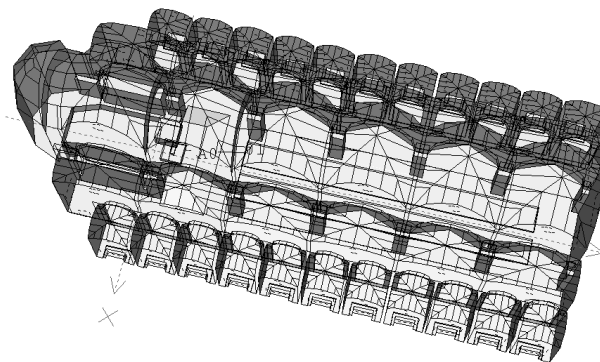


Fig. 4 Virtual model of the Basilica

The calibrated model was then used to simulate the effect of occupancy. Seated audience was distributed along the main nave, spanning three bays and a half and covering an area of about 1100 m², while side aisles were assumed to be fully covered by standing people in the first four bays (so

that the aisles flanking the chancel and the “crossing” were unoccupied), covering an area of 1300 m². In this way, assuming a density of 2 persons/m² for seating blocks and a minimum of 3 persons/m² for standing people follows an average occupation of about 6000 people. During major holidays the *Cappella Musicale* (that normally was made by about thirty musicians and singers) included several extraordinary members, so that their number sometimes exceeded 150 persons. Consequently the whole upper area of the choir (where the musicians usually stood), together with the lower stalls for the priests were assumed to be fully occupied. Taking into account the absorption coefficients of occupied seats, as reported in Table 2, the resulting reverberation times appear significantly reduced at medium and high frequencies, with a mean value of 6.5 s, while at low frequencies the mean value is 9.0 s, with a consequently high BR equal to 1.38. As a consequence of increased sound absorption average G lowers to -0.75 dB, C80 increases to -7.7 dB, while LF remains stable at 11%.

| | Octave band frequencies | | | | | |
|-----------|-------------------------|-----|-----|------|------|------|
| | 125 | 250 | 500 | 1000 | 2000 | 4000 |
| Audience | 30 | 40 | 70 | 80 | 85 | 85 |
| Musicians | 27 | 53 | 67 | 93 | 87 | 80 |

Table 2 Absorption coefficients for audience and musicians

4 Simulation of festive decorations

In order to understand whether the acoustic effect of festive decorations could be perceived by the listener and, consequently, assume that it could have been taken into account by the directors of the *Cappella Musicale* in their compositions, the first step was to define the amount, quality, and placement of draperies.

Archival researches were carried out in the *Archivio della Fabbrica di San Petronio* analyzing the receipts of the payments made in occasion of the celebrations for the patron saint from 1719 to 1927. One of the most detailed documents (dated 1721) reports that were used 122 pieces of damask having a length of 7 *braccia*, and 220 pieces of damask having a length of 6 *braccia*. The following year (1722) the amount was quite different because 175 pieces were 7 *braccia* long and 33 pieces were 6 *braccia* long. Several other documents may be found but they often report only the number of pieces and not their dimensions. They also report the use of additional pieces of “cendaline” (a lighter fabric similar to canvas), veils, and taffeta (the last one generally used to decorate columns).

Now, in order to quantify the surface of draperies used during such festivities it was first necessary to convert the old Bolognese *braccio* in meters. According to [9] in the Bolognese area 1 *braccio* corresponded to 0.64 m. Then the following step was to define the width of each piece, generally determined by the width of the loom, but according to several historical reports a typical measure for the piece was about 0.75 m. In this way it was possible to calculate that in 1721 about 1100 m² of damask draperies were used, while in 1722 they reduced to 680 m². Additional pieces of other fabrics may only increase this figure.



Fig. 5 Engraving by A.A. Scarselli representing the interior of the Basilica with draperies used during Cardinal Grimaldi’s funeral in 1733

These information were compared with some iconographic material found in the archives (Fig. 5). According to these pictures the draperies were generally hung all around the chancel (in particular in the apse and on the organs), on the arches between the central nave and the aisles, and on the vaults between each bay (at least for those close to the chancel). Draperies were also hung from all the balconies and on the columns of the nave. Taking into account the shape of the drapes reported in Fig. 5 an hypothetical layout was finally obtained, yielding to an area of about 1200 m², compatible with the amount derived from archival research.

Taking into account that the weight of the damask fabric is about 300 g/m² and that according to the engravings the draperies appeared moderately folded, absorption coefficients of 0.06, 0.22, 0.41, 0.61, 0.66, 0.60, respectively at frequencies from 125 to 4000 Hz, appeared to be a reasonable choice.

The previously calibrated acoustic model was finally modified by adding this amount of draperies. Only the occupied condition was taken into account in order to analyze whether the variations in the acoustics due to the draperies could be detected by the audience. Taking into account that draperies are acoustically transparent materials and that their placement in the church may also emphasize the subdivision into acoustically different volumes (decreasing acoustic coupling), the alternative “late part ray trace” algorithm [10] available in CATT-Acoustic was considered more appropriate in this case.

The results of the simulation (Table 3 and Fig. 2) show that the variations in the acoustic parameters should be clearly perceivable. In fact, mid-frequency reverberation time lowers to 5.2 s with a reduction of 20% well above the corresponding JND. Unfortunately low frequency values remain quite high, with a relative variation of 7.7% which give rise to a high BR equal to 1.58. Other acoustic parameters vary as well, with a further reduction of G, which assumes negative values all along the nave and the aisles, and a slight increase of C80.

| | | |
|---------------------|-----------------------|-----------------------|
| $RT_{mid} = 5.2$ s | $RT_{low} = 8.3$ s | BR = 1.58 |
| $EDT_{mid} = 5.0$ s | | TR = 0.64 |
| G = -1.6 dB | $G_{min} = -3.8$ dB | $G_{max} = 1.8$ dB |
| C80 = -4.4 dB | $C80_{min} = -8.5$ dB | $C80_{max} = +2.9$ dB |
| $LF_{nave} = 8\%$ | $LF_{aisle} = 20\%$ | |

Table 3 – Results of the acoustic simulation with draperies

When the sound source is located in the upper part of the choir (the so called *coretto*) and the receiver at the center of the priests' stalls, further differences were observed. In particular T30 lowers to 3.7 s and EDT lowers to 2.2 s. Low frequencies show less sensitive variations (with average T30 equal to 7.2 s) leading to a BR of 1.95. Energy based parameters show a significant increase, G is 8 dB and C80 is +8.4 dB, as a consequence of the smaller distances traveled by the sound waves and of the smaller volume of the chancel which under these circumstances appears weakly coupled with the main volume of the church. The weak coupling ensured much better acoustic conditions to performers, priests, and nobles which were in the chancel, than to the congregation located in the nave and in the aisles where listening conditions were poorer.

The most interesting results deriving from the installation of draperies may be summarized in a reduction of the mid frequency T30 not compensated in the low frequency range with the spectral content resulting strongly unbalanced. Reduction in G is also interesting because it might explain the need to increase the number of singers and musicians during the holidays. In fact, as stated above, the number of musicians employed during the holidays was about four times those normally employed in the *Cappella*. The particular reinforcement in the bass section (where may be found more than 20 basses and tenors) contradicts the observed reduction of relative level in the medium and high frequencies, but this may have different interpretations. From the most simplistic (a misinterpretation of the acoustical phenomenon) to the more subtle consideration that the frequency range where trained voice of male singers may overcome other instruments (the so called singer's formant) is located, even for basses and tenors, between 2 and 3 kHz, a frequency range where reinforcement was particularly needed. The latter hypothesis is hard to be demonstrated but, if true, would show a good knowledge of the acoustic phenomena.

5 Acoustic influences over music

In order to analyze whether acoustic conditions observed in San Petronio Basilica during major holidays could have actually influenced musical compositions of the different

directors, a comparative analysis was carried out. At this early stage of the research only recorded material was taken into account, even though a more detailed analysis of the scores is under way. Two different works by G.A. Perti were analyzed. The first is the "eight voices Mass in D major" composed in 1683 and later rearranged, which may be considered a typical example of music used during solemn celebrations in the Basilica. The second is the oratorio "San Petronio" commissioned by the Congregation of the Oratory of St. Philip Neri who was located in the (much smaller) Church of Madonna di Galliera where the work was performed.

In order to analyze the musical difference between the compositions a modified version of Ando's approach [11] was used. In fact, Ando suggests to characterize a music motif by calculating the effective duration (τ_e) of the running auto correlation function (ACF) obtained by the delay at which the envelope of the normalized ACF becomes 0.1. Then each motif is characterized by the minimum (τ_e)_{min} value calculated on the A-weighted signal, with a 100 ms interval and an integration time (2T) assumed equal to 2 s. This value represents a sort of time unit of the sound field in the performing space and, depending on the internal coherence of the music motif, is strongly influenced by tempo and performing style. Fast tempo and staccato playing results in short τ_e , slow tempo and legato playing result in long τ_e . For the purpose of this research each music motif was low-pass filtered and hi-pass filtered with a cut-off frequency of 500 Hz, then τ_e was calculated independently for the two parts, without A-weighting, and the statistical distribution of the τ_e values was obtained. The 10th and the 50th percentile values were assumed as numerical descriptors, respectively indicated as (τ_e)₁₀ and (τ_e)₅₀.

Fig. 6 reports the results of the statistical distribution calculated for the "Christe", the only piece of the recording which was entirely taken from the revised version of the Mass (rearranged when the author was probably more aware of the features of the Basilica). It appears that the bass part is completely different from the other, as the τ_e values are distributed almost linearly, with a (τ_e)₁₀ = 176 ms and (τ_e)₅₀ = 548 ms. The treble part shows a rapid growth of τ_e values with a (τ_e)₁₀ = 43 ms and (τ_e)₅₀ = 160 ms. These values suggest that Perti might have deliberately composed its music in order to allow low frequencies to fill the space and then decay in a slow modulation strongly influenced by the long reverberation. Conversely, the high frequencies appeared more richly articulated with faster passages. Substantially similar results, although slightly smaller in absolute values, were found for the other tracks, suggesting that the compositional style was already defined.

The results found for the oratorio (Fig. 7) are markedly different, with a statistical distribution of τ_e which is much more similar for both low and high part. For the first (τ_e)₁₀ = 27 ms and (τ_e)₅₀ = 103 ms, for the second (τ_e)₁₀ = 30 ms and (τ_e)₅₀ = 104 ms. Similar, but slightly higher values may be found for the other parts of the oratorio, confirming both a different treatment of the low and high frequencies, and a preference for generally shorter τ_e in the oratorio, in good agreement with the different acoustic characteristics of the two churches.

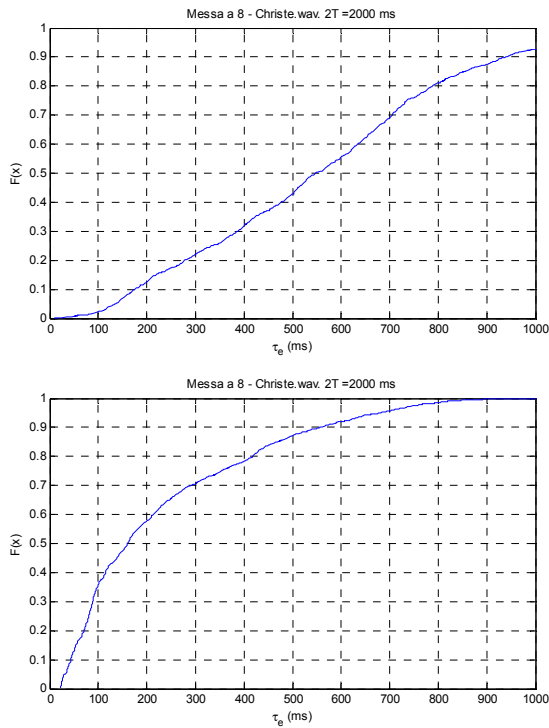


Figure 6 Statistical distribution of τ_c values for the Mass “Christe” motif low-pass (up) and high-pass (down) filtered

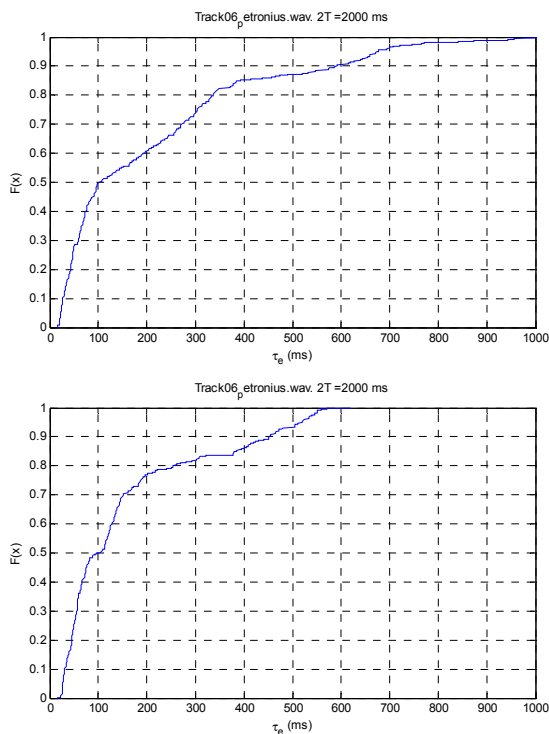


Figure 7 Statistical distribution of τ_c values for the Petronius' recitativo “Lungi da me”, low-pass (up) and high-pass (down) filtered

5 Conclusion

The paper reports an investigation on the acoustic effect of Baroque temporary decorations used for major holidays in the Basilica of San Petronio in Bologna. This huge church is characterized by a long reverberation time, exceeding 10

s in empty conditions. The reconstruction started from actual acoustic measurements of impulse response carried out with current techniques. A virtual acoustic model was then created and calibrated using measured acoustic data. The effect of occupancy was investigated, by adding seated audience in the nave and standees in the aisles, obtaining a significant reduction in reverberation time (which lowers to 6.5 s). The amount and the typology of draperies used in the Basilica were derived from an archival research carried out in the *Archivio della Fabbrica di San Petronio*, from which were obtained both quantitative information and iconographic material showing the placement of such material. According to these findings a further model was realized including about 1200 m² of draperies. The acoustic effect of the curtains proved to be significant, determining a further reduction of the mid-frequency reverberation time to 5.2 s. Unfortunately both people and draperies absorb little sound at low frequency, allowing a T30 as long as 8.3 s, with a significant spectral unbalance. However, the analysis of musical motifs composed for the Basilica by means of Ando's running duration of the ACF, showed that composers working in the church appeared to be aware of such flaw as they treated low and high frequencies in different way. A comparison with music of the same author composed for a different church seems to confirm this hypothesis.

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