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The Only Architectural Testimony of an 18th Century Italian Gordonia-Style Miniature Theatre: An Acoustic Survey of the Monte Castello di Vibio Theatre

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Abstract: The acoustic characteristics and spatial features of the world's only surviving Italianate Gordonia-style miniature theatre, one of the smallest theatres in the world, have inspired the author to analyse the acoustic behaviour of the Monte Castello di Vibio theatre, also called "Teatro della Concordia". In this paper, the geometric and architectural features of this historical and unique performing art space were first reproduced, considering that these features are essential factors affecting acoustic characteristics. Subsequently, the acoustic measurements were taken throughout the stall and inside some selected boxes, and their main parameters were acoustically characterised according to ISO 3382-1. Lastly, the main acoustic parameters of the Monte Castello di Vibio theatre were compared to those of the 1763 theatre in Bologna, which is also a miniature theatre of similar size. The aim is to explore the main influences on the acoustic parameters of miniature theatres, and the results show that the plan layout of the theatre and interior decoration are the main factors influencing the acoustic characteristics rather than volume. Preserving the acoustic features of this unique heritage building is also seen as one of the goals of this paper.

Keywords: cultural heritage; acoustic simulations; main influences; the smallest theatre

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1. Introduction

Monte Castello di Vibio theatre, also called "Teatro della Concordia", is located in Monte Castello di Vibio, in the Umbria region in Italy. It is considered to be the smallest theatre *all'italiana* in the world. In 1997, the Monte Castello di Vibio theatre was twinned with probably the largest theatre in the world, the Parma Farnese [1]. Famous artists that have performed at the theatre include the Italian actress Gina Lollobrigida and the Austrian classical guitarist Johanna Beisteiner [2].

The paper begins with an investigation into the architectural spatial characteristics of the theatre, namely the volume and shape of the main hall, the composition of the stalls, and balconies as well as corridors within the theatre. This all has an important influence on the acoustic characteristics of the theatre space. On this basis, this paper discusses the acoustic characteristics of the Monte Castello di Vibio theatre, measured in accordance with the requirements of the ISO 3382 standard [3,4] in order to record the impulse response at different locations throughout the seating area. The results are also compared with those of a 1763 theatre in Bologna, of the same volume but with a different plan layout and interior decoration. The main factors affecting the acoustic characteristics of the mini-traditional theatre are summarised. Additionally, the measurements show that the acoustic response of the Monte Castello di Vibio theatre is more ideal for speech performances than for music. The acoustic parameters are more suitable for being used as a conference hall than the standard for theatres of similar room volume.

The limitations of this study can be seen in the fact that different scenarios were not simulated to compare further the different acoustic properties exhibited by lecture activities and musical events. However, the present measurements and data analysis can support the conclusions of this paper.

2. Historical Background

2.1. History of the Monte Castello di Vibio Theatre ("Teatro della Concordia")

The Monte Castello di Vibio theatre, shown in Figure 1 [5], is considered the most miniature Italian-style theatre and one of the smallest in history. It is the only architectural testimony of a miniature Gordonia-style Italian theatre of the 18th century [1].

Figure 1. View of the Monte Castello di Vibio theatre [5].

The theatre was built in the early nineteenth century as a venue for entertainment and meetings at the request of nine wealthy local families during the Napoleonic occupation. Its inauguration is dated 1808, and in 1823 the owners established the Concord Theatre Membership Academy for the theatre's management [1].

In 1951, the theatre was closed due to inoperability. In 1976, the roof and some of the theatre's stalls further partially collapsed and Mayor Vittorio Antonini decided to make an emergency intervention to save the salvageable. However, the deficit in the municipal treasury made the restoration difficult. Fortunately, with the support of citizens and some small local construction companies, the first repairs to the theatre were achieved, preventing further damage to the structure.

In July 1993, after 42 years of neglect, the Monte Castello di Vibio theatre was restored with the help of European funds. Under the direction of architects Paolo Leonelli and Mario Struzzi, the restoration was successfully completed, thus preserving the original wooden structure that supported the box [1].

In 1997, the Teatro della Concordia (i.e., the Monte Castelli di Vibio theatre) was twinned with the Teatro Farnese in Parma, considered the largest theatre in the world [1].

2.2. History of the 1763 Theatre in Bologna

The 1763 theatre in Bologna, shown in Figure 2 [5], was built approximately in the same period as the Monte Castello di Vibio theatre. It was a small theatre in the Villa Aldrovandi Mazzacorati, privately owned by the Aldrovandi family, in the left wing of the building. After the demise of the Aldrovandi branch, the villa was resold several times before it was ceded to Fascist soldiers in 1928. Although the estate was damaged during the Second World War, the theatre survived the war and has retained its original shape, including the canvas backdrop, the ten scenes on the stage, and most of the original chairs [6].

Figure 2. View of the Villa Aldrovandi Mazzacorati, which hosts the 1763 theatre [5].

3. Architectural Characteristics

3.1. Architectural Characteristics of the Monte Castello di Vibio Theatre

The Monte Castello di Vibio theatre building is bell-shaped in the plan, with a deep narrow hall leading to the vestibule and the stage, typical of Italian theatre design. It possesses the three fundamental elements that Goldoni demanded for theatre construction: wooden boxes, a bell-shaped plan layout and a ceiling built using the camorcanna technique. The theatre has only 99 seats, 62 distributed among boxes and 37 in the stalls, as shown in Figure 3. The auditorium has an area of 68 square metres; the stage is 50 square metres and the entrance hall is 29 square metres. The hall is decorated in bright colours, and the theatre is endowed with a strong vitality of paintings by the young painter Luigi Agretti. The plan layout is shown in Figure 3, whilst the interior is shown in Figure 4.

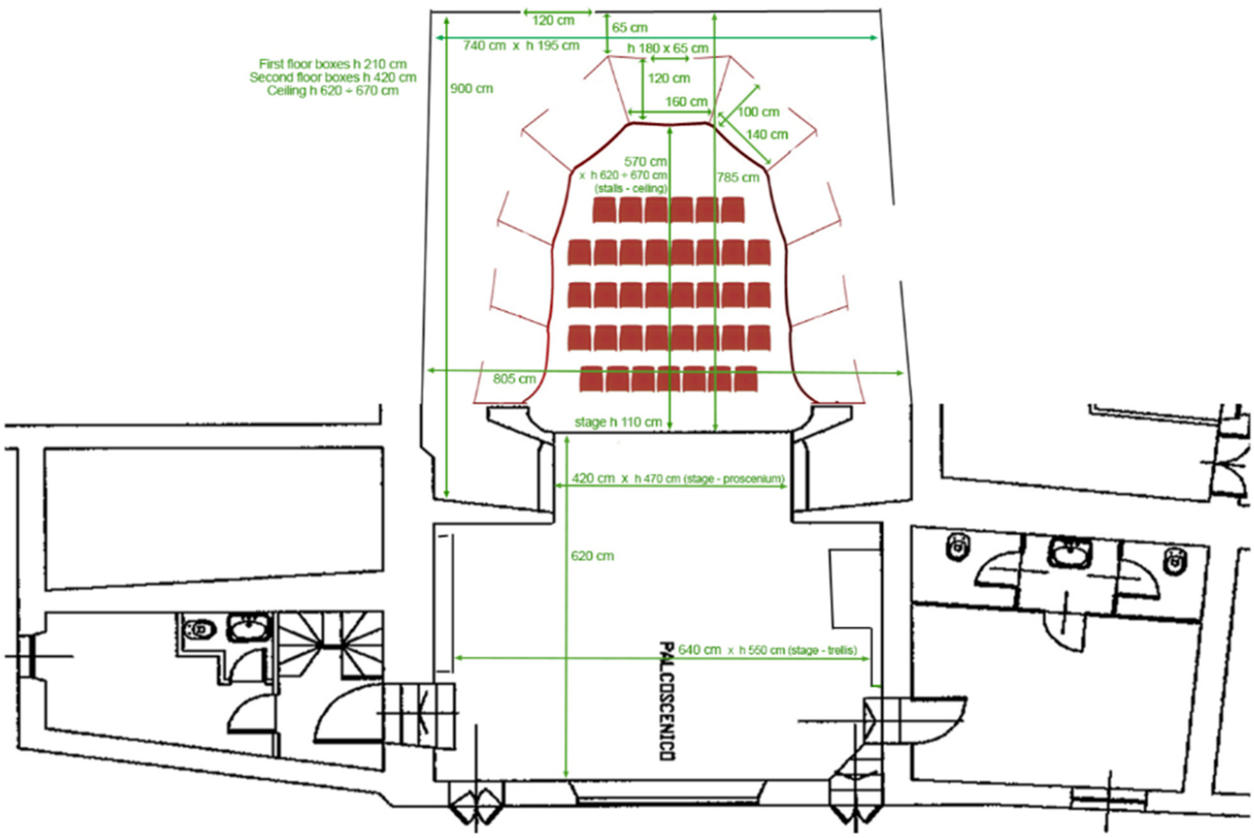


Figure 3. Plan layout of ground floor.

Figure 4. View of the main hall from the stage [1].

3.2. Architectural Characteristics of the 1763 Theatre

The 1763 theatre has a backstage, raised stage, tool room, foyer and double access from the outside, and an exit to the inner hall. It can accommodate 80 people, but the original stalls and balconies could accommodate 200. It shares the same volume as the Monte Castello theatre but has different plan shapes; the Monte Castello theatre has a classic bell shape while the 1763 theatre has a "U" shape, as well as different interiors, as shown in Figure 5 [6].

Figure 5. Interior view of the 1763 theatre [6].

Attributed to the excellent relationship between the depth and width of the main hall and the use of local building materials, the theatre has the title of "perfect acoustics". Because there is no echo effect, microphones are not needed, and the voice actors on stage can be heard even from the balcony [6]. As a result, musical and prose performances have been taking place without any amplification for 25 years, with a high level of intelligibility and acoustic quality.

4. Acoustic Measurements

4.1. Acoustic Measurements of the Monte Castello di Vibio Theatre

Acoustic measurements were carried out in the Monte Castello di Vibio theatre to understand the acoustic response of the hall by the requirements of the standard set out in ISO 3382-1 [3], which is considered the international reference standard for objectives of acoustic parameters. During the survey, thermal and humid conditions were taken into account [7]. The equipment involved in the study and how the signals they recorded were used to calculate the relevant acoustic parameters were as follows:

- Equalized omnidirectional loudspeaker: a light yet powerful sound source for measurement applications in the room and building acoustics. It is built from twelve specially developed dynamic drivers that ensure a uniform emission of the acoustic test signal. This speaker was used to reproduce the ESS signal in the theatre;

- Binaural dummy head: a professional dummy head made by Neumann. It is a binaural stereo microphone, and two omnidirectional condenser capsules are built into artificial ears mounted on an enclosure resembling a human head. The Neumann dummy head has very low self-noise and can handle high sound pressure levels of up to 135 dB without audible distortion. This head was used to record binaural stereo files, which were used to calculate interaural cross-correlation (IACC early);
- B-Format microphone: it is a Sennheiser Ambeo microphone to record 360° spatial audio. The Ambeo is an Ambisonics microphone fitted with four matched KE 14 capsules in a tetrahedral arrangement. This unique design lets users capture the surrounding sound from one single point. The capsules of the Sennheiser Ambeo deliver A-format, a raw four-channel output that has to be converted into a new set of four channels, the Ambisonics B-format. B-format is a W, X, Y, and Z representation of the sound field around the microphone. W is the sum of all four capsules, whereas X, Y, and Z are three virtual bi-directional microphone patterns representing front/back, left/right, and up/down. In this study, only the W and Y signals were used to compute Lateral Fraction (LF) and Lateral Efficiency (LE);
- Omnidirectional microphone: a Bruel & Kjaer $\frac{1}{2}$ inch prepolarised free-field microphone. It is an ultra-linear condenser microphone for measurement and recording applications, ideally suited for room equalisation, high-resolution studio recording, and live applications. It has a flat frequency response from 15 Hz to 20 kHz and an actual omnidirectional pattern. The omnidirectional microphone was used to record mono signals, which were used to calculate other main acoustic parameters (in this survey, the Reverberation Time (T_{20}), Early Decay Time (EDT), Clarity indexes (C_{80} and C_{50}), and Definition (D_{50}) were included);
- Audio interface: a Zoom F8 audio interface was used to record the signals coming from microphones, with 8-input/10-track recording, super low-noise preamps, and support for 24-bit/192 kHz audio. Through it, seven channels of audio files were recorded, with tracks from one to four for the Ambeo microphones, 5–6 for the binaural recordings of the dummy head, and the last channel for the mono recording from the omnidirectional microphone.

The sound source was placed 1.6 m above the finished floor. In comparison, the receiver was mounted at 1.4 m across the stalls and inside several boxes to cover the spectator area and the complete setup was composed of a dummy head, a B-Format microphone, and an omnidirectional microphone, as shown in Figure 6. The receiver points chosen for the measurements were sufficient to understand the acoustic response of the hall, taking into account the axisymmetry of the volume. The excitation signal feeding the sources was an Exponential Sine Sweep (ESS) with a duration of 15 s at a constant sound pressure level from 40 Hz to 20 kHz [8]. The ESS signal was used to feed the omnidirectional loudspeaker rather than white or pink noise in order to obtain the impulse response (IR) of the room. The ESS technique was used instead of other techniques developed in the past (e.g., MLS) because by using ESS it is possible to obtain better impulse responses, removing all the distortions due to the electronic equipment (e.g., distortion in the loudspeaker, in the microphones, etc.) [9]. This followed the reference standard to be used at each relevant point. The excitation signal should have sufficient energy at each octave band [10]. The measurements were carried out under unoccupied conditions. Figure 7 shows the measurement positions of the instrument in the sitting area.

Figure 6. A 360 picture of the measurements in the Monte Castello di Vibio theatre with the equipment.

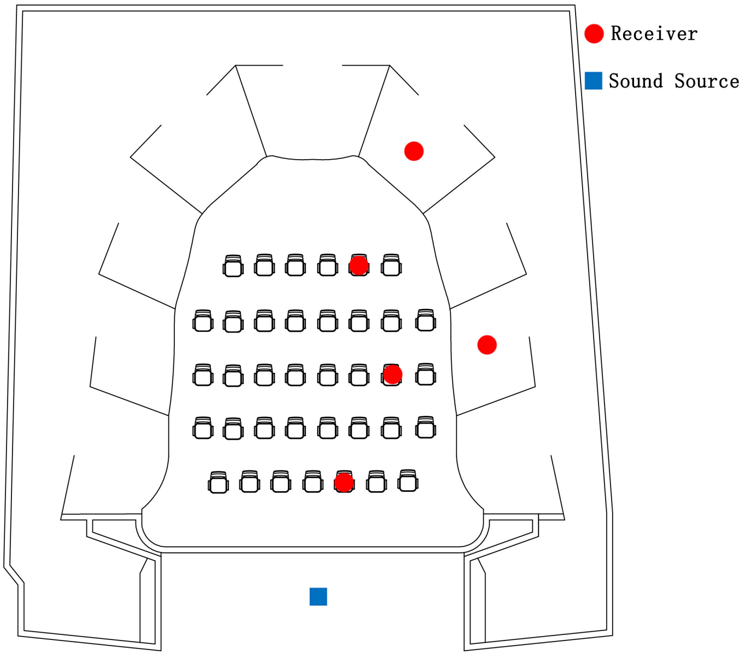


Figure 7. Scheme of the equipment location during the acoustic survey.

The methodology was first introduced in 2013 [11] and during these measurements the SoundField microphone was substituted with the Sennheiser Ambeo. Furthermore, instead of two cardioid microphones in the ORTF configuration, only one monoaural microphone was utilized for the surveys.

4.2. Acoustic Measurements of the 1763 Theatre

As the measurement tools and post-processing methods are identical to those of the Monte Castello theatre, they were described in detail in the last part and will not be repeated here. Only the plan layout and the arrangement of the measuring tools for the measurements are described.

In this paper, with reference to paper [6], we considered the latest measurements conducted in the 1763 Theatre. During these measurements, a SoundField MKV microphone was used instead of the Sennheiser Ambeo (not available at that time). Nevertheless, the

SoundField microphone could be considered very similar to the Ambeo mic and, therefore, the results are comparable to each other.

In this acoustic survey, the omnidirectional loudspeaker (LookLine) was set on the stage as a sound source. The dummy head (Neumann KU100) was fixed in the middle of the room as a reference measurement. At the same time, the B-Format microphones (Sennheiser Ambeo microphone) were moved along the second row from the left side of the theatre to 10 different positions on the right side, as shown in Figure 8 [6]. The measurements intended to analyse the variation of the sound characteristics in the 1763 theatre with different heights of the microphones, together with the variation along the raw.

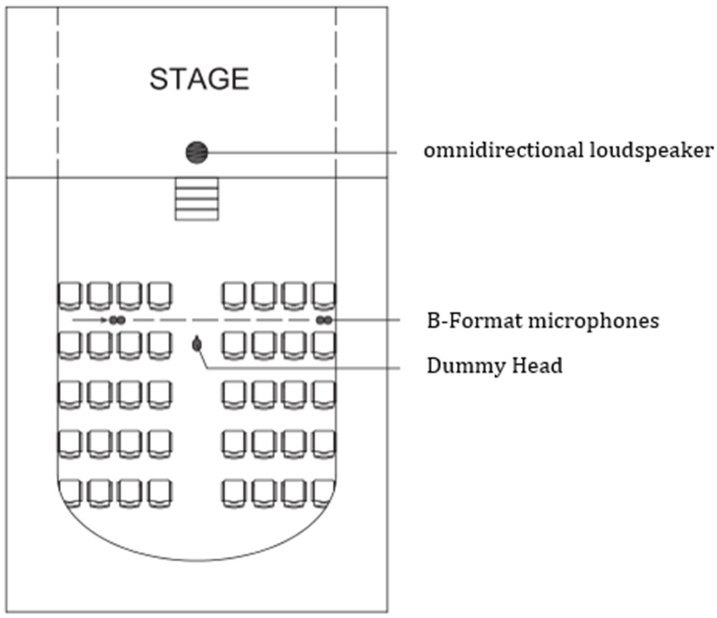


Figure 8. Plan of 1763 theatre: position of microphones for the acoustic measurements.

5. Acoustic Measurement Results of Monte Castello Theatre

In this section, after the IRs were obtained, the acoustic parameters were calculated using Aurora, a plug-in for Audition 3.0.

The main acoustic parameters have been analysed, to be considered the average of all source-receiver positions in unoccupied conditions. Different acoustic parameters defined by the international standards ISO 3382-1 have been analysed and commented on, to be included are as follows:

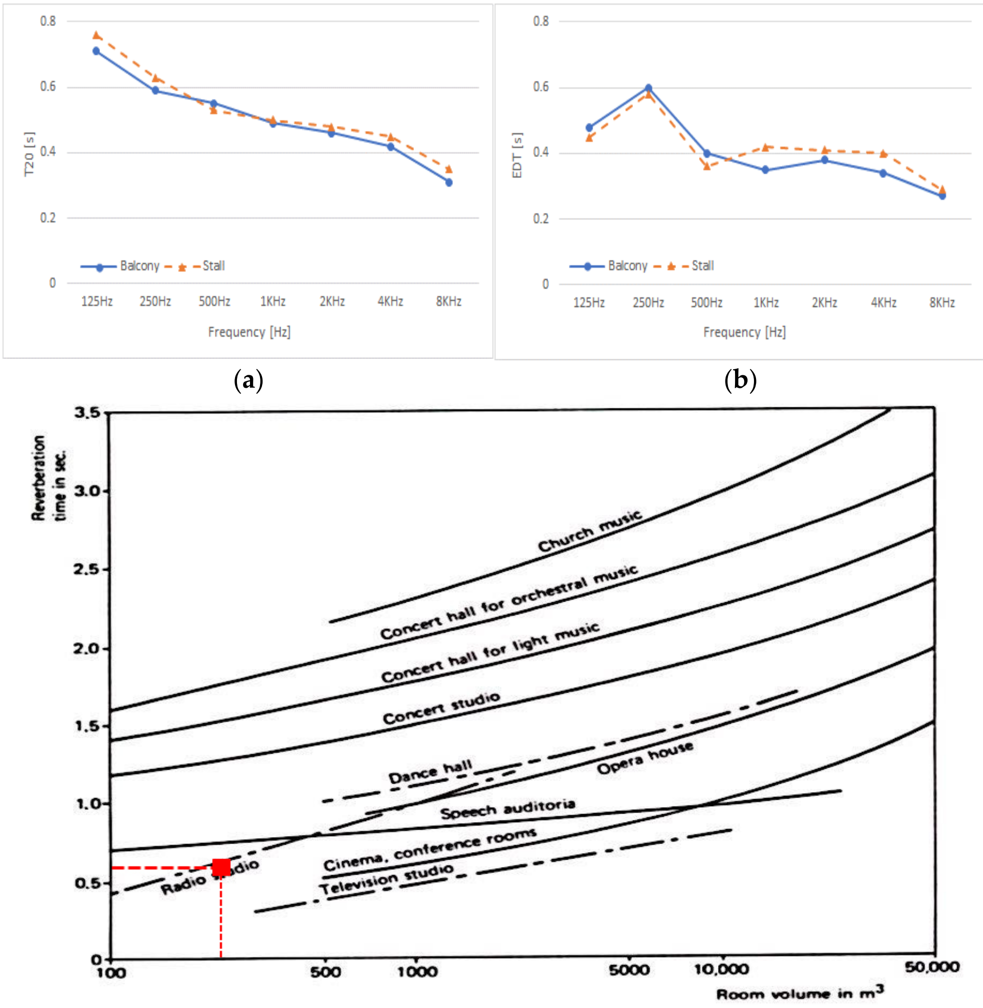
- Reverberation Time (T_{20}): it is one of the most essential parameters to express the acoustic characteristics of a space;
- Early Decay Time (EDT): it combines with the reverberation time to reflect the overall acoustic condition of a room;
- Clarity indexes (C_{80} and C_{50}): C_{80} refers to the measurement of a hall for musical performance; the clarity evaluated for speech performances is C_{50}. They are the main parameters for assessing the acoustic quality of theatre spaces;
- Definition (D_{50}): it is used to evaluate the quality of speech perception in rooms. Unlike concert halls, a large number of opera performances are staged throughout the year in theatres, so the speech intelligibility conveyed to the audience is also an important factor in expressing its acoustic characteristics;
- Lateral Fraction (LF): it represents the ratio of the laterally reflected sound energy in a room over the sound energy arriving from all directions, including the direct sound energy coming from the source. These reflections are responsible for the extensive perception of the sound source. The lateral fraction is a measurement of the spaciousness of a room. Lateral sound energy and sound energy that arrive

to the listener from all directions should be considered separately, which is why omnidirectional microphones must be used in investigations;

- Interaural Cross-Correlation (IACC): it is called the Interaural Cross-Correlation Coefficient for music and speech. In particular, the IACC represents a value that measures the maximum similarity between waves arriving at the two ears.

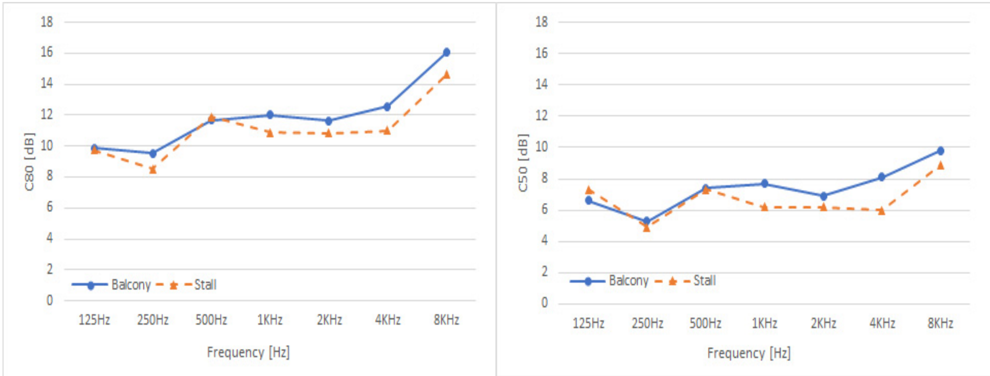
The main acoustic parameters are reported in the octave bands between 125 Hz and 8 kHz.

Figures 9–13 show the graphs of the measurements of the main acoustic parameters. Measurement results relate to a comparison with the stalls and balcony. The sound source has been installed in the centre of the stage. The receivers have been located across the stalls and in some selected boxes.



(**a**) (**b**) (**c**)

Figure 9. Measurement results of the acoustic parameters: Reverberation Time (**a**), Early Decay Time (**b**), and Optimal T_{20} values at 500 Hz, based on room volume (**c**).



(**a**) (**b**)

Figure 10. Measurements results of the acoustic parameters: Clarity indexes (C_{80}) (**a**) and Clarity indexes (C_{50}) (**b**).

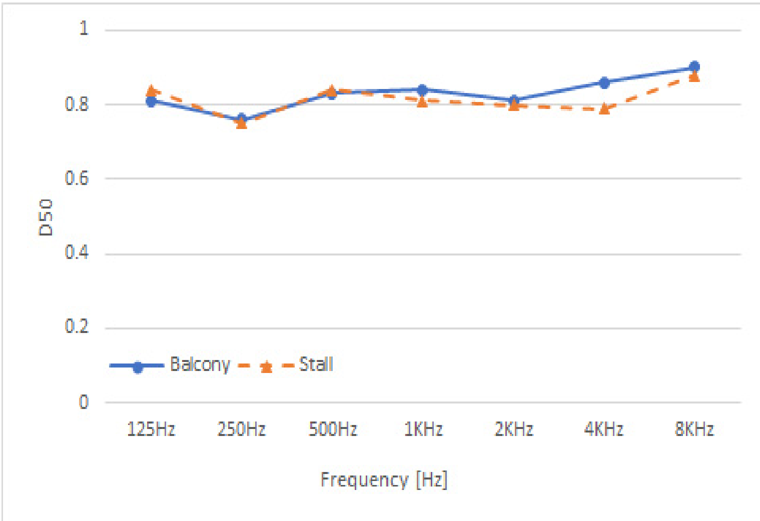


Figure 11. Measurements results of the Definition (D_{50}).

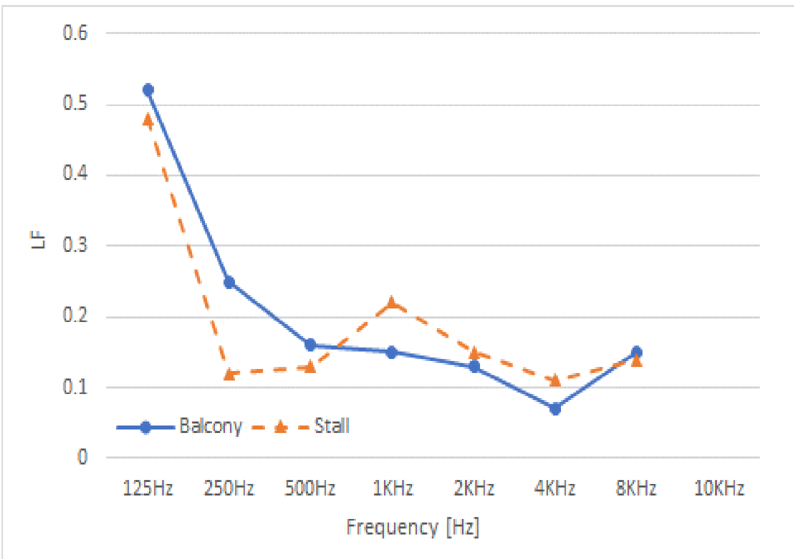


Figure 12. Measurements results of the Lateral Fraction (LF).

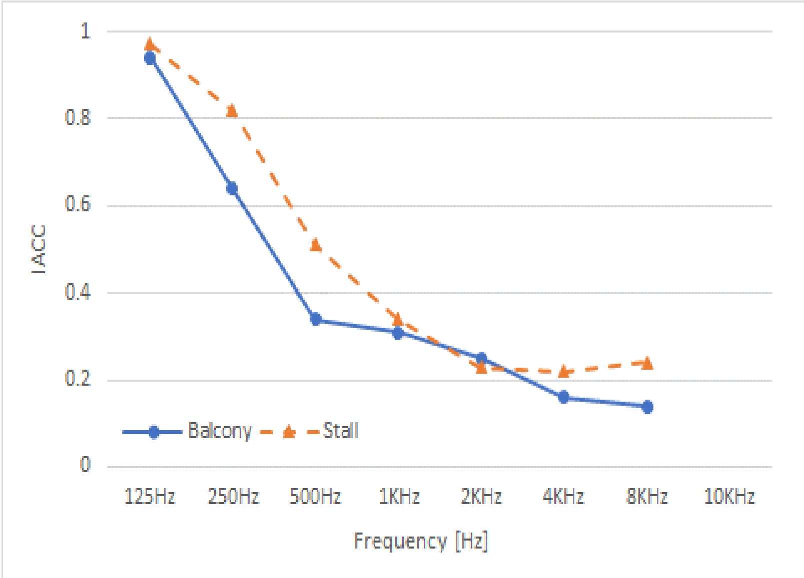


Figure 13. Measurements results of the Interaural Cross-Correlation (IACC).

Figure 9a indicates that the averaged values of T_{20} are around 0.5 s at mid frequencies, which are found to be very similar for the stalls and balcony. In conjunction with Figure 9c, the T_{20} value at 500 Hz, it can be clearly seen in the results that the Monte Castello di Vibio theatre is below the ideal Reverberation Time for an opera house with this volume size [12]. It is more suitable as a radio studio and conference room.

In terms of Early Decay Time (EDT), as shown in Figure 9b, it was found to be very similar between the stalls and balcony. Between 500 Hz and 4 kHz, the values fluctuate around 0.4 s, while at lower frequencies, the results rise to 0.6 s, and at higher octaves, the values drop to 0.2 s. The overall outcome is slightly lower than the optimum range set by the Opera House [13].

The graph of Figure 10a indicates that the clarity index related to music (C_{80}) for both the stalls and balcony has been found to be too high in all octaves, and according to the standard, C_{80} should be at most 1–2 dB for good musical performance [14]. This result negates the suitability of the Monte Castello di Vibio theatre for opera and orchestral music.

The values of the speech Clarity index (C_{50}), as shown in Figure 10b, were very similar between the stalls and the balcony. And the values in the stalls were found to be better than those on the balcony. For ideal speech transmission, the C_{50} should be higher than 4 dB [15], and the measured values are above this limit in the entire frequency band. At high frequencies, the intelligibility index is significantly higher.

The values of Definition (D_{50}), as shown in the graph of Figure 11, are fluctuating between 0.75 and 0.85 at low and mid frequencies and rise to 0.9 at high-frequency bands, meaning that the speech definition is considered good inside the Monte Castello di Vibio theatre; values higher than 0.5 are preferable [16], considered very suitable for opera.

The graph of Figure 12 indicates that the values of the stalls and balcony have the same trend. They are supposed to be fluctuating between 0.1 and 0.25 at mid to high frequencies while rising up to 0.5 at low-frequency bands. This means that the overall results confirm that the LF values are not in the ideal range [17], even though the values of the balcony are optimal at 250 Hz (0.2 or 0.25).

The values of Interaural Cross-Correlation (IACC), as shown in the graph of Figure 13, have been found to drop from 1 at 125 Hz to around 0.2 at 8000 Hz. IACC indices were measured by binaural microphones in the ears of the dummy head, and the mean of five different measurements was calculated. Results can be seen from the graph; the values are at the optimal value in the mid-frequency band, around 0.3 [17].

6. Acoustic Comparison

This section compares and analyses the main acoustic parameters [6] of the Monte Castello di Vibio theatre and the 1763 theatre in Bologna to find out whether their performance spaces exhibit different acoustic characteristics. The physical conditions of the two theatres in the survey were not significantly different and slight variations would not have affected the measurements. The same operators and equipment were used for the measures as far as possible. The leading influences on the acoustic characteristics of these miniature theatres are discussed.

The comparison of the measured results of the main acoustic parameters of the Monte Castello di Vibio theatre and 1763 theatre is shown in Figure 14.

Figure 14. Monte Castello di Vibio theatre vs 1763 theatre main acoustic parameters.

Figure 14a indicates that the EDT of both theatres has a small climb in the mid-frequency bands, and then the 1763 theatre drops in the high frequencies while the Monte Castello di Vibio theatre stabilises at 0.4 s. It is easy to see from the results that the 1763 theatre is more suitable as an opera hsouse than the Monte Castello theatre. Figure 14b shows the same downward trend in both theatres. The averaged values of T_{20} in Monte Castello theatre are around 0.5 s at medium frequencies, which is lower than the Reverberation Time of Italian opera houses (Figure 9c), while the T_{20} measurements of the 1763 theatre show an average value at mid-frequencies of 1.2 s. This value is above the Reverberation Time of Italian opera houses (Figure 9c).

The values of the speech Clarity index (C_{50}), as shown in Figure 14c. And the measurements of the Monte Castello theatre were found to be better than the 1763 theatre. The graph in Figure 14d indicates that the Clarity index related to music (C_{80}). The result shows that the 1763 theatre is more suitable for opera and orchestral performances than the Monte Castello theatre.

In terms of Definition (D_{50}), as shown in the graph of Figure 14e, it has been found that the values at all frequencies of the Monte Castello theatre and the high-frequency bands of the 1763 theatre are above 0.5, meaning that the speech Definition within these frequencies considered to be good.

The values of Interaural Cross-Correlation (IACC), as shown in Figure 14f, show the same trend of variation in both theatres. Additionally, the values of the Monte Castello theatre are at the optimal value in the mid-frequency bands, while in the 1763 theatre, the optimum values are found in the low frequencies. Although the two theatres share the same volume, they have very different acoustic characteristics due to their various plan layout and interiors. Compared to the 1763 theatre, the Monte Castello di Vibio theatre is more suited to lecture events than opera.

It should be also highlighted that the two theatres have a different plan shape. This means that the Monte Castello theatre (a horseshoe theatre), built at the beginning of the 19th century, was explicitly erected for opera, whilst the 1763 theatre, built 40 years before, was explicitly erected for music. The acoustic outcomes confirmed these two different intended uses of the two theatres.

7. Conclusions and Future Recommendations

This paper is concerned with the presentation of the acoustic results obtained from a survey carried out at the Monte Castello di Vibio theatre and analyses the main acoustic parameters compared with the Teatro 1763 in Bologna with the same volume. The measurements were carried out using an omnidirectional sound source and four types of microphones.

The evaluation of the acoustic measurements carried out inside the Monte Castello di Vibio theatre shows that it responds well to speech because of its smaller volume compared to other traditional theatres. It is a more suitable venue for lecture events, as evidenced by the analysis of the main acoustic parameters: a shorter Reverberation Time and the value of the Early Decay Time (EDT) is lower than the ideal value that an opera house should have. For the Clarity index, the C_{80} is far above the ideal level for musical performances, while the C_{50} has a good performance. The Lateral Fraction (LF) and the Interaural Cross-Correlation (IACC) also confirm this statement. However, as an Italian theatre also with a small volume, the 1763 theatre shows a difference in the main acoustic parameters. This leads to the conclusion that a theatre's plan layout and interior decoration determine its acoustic characteristics more than its size.

Based on this acoustic investigation, future research may focus on two areas: firstly, the exploration of acoustic simulations of some theatrical performances to find out which ones are better suited to this unique historic theatre. Secondly, based on the results obtained in comparison with the 1763 theatre, the Monte Castello theatre could be modified, for example, by choosing fabrics with different absorption coefficients for the interior and by adding components to improve the acoustic properties.

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