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ACOUSTICAL CHARACTERISATION AND RESTORATION OF THE GOLDONI THEATRE IN LIVORNO

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1. INTRODUCTION

During the 18th and 19th century a great number of small and big halls were built. The Goldoni theatre is one of the biggest, its overall volume being almost 14000 m^3, and it has the typical "horse-shoe" shape.

During the eighties the theatre was closed for safety problems and it was abandoned. Now a project of restoration has been settled and a survey of its acoustical characteristics has been performed before and during the restoration.

Series of monaural acoustical measurements were taken at several sources and receiver locations (more than one hundred). The measurements included Reverberation Time, Early Decay Time, Center Time, RASTI index, Clarity index, etc.

The results we obtained permitted the characterisation of the hall, that has been reconstructed in 3D by CAD technique on computer. The acoustical measurements have been used to calibrate the input parameters of *Ramsete* software, a modelling program based on the ray tracing method. In this way, changes of architectural features or changes in the materials can be simulated to predict the effects on acoustical characteristics of the theatre.

2. HISTORICAL NOTES

Early in 1658 a theatre was built in Livorno [1]; it was called *'Lo stanzone delle commedie'* and it was only used for performances, especially operas. This theatre was demolished 120 years later and many other theatres (as many as 11) were built during the following years: this was a demonstration of the large cultural activity of the town. In 1843 they began to build the *Leopoldo Theatre*, this theatre has changed its name many times and nowadays it is called *Goldoni Theatre*.

The works lasted 4 years under architect Cappellini guidance and the theatre was inaugurated 24 July 1847 with two performances: an evening performance and a matinée on 25 July. This was the chief characteristic of the theatre, namely to be used for matinées, too, because it had a big skylight on the roof over the central zone of the stalls. The skylight is the most innovating element of the entire project of the building and it is made of even 1400 glass slabs that weighted 4 tons and of an iron frame that weighted 30 tons. The theatre had, and keeps, a "horse-shoe" shape (fig. 1) and 115 boxes subdivided into 4 tiers and a gallery.

The theatre has been repaired many times since its construction because of a seepage of water from the skylight; it has had many different owners, and many operas and prose works have been performed there. In the beginning of 20th Century it became a *'Caffè concerto'* and the first cinematographic experiments have been carried on.

In 1984 the theatre closed because of safety reasons and in 1993 new repairing works began. Before this last improvement the theatre had 1305 seats: 600 in the stalls divided into four sectors, 200 in the gallery, and the others in the 101 boxes.

The boxes are 4 meters deep, the stalls are 20 m wide and 22 m long, the first line of the stalls is 7 m far from the stage and the roof is 26.3 m high. The original walls of the stalls were made of plaster and it has been replaced by a covering made of marble about 3 metres high, coming from Siena, during the repairing in 1980.

The stage has a trapezoidal shape because of historical reasons: they could not buy the land behind it. It is 30 m wide, 18 m deep and 18 m high. The box for the orchestra is :5 m deep from the stalls, 5 m wide and 18 m long and can hold even 120 musicians.

During the repairing works they discovered a hollow 1 m high, it was filled and a wooden floor was put on the top of it. In the rear of the stage they found two jars (one broke down during the first years after the theatre's construction as it is said in the news) and three arches of different sizes. These objects and structures could be attempts made by the architects in the past to improve the acoustics of the theatres.

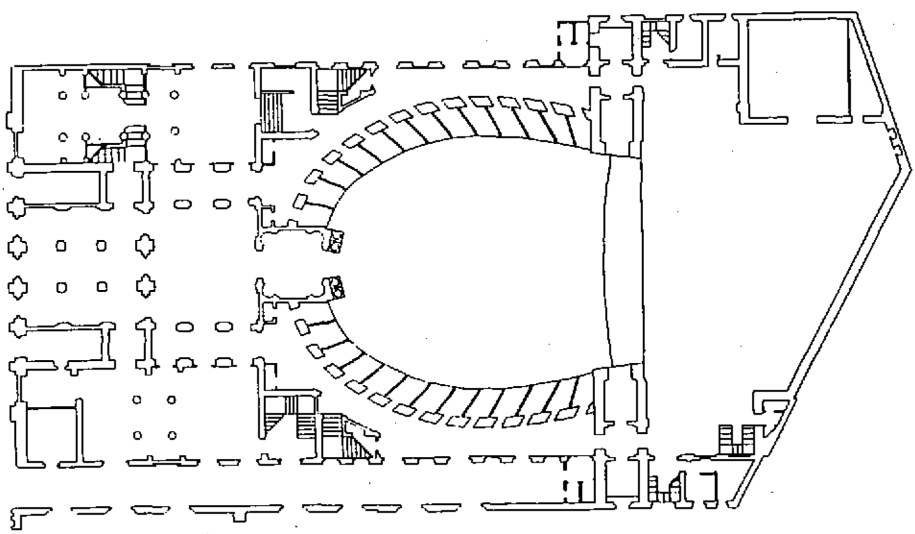

Fig. 1. The Goldoni Theatre plan.

3. MEASUREMENTS METHODS

Before the renovation of the Goldoni Theatre we performed a lot of measurements to give an accurate picture of the acoustical situation. The hall was unoccupied, deteriorated because it had been closed for a long time; the proscenium and all the stage were empty, without backdrops, scenery, curtains, etc. Also the boxes were empty, without chairs and curtains. In the stalls the seats were upholstered with velvet.

To evaluate the various acoustical indexes we used an instrumental chain composed of a B&K 2144 dual-channel real time frequency analyser, equipped with a B&K 4165 microphone (Type 1 precision), two B&K 2231 phonometers, a pistol and another sound source, consisting of a loudspeaker, a power amplifier and a pink noise generator, in order to obtain sound level decay times with the two different techniques of cut-off noise and impulsive noise.

The real time analyser is used to capture, ensemble average, and filter the pulse responses, which are then transferred digitally to a portable computer. Decay times are calculated from least-squares fits to portions of the decay curves obtained by the Schroeder backward integration technique [2].

Finally we developed a suitable software to compute the principal indexes from time acquisition of sound decay and to statistically analyse the results.

3.1 Sound Pressure Level Distribution

Both measurements in the stalls and in the boxes were repeated for each receiver, putting the sound source on the stage in three different positions: on the left, on the right and in the middle of the proscenium.

In the stalls sound levels and frequency spectra were acquired in 58 different positions, distributed between the seats (40) and along the central aisle (18). Measurements in 74 different positions were performed in the boxes: in this case the receivers were distributed homogeneously again between the various tiers.

3.2 Reverberation Time

Measurements were performed in 115 different positions: 40 in the hall and 75 in the boxes interrupting the sound source put on the proscenium; we also repeated each at least three times and averaged the results.

Twelve receivers, representative of the stalls, were also chosen to acquire the decay time obtained by pistol shot technique.

3.3 Speech Transmission Index (STI)

Everywhere verbal communication takes place, the quality of the speech transmission is of primary interest. In theatres it is of paramount importance, particularly for Operas in which the sung word should remain clear and intelligible. Perfect transmission of speech implies that the temporal speech envelope at the listener's position replicates the speech envelope at the speaker's mouth.

We used RASTI (Rapid Speech Transmission Index) method [3], standardised by the IEC [4], to obtain objective measurements of the quality of speech transmission with respect to intelligibility.

RASTI measurements were made by sending the special test signal by a B&K 4225 transmitter placed on the stage and analysing it by a B&K 4419 receiver at different listener's position (32 in the hall and 22 in the boxes). During the measurements we performed the output level was 10 dB higher than the reference one.

4. RESULTS AND DISCUSSION

4.1 Acoustical Indexes

The sound level distribution measured in the stalls is shown in fig. 2. The values were computed considering the sum of the contributions of one source positioned in the three different places on the stage. It is worth noting the symmetry with respect to the longitudinal axis and the good uniformity of the sound level distribution; this fact was also found in each frequency band.

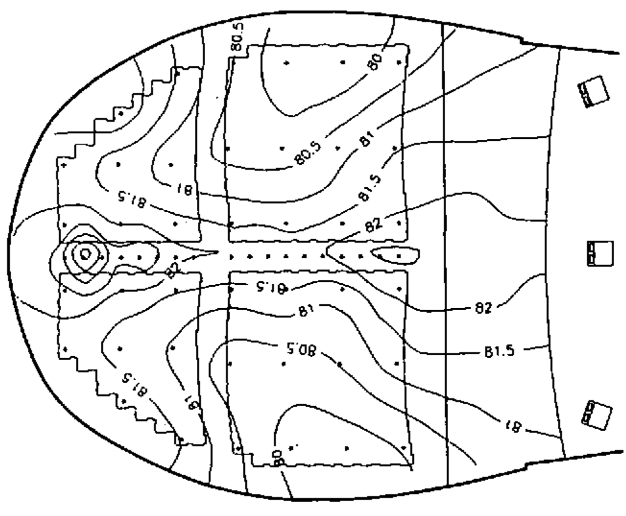

Fig. 2. Sound level distribution in the stalls: each star represents one receiver.

One focalization point was found in the rear of the stalls; therefore an evident sound reinforcement was observed. The hall shape and the marble facing the walls could be the causes of this phenomenon, that we will try to reduce during the renovation.

In the boxes there were more pronounced differences in sound levels, depending on the distance from the stage and on the tier of the box.

Fig. 3 shows the reverberation time (RT) with the spatial standard deviation measured for each octave frequency band in the stalls and in the boxes and in fig. 4 we report the reverberation times of many halls [5] with the Goldoni Theatre position highlighted.

The RT is a little high at low frequencies, but we have to keep in mind that there were not scenes on the stage, so it was completely empty. This condition causes the joining of the stalls with all the stage, that is normally delimited by the scenery. This means that the volume passes from 8900 m^3 to 13900 m^3.

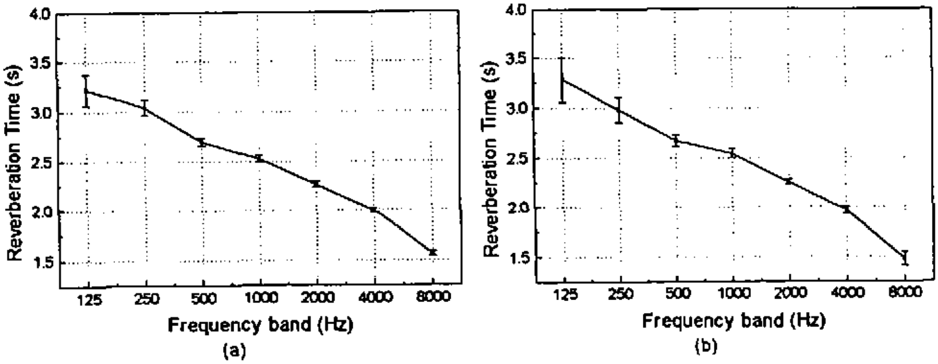

Fig. 3. RT in the stalls (a) and in the boxes (b) respectively with their own spatial standard deviation.

The excellent uniformity of the RT spatial distribution can be derived from the low standard deviation, especially in the stalls. This is an important characteristic of the hall: the theatre can offer quite similar acoustical conditions to all the public.

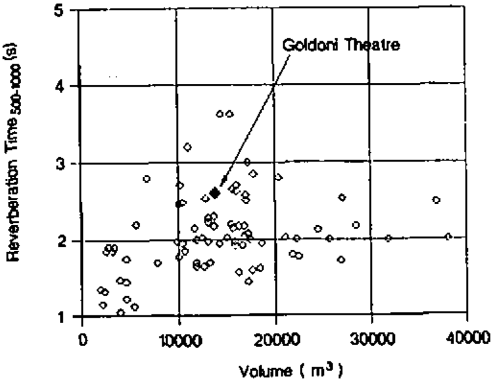

Fig. 4. Comparison between the RT of the Goldoni Theatre and many other ones as a function of the volume.

RASTI results can be interpreted in a qualitative manner by using a RASTI vs. subjective intelligibility scale, composed of five levels: bad (< 0.3), poor (< 0.45), fair (< 0.6), good (< 0.75), excellent (> 0.75).

Experimental values range between 0.45 and 0.58 in the stalls and between 0.40 and 0.54 in the boxes (fig. 5). Due to the big hall volume we can judge the speech intelligibility in the theatre good enough, particularly in terms of spatial symmetry.

(a)

(b)

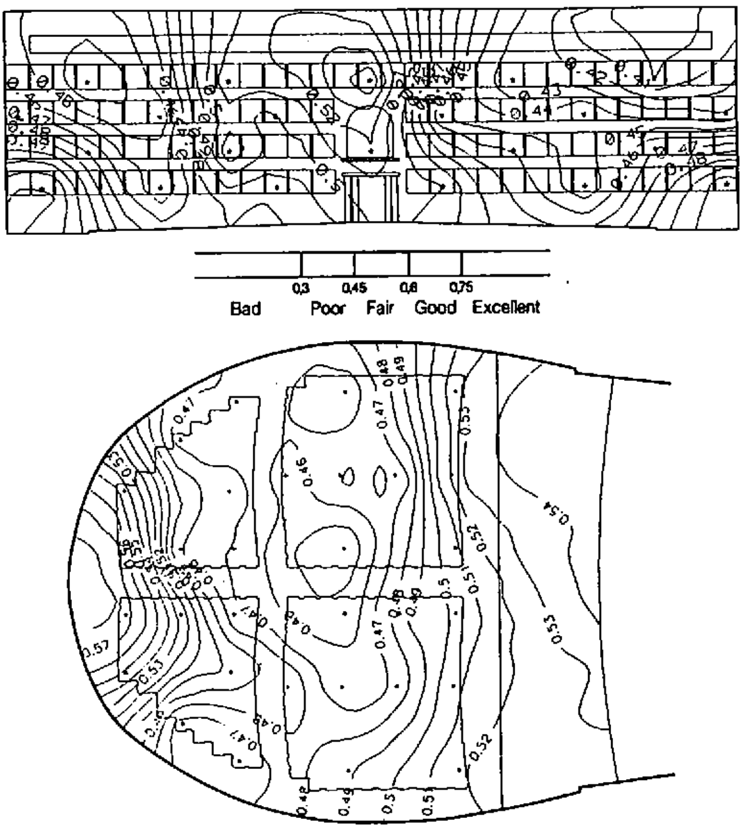

Fig. 5. RASTI values in the boxes (a) and in the stalls (b).

In tab. 1 we report several acoustical indexes, that different authors defined in the last decades. Particularly, D (definition) [6], C (clarity index) [7], Ts (Centre time) [8] and ITDG [9], are normally connected with a good subjective assessment. EDT(f) (Mean of six octave band results of Early Decay Time), TB (Tonal Balance), Bass ratio, Treble ratio are timbre - related parameters [10] obtained by grouping measurements as low-, medium-, or high frequency values of EDT (Early Decay Time).

The comparison between the indexes' values we measured and the optimum values reported in literature shows that the stalls present both good acoustical characteristics and quite uniform spatial response.

	Experimental index value	Spatial standard deviation	Optimum value
D	0.47	0.06	< 0.50
C (dB)	1.94	.91	- 2 + 2
Ts (s)	126	25	< 140
ITDG (ms)	37	1	17 + 35
TB (dB/oct)	- 0.18	0.11	0.1
EDT(f) (s)	0.5	0.1	0.3 + 0.4
Bass ratio	1.36	0.12	< 1
Treble ratio	0.89	0.07	< 1

Tab. 1. Indexes' values used as other criteria to judge architectural acoustics of the stalls.

The indexes' values based on EDT and including low frequency bands (Bass ratio, TB) are in accordance with RT results. These results show that the hall is suitable for orchestral music because in this case the perception of the *warmth*, i.e., the sensation of rich bass sound, is important.

The indexes' values connected to clarity (D, C) are good enough, but not much satisfactory for the speech, as RASTI index indicated, therefore confirming the well-known correlation between these parameters.

4.2 Modelling of the Theatre

In fig. 6 we show a 3D CAD accurate picture of the theatre. As a first approach it was acoustically modelled using *Ramsete* software [11] with some approximations: the shape was digitized and details of the structures were smoothed, so that the computing time was not excessive. Boxes, for the same reason, were considered strongly absorbing walls, supposing that the medium and high frequencies can't come out easily once the ray impacted on the box.

The software is based on a Pyramid Tracing algorithm. In this method the spherical source is subdivided into adjacent triangular pyramids, which completely cover the surface without overlapping as in the Cone Tracing models. The detection of each sound path is performed deterministically: a correction of the reverberation queue is applied by multiplying the received energy by the ratio between the expected temporal density of reflections and the density obtained from the pyramid tracing.

Using the tools of *Ramsete* software we estimated the absorption coefficients of the materials and we adjusted these values until the experimental and predicted values of the reverberation time for each frequency were close enough.

Using another special tool of the program, based on ISO 3744 [12], the directivity of each sound source we used in the measurements was computed.

The most accurate simulations were performed with a large number of pyramids (32768) in order to respect the principle that the pyramid's base at first impact was smaller than each structure detail. This choice causes a higher computing time, but it permits more satisfactory results.

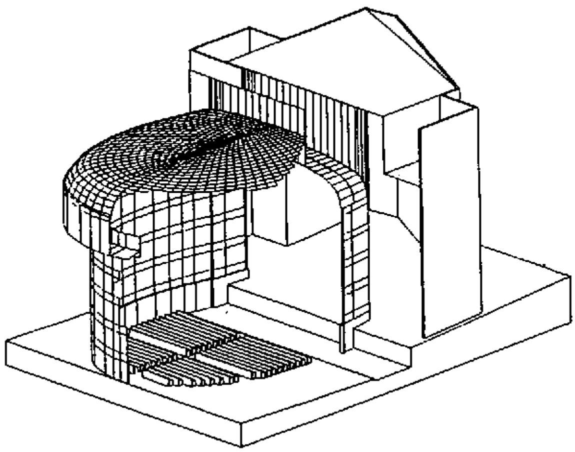

Fig. 6. Detailed 3D representation of the Goldoni Theatre.

4.3 Preliminary Results.

In order to test the reliability of the modelization of the theatre we compared some experimental vs. predicted results. Particularly in fig. 7 we show this comparison for the sound level profiles along the central aisle. The results from the model are close enough to the experimental ones, even if the experimental profile appears underestimated in the first part and smoothed in the part around the focusing point. This effect could be caused by the approximation in the shape of the walls, as we can see in fig. 8.

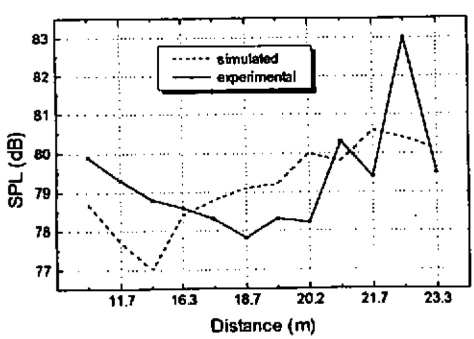

Fig. 7. Simulated and experimental sound level profiles along the central aisle. The distance is measured from the source, placed in the center of the stage.

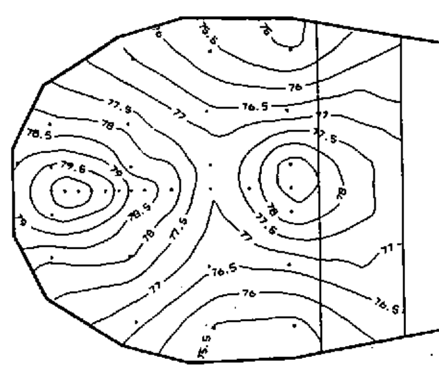

Fig. 8. Simulated spatial distribution of the sound level in the stalls, obtained with a sound source placed in the center of the stage.

In it we besides report the simulated isolevels; they resemble the measured ones in the same experimental conditions. Better results might be obtained using a more detailed shape (as the one reported in fig. 6).

In tab. 2 we report RASTI results referring to the experimental vs. predicted values; as we can see the agreement is excellent.

RASTI Index	Interval	Mean value	Spatial standard deviation
Experimental	0.44 ÷ 0.58	0.50	0.04
Predicted	0.42 ÷ 0.55	0.49	0.03

Tab. 2. Comparison between experimental and predicted RASTI values.

We, encouraged by the good results obtained, finally tried to introduce some variations in the materials, particularly we performed some simulations substituting the marble of the stalls with plaster or with velvet curtains.

The results show that the sound level distribution does not change much (about 1 dB lower): the sound reinforcement at the rear of the stalls still continues to be present in the same position, but the reverberation time (fig. 9) is diminished, especially at low frequencies. This fact is not unexpected, because the sound distribution is primarily due to the geometrical structure of the theatre, while the reverberation time is increased by the higher absorbing coefficient of the materials used in the last simulations.

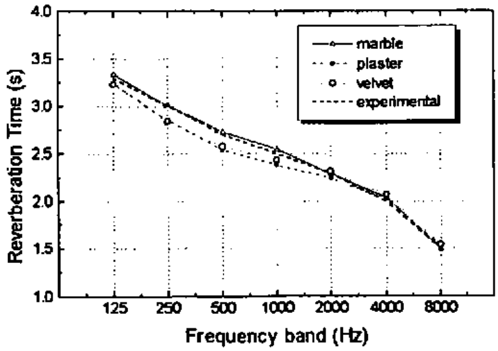

Fig. 9. Comparison between RT experimental and simulated ones, referring to different materials.

5. CONCLUSIONS

The results of the survey we have described represent an accurate acoustical picture of the present situation of the Goldoni Theatre. These modern objective measurements will be repeated systematically, when it will be possible, in order to improve our understanding of whether the changes made in the hall are a success or a failure. The quantities and the indexes obtained show that the acoustics of the theatre were good enough for orchestral music, even though the building is deteriorated. Particularly, it is noteworthy the present response uniformity in terms of the reverberation time and the sound level distribution.

After restoration a reduction of the reverberation time will come from the realisation of the structures of the proscenium and of the stage, that will delimit the hall volume. The restoration of the cavity under the stalls will be studied in order to permit a remaking of the original condition, with an improvement of the quality of the sound.

The characterisation of the present materials in laboratory will permit to calibrate the input parameters of *Ramsete* software better. However the program already gives us useful indications on the choices that should be made in the restoration process.

6. REFERENCES

[1] D. FILIPPI, 'La Fabbrica del Goldoni. Architettura e Cultura teatrale a Livorno (1658 - 1847)', *Cataloghi Marsilio*, (1989).
[2] M. R. SCHROEDER, 'New Method of Measuring Reverberation Time', *J. Acoust. Soc. Am.* 37 p409 (1965).
[3] JOHN ANDERSON and TORBEN JACOBSEN, "RASTI Measurements in St. Paul's Cathedral, *London*", *B&K Application Note*, 1985.
[4] IEC draft Publication 268: Sound System Equipment Part 16: 'Report on the RASTI Method for the Objective Rating of Speech Intelligibility in Auditoria'
[5] R. H. TALASKE, E. A. WETHERILL & W. J. CAVANAUGH 'Hall for Music Performance - Two Decade of Experience, 1962 - 1982', 103 *Meet. Am. Ac. Soc.* Chicago (1982).
[6] R. THIELE, 'Richtungsverteilung und Zeitfolge der Schallrückwürfe in Räumen' *Acustica*, 3 p100 (1953).
[7] W. REICHARDT, D. A. ALIM & W. SCHMIDT, 'Definition and Messgrundlungen eines objektiven Masses zur rmittlung der Grenze zwischen brauchbarer und unbrauchbarer Durchsichtigkeit bei Musikdabeitungen', *Acustica*, 32 p126 (1975)
[8] J. P. A. LOCHNER & J. F. BURGER, 'The intelligibility of speech under reverberant conditions' *Acustica*, 11 p195 (1961)
[9] L. L. BERANEK 'Music Acoustics and Architecture' John Wiley, New York (1962).
[10] J.S. BRADLEY 'A Comparison of Three Classical Concert' *J. Acoust. Soc. Am.* 89 p1176 (1991).
[11] ISO 3744 'Acoustics - Determination of Sound Power Levels of Noise Sources - Engineering Methods for Free-Field Conditions over a Reflecting Plane'
[12] A. FARINA & A. COCCHI, 'Correzione Acustica di Ex-Chiese Riadattate per Utilizzo Concertistico: un Esempio di Progettazione di Interventi non Sabiniani con l'Ausilio del Calcolatore' Atti della Conferenza Internazionale 'Acoustics and Recovery of Spaces for Music', Ed. Carletti & Stanzial, Ferrara p81 (1993).

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