ENERGY CRITERIA IN ITALIAN HISTORICAL OPERA HOUSES: A SURVEY OVER 11 THEATRES

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1 INTRODUCTION

Sound energy distribution in enclosed space has been largely investigated both experimentally and theoretically. In this regard, the milestone is represented by the semi-reverberant field theory. Thanks to the availability of a significant set of measurements, Barron and Lee[1] proposed a revision to this theory which could take into account the behavior emerging from the measurements they performed in northern Europe concert halls, a behavior differing from the classical predictions. This work is intended as a preliminary analysis in the definition of a revised theory for sound energy distribution specifically tailored for Italian historical opera houses. In fact, the concave shape of these halls and the early reflection pattern generated by a combination of acoustical/architectural features give rise to a spatial distribution of the early reflected sound field which calls for a customised analysis.

In 2014 a detailed measurement campaign was carried out in eleven Italian historical opera houses in a region in the North of Italy, all lying within a radius of 30 km. In each theatre, monaural and binaural measurements were performed with two analogous source positions; more than 7,000 IR were acquired and processed. During the measurement campaign, all the relevant architectural data were collected and related to the acoustic features of the theatres. The availability of these data allowed studying in detail the temporal and spatial distribution of the sound energy in the early reflection regime.

The paper is organised as follows. In section 2, the architectural features of the Italian historical opera houses are highlighted with regards to their implication on the acoustics of the hall. In section 3, the measurement setup which was replicated in all the theatres is described in detail. In section 4, the EDT and G values measured in the stalls areas of the theatres are presented and commented by means of interpolation maps built over the available data. In particular, the sound strength values are calculated with various time thresholds, in order to point out the pattern caused by early reflections in these theatres. Significant time thresholds were found by a visual inspection of these interpolation maps. Section 5 discusses the results of the analysis presented and finally some conclusions are drawn aimed at addressing future investigation issues.

2 ACOUSTICS AND ARCHITECTURE OF ITALIAN HISTORICAL OPERA HOUSES

The Italian historical theatre is a typology that was born for the opera and that developed in the treaties of the eighteen century, to reach to a final standard in the middle of the nineteenth century. Its peculiar characteristic is that the movement of the scenes required a huge covered space above the stage. This created a separation between the areas for the audience and performers that was rendered physical by the introduction of the proscenium arch. This architectural element has a great interest in the separation of two coupled volumes: the stagehouse and the stalls area.

The main hall of a typical Italian historical opera house presents some peculiar architectural elements with a great importance for the acoustics: among all, the shape of the hall and the reflecting side surfaces. The plan shape of the main hall is characterised by the typical concave shape, whose optimisation has been widely discussed in the literature mainly concerning visual criteria. While in the early design periods the elliptical shape was deemed optimal, the design standards shifted towards the bell shape and finally the horseshoe shape. This typology of theatres is also characterised by the absence of overhangs, typical of the concert halls of northern Europe. Another feature of relief is the lower part of the audience, characterised by the presence of a very reflecting surface finished with the *marmorino* technique. It is a very smooth plaster made of marble powder and slaked lime which provides very strong reflections to the listener in the audience.

The eleven theatres under study are: the Bonci Theatre in Cesena (BON), the Alighieri Theatre in Ravenna (ALI), the Masini Theatre in Faenza (MAS), the Rossini Theatre in Lugo (ROS), the Stignani Theatre in Imola (STI), the Goldoni Theatre in Bagnacavallo (GOL), the Dragoni Theatre in Meldola (DRA), the Communal Theatres in Russi (RUS), Cesenatico (CES), Cervia (CER) and the Petrella Theatre in Longiano (LON). A synthesis of the peculiarities of these theatres can be found in Table 1.

Table 1: Architectural features of the eleven investigated Italian historical opera houses.

Theatre	V_{hall} [m^3]	V_{stage} [m^3]	V_{tot} [m^3]	Capacity	Seat upholstering	Side surfaces
BON	3130	11630	16490	798	wood/velvet	smooth
ALI	3360	8260	12960	835	velvet	smooth
MAS	2580	4300	7540	500	velvet	smooth
ROS	1490	3610	5790	448	wood/velvet	smooth
STI	1750	3900	6260	550	velvet	smooth
GOL	1430	4130	6250	390	wood/velvet	smooth
DRA	1140	1080	2880	318	wood/velvet	velvet
RUS	900	1370	2910	305	velvet	rough
CES	870	1320	2760	271	velvet	smooth
CER	730	1140	2270	224	velvet	smooth
PET	630	1390	2620	241	wood/velvet	smooth

These theatres were built within a time lapse of 150 years (Masini the oldest, inaugurated in 1723, and Petrella the newest, inaugurated in 1870), i.e. in the period in which the typology of Italian opera house was setting to a standard. These theatres also share the geopolitical contest, as they all lie within a radius of 30 km and often the same workers contributed to the construction sites of neighbouring theatres. As visible in Figure 1, the shape of the main hall varies significantly between the theatres. Though they can all be abscribed to the Italian opera house typology, the shape varies from elliptical (STI, ROS) to horseshoe shaped (BON, MAS).

3 MEASUREMENT SETUP

The source positions on the stage were chosen similarly in all the theatres: one in the front of the stage, at 1 m from the edge, and the other in a barycentric position on the stage, i.e. at the middle point between the edge of the stage and the back lining. The sound source constituted of a subwoofer and a dodecahedron; the IR measured with the subwoofer were used for the analysis of the 63 and 125 Hz octave bands while the analysis of the 250-4000 Hz octave bands was conducted over the IR measured using the dodecahedron alone as a sound source. The theatres were unoccupied during the measurement sessions.

This measurement campaign was characterised by a significant amount of measurements in all regions of the hall. For the purpose of this paper, only monaural measurements performed in the stalls are considered; here measurements were performed at all seats for the two source positions. In each theatre, the amount and type of curtains were considered. The curtains were set for standard performance of a medium-sized orchestra for large theatres and in the standard configuration for the smaller theatres. For the latter ones, the minimum amount of absorbing material suggested in the charter of Ferrara[2] of 500 m^2 could not be satisfied.

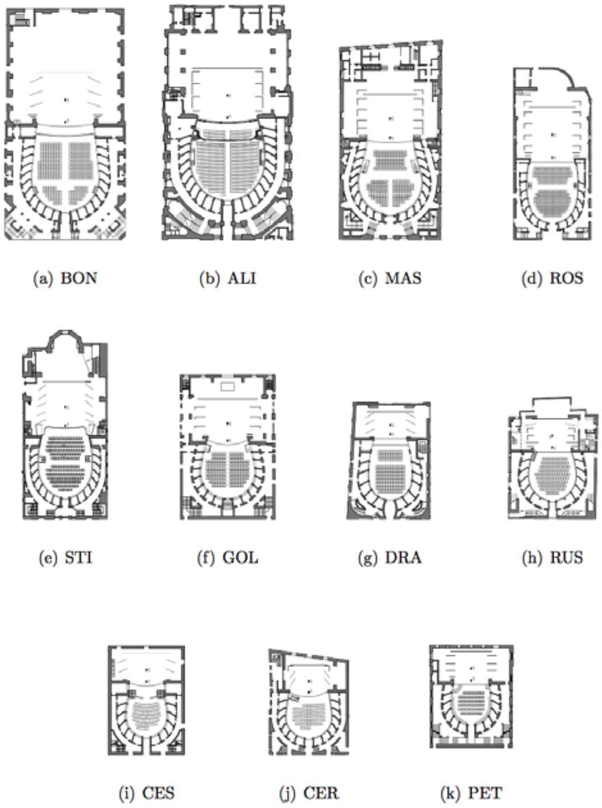


Figure 1: Plans of the eleven investigated theatres with the source positions on the stage (metric scale).

Two monaural criteria were chosen and related to the early reflections distribution: early decay time EDT and sound strength G. These criteria are analysed in the stalls area in the frequency range 500 - 2000 Hz. EDT is computed using the pre-processed energy detection method[3,4], which allows a better definition on the early decay as will be pointed out in the following. G is calculated with a code written *ad hoc*, where the denominator is built as an energetic average of six IRs measured at 1 m from the dodecahedron, windowed over 10 ms and brought back to 10 m using a logarithmic difference[5]. In order to point out the early reflections regime, G is calculated by choosing different superior time thresholds and the relative spatial distribution is analysed by means of interpolation maps.

4 SOUND ENERGY DISTRIBUTION INSIDE ITALIAN HISTORICAL OPERA HOUSES

4.1 Formulation of the problem

The semi-reverberant field theory describes the sound level in an enclosed space as a sum of a direct component proportional to $1/r^2$, where r is the source-receiver distance, and a diffuse component, constant with r. To account for some anomalies found in northern Europe concert halls, i.e. a reduction in sound level with increasing distance outside the critical radius, Barron and Lee[1] developed a revised theory that assumes a linear decay of the reverberant region. This theory was tested for concert halls with a mean volume of 18,700 m^3 and characterised by not excessively diffusing ceilings, some diffusion of the side walls, no focusing concave surfaces, no subdivision into independent spaces, presence of balconies and proportionate dimensions.

The characteristics of Italian historical opera houses share with the mentioned theatres a minority of features, thus it is not surprising that the sound energy distribution inside Italian historical opera houses does not follow neither the semi-reverberant field theory nor the revised theory. In fact, among the halls analysed by Barron, the most critical was the Usher Hall, in Edinburgh, which is actually the most similar in shape to Italian theatres.

The availability of a great number of measurements performed inside Italian opera houses allows to study in detail the sound energy distribution both in time and in space. In fact, the analysis of relevant energy criteria with varying the time threshold reveals that in Italian theatres the sound field is not homogeneous and the availability of one measured IR per each seat in the stalls area permits to analyse in detail the acoustical regions of the audience.

The sound strength G was calculated with different superior time thresholds for the term at the numerator, ranging from 20 to 100 ms with a time step of 10 ms, and is referred to as G_x in the following. In these theatres, the early reflections regime depends strongly upon the position of the listener. When the source is placed on the proscenium, for early thresholds (say up to 50 ms) there is a region in the centre of the halls which shows significantly lower G values with respect to points located close to the side surfaces. After this threshold, the behaviour of the audience becomes homogeneous and G values increase with the time threshold almost linearly. Analysing this in terms of sound energy decay, it seems that the energy decay in the side regions is linear, while the decay in the central part of the stalls is linear with two slopes, the knee lying around the time threshold of 50 ms.

4.1.1 Detection of a significant time threshold

The time threshold after which the local focussed behaviour fades can be derived in several ways. Here, a time threshold is searched both analysing the variation of the standard deviation with an increasing time threshold and studying the spatial distribution of the G_x criterion.

One approach for the determination of the threshold is its identification through a statistical analysis of the data. In particular, the authors[6] investigated the early-to-late threshold in Italian opera houses analysing the mean value and standard deviation of the criterion C_x, i.e. clarity evaluated with different time thresholds. The authors also correlated the skewness of a distribution of energy criteria to the spatial distribution pattern of these criteria inside Italian opera houses[7]. Here, the time threshold is searched after which the standard deviation flattens or assumes linear values with time. The time thresholds corresponding to knees in the standard deviations calculated on the G_x values are reported in Figure 2 in the stalls area at 1000 Hz.

The other method used for the detection of the critical time threshold is to plot contour curves superimposed to the interpolation maps and to identify by visual inspection the threshold corresponding to the fading of the local focused behaviour. For each theatre, a measurement position is chosen, placed roughly in the middle of the stalls area but not lying on the longitudinal symmetry axis. Starting from the value of the criterion in this point, contour maps are plotted in order to highlight measurement positions assuming values lying within a fixed threshold (1 dB for G values). An example is reported in Figure 3, where interpolation maps of the Goldoni Theatre in Bagnacavallo are plot in the 1000 Hz octave band. In order to avoid ambiguities due to the interpolation of criteria, the seat distribution is reported in transparency on the interpolation maps; in this way it should be easier to detect which regions of the theatre are interpolated basing on the spatial resolution of the values measured at a seat and which correspond to empty regions.

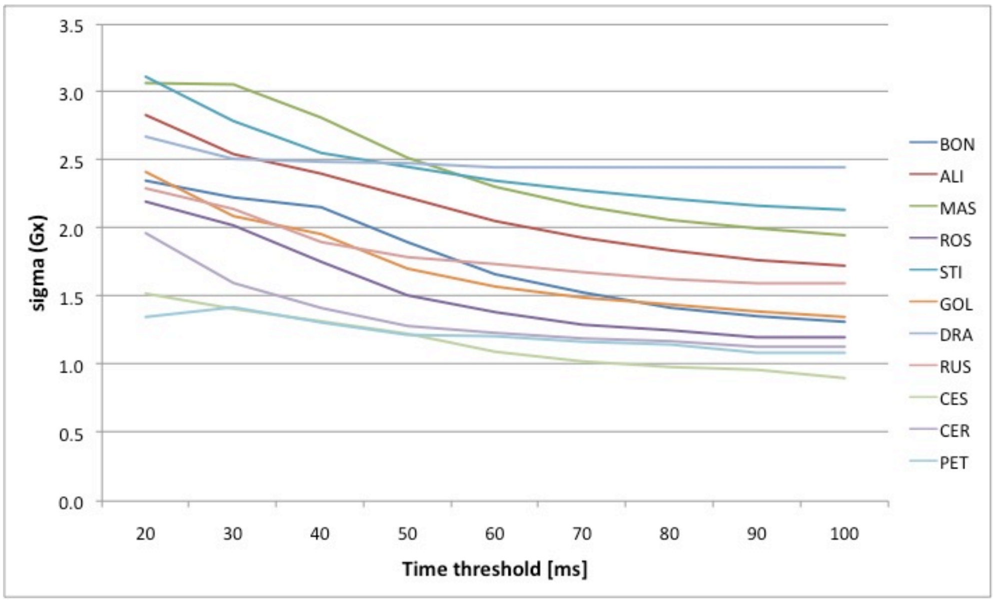
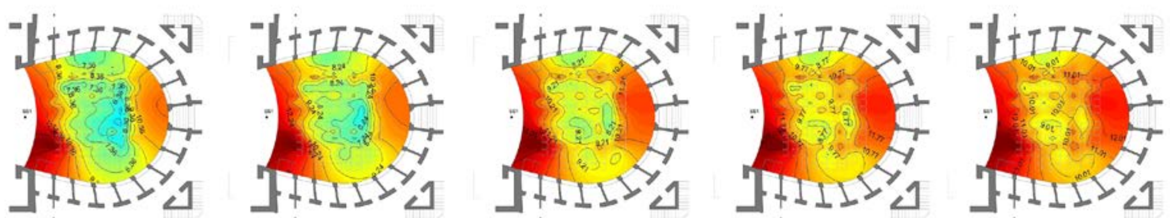


Figure 2. Variation of the standard deviation of the G_x criterion calculated at 1000 Hz for the eleven theatres.

Once the time threshold has been detected, it is useful to try to locate this threshold in the energy decay, i.e. identifying where this threshold falls “in dB”. Since to this aim it is necessary to have a reference value, EDT is selected as the most fitting criterion. The same procedure is thus followed concerning the EDT values, the contour maps being plotted with a time resolution of 0.1 s. In fact, if this focussing behaviour is located within the first 3 dB of decay, it should result also in the difference between EDT and T_{30}, as the time thresholds of the two criteria do not overlap in the -3 dB region. Due to the cumulative nature of the Schroeder's integral, the difference between these two criteria is expected not to be strongly marked. Thus, in order to characterise the early decay, EDT is extracted from the envelope of the squared IR using the PPED algorithm[3,4]. Given the local definition of the envelope, the same spatial distribution observed for G_x is found for the EDT. The comparison between G_x and EDT, which is a characteristic of the IR and thus fixes a dB (or time) threshold, is very useful. Once some spatial regions are detected, from the EDT value it is possible to detect time threshold which are significant with respect to a *n* dB decay and to identify where in the energy decay the thresholds lie.



[30 ms] [40 ms] [50 ms] [60 ms] [70 ms]

Figure 3. Interpolation maps of G_x in the Goldoni Theatre (GOL) in the 1000 Hz octave band. A time threshold of 50 ms is detected as the limit that denotes a significant variation in the spatial distribution of the criterion; above this value, the spatial distribution is not strongly affected by the increase in time threshold.

5 DISCUSSION

The analysis of the time threshold derived from the two methods (statistical analysis and study of the interpolation maps) is reported in Table 2 in the octave bands 500-2000 Hz. Columns 2-4 refer to the identification of the threshold through a statistical analysis, while time thresholds reported in columns 5-7 refer to the analysis of the interpolation maps. Some theatres display a good agreement between the two methods. Among these, STI, GOL, RUS, CER, PET. The differences among all of them are significant; they do not resemble indeed in proportions, shapes, volumes or presence of absorbing linings.

Table 2: Identification of the significant time thresholds for sound energy distribution from G_x: statistical approach and analysis of interpolation maps.

Theatre	Time thresholds [ms] from stat. approach			Time thresholds [ms] from maps		
	500 Hz	1000 Hz	2000 Hz	500 Hz	1000 Hz	2000 Hz
BON	40-60-90	40-60-90	40-60-90	50	70	*
ALI	40-80	30-60-90	40-70	-	-	-
MAS	30-60	30-60	30-60	60	70	70
ROS	60-80	50-80	50-80	50	50	40 (?)
STI	40	40	=	40	40	=
GOL	50	50	60	50	50	50
DRA	40	30	30-70	50	*	*
RUS	40	40	40	40	40	40
CES	30-70	60	40-60	60	60*	50
CER	40	50	40	40	40	40
PET	60	50	50	60	50	50

* indicates that there is no detectable threshold as an increase in time corresponds spatially to an almost linear increase in G.

In a similar way, significant time thresholds are derived by analysing the interpolation maps of EDT. A spatial subdivision is found matching the criteria used for the G_x and, from the EDT values, the time thresholds corresponding to 1 dB of decay are calculated assuming a linear decay in the first 10 dB and reported in Table 3 (columns 2-4). The right side of the same table (columns 5-7) reports the dB decay relative to the time thresholds derived from Table 2 (columns 5-7), which is merged with the information of the slope of the early decay provided by the EDT. Since the EDT values are not calculated from the energy decay curve but from the envelope instead, they matches closely the shape of the very first part of the decay of the squared IR. On the one hand, this prevents a direct

Table 3: Identification of the significant time thresholds in the energy decay based on the inspection of EDT and G interpolation maps.

Theatre	Time thresholds [ms] from maps corresponding to 1dB of decay			[dB] decay corresponding to the time threshold derived from G_x		
	500 Hz	1000 Hz	2000 Hz	500 Hz	1000 Hz	2000 Hz
BON	11	9	9	4.5	7.8	-
ALI	-	-	-	-	-	-
MAS	11	11	10	5.5	6.4	7.0
ROS	9	8	9	5.6	6.3	4.4?
STI	8	7	7	5.0	5.7	-
GOL	9	9	9	5.6	5.6	5.6
DRA	8	8	9	6.3	-	-
RUS	8	7	7	5.0	5.0	5.7
CES	11	9	9	5.5	-	5.6
CER	9	7	7	4.4	5.7	5.7
PET	9	8	7	6.7	6.3	7.1

correlation with other energy criteria, but on the other hand it is very useful in the characterisation of the early reflection regime. In order to determine a correlation between the dB threshold and the time threshold *x* (in ms) derived from the G_x, EDT was used as it describes a property of the filtered IR. The ratio between the time threshold emerging from the G_x analysis was divided by the time threshold derived from the EDT maps corresponding to a decay of 1 dB. The values obtained show that the knee detected for the G_x corresponds at a point in the relative normalized squared IR at -5 ± 1dB, irrespective of the theatre and of the octave band considered. Of course some uncertainties arise due to the determination of these thresholds from a visual inspection of the interpolation maps.

6 CONCLUSIONS

The aim of this paper is to present a preliminary study on the energy distribution of the sound field inside Italian historical opera houses. Due to the concave shape of the main hall and to several other architectural features that have a significant implication on its acoustics, the halls show a local focused behavior in the centre of the stalls area.

The sound strength is analysed both regarding its spatial distribution and, using different time thresholds, the temporal distribution of the sound energy. A significant threshold was found that allows individuating a region in the centre of the theatres whose behavior strongly differs from any classical formulation. In order to define a revised model of energy distribution inside Italian historical opera houses, the first step was to identify this threshold. The results derived from the statistical analysis and from the visual inspection of the maps return similar results, locating the threshold around 40 ms for small theatres and 60 ms for mid-sized theatres. Then the spatial distribution of the EDT calculated from the envelope was correlated to the time thresholds detected from the strength values and also in this case a good correlation was found. The analysis showed that the knee (time threshold) derived from G_x locates at -5 dB, irrespective of the theatre under study.

Once the time threshold has been detected and its position in the decay curve has been spot, some hypotheses can be made regarding the surfaces that mostly influence this time region. In particular, considering the mean free path of these theatres, two significant surfaces can be identified: the proscenium arch and the side walls. Future work will focus on the detection of the influence of those surfaces on the IR and on the elaboration of a model of energy distribution inside Italian theatres in agreement with the empirical correlations derived from measurements.

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