The Acoustics of the Italian-style Opera House

Carmine Ianniello

DETEC – University of Naples FEDERICO II, P.le Tecchio 80, 80125 Naples, Italy

Recent years have seen a renovated interest in opera in many countries. This art form, often considered as extravagant and expensive, was born in Italy more than four centuries ago. The commercial success of opera at its birth time led to the construction and adaptation of theaters for the purpose. The horseshoe plan with boxes in the walls was the auditorium shape preferred by many Italian architects of the time. This basic theater shape was adopted also elsewhere becoming a classic choice for more than two centuries. It is the aim of this paper to give a brief account about the development, the general acoustical features of the Italian-style opera house and the trends in the objective assessment of opera house acoustics in modern terms.

THE ORIGIN OF THE ITALIAN-STYLE OPERA HOUSE

Historical theatres constitute a rich architectural heritage that is spread throughout Italy. They were cultural landmarks for the communities that built them in the past and still are for today communities that take care of their survival. Open-air types from Greek and Roman times are still in use (e.g. Siracusa, Taormina and Pompei). During the medieval age no building for public show was purposely erected. Drama, music and other art forms, often of sacral inspiration, were performed for a large mass of people predominantly inside churches or in open spaces nearby. Sometimes other public building or temporary structures served the purpose. So, no theater was handed down from this age to the posterity. During the Renaissance age the idea of the theatrical building proper was pursued. Theaters were built as large rooms having interiors inspired by classical ancient open-air theaters: e.g. Palladio’s Teatro Olimpico (1584) in Vicenza, Scamozzi’s Teatro (1590) in Sabbioneta and Aleotti’s Teatro Farnese (1618) in Parma. Various steps in the formal modification of the ancient Greek and Roman amphitheatre are believed to be the way that led to the Baroque-type theatre. For example, the elongation of the half-circumference distribution of the audience in the Teatro Farnese in Parma and the appearance of loges and galleries were the prelude to a new audience distribution. The introduction of a more elaborate rear stage wall was a seed for the perspective scene. For example, Scamozzi constructed three-dimensional street scenes visible through door openings in the rear stage wall of the Teatro Olimpico in Vicenza. Renaissance artists developed new rules of the perspective that permeated both architecture and figurative arts. No wonder that this led to the construction of theaters with very deep stages to arrange sceneries that produced a realistic visual impression to the audience. To preserve a correct scale with the sceneries the actors were forced to play only in the fore part of the stage (proscenium). The acoustical bonus for this was a good projection of the voice to distant listeners. During the 17th and 18th centuries an architectural and acoustical debate was carried out among theater’s experts about the materials and the shapes. One of the issues was the most suitable shape of the plan of the auditorium. For instance, the devotees of the elliptical ground-plan believed in the acoustical virtues of the two foci and in the elliptical nature of the sound waves emanated by a speaker. Probably, the bell shape was given some preference because of its resemblance with a musical instrument. In this regard a funny comment is reported in an Essay about Opera (1762) by count Algarotti [1]: “It is absurd to imagine that a singer is able to excite the vibration of the walls of the theater by standing at the location of the bell striker.”. Various auditorium plan forms were tried: the U-shape, the bell-shape, the horseshoe, the truncated oval, ellipse or circle, etc.. The horseshoe plan with boxes in the vertical walls became a typical solution. Born in Italy, it was adopted also elsewhere soon later. This basic form, with various implementations of size and decor, revealed itself particularly suitable for opera performance. During the 17th century more than a dozen of theaters were built in Venice after the successful opening of the Teatro di S. Cassiano to public opera in 1637. Similar theaters were constructed also in other places in Italy. Many are lost, but a number dating to the 18th century - although rebuilt in the original fashion with some modifications along their life – are still operative. To name the largest: Teatro Filarmónico in Verona (1732), Teatro Argentina in Rome (1732), Teatro di S. Carlo in Naples (1737), Teatro Comunale in Bologna (1763), Teatro alla Scala in Milan (1778) and Teatro Comunale in Ferrara (1798). La Fenice in Venice (1792), burnt out on January 29 1996, will return soon into the above reported list.
THE BIRTH OF OPERA

Opera may be considered as drama adapted to music. However, music is an important part integrated with sung lyrics. Opera dates back to the end of the 16th century and takes its roots from song and dance entertainment on special occasions, like marriages and royal visits, at the court of Medici’s in Florence. It is reported that the first opera was the now lost Dafne written by the court composer Jacopo Peri between 1594 and 1598. However, the first known one is the “favola in musica” (musical tale) Euridice (text by Ottavio Rinuccini, music by Jacopo Peri, with some insertions by Giulio Caccini). It was performed on October 6, 1600 in palazzo Pitti (Florence) on the occasion of the marriage of Maria de’ Medici with the French King Henry the IV. Euridice marks the birth of modern opera four centuries ago.

GENERAL ACOUSTICAL FEATURES

The clarity was a primary feature of the early theaters: a sound quality that was well suited for listening to the articulate details of operas of contemporary composers. The clarity in the auditorium stemmed from both the relatively short distance of listeners from the stage and the low reverberation. The low reverberation times of the largest opera houses of the 18th century, and the 19th century as well, is due in part to the lavish use of plush furnishings and in part to the many tiers of deep sound-absorbing boxes. In this regard, it has been postulated that the box openings behave like black bodies for medium and high audio frequencies and as resonators that give back time-smeread sound energy in the low frequency range. No experimental evidence of such a behavior has been published yet. Baroque theater construction implied a general use of wood and suspended wood panels, in particular. These resulted to behave as efficient sound-absorbers in the low-frequency range: a beneficial complement to the sound-absorption of furnishings and audience. Wood use was not scot-free as these theaters were victims of the fire set often by the illuminating and heating devices of their age. Forsyth [1] estimates that the average life of such theaters was about eighteen years.

Balconies, boxes, stuccoes and other ornamentation elements produced a kind of diffusion of the reflected sound that may be supposed to be an ingredient of the aural pleasantness of opera when performed in Baroque theaters. Recent subjective studies support the importance of diffusion for the sound quality [2,3].

Orchestras of the 18th century were not as large as those of the subsequent century when the Grand Opera was developed. Furthermore, various instruments were not as powerful as the more refined to come later. Therefore, musicians were located between the proscenium and the audience to preserve a sufficient loudness and clarity of music. With the advent of Grand Opera, larger orchestras had to be accommodated without obstructing sightlines from the stalls to the stage and, possibly, without wasting precious area of the stalls. The orchestra pit, with an area covered partially by the overhanging proscenium floor, was the remedy that was adopted frequently. In spite of the screen effect of the overhanging and the pit rail, problems of balance between the loudness of the orchestra sound and that of the singer’s voice can be supposed to exist in the past as they are often reported by listeners still today. Incidentally, one may ask how a single singer can contend with the whole orchestra, that is how the singer’s voice does not suffer the overpowering of the instrumental sound. Within certain limits, it is a matter of players, singers, conductor and acoustics of the theater. However, Sundberg [4] discovered that trained operatic singers develop a powerful directional fifth formant that is absent in the voice of a typical speaker. This formant is centered around a frequency in the range from 2.5 kHz to 3 kHz. Its sound level is often higher than the concomitant sound level due to the power radiated by the orchestra from the pit in the same frequency range.

The control of the balance with partially covered pits reduced the brilliance of music in the stalls and at the front of the boxes where the direct sound of the orchestra resulted shadowed by the pit. Problems arose also on the musicians’ side. The room acoustical conditions for players had changed drastically and complaints about this issue are well known in present days.

Performers in a concert hall are in the same large volume occupied by the audience. In opera houses two large rooms are coupled through the proscenium opening. One for the audience, the other for singers and scenery. The reverberation time of the auditorium is usually low while the stage house may have a higher reverberation time, depending on the scenery fitted in the stagehouse. An example of the influence of scenery is reported in Fig. 1.

FIGURE 1. Reverberation time for two different stage scenery in the Teatro di S. Carlo (Naples). Same sound source and receiver locations.
On some occasions sound events on the stage may be perceived in the auditorium with inappropriate acoustical characteristics (e.g. the voice of the singers behind the proscenium arch suggest distance and hollowness).

Most of the theaters shaped in the same mold are affected by more or less severe visual and acoustical restrictions. Almost one third of the audience lacks a clear vision of the action on the stage. Besides bad sight, listeners in the rear of the boxes experience a muffled and weak sound. Fig. 2 shows an example.

FIGURE 2. Clarity index $C_{80}$ and Sound Strength $G$ at a front, middle and rear seat in a lateral box of the Teatro di S. Carlo (Naples). Sound source in the pit.

Sound focusing in the areas near the side-walls of the auditorium produce inhomogeneous listening conditions in the stalls. The first reflected energy caused by a sound source located at the proscenium centerline reaches more the farthest listeners than the others in the stalls. Due to the curvature of the vertical walls, a sound source near a lateral end of the proscenium may give rise to a sort of whispering-gallery effect (Fig. 3). Perceivable echoes from ceiling are also reported (e.g. in La Scala).

FIGURE 3. Ray-tracing in the ground plan of the Teatro di San Carlo Naples for two sound source locations.

One reason for the presence of the boxes in the Italian-style opera houses was the need to accommodate as many paying people as possible in a given auditorium volume. Now, it is possible to argue that balconies and open galleries might have served the same purpose better. However, the matter must be considered in the perspective of the social habits at the time the theaters were built and/or used. Saunders [5] commented after a visit to San Carlo in 1790 that “it is the fashion in Italy to receive visitors in the boxes, to play at cards, and often to sup there; this doubtless first gave occasion for enclosed boxes, which from whence was adopted in other countries”. Already by 1773, Francesco Milizia [5] was commenting that “boxes were bad for seeing and hearing as well as immoral...they make serious listening and serious plays impossible”. During the splendor of Grand Opera, attending to an opera was an occasion “to see and to be seen”. It was at least as important to see the king’s box from everywhere as to see the stage and the situation of a seat with respect to the king’s box. The box location was a social classification for its possessor.

In spite of the inherent visual and acoustical shortcomings, many destroyed Baroque-type theaters have been reconstructed in the intent to restore them as they were.

TRENDS IN THE ASSESSMENT OF OPERA HOUSE ACOUSTICS

Until the early eighties acoustical objective data published for opera houses was limited to the reverberation time. The findings of the research about the acoustics of a concert hall taught us that there is much more than the optimal reverberation time to be concerned with. The need of guidelines for the design of new venues has drawn much attention on the assessment of existing opera houses. A first notable study in three British houses was published by Barron [6]. He stated in simple terms some subjective attributes for good listening in an opera house. Although the naïve listener is able to understand only a low percentage of words of the libretto, the speech should be intelligible. The orchestral sound should have a suitable clarity and convey an adequate sense of reverberance. Both the voice of the singer on the stage and the sound of the orchestra in the pit should reach the listener with a sufficient loudness. Of greatest concern is the balance between the singer’s voice and the sound of the orchestra. The sound envelopment may be of minor importance with respect to the requirements of loudness and balance. The aspects for orchestral music were described with the objective parameters reverberation time $RT$, early decay time $EDT$, clarity index $C_{80}$, sound strength $G$ and early
lateral fraction LF as defined in Ref. [6]. These parameters should be measured with an omnidirectional sound source in the pit. On the side of singer’s voice Barron evaluated the objective clarity by measuring an early energy descriptor DSO as proposed by Thiele [7]. He used a sound source on the stage that simulated the directivity of the human voice roughly. The same sound source was used for the measurement of the sound strength G related to the loudness of the singer’s voice. The balance at a listener location was described by the difference between the sound strength measured with the directional sound source on the stage and the sound strength measured with a non-directional sound source emitting the same sound power in the pit. Barron discussed also desirable values for the adopted objective descriptors.

Another extensive study about opera house acoustics was published by Hidaka and Beranek [8]. They measured the objective parameters reverberation time RT, early decay time EDT, clarity index C80, bass ratio BR, sound strength G, interaural crosscorrelation coefficient IACC and initial time delay gap ITDG, as defined in [2], in 23 unoccupied opera houses located in Europe, Japan and Americas. As far as possible, the measured data was related to the responses of questionnaires given by conductors about the sound quality as heard by them both in the audience area and in the pit of the opera houses that they knew well. As far as it concerns Italian historical theaters, La Scala in Milan and S. Carlo in Naples were rated subjectively “One of the best” and “Very good” respectively in a rating scale having five steps from “Poor” to “One of the best”. The main conclusions of the study were that at least five orthogonal objective acoustical parameters are important for opera house quality: the reverberation time at mid-frequencies RTM (average 0.5-1 kHz octave band) in the occupied theater should be in the range 1.4 – 1.6 s. Although correlated with RT and EDT, C80,3 (average 0.5-1-2 kHz octave band) should lay between 1 and 3 dB in the unoccupied theater with the sound source on the stage and negative with the sound source in the pit. The hall-averaged spaciousness factor 1 – IACC83 (average 0.5-1-2 kHz octave band) should exceed the value 0.6 with the sound source on the stage. The spaciousness factor is an important parameter but “to be used along with others”. The measure of intimacy ITDG at a location near the center of the main floor should be 20 ms or less. The sound strength GM (average 0.5-1 kHz octave band) in the unoccupied theater with the omnidirectional sound source on the stage should be in the range 1-4 dB. The bass ratio BR, that is the ratio \(RT_{125000} - RT_{150000}\) \(RT_{300000} - RT_{350000}\) should be larger than 1.05. Besides these clearly quantifiable objective parameters, Beranek and Hidaka suggest that further components of the sound quality are the texture and the “patina”. The first one depends on the richness of reflected sound energy in the first 80 ms after the time of arrival of the direct sound as it appears in the impulse responses at the listener locations. The “patina” is linked with the degree of diffusion of the sound reflections caused by geometrical irregularities of both the ceiling and the walls. These Authors do not mention explicitly a measure of the balance between the singer’s voice and the orchestral music. However, the implicit consideration of this very important aspect of opera houses may be found in the criteria suggested for C80,3. In fact, this measure of the early sound should yield negative values when the omnidirectional sound source is located in the pit. In this respect, O’Keefe [9] discusses that the balance is represented better by the strength of the early sound (10 ms and/or 50 ms after the arrival of the direct sound) measured once with a directive sound source on the stage and a second time with an omnidirectional sound source in the pit, the radiated sound power being the same. Furthermore, these early sound strengths should be evaluated with 1/3 octave band filters in the aim of analyzing the influence of seat dip and head dip effects.

**CONCLUSION**

The brief review reported above discloses that the sound quality in opera houses is a very intriguing matter and a risky challenge for the room acoustics designer. Except for La Scala in Milan, into which a measurement microphone entered since 1946, only few of the other surviving Italian historical theaters have been assessed objectively to a certain degree in recent years. What emerges from these few studies is a high clarity and a general lack of lateral sound, except in the rear of the stalls. Obviously, a new and competently designed opera house would yield more visual, aural and instrumental (measurement) satisfaction, but the magic of history and tradition is a mermaid song hard to resist.

**REFERENCES**

A study on balance inside an historical opera house

R. Pompoli, N. Prodi

Dipartimento di Ingegneria, Università degli Studi di Ferrara, 44100 Ferrara, Italy

Though the importance of balance in opera houses is generally accepted, little means for its qualification and improvement have been developed. In this paper some aspects of the measurement procedure and of the analysis of balance in an historical opera house are dealt with and the results discussed.

INTRODUCTION

One of the more outstanding aspects of the acoustics of opera houses which is still not sufficiently investigated is the balance between the orchestra pit and the stage. In particular a unique definition of an objective parameter and its subjective significance, its optimal range and a suitable measurement technique has not yet been agreed. Meyer [1] pointed out the importance of the spectra of emission of single instruments compared with the singing voice. This author gave justification for the capability of the voice to be heard when playing together with the orchestra. From this fundamental work it is understood that most of the attention on balance could be concentrated on the bands were a competition between the voice and the orchestra is possible, that is in the region of the formants at approximately 3kHz. Furthermore bandpass values of balance were reported by Barron [2] as the ratio of the sound level emitted by a directional source on the stage and by an omnidirectional one with the same sound power placed in the pit. Later O’Keefe [3] proposed a specific parameter in the form of an energetic ratio with time limit set generally at 50ms. In this case the measurement technique involved one omnidirectional source in the pit and a directional source on the stage, which was obtained by sealing all speakers but one in the dodecaedric source. Moreover a 1/3 oct. band analysis showed some differences of balance between the low and high frequency ranges, but the significance of such data is still an open question. In addition, the problem of balance of pit and stage is relevant also for performers and for the conductor. Some new measures were done recently [4] to clarify this specific problem. With the present knowledge the factors which mostly affect the balance for the audience seem to be:

- sound power of sources, their directional properties and placement;
- geometry of the pit (in particular shielding effect of rail especially at high frequencies);
- geometry of proscenium opening;
- grazing incidence for lower frequencies in the stalls.

It is also to note that the sightlines for the audience change completely from stalls to boxes, so that the balance is potentially very sensitive when moving from one area to the other. This work will present some measurements of balance in an historical opera house which aim at testing a different calibration scheme for the sound sources and a simultaneous multi-source operation mode in order to reproduce some features of the real performance.

MEASURES OF BALANCE

A measurement session for balance was done inside the Teatro Municipale “Romolo Valli” in Reggio Emilia. The theatre was set with open curtains so that the stagehouse was communicating with the main hall. Firstly the positions for two omnidirectional sound sources were fixed in the orchestra pit: the former was the 1° violin (named S01 - at 1m from the pit rail and from central line) and the latter below the overhang on the right side (named S02 – at 1m from the back of pit and 3.5m from central line). Then two commercial monitors were used as directional sources and their half-plane of emission was directed towards the hall. The former (S03) was at 1.5m from the stage border and at 1m from the central line and the latter (S04) was 2.5m behind it, placed on the right side at 3m from the central line. All of the sound sources had their acoustic center at 1.5m above the floor. In Figure 1 the positioning of sound sources is shown. The calibration was done, before positioning, at 1m distance above the reflecting stage floor and obviously S03 and S04 were measured at 0° degree incidence. In these conditions the four sources gave $L_{eq}=94dB(A)$. Then two receivers were fixed, respectively one in a central position in the stalls on the right side and one in a central box of III order. The receiver consisted of a Sennheiser MKE2002 binaural...
system. The impulse responses for the combinations of single and multiple operating sound sources were measured by means of the logarithmic sine sweep technique. Finally all of the acoustical parameters were calculated. In order to evaluate the balance it was first necessary to obtain the relative level for each impulse response, both for those with a single source and for those with multiple sources playing at the same time. This was done by setting as the reference level the measure in the stalls with four sources working simultaneously. Finally the balance was derived as the difference of such normalized values between stage and pit for the octave band centered at 4kHz. The most interesting results are reported in what follows and reference is made to other data not included here.

**Results for a single operating source**

In the Figures 2 and 3 the values of RT20 and C80 are reported for the four single sources and the receiver in the stalls. The parameter RT20 has a significative variability and the curves cross each other. While S01 shows higher values in the higher frequency range, the sources S03 and S04 have lower values in the same range. In the box (not shown) the variations are limited to the 125Hz oct. band, while the four curves can be hardly distinguished in the rest of the passband. The parameter C80 has clearly separated trends for the sources on the stage and the pit, as easily predictable. This trends are conserved with minor changes for the box (not shown). Then in Figure 4 it is presented the balance for the four combinations of single sources on the stage and in the pit. Each combination is reported on the x-axis (i.e. S03 - S01 means that S03 is compared to S01). In the box the balance always favours the stage.
and mostly depends on the degree of visibility of the sources in the pit, which might be partly shielded when positioned close to the pit rail. The position of the “singer” on the stage is far less influent. Viceversa in the stalls the balance is primarily affected by the placement of the singer and the values are worse if the source is working in the back of the pit.

**Results for multiple operating sources**

When more sources are operating simultaneously (i.e. the indication S0103 means that S01 and S03 are played together), RT20 diminishes its variability both in the stalls and in the box. While also EDT in the stalls has limited span of values, it has an interesting behaviour in the box (see Figure 5). In this case when two sources are driven at the same time (and one of them is S03) EDT has lower values even when S03 is combined with
DISCUSSION

The calibration of the sound sources is a crucial point in the measurements of balance. The present choice implies that S01 and S02 represent different sections of the orchestra (i.e. all of the strings and all of the woodwinds) whose sound power is assumed greater than that of the singer. In fact they produce the same sound level at 1m on reflecting floor but S01 and S02 are omnidirectional. This is even more relevant when the sources in the pit are playing a sort of “tutti” (namely the condition S0102). Moreover this calibration gives to the omnidirectional sources, when later placed in the pit, a more directional emission seen from the hall. That is, their sound power is projected onto a smaller solid angle in the hall. This makes the problem of sightlines from the receivers even more serious. In fact, while S02 is fully visible in the box, S01 is partly shielded. The rate of shielding is different also in the stalls, where S02 is now favoured. As a result the two receivers show a variability as great as 8dB (which becomes 10dB with multiple sources). It clearly separates the stalls, where competition between singer and orchestra seems more balanced, and the boxes, where the sound from the stage appears always masked to some degree by the pit. On the other hand it is difficult to objectively rate such condition (which should be worse for the singer), since a specific scale value for balance is still not available. In the frame of testing parameters and procedures for the evaluation of balance, the above scheme has the advantage of easier operation and good sensitivity. The measurements with multiple sources are easily interpreted regarding the balance, since in a real performance many kinds of combinations of singer and instruments are expected. Regarding clarity and reverberation time, they are used for the sound field of a single source and no clear significance is established for them in the case of simultaneous use of more sources. Nevertheless, in the case of competing sound sources, and especially for the bands where their outputs are comparable, the discrimination among them is far from simple. The balance might also be influenced by the details of the resultant impulse responses, whose peculiarity can be investigated by the energy fractions. In this case the measures show that the resulting parameters are generally governed by the pit but the stage sources can still contribute separately in the early part of the energy decay or in the highest frequency range for clarity.

CONCLUSIONS

The acoustical measurements of the Teatro Comunale “Romolo Valli” in Reggio Emilia presented here integrate the results for a different setup presented in [5]. The study of balance was based on a particular calibration of the sound sources over a reflecting floor. The results, for single sound sources, evidenced very different listening conditions in the theatre and the use of multiple sources further confirmed the difficulty for the singer to be heard when a full orchestra is playing. Then the dependence of balance from other factors like reverberation time and clarity with multiple operating sources has been addressed. Dedicated subjective tests (like those reported in [6]) will be necessary to establish a scale value for the parameter.

This work was supported by contract CNR99.0380.PF36 of the National Research Council of Italy.

REFERENCES

Acoustical Problems in Orchestra Pits; Causes and Possible Solutions

Anders Christian Gade a, John Kapenekas b, Jan Inge Gustafsson c, B. Tommy Andersson d

a: Ørsted, DTU, Acoustic Technology, Technical University of Denmark, Building 352, Ørsted Plads, 2800 Kgs. Lyngby, Denmark  
b: Hovkapellet, Royal Opera, Stockholm, P.O. Box 16094, S-103 22 Stockholm, Sweden  
c: St. Eriksgatan 82, S-113 82 Stockholm, Sweden  
d: Akustikon AB, Baldersgatan 4, S-411 02 Göteborg, Sweden

On the basis of a study carried out by the authors on acoustic problems in the orchestra pit in The Royal Opera in Stockholm, this paper discusses possible reasons and solutions to the problems found in many orchestra pits today. The study in Stockholm included a survey in which questionnaires were distributed to a large number of other opera houses around the world. From this survey it has been possible to extract general knowledge about 1) the physical layout and 2) the extent of problems in orchestra pits. It has also been possible to find certain relationships between the two. In particular, the available area per musician seems to be an important factor: problems with excessive loudness and difficulties in ensemble playing are more frequently found in pits allowing less than 1.5 m² per musician. On the other hand, it is likely that changes in performance style and developments in instrument technology over the last half century are the main reasons for some of the problems encountered. Consequently, physical changes to the hall alone may bring only limited improvement – absorption treatment can even have negative effect. Conscious changes in musicians’ attitude regarding choice of instruments and performance style are probably the only lasting solutions to these problems.

INTRODUCTION

In the Royal Opera in Stockholm – like in many other opera houses – excessive sound levels are regarded a major problem for the pit orchestra members. As one of the means to approach this problem, the president of the resident opera orchestra, Hovkapellet, John Kapenekas, in 1998 initiated a questionnaire survey among other opera houses to collect data regarding conditions and problems in other orchestra pits. The hope was that the information so obtained could reveal possible causes and perhaps solutions to the problems in Stockholm. In 1999 a group consisting of the three remaining authors of this paper were asked to suggest possible solutions to the problems. Besides our acoustic experience, Tommy B. Andersson, being a conductor of profession, brought knowledge to our work from his studies on how performance practice have changed over years. In the following, hypotheses and results of general interest from this project will be presented and discussed.

PIT PROPERTIES AND PROBLEMS

Questionnaire forms were returned from 46 opera houses all over the world with information about the geometry and construction of the pits, the pattern of use and about eventual acoustic problems.

Among the 46 halls, 61% were designed specifically for opera while another 22% were originally drama theatres. The halls can be characterized briefly by the statistics shown in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Average</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building age (years)</td>
<td>94</td>
<td>8</td>
<td>254</td>
</tr>
<tr>
<td># seats</td>
<td>1334</td>
<td>260</td>
<td>3100</td>
</tr>
<tr>
<td># performances / year</td>
<td>107</td>
<td>15</td>
<td>310</td>
</tr>
<tr>
<td># different perform./year</td>
<td>13</td>
<td>1</td>
<td>58</td>
</tr>
<tr>
<td># different perform./week</td>
<td>3.2</td>
<td>&lt;1</td>
<td>7</td>
</tr>
</tbody>
</table>

Details regarding the orchestra pits are listed in Table 2.

### Table 2

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Average</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. area of pit floor (m²)</td>
<td>109</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>Floor area under forestage</td>
<td>37 %</td>
<td>2 %</td>
<td>80 %</td>
</tr>
<tr>
<td>Pit floor depth rel. stalls floor</td>
<td>-2.3 m</td>
<td>0 m</td>
<td>-4.5 m</td>
</tr>
<tr>
<td>Max. # of musicians in pit</td>
<td>72</td>
<td>15</td>
<td>110</td>
</tr>
<tr>
<td>Pit area / musician (m²)</td>
<td>1.7</td>
<td>0.91</td>
<td>2.1</td>
</tr>
</tbody>
</table>

1 In 55 % of the halls, the pit size can be reduced.  
2 These data relate to halls in which the pit is partly under the forestage. (The remaining 13 % of the halls had fully open pits.)  
3 In 15 % of the halls, the pit floor is at the same level as the stalls floor.
In 75% of the halls the depth of the pit can be changed and 85% of these halls use this possibility. In general, the high pit position is reported to be selected for Mozart and other operas requiring only a moderate sized orchestra. (As these smaller ensembles do not need the space under the forestage – or to be attenuated in a deep, covered pit - it is recommendable to bring the orchestra further up, resulting in better contact between stage and pit and improved fullness of the orchestral sound - especially from the strings.)

Regarding surface materials, all but two halls had a pit floor made of wood, and in 70% of the halls wood was also chosen for most of the pit wall surfaces. Other wall materials are concrete, bricks and gypsum board (mentioned in order of frequency of use).

The opera managements were asked whether one or more of five different problems were experienced in their pits and whether screens and personal hearing protectors were used by orchestra members. The answers are listed in Table 3 along with the percentage of positive answers.

Table 3 Problems addressed in the international pit survey and percentage of halls answering to the affirmative

<table>
<thead>
<tr>
<th>Problem</th>
<th>“Yes”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of space</td>
<td>68%</td>
</tr>
<tr>
<td>Difficulties arranging orchestra seating</td>
<td>48%</td>
</tr>
<tr>
<td>Excessive sound levels</td>
<td>69%</td>
</tr>
<tr>
<td>Difficulties hearing other orchestra members</td>
<td>46%</td>
</tr>
<tr>
<td>Lacking quality of the sound</td>
<td>36%</td>
</tr>
</tbody>
</table>

To reduce noise levels screens between musicians are used in 23% and hearing protectors in 48% of the halls. (Actually, screens are less often used in crowded pits which have no extra room for them!)

It is quite alarming that lack of space and excessive sound levels are experienced in two out of three opera houses. Many possible reasons for this come to mind: in our modern, noisy and health oriented society we are much more sensitive to work environmental issues than earlier generations, conductors and audiences - influenced by the playing style in American orchestras - demand more powerful expressions nowadays, the size of orchestras have increased beyond what the old halls can accommodate or instruments are being developed towards generating more acoustic power. Which of these are true is not clear today. E.g. there are many testimonies that modern wind and percussion instruments being more powerful than those used a few decades ago; but no documentation seems to exist.

In the search for answers, it was attempted to test for differences in mean values of the physical data belonging to the “yes” and “no” group respectively. However, the variance in the numerical data was obviously too large for any significant relationships to appear. Still, it seems relevant to show the fairly large differences that were observed between the average space per musician in pits with “Yes”- and “No”- answers respectively.

Figure 1: Average floor area per musician in pits with and without reported acoustic problems.

**DISCUSSION: POSSIBLE SOLUTIONS**

As seen, there is a strong indication of pit size being a parameter influencing level and ensemble problems. If enlarging the pit can be considered, it is better to extend it into the stalls area – by removing one or more seat rows - than by extending it under the forestage. The alternative might be to limit the number of musicians in the pit by planning the season program with the size of the hall in mind since it is also very important to maintain a proper balance between the overall size of the room and the size of the pit and orchestra.

Traditional thinking might lead one to recommend absorption treatment on the wall surfaces in the pit. However, objective measurements in the Royal Theatre in Copenhagen have clearly shown that the result will be reduced acoustic support to the musicians (ST<sub>early</sub>) whereas total level (G) remains almost unaltered. Besides, the musicians are more likely to play too loud if they can’t hear themselves, have no sense of balance with their colleagues or feel no response from the hall. Therefore, if possible, increasing reflections in the pit and reverberation in the hall are much better ideas.

However, re-thinking some current trends in performance practice might be much more efficient in overcoming the current problems in orchestra pits - as will be discussed during the aural presentation.
The Importance of Sound Strength (G) in Opera House Acoustics: Intimacy and the Role of Early Reflections

Jerald R. Hyde

P.O. Box 55, St Helena, CA 94574 USA

Abstract - Sound strength is shown to be a key acoustical factor in the success of opera house design with a major component being the early sound field as provided by the room design and geometry. The early sound field, along with the late energy and visual factors, are also hypothesized to be related to acoustical Intimacy.

CONCERT HALL AND OPERA HOUSE ACoustical Relationships

It's difficult to quantify the relative importance of acoustical factors for opera houses, given the multidimensional characteristics of the opera performance and audience experience. The extracoustic visual aspects of the acting, costumes, scenic perspective, stage source position and so on can dictate room design which, for large occupancies, may detract from the architectural requirements essential to providing the necessary acoustical portion of the house's response. With a good understanding of the essential acoustical factors, and how they interrelate, an excellent acoustical outcome within the visual constraints is indeed possible. For large houses however, the traditional classical opera house design approach may not provide the desired results. The subject of this analysis is how the known concert hall parameters may apply to acoustical quality in opera houses.

Classical Theory and Concert Halls

The issue of normalizing the history, culture and mythology of established opera houses from judgment based purely on their acoustical response has never been squarely faced. The visual and physical relationships between performer and audience is the main differing element between the use of concert halls and opera houses. It is suggested here however that the purely acoustical factors must be sorted out for opera houses first, independent of visual, cultural or historical judgments or biases.

A half century of concert hall research has provided us with the many acoustical attributes as well summarized by Beranek [1] and Barron [2]. Of the key subjective acoustical factors identified, acoustical Intimacy remains as yet illusive of definition and remains undefined in terms of its parameter correlates. The thesis developed in this paper will at the least suggest the factors to research, if such multidimensional analyses are possible at all, in defining "Intimacy."

For auditoria, starting with Sabine [3], sound needed to be "sufficiently loud," with speech or music to be "clear and distinct." Sabine derived statistical relationships for sound in rooms which essentially say that clarity and sound strength are inversely proportional. The generalized relationships are as follows, where the values for Clarity (C80) and Sound Strength (G) are approximated for greater distances in large rooms with volume (V) and room constant (A) (metric):

\[ C_{80} \approx 10 \log \left( e^{7A/V} - 1 \right) \text{ dB} \]

\[ G \approx 10 \log \left( \left(40^2 \pi^2 \right)/A \right) \text{ dB} \]

This classical prediction says that when the room constant A (proportional to the number of seats) changes, one measure will decrease while the other increases, and vice versa. The room constant is the key factor in all classical predictions of G, where reverberation time (RT) is only a dependent variable, since "it's the level (of the reverberant field) that counts."[4] While this inverse relationship is somewhat true between concert halls, when the same averages between opera houses are compared, there is no meaningful correlation between C80 and G as shown in the study by Hidaka and Beranek [5]. While in apparent conflict, surely, both are important for the successful opera house.

Many [see 6] have noted that the statistical or classical mathematical approach to quantifying the acoustical event in an enclosure, while allowing for a simplification and approximation of what is an extremely complex event, can often provide results which are far from reality, including the equations given above. Beranek [7] has cleverly solved this problem for the calculation of (RT) by normalizing absorption coefficients to Sabine's simple equation. Such adaptations are not as easily done for the other parameters which are related to integrating the transient energy as a function of position within a space. Barron [8], however, has greatly improved the prediction of the behavior of G and C80 in large rooms with his "revised theory." Suggested ranges for acoustical parameters in concert halls are found in the literature [1,2,6,9,10].

Acoustical Factors in Opera Houses

That sound strength G is an important subjective factor in concert halls has been well established going back to work reported by Eysholdt &
COMPONENTS OF "G" ARE IMPORTANT TO ALL OPERA HOUSE ACOUSTICAL FACTORS

In the study by Hidaka and Beranek [5], the major acoustical factors important to concert halls are found to be valid for opera houses as well, with C80 highly correlated with RT. Further, it has been demonstrated through room acoustical measurements [3,14] and computer modeling [15], that the early reflected sound in a hall up to around 80 msec. are a major factor in the value of G achieved in any space. As pointed out above, this is contrary to "classical" theory. Application of this concept in large hall design has been accomplished through the directed reflection sequence (DRS) design approach as discussed in the literature [16,2(See.4.1)]. and of which the Christchurch Town Hall and Segerstrom Hall [1] are prime examples. Extensive measurement data from these halls have clearly demonstrated that G has a strong early energy component not at all predicted by classical or "revised" theories. Since sound strength G is difficult to achieve in large spaces, the early reflected energy issue is of singular importance in achieving the desired results through architectural design.

The early sound field, which is strongly linked to the architectural design and geometry of the room, is therefore found to be a component in the major acoustical factors of sound strength, clarity, spaciousness and Intimacy. The ability of listeners to judge differences in G due to changes in the early sound field has been reported to be at around 1.0 dB [17]. Kahle [18] has reported a similar degree of discrimination between different halls.

The Role of Early Reflections and "G" in Achieving Acoustical Intimacy

Subjective acoustical Intimacy is not easily defined and may well vary in the listening process between people. Likewise, its objective attributes are also elusive. Beranek [1,5] has made a connection between Intimacy and his initial time delay gap (ITDG) taken at two seat locations, indicating a delay difference of around 10 msec. as defining the difference between excellent and not so acceptable ITDG values. Barron's [19] studies on the other hand have found no correlation between ITDG and Intimacy, but a correlation between loudness and Intimacy which therefore connects Intimacy to both the early and late sound fields. Toyota's [14] REC curves further connect Intimacy with strong early reflections in the first 80 msec. For further discussion on the links between G, visual perception and Intimacy, refer to Barron [2,19(pg.525)]. In summary, Intimacy is surely multidimensional, with at least early sound field, G and visual components.

Architectural Correlates to Increased Early Reflections

Sufficient values of G in large opera houses must be achieved through both reverberation efficiency (keeping A low) and importantly by providing significant multiple early reflections through architectural design and room geometry. For larger rooms, major reflectors may need to be added which are independent of the room's volumetric shell. General design opera house design approaches are well summarized by Hidaka, Beranek and Barron [1,2,5] with the general DRS design approach given in several published references including [2-Sec.4.1], 16,9,6,15].

REFERENCES

4. V.O.Knudsen, personal communication.
18. E. Kahle, personal communication.
Stage acoustics for an Opera House orchestra

C. Semidror

GRECO-ERIAC, Ecole d’Architecture et de Paysage de Bordeaux, 33400 Talence, France

A lot of Opera Houses are also used for concert performances. For musicians playing on the stage, the presence of the flytower construction forms a big problem. Some studies show, that the quality of the musicians performances is partly dependent on the possibility to hear each other and themselves. To evaluate these qualities some acoustical measurements were conducted on the stage of the Grand Theatre of Bordeaux and the results were compared with the optimum values. The first results show the existing listening difficulties between the prosenium and the backstage due to the flytower construction. A good solution would be a canopy above the orchestra.

INTRODUCTION

A lot of Opera Houses are also used for chamber music or symphonic concert performances. These orchestras are sometimes composed of more than 100 musicians. Some studies [1, 2, 3] show, that the quality of the musician's performances is partly dependent on the possibility to hear each other and themselves. Because a part of the orchestra is sitting under the flies, it is interesting to know how the flytower volume modifies the acoustical sensations between the different groups of players.

ACOUSTICAL SURVEY

Measurements

In order to evaluate the listening comfort of the musicians some acoustical measurements were conducted on the stage of the Grand Theatre of Bordeaux (GTB) and the results were compared with the optimum values. The objective criteria measured by a MLS system, are the Reverberation Time RT60 and 'Ease for Ensemble' ST1 defined by A.C. Gade [2] as:

$$ST1 = 10 \log \frac{\int_{0}^{\infty} p^2(t)dt}{\int_{0}^{\infty} p^2(t)dt}$$ (dB)

which optimum value is −12 dB ± 1 dB.

The positions of the selected sound source points (SSP) correspond to the 'classic' orchestra configuration: strings (Violin 1) (S1), wood winds (S2), cello (S3) and percussion instruments (S4). The receiver points are sometimes a SSP (E5 = S4, E6 = S3), sometimes points representing other groups of players: brasses (E4), strings (Violins 2) (E2), or the conductor's position (E1) as shown on Figure 1. During the measurements, the stage was only occupied with chairs and music stands.

To have reference data, measurements are systematically carried out on two points in the audience area at the ground floor level (M2) and at the gods (A14) [4].

Analysis of the results

The RT60 measurements are used for the survey's validity. Comparing with a previous survey [4] and in the same conditions (open flytower, closed pit), the same values have been found for the points M2 and A14.
By definition ST1 represents the musician's listening conditions. If the value is too high (> –11 dB) the playing conditions are bad.

When the SSP is at the 1st violin location (Figure 2) only the conductor is able to listen well. The listening quality of the 2nd violins, the cello and the wood winds, depends on the frequency (coloration problem). The brasses and percussion have a bad listening quality.

If the SSP is at the wood winds only the brasses can hear well (Figure 3) and besides some coloration problem due to the low frequencies, conductor, brasses and cello can listen well.

When the SSP is at the cello (Figure 4) the listening conditions are well for the conductor and besides some coloration problem, quite well for the 1st violins and the wood winds.

When the SSP at the percussion, only the brasses and the wood winds can hear well (Figure 5).

CONCLUSION

The first results show that the musicians listening conditions are mediocre on the GTB stage. For the moment the actual permanent conductor prefers to put the whole orchestra under the flies. But in this case the audience listening quality diminishes; a reduced level of sound power, particularly in the low frequencies. A moving canopy above the orchestra would be a good solution.

REFERENCES

The Acoustics of the “Teatro di Corte della Reggia di Caserta”

G. Iannacea\textsuperscript{a}, C. Ianniello\textsuperscript{a}, L. Maffeib, R. Romano\textsuperscript{a}

\textsuperscript{a}DETEC – University of Naples FEDERICO II, P.le Tecchio 80, 80125 Naples, Italy
\textsuperscript{b}DISPAMA – Second University of Naples, Borgo S. Lorenzo, 81031 Aversa, Italy

The “Teatro di Corte della Reggia di Caserta” is a small theater within the majestic royal palace built for king Charles III of Bourbon in Caserta (Italy) by the famous architect Luigi Vanvitelli. He conceived the theater since 1756. After various vicissitudes, it was completed and opened in 1769 during Carnival time. Vanvitelli himself took care meticulously of each detail conjugating late baroque with his innate classicism. The result was a true triumph of the skill and mastery of the involved craftsmen. Many types of materials were used for the finish. In particular, wood and papier mâché simulating other materials. It is reported that papier mâché was also used for room acoustics reasons. As the court theater was restored in 1994, supposedly as it was, the authors present the results of acoustic measurements carried out for the first time in the theater in terms of modern descriptors of its sound quality.

MAIN FEATURES

The Teatro di Corte presents many characters of the Baroque-type theatre. The auditorium displays a horseshoe shaped plan and five tiers of boxes. One can count 41 boxes and the royal box whose height is three tiers. The rear of the royal box is open toward a corridor that leads to a couple of rooms and then to the open. This determines an acoustic coupling of the corridor with the auditorium. The frescoed vault is sustained by twelve stone pillars with leaning half columns of alabaster. The lunette shape of the of boxes of the highest tier configure the dome vault like a seashell. The stage-house has a large door that in the past opened on the famous gardens of the royal palace that could become part of the scene visible through the prosценium arch. 110 heavily upholstered seats are in the stalls and about 200 wooden seats in the boxes. The length from the stage edge to the rear wall of the auditorium is 14 m. Its maximum width is 12.5 m. The volume is about 2000 m\textsuperscript{3}. The stage area is 20 m (depth) x 11 m (width) and its volume is 2800 m\textsuperscript{3}. The Teatro di Corte has no orchestra pit.

ACOUSTICAL MEASUREMENTS IN THE TEATRO DI CORTE

In the past Bourbons used the Teatro di Corte for Baroque opera performance. In recent times it is used primarily for music, drama and conference. To assess the sound quality of the theater impulse responses were recorded with a MLSSA\textsuperscript{\textregistered} based system at eight listener locations in the unoccupied theater having a bare stagehouse. Four were distributed in the left side of the stalls and four at the front of four boxes belonging to the lower four tiers. Receiving points and two locations of the dodecahedral sound source, S1 and S2 on the stage, are shown in the plan in Fig.1.

Further 55 impulse responses were recorded according to a uniform grid in the left half of the stalls to ascertain the space distribution of the early sound with the sound source located in S1. Some acceleration impulse responses were recorded to check the participation of suspended wood panels to the acoustics of the theater when excited by the sound field caused by the sound source in S1. An example of measured acceleration responses is reported in Fig. 2.

Acoustical objective parameters relevant for the music were calculated by computing the reverberation.
time RT, the early decay time EDT, the clarity index C80 and the sound strength G for the octave bands having the center frequency from 125 to 4 kHz. The definitions of the above mentioned acoustical parameters can be found in ISO 3382 [1]. Fig. 3 shows the average values of RT, EDT, C80 and G for the eight receivers and the two sound source locations.

For each receiver location the early energy lateral fraction LF [1] in the frequency range defined by the octave bands from 125 Hz to 1 kHz was calculated by combining a pair of impulse responses recorded at two points at a distance of 5 cm. This allowed the simulation of the behavior of a figure of eight microphone aiming a null-sensitivity direction toward the sound source. Table 1 presents the ranges of the values of the early energy lateral fraction LF (angular weight cos²). Fig. 4 presents the mapping of the early reflected sound energy (5 – 50 ms) in arbitrary dB.

**FIGURE 3.** Early decay time EDT, reverberation time RT, clarity index C80 and sound strength vs. frequency. Average values in the stalls (●) and in the boxes (■).

**FIGURE 4.** Early reflected sound distribution (500 Hz octave band).

<table>
<thead>
<tr>
<th></th>
<th>Stalls</th>
<th>Boxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Max</td>
<td>0.46</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**CONCLUSION**

The Teatro di Corte in the setting observed suggests the existence of a rather high acoustic coupling between the auditorium and the stagehouse. It is responsible of the high reverberation time at low frequencies. This determines a lack of clarity in the same frequency range. The parameter LF, that is related to an aspect of the spaciousness, seems adequate for music. Fig. 4 shows the typical focusing behavior of the horseshoe plan.

**ACKNOWLEDGEMENTS**

The authors are indebted to the management of Reggia di Caserta for allowing the measurements in the theater.

**REFERENCES**

Acoustic Measurements in the “Teatro dell’Opera” in Rome

G. Iannace\textsuperscript{a}, C. Ianniello\textsuperscript{a}, L. Maffe\textsuperscript{b}, R. Romano\textsuperscript{a}

\textsuperscript{a}DETEC – University of Naples FEDERICO II, P.le Tecchio 80, 80125 Naples, Italy
\textsuperscript{b}DISPAMA – Second University of Naples, Borgo S. Lorenzo, 81031 Aversa, Italy

This paper reports the main results of a survey about the objective acoustical behavior of the Teatro dell’Opera in Rome with reference to the performance of opera. The “Teatro dell’Opera” was designed by the producer Domenico Costanzi in 1877 and bore his name up to 1928 when it was renamed “Teatro Reale dell’Opera”. After World War II it was given the present name. The theater was opened on November 27, 1880 with King Umberto I and Queen Margherita of Savoy being present at the performance of Rossini’s opera \textit{Semiramide}. Many opera masterpieces were premièred in the theatre, e.g. Mascagni’s \textit{Cavalleria Rusticana} and Puccini’s \textit{Tosca}. The voice of famous singers - like Caruso, Gigli and Callas – and the batons of celebrated orchestra conductors – like Klemperer, Toscanini and De Sabata – as well, delighted the audiences in the past. Architect Piacentini carried out a major restoration of the theater in 1926. He reshaped and decorated the auditorium almost as it appears today.

\textbf{MAIN FEATURES OF THE THEATER}

The Teatro dell’Opera in Rome reflects many features of the traditional Baroque-type theater. The auditorium is horseshoe shaped in plan. Its length from the pit rail to the back wall is 19.9 m. The maximum width amounts to 22.0 m. It appears from the auditorium as having four tiers of boxes, a total of 135, and an upper gallery. Really, about the rear half of the boxes of the fourth tier are not divided by walls but form a sort of gallery. The ceiling is constituted of a decorated shallow dome with a skylight. The volume of the auditorium is about 10000 m\textsuperscript{3}. For safety reasons only 1500 seats are available. Chairs in the stalls are heavily upholstered and covered with red velvet. The remaining seats in the boxes and galleries are lightly upholstered. The orchestra pit can be given a variable opening depending on the stage area required for a specific performance. Its average width is 17 m and its axial length from the stage edge to the pit rail is 5.8 m. The height from the floor of the pit to the stage floor was 2 m at the moment the tests were performed. Chairs and stands were present therein. The stage floor is 21 m x 28.5 m and the volume of the stage house is about 13500 m\textsuperscript{3}. Opera, concerts and ballet are regularly performed in the Teatro dell’Opera in Rome.

\textbf{MEASUREMENT OF ACOUSTICAL OBJECTIVE PARAMETERS FOR OPERA}

The listening condition in the Teatro di Roma were assessed by considering objective parameters similar to those reported by Barron [1] in connection with his survey of three British opera houses. The main difference being the use of the same omnidirectional sound source both on the stage and in the pit instead of a sound source approximating the directivity of the human voice on the stage, as Barron did. The definitions of the considered objective parameters can be found in Ref. 1 and Ref. 2. Measurements were carried out in the unoccupied theater fitted for the performance of the light opera “Prova d’Orchestra” by Giorgio Battistelli. During the tests a very light velour separated the auditorium from the almost bare stagehouse. Impulse responses were recorded with a MELSSA\textsuperscript{\textregistered} based system in nine listener locations. Six were distributed in the left side of the stalls and three at the front of three boxes belonging to the first three tiers. Receiving points and two locations of the dodecahedral sound source, S1 on the stage and SF in the pit, are shown in the plan of the theater in Fig. 1.

\textbf{FIGURE 1.} Plan of the Teatro dell’Opera di Roma. Sound sources and receivers.

Acoustical objective parameters relevant for the music produced by the orchestra in the pit (sound
source in the pit) were calculated by computing the reverberation time RT, the early decay time EDT, the clarity index C80 and the sound strength G for the octave bands having the center frequency from 125 to 4 kHz. For each receiver location the early energy lateral fraction LF in the frequency range defined by the octave bands from 125 Hz to 1 kHz was calculated by combining a pair of impulse responses recorded at two points at a distance of 5 cm. This allowed the simulation of the behavior of a figure of eight microphone aiming a null-sensitivity direction toward the sound source. The parameters measured in relation to the voice of singers (sound source on the stage) are EDT, RT, G and D50. The last is an early energy fraction introduced by Thiele [3] as a simple measure of the speech intelligibility. The balance between the voice of the singer and orchestra sound was quantified by the difference $\Delta G_{\text{stage-pit}}$ of the sound strengths measured once with the sound source on the stage and a second time in the pit.

Fig. 2 shows some average data for the stalls and box fronts when the sound source was in the pit. Data shown in Fig. 3 refer to the sound source on the stage and the balance.

Table 1 reports the early lateral energy fraction LF.

![FIGURE 2](image2.png)  
FIGURE 2. Early decay time EDT, reverberation time RT and clarity index C80 vs. frequency in the teatro di Roma with the sound source in the pit. Average values in the stalls (●) and in the boxes (■).

![FIGURE 3](image3.png)  
FIGURE 3. Early decay time EDT and early energy fraction D50 vs. frequency in the teatro di Roma with the sound source on the stage. Balance $\Delta G_{\text{stage-pit}}$. Average values in the stalls (●) and in the boxes (■).

<table>
<thead>
<tr>
<th>Source in the pit</th>
<th>Source on the stage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stalls</strong></td>
<td>Min 0.50 0.43</td>
</tr>
<tr>
<td></td>
<td>Max 0.25 0.16</td>
</tr>
<tr>
<td><strong>Boxes</strong></td>
<td>Min 0.41 0.39</td>
</tr>
<tr>
<td></td>
<td>Max 0.11 0.20</td>
</tr>
</tbody>
</table>

**CONCLUSION**

The Teatro di Roma in the setting observed suggests the existence of a rather high acoustic coupling between the auditorium and the stagehouse. The reverberation times are in the higher part of the range typical for these theaters. Clarity and intelligibility appear adequate. As typical, early lateral energy is relatively low, except in the rear area of the stalls. The balance appears better in the stalls.

**AKNOWLEDGEMENTS**

The authors are indebted to the management of Teatro di Roma for allowing the measurements in the theater.

**REFERENCES**


On the testing of renovations inside historical opera houses

P. Fausti, L. Parati, N. Prodi, R. Pompoli

Dipartimento di Ingegneria, Università degli Studi di Ferrara, 44100 Ferrara, Italy

This paper deals with the acoustical impact of works inside the Teatro Valli in Reggio Emilia. Surveys were held in the theatre before renovations and were repeated with identical procedure and instrumentation also after their completion.

INTRODUCTION

The Municipal Theatre “Romolo Valli” in Reggio Emilia opened on April 21th 1857 and was designed by the architect Cesare Costa. The building occupies an area of 3890 m² and is situated near a green area. The main hall has horseshoe plan and is subdivided into stalls, four orders of boxes (summing up to 106) and a lodge. This area is peculiar because its central part is rather deep and hosts a small raked tier. The total number of seats in the theatre is 1136. In Tab. 1 some geometrical data of the main hall are reported. Recently the theatre was restored mainly for safety reasons. In particular in 1998 the upholstery of the seats in the stalls was renovated and in 2000 the furnishing and wallpaper of the boxes were changed, while the painted surfaces and the decorations of the main hall were all polished. In 1997, before the renovations took place, a first set of acoustical measurements in the theatre was made and in 2001, after their completion, a second survey was carried out. In both cases the same setup of the theatre was prepared and the same operating scheme was kept. The comparison between the two sets of data makes it possible to investigate the impact of renovations on the acoustics of the theatre.

THE ACOUSTICAL MEASUREMENTS

For both surveys the theatre was set up for chamber music recital, which means that the fire curtain and painted curtain were lowered and the orchestra pit was up. The sound source, a Norsonik dodechaedron, was placed in a symmetric position in the centre of the stage, at 3.5m from its border. A group of 11 receivers were distributed around the left part of the stalls, 4 in the I order boxes, 4 in the III order boxes and 4 in the lodge. The test sequence was an MLS signal of order 16 and the sound probe a Sennheiser MKE2002 binaural system. While the source was looped, in each position a sample of about 30s of test signal was recorded on DAT and a sound level meter measured the $L_{eq}$. Later in the laboratory the recordings were processed in order to obtain related impulse responses and, by means of Aurora software, most of the acoustical parameters indicated in the norm ISO3382. The only difference between the two measurement campaigns regarded the sound power level of the source during the operation. This caused some difficulties in the analysis of the data and a procedure to compensate the difference was implemented. In Fig. 1 and 2 the averaged values of RT20 and C80 measured in 2001 are presented respectively. The main hall shows a rich reverberation in the lower range, which fits the requirements for opera in the higher range. While the I ord. boxes show a slightly lower RT20 than the stalls, the lodge has a markedly higher reverberation in almost the whole band. This is the effect of the addi-

\begin{table}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
  & S & H & V & N & V/N & S/N \\
\hline
Stalls & 340 & 13.9 & 4700 & 414 & 11.3 & 0.82 \\
Boxes & 625 & 2.5 & 1500 & 722 & 2 & 0.86 \\
& Lodge & & & & & \\
TOT. & 965 & - & 6200 & 1136 & 5.45 & 0.85 \\
\hline
\end{tabular}
\end{table}

Table 1. Basic geometrical data of the main hall of the theatre; plain surface (S), height (H), volume (V) and number of seats (N).
The C80 has optimal values in most of the passband. Then in Fig. 3 the comparison of averaged values of RT20 and EDT between the 1997 and the 2001 sessions is reported. Both parameters show that the reverberation has undergone a moderate increase in all the bands, which becomes evident above the 2kHz oct. band. In the case of EDT a wider increase regards also the lower range. Finally in Fig. 4 it is seen that the levels measured in 2001 in the stalls do not differ much from 1997 because of the implemented normalisation. In the boxes an increase is reported for the higher frequencies while in the lodge it regards the whole passband.

DISCUSSION AND CONCLUSIONS

Though it is not possible to define the exact effect on acoustics of each single renovation, it is important to consider that the upholstering of seats in the stalls, the furnishing and wallpaper in the boxes caused the greater change in the RT. It seems more difficult to evaluate the effect of the polishing of plasters and decorations. In any case, the present conditions of the theatre are to be preferred considering the optimal values found in literature for this type of hall. The benefit of renovations is extended to every section of the main hall. In particular the sound will be more frequency-balanced thanks to an increased RT in the higher range and, by the correlated effect of a lower clarity, better mixed between players. The lodge seems to have had even better outcome of renovations, but the acoustical conditions (especially in its central part) are still markedly different from the rest of the hall. This work validates the renovation procedure and confirms that matching safety requirements and acoustic quality is nowadays possible. Nevertheless it is necessary to introduce more systematic rules which would take into account the acoustic properties of both the old materials being replaced and the new ones being used in the renovation work.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the architect Mauro Severi who realized the renovations in the theatre for his fruitful information on the works. Andrea Gabbi and Attilio Zannoni from the staff on the theatre are also kindly acknowledged for their support in the measurements and for providing samples of the materials.
Concerts in the Opera House

D. Commins

commins acoustics workshop, 15, rue Laurence Savart, F-75020 Paris, France,
comminsacoustics@compuserve.com

Opera houses ought to be dedicated solely to opera since there are major contradictions between the acoustical requirements for opera and for concerts. Actually, concerts do take place in the opera house for several reasons: economical first and to give the opportunity to orchestras to come out of the pit from time to time. To try to create the best possible conditions for concerts in an opera environment, orchestra shells are being built in existing houses; new buildings are often designed for both concerts and operas. The present paper reviews the principles of the design of orchestra shells and provides examples.

INTRODUCTION

As the acoustical community knows well, the acoustical design of an opera house is a complex matter since one must obtain simultaneously musicality and clarity. A rich reverberation helps music but may be harmful to singing. A limited reverberation may have the opposite effects.

One easily observes that there is a blatant contradiction between the optimum criteria for symphonic music and those for opera. In principle, one should avoid mixing the two genres. Today, however, it is a fact that concerts do take place in the opera house.

There are two main cases: new buildings and existing building. The design of a new opera house should include concert conditions and should provide an adequate orchestra shell. In existing opera houses, an orchestra shell is obviously needed but the outcome depends on the acoustics of the room; in some very dry rooms, it is not possible to obtain good conditions for concerts while, in some reverberant opera houses, it is sometimes possible to transform the room into a genuine concert hall.

The purpose of the present paper is to explain the design criteria, to describe the principles of the design and to explain the practical problems that must be overcome.

EXISTING BUILDINGS

For well-known reasons, the specific volume is usually smaller in an opera house than in a concert hall, reverberation time is shorter and the response is usually steeper or altogether truncated.

The rule of thumb that consists in defining a specific volume for concerts and another for opera applies differently to the two types of performances: traditionally, for opera, the specific volume rule applies only to the public part of the space and excludes the stage tower; for concerts, the entire volume of air is counted.

Similarly, the reverberation time rule for opera applies in a fuzzy manner since the influence of the set installed on stage is not taken into account.

Similar considerations apply to some other design parameters.

This means that when transforming the opera house into a concert hall, one must try to optimize the ‘acoustical volume’, the reverberation time and the impulse response. Stated in this manner, it looks like a very simple process; in reality, one is considerably restricted by practical considerations.

NEW BUILDINGS

When designing a new opera house that is known to become a concert hall at times, as it most often the case, one must from the onset take the above considerations into account and select the appropriate values for the design parameters, so that opera and concerts may be compatible in the same space.

This means that one may choose a longer reverberation time than the usual rules would recommend, to design
for an extended response. Of course, since opera remains the main activity, one must keep constantly in mind that optimum conditions must be reached, not only for music but also, and essentially, for the voice.

The problem is relatively trivial in an opera house of moderate size: a healthy design associated to a functional orchestra shell usually leads to reasonably good results. In very large opera houses, the compatibility between symphonic music and lyric music is more problematic. The design must follow rigorously the well-known acoustical design rules.

THE OPERA HOUSE ORCHESTRA SHELL

In both cases of existing or new opera houses, the key element that permits the transformation of the opera house into a concert hall is the orchestra shell. It plays an important acoustic role for the audience and for the musicians on stage but also on the architecture of the concert configuration. Even though, it all seems simple and obvious, it may be worthwhile to enumerate the key characteristics of orchestra shells. For acoustical and practical reasons, the design of a genuine orchestra shell is quite complex:

- The shape should distribute the sound correctly to the audience and to the musicians.
- It should be associated with a proper orchestra platform.
- It should have some flexibility to accommodate recitals, chamber music, symphony orchestras with and without chorus.
- The time to erect and dismantle the shell should be as short as possible to avoid interference with the many activities, artistic and technical, that take place in the house.
- Its material should be light without any acoustical compromise.

Therefore, the most important criteria that should influence the design of the orchestra shell are the following:

- Maximum ‘acoustical volume’.
- Adequate orchestra platforms.
- Optimum early reflections for musicians and audience.
- Increased reverberation over the full musical frequency range.
- Good ensemble conditions.
- Lightweight.
- Ease of use.
- Convenient storage.

Short construction and dismantling times.

It is essential to choose at the preliminary design phase to install the orchestra over the orchestra pit or on stage. The decision actually depends on the characteristics of the ceiling of the opera house, that may have positive or negative effects on ensemble conditions and on homogeneity.

EXAMPLES

FIGURE 1. Teatro S. João, Porto

FIGURE 2. Staatsoper, Munich

FIGURE 3. Opéra Garnier, Paris

FIGURE 4. Early model, New Scala
Some Missed Effect in Opera House Design

A.Cocchi

Department of Energetic, Nuclear and Environmental Control Engineering, D.I.E.N.C.A., University of Bologna, Viale Risorgimento 2, 40123 Bologna, Italy

At the state, it is possible to evaluate, either within an actual theatre or on a computer model, a lot of energetic, temporal and spatial, parameters: so, it seems possible to judge about the acoustical quality just in each place available for listeners. Beranek and Ando presented also some kind of synthetic evaluation of preference, based on a blend of physical measurements and statistical judgements from qualified listeners. Despite of this wide possibility of physical analysis, there are yet many factors that influence the listening quality of music in closed spaces. This paper will analyse some of them, coming back to the old idea of Forsith that the ancient Architect was the unique man able to design an optimal closed space for musical performances and, in the case of failure, it was the fire the final judge of its work. Now that the fire is quite, but not everywhere, under technical control, the unique designer must be surrounded by many technicians and the acoustic one must be the first. But the acusticians must not limit its work on avoiding echoes and preventing geometrical, energetic and spatial annoying effects, but also temporal defects that can arise from some missed element.

Many papers have been written till now about the capability of ancient Architects in taking into account the acoustical problems in the design of theatres : if we want to check this sentence, as we are dealing with ancient cultural heritages we can work only on stones and written documents, and the last ones are very few, in particular on the subject of the acoustical design.

Unfortunately, even if some Architect left to us some written paper, we don’t have so many informations on the acoustical design also in the middle age, till the eighteenth century: we know something about the work of Galli Bibiena, but for example we don’t have any idea about the acoustical reasons that convinced the Architect to build up the Municipal Theatre in Bologna all in masonry, then the Scientific Theatre in Mantua all in wood [1].

Some years ago a terrible fire destroyed the “La Fenice” theatre in Venice: this was the opportunity for many acousticians to study the documents left by the Architect. From an accurate study presented in Seattle, published in [2], it was clear that neither formulas nor design were utilized to justify the choices made in the name of acoustic quality. A first conclusion we can get is that it was a blend of experience, knowledge of good theatres already built, some knowledge also of acoustical basic rules and, may be, some lucky event, that supported those who designed acoustically good theatres: as wonderfully said by Forsith [3], the fire made justice of quite all the examples of unlucky design, so now we can look only to the good ones.

Even now, when the acoustical design of theatres has become a science, with the support of the computer technology that allows us to evaluate the acoustical field everywhere, with such a detail of indications that doesn’t correspond to that of our knowledge both of the acoustical properties of materials and human response, the acoustical support to the Architect is not so deep, as we can see in the volume devoted to the project of the new “La Fenice” in Venice [4].

Scientists working in this field, knocked down from the river of computer simulations, doesn’t realize that such a detail is sometimes very far from what is really possible to realize, while, may be, are missing some important detail. For instance, even if now it is possible to measure or simulate quite any acoustical field, scientist are working with no adequate attention to the articulation in frequency of a musical message. The alteration in the frequency balance of a musical motif can be measured issuing a pink or white noise in the hall, then picking up the message in the stage, in the stall and in the balconies, quite in every position occupied by the public, as it was usual thirty years ago [5], but this analysis is not between those stated as criteria for testing the acoustical quality of theatres. May be, the frequency balance in reverberation time [6] or in IACC values [7] are not enough to guarantee that a motif will not be heard with some frequency missing or too amplified.

Coming again to the scope of this paper, we read somewhere that ancient Greeks built their theatres laying the terrace on a hill, having in mind an exposure toward the sun and possibly a water-course running near the stage; the question rises if there is, as someone says, some acoustical meaning in these choices.

To check these points a little research has been made in the theatres built in the south of Italy during the period 350-50 b.C.[8]: figure 1 shows the exposition related to the sunrise and sunset in the south of Italy, figure two in Sicily. As we can see, the facing choice was firstly based on view reasons, in particular in Sicily.
As for the presence of a water-course, it seems clear that this opportunity was useful for moving away wastes produced by the public, as quite in every theatre we find some kind of artificial drain running along the terraces, then flowing together in a natural water course.

Nevertheless, it is possible to think also to some acoustical reason.

Everybody working in acoustics knows that the propagation of an acoustical ray is deviated from the straight path if there is either an air stream or a temperature gradient perpendicular to the path itself.

It is very simple to explain the first effect in terms of temperature gradient perpendicular to the path itself.

Everybody working in acoustics knows that the propagation of an acoustical ray is deviated from the straight path if there is either an air stream or a temperature gradient perpendicular to the path itself.

So, the presence of the sea in front of the terraces can generate during the day, and chiefly in the afternoon, an air stream, usually called “sea breeze”, whose mean speed W can reach, in sunny days, values even of 1 m/s. If we assume a terrace depth of about 30 meters (as it is for instance the case of Taormina, now Taormina, faced south and to the sea), so having a stream depth of about 15 meters, the rise up is of about 25 centimetres, to be compared with an elevation of the sound ray of about 8 centimetres at the top.

As for the second effect, the radius of curvature of the sound ray crossing a depth L of a zone with a temperature gradient ΔT/Δz, generating a sound speed gradient Δc/Δz, is

\[ R = \frac{c \Delta z}{\Delta c}, \] (2)

the angle θ formed between the new sound ray direction and the initial horizontal one is

\[ \frac{L}{R} = \sin 2 \theta. \] (3)

Following the same example as above, in the afternoon of a sunny day we can have an air stream flowing along the terrace with a temperature gradient of about 3 °C/m, that is to say a sound speed gradient of about 1.8 s⁻¹, a radius of curvature of 190 meters, an angle of deviation of 4.5 degrees and a rise up of the sound ray of about 8 centimetres at the top.

Surely these quantities seem meaningless in an open air theatre, where there are many other reasons that can reduce the strength of the sound field, but may be they contributed to lower the loss of strength, as surely was in theatres very height like in Epidauros, now Epidaurus.

Now we are dealing with indoor propagation but these effects must not be neglected while modelling the acoustical field within a modern theatre where the air conditioning system can change the temperature distribution, or in the restoration work of a classical Italian style Opera House where originally there was only an hot air heating system from the bottom, with a very high reversed temperature gradient.

In the first case, while changing from winter to summer conditions we change also the temperature of the air stream produced by the HVAC plant, and this air stream is put in with a velocity that push the air from the top to the stall, reducing itself during the way: in short, we have a non uniform velocity field within the hall that influence the straight propagation of sound rays in a different way while changing the external climatic conditions, so altering the foreseen sound pressure distribution.

In the second case, the influence of the HVAC plant is more evident then before, as we don’t usually have the possibility of calling down the air under the public area, but we can do it only with some return outlet distributed along the side walls, as it is the case in the Municipal Theatre of Bologna, where the original outlets for the hot air are now utilized as return outlets.

REFERENCES
Temporal and Spatial Acoustical Factors for Listeners in Boxes in a Historical Opera Theatre

H. Sakai\textsuperscript{a}, N. Prodi\textsuperscript{b}, R. Pompoli\textsuperscript{b} and Y. Ando\textsuperscript{a}

\textsuperscript{a}Graduate School of Science and Technology, Kobe University, Rokkodai, Nada, Kobe 657-8501, Japan
\textsuperscript{b}Department of Engineering, University of Ferrara, Via Saragat 1, 44100 Ferrara, Italy

In order to clarify acoustical quality of a sound field for listeners inside boxes of a historical opera house, acoustical measurements were conducted in an existing opera house. In order to investigate the effects of multiple reflections between walls inside a box and head scattering of persons, the location of a receiver and the number of persons in the box were changed. For each configuration, four orthogonal factors and additional factors in a sound field were analyzed from binaural impulse responses.

INTRODUCTION

There are some systematic reports to investigate objective and subjective data in relation to opera houses \cite{1, 2}, however, detailed acoustical characteristics inside boxes are not found. In order to improve the listening condition or acoustic design of boxes, it is necessary to know how the physical characteristics inside boxes are affected by a different location or a different number of listeners.

The purpose of the present study is to obtain knowledge of listening conditions of listeners inside boxes in a historical opera house. For this purpose, acoustical measurements were conducted in a typical Italian opera house the “Teatro Comunale” in Modena. The theater has a horseshoe-shape in plan and four tiers of boxes plus a gallery. Number of the seats is 900. Volume of each box is approximately 6 m\textsuperscript{3}, and opening surface is 1.8 m\textsuperscript{2}. Orthogonal factors, which are listening level (\textit{LL}), initial time delay gap between the direct sound and the first reflection (\textit{t}_{1}), subsequent reverberation time (\textit{T}_{\text{sub}}), and IACC, and in addition related factors, which are the total amplitude of reflections (\textit{A}), interaural time delay (\textit{\tau}_{\text{IACC}}), width of the interaural cross-correlation function (\textit{W}_{\text{IACC}}), \cite{3} were analyzed.

MEASUREMENTS

Using the signal of maximum length sequence (MLS), measurements were conducted to analyze binaural impulse responses for two source locations. Locations of sound sources and receivers are illustrated in Figure 1. An omni-directional loudspeaker was used as a sound source on the stage or in the orchestra pit. As listener’s locations, one position in the stall and two boxes (Box A and Box B) were selected. The locations of the listener with and without other listeners in the boxes were arranged according to four patterns as shown in Figure 2. During the measurements, the stage was empty, and the theater was unoccupied.

FIGURE 1. Locations of sound sources and receivers.

FIGURE 2. Arrangements of persons in a box (Pattern 1–4). Hatched person represents a listener with condenser microphones at the ear entrances.
RESULTS AND REMARKS

In the measurements, the characterization for listening conditions in boxes in a historical opera house are partly clarified by use of orthogonal factors of a sound field. Regarding variable conditions including the sound source location, the receiver location, configurations of persons inside a box, temporal and spatial factors in relation to the subjective evaluations vary, due to the multiple reflections between walls inside the box and the scattering effect by persons close to the listener. Consequently, it can be supposed that the psychological responses also vary. Following is the main results of the measurement.

![Diagram](https://via.placeholder.com/150)

**FIGURE 3.** Measured results. (a) $T_{sub}$ for the source on the stage; (b) $T_{sub}$ for the source in the pit; (c) IACC in the stall for the source in the pit; and (d) IACC in Box A for the source in the pit.

In the impulse responses in the box, many reflection components are added between the direct sound and the first reflection coming from the lateral walls in the hall due to the multiple reflections between walls inside the box and the scattering effects by the persons close to the listener. These reflections are effective to decrease IACC at listeners in the box.

For listeners in the deep box, as the strong reflections from walls of the hall are screened by the front or lateral wall of the box, the maximum $LL$ at all pass band in the box is observed at the opening surface. The range of $LL$ in the same box is up to 5 dB. Values of $LL$ at 125 Hz are boosted for the pit source, especially at the listener in the stall (up to -14 dB) due to the interference effects between the direct sound and initial reflections between walls inside the orchestra pit.

Regarding the factor $\Delta t_1$, more uniform listening environment for the rear box compared to the frontal one close to the stage was observed. The $\Delta t_1$ is almost the same value for a person at rear seats almost independently, even if some persons in the front row exist or not when the listener is at second row in the box.

The $T_{sub}$ greatly distributed into a wide range in the theater, but not due to the listening position and the number of persons in the box. In the front box A close to the stage, $T_{sub}$ become long by the coupled-room effect of the stage house, and has a peak at 1 kHz as shown in Figure 3(a,b). In the backward box B, monotonic decrease of $T_{sub}$ against frequency was observed and this characteristic is similar to the $T_{sub}$ in the stall. Such a variety of $T_{sub}$ suggests the importance of the selection for a preferred listening position, comparing to that in the concert hall.

At the receiver position inside the deep box, IACC is normally smaller than that at the opening surface because the multiple reflection components relatively increase in such a deep position in the box. For both source locations, IACC dramatically decreased between 250 Hz and 500 Hz in boxes comparing to that in the stall as shown in Figure 3(c,d).

ACKNOWLEDGMENTS

The authors are deeply indebted to a stuff of the “Teatro Comunale” in Modena for providing opportunity of the measurement. In addition, authors wish to thank Francesco Pompoli for his cooperation and considerable assistance of the measurement.

REFERENCES

Vocal Expression and Preferred Stage Acoustics for Singers

Dennis Noson\textsuperscript{a,b}, Shin-Ichi Sato\textsuperscript{a}, Hiroyuki Sakai\textsuperscript{a}, and Yoichi Ando\textsuperscript{a}

\textsuperscript{a}Graduate School of Science and Technology, Kobe University, Kobe 657-8501, Japan
\textsuperscript{b}BRC Acoustics, 3208 15\textsuperscript{th} Avenue West, Seattle, WA 98119, USA

Vocal performance characteristics, such as tempo, color, and expressiveness of singers are part of the unique artistic impression of individual performers and individual performances. Subjective pair-comparison studies of singers in a previous study demonstrated that singers prefer added reflections with delays in the range of 10 to 20 ms. However, the range of values between singers in effective duration of the autocorrelation of the singer’s voice was limited, and insufficient to demonstrate a relationship between individual vocal characteristics and the preferred delay time of reflections. In this study, to investigate singer’s preferred acoustics with a change in singing style, subjects were asked to perform using exclusively non-fricative “la” syllables (\textit{melisma} singing). A resulting shift in preferred time delay was observed. The extent of the shift in preferred reflection time delays is shown to be directly related to the minima of the running autocorrelation function calculated from each singer’s voice.

\section*{INTRODUCTION}

Singers are unique among musicians. As performers, their musical instrument is located within very close proximity to the ears, and generates significant perceived sound levels via bone conduction in the head. In determining sound field conditions for musical performances, singers should therefore receive special attention. Nevertheless, only a few studies have attempted to delineate the characteristics of the acoustical environment preferred by singers.

In addition, no previous study has demonstrated the influence on singer preference for varying stage acoustics due to changes in singing styles. Singers control the artistic effect of their performances by varying color, tempo, and emotional expressiveness. This study examined the effect on the preferred reflection time delay while singing without words, using non-fricative syllables (\textit{melisma} singing).

\section*{PREVIOUS STUDIES OF SINGER PREFERENCE}

Performer studies with simulated sound fields, conducted with instrumental musicians, have concluded that strong ceiling reflections are very important both for instrumental soloists and for ensembles. Similar attempts to determine singer preferences in simulated sound fields are rare [1, 2, 3]. Noson et al. [3] made direct observations of singer acoustical preferences while in performance on a full-scale stage and in using simulated reflections in a semi-anechoic room. The on-stage study utilized an electronically-added, variable time-delay reflection to simulate relocating stage walls. During fast tempo singing, singer preference increased with the addition of short-delay reflections, with the highest preference at delays ranging from 20 to 30 ms. Anechoic room simulations of singer stage acoustics determined subjective scale values for sound fields with a single reflection. As proposed by Ando [4], the maximum scale values for each singer also suggested that the preferred time delay was related to the minimum value of the running autocorrelation function (ACF), calculated for each singer, although the range of the ACF values and consistency of the singer pair comparisons was not reliable enough to establish the relationship conclusively.

\section*{EXPERIMENTAL PROCEDURE}

Simulated sound fields, consisting of one delayed reflection, were presented to five melisma singers in one session, and to six singers in session two. Previous preference data for 3 singers from the earlier study of lyric singing plus one new lyric singer are included for comparison. Sound fields were simulated in a 125 m\textsuperscript{3} semi-anechoic chamber, specifically developed with a larger cubic volume, in response to suggestions from the singers. The simulation loudspeaker was located 3.0 m behind the singer, reproducing a delayed signal at –5 dB below the level of the direct sound, as measured by a microphone at the singer’s ear canal entrance.

Four simulated sound fields consisted of a delayed reflection \(\Delta t_{1}\) at 10, 20, 40 and 80 ms. The notes of the melody from the traditional Irish melody “Slane” were sung in \textit{melisma} style as the syllable “la.”

Six unique pairs from 4 sound fields were presented to each singer in five repeats, in random order. The singer’s scale value of preference for each sound field was determined using Thurstone’s method [5], for each type of singing (lyrics and \textit{melisma}). Statistical tests for consistency and agreement were applied to assess the validity of pair comparison results.
RESULTS

Scale value results calculated for 9 sessions (6 singers, 3 singers twice) are shown in Figure 1. Measured preferred time delays $[\Delta t_1]_p$ for the singers were determined from a regression curve fit to the scale values, as listed for each singer in Table 1.

![Graph showing scale value preference for sound fields with one delayed reflection, melisma singing. Global (average) results for 9 melisma sessions shown with bold line.](image)

The results show a maximum value of preference in the range from 20 to 40 ms, with an average 23 ms preferred delay for combined data (Table 1).

<table>
<thead>
<tr>
<th>Subject</th>
<th>$[\Delta t_1]_p$</th>
<th>max SV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Soprano</td>
<td>29</td>
<td>3.6</td>
</tr>
<tr>
<td>B Alto</td>
<td>18</td>
<td>2.4</td>
</tr>
<tr>
<td>C Tenor (2)</td>
<td>15</td>
<td>2.1</td>
</tr>
<tr>
<td>D Tenor (2)</td>
<td>26</td>
<td>2.6</td>
</tr>
<tr>
<td>E Soprano (2)</td>
<td>28</td>
<td>3.1</td>
</tr>
<tr>
<td>F Tenor</td>
<td>26</td>
<td>3.6</td>
</tr>
<tr>
<td>Global All singers</td>
<td>23</td>
<td>2.6</td>
</tr>
</tbody>
</table>

As shown in Table 2, text (lyric) singing resulted in a preferred range for reflection $\Delta t_1$ of 10 to 20 ms, averaging 14 ms, while melisma singing, without the fricative consonants of the sung lyrics, the maximum preference was observed to increase by 4 to 11 ms, with a difference in the average values of 9 ms, an approximate increase of 60%.

![Graph showing relationship between singer preferred reflection time delays (ms) and calculated minima of running ACF.](image)

DISCUSSION

The relationship between singer preference and singing style is shown in Figure 2. In the theory of performer acoustics [4], measured preferred values of reflection delays are directly related to the minima of the running ACF for each singer’s performance. Figure 2 shows a linear relationship, established by varying the style of singing from lyrics to melisma, as predicted by the increase in the minimum of the running ACF.

![Graph showing relationship between singer preferred reflection time delays (ms) and calculated minima of running ACF.](image)

REFERENCES

Acoustics of a Baroque Opera House

N. Edwards\textsuperscript{a}, and D. Kahn\textsuperscript{b}

\textsuperscript{a}Acoustic Dimensions, 24 Styvechale Avenue, Coventry, CV5 6DX, nedwards@acousticdimensions.co.uk
\textsuperscript{b}Acoustic Dimensions, 2 East Avenue, Larchmont, New York, 10538, dkahn@acousticdimensions.com

The proscenium of the Baroque opera house provides an acoustic that favors a good balance between singers and orchestra. There are no opera houses today that have the acoustical properties of an original Baroque opera house because their forestages have been replaced either with audience seating or with an orchestra pit. This project provides an opportunity to restore an acoustical excellence that has not been heard for centuries.

Baroque opera houses combine acoustical characteristics that are found in small-scale recital halls with those that evolved into the nineteenth century grand opera house. In the recital hall, both singers and orchestra share the same acoustical space as the audience; the performers are surrounded on three sides by acoustically reflective walls, with the fourth side occupied by the audience.

In the Baroque opera house, the upstage wall of the recital room is replaced by the occhio della scena (the upstage opening of the proscenium at the stagehouse plaster line), but importantly the singer is still located between acoustically reflective ‘side walls’ – in this case the deep side walls of the proscenium. The singer is elevated well above the main floor audience ensuring an excellent line of direct sound to each member of the audience. The proscenium arch forms an acoustical overhead reflector that assists the singers’ projection of sound both when they are located downstage and upstage.

The orchestra, on the other hand, is located in a less acoustically-favorable location, without being acoustically suppressed by the orchestra pit overhang of later opera houses. The orchestra placement at main floor level and behind a pit wall ensures the orchestra’s sound is grazing over the heads of the main floor audience, which will naturally attenuate it. The orchestra do not gain acoustical advantage from the proscenium walls or the lower ceiling of the proscenium arch that aid the singer, as these are fully upstage of the orchestra and serve only to project the orchestra’s sound to the upstage areas.

These are not newly-discovered aspects of Baroque opera house acoustics. In 1676, Motta reported on the acoustical importance of the deep proscenium in his ‘Treatise on the structure of theatres and scenes’[1].

For speakers or singers located in the area between A and B in his illustration he notes: ”[Those] who perform here to the accompaniment of the orchestra are heard just as beautifully as the orchestra.... This is a most important and necessary point” [1, p.26].

We have studied the acoustical importance of the Baroque opera house proscenium, forestage and orchestra pit locations using acoustical computer modeling techniques.

In our computer model of the Baroque opera house, we have ‘illuminated’ the room surfaces using a sound source located on the forestage on stage right, facing stage left.

In the model, we have adopted the voice directivity of 1kHz speech.
FIGURE 3. Scalar intensity of singer’s voice is mapped as color on room surfaces.

In the computer model, the color indicates the strength of the direct sound impinging upon the surface. Note the red colors to the walls of the proscenium and to the soffit of the arch: these surfaces are strongly ‘illuminated’ by the singer’s sound, and will scatter this sound into the main floor audience areas.

For comparison, we show below the same opera house but with the Baroque proscenium replaced by the thin proscenium wall of the later opera house:

FIGURE 4. As Figure 3, but without Baroque proscenium

There is far less ‘red’ area in this view from the main floor. The largest red area remaining is in fact the stage floor, which will become a more visible from the upper levels of the opera house – and indeed the singer’s voice would be more audible from the balcony levels of the house.

Similarly, views of the same computer model from the stage reinforce Motta’s seventeenth century observations on the acoustical importance of the deep proscenium.

FIGURE 5. As Figure 3, but view from stage.
Model with Baroque proscenium

FIGURE 6. As Figure 4, but view from stage.
Model without Baroque proscenium

In conclusion, the true Baroque opera house acoustic ensures that the natural acoustics provide an excellent balance between the singer and the orchestra – even when a performer is acting and facing across stage or partly upstage.

This Baroque opera house project provides an opportunity to restore an acoustical excellence that has not been heard for centuries.

REFERENCES

Acoustical measurements of spatialization in an Opera House in the center region of Italy

L. Tronchin, A. Cocchi
Department of Nuclear, Energetic and Environmental Control Engineering, DIENCA
Bologna University, 40136 Bologna, Italy

The optimization of acoustical characteristics in opera houses represents the main goal during the design of the restoration of theatres, and the measurements and conservation of sound quality of the main hall are nowadays considered like a cultural heritage. In this paper the acoustical characterization of two Italian Opera Houses has been described. In the first case measurements of IRs, in an historical theatre have been performed. The measurements have been carried out by using both traditional methods (dummy head) and novel instrumentation (like SoundField MKV b-format microphone) have been experimentally done in several positions in the audience and balconies, moving the omnidirectional sound source in different positions. In the second case, a numerical model of a modern theatre has been generated. Many attempts were tried in order to improve the acoustical quality in the audience, which resulted quite poor after experimental measurements. Such limitations were referred especially in the shape of the theatre, which represents a non-typical Italian Opera Houses. Different designs of panels in the ceiling were considered and an optimal solution was then found. The sound characterization was therefore improved, especially in some positions far away from the stage.

ACOUSTICAL QUALITY AS CULTURAL HERITAGE

The problem of considering acoustical quality of the theatre like cultural heritage has been considered since the burning of La Fenice Theatre, in 1996. In that case, binaural measurements were made just two months before the burning. It allowed the scientific community to preserve the acoustics of the Theatre [1]. In 1998 a general agreement between many researchers was established at CIARM [2]. This paper is therefore concerned with the sound characterization of an ancient theatre, both for preservation the sound quality, and both in order to design an acoustical shell in case of unsatisfying quality.

SPATIALIZATION IN THE THEATRE

Spatialization represents quite important characteristic that nowadays has to be considered during measurements and design in Opera Houses. It is considered like an important aspect that should be measured and preserved. In last years any efforts have been carried out aiming to make available a correct methodology able to define and measure spatial parameters. Binaural measurements have been enhanced with spatial measurements, by meaning of 3D Impulse Responses measurements, as firstly reported in [5]. In that case a simple omnidirectional microphone was used and subsequently positioned in different axes positions. In further studies, binaural measurements were associated with 3D measurements, by meaning of both dummy head (Sennheiser) and 3D microphone (SoundField MkV).

THE MEASUREMENTS IN AN ANCIENT THEATRE

The Teatro dell’Aquila in Fermo represents a typical Italian Opera House. His historical background goes back until 1687, but perhaps since Roman time a theatre was operating in the same area. In 1791 the theatre was completely restored, but in 1826 in burned down. It was restored again in 1840, 1880, 1926, until last works in 1985-97.

The acoustical measurements in the theatre were conducted following ISO 3382 and Guidelines proposed by CIARM [2]. The sound source (an omnidirectional loudspeaker with flat frequency response) was put in the stage, whereas the receivers were moved in 21 positions, among audience and balconies. Furthermore, measurements were conducted in one position moving the sound source in the stage.

FIGURE 1. Setup of the acoustical instrumentation.

The SoundField microphone (MKV) and a dummy head (Sennheiser) were connected to a multi-channel...
sound-board (Layla, by Event). For each position, 8 different IRs were measured. A sine sweep signal was utilized, with a synchronous average of 5 measurements for each position.

RESULTS FROM MEASUREMENTS

From the measurements some particular results grew up. Firstly, a strong focalization was found in some position in the audience, far from the stage. Some musicians that reported some difficulties in those seats already found it out. Spatial acoustical parameters, like LE and IACC, were measured. Besides, results from dummy head (Sennheiser) and the microphone (SundField) were compared. A remarkable difference was found out, due to the absence of the diffraction effect of the head during the measurements with the SoundField.

The measurements revealed a proper characterization of sound field for speech and opera, since reverberation time was slightly low at mid frequencies. Considering energetic parameters, like Clarity and Center time, some late strong reflections were found especially in the middle of the audience, coming from the ceiling and the marble panels covering the rear walls. However, the values of clarity in the other positions and in the balconies revealed a suitable value for opera and speech, whilst for music an acoustic chamber could improve sound quality in the stage and slightly improve early reverberation time in the audience.

ACKNOWLEDGMENTS

The authors wish to thank Roberto Tascini for his help during the acoustical measurements and subsequent data analysis.

REFERENCES

2. CIARM, Guidelines for acoustical measurements inside historical opera houses, Ferrara, 1999
Room Acoustics Measurements at the Royal Opera House, London

J. P. Newton BSc(Hons), MIOA

Arup Acoustics, Parkin House, 8 St Thomas Street, Winchester, Hampshire, SO23 9HE, England

The redevelopment of the Royal Opera House, Covent Garden, London, UK provided new production and rehearsal facilities for the Royal Ballet and Royal Opera companies. As part of the works the heritage-listed auditorium has been substantially refurbished. Measurements of the room acoustic were made before, during and after the refurbishment works. An overview of the changes to the fabric of the auditorium, details of the measurements and a summary of selected results are presented in this paper.

INTRODUCTION

The auditorium of the Royal Opera House, Covent Garden, London is listed by the UK government as a building of exceptional architectural importance. Originally built in 1858, the building was extensively redeveloped over a three-year period culminating in its reopening at the beginning of December 1999.

The works included increasing the total capacity (seating and standing) from 2257 to 2366, full refurbishment of the auditorium (including new floors, walls and seating), new technical installations and the introduction of a ventilation system to provide comfort cooling.

The acoustic of the auditorium prior to the refurbishment works has been discussed in various texts [1,2] and was considered reasonable, good in many seats. The sound was clear, but lacking in reverberance and warmth.

The acoustic aims of the refurbishment works were to retain the positive aspects of the sound, but to make modest improvements to the deficiencies where possible.

REFURBISHMENT WORKS

Owing to the heritage-listed nature of the auditorium, any changes had to be carefully integrated and be in harmony with the original design. The works to the main auditorium offered some opportunity for acoustic improvements to be made. Changes to the fibrous plaster dome were ruled out, but the floor, walls, box partitioning and amphitheatre ceiling were all re-engineered to reduce low frequency absorption. All carpet was removed and the box partitions cut back to allow better sight- and sound-lines. More details of the acoustic changes are given in [3].

MEASUREMENTS

In order to establish the acoustic ‘starting point’ for the renovation works, Arup Acoustics undertook subjective listening tests and measurements of the existing auditorium acoustic in November 1995. The impulse response at a number of locations in the auditorium (in both unoccupied and occupied states) was derived from recordings of a pistol shot. Source locations were mid stage, forestage, and pit (first violin). Analysis was carried out using the MIDAS system and included EDT, T30, C80, D50, and G. Summary results for T30 are given in Figure 1.

FIGURE 1. Average T30 during different phases of the redevelopment.

Measurements of two types of the existing auditorium seating, from the stalls and the amphitheatre, were made in an independent laboratory. The results of these measurements were used to specify the acoustic requirements for the new seating. Arrays of the replacement seats were tested at the same laboratory in both occupied and unoccupied states.
Other measurements that were carried out as part of the design development process were as follows: sound power level measurements of the under seat ventilation diffusers (designed to achieve PNC 15); house lighting including transformers; and production lighting and dimmer combinations. Whilst the latter influenced the purchase of some production lighting, a greater problem in the achievement of low noise levels in opera houses is that of cooling fans. Whilst the mechanical and electrical systems achieved a noise level of PNC 15 throughout the auditorium, fans on production lighting has lifted this level to PNC 20+3.

In July 1999 a second set of measurements were made in the auditorium. The flooring and most of the finishes were complete, but no seats had been installed. Measurements were taken with the fire curtain as low as it was possible at the time of the measurements to decouple the large flytower volume from the auditorium. Subjectively this was achieved, despite a gap of around a metre between the fire curtain and the proscenium. The impulse response at two locations was derived from recordings of the room’s response to a swept sine signal played through an omnidirectional loudspeaker. Analysis was carried out using Matlab algorithms. The T30 results are included in Figure 1.

In order to assess the auditorium prior to opening, a further set of measurements were made in the unoccupied auditorium in October 1999. The measurements were carried out at 19 locations (the same as those before refurbishment) for three sources – forestage, mid-stage and pit. The measurements yielded surprisingly high values for T30, as can be seen in Figure 1. A possible explanation may have been the coupling effects of the auditorium to a very large (40,000 m³) flytower with only a little scenery on stage (and a little flown at high level). The measurements with the fire curtain down, however, also showed longer T30s than expected.

No further objective measurements were possible before the building opened. The response of conductors and subjective listening tests during the first rehearsals and performances suggested that the acoustic had changed, and that the changes were positive.

A definitive set of measurements was finally completed in June 2000. The measurements were conducted with a set on stage, and other soft hangings at high level in the flytower. Using the swept sine source, measurements were made in general accordance with the procedure detailed by C.I.A.R.M [4] at 17 seating locations and two pit locations with sources at locations on the stage and in the pit. Analysis was performed using Matlab algorithms to determine EDT, T30, C55, C90, D50, G and LEF (using a soundfield microphone).

It is interesting to note that the measurements taken with the auditorium and flytower decoupled and coupled tie in closely with established theory for the effect on reverberation time of coupled spaces [5].

![Figure 2](image-url)  
**FIGURE 2.** Measured reverberation times showing effect of coupling of auditorium to flytower.

**CONCLUSIONS**

Based upon the unoccupied T30 measurements given in Figure 1, it may be concluded that the acoustic aims have been achieved.

**ACKNOWLEDGMENTS**

The author would like to thank the staff of the Royal Opera House for their cooperation in the measurements and colleagues Joe Solway and Ben Cox at Arup Acoustics for their assistance and support.

**REFERENCES**


Stage set and acoustical balance in an auditorium of an opera house

Jan-Inge Gustafsson, Georgios Natsiopolos

Akustikon AB, Baldersgatan 4, S-411 02 Göteborg, Sweden

The acoustical balance in an auditorium of an opera house is to a large extent dependent upon the stage set. This is especially important when the reverberation time is relatively long so that the hall is fairly undamped. A lot of measurements have been carried out at The Gothenburg Opera with different stage sets. They clearly show the difficulty in describing the acoustics in an opera hall and also the importance of the design of the stage set considering the acoustics.

INTRODUCTION

The acoustics of an opera hall is not as easy to describe as the acoustics of a concert hall. It depends on the fact that the opera hall contains of two different rooms, the stage and the auditorium, which are coupled to each other. The acoustic situation on stage can be very different depending on the design of the stage set. This is of course of most importance for the singers on stage but even the orchestra in the pit will feel the influence. Long reverberation time means a low clarity, especially from the pit where the direct sound is shielded. With the right treatment of the stage set, it might be possible to achieve a relatively high clarity from the singers on stage. This will of course give a pretty good speech intelligibility. However this can give a poorer balance between singer and orchestra, depending on the fact that the voice will lack of "singing tone" and will be perceived as thin in comparison to the orchestra sound.

MEASUREMENTS

Since the opening of the Gothenburg Opera, 1994, a lot of acoustical measurements have been carried out with different stage sets. All the measurements, which are shown here, have been made without audience. The influence of the audience in the Gothenburg Opera is not very big and the reverberation time will decrease with only about 0.1 sec. All the measurements have been carried out with measurement system MLSSA and with an omni-directional loudspeaker. The microphone position has always been in the same height above the chair. The omni-directional source will not correspond to a human voice but is still very good to describe the acoustics as the singers will sing in different directions.

The reverberation time is less dependant on the stage set than other acoustic criteria. This is valid for source positions on stage as well as positions in the pit. As seen in fig. 1, Cosi fan tutte is an exception. In this opera the acoustic curtains were rolled down and the reverberation was decreased. Anyhow the stage set gave a clear elongation of the reverberation in higher frequencies.

Clarity is a criteria, which of course is of big importance in an opera hall. A long reverberation time has the disadvantage that the clarity is relatively low. In the measurements, which are shown here the measurement positions m1 - m4 are in the stalls and m11 is on the first balcony. The source position s1, is 2m from the stage front, s2, 6 m from the stage front, s5 10 m from the stage front and s3 is in the pit. S7 is a stage position on a bridge above the front part of the pit. In addition to the clarity-values (C80), the Definition (Deutlichkeit) -values (D50) are shown, which may be of interest for speech but also for singing. A very high Definition value (in long reverberation), may however indicate a thin sound.

Figure 1: Reverberation time with different stage sets.
Deutlichkeit 1 kHz, source position s2 (except Cosi fan tutte - src pos s7)

Figure 2: Definition with different stage sets.

Clarity 1 kHz, source position s3

Figure 3: C80 with diff. stage sets. Source in the pit.

In the diagrams you can see that the Definition values may vary within 35 % for different stage sets in one position. The variation between different source positions is less, normaly 10 - 15 %. In Carmen the C80 and D50 values are relatively low. During the performance they were higher depending on the acoustic curtains, which were down and the reverberation time was decreased to 1.4 seconds. Carmen which contains a lot of speech did work very well. One interesting reason may be that the difference of clarity between stage and pit was rather small, which might be explained by the fact that the position of the pit was in a 0.5 m higher level than the other. A higher level of the pit may give a better balance between stage and pit depending on a better contact with the singers. The orchestra will be more flexible and follow the dynamics of the singers and the orchestra will be felt as more integrated to each other. In a reverberant opera hall with an acoustically damped stage this might be a problem.

Cosi fan tutte was performed with reduced reverberation, which also is the case for the measurements. Considering this the clarity was not very high and was obvious low from source position s7 in front of the orchestra. The stage designer was wrong when he thought that the clarity should increase when the singers came closer to the audience.

The dependence of the stage set on the sound level is of course very interesting. It must be said that these measurements are very sensitive which means that some of the differences are depending of the accuracy of the measurements. In the diagram below you may compare the sound level in different frequencies for four different stage sets (the sound source is not normalised). The set of the Lohengrin and MacBeth2 has partly suspended ceiling, which also support the sound level. In MacBeth2 the set consists of a lot of frames with thin projecting cloth. The reflection of this can not be very good at lower frequencies which also can be seen in the measurements. Anyhow it is pretty good. In Carmen the sound level increases a lot in higher frequencies and in this position there is a reflecting element situated relatively close to the source.

DISCUSSION:

These measurements clearly show the difficulty in describing the acoustics of an opera hall without defining the circumstances on stage. They also show the importance of the design of the stage set considering the acoustics. It is our opinion that the design of the set must be more careful according to the acoustics in a hall with longer reverberation. Further on the clarity on stage might not be too high in comparison to the clarity in pit.
Mechanism of Sound Absorption by Seated Audience in Halls

Noriko Nishihara*, Takayuki Hidaka*, and Leo L. Beranek†

* Takenaka R&D Institute, 1-5-1, Otsuka, Inzai, Chiba 270-1395, Japan
† 975 Memorial Drive, #804, Cambridge, MA 02138, USA

Abstract: This paper deals with the cause of the differences in the audience absorption measured in a reverberant chamber and in actual halls at low frequencies. A probability density function of the incident angles of the sound rays that impinge on the audiences, $P(\theta)$, is calculated for each case. Using a unique method, the sound absorption coefficient of a seated audience is determined in an anechoic chamber and from it, the “effective” statistical absorption in real field, $\alpha_{\text{field}}$, is derived. As a result, it is shown, using this method, how the absorption coefficients of an audience can be predicted to agree with those measured in a real hall.

INTRODUCTION

Several studies on sound absorption by seated audiences have been published [2-5]. In general, they have concluded that the reverberation times in an actual occupied hall cannot be predicted satisfactorily from absorption coefficients measured in a reverberant chamber. From the comparison of existing methods to predict RT with measurements in six halls, the Kath & Kuhl method [1,2], which uses a reverberant chamber for the measurements, was most accurate at mid-frequencies, while it had large discrepancy at low frequencies. This paper attempts to show the reason for this low frequency discrepancy and to recommend a means for eliminating it.

PHYSICAL DIFFUSION IN A ROOM

The absorption coefficient of a seated audience measured in a reverberant chamber, $\alpha_s$, will equal to the statistical absorption coefficient, $\alpha_{\text{stat}}$, if the diffusion of the sound field is perfect:

$$\alpha_s \equiv \alpha_{\text{stat}} = \frac{1}{2} \int_0^{\pi/2} \alpha(\theta) \cos \theta \sin \theta d\theta$$

Taking into account of the imperfect diffusivity in an actual room, the corresponding absorption coefficient $\alpha_{\text{field}}$ in the field can be defined as:

$$\alpha_{\text{field}} = \int_0^{\pi/2} P(\theta) \cos \theta \sin \theta d\theta$$

where $P(\theta)$ is a probability density function. Figure 1 shows the example of $\cos \theta P(\theta)$ for a reverberant chamber and a typical shoebox hall, which is obtained by CAD models and ray tracing method. The expected values in actual occupied halls are different above 50º in the vertical plane from those in a reverberant chamber with ideal diffusion.

OBLIQUE ABSORPTION

Table 1 is a comparison of $\alpha_s$, $\alpha_{\text{stat}}$, and $\alpha_{\text{field}}$ determined in the reverberant chamber for seated audiences, where the $\alpha_{\text{field}}$ is given by the discrete form:

$$\alpha_{\text{field}} = \frac{1}{\pi} \sum_{\theta} \alpha(\theta) \cos \theta \sin \theta / \sum_{\theta} \cos \theta \sin \theta$$

where $\alpha(\theta)$ was measured using 20 chairs with stiff barriers around them. This result indicates the sound field in the reverberant chamber is close to perfect diffusion.

The same comparison was carried out in five concert halls. In this case, “modified” edge effect around audience corresponding to each sound field must be taken into account. After Waterhouse [6], the mean squared sound pressure $\langle p^2 \rangle$ at a point located at a vertical distance $x$ from a rigid surface in a perfectly diffuse sound is written by

$$\langle p^2 \rangle \approx \frac{1}{2\pi} \int_0^{\pi/2} \int_0^{\pi/2} \cos(2\pi x \cos \theta) \sin \theta d\theta d\phi$$

so that the incremental value of squared sound pressure from 0 to $x$ becomes.

COEFFICIENT OF AUDIENCE

A new type of measurement of oblique absorption, $\alpha(\theta)$, was executed for a seated audience in an anechoic chamber. Using 17 measuring points, $\alpha_i(\theta_j)$ were obtained as the representative values of 9 elements (Fig.2). Then, the absorption coefficient, $\alpha(\theta)$, for the hypothetical horizontal plane in Fig.3, is defined by:

$$\alpha(\theta) = \sum_{\theta} \alpha(\theta) \cos \theta / \sum_{\theta} \cos \theta$$

where $S_i$ is the area of each part of the seated audience. The $\alpha(\theta)$ increases as the incident angle approaches grazing incidence and this characteristic resembles that of the behavior of a porous material with rigid backing (Fig.4).
Contrariwise, Eq.(5) should be modified by replacing \(\sin \theta\) term with \(P(\theta)\) in a hall, similar to the case of derivation of Eq.(2), therefore one obtains,

\[
\Delta p^2 \propto \int \left[ \frac{1}{(p_{in}^2)} - 1 \right] dx \approx \frac{\lambda}{8}, \quad \chi \lambda
\]

Based on numerical calculations for five halls, the \(\Delta p^2\) was found to be ca. \(\lambda/3\) in average. If this is converted to the acoustical audience area including edge effect for RT calculation, those at 125Hz and 250Hz coincides with the total floor area and the geometrical audience area with 0.5m addition defined by Beranek [3], respectively.

In Table 2, the predicted absorption coefficients of the audience in each hall were compared with the actual values of \(\alpha_{\text{hall}}\) obtained from the measurement of RT using the Sabine equation. It is seen that they are in satisfactorily agreement with actual values.

**CONCLUSIONS**

![Fig. 1](image1.png) Typical example of \(\cos \theta \cdot P(\theta)\) in median plane. The black dots mean the average distribution at intervals of 15 degrees.

![Fig. 2](image2.png) Occupied area per seated person and the definition of the representative measuring points in each part.

![Fig. 3](image3.png) Definition of the incident angle \(\theta\) and the hypothetical horizontal plane.

Measurements of low frequency absorption coefficients of an audience in a reverberant chamber differ at low frequencies from those measured in real halls. The reason is shown to be caused by the uneven diffusivity in actual halls. By using the effective statistical absorption coefficient and including the corrected edge effect, \(\lambda/3\), it was found that the reverberation time at low frequencies in a hall can be calculated within acceptable accuracy.

**REFERENCES**


**Table 1** Comparison of \(\alpha_s\), \(\alpha_{\text{stat}}\) and \(\alpha_{\text{field}}\) for the reverberation chamber.

<table>
<thead>
<tr>
<th>Hz</th>
<th>125</th>
<th>250</th>
<th>125</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha_s)</td>
<td>0.26</td>
<td>0.44</td>
<td>0.43</td>
<td>0.64</td>
</tr>
<tr>
<td>(\alpha_{\text{stat}})</td>
<td>0.26</td>
<td>0.56</td>
<td>0.35</td>
<td>0.65</td>
</tr>
<tr>
<td>(\alpha_{\text{field}})</td>
<td>0.27</td>
<td>0.56</td>
<td>0.35</td>
<td>0.66</td>
</tr>
</tbody>
</table>

**Table 2** Comparison of \(\alpha_{\text{hall}}\) and \(\alpha_{\text{field}}\) for five halls.

<table>
<thead>
<tr>
<th>Hall Type</th>
<th>Hz</th>
<th>(\alpha_{\text{hall}})</th>
<th>(\alpha_{\text{field}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamarikyu Asahi Hall</td>
<td>125</td>
<td>0.48</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>0.73</td>
<td>0.69</td>
</tr>
<tr>
<td>Boston Symphony Hall</td>
<td>125</td>
<td>0.52</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>0.71</td>
<td>0.61</td>
</tr>
<tr>
<td>Vienna Musikvereinssaal</td>
<td>125</td>
<td>0.47</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>0.64</td>
<td>0.68</td>
</tr>
<tr>
<td>TOC Concert Hall</td>
<td>125</td>
<td>0.41</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>Mitaka Concert Hall</td>
<td>125</td>
<td>0.48</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>0.63</td>
<td>0.63</td>
</tr>
</tbody>
</table>

![Fig. 4](image4.png) \(\alpha(\theta)\) at the hypothetical plane of a seated audience for Musikvereinssaal (solid line) and Burgtheater (dotted line) model.
The delayed Phantom of the Opera

Tor Halmrast

Statsbygg, p.b. 8106, Dep, N-0032 Oslo Norway, tor.halmrast@statsbygg.no

False localisation/image shift is observed in many otherwise excellent opera halls, from San Francisco through Europe to St. Petersburg. Such “phantom sources” are often considered as “something we should just avoid” in acoustic design, and the effect is not covered by common room acoustic criteria. However, a controlled amount of false localisation might be useful, to broaden the apparent orchestra width/height, and: if we did not have any false localisation, parts of the audience would not hear most of the treble part of the opera orchestra. This paper focuses on a special version of disturbing “phantom-sources” that not only gives false localisation, but also a rhythmic distortion (“delayed Phantom of the Opera”) between the bass and treble instruments of the orchestra. This disturbing effect was observed at some seats in the (otherwise excellent) Munich Opera.

IMAGE SHIFT=PHANTOM

An image-shift/phantom-source describes that a sound is not perceived to arrive from its real localisation (see Barron [1]). Such false localisations are commonly reported for high pitched instruments in orchestra pits. Actually, most of the sound from these instruments should not be heard in the stalls of an opera house, as most of the audience do not see them.

Meyer [2] gives interesting results of how the treble part of the orchestra is reduced in the stalls of an opera house. However, these results do not indicate direction and time delay of the treble components received.

In order to set the acoustic criteria for the new opera in Oslo, we visited a number of opera houses, from S. Francisco, Metropolitan through Europe (Covent Garden, Bastille, Lyon, Frankfurt, Munich, Berlin, Dresden, Gothenburg, Helsinki), to St. Petersburg (Kirov). In all these houses we observed some kind of false localisation from the orchestra. The impression of this effect ranged from “perhaps OK for most of the public” to “problem”, but on the other side: “excellent!”, indicating that the false localisation actually gave a needed “broadening of the apparent orchestra source width and horizon”. Most of these opera houses are covered in literature on acoustics, but without much comment on “false localisation”.

Okano [3] shows investigations of image shift, mostly for concert halls and for symmetrical situations. We observed that perceived false localisation in opera houses are often far from symmetrical, even for seats close to the centre line of the hall, this also due to the asymmetrical position of the orchestra in the pit.

Svensson [4] gives a model for investigation of the diffraction of the orchestra due to the pit-rail, used by Dammerud [5]. This confirms why treble instruments do not “climb over the pit rail as easily as the bass”.

TYPICAL TYPES OF PHANTOMS

Typical time delay $\Delta t$ and angle of arrival $\Phi$ (clockwise) of “image shift” from an opera orchestra in the pit are given for typical seats to the right, 2/3 back in the stalls of horse shoe shaped opera halls of moderate size.

1) From a low reflector over the proscenium $\Phi=0^\circ, \Delta t=ca 2 - 10ms$. The “Apparent Source” of the orchestra is raised, almost as if the orchestra appears to be situated on the stage. Not noticeable as a “phantom source” for most listeners, but might disturb the stage/pit balance and the ability to discriminate the vocal line. For seats at the rear of stalls, the $\Delta t$ might be as small as to give “Box-klangfarbe” [6].

2) From the proscenium side-walls $\Phi=15^\circ, \Delta t=ca 15-20ms$, typically from upper parts of the walls between proscenium walls and ceiling/reflector (proscenium splay), or from “wedges” on these surfaces (Gothenburg, Helsinki, and Bastille, with longer $\Delta t$).

3) From frontal parts of (curved) sidewalls $\Phi=15-30^\circ, \Delta t=ca 10-20ms$. (S. Francisco, Metropolitan etc). If one forgets that the orchestra should be perceived from the pit, some phantom sources of this type are not always that annoying. Rhythmically, the reflections in 2) and 3) are almost in time/direction with the “bass/rhythm” from the pit. Such reflections might give an excellent broadening of the apparent orchestra source width (Dresden) but might give very strange effects like “flutes hanging high up along the sidewalls or snare drums under the balcony”.

4) From the middle part of sidewalls $\Phi=75-120^\circ, \Delta t=ca 25ms$. Often such phantom reflections have passed more than one surface. Example: A source in the orchestra pit is reflected from the underside of the first balcony, then from the side wall and down to the stalls. This often sounds like a bad loudspeaker, due to the limited high-frequency range transmitted.

When the Munich Opera was rebuilt, the acoustic consultant [7] proposed diffusing elements on the sidewalls at floor level of auditorium (stalls), but this was not possible. The overall acoustic impression of this opera house is excellent, but there have been some remarks of focusing for seats at the sides at the back of the stalls. We had the opportunity to examine these seats, and found that they did not only give focusing, but also a clear rhythmic distortion. The bass (diffracted over the pit-rail) and the treble was not received “in rhythm”. At these seats we received a
divided orchestra: Bass from the pit, and Treble arriving later from the side/back, with a time delay that gave severe rhythmical problems (Bizet: Carmen, Troubadour-March). A computer study shows that \( \Delta t \) for these sideways reflections in Munich are clustered between 23-25 ms.

This is shorter than the 50ms often referred to as the integration time of our hearing organ/“echo-limit”, but still dramatic, as it splits the orchestra into 2 layers, and gives a delayed Phantom of the Opera.

In musical notation Bizet’s up-tempo-march was perceived almost like this:

where the upper staff indicates the perceived delayed phantom (picc.flute/tambourine etc.) which should be “in rhythm” with staff 2. The fact that the delayed / treble part (“staff 1”) of the orchestra was received from the back/ side, \( \Phi=90-120^\circ \), made our listening experience even more disturbing.

5) From sidewalls/rear walls close behind the listener (San Fransisco, Nat.Theatre Oslo).
\( \Phi > +/- 130^\circ, \Delta t= 5-20\)ms. Such Phantoms might give some disturbances for orchestra, but on the other hand extra clarity for vocal/speech, some uncertainty about localisation and Box-Klangfarbe [6].

6) Reflections from the opposite side of the hall, Echos \( \Phi=-(90-120)^\circ, \Delta t= >50 \) ms. (Kirov, St. Petersburg), and for some seats in Covent Garden. Such echoes will not be discussed further in this paper.

**COMPUTER MODELLING OF PHANTOMS**

The sidewalls of the Munich Opera are almost circular. This gives a problem for computer modelling. An overall model, with a small number of surfaces might give good results for most common acoustic criteria, given the right diffusion/scattering coefficients.

However, to visualise the observed focusing effect, we need to divide the sidewalls into many small surfaces, to show the direction of the focusing “phantom” observed in the Munich Opera.

This model gives some 20 reflections clustered between 23-25 ms (shown in the “echo-gram” above). However, such a detailed room-model for all surfaces might not give correct results for the overall acoustic criteria.

**CONCLUSION**

Phantom sources from the orchestra pit are common in most opera houses, and should be controlled as part of the acoustical design. A controlled broadening/ heightening of the orchestra “apparent source width/height” might be beneficial. Image shifts of single instruments and specific frequency ranges should however be avoided, especially if received from the side/rear, giving rhythmic distortion.

**REFERENCES**

   JASA 106, 2331(1999)
6.Halmrast, T: “Orchestral Timbre, Comb-Filter Coloration from Reflections”
7) Mueller H: Private conversation
Western Culture and Tradition are symbolized by Topt curves in Fig.1a especially in the case of concert halls where the effect of rich reverberation is required. Besides those, an interesting and well designed guide was presented by A.J.Jones as in Fig.1b.

Linkage of Factors Connecting Building to Acoustical Impression

It is true that the reverberation time is not the unique factor for room acoustical design. It is still important and meaningful.

The idealized time profile of reverberant sound shown in Fig.2 can be discussed using existing equations (1a) and (2a). Empirical equations (3) and (4) have been introduced in addition after supplemental studies. Finally the mutual relationship of factors is arranged between building condition and acoustic impression as in Fig.3.

The average sound absorption coefficient $\bar{\alpha}$ and the stationary state level $L_{rev}$ calculated in relation to the optimum reverberation time value, in addition the quantity of reverberation $L_{qr}$ was calculated using the $L_{rev}$ and the Topt values. The results show that the Topt value for concert halls can hardly be related to any factor in a simple way while in case of radio or TV studios that can be related to a certain fixed $\alpha$ or $L_{qr}$ value and that the existing famous halls have already come nearly to the upper limit of the size if a pleasant impression of a rich reverberation is required.

On the Guide to Optimum Values of Reverberation Time

S. Nakamura

1-30-2-406 Unomori Sagamihara 228-0801, Japan

The average sound absorption coefficient $\bar{\alpha}$ and the stationary state level $L_{rev}$ calculated in relation to the optimum reverberation time value, in addition the quantity of reverberation $L_{qr}$ was calculated using the $L_{rev}$ and the Topt values. The results show that the Topt value for concert halls can hardly be related to any factor in a simple way while in case of radio or TV studios that can be related to a certain fixed $\alpha$ or $L_{qr}$ value and that the existing famous halls have already come nearly to the upper limit of the size if a pleasant impression of a rich reverberation is required.

On the Guide to Optimum Values of Reverberation Time

S. Nakamura

1-30-2-406 Unomori Sagamihara 228-0801, Japan

The average sound absorption coefficient $\bar{\alpha}$ and the stationary state level $L_{rev}$ calculated in relation to the optimum reverberation time value, in addition the quantity of reverberation $L_{qr}$ was calculated using the $L_{rev}$ and the Topt values. The results show that the Topt value for concert halls can hardly be related to any factor in a simple way while in case of radio or TV studios that can be related to a certain fixed $\alpha$ or $L_{qr}$ value and that the existing famous halls have already come nearly to the upper limit of the size if a pleasant impression of a rich reverberation is required.
Topt Related Value of Factors

The difference in design concept is clearly described between studios and halls. Acoustical consistency is found only in the case of studios where the Lqr value does not depend on the room volume.

Some ideas are suggested by the guide presented by Jones. Both ends of curves can be related to Lrev and $\alpha$ respectively.

Acoustical Design with Fixed $\alpha$ Values

$Lqr(V)$ curves in Fig.7 have been reformed by replacing $V$ and $Lqr$ with $T$ and normalized $Lqr$ as in Fig.8. Then it is found that the $Lqr$ value is considered to be fixed in a range around the top as $0.43 \leq T \leq 2.0$ s if the deviation of as much as 3 dB is allowed.

That may support what the experts are observing in acoustic design practice.

Conditions for Useful Reverberation

As in Fig.9 three limiting conditions have to be considered. The $Lqr(=25dB)$ curve would give the lower limit since it is the border of "live" and "dead". In contrast to that the $Lrev$ and the $T$ curve which give the upper limit should naturally be shifted up- and downwards depending on the sound power of the source and or the use of the room.

Thus the unmasked zone represents the condition expected to provide a pleasant effect of reverberation.
Subjective Preference for Sound Sources Located on the Stage and in the Orchestra Pit of an Opera House

S. Sato\textsuperscript{a}, H. Sakai\textsuperscript{a}, Y. Ando\textsuperscript{a}, N. Prodi\textsuperscript{b} and R. Pompoli\textsuperscript{b}

\textsuperscript{a}Graduate school of Science and Technology, Kobe University, Rokkodai, Nada, Kobe 657-8501, Japan
\textsuperscript{b}Faculty of Engineering, University of Ferrara, Italy

The present study investigates whether or not the subjective preference theory can be applied to the sound field in an opera house. The subjective preferences for different combinations of source positions on the stage and in the orchestra pit of an opera house were judged from specific seats using the paired-comparison method. The relationship between the scale values of subjective preference and orthogonal physical factors obtained by acoustical measurements was examined using factor analysis, and the results show that the preference theory is applicable.

INTRODUCTION

The theory of subjective preference allows us to calculate the scale value of subjective preference for a sound field, in terms of four orthogonal acoustical factors: listening level (LL), initial time-delay gap between the direct sound and the first reflection ($\Delta t_1$), subsequent reverberation time ($T_{\text{sub}}$), and magnitude of the interaural cross-correlation function (IACC). These factors were identified from the systematic investigation of sound fields using computer simulation and listening tests (paired-comparison tests) [1]. The subjective preference theory has been validated by tests in concert halls [2, 3].

In our experiment, we studied whether or not the theory of subjective preference can be applied to the sound field of an opera house.

PROCEDURE

The opera house used in the experiments was the Teatro Comunale in Ferrara, Italy (Figure 1), and "Tormento" by P. Tosti was used as the source signal. The vocal (soprano) and piano accompaniment were channeled separately. Two loudspeakers reproducing the vocal signal were located on the stage and two, reproducing the piano signal, were placed in the orchestra pit (Figure 2).

Paired-comparison tests using four sound sources in various combinations (Table 1) were conducted to obtain scale values of subjective preference. Forty-seven listeners participated in the experiments. The listeners were divided into ten groups and were seated at specific seats. As the source locations of the music shifted, listeners were asked to give their preferences.

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
<th>Condition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit</td>
<td>Front</td>
<td>Front</td>
<td>Rear</td>
</tr>
<tr>
<td>Front</td>
<td>Pit</td>
<td>Front</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear</td>
<td>Front</td>
<td>Rear</td>
<td>Front</td>
</tr>
<tr>
<td>Rear</td>
<td>Front</td>
<td>Rear</td>
<td>Front</td>
</tr>
</tbody>
</table>

FIGURE 1. Plan of Teatro Comunale in Ferrara.: Listener locations.

FIGURE 2. Configuration of the loudspeaker settings.
MULTIPLE DIMENSIONAL ANALYSIS

The relationship between the scale values of preference and physical factors obtained by acoustical measurements were examined using factor analysis [4, 5]. The outside variable to be predicted was the scale value of preference. The explanatory variables were: (1) LL, (2) IACC, (3) $t_{IACC}$, (4) $\Delta t_1$ for the pit source, (5) $\Delta t_1$ for the stage source, (6) $T_{sub}$ of 1 kHz for the pit source, and (7) $T_{sub}$ of 1 kHz for the stage source.

The LL scores increased with a decrease in the LL. For the IACC, the scores decreased with an increase in the IACC. The effect of the $t_{IACC}$ on the scores was minor because all of the loudspeakers were located on the center axis of the hall and the listeners faced the center of the stage. The scores of these three factors agree with those obtained for sound fields in a concert hall [3].

The scores of $\Delta t_1$ for the pit increased with a decrease in the $\Delta t_1$. On the other hand, the scores of $\Delta t_1$ for the stage increased with an increase in the $\Delta t_1$. For $T_{sub}$ on the stage and in the pit, the scores increased with an increase in the $T_{sub}$. The effects of the $T_{sub}$ on the scores were minor.

REMARKS

To determine whether the subjective preference theory can be applied to the sound field of an opera house, we used factor analysis to examine the relationship between the scale values of preference and the orthogonal physical factors. Our results show that the scores obtained using factor analysis are similar to those obtained from experiments in a concert hall. The scale values of preference can be calculated using the total scores obtained from factor analysis ($r = 0.86, p < 0.01$).

ACKNOWLEDGMENTS

The authors wish to thank the staff of Teatro Comunale in Ferrara for their cooperation during the experiment. The authors would also like to thank the students who participated in the experimental sessions and Mr. T. Hotehama for his helping with the acoustical measurements. This work was supported in part by a grant-in-aid for scientific research from the Japan Society for Promotion of Science.

REFERENCES


FIGURE 3. Scores for each category of factors obtained by factor analysis. $p$: partial correlation coefficient.
The influence of the simplified architectural model on the acoustical simulation results

S. Kouzeleas, C. Semidor

GRECO-ERIAC, Ecole d'Architecture et de Paysage de Bordeaux, 33400 Talence, France

The sometimes complex architectural shape of halls creates modelling difficulties as the simulation computing systems need plane surfaces. In order to approach a perfect shape of curved surfaces, a big number of facets is necessary. This poses, as a consequence, computer memory problems which is the case of the horse shoe shaped Opera House with its richly decorated columns, balconies....... This paper compares the acoustical measurement results and the calculation results of a computer simulation software applied on several models (from the most simple till the most complex ones) of the Grand Theatre of Bordeaux.

INTRODUCTION

Most historical opera houses have curved shapes, both the inside geometry of the hall and the other architectural elements. During the modelling, in order to carry out the acoustical simulation calculations, we were forced to introduce simplifications as the software requires plane surfaces.

The best approach of curved surfaces necessitates a big number of facets. This often poses a problem for the computer program memories are limited. The here presented research on the Grand Theatre of Bordeaux is a good illustration of this type of problems. In order to compare the Reverberation Time measures and the calculated values for different hall configurations (open flytower and closed pit, open flytower and open pit and closed flytower and closed pit) with the Epidaure software several models were constructed under Autocad.

COMPARATIVE RESEARCH

Elaboration models

We compared each configuration listed above with the 4 hall models in all degrees of complexity (1-4). The different models are presented on Figure 1.

The model nearest to the actual hall shape possesses such a big number of flat facets that it necessitates to work on a half-hall. In this case a perfectly reflective plan closes the hall volume. For that reason a comparison is only possible if we put a central sound source on the stage.

Concerning the other models, the facet reduction due to the shape simplification, allows us to work on the entire hall. Figure 2 shows the reduction process.

Starting from model 1 we made the adjustment and as a consequence the material selection for all the models (see Table 1).

### Table 1. Materials properties

<table>
<thead>
<tr>
<th>Surface</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood 1</td>
<td>0.33</td>
<td>0.27</td>
<td>0.24</td>
<td>0.17</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.11</td>
<td>0.09</td>
<td>0.07</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Seats</td>
<td>0.15</td>
<td>0.30</td>
<td>0.37</td>
<td>0.43</td>
<td>0.40</td>
<td>0.38</td>
</tr>
<tr>
<td>Wood 2</td>
<td>0.03</td>
<td>0.04</td>
<td>0.08</td>
<td>0.12</td>
<td>0.12</td>
<td>0.20</td>
</tr>
<tr>
<td>Stage</td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

We can see in figure 4 the differences due to the form simplifications: the less facets the model possesses, the more the calculated RT 60 is small and as a consequence the expectation with regard to the reality will be incorrect.

### CONCLUSION

We were able to give prominence to the simplification role of the geometrical form of a hall model on the simulation calculations. We can imagine that the more we simplify the model, the more the predicting results will be incorrect.

### REFERENCES

Blending Voice Source and Temporal Factor of Sound Field by Selecting Different Singing Types

K. Kato and Y. Ando

Graduate School of Science and Technology, Kobe University, Rokkodai, Nada, Kobe 657-8501 Japan

An attempt is made here blending voice source of singing and the temporal factor of sound fields in a concert hall. A method to control the minimum value of effective duration \( \tau_{\text{e}} \) of running autocorrelation function (ACF) of voice source is proposed for a given sound field by proper choice of two different types of singing, “voce de finte” and “operatic singing”. The initial time delay gap \( \Delta t \) between the direct sound and the first reflection and subsequent reverberation time \( T_{\text{sub}} \) in the concert hall are usually fixed. The most preferred conditions of the temporal factors for a number of subjects were analyzed by Ando [1] to derive \( [\Delta t]_p = (1 - \log_{10} A) \tau_{\text{e}} \) and \( [T_{\text{sub}}]_p = 23 \tau_{\text{e}} \) where \( A \) is the total amplitude of reflections. Experimental analysis on \( \tau_{\text{e}} \) of sound source with five solo singers (tenor) in an anechoic room was conducted. The result of variance analysis yielded significant differences between these two types of singing to show that singers can control \( \tau_{\text{e}} \) of singing voice sources.

INTRODUCTION

Methods to select music or playing style for a given concert hall has received limited attention while there are many papers concerning improvements in hall designs. Here, a special notice is made to control physical parameters of sound source to blend sound source and sound fields, because the physical parameters in a given concert hall, the initial time delay gap \( \Delta t \) between the direct sound and the first reflection and subsequent reverberation time \( T_{\text{sub}} \), are usually fixed in a room.

Toma (1997), a conductor of a chorus group, suggested that “voce de finte” is proper to sing in a concert hall in which reverberation time is longer [2]. According to this types of singing, singers exhibit less singer’s formant than operatic singers [3]. Ando (1987) proposed that the most preferred conditions of the temporal factors for a number of subjects are approximately given by

\[
[\Delta t]_p = (1 - \log_{10} A) \tau_{\text{e}} \quad (1)
\]

\[
[T_{\text{sub}}]_p = 23 \tau_{\text{e}} \quad (2)
\]

where \( A \) is the total amplitude of reflections, \( \tau_{\text{e}} \) is the minimum value of the effective duration of the running ACF of sound sources [1].

Referring to these two theories, and the fact that \( \tau_{\text{e}} \) tend to be longer when the voice source contains less overtones, we assume blend voice source and temporal factor of sound field, if singers can control \( \tau_{\text{e}} \) of voice sources by proper use of these two types of singing: voce de finte and operatic singing.

The present study examines whether or not \( \tau_{\text{e}} \) of voice sources can be controlled by using these two different types of singing so as to show scientific effectiveness of Toma’s theory of singing.

PRIMARY STUDY WITH ONE SINGER

It is impossible to examine whether or not \( \tau_{\text{e}} \) of voice source of all music motifs can be controlled. Therefore, experimental analysis on \( \tau_{\text{e}} \) of sound source with a solo singer (tenor) in an anechoic room was conducted selecting some motifs which is easy to control the \( \tau_{\text{e}} \) of sound source.

Figure 1 shows four music motifs used in this experiment. Among them, E4 “oh” vowel and motif I were presented as motifs with a simple structure: the length of each note is longer than eighth notes, the musical intervals between neighboring sounds ranged within 2nd, and there exists no staccato or accent. Therefore, in these two motifs, types of singing would characterize physical parameters of the voice source. These voice sources by the singer were picked up by a microphone located 25 ± 1cm in front, and 5 ± 0.5cm on side of the singer’s mouth. The music tempo was maintained with the help of a visual metronome. Each music motif was sung ten times for each singing types.

1. E4 (330Hz) “oh” vowel
   ![E4 oh](image1)

2. Music motif I
   ![Music motif I](image2)

3. Music motif II
   ![Music motif II](image3)

4. Music motif III
   ![Music motif III](image4)

FIGURE 1. Music scores of four motifs
1. E4 "oh" vowel: Operatic Singing,  Falsetto
2. Music motif I: Operatic Singing,  Voce de finte

FIGURE 2. Example of cumulative frequency distribution of $(\tau_{\text{min}})$ obtained in 10 trials (for single subject AH).

**DISCUSSION AND CONCLUSION**

In this study, it was shown that singers can control $(\tau_{\text{min}})$ by using two different types of singing: voce de finte and operatic singing under certain conditions.

Thus, proper selection of these two singing types is useful method to realize blending voice source and sound field in a concert hall. This is attributed to the most preferred conditions depend on $(\tau_{\text{min}})$ of voice sources given by equations (1) and (2). For example, if the $\Delta t_1$ and $T_{\text{sub}}$ in a given concert hall are longer, use of voce de finte is effective. Reversely, if $\Delta t_1$ and $T_{\text{sub}}$ are shorter, choice of operatic singing is recommended.

However, use of different singing types for playing the same motif may not sometimes be realistic, since the singing types are almost determined by the essential nature of the music itself. Therefore, it would be better selecting proper motifs for sound field in advance.

In conclusion, a method to control $(\tau_{\text{min}})$ of voice source by choosing either of the two different singing types, “voce de finte” and “operatic singing” is proposed here so that blending voice source of singing and the temporal factor of sound fields in a concert hall is attained.

**REFERENCES**


**Table 1.** Range of $(\tau_{\text{min}})$ (Average ± Standard Deviation) for music motifs played by two different types (subject AH).

<table>
<thead>
<tr>
<th></th>
<th>Falsetto or Voce de finte</th>
<th>Operatic Singing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. E4 &quot;oh&quot; vowel</td>
<td>452 ± 109</td>
<td>47 ± 10</td>
</tr>
<tr>
<td>2. Motif I</td>
<td>49 ± 10</td>
<td>27 ± 7</td>
</tr>
<tr>
<td>3. Motif II</td>
<td>27 ± 8</td>
<td>25 ± 6</td>
</tr>
<tr>
<td>4. Motif III</td>
<td>32 ± 7</td>
<td>20 ± 5</td>
</tr>
</tbody>
</table>

The $(\tau_{\text{min}})$ of the running ACF obtained in 10 trials are listed in Table 1. Significant differences (probability $p<0.0001$) were observed in the case of E4 "oh" vowel and motif I, but in the other motifs. This suggests that it is easier to control $(\tau_{\text{min}})$ of the running ACF of E4 "oh" vowel and music motif I than the other music motifs. Figure 2 shows cumulative frequency distribution of $(\tau_{\text{min}})$ of these two controllable motifs.

**INDIVIDUAL DIFFERENCES**

Then, experimental analysis on $(\tau_{\text{min}})$ of sound source with five solo singers (tenor) was conducted in order to examine individual differences. The music motifs used in this experiment were E4 "oh" vowel and music motif I. As a result of one-dimension variance analysis, significant differences ($p<0.05$) between these two types of singing can be seen except for one case. This shows a possibility to control $(\tau_{\text{min}})$ by selecting one of the two different types of singing.

**REFERENCES**


Acoustic restoration of the “Teatro Comunale”
"Gioachino Rossini" in Pesaro

M. Facondini

This report describes some of the methods used in acoustic re-qualification during the restoration of the Teatro comunale “Gioachino Rossini” in Pesaro. In view of the particular architectonic complexity of the Italian-style theatre and considering the inevitable approximation of today’s available models of acoustic simulation, use has been made of mainly comparative criteria and measurements carried out during operations in order to evaluate the effective sound yield of the theatre with regard to the new covering materials foreseen by both the acoustic project and normative conformity. In particular, an in depth comparative analysis has been made with the Teatro comunale “Alessandro Bonci” in Cesena that, having numerous analogies with the Pesaro theatre, has been used as a reference model [1].

COMPARATIVE ANALYSIS

Designed in 1846 by the architect Vincenzo Ghinelli who had inherited the art and neo-classic style of his uncle Pietro Ghinelli [the original designer of the Rossini Theatre in 1818], the Bonci theatre has an architectonic structure rather similar to the Pesaro theatre. A similarity also to be found in the Rossini theatre interior that Vincenzo Ghinelli was appointed to renovate in 1854 carrying out “various additions to the building, inspired by progress in luxury and the desire for greater comfort” [2]. The interior volumetrics are very close and the finishings – by the same designer – have assured both theatres a very similar acoustic response that today allows us to make a reliable and extremely precious comparison for the acoustic re-qualification study of the Theatre [3].

Over time, however, the two buildings have undergone different destinies: while the Bonci theatre has remained intact thanks to the rigorous restoration carried out in 1996 that has maintained the original structure without damaging its famous sound yield, the Rossini theatre has been altered many times up to the last restoration going back to 1980 where furnishings in fabric were preferred for the boxes rather than restoring the original structure, in this way compromising the excellent sonority that, like all the works of Ghinelli, had rendered it famous.

The theatres possessed, therefore, analogous acoustic properties that in the case of the Pesaro theatre have unfortunately been lost. To understand better how the sound balance can be changed by restorations very distant from the original model, let us observe a number of parameters measured in both theatres under the same conditions: the differences are evident and can be easily read in the graph of impulse responses where the Rossini theatre shows a worrying scarcity of prime reflections.

The main problem is identifiable in the excessive absorption caused by the finishings of the boxes [heavy
fabric and wall-to-wall carpeting] that inhibits the natural propagation of the reflexes that make the sonority of the Italian-style theatre so characteristic.

In fact, from the acoustic point of view, the box behaves like a resonance cavity, open to one side: meeting rigid surfaces such as a wall, or moderately vibrating like wood, the energy progressively decreases, contributing to the increase in sound pressure and vibration. On the contrary, in the presence of absorbing materials such as these, the energy is precociously deadened, thwarting the resonance properties of the box itself that, therefore, cannot participate in the overall acoustic yield of the theatre.

**Measuring the boxes**

Being a significant restoration able to change the theatre’s sound yield radically and evaluating the new furnishings envisaged by the design, specific measurements were carried out within the boxes, substituting the traditional modelling based on the coefficients of theoretical absorption. For the simulation, two contiguous and communicating boxes of the 1\textsuperscript{st} order were observed that, excluding the flooring, were entirely covered with 2 cm wooden panels adhering to the lateral walls, the roof and the internal parts of the parapet. The instrument measures were then carried out under both conditions and then compared. This is what physically happened inside the boxes:

The comparison has furnished useful technical indications as well as interesting in depth historical information about the original acoustics of the Rossini theatre before the various ‘‘embellishing and decorative’’ interventions that have followed each other over the years. In this case there are small variations – all ameliorative even if limited to the study of only two boxes – that, however, need to be read and interpreted as an acoustic model to carry over into the overall theatrical setting. In fact, on a larger scale, taking all the theatre boxes into account, the contribution will be very much more evident, significantly increasing the outlined measurements that concur to positive change in the sonority of the Rossini theatre.

Once the restoration is completed, envisaged for May 2002, a final report will be presented with the results attained.

**BIBLIOGRAPHY**

Variable sound orchestra pit for the "Teatro Comunale" of Bologna

M. Facondini\textsuperscript{a}, L. Bignozzi\textsuperscript{b}

\textsuperscript{a} Studio Tecnico TanAcoustics, Via Gargattoli 23 – 61100 Pesaro Italy
\textsuperscript{b} SUONO VIVO S.r.l. Via Pitagora, 16/G – 35030 Rubano (PD)

Even though introducing an absolute innovation into the panorama of the historical Italian theatre, the variable sound orchestra pit is a technical solution in growing evolution and diffusion that has produced optimum results in numerous, recently constructed, European theatres. The possibility of optimising the balance of the timbre of the orchestra, as well as the sound balance between it and the singers on the stage, creates a tuning system able to correct significantly the overall yield of the music as a whole. This report describes the various phases of study and intervention in correcting the acoustics of the orchestra pit of the "Teatro Comunale" of Bologna, carried out in May 2000.

**INTRODUCTION**

The fundamental acoustic requirements of the orchestra pit, like the correct dimensions, the sound balance with the singers on the stage, the relationship between the covered and the uncovered areas, the diffusion and quantity needed to assure correct reciprocal audibility among the musicians, are aspects quite other than secondary in the setting of the overall sound quality of the theatre, so much so that often the sound level of the orchestra is considered too high to permit the correct audibility of the voices, and the main disturbance is usually identified in the excessive sound level of the brasses and the percussion instruments.\cite{1}. It is important to underline that the acoustic efficiency of modern musical instruments is certainly greater than those of even only 50 years ago. There are no studies published with respect to this but, normally, a modern trombone or clarinet produces sound levels of 5\,10 dB superior to the corresponding period instruments\cite{2}. Testimony to the minor sonority of the instruments of the past is the reminder that in many ancient theatres a resonance cavity used to be created, placed under the flooring of the orchestra pit to increase the sound level and, in this way, compensate the acoustic imbalance with the voices\cite{3}.

**Data analysis: audibility in the orchestra pit**

The measurements, made with an energy source, and taken in correspondence to the director’s podium, shows the rich reflections of the impulse response [Fig. 1]. while the frequency flow, made with stationary white noise, indicates an energy concentration identifiable at low frequencies between 63 and 125 Hz inclusive, shown in the graph.

[Fig. 1 Impulse response]

[Fig. 2 Frequency analysis]

The structural and dimensional characteristics of the orchestra pit generates, therefore, a series of stationary waves that trigger off a natural amplification of the lower sounds. Finally, the reverberation measurement confirms the presence of stationary waves at the lower frequencies that cause an anomalous increase in the slope of the curve between 63 and 125 Hz.
Variable sound orchestra pit

Acoustic correction was entrusted to a series of panels in milled wood based upon the combined principle of vibrating resonator-diaphragms. They carry out a phonono-absorbing function limited to the low frequencies without altering the timbre balance in the rest of the spectrum region. They can be positioned on the vertical walls, near the sections that are to be attenuated, or in correspondence with the parallel surfaces such as the balcony and the covering [Fig.3].

The panels are anchored with screws and release systems allowing quick modification of the acoustic characteristics of the pit. During orchestra rehearsals it will, therefore, be possible to carry out all the adjustments of adding, moving or removing absorbing elements until reaching the conditions considered optimal for the programmed performance. A further amelioration, available later, consists of a series of inclined panels (or an inclined balustrade) with a large-band reflexive acoustic function able to redirect part of the acoustic energy of the pit in favour of the singers on stage. In this way the double effect of withdrawing energy from the pit and restoring it as a sound "return" to the stage is obtained, facilitating the work of the singers.

Measurements

The panels were measured with three 10, 12 and 15 cm air-differentiated interstices to verify the efficiency in relation to the available occupied space of the pit. All the tests showed optimum values of absorption with an evident selectivity at low frequencies, typical of Helmotz resonators. Those of 10 cm were preferred because of their minor selectivity and minor encumbrance.

Conclusion

The positive opinion of the musicians showed a better timbre balance and greater facility in the dynamic control of the bass instruments, making performance easier. The graph illustrates the pit reverberations with all the absorbers in place, but there are numerous intermediate acoustic variants with the removal of one or more elements.

BIBLIOGRAPHY

A new Opera House in Oslo

T. Halmrast

Statsbygg, p.b. 8106, Dep, N-0032 Oslo Norway, tor.halmrast@statsbygg.no

This poster will give information about the new Opera house under design in Oslo, Norway, including model-photos and drawings up to the time at the ICA conference.

A NEW OPERA HOUSE IN OSLO

The Norwegian Opera Company has been located in a lyric theatre since its opening in the 1950’s. A new opera house in Oslo is important not only for opera lovers, but also for the development of a part of the city now covered half by a traffic machine, half by water.

The Space Allocation Program for the new opera house calls for a Main Auditorium (1300-1400 seats) with a traditional, more or less “horse-shoe-shape” and a long reverberation time and detailed specifications about early reflections, a Small Flexible Auditorium (400 seats), an Opera Rehearsal Room and an Orchestra Rehearsal Room (both open to the public), and an Informal Performance Space in the foyer, in addition to rehearsal rooms for ballet, opera and musicians, workshops, offices etc.

INTERNATIONAL ARCHITECT COMPETITION

The international architect competition gave 240 entrees. They were all presented at a large open exhibition where people actually stood 3 hours in line! When opening the anonymous envelopes, it was found that about 1/3 of the competitors specifically mentioned that they had used an acoustic adviser for the architectural competition. This means a huge amount of acoustic knowledge.

ACOUSTICAL BRIEF

The poster will give information about the detailed acoustic briefs given by Statsbygg both for the architectural competition and for the detailed tender for acoustic consultant, which received interest from acousticians from all over the world.
ONGOING PLANNING

The poster will give information about the ongoing planning, with the winner of the competition, the Norwegian architect firm Snohetta (known for their winning project for the Library in Alexandria, Egypt, now under completion), and acoustic consultant Brekke and Strand/Arup, a joint Norwegian/English group, with Rob Harris responsible for the design of the main auditorium, and TPC, Theatre Projects Consultants (UK) as theatre consultants.

ACOUSTIC REFERENCE GROUP

This project might be somewhat interesting, by the use of detailed acoustic specifications given by Statsbygg, and the use of an Acoustic Reference Group (ARG) including
- Mike Barron
  Univ. Bath, UK
- Anders Chr. Gade
  Techn. University of Denmark
- Jan Inge Gustafsson
  Akustikon, Gothenburg, Sweden,
  acoustic consultant for the Gothenburg Opera
- Tor Halmrast, Statsbygg.

FURTHER WORK

The pre-engineering part of the project will be due by early 2002, as a basis for a final decision by the Norwegian Government

REFERENCES

1. Statsbygg (T Halmrast)
   (Norwegian State, Directorate of Public Construction and Property)


3. For additional info: tor.halmrast@statsbygg.no