Acoustics of the former teatro "la fenice" in Venice

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ACOUSTICS OF THE FORMER TEATRO “LA FENICE” IN VENICE*

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The acoustic characteristics of the former “La Fenice” theater have been analyzed. Binaural measurements of the impulse responses were performed at a large number of measuring points within the hall. Following the recent ISO standard 3382 [1], many mono and binaural acoustical parameters were calculated from the impulse responses, such as reverberation time, clarity, center time, strength, initial time delay gap, interaural cross correlation, and others. Finally, Ando’s preference maps were developed, taking into account two different kinds of musical signals. The measurements underlined the peculiar acoustical behavior of the theater, characterized by a greater initial decay of the reverberant tail and a subsequent reverberation that allowed a remarkable fusion of the sound and sustain to the musicians.

1 HISTORICAL PREVIEW

In 1774 the San Benedetto theater, which had been Venice’s leading opera house for more than 40 years, burned to the ground. No sooner had it been rebuilt that a legal dispute broke out between the company managing it and the owners, the Venier family. The issue was decided in favor of the Veniers, with the result that the theater company decided to build a new opera house of its own on the Campo San Fantin. From the 29 architectural plans that were submitted, the one by Gian Antonio Selva was chosen. The construction began in 1790 June; by 1792 May the auditorium was completed. It was named “La Fenice” (the phoenix) in an allusion to the company’s survival, first of the fire, then of expulsion from its former base. La Fenice was inaugurated on 1792 May 16 with an opera by Giovanni Paisiello entitled “I Giuochi di Agrigento.”

The hall had a half-elliptic plan, modeled after—it seemed—the Teatro Argentina in Rome.

From the beginning of the nineteenth century, La Fenice acquired a European reputation. Rossini mounted two major productions in the theater and Bellini had two operas premiered here. Donizetti, fresh from his triumphs in Milan and Naples, returned to Venice—and La Fenice—in 1836, after an absence of 17 years. Thus the three greatest Italian composers of the period each affirmed the theater’s preeminence, but in 1836 December it tragically burned down yet again. The following year Giambattista and Tommaso Meduna were commissioned to design a new theater, with decor by Tranquillo Orsi. La Fenice rose once again from its ashes, in Fiorito style, on the evening of 1837 December 26.

Many world-famous musicians wrote again music pieces for the “new” Fenice theater. Verdi’s association with La Fenice began in 1844, with a performance of “Ernani” during the Carnival season. Over the next 13 years, “Attila,” “Rigoletto,” “La Traviata,” and “Simon Boccanegra” all were performed there. The theater attracted the world’s greatest singers conductors, and composers, such as Stravinsky, Britten, Berio, Nono, and Bussotti, who would write for La Fenice.

Many people wrote about the elliptic plan of a theater. Pierre Patte, in a 1774 “Essai sur l’architecture théatrâle,” thought that the elliptic auditorium was the nat-

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ural shape of a theater because the human voice propagates as elliptic acoustic waves, as opposed to other acoustic sources that are quite omnidirectional (such as the bell).

Although now we know that an elliptical shape is very dangerous, as it can cause focalizations and uneven sound distribution, it must be taken into account that fortunately the Italian theaters are not highly reflecting, having their walls covered with artistic paintings and stuccos, especially in the neoclassical style, which prevent specular reflections and tend to give a diffuse sound field. So La Fenice also gained a high reputation with regard to its acoustic behavior, which was due to the particular association of an unusual shape and properly adjusted absorption properties.

The theater maintained its characteristic charm until it burned again completely on 1996 January 29.

2 MEASUREMENTS OF ACOUSTIC PARAMETERS

Italian theaters are usually characterized by low reverberation times and high absorption of the hall. These circumstances create a suitable acoustic comfort for operas that were composed especially in Italy during the nineteenth century. Often Italian theaters are considered "to sound" very well for operas, but to be too "deaf" for music.

While during the last century Italian theaters were used to present operas exclusively, nowadays they are also used for symphonic music. In that case, in a typical Italian theater the orchestra is located on the stage, and it appears that the acoustics of the hall are not perfect for this configuration.

The Venetian Teatro La Fenice, while having remarkable acoustics with regard to operas, had some limitations for symphonic music, when the orchestra was located on the stage. As in many other opera halls, an orchestra shell was required to give proper coupling of the stage with the main hall during the performances of large ensembles, and to give stronger reflections to the stage.

In the summer of 1995 the artistic direction of the theater decided to perform measurements of the acoustic behavior of the hall, which had to be the basis for the acoustic design of the orchestra shell. The theater was under restoration to meet the European security standards, and the construction of an orchestra shell had been added to the list of proposed improvements.

2.1 General Characteristics of the Hall

The main hall, typically in the Italian style, had four tiers of balconies plus the last one, called "loggione." The scenic tower was equipped with technical devices of the baroque period, such as the wooden grating, the flies, and the wooden stage area. The orchestra pit of about 77 m^2 was filled with practicables in order to align the floor with the stage during the symphonic performances.

During the measurements, the proscenium was completely empty, with the curtain open and without any scenic arrangements on the stage (Figs. 1–3). These were the main geometric characteristics of the former theater:

- Global volume 21 800 m^3
- Floor surface (main hall and balconies) 1480 m^2
- Total internal surface (lateral walls, floor, and ceiling) 7500 m^2
- Seats 819
- Proscenium 13.3 m wide by 8.5 m tall
- Main hall, 19.0 m wide by 13.7 m high by 23.8 m long
- Stage 27.5 m wide by 28.2 m high by 18.6 m deep.

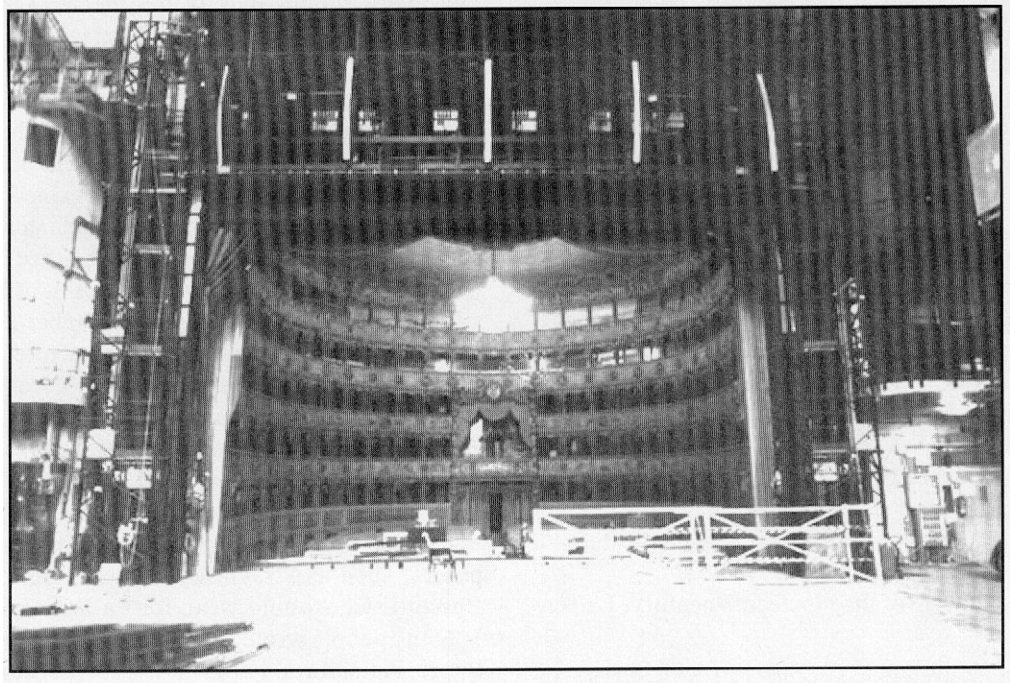


Fig. 1. Theater during measurements.

2.2 Measurement Technique

The measurements in the empty room were made during three days: 1995 October 14, 28, and November 4. The absence of the audience was not particularly important, as the seats were heavily upholstered, and some of them were covered with a thin tissue, which added some absorption. Although in the past no measurements had ever been made with the audience in this theater, experimental results obtained by the authors in other similar Italian theaters show that the reduction in reverberation time due to the audience is less than 0.1 s at midfrequencies.

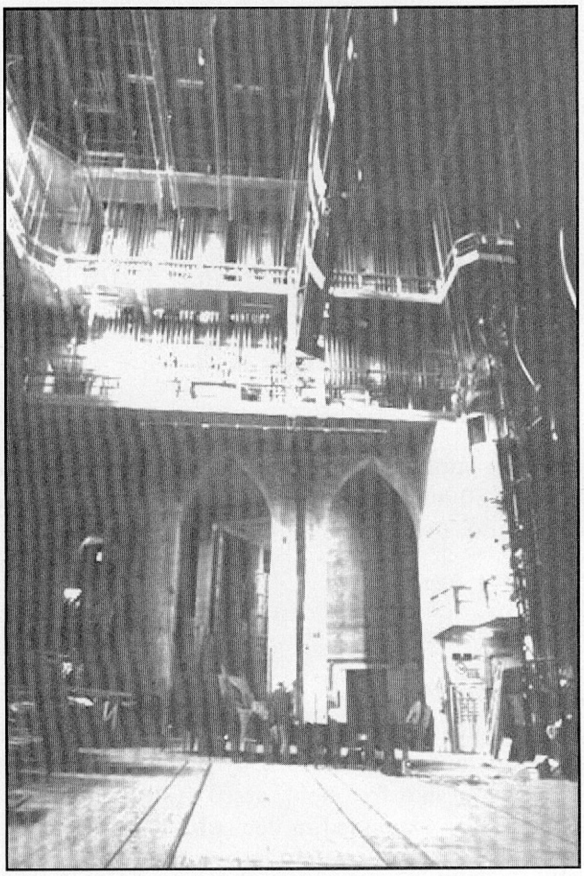


Fig. 2. Stage during measurements.

The experimental setup used at the theater, shown in Fig. 4, consisted of a blank shot gun, a dummy head with binaural microphones (Sony DRW70C), and a DAT recorder (Aiwa St-1). In the laboratory the impulse responses were transferred digitally in .WAV files by using a digital audio board (Multi!Wav Digital Pro) and then analyzed by using a wave editor (COOLEDIT 95) with homemade extensions (AURORA) and a specialized software (MLSSA 10.0C).

The basic measured quantities are 64-k-sampled long binaural impulse responses, from which the acoustic parameters are computed according to ISO 3382. A brief description of these objective parameters is given in Section 2.3.

The sound source was located exactly in the center of the proscenium, under the fire curtain. The recordings of the gun shots were taken at 27 points, uniformly distributed on the main floor and balconies of the right side of the hall (which was perfectly symmetrical), as shown in Figs. 5 and 6. Some additional measurements were made to check the symmetry and the effect of different source positions. Fig. 7 shows the binaural impulse responses of a point in the middle of the main floor.

2.3 Acoustic Parameters

Since the first definition of reverberation time by Sabine [2], many acoustic parameters have been developed to describe the acoustic behavior of a hall. According to the definitions contained in ISO 3382 [1], among the physical parameters already defined, the following were chosen for the analysis.

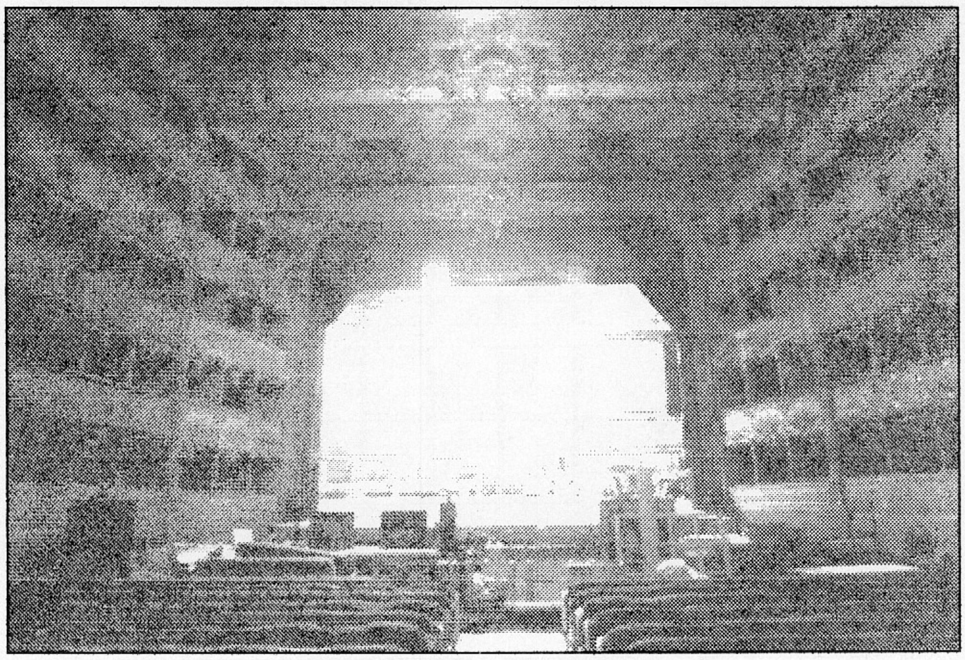


Fig. 3. Main hall during measurements.

2.3.1 T_{15}, T_{30}

Reverberation time calculated from the decay range between -5 and -20 dB (T_{15}) and between -5 and -35 dB (T_{30}) on the integrated Schroeder curve, in seconds.

Schroeder [3] found that the reverberant decay can be described by a backward integration of the impulse response,

$$\langle p^2(t)\rangle = N\int_t^{\infty} h^2(\tau)\,\mathrm{d}\tau \tag{1}$$

where

$\langle p^2(t)\rangle$ = time average of infinite number of decays
$h^2(\tau)$ = impulse response

Eq. (1) can be written as

$$\langle p^2(t)\rangle = N\left[\int_0^{\infty} h^2(\tau)\,\mathrm{d}\tau - \int_0^{t} h^2(\tau)\,\mathrm{d}\tau\right]. \tag{2}$$

Eq. (2) can be represented in a (p^2, τ) diagram, as shown in Fig. 8.

2.3.2 Early Decay Time (EDT)

Since Jordan [4] demonstrated that the subjective perception of reverberation is correlated more strongly with the initial decay of the reverberant tail, he suggested to calculate the reverberation time from the decay range between 0 and -10 dB on the integrated Schroeder curve, in seconds.

2.3.3 Center Time t_s

It was defined by Kürer [5] as *Schwerpunktzeit* in the equation

$$\tau_s = \frac{\int_0^{\infty} \tau\, h^2(\tau)\,\mathrm{d}\tau}{\int_0^{\infty} h^2(\tau)\,\mathrm{d}\tau}. \tag{3}$$

It is the first-order momentum of the squared pressure impulse response, expressed in milliseconds.

2.3.4 Initial Time-Delay Gap (ITDG)

Defined by Beranek [6], it is the delay of the first reflection from the direct wave, expressed in milliseconds. It is usually calculated directly from the impulse response.

2.3.5 Interaural Cross Correlation (IACC)

As suggested by Ando [7], it is the normalized correlation coefficient between the first 50 ms of the pressure impulse responses measured at the two ears of the binaural microphone. From the definition of the cross-correlation function, given by

$$\rho(\tau) = \frac{\lim_{T\to\infty}\left[\frac{1}{2T}\int_{-T}^{T} h_d(\tau)\cdot h_s(\tau+t)\,\mathrm{d}\tau\right]}{\lim_{T\to\infty}\left[\frac{1}{2T}\sqrt{\int_{-T}^{T} h_d^2(\tau)\,\mathrm{d}\tau\cdot\int_{-T}^{T} h_s^2(\tau+t)\,\mathrm{d}\tau}\right]} \tag{4}$$

and taking into account that the limitations of the integral are often 50 ms, the IACC is defined as the maximum value of Eq. (4), that is,

$$\mathrm{IACC} = |\rho(\tau)|_{\max} \tag{5}$$

where $\tau \leq 1$ ms.

2.3.6 Strength G

It is the difference between the measured sound pressure level, and that produced by the same omnidirectional source in a free field, at 10-m distance from its center, and is expressed in decibels. It was defined in ISO 3382 and expressed by the equation

$$G = 10\log\frac{\int_0^{\infty} h^2(\tau)\,\mathrm{d}\tau}{\int_0^{\infty} h_{10}^2(\tau)\,\mathrm{d}\tau}. \tag{6}$$

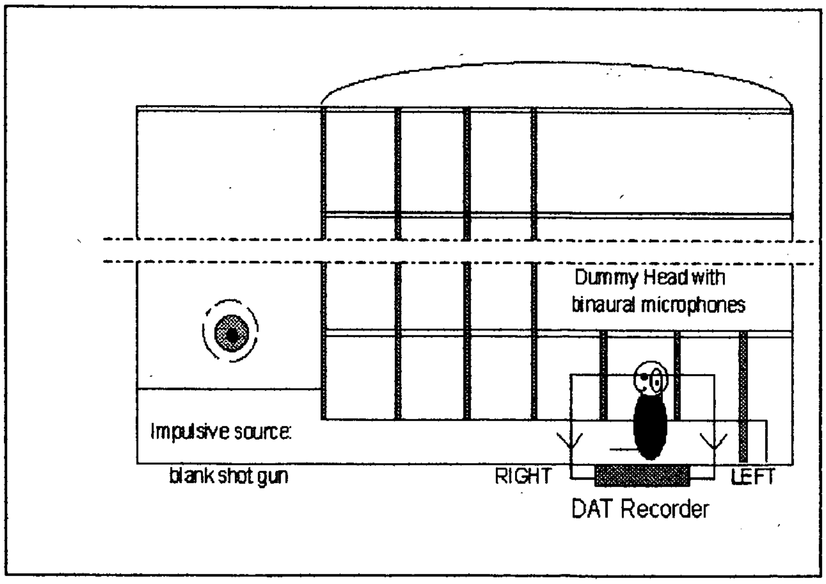


Fig. 4. Measuring system of binaural impulse responses.

2.3.7 Klarheitsmass or Clarity C_{80} and C_{50}

It is defined [8] by the equation

$$C = 10 \log \frac{\int_{0}^{80\text{ms}} h^2(\tau)\,d\tau}{\int_{80\text{ms}}^{0} h^2(\tau)\,d\tau}. \qquad (7)$$

When the clarity is related to musical perception, the time interval is limited to 80 ms, whereas if the clarity is related to speech, the time interval is set to 50 ms. Reichardt, Abdel Alim, and Schmidt defined such an acoustic parameter in order to relate the "transparence" of the music to an energetic parameter.

2.3.8 Speech Transmission Index (STI) and Rapid Speech Transmission Index (RASTI)

These parameters were defined by Houtgast and Steeneken [9]–[11]. They are computed from the values of the modulation transfer function (MTF). This quantity

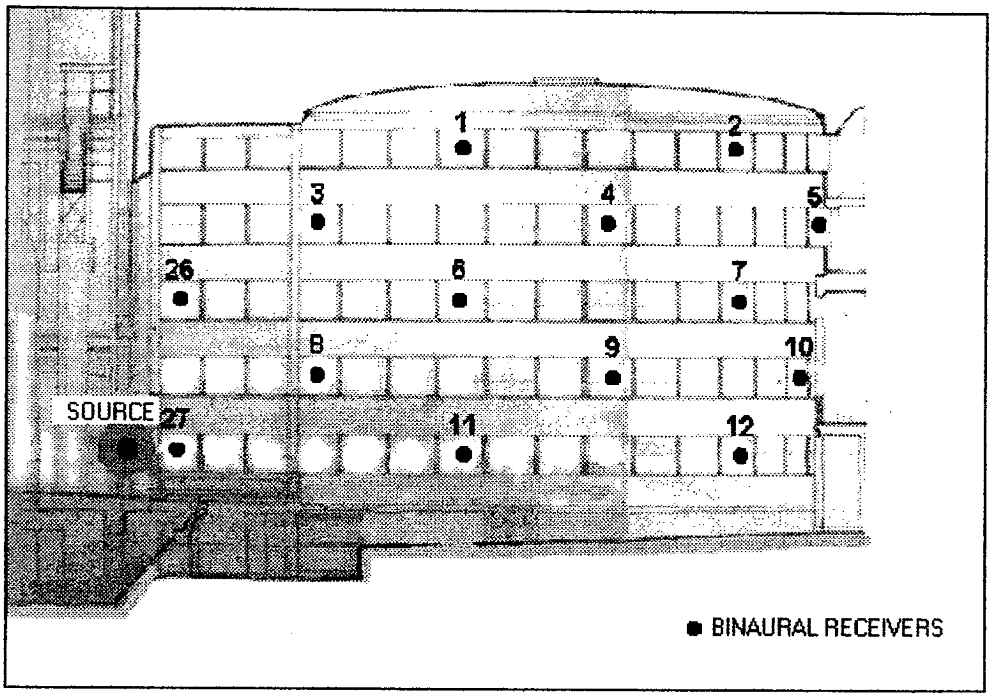


Fig. 5. Sound source and receiver positions on balconies.

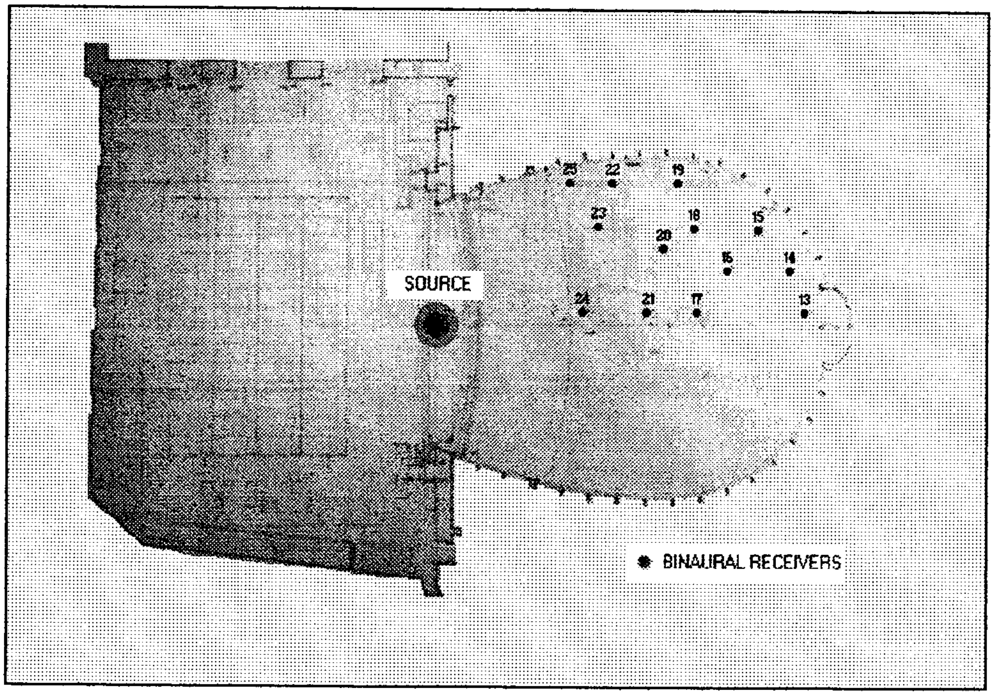


Fig. 6. Sound source and receiver positions in stalls.

is defined by the ratio of the received modulation amplitude to the original modulation amplitude, making use of an excitation signal obtained by an octave-band filtered pink noise, having an energy envelope (squared amplitude) slowly modulated at frequency F, as shown in Fig. 9.

At the receiving microphone the sampled signal presents an energy envelope with reduced modulation depth. The ratio between the output modulation amplitude and the input modulation amplitude is the MTF,

$$m(F) = \frac{m_{\text{out}}}{m_{\text{in}}} . \tag{8}$$

The value of $m(F)$ can be computed for each modulation frequency F in one-third-octave increments from 0.63 to 12.5 Hz, covering the range of the human voice modulations. Furthermore, the octave-band filtered carrier signal can be produced for any octave band from

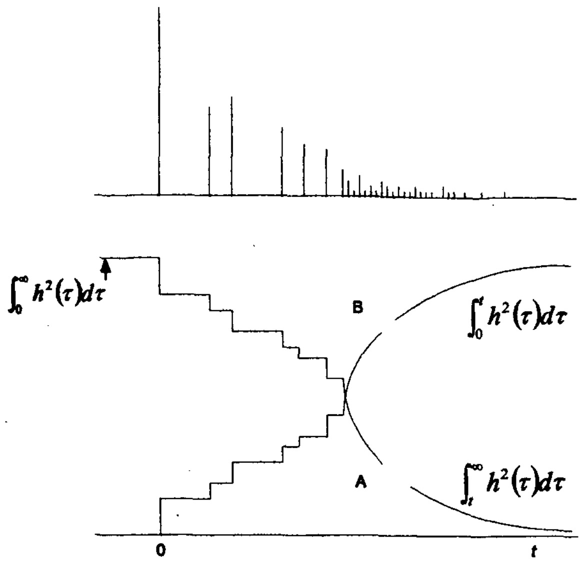
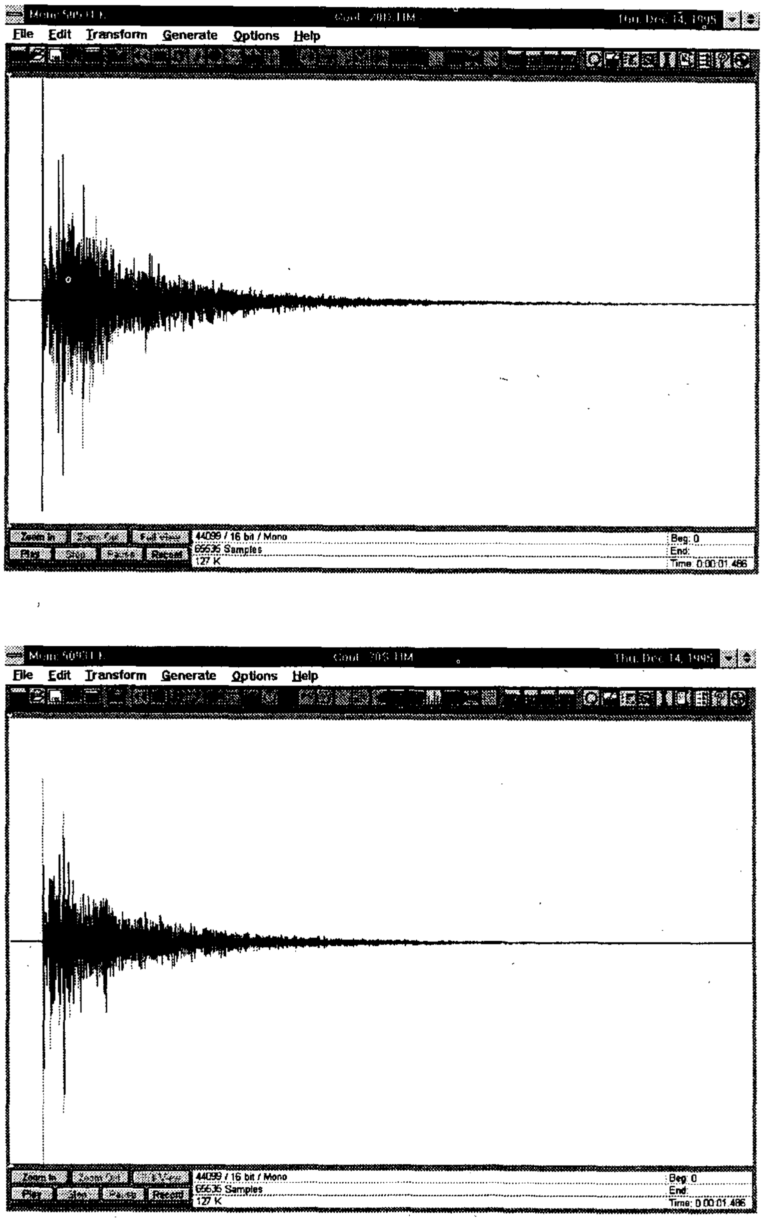


Fig. 8. Schroeder plot as represented by Eq. (2).



44099 / 16 bit / Mono
65536 Samples
127 K
Beg: 0
End:
Time: 0:00:01.486

44099 / 16 bit / Mono
65536 Samples
127 K
Beg: 0
End:
Time: 0:00:01.486

Fig. 7. Impulse responses at point n.20.

125 Hz to 8 kHz. Thus a complete set of MTF values for seven octaves is obtained. The STI is computed from the seven MTFs.

Although the STI is an exhaustive acoustic parameter, describing the intelligibility of concert halls, Houtgast and Steeneken [11] found out that it was not necesary to obtain a detailed set of MTFs to quantify the intelligibility of an enclosed space. Hence they defined a shorter parameter, the rapid speech transmission index (RASTI), limiting the analysis to a restricted number of data. The procedure is very similar, but the carrier's frequencies are referred only to the octave bands of 500 and 2000 Hz.

The values of $m(F)$ can be computed directly from the impulse response of a system, provided that it is a linear, passive, time-invariant system, as shown by Schroeder [12]. These hypotheses correspond to the assumption of very little background noise, so that the modulation depth reduction is due only to the room's reflections, echoes, and reverberation. This assumption is certainly met in this case, because the theater was very silent, and no external noise could affect the listening conditions.

Since the effective signal-to-noise ratio is of no influence, there is no problem employing a sound source with a spectrum different from the normalized spectrum defined in the original works of Houtgast and Steeneken [9]–[11] or those defined in the new IEC 268-16 [13]. The only problem connected with the use of an impulsive source (a gun shot in this case) is the directivity of the source, which does not resemble the normalized directivity of the human voice since it is almost perfectly omnidirectional. Furthermore, the recording of the impulse response is not made with an omnidirectional microphone, but with a binaural one. These deviations are, to a certain degree, compensating reciprocally. Furthermore, the measurements under these conditions are probably more representative of the real listening conditions in a theater, where the listeners are always facing the stage while the speaker is moving around on it.

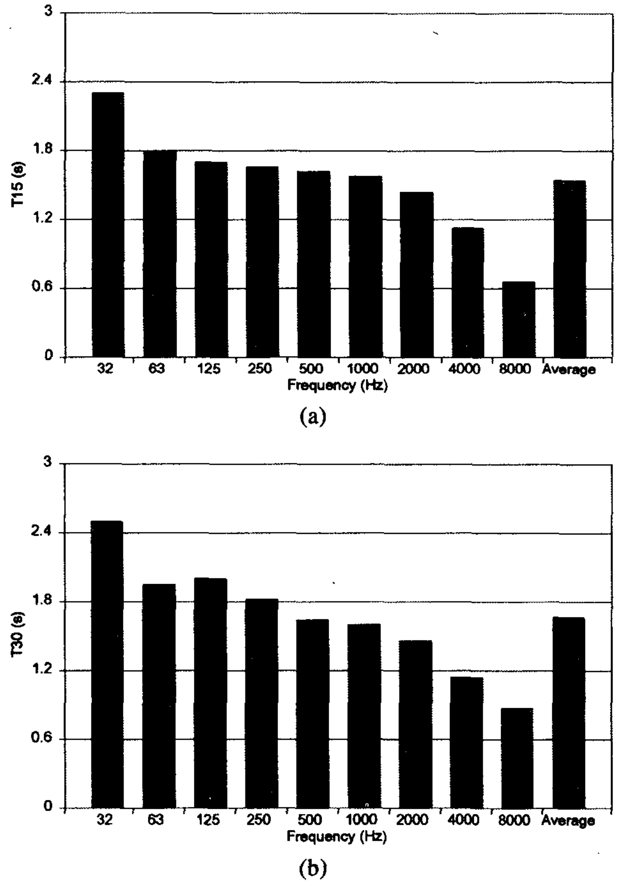
To compute each value of $m(F)$ from the impulse response $h(t)$, an octave-band filter is first applied to the impulse response in order to select the carrier's frequency band f. Then $m(F)$ is obtained using the formula

$$m(F) = \frac{\int_0^\infty h_f^2(\tau) \cdot \exp(-j2\pi\tau)\, d\tau}{\int_0^\infty h_f^2(\tau)\, d\tau} . \qquad (9)$$

2.4 Discussion of Experimental Results

Fig. 10 shows that the values of T_{15} and T_{30} ($T_{15} \approx 1.75$). These values are well suited for operas and symphonic music, with on average better results than those of other Italian theaters (for example, Milan's La Scala), which sound often too "dry" for ensemble performances. This is certainly one of the reasons for the good acoustic reputation held by the La Fenice theater.

In Fig. 11 the values of the early decay time and the center time are shown. The EDT value (EDT $\approx$ 1.25) is lower than T_{15} and T_{30}, showing that the first part of the impulse response carries much more energy than the late part. This causes the Schroeder integrated decay curve to exhibit a double-sloped shape, with a fast initial decay, followed by a slowly decaying tail, as shown in Fig. 12. This behavior is useful in a multipurpose theater because it produces good clarity and intelligibility for



(a)

(b)

Fig. 10. Reverberation times in octave bands for La Fenice. (a) T_{15}. (b) T_{30}.

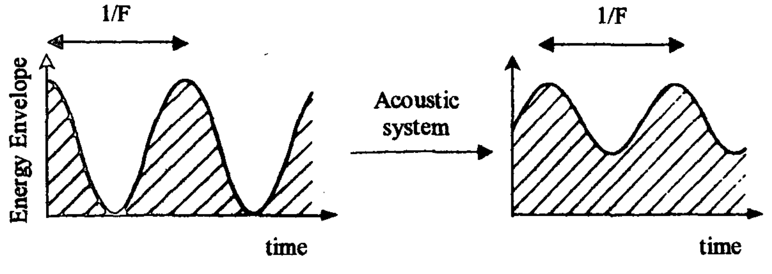


Fig. 9. Modulation of energy envelope at input and output.

speech and songs, while the musical performances can benefit from the liveness and blending caused by the high reverberation time.

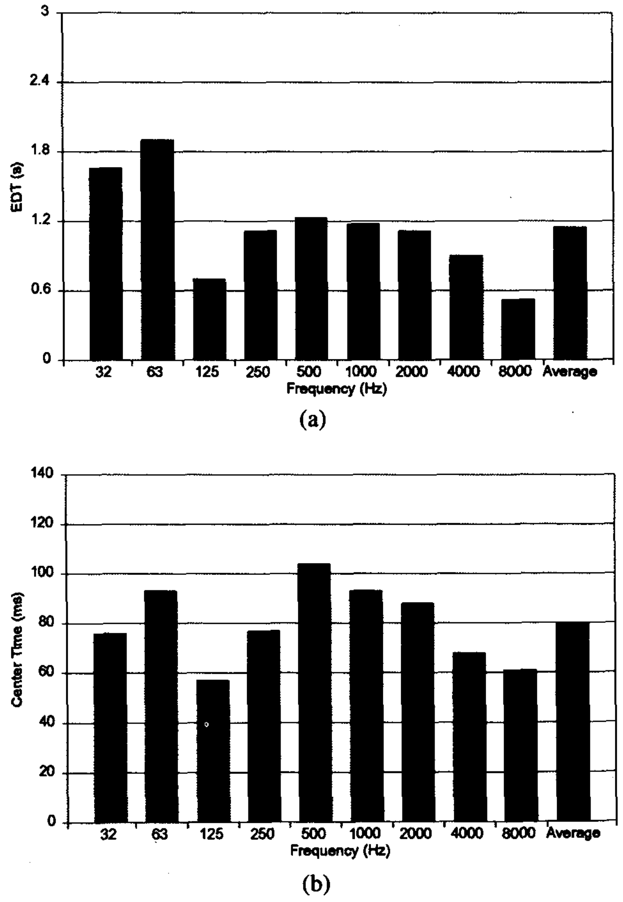
Fig. 13 shows the map of strength G. It can be seen how the spatial distribution of G is quite uniform on the main floor. Instead of the focalization, which affects many horseshoe-shaped Italian theaters, there is little reduction in sound level in the center of the rear part.

The intelligibility index RASTI is distributed uniformly. The highest values were found in the seats close to the walls, as shown in Fig. 14. This is typical for these positions, which benefit from wall reflections with a short delay.

The clarity, measured at 50 and 80 ms is more suitable for speech and operas than for symphonic music, being around 0.24 and 3.8 dB, respectively (Fig. 15 and 16). The same holds for the center time t_s, shown in Fig. 17, with an average value of 80 ms.

The interaural cross correlation $IACC_{50}$, having values around 0.2–0.3, is quite low, ensuring a good spatial impression and envelopment of the listeners (Fig. 18). This was certainly one of the better acoustic characteristics of the theater, as usually it is difficult to have low values of IACC coupled with high values of clarity, and it is well known that a good spatial impression is the most important parameter for the overall musical acoustic quality.

From the measured objective parameters the preference index according to Ando's theory has been computed by using a specialized homemade software, taking into account the temporal characteristics of a well-known music piece, the *Sinfonia Jupiter*, K551, by W. A. Mozart, which has an effective duration of the autocorrelation function τ_e = 38 ms. The contour map of Ando's preference index is shown in Fig. 19. The values are high, ranging between -1.5 and -0.5, which means that this room was perfectly suited for the kind of music represented by this τ_e value.



(a)

(b)

Fig. 11. Early decay and center times for La Fenice. (a) EDT. (b) t_s.

3 COMMENTS AND CONCLUSIONS

The acoustic assessment of the former theater La Fenice in Venice included many objective measurements to define the properties of this theater. The measures evaluated were reverberation time (T_{15}, T_{30}, and EDT), center time t_s, initial time delay gap (ITDG), interaural cross correlation (IACC), strength (G, level distribution), clarity (C_{80}), and speech transmission index (STI). An analysis of the results showed the following.

1) *Reverberation Time*: The reverberation time T_{30} showed an average value of 1.8 s with a regular distribution over the frequency range. This value is perfectly suited for operas and speech, while it seemed too low for symphonic music. The mean value of EDT is still lower, showing that the initial slope of the decay is steeper than the subsequent tail. This is a favorable condition for a multipurpose theater, as the speech intelligibility is not affected while the music is blended and sustained by the reverberant tail.

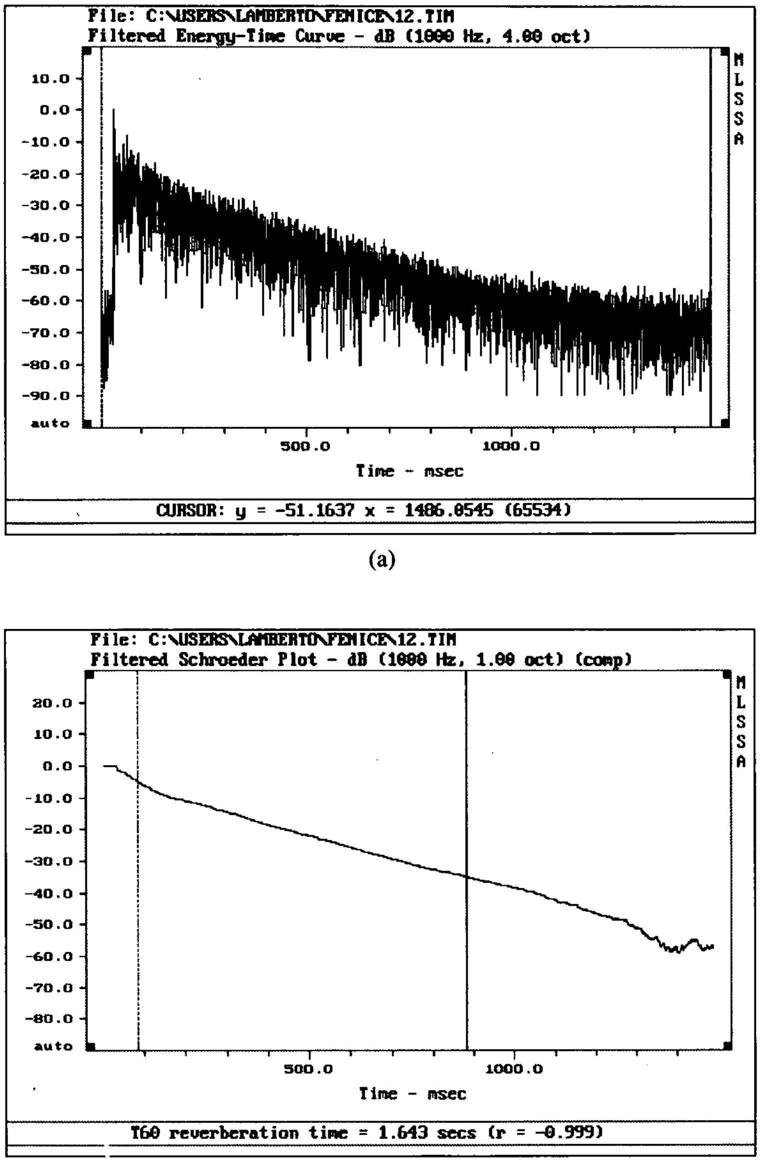
2) *Clarity and Center Time*: The clarity and center time values are optimal for speech and operas, but they exhibit a sound field a little too defined for symphonic music, particularly for a certain kind of music characterized by a low tempo and consequently a very long value of the effective duration of the autocorrelation function τ_e.

3) *IACC and ITDG*: The $IACC_{50}$ amounts to a value of 0.25 at most positions. This is due to lateral reflections. It ensures a good spatial sensation. The ITDG values (ranging from 7 ms close to the walls to 25 ms in the middle of the hall) confirm the benefits of lateral strong reflections.

4) *Strength*: The distribution of the strength on the main floor is quite uniform. Maximum level differences of 6 dB are found, but typically they are only 2 dB. The horseshoe shape of the theater does not show a big focus effect because of the presence of absorption at relevant places.

5) *STI*: The uniform distribution of the STI (0.50–0.60) is related to a fair to good intelligibility. This is essential for an auditorium such as required for opera use. The uniform distribution of the STI also indicates a uniform distribution in the temporal properties of the hall. Close to the walls the STI value increased slightly. This effect is typical as reflections close to the wall increase the effective signal-to-noise ratio.

The objective acoustical properties of the theater agree quite well with the subjective reputation of this hall, which had been gained over a time period of more than 100 years.



File: C:\USERS\LAMBERTO\FENICE\12.TIM
Filtered Energy-Time Curve - dB (1000 Hz, 4.00 oct)

CURSOR: y = -51.1637 x = 1486.0545 (65534)

(a)

File: C:\USERS\LAMBERTO\FENICE\12.TIM
Filtered Schroeder Plot - dB (1000 Hz, 1.00 oct) (comp)

T60 reverberation time = 1.643 secs (r = -0.999)

(b)

Fig. 12. (a) Energy-time curve at point n.12. (b) Schroeder plot at point n.12.

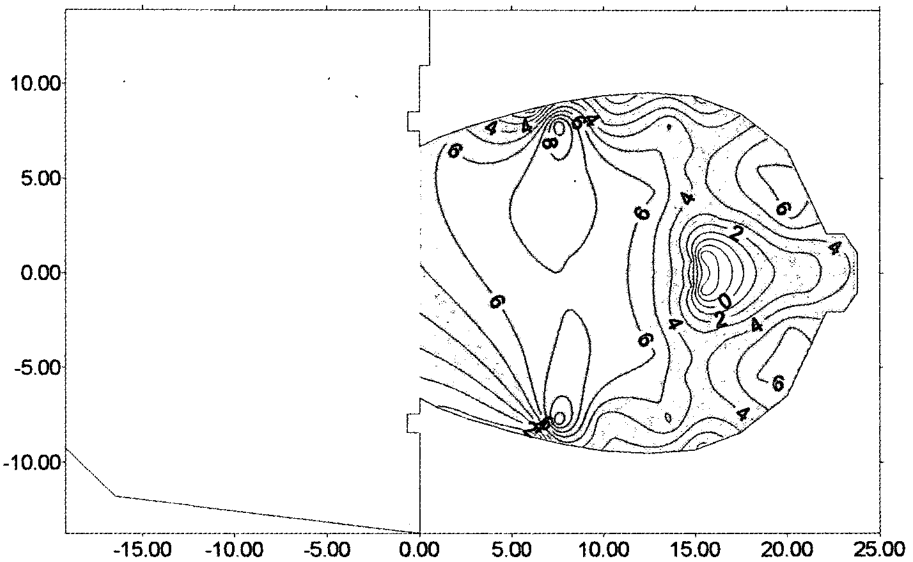


Fig. 13. Spatial map of strength G.

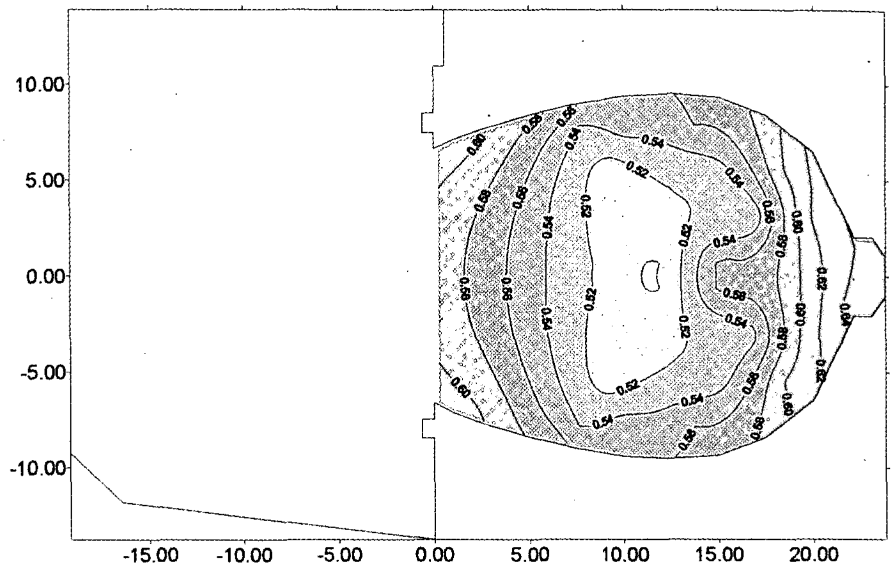


Fig. 14. Spatial map of RASTI.

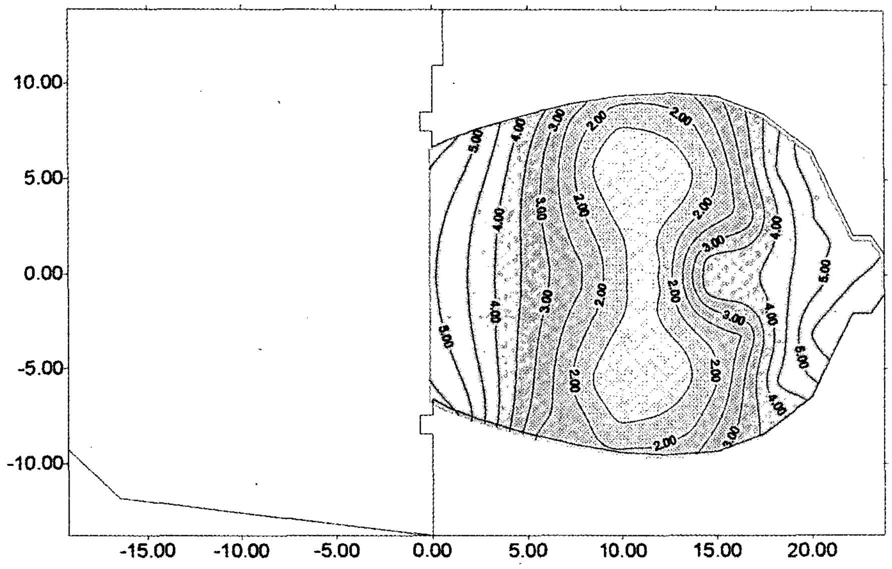


Fig. 15. Spatial map of clarity C_{50}.

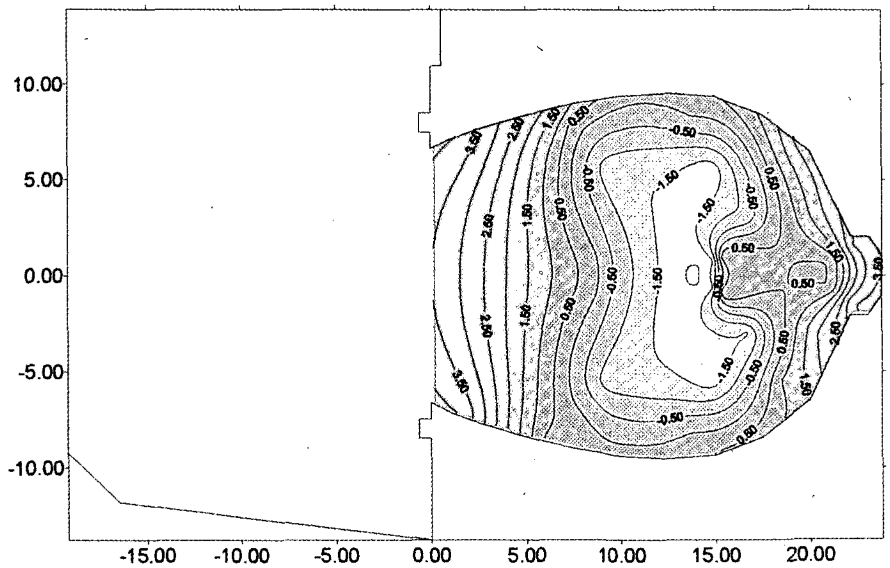


Fig. 16. Spatial map of clarity C_{80}.

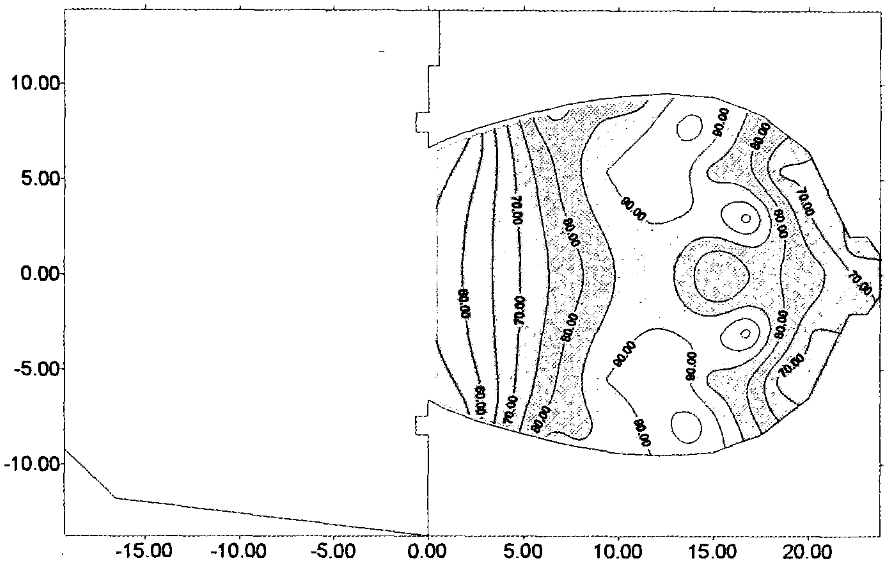


Fig. 17. Spatial map of center time t_s.

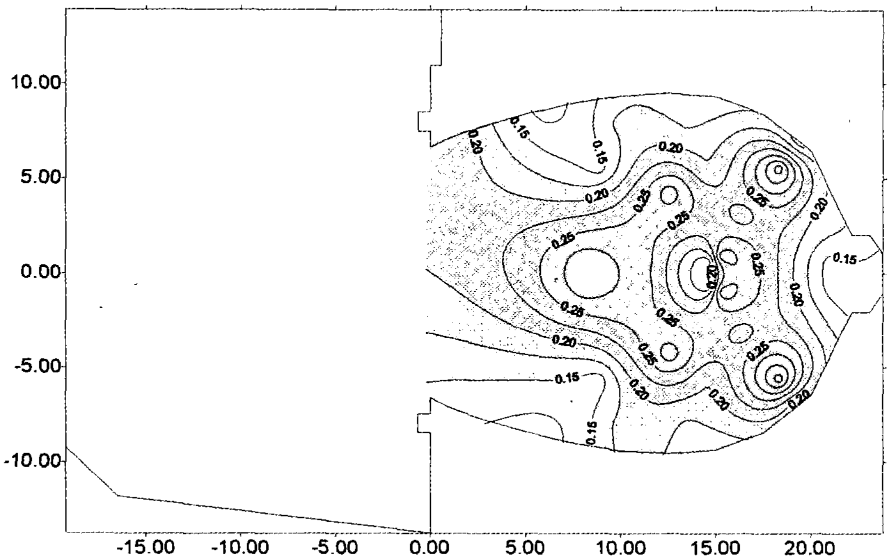


Fig. 18. Spatial map of interaural cross correlation $IACC_{50}$.

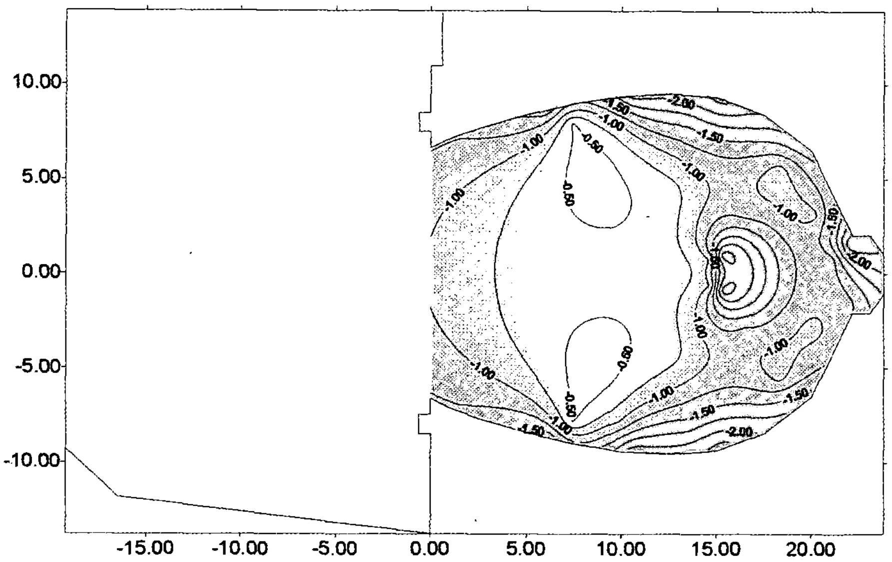


Fig. 19. Ando's preference' index S (Mozart's *Sinfonia Jupiter*, k.551, t_e = 38 ms).

4 ACKNOWLEDGMENT

Special acknowledgment is due to Giovanni Farolfi, who had to plan the acoustic chamber of the theater, and to Alessandro Cocchi, who encouraged us to write this paper.

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