Journal of Sound and Vibration (2000) **232**(1), 281–301
doi:10.1006/jsvi.1999.2821, available online at http://www.idealibrary.com on IDEAL®

GUIDELINES FOR ACOUSTICAL MEASUREMENTS INSIDE HISTORICAL OPERA HOUSES: PROCEDURES AND VALIDATION

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(*Accepted* 9 *December* 1999)

The acoustics of Italian historical theatres is to be regarded as a cultural heritage, which is to be preserved and studied. These actions are imperative for handing down the heritage to future generations and to avoid its loss. In this paper, the technical means for scientific quantification of the acoustical heritage are presented in the form of operative guidelines for acoustical measurements inside historical theatres. The document includes the advice of international experts and is being employed during an extended measurement campaign inside renaissance and baroque historical theatres. A relevant part of the paper deals with the experimental validation of the recommendations given in the guidelines, achieved by a dedicated test session inside the Municipal Theatre of Ferrara.

1. FOREWORD

The following guidelines are conceived with the intent of providing a technical and operative support to a systematic measurement campaign inside a wide ensemble of Italian historical theatres.

The measurement campaign aims at quantifying in a scientific way the acoustical heritage which is typical of historical theatres, with the aid of the resources of the more recent researches in the field of technologies for roomacoustical measurements.

The use of the collected acoustical data will have many sipn-offs, which involve the life and the acoustical heritage of historical theatres.

Some of the more prominent ones are as follows: documentation: detailed description of the acoustical environment inside historical theatres; safeguard: systematic collection and cataloguing of the acosutical primary data in the deputed institutions (this material is to be considered in case of restorations) education: diffusion of the awareness of the acoustical heritage, especially among young people, by means of the latest multimedia technologies; research: development of the objective and subjective criteria for the evaluation of the acoustical environment in enclosures.

0022-460X/00/160281 + 21 $35.00/0

The development of the measurement campaign is linked to the Special Project on Cultural Heritage of the National Research Council of Italy [1] and, in particular, to the operative unit at the Department of Engineering of the University of Ferrara, Italy.

2. INTRODUCTION

The importance of the indicated measurement campaign, which will presumably involve different teams to be carried out, has evidenced two fundamental technical requisites: (a) the necessity of adapting the acoustical measuring techniques to the architectural typology of historical theatres; (b) the need of standardizing the measurement sessions (and thus to make the results comparable) inside different theatres, independently of the team which will make the surveys.

To give an answer to the former points, the first step has been to contact and to co-ordinate a group of international specialists on roomacoustical measuring techniques. The present document includes the suggestions and experiences which have been collected by meetings and personal contacts. The final objective of the action is to elaborate a complete methodology which might start with the measurement of primary acoustical data according to the state-of-the-art techniques and end with the definition/selection of the suitable parameters to fully describe the acoustic field inside these places. This calls for many subtasks whose development is currently in progress.

In this paper, the definition of the measurement procedures, regarding the set-up of the theatres and the positions of sound sources and receivers will be dealt with. Moreover, the choice of the measurement methodology and of the measurement chain will be discussed.

As regards the definition of a set of objective acoustical parameters to qualify the sound field, a further effort will be necessary to pursue an extended comparison between experimenters measuring different quantities.

The procedures indicated in the next paragraphs are partly well established and partly only recently proposed. After expounding the technical content of the guidelines in the paper the results of a test session inside the Municipal Theatre of Ferrara will be presented to support and discuss some of the indicated procedures.

3. MEASUREMENT PROCEDURES FOR CAMPAIGNS INSIDE HISTORICAL THEATRES

The most important normative reference for measurements of the kind considered here is the norm ISO3382 [2]. The intention of the procedures outlined in the paper is to integrate the norm in some respects and specialize the approach to historical theatres. The goal of the campaign is to characterize the theatres dating from the renaissance, when the modern theatre was born, to the theatres equipped with tiers of boxes, whose design dates to the baroque age but lasted up to the 19th century. Both these typologies of buildings can be found with many differences from theatre to theatre regarding, for instance, plan shape and interior design. For simplicity, in the following only two basic models will be addressed and it will be the duty of the experimenters to adapt the information to the actual case.

The basic issue of the guidelines is to characterize the historical theatres for executions of opera, from its very early days to traditional repertoire. Nevertheless, it is known that they currrently house different kinds of events like symphonic and small ensemble concerts or recitals so that specific information will be referred to (see Appendix A).

In the following sections the two typologies of theatres will be dealt with separately starting from the baroque theatres, whose procedures are more elaborated. Some parts of the process will be then transferred to renaissance theatres.

3.1. THE CASE OF THE BAROQUE THEATRES

3.1.1. *Set-ups of the baroque theatres*

To characterize the baroque theatre, which has been expressively conceived for opera, it is necessary to investigate three systems: the cavea (which contains the audience subdivided into stalls, boxes and gallery), the stage (usually equipped with opera scenery) and the third system which is the sum of both the stage and the hall. The importance of the acoustics of the stage has been underlined by many authors (as in references [3, 4]) and is common experience of the performers, especially of singers, who know all acoustical merits and faults of the stage due to their familiarity to this place.

The three systems can be described, from the acoustical point of view, considering two set-ups of the theatre, which will be prepared before the measurements take place and will be maintained during the session. A brief description of the two set-ups can be as follows.

A. *Hall and stage coupled.* The orchestra pit, which in many baroque theatres has been added after construction, is lowered in the configuration usually employed for opera. The stage is in the full length and does not contain any scenery. To simulate the absorption of the scenery in a standardized way, 500 m^2 of heavy curtains will be hung from the ceiling in the back of the stage. If some fittings were present and the above conditions could not be met, it will be the duty of the experimenter to give a detailed description of the scenery in the report of the results.

B. *Hall and stage decoupled.* This is like set-up A as concerns the orchestra pit and stage. In this case, the fire-curtain and the curtain are lowered to make the hall and the stage acoustically independent.

The two set-ups are pictured respectively in Figures 1 and 2 where also the positions of sound sources and receivers are indicated as explained in the following.

The measurement conditions will be as similar as possible to those during performances as regards the curtains in the hall, the furniture of boxes, the doors

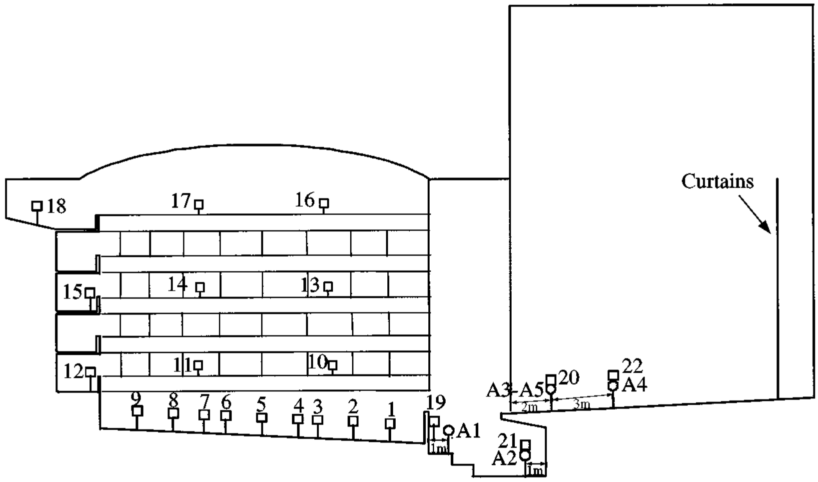

Figure 1. Section of the baroque theatre in the set-up A with hall and stage communicating. The sound sources are represented with a small circle and indicated with A followed by progressive number. The receivers are represented by small squares and a progressive number. Refer to the text for the explanation.

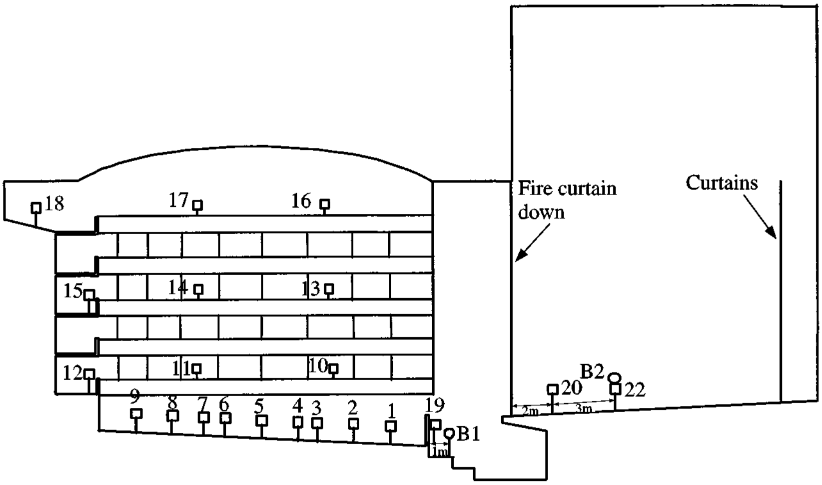

Figure 2. Section of the baroque theatre in the set-up B with hall and stage decoupled by the fire-curtain. The numbering follows criteria of Figure 1.

and the air conditioning apparatus. Whenever possible the orchestra pit will be equipped with chairs and music stands. The whole measurement session will take place without the audience. Nevertheless, the possibility to take a reduced set of measures with the audience present will be verified (see also section 3.1.3 below).

3.1.2. *Positions of sound sources and of receivers*

The sound sources and the receivers are positioned in order to characterize the acoustical environment for the audience and for the performers, who might suffer

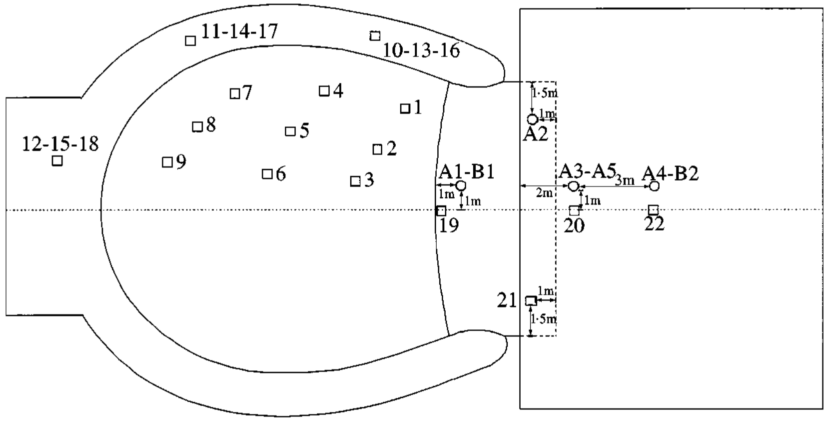

Figure 3. Plan of the baroque theatre with the positioning of sound sources for each set-up and with the complete grid of receivers. The grid in the hall, though maintaining the indicated form, has to be adapted to the conformation of the stalls (number or rows) and to that of the boxes (number of boxes for each order).

the acoustical conditions in some circumstances (i.e., references [5, 6]). In the zone of the theatre occupied by the performers (that is orchestra pit and stage) both sources and receivers will be positioned whereas in the hall, where only the audience is supposed to be accomodated, only receivers will be placed. Figure 3 shows the plan with the positions of sources (indicated with small circles) and of receivers (indicated with small squares). The numbering of sources reports the letter relative to the set-up and a progressive number, while the numbering of receivers is simply progressive. In the pictures also an indication of the distance from reference points in the orchestra pit and on the stage is shown. The sound sources are omnidirectional (unless otherwise stated) and each position of a sound source which is marked in the plan corresponds to a complete set of measures of the grid of receivers.

All the positions of sound sources, except the one indicated by A2, lie along a line which is parallel to the longitudinal axis of symmetry of the theatre at a distance of 1 m from it. The off-axis positioning of the sound sources avoids those spurious effects due to the symmetry of the hall which might contaminate the data.

The sound sources are placed as follows.

A. *Hall and stage coupled.* Two positions in the orchestra pit, one named 1° violin (A1) and another in the covered part of the pit in the usual position of double basses or trombones (A2); two positions on the stage, one at 2 m from the line of the firecurtain (A3) and the second at least 3 m behind (A4); one position for a directional source (A5).

B. *Hall and stage decoupled.* One position in the orchesrta pit, 1° violin (B1); one position on the stage at 5 m distance from the fire-curtain (B2).

The sound sources are placed at 1·2 m from the floor except for the directional A5 source that can be placed at 1·5 m height.

The grid of receivers consists of 22 points: 9 in the stalls, 3 in the first order boxes, 3 in the third order boxes, 3 in the gallery, 2 in the orchestra pit and 2 on the stage. If the time available to make the measurements limits the possibility of going through the complete grid, it is possible to use a reduced grid of receivers, made up of 12 points. This simplified grid can be easily obtained by considering only the even (or odd) positions of receivers in the plan. The receivers numbered 19, 20, 21 and 22 are to be taken in any case.

Due to the supposed acoustical symmetry of the hall the receivers are positioned only on one-half of the hall at 1·1 m above the floor facing the sound source. The verification of the symmetry can be left to the occurrence of visual discrepancies between the two halves.

The position 19, corresponding to the conductor, the position 20, corresponding to the front singer and the position 22 of the back singer lie on the symmetry axis while position 21 (deep instruments) is at 1·5 m from the lateral wall and at 1 m from the back wall of the orchestra pit.

The measurement procedure when the sound source is in the markedly asymmetric position A2 is divided into three steps: (a) the sound source is placed in A2 and measures are taken for the receivers indicated from 1 to 22; (b) the positions of the sound source and that of receiver 21 are swapped; (c) measures are taken for the receivers from 1 to 18.

In the set-up B the receiver 21 is not included. Moreover, in this set-up the measures in the positions from 1 to 19 are taken when the source is in B1, while when the source is in B2 only one measure in the position 20 or 22 is taken.

3.1.3. *A simplified procedure for baroque theatres*

Due to the frequent necessity of a quick procedure for obtaining useful data with least effort of time inside the baroque theatre, it is possible to go through a simplified map of sources and receivers. The aim of having a simplified version of the measurement procedure affects mainly the map of receivers, whose increase in number is generally responsible for the need of a longer time. This set of points can also be used if measurements with audience can be made.

The set-ups of the opera house remain as described above and, in case of a very short time available, the measurements can be limited to the set-up A.

With reference to Figures 1–3, the positions of sound sources are reduced to two for both set-ups, namely the positions marked A1, A3 for set-up A and B1, B2 for set-up B. The receivers are limited to a number of three for source positions A1, A3 and B1: the first one is located in the middle of the stalls at position 5, the second one is in a central box of the third tier, namely position 14, and the third is in the same tier at central position 15. When the source is placed in B2 the measurement point can be either 20 or 22.

Reducing drastically the number of receivers should imply less operational effort and time. The measurement methodology is not affected by the present simplification since the experimenter can decide previously which of the suggested measurement chains (see below) can be employed.

3.2. THE CASE OF RENAISSANCE THEATRES

3.2.1. *Setup of the renaissance theatre*

Since the typology of renaissance theatres derives from classical models, the parts of the theatre are commonly named after their classical counterparts. The stage is the place where the action takes place and the cavea is subdivided into orchestra, which is a plain space right in front of the stage, the auditorium, consisting of tiers, and a loggia closing the cavea in the upper back.

These theatres are not equipped with a curtain and fire-curtain so that it is impossible to divide acoustically the different spaces and investigate them separately. Another valuable characteristic of such theatres is the very scarce presence of heavily sound-absorbent material (draperies, velvets, ornaments) which was probably present to some extent when the theatres were flourishing.

To qualify the acoustics of such spaces one set-up will be considered (named set-up A) corresponding to stage and cavea acoustically coupled. The stage is thus without scenery and the orchestra is without the chairs for the public. The access doors to the orchestra and auditorium are preferably closed as those introducing to the loggia.

3.2.2. *Positions of sources and receivers*

The sound sources are all placed along a line located at 1 m from the symmetry line of the theatre. The first position is named A1 and corresponds to the position of musicians in the early days of opera, whereas the positions named A3 and A4 correspond to those of a singer or of a trained speaker in case of drama venues respectively for front and back positions on the stage.

The grid of receivers covers the space for the public and of performers and in particular the orchestra is covered with a regular set of receivers from 1 to 11. In case that this zone has smaller extension (like semicircular orchestras) the first two rows can be dropped. The positions in the auditorium are placed on three parallel rows, the middle one corresponding to the mid-step. The first column of receivers in the auditorium is to be dropped for semispherical theatres.

The receiver 21 is noticeable since it corresponds to the so-called "ducal box", the outstanding location inside the theatre. In the loggia two points can be found: these points can be dropped if the conditions of accessibility of the zone are not favourable.

The complete set of sources and receivers to be considered inside renaissance theatres is resumed in Figures 4 and 5 where also an indication of reference distances for the sound sources are reported.

The sound sources are placed at 1·2 m from the floor and the receivers, facing the source are at 1·1 m height.

3.2.3. *A simplified procedure for renaissance theatres*

As indicated above, the time constraint can be met also for this typology by limiting the number of receivers. The sound sources are still placed in the indicated positions whereas, referring to Figures 4 and 5, the receivers being considered remain only numbers 5, 16 and 21.

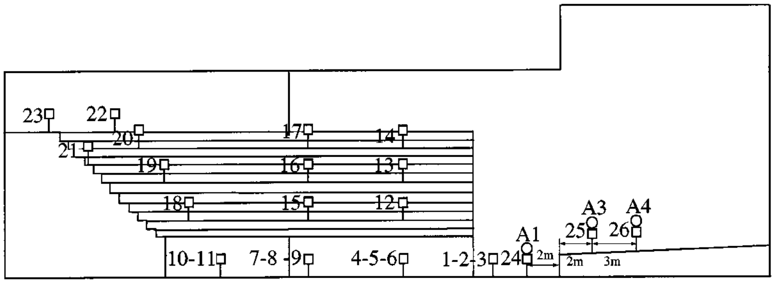

Figure 4. Section of set-up of the renaissance theatre with positions of sources (indicated with a circle) and receivers (indicated with a square).

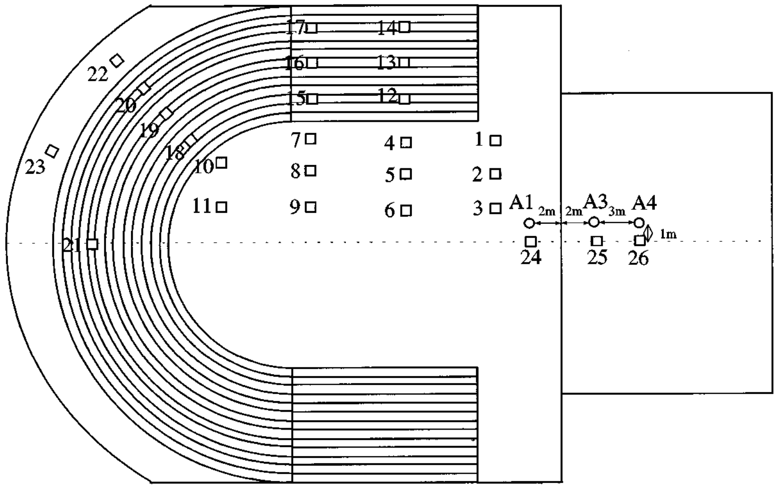

Figure 5. Plan of the renaissance theatre. The first two rows in the orchestra and the first column in the auditorium must be dropped if the plan is semicircular.

4. MEASUREMENT METHOD

Once the procedure of set-up and of relative positions of sources and receivers has been decided, the measurement can be based upon different methodologies. These choices are not linked to the typology of space and result in many suitable measurement methods.

4.1. MEASUREMENT PRINCIPLES

The primary data for the acoustical evaluations of the opera houses and for the application of the technologies of virtual acoustics are the impulse responses in the different positions inside the hall. To obtain impulse responses of good quality in terms of signal-to-noise ratio a widely employed method is the joint use of pseudo-random sequences as test signals (i.e., maximum length sequences) and of correlated time averages [7]. This approach is here proposed as the basic method for measurements inside historical opera houses.

An alternative principle, which is currently being tested and compared with the former during the course of the measurement campaign, involves the use of a signal called "time stretched pulse" and the respective deconvolution of this signal from the system's response. This method, as suggested by its current users [T. Hidaka Pers. Comm.], proves more robust against the microvariations of the thermo-igrometric conditions of the hall during the measurement since it is based on a shorter time emission of the test signal.

4.2. RECORDING THE OPERA HOUSE RESPONSES: MONAURAL, BINAURAL AND B-FORMAT MEASUREMENTS

To record the test signal there exist different methods, each involving favourable aspects and unfavourable ones. In the present context, a balance has to be struck between the needs of having a simple methodology and of making the most accurate measurement possible. With this in mind, the procedure of making the measurements can follow three separate methodologies, which permit one to retrieve in each case the basic acoustical data but which provide raw data of different kinds.

The choice of the methodology is left to the experimenter and strongly depends on the time available for measures and post-processing, and on the equipment that can be employed during the surveys.

4.2.1. *Monaural recordings*

The fundamental methodology of recording the hall responses employs a monaural probe consisting of an omnidirectional microphone. Monaural measurements of this kind allow the straightforward calculation of a set of useful objective parameters and can thus be regarded as the basic choice for a general purpose investigation.

To gain insight into the spatial characteristics of the sound field a combination of monaural measurements with microphones of different directivities is needed (i.e. omnidirectional versus figure-of-eight with null axis pointing to the source). This latter choice can be regarded as an enhancement of the monaural recording methodology, mainly linked to the set of parameters to be evaluated.

4.2.2. *Binaural recordings*

For a complete evaluation of the spatial attributes of the acoustic field it is necessary to have the binaural impulse responses which contain the dissimilarity perceived at the positions relative to the ears of an anthropometric sound probe, typically a dummy head equipped with two microphones [8]. But, while there is generally a good agreement on the measurement method of monaural impulse responses, the procedure of measuring with dummy heads is far less standardized and strongly depends on the sound transmission characteristics of the probe used.

4.2.3. *B-format recordings*

The third choice of recording is the use of a sound probe called "Soundfield" microphone [9] and to record the impulse responses according to the so-called B-format standard [10, 11]. The sound field microphone measures four monaural signals, the first being omnidirectional (sound pressure) and the other three corresponding to figure of eight directivities with major sensitivities directed along the Cartesian axes.

This approach permits a close reconstruction of the sound field without the need of anthropometric probes. Within this scheme the omnidirectional signal can be employed to evaluate monaural criteria and the spatial characteristics of the sound field are enclosed in the three directional signals. Moreover, this standard offers an easy implementation for the scopes of auralization. This technology is to be preferred to binaural technology since the translation from B-format to binaural format is possible whereas the *vice versa* is not.

5. TYPOLOGY OF MEASUREMENT EQUIPMENT

5.1. SOUND SOURCES

The sound sources for acoustic measurements shall meet strict requirements of omnidirectionality, particularly in the higher frequency range. In particular the limits in Table 1 of reference [2] must be largely satisfied. Together with the directional characteristics, a critical point of customary sound dodecaedric sources widely used for room acoustics measurements is their frequency range. For auralization purposes, it is necessary to guarantee an almost flat spectrum of the sound source from the octave band centred at 50 Hz to that at 8000 Hz, which seems actually to be rather critical to be obtained with commercial sources.

As far as the directional source to place in position A5 is concerned, its emission has to resemble the directivity of the singer (see reference [12]). But, since no standard sound sources are available for emulating the singing voice, the directivity pattern of the employed directional source shall be included in the documentation of the measures.

5.2. SOUND PROBES

The choice of the measurement method has a counterpart in the use of a suitable sound probe. For basic monaural measurements it is sufficient to use an omnidirectional microphone (typically 0·5 in) while enhanced monaural spatial measurements require a figure of eight microphone.

For standardized binaural measurements it is suggested to adopt either a spherical microphone which has exactly predictable acoustic transmission characteristics or a Kemar head whose acoustical data are fully available [13]. The binaural measurements can anyway be taken with any different dummy head provided that the probe meets the requirements of reference [2].

Finally, a special probe is required if the experimenter records the responses in the B-format standard. This probe is a four-channel soundfield microphone.

5.3. ACQUISITION AND ELABORATION DEVICES

The device employed for recording cannot be analogue: PC sound cards or DAT systems are both suitable digital solutions. In the latter case the retrieval of data for elaboration is made off-line. The quantization of the acquisition system is $\geqslant 16$ bits and the sampling frequency is $\geqslant 44.1$ kHz. In any case, the minimum S/N ratio of the acquisition system is 75 dB. The quality of primary data is ameliorated with the choice of an appropriate pseudo-random sequence length, which is set for an expected reverberation time of 2 s for the hall (upper limit) and 4s for the stagehouse.

5.4. CALIBRATION OF THE MEASUREMENT CHAIN

It is necessary to study the measurement chain in detail in order to guarantee a good repeatability of the surveys. The results also depend on the implementation of the descriptors but the approach in reference [2] ensures a sufficient compatibility between different strategies. In fact the global uncertainties deriving from different implementations of the acoustical descriptors all satisfying the cited norm are kept within the subjective threshold of variation of acoustical parameters [14]. As far as the calibration is concerned, the minimal requirement is the amplitude calibration of transducers by a pistonphone.

6. VALIDATION OF THE PROCEDURE

The indicated set of procedures and methodologies is constantly subject to ameliorization since new experiences are gained and new resources are developed. The first step in refining the guidelines was a test session inside the Municipal Theatre of Ferrara whose results supported the approach outlined in the document. In the following some of the most relevant points are reported and discussed.

Later, some other similar contributions both from renaissance and baroque theatres were collected though not included in this paper. The measurement inside the Municipal Theatre of Ferrara focussed mainly on verifying the criteria that led to the proposed set-ups concerning the preparation of the stage and the hall and the distribution of sources and receivers. Moreover, some hints for improving the measurement chain were also obtained.

To test the guidelines it was necessary to calculate some of the acoustical parameters commonly used in qualifying the acoustical environment inside enclosures so that the discussion could be based on objective criteria.

6.1. A MEASUREMENT CAMPAIGN INSIDE THE MUNICIPAL THEATRE OF FERRARA

The Municipal Theatre of Ferrara, dating back to 1798, was designed by Antonio Foschini e Cosimo Morelli and has an elliptical (truncated) plan with five tiers of boxes housing 2/3 of the 800 seats. In view of the acoustical measurements the theatre was prepared with a lowered orchestra pit and this implied a serious conflict with the current venues (drama, concerts, ballet, etc.) which are continuously held in the theatre. So, the experimenters had only one day for the acoustical measurements and they had to skip part of the indications given in the guidelines reported above.

First of all, it was not possible to suspend curtains at the back of the stage as recommended for the set-up of the stagehouse. The stage was completely free of scenery and offered the view straight to the back wall at the end of it, as shown in Figure 6. In Figure 7 the view of the lateral walls of the stagehouse is presented and it can be seen that there were no lateral wings.

As regards the positions of sources, the one in the pit, named A1, was that of the 1st violin (see Figure 8) and the one on the stage (A3) was the position of the singer, under the proscenium arch at 5.8 m from the side wall (see Figure 9). The positions of deep instruments at the back of the pit and of the singer at the back of the stage have not been investigated. It was also impossible to use a directional source to better emulate the singer.

Only a reduced set of 12 receiver points was used instead of the 22 positions which are required for a thorough survey. In Table 1 the numbering of measured positions is in accordance with the former guidelines.

After the first round of measurements the fire-curtain and two lateral curtains were closed and the measurements were repeated with the stage enclosure and hall uncoupled, at the same points inside the hall with the source in the position of the 1st violin, namely position B1. Measures were also taken at one point in the middle of the stagehouse with source on the same side (position B2).

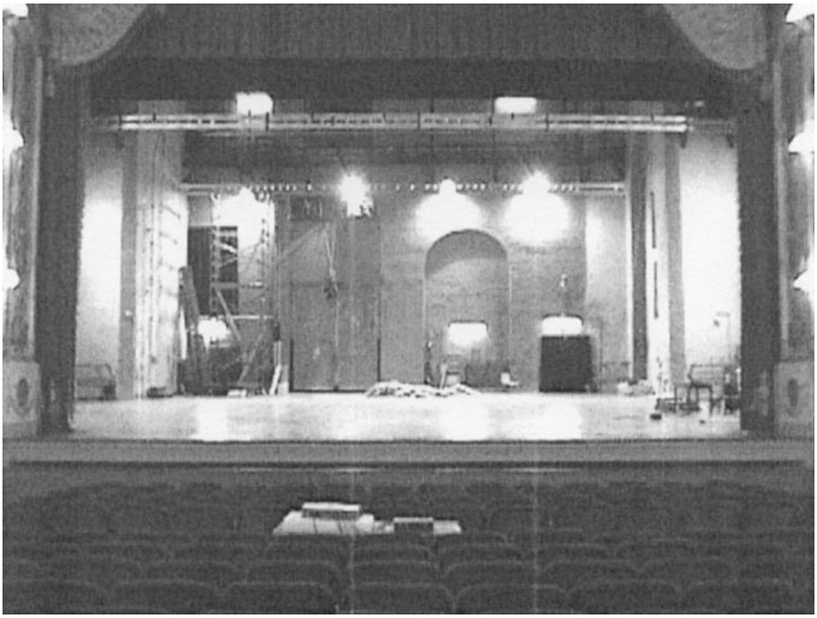

Figure 6. View of the empty stage from the hall.

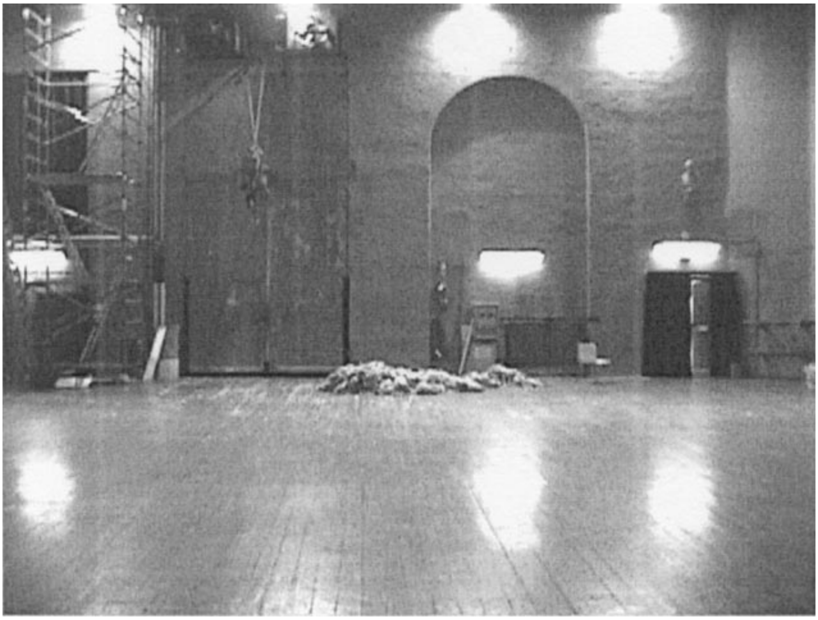

Figure 7. View of the side-walls of the stagehouse.

Figure 8. Position A1 corresponding to the 1st violin.

Figures 10 and 11 help in describing the experimental conditions.

Regarding the measurement technique and methodology, in the test session both B-format (with sound field microphone) and binaural (with Sennheiser dummy head) measurements were obtained. Sources and receivers were placed at the correct height from the floor and the latter faced the sound source.

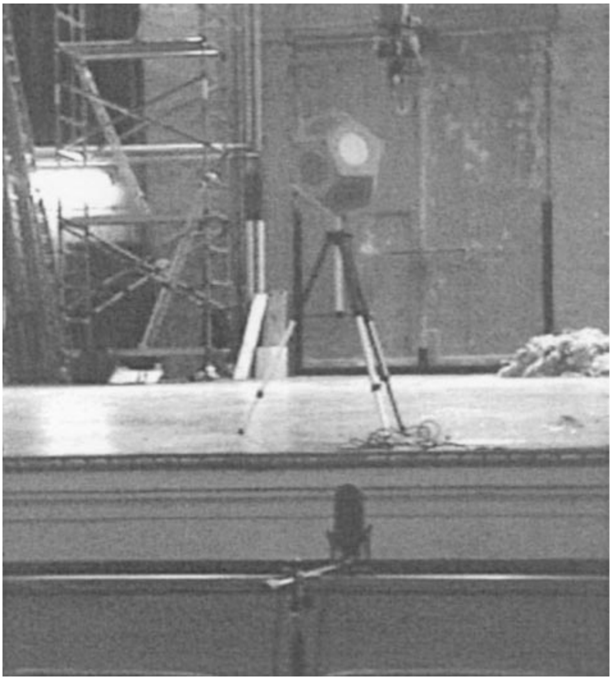

Figure 9. Position A3 corresponding to the singer with sound field microphone in the position of the conductor.

TABLE 1

Positions of receivers for the test session inside the Municipal Theatre of Ferrara, the numbering is referred to from Figures 1 *and* 3

Stalls	*Gallery*
Seat 3 Row 6 → P2	Seat in line with box 4 I° Tier → P16
Seat 1 Row 11 → P4	Seat in line with box 9 I° Tier → P18
Seat 5 Row 13 → P6	*Orchestra pit*
Seat 7 Row 15 → P8	Conductor → P19
Boxes	Deep instrument under overhang → P21
Box 4 I° Tier → P10	*Stage*
Box 9 I° Tier → P12	Singer (under proscenium arch, at 6·8
Box 7 III° Tier → P14	from side-wall) → P 20

The test signal was a maximum length sequence of order 16 in the cavea and 17 in the stagehouse. Due to the lack of time no sweep signals were used. The dodecaedric source was a standard Norsonic.

After collecting the primary data in the field the acoustical parameters, like reverberation time, clarity, early decay time, interaural cross-correlation, etc., were later calculated in the laboratory.

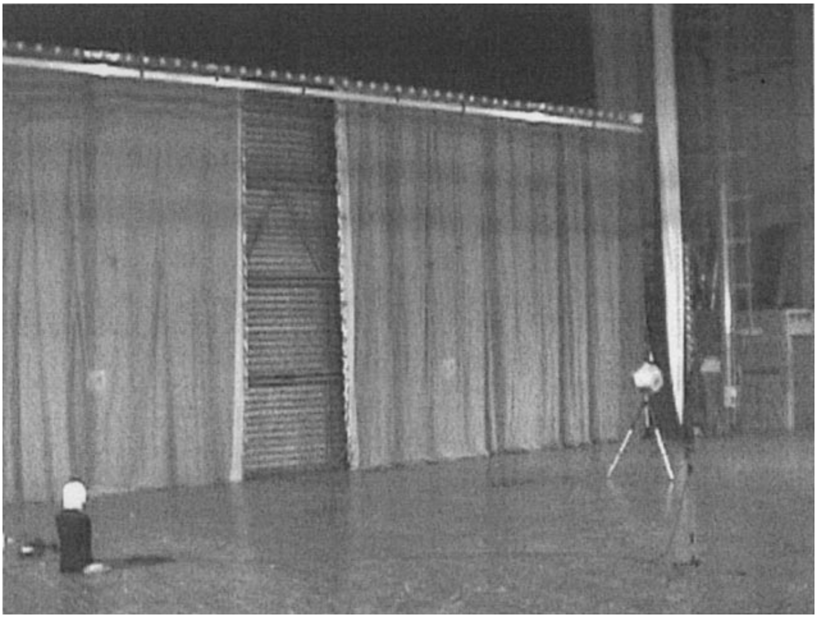

Figure 10. Position of the source and of the B-format and binaural receivers in the stagehouse.

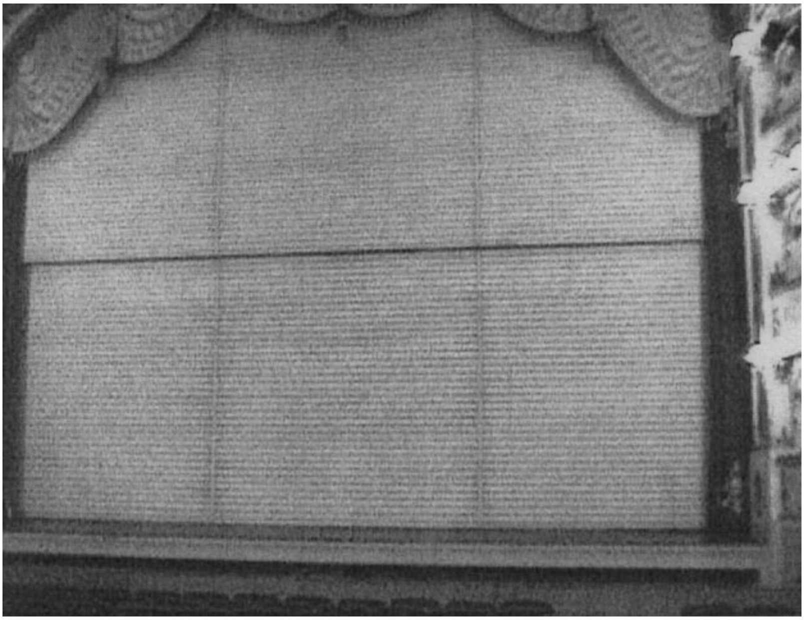

Figure 11. View of the fire-curtain from the hall.

6.2. VERIFICATION OF SET-UPS

The prescribed choice of the set-ups to be considered inside the theatre had to be investigated experimentally since the relationship of the cavea with the volume of the stagehouse is, to the knowledge of the authors, not extensively documented in the literature.

The main criteria to be verified were actually two: fitting of the stagehouse to make its reverberation time comparable with that of the cavea; suitability of the separation to allow the acoustical description of the cavea.

The first point turned out to be rather critical because the special fittings required, consisting of 500 m^2 of heavy curtains, could not be mounted at the back of the stage. The resulting values of reverberation times are shown in Figure 12, where the receiver position in the stagehouse (sound source in B2) is compared with the averaged values of reverberation time calculated in the stalls for the sound source in B1. The two sets of data show the same trend across the considered frequency range, with a mean difference of nearly 0·2 s between the respective values. One difference is found at the highest frequency, where the B1 line overcomes the reference line. In this case the nature of the fire-curtain, which is almost reflective but not sound absorbing as shown in Figure 11, probably affects the reverberation time in the cavea.

The reverberation time measured in the stagehouse takes into account the absorption of only the two lateral curtains (see Figure 10) which had to be pulled after lowering the fire-curtain.

From these results of unbalanced reverberation in the two uncoupled enclosures the need of a wider absorbtive area in the stagehouse is confirmed , that can be prepared with one curtain or more lateral wings if easier.

Secondly, the collected data had to validate the suitability of set-up B in order to acoustically describe the cavea independently of the stage, whose fitting and acoustical response is strongly dependent on the current venues in the theatre.

Figures 13–15 show the reverberation times as calculated in the stalls, in the boxes and in the gallery respectively for the three positions of the sound source A1, A3 and B1. The three graphics share equal behaviours but also show some differences. In particular, the A1 to A3 lines have an almost constant distance of nearly 0·1 s in the whole band due to the more relevant excitation of the volume in the stagehouse when the sound source is placed on the stage.

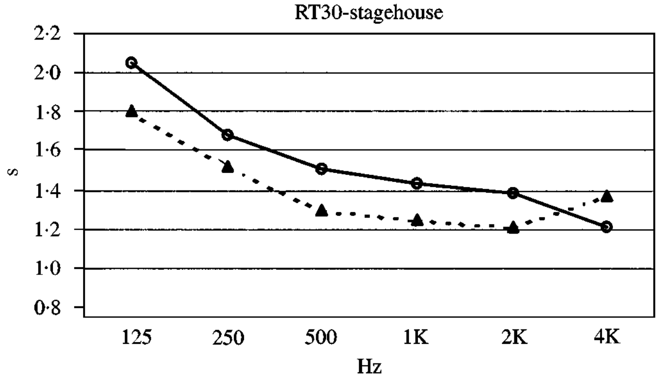

Figure 12. Comparison of the reverberation times in the cavea and in the stagehouse. Comparable values are not met with described fitting: —●—, B2; ---▲--, Ref.

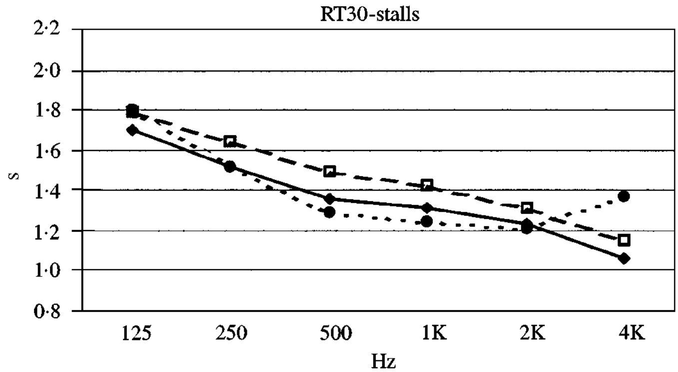

Figure 13. Reverberation times measured in the stalls for three positions of the sound source. Note the behaviour of A1 relative to A3 and B1 relative to A1: —◆—, A1; – –□– –, A3; - - -●- - -, B1.

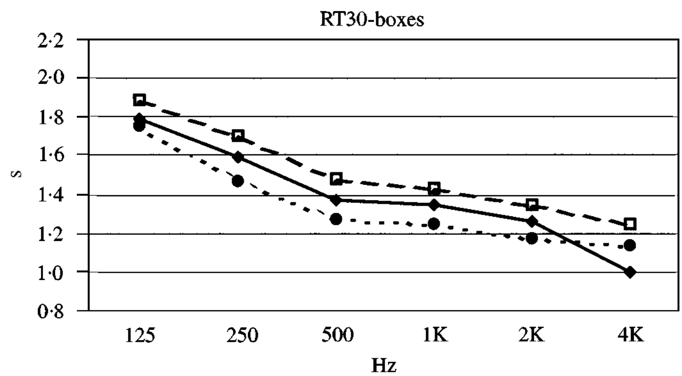

Figure 14. Reverberation times measured in the boxes: —◆–, A1; – –□– –, A3; - - -●- - -, B1.

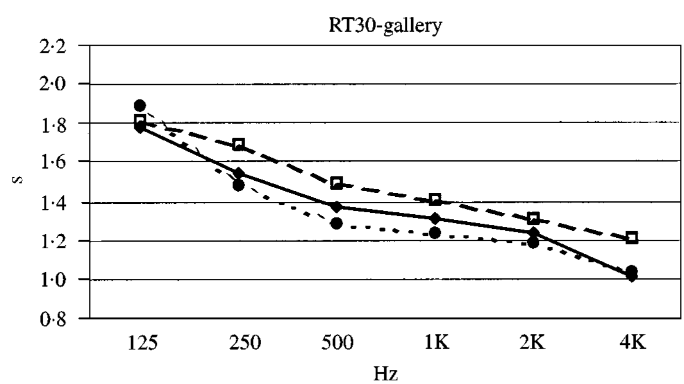

Figure 15. Reverberation times measured in the gallery: —◆—, A1; – –□– –, A3; - -●- - , B1.

This measure provides hints to spot the different perception of sources in the pit and in the stage as heard by listeners in the theatre, and the effect seems to be equally perceptible at every position inside the cavea.

It is also interesting to compare the A1 and the B1 lines. The latter should in fact, in the intention of the guidelines, be regarded as a curve for characterization of the cavea alone. This curve has generally lower values than either A1 or A3 because of the smaller volume and higher sound absorption involved in the reverberation process and, apart from deviations at the borders of the measured frequency interval, it shows the same behaviour as the A curves. While the excessive reverberation time at higher frequencies can be probably ascribed to the nature of the fire-curtain, the reason for the higher values found at the lower frequencies is not easily spotted.

In conclusion, the prepared condition for the separation of the cavea and the stagehouse gives the opportunity to make acoustic tests under specified and repeatable conditions, which can be greatly useful if some changes are introduced in the cavea. In particular, if some renovations introduced in the furniture alter the reverberation time, it will be possible to compare the reverberation time curves taken for the same set-up before and after the restorations. In this case, it is advisable to take into consideration also the contribution of the typology of separation betweeen cavea and stagehouse

6.3. VERIFICATION OF POSITIONS OF SOURCES AND RECEIVERS

As reported above, the distribution of sources and receivers could not be optimal during the test session owing to the time constraints that forced the experimenters to reduce measuring points and source locations. Should the time limits be even more serious, in the guidelines a simplified procedure is indicated which is the most time-saving approach for obtaining acoustical data inside the historical theatres.

In this context, a balance has to be struck between accurate documentation and resources available to pursue the surveys. The criteria for considering an optimal grid of points in the different parts of the theatre is the ability of such data to discriminate on average the zones of the theatre in terms of acoustical parameters. In other words, the best grid should be able to describe, with few points, the different listening conditions experienced inside the theatre for different positions of sound sources.

After these premises the set of acoustical parameters has been investigated and some of the results are reported here. In particular, in Figures 16 and 17 the clarity for music is considered as measured in the stalls and in the boxes for the source positions A1 and A3. In each graphic the averaged values on the measured grid and those calculated in the points recommended for the simplified procedure (see section 3.1.3) are compared.

The clarity has generally appropriate values in the theatre [15], with a global increase when the sightline between source and receivers is free. Moreover, the different listening conditions between stalls and boxes are also well evidenced by the grid chosen.

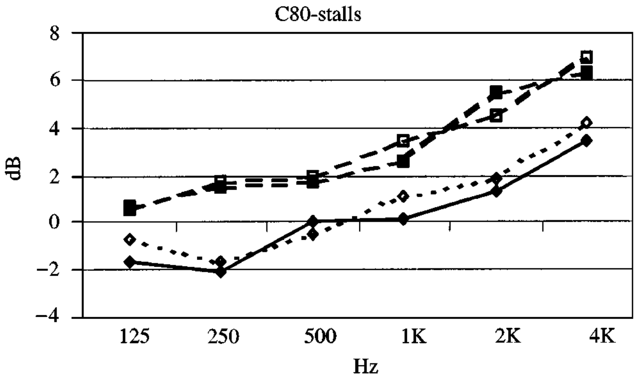

Figure 16. Clarity in the stalls for two positions of the sound source. The measurement location of the simplified procedure (P5) is included for comparison: —◆—, A1; – –□– –, A3; – –◇– –, A1P5; – –■– –, A3P5.

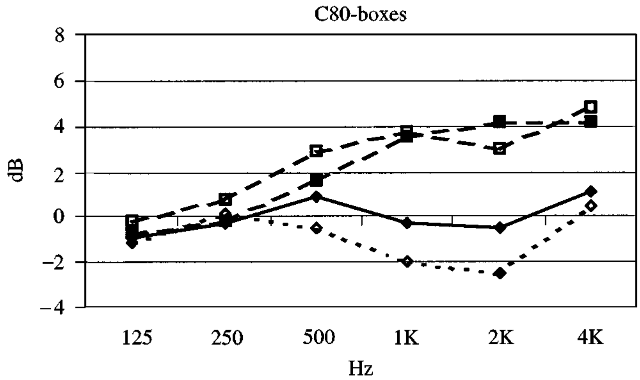

Figure 17. Clarity in the boxes. The position P14 indicated in the simplified procedure is also included: —◆—, A1; – –□– –, A3; – –◇– –, A1P14; – –■– –, A3P14.

It is also interesting to note that, if one considers only the points for the simplified procedure, only minor differences show up for positions in the stalls, where the listening conditions seem to be more uniform. The same concept, when applied to one position in the boxes, causes a wider gap in the parameter, which is nevertheless acceptable considering that the just noticeable difference for clarity is usually set between 0·5 and 1 dB. The simplified procedure can thus be considered as a good alternative for making surveys with reduced effort.

7. CONCLUSIONS

In the paper the guidelines for acoustical measurements inside historical theatres have been presented with reference to the typologies of renaissance and baroque theatres. The work profitted from the advice of international specialists of acoustical measurements inside theatres and has the intention to serve as an operational tool for measurement campaigns within both topologies of acoustical spaces.

The indications reported in the document have successively been tested with a dedicated measurement session inside the Municipal Theatre of Ferrara. The results presented in the paper regarded the main issues of the guidelines, concerning the choice of the set-up and the distribution of sources and receivers in the theatre. In both cases the validity of the recommendations were verified and their limits were also clarified better.

ACKNOWLEDGMENTS

The authors express their gratitude to the members of the working group that gave advice in the development of the guidelines: Yoichi Ando, Michael Barron, John Bradley, Alessandro Cocchi, Daniel Commins, Robert Essert, Angelo Farina, Patrizio Fausti, Anders Gade, Takayuki Hidaka, Carmine Ianniello, Eckart Mommertz, John O'Keefe, Hiroyuki Sakai, Shin-ichi Sato, Catherine Semidor, Domenico Stanzial. This work has been supported by the National Research Council of Italy, contract No. 97.00686PF36.

REFERENCES

1. C. N. R. 1997 *Progetto Finalizzato Beni Culturali*, Roma.
2. ISO/DIS 3382 1997 *Acoustics: Measurement of the Reverberation Time with Reference to Other Acoustical Parameters*. International Organization for Standadization.
3. M. BARRON 1993 *Auditorium Acoustics and Architectural Design*. London: E & FN Spon.
4. L. CREMER and H. A. MUELLER 1982 *Principles and Applications of Room Acoustics*. London: Applied Science Publishers.
5. J. MEYER 1998 *Proceedings of ICA-ASA '98, Seattle (WA)*, 20–26 June, 337. Sound fields in orchestra pits.
6. C. N. BLAIR 1998 *Proceedings of ICA-ASA '98, Seattle (WA)*, 20–26 June, 339. Listening in the pit.
7. D. RIFE and J. VANDERKOOY 1989 *Journal of Audio Engineering Society* **37**, 419–444. Transfer function measurement with maximal-length sequences.
8. Y. ANDO 1998 *Architectural Acoustics: Blending Sound Sources, Sound Fields, and Listeners*. New York: Springer Verlag.
9. K. FARRAR 1979 *Wireless World* Ott. & Nov. 99–103. Soundfield microphone: Part 1 & 2.
10. P. B. FELLGETT 1974 *Nature* **252**, 534–538. Ambisonic reproduction of directionality in surround sound systems.
11. M. GERZON 1975 *Journal of Audio Engineering Society* **23**, 569–570. Recording concert hall acoustics for posterity.
12. H. MARSHALL and J. MEYER *Acoustica* **58**, 130–140. The directivity and auditory impressions of singers.
13. B. GARDNER and K. MARTIN 1994 *Technical Report* 280, *MIT Media Laboratory of Perceptual Computing*. HRTF measurements of a Kemar dummy-head microphone.
14. M. VORLAENDER and H. BIETZ et al. 1995 *Acoustica* **81**, 344–355. Uncertainties of measurements in room acoustics.
15. H. A. MUELLER 1993 *Proceedings of International Conference on Acoustics and Recovery of Spaces for Music, Ferrara*, 51–60. Roomacoustical criteria and their meaning.

APPENDIX A

A modification of the preceding guidelines is possible if the opera house is equipped with an orchestra shell. This acoustical device, which can actually be found only in few theatres, shoul be indispensable for the performances of symphonic music. Should the orchestra shell be present, a set of primary data will be taken with the shell mounted as during the executions of symphonic music. The distribution of sources and receivers is, in this case, similar to the set-up A, with the following differences: sources A1–A4 keep their positions in plan as in Figure 1 but are on the stage since the orchestra pit disappears during symphonic concerts; Receivers 19, 20, 21 and 22 are on the stage for the same reason.