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Computer model investigations on the balance between stage and pit sources in opera houses

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Abstract

The acoustical balance between the singer on the stage and the orchestra in the pit is typically found inside an opera house. The competition of the two sources is crucial, since in an opera the singer and the orchestra are performing at the same time. This topic of balance is receiving increasing attention in recent years, but several aspects are still to be clarified. The aim of this work is twofold: firstly the procedure for the acoustical qualification of the balance between the singer and the orchestra is investigated and secondly the means of controlling the balance at the design stage or during renovations is considered. For both tasks the study was conducted in a group of opera houses modelled within an acoustical CAD program. As regards the qualification of the balance this investigation compares the directional characteristics of two loudspeakers and of a dodecahedron omnidirectional loudspeaker in the emulation of a soprano during simulated room acoustics measurements. It is shown that, in order to emulate a soprano singer, the directional characteristics of the source on the stage are quite important. The control of balance was also studied and the work reserves a special emphasis to the case of historical opera houses. In fact, when such theatres are refurbished, the range of possible architectural interventions is often limited to the orchestra pit only, due to the heritage nature of the hall which prevents from any substantial change in the area of the forestage. For this reason it is important to investigate the effectiveness of such limited interventions in the pit, and this is done here by a detailed study of the effects on balance of some major changes of the orchestra pit only.

Keywords: Balance; Opera house; Qualification; Design

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1. Introduction

The interplay between orchestral and vocal sources is most critical for an opera. These two sources have different acoustical needs: for the singer the clarity and intelligibility of his/her voice is of paramount importance, while reverberance and spatial impression are required for the orchestral sound. Thereby in the acoustical design of an opera house a compromise has to be found. A good balance between the singer on the stage and the orchestra in the pit is achieved when the combination of the two sources preserves both clarity and intelligibility together with a suitable sound level and spatial attributes. Earlier studies [1] showed that the balance between the singer and the orchestra depends basically on their sound power ratio. The singer can be heard over an orchestra because of the formant frequencies of the singing voice, which usually can be found in the frequency range 2500–3000 Hz [2]. In that frequency range the singer spectrum dominates over the sound of an orchestra. Some psychoacoustics tests have been carried out in the field [3] to assess subjects' preference for pit and stage sources. Then the level ratio of stage and pit sources was thought to be the clue for the balance qualification, and by listening tests a set of appropriate values was extracted [4]. Moreover the role of reverberation time and interaural cross-correlation on balance were also considered [5] and their relevance was discussed.

Together with the systematic study of the perception of balance by listeners some efforts were done in the past to assess the measurement procedures for the attribute. Unfortunately the technical norm [6] still does not give hints for this task and even the specialized document [7] for qualification of historical opera houses was actually not exhaustive on this issue. The main contributions on the qualification of balance are due to Barron [8] and O'Keefe [9]. The former carried out measurements in three British opera houses using a loudspeaker source with a directivity close to that of the human speaker on the stage and an omnidirectional source in the pit. The balance was evaluated comparing the sound pressure level in the auditorium emitted by two sources playing with the same sound power level. O'Keefe defined two different balances from the listener's perspective: on the orchestra level (stalls) and on the balconies. In the stalls, the direct sound from the pit is subjected to the barrier effect due to the pit rail. In the balcony positions the listeners can see both the stage and most of the pit. This means that they can be reached by direct sound without any barrier effect. He used an omnidirectional dodecahedron source in the pit and a directional source on the stage which was fashioned from the dodecahedron by sealing eleven units with steel plates.

Regarding the measurement procedures for the qualification of balance one of the main points that needs clarification is the definition of a suitable stage source in order to emulate a singer. In fact using a conventional dodecahedron might result in deviation from the effective singer sound emission but the amount of such discrepancies and their acceptability in the context of balance qualification is still to be assessed. Recently an experimental study inside an historical opera house [10] compared the performance of two different two-ways loudspeakers with an anthropometric sound source in the context of balance qualification. The solution of a two-ways sound source in the emulation of the singer resulted in excessive inter source variability.

Other issues have to be explored in order to effectively control the balance between singer and orchestra. In particular the relation between this attribute and the design of a theatre is not sufficiently studied, so that it is not clear what are the most important surfaces that allow the control of balance in the design process. In this respect few experiences were reported, in [11] the role of a single reflection was tested by means of scale model measurements.

The present work was focused on two major issues: firstly the optimization of the measurement procedures for the problem of the objective qualification was considered and secondly the control of balance by architectural elements was investigated.

As detailed below, the study was based on computer model simulations which took into consideration a group of different theatres, sound sources and architectural changes in order to possibly derive more general conclusions on the former issues.

2. Measurement procedure for the objective qualification of balance

2.1. The simulated theatres

The studies of balance were carried out by room acoustics simulations of three opera houses using the software Odeon® 6.0 [12]. The simulations were performed in the models of the Royal Theatre of Copenhagen (RO), of the Ankara Congress and Cultural Centre (CO) and of the Alberta Jubilee Auditoria (AL). The basic models were provided by the acoustics group at the Technical University of Denmark (DTU) and were later modified according to the scopes of the present research.

While RO and CO have a horseshoe shape plan, AL has a fan shaped plan. Moreover the three theatres belong to different historical periods. RO is a classical example of the Italian Baroque style while CO is a new opera house, still under design, in which the concept of a horseshoe shape has been applied in a modern perspective. The fan shaped theatre AL dates to the early sixties. The plans and the sections of the house models are shown in Figs. 1–3 for RO, CO and AL respectively. Moreover their main geometrical characteristics (Table 1) show that their overall dimensions span over a wide range from the smaller CO to the bigger AL. In the table also the mid frequency reverberation time of each hall is included for reference. Those values were obtained by a conventional model calibration procedure either to match the experimental data or, in the case of CO which was at a design stage, as an acoustical target to be achieved.

Once the models were available also the positions of the sound sources and of the receivers were investigated. RO was firstly used to fix the suitable source positions on the stage and in the pit, and the receiver positions too. The source positions on the stage are the same in each theatre and are resumed in Table 2. The only difference is found for the source location named "P2", where the distance to the symmetric axis depends on the width of the pit. In order to define the number and location of the receivers, a grid response was simulated. The receiver positions were defined as the positions in which noticeable differences in the obtained values could be observed. Once the source and receiver positions were fixed in RO, and simulations were carried out, the other theatres were considered too. In CO and AL the symmetry was verified so the receivers were confined to half of the hall. Since in the context of balance the stage design is quite relevant, it was decided to model a stage set with the same characteristics in the three theatres. Fig. 1 includes the plan and the lateral view of the stage set with indication of the sound absorption of the main surfaces. The design of the stage set was the same in each hall but its overall dimensions were adapted to those of the specific stage.

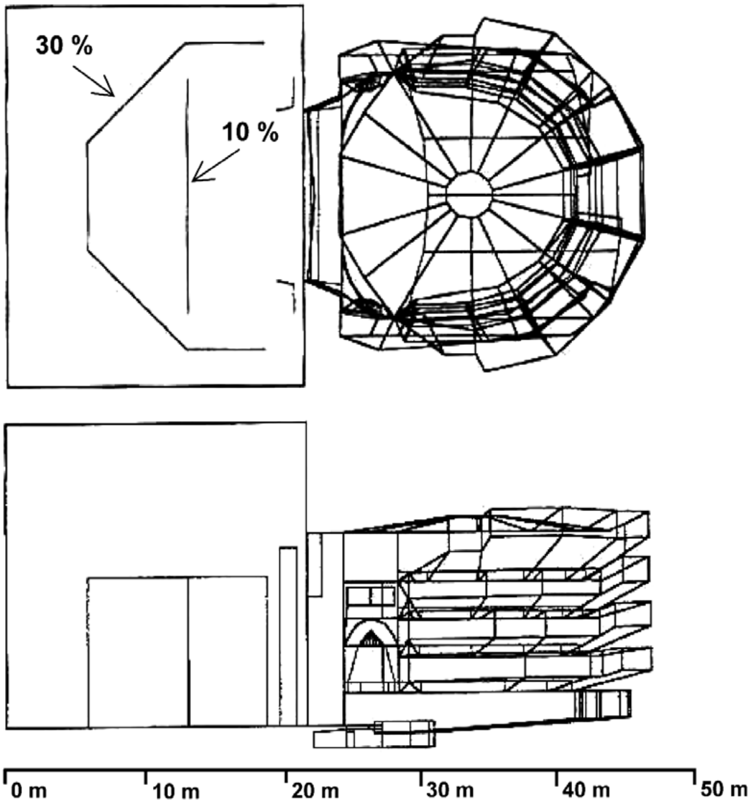


Fig. 1. Plan and section of the Royal Theatre in Copenhagen. A simple sketch of the scenery is included with indication of the simulated sound absorption. The overall stage settings dimensions depended on the specific stage dimensions within each theatre.

2.2. The measurement and simulation of the sound sources

In order to extract valid balance data from the computer models an extended study on the directional characteristics of the sound sources to use was performed. In particular the target source was defined as a soprano voice, whose directivity was measured in an anechoic chamber. The measurement were done with a multi-channel system consisting of 23 microphones. One of them acted as a reference in front of the singer to calibrate the level of the other 22 positions which were arranged on two arches. These were respectively an elevation arch with a span of 90° and an azimuth arch with a span of 180°. The setup for this measurements is shown in Fig. 4.

The singer was rotated 90° each time and measured with a resolution of 10°. She was asked to sing isolated tones in two octaves from A4 (220 Hz) to A6 (880 Hz). This was done to cover most of the soprano register, but only a subset of this data was used for the later processing. The recordings from the four positions were then used to build up the average directivity patterns in the octave bands from 125 to 8000 Hz. These

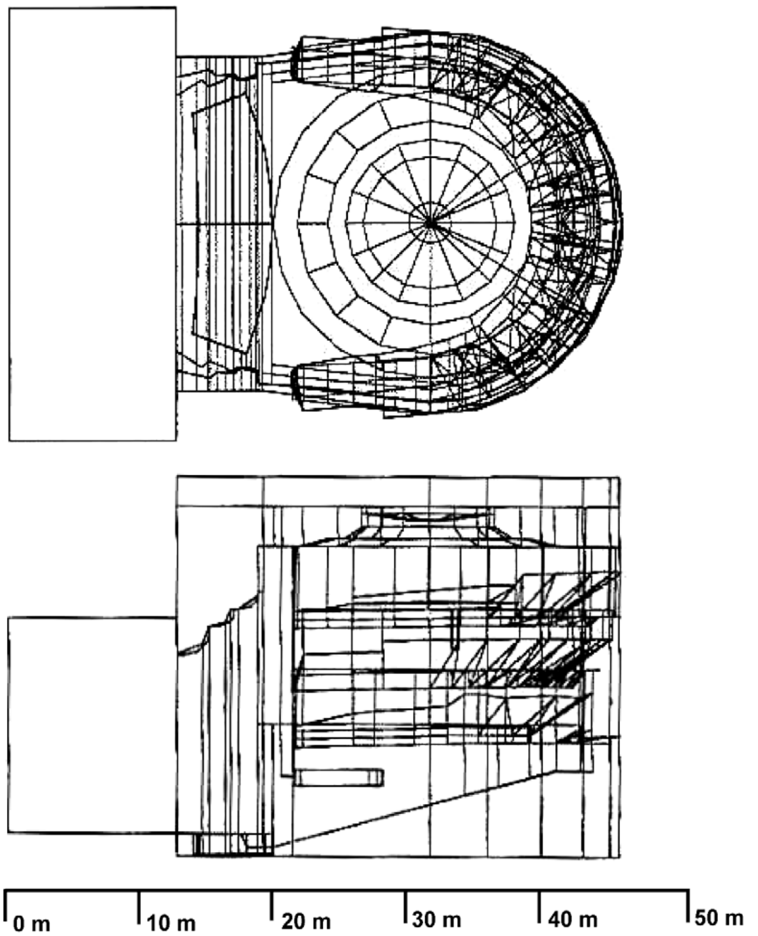


Fig. 2. Plan and section of the Congress and Cultural Centre in Ankara.

measurements can be compared with former results for a baritone voice [13]. The comparison of the two voice registers shows a substantial agreement in the radiation patterns. Their azimutal directivities both at 500 Hz and 1 kHz are closely matching. In particular it is interesting to note that for both of them at 1000 Hz and at the angle of $\pm 60^\circ$ the emission is stronger than the frontal one. The only significant deviations are in the 2 kHz and 4 kHz bands where the directivity of the soprano is a little sharper in the front and slightly smaller in the back. The elevation data are matching at all frequency bands. Clearly the above comparison cannot cover the individual variability which might alter the directivity pattern in some respect: anyway this is believed to be representative of the general trend of the two voice registers.

In order to define a loudspeaker which is suitable to emulate the soprano the directional characteristics of two directional full range loudspeakers were measured in an anechoic chamber too. They were selected as being representative of conventional loudspeakers that

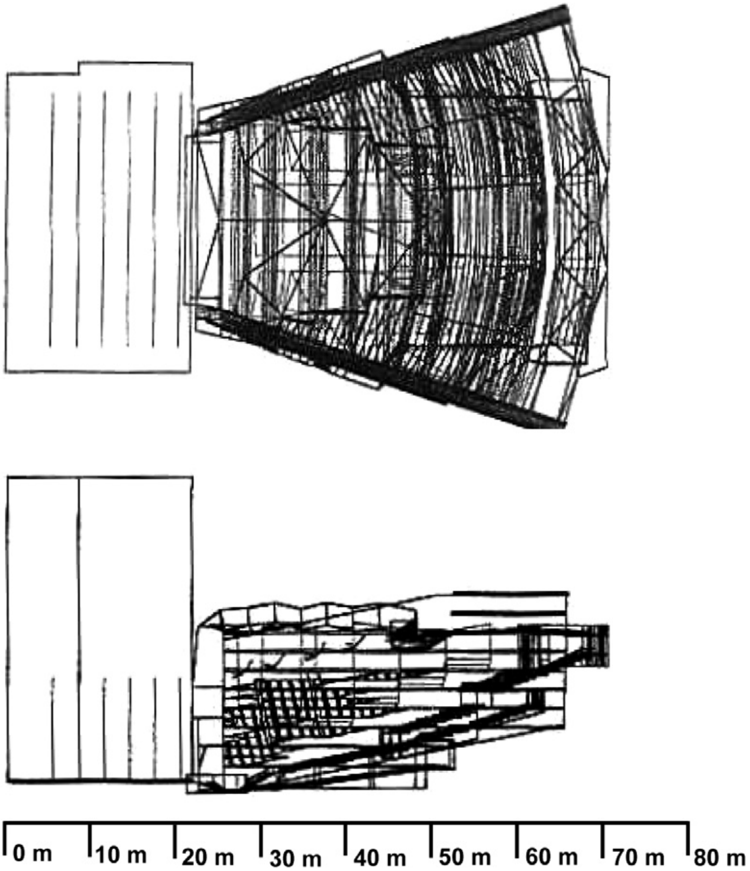


Fig. 3. Plan and section of the Alberta Jubilee Auditoria.

could be used in the context of balance measurements. The loudspeakers had different shapes and sizes in order to evaluate the influence of their cabinets. The first one, called "A" thereafter, was a dodecahedron with 12 units arranged one per face. Each unit is 5" and a directional behaviour was obtained by connecting just one frontal unit while keeping the others unplugged. The second source was a 6" unit mounted in a rectangular wooden box of dimensions $20 \times 20 \times 15$ cm and will be called "B". The two sound sources are shown in Fig. 5.

Thus their directivities were measured in the step of 10° by means of a rotating apparatus and a single microphone at a fixed position. In this case the measurements were focused on the octave bands from 500 Hz up to 4000 Hz.

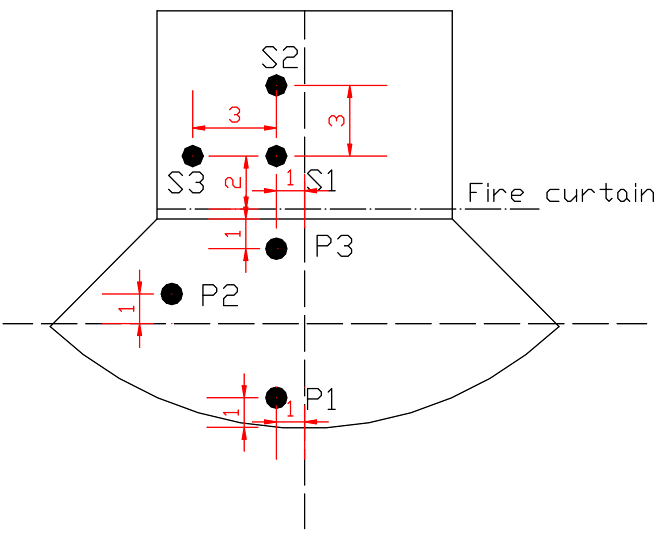
The radiation patterns of the soprano was compared with the radiation patterns of the loudspeakers in the four octave bands of interest as reported in the Figs. 6a and 6b (azimuth) and Figs. 7a and 7b (elevation). The azimuth data at 1 kHz at the angle between 90° and 270° shows values 8 dB higher for the soprano. On the contrary at 2 kHz and between 60° and 300°, the directivity of the soprano is 4–8 dB lower than either A or B.

Table 1
The main geometrical and acoustical data of the simulated theatres

	Royal theatre of Copenhagen (RO)	Ankara congress and cultural centre (CO)	Alberta Jubilee Auditoria (AL)
Total volume [m^3]	20.950	42.000	87.000
Stage tower volume [m^3]	12.977	6.602	28.000
Proscenium surface [m^2]	115	202	206
Number of seats	1400	1350	2750
RT30 [s]	1.1	1.3	1.4
V/N [m^3/seat]	5.7	26.2	21.4
Pit surface [m^2]	129	93	138
Max dimensions			
Height	23.40	28.75	38.06
Length	46.25	45.88	71.38
Width	27.70	32.50	54.28

The elevation data at 4 kHz between 30° and 180° show as much as 10–12 dB of prominence of the soprano with respect to either A or B. At the other octave bands the radiation patterns are close to each other. In the next section the influence of such differences will be illustrated.

Table 2
A sketch of the locations of the sound sources in the pit and on the stage of the models



Theatre	Source		Receivers	
	Stage (height: 1.5 m)	Pit (height: 1.2 m)	Stalls	Balconies
Royal Theatre of Cop. (RO)	S1, S2, S3	P1, P2, P3 P2 at 4.5 m to the symm. axis	8	13
Ankara Cong. Centre (CO)	S1, S2, S3	P1, P2, P3 P2 at 7 m to the symm. axis	8	10
Alberta Jubilee Aud. (AL)	S1, S2, S3	P1, P2, P3 P2 at 8.5 m to the symm. axis	5	6

The number of the receivers and their distribution between stalls and balconies is also reported.

Fig. 4. The setup used for the directivity measurements of the soprano singer in an anechoic chamber.

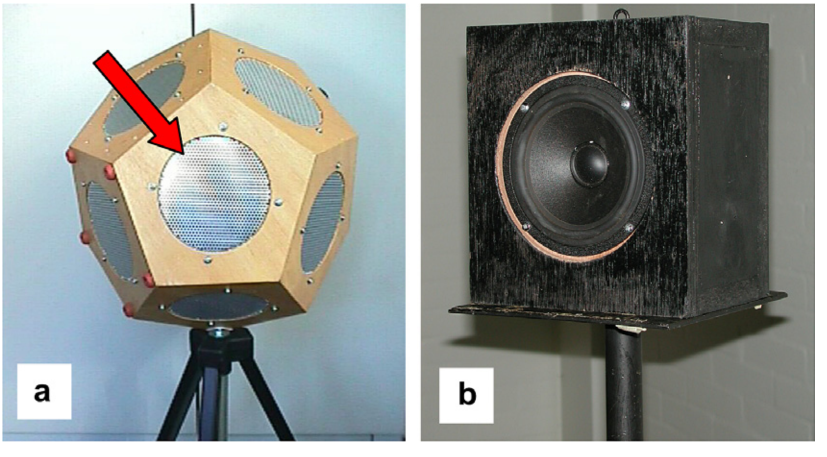


Fig. 5. The two directional sound sources used to reproduce the directional emission of the soprano. Source A is a dodecahedron with only the frontal unit working whereas the B source is a full range loudspeaker enclosed in a cabinet.

2.3. Results of simulated balance measurements

The theatre models were joined to the sources and the stage sets to perform simulated measurements of balance. Clearly the aim was to investigate the impact on balance qualification of the directional sources (named A and B) and of the omnidirectional one (called

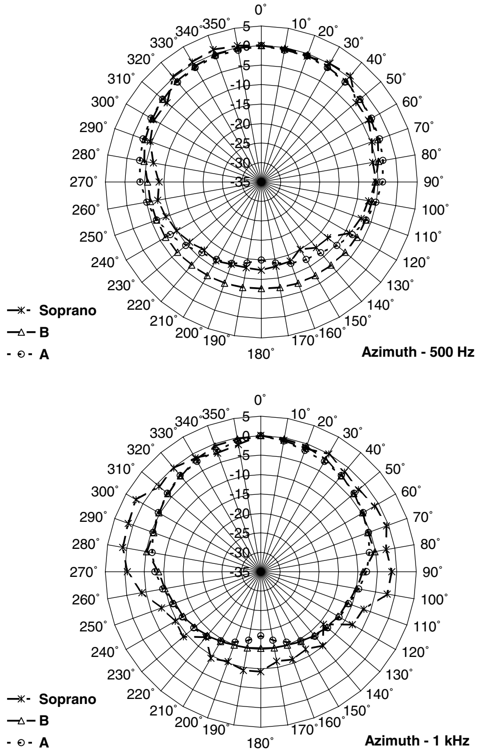


Fig. 6a. Comparison of the azimutal octave band directivities of the soprano and of A and B sources. Top: 500 Hz; bottom: 1 kHz.

O) when compared to the soprano (S), which was taken as the target. To avoid artefacts each source was simulated with the same sound power level in each octave band, that is 90.7 dB in the octave range from 63 Hz to 8000 Hz corresponding to an all pass sound power of 99.7 dB (97.7 dBA) which is realistic for operatic singing at top emission.

The complete set of four sound sources O, A, B and S was simulated for each of the three positions on the stage whereas only O was simulated in the pit positions.

The balance results are the sound level from the stage (alone) obtained with any of the directional sources relative to the omnisource in the pit taken as the reference. Then the results obtained with S were subtracted from the others in the respective combinations of sources and receivers. This means that the closer the values are to zero, the more the behaviour of the given source is similar to the soprano.

Finally, to better focus the effect of sources' directivities on balance, only the results in the octave bands from 500 Hz to 4 kHz were considered. Two graphics are shown: the average between 500 Hz and 1 kHz (Fig. 8) and that between 2 kHz and 4 kHz (Fig. 9). Both graphics include the max and min bar deviations as a measure of the range of values to be expected and a rough estimate of their scatter.

Actually the 500 Hz to 1 kHz bands show rather limited discrepancies of the simulated sources compared to S. The closer match is obtained in RO whereas CO produces a wider spread of data for all of the sources. Remarkably in the AL case the data show a limited

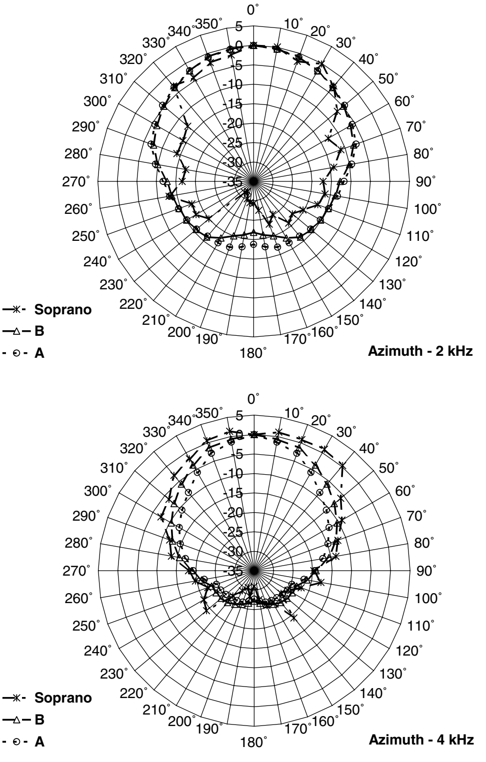


Fig. 6b. Comparison of the azimutal octave band directivities of the soprano and of A and B sources. Top: 2 kHz; bottom: 4 kHz.

spread. Moreover there is a tendency in the results to have the stalls with more energy compared with the balconies. This might be due to the slightly more pronounced sound projection of the soprano upwards (Fig. 7a) compared to the electro-acoustic sources. Anyway from this two bands one could conclude that the performance of O is almost comparable to that of both A and B in the simulation of the soprano, since the obtained biases are quite comparable for the three sources in the three theatres.

Then the average of 2 kHz and 4 kHz bands can be considered. In this second group of average results some more remarkable deviations are observed. In particular it is found that the O–S comparison is worst for all theatres. In particular CO and AL are systematically underestimated by nearly 3 dB or more, which is a clearly remarkable and perceptible quantity. Interestingly this is not the case for RO where the stalls value is actually quite close to 0 dB, and also the balcony data for the same theatre give a little less than 1.5 dB deviation. The A and B data show on average a very similar trend and a much better matching with S, though it is confirmed that CO suffers from a higher local scatter of data. Despite this spread on minima and maxima one can observe that the average results are less then or close to 1 dB. This seems acceptable in the context of balance qualification, where the smallest interval of scale values can be assessed at about 2 dB [4].

Like before it is seen that in CO the data are more scattered and the galleries are receiving less energy than the stalls in the case of A and B sources if compared to S, mostly due

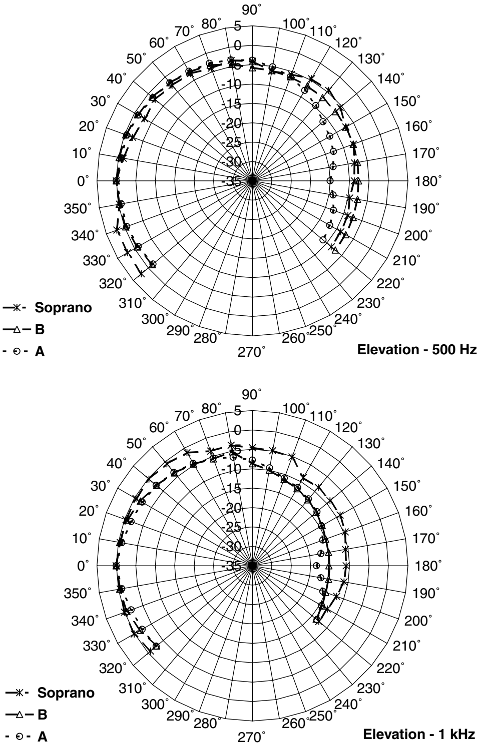


Fig. 7a. Comparison of the elevation octave band directivities of the soprano and of A and B sources. Top: 500 Hz; bottom: 1 kHz.

to the marked elevation directionality of S itself at 4 kHz. A similar trend is not seen regularly in AL probably because of the disposition of the balconies, which are at a lower level compared to the horse shoe theatres.

The result in Fig. 9 marks the distinction between the omnidirectional source and the two directional ones in reproducing a soprano voice. The sources A and B performed better in all of the halls. On the contrary O overestimated a little the soprano in the RO balconies and underestimated it by a relevant quantity, which was similar in CO and AL. These two halls have different plan shape, volume and geometry and this behaviour cannot be easily explained due to the peculiar interplay of all the above elements in each hall. It can be argued that the efficiency of the forestage in projecting the sound from the stage towards the audience is not optimal both in CO and in AL. From Fig. 2 one can in fact deduce that in CO the width of the proscenium opening is as big as 37.6 m so that the lateral reflections are less efficient, while in AL the fan shape could be responsible for that. This latter hypothesis for AL would also be confirmed by the lowest value found in the stalls in the O–S case, which evidently is caused by the known fan shape deficiencies of reflection coverage in the central area of the stalls. Clearly O suffers from the two hall-specific conditions more than the directional sources. The conclusion is that systematic errors can occur if O is used instead of S depending on the layout of the hall, and that they are more severe here in bigger halls.

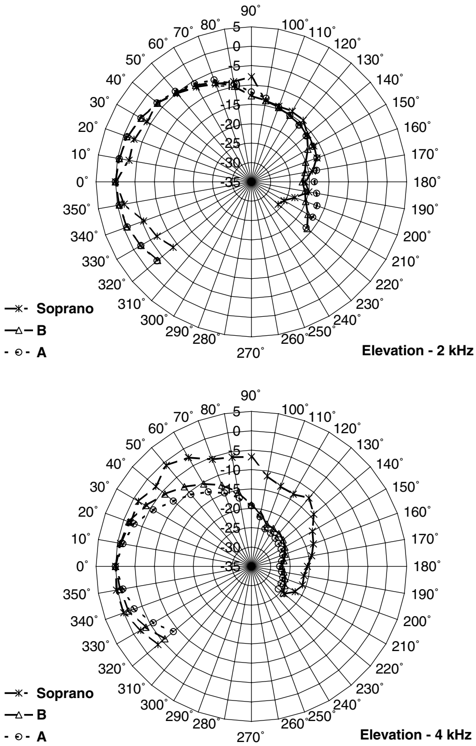


Fig. 7b. Comparison of the elevation octave band directivities of the soprano and of A and B sources. Top: 2 kHz; bottom: 4 kHz.

The whole exercise was repeated after the stage setup was removed in the models. A second set of data was produced and is reported in Figs. 10 and 11 which can be compared to the respective conditions in Figs. 8 and 9.

In RO the stage set removal only affects O in the balconies at higher frequencies, and the improvement with respect to the previous condition is as modest as 0.4 dB. For all the other combinations of sources and frequencies the RO values are close to zero and the hall seem less sensitive to the stage changes.

In the case of CO one finds that both at mid and high frequencies A and B are only slightly affected, while O is always worse than the condition with the stage set of about 1–1.5 dB at all frequencies.

Finally AL shows that some more complicated influence can occur: in this case the removal of stage set produces changes of different sign respectively in the mid and higher frequency ranges. In particular at mid frequencies O decreases of nearly 2 dB while the A and B values are still close to zero even if they change sign from positive to negative. It is interesting to note that at higher frequencies O is improved by the removal of the stage, but the values keep being a little less than -2 dB with respect to the soprano. On the contrary the A and B values increase and get in this case worse, especially in the stalls.

This comparison between the two groups of data shows that the stage set, or better a standard simulation of it, can alter the balance in a way which is again dependent on the same design factors as above, with the addition of the coupling of the hall to the

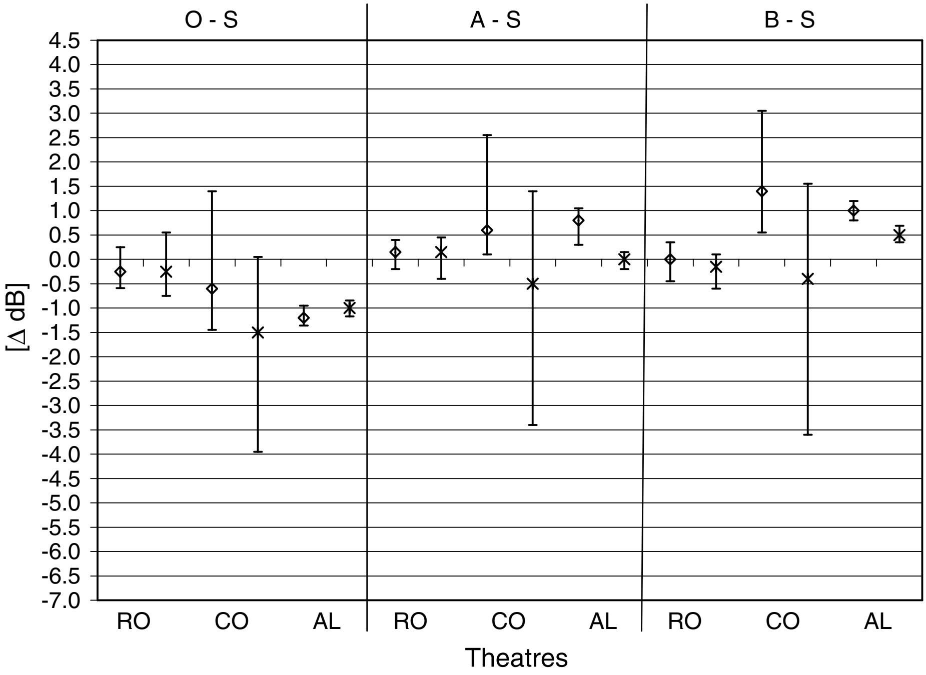


Fig. 8. Differences in the simulated balance values between the use of a soprano source and the use of an omnidirectional (O) or of two directional sources (A and B) on the stage. Average values of the octave bands centred at 500 Hz and 1 kHz. Symbols are: $\diamond$ stalls; $\times$ balconies. Max and min bars are also included.

stagehouse. This seem to happen more seriously for source O and, regarding the halls, in AL and to a less extent in CO, while RO is much less affected.

To corroborate these results obtained for a limited group of theatres the common experience tells us that the stage set-up and the stage tower characteristics have a strong and documented impact on the real measurement conditions [14]. To justify the hypothesis that O is more sensitive to the stage set a simple energetic argument can be introduced. In fact O emits directly a fraction of sound backwards towards the stagehouse and the amount of such sound power is almost equal to that projected in the main hall, as the solid angle under which the respective volumes are seen is not much different for positions located in the frontal part of the stage. For this reason the effect of the back of the stage or of the scenery reflections is exalted and has the typical result of making the measured balance to depend critically on the scenery design or the stage setup. This is an evident issue of reproducibility of balance in an opera house where these factors are rather unpredictable. In order not to heavily rely on variable elements the use of a directional source is thus preferable, since the surface behind the singer are invested by a smaller amount of energy.

All of the above results show also that, despite their fine characteristics, the two single-unit loudspeakers behave quite similarly. This means that the type of directional device is of minor concern for the purpose of balance measurements provided that their typology is the same as the present sources. In this respect a good solution could be source A, which is a modified dodecahedron source with just one unit working. The modifications will

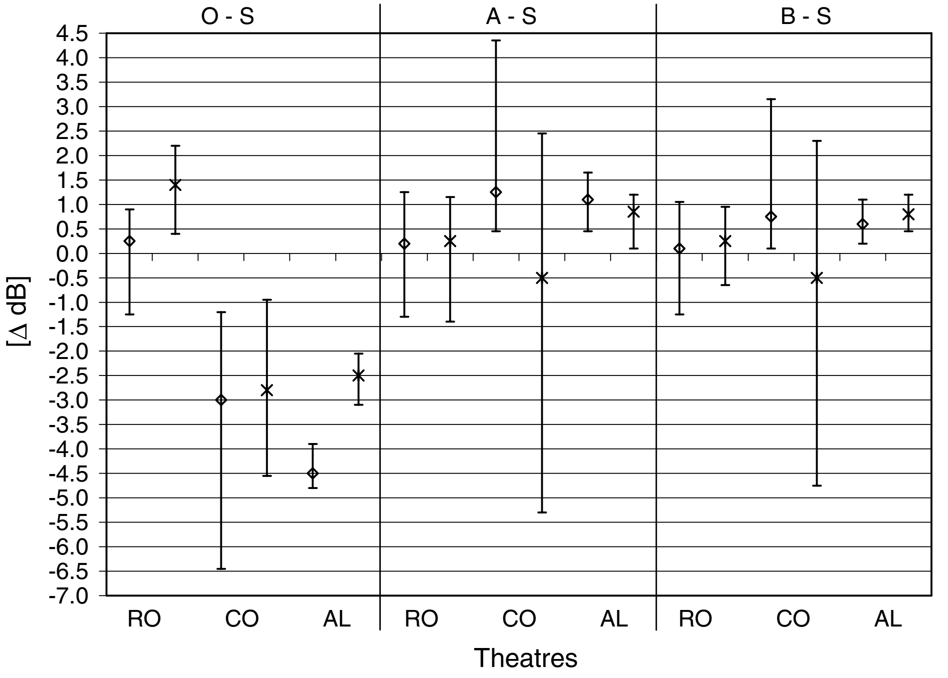


Fig. 9. Differences in the simulated balance values between the use of a soprano source and the use of an omnidirectional (O) or of two directional sources (A and B) on the stage. Average values of the octave bands centred at 2 kHz and 4 kHz. Symbols are: ◇ stalls; × balconies. Max and min bars are also included.

involve both electronics to ensure the same sound power output and some mechanical adaptation in order to direct the active unit in the horizontal direction.

3. The control of balance by means of architectural elements in the pit

In this part of the work some of the architectural elements which can influence the balance have been investigated by means of computer simulations. The study focused only on a subset of the many surfaces that are known to be effective in the design for the balance, which are mainly concentrated around the proscenium opening. This choice was the result of the several design constraints that are imposed inside historical opera houses, whose original design can often be only minimally altered in the forestage. For this reason the attention was directed to the pit layout and its optimization in the context of balance control became the target of this part of the work.

The elements under investigation were: the pit floor level, the pit rail height, the sound absorbing treatment of the pit back wall and of the pit rail. These modifications were chosen since they can actually be safely implemented in real historical opera houses. Clearly the above changes can have a significant impact on the acoustical conditions of musicians in the pit and their feasibility must consider this issue too.

The study was implemented for the three models to have a comparison of the effectiveness of the above changes both on an historical theatre (RO) and on two modern ones (CO and AL).

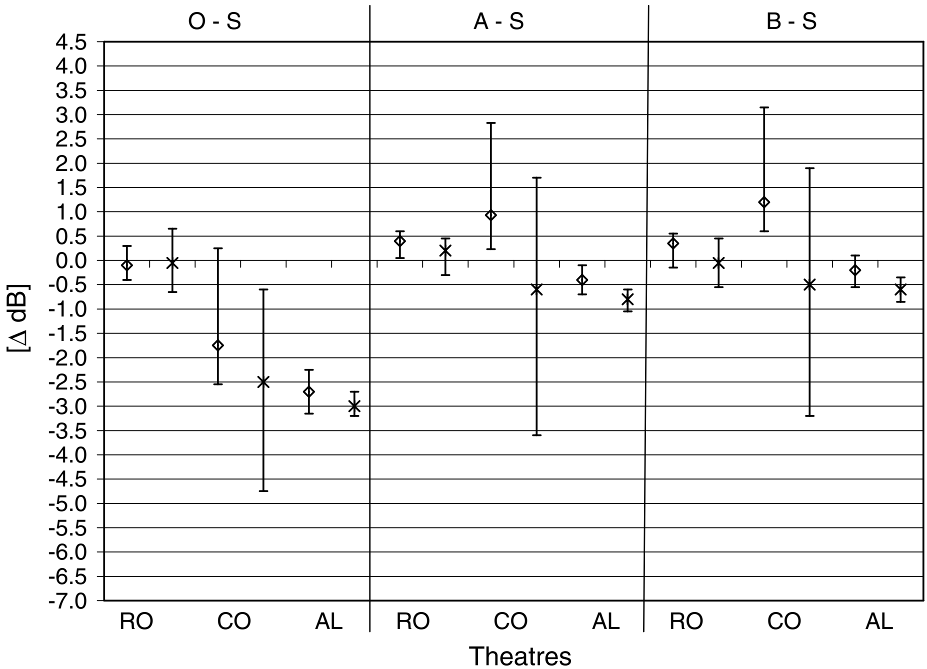


Fig. 10. Differences in the simulated balance as in Fig. 8, but without the stage set.

The same operational scheme as in par. 2 was adopted and also the source and receiver positions were kept unaltered. In this case just the S source was simulated on the stage and O occupied the pit locations.

3.1. Pit changes

RO was firstly considered as it is a good example of a historical opera house. The first attempt was to investigate the pit depth. The simulation started with a pit floor depth level of 1.5 m from the edge of the pit rail and this was defined as "Cond. 0". Then the depth of 2 m was introduced as "Cond. 1". Subsequently the influence in changing the materials of the pit walls was evaluated. Firstly the pit back wall was treated with a sound absorbing material ("Cond. 2") and secondly also the pit rail was covered with a lighter absorbing material ("Cond. 3"). The absorption coefficients of the materials used for the virtual treatments is reported in Table 3 and it is seen that it is mainly concentrated in the middle-high frequency range. Actually similar values were intended to simulate wooden panels with a light or heavier sound treatment with porous layers respectively in the case of the pit rail and of the back wall. In Table 4 a summary of the changes implemented in the pit is reported.

The same approach as above was implemented in CO and AL though with slightly different initial data regarding the absorption coefficients of the surfaces involved which derived from the model themselves.

For RO also an investigation on the barrier effect of the pit rail was carried out. The pit floor was firstly fixed as in "Cond. 2" above. Then the height of the pit rail was set in

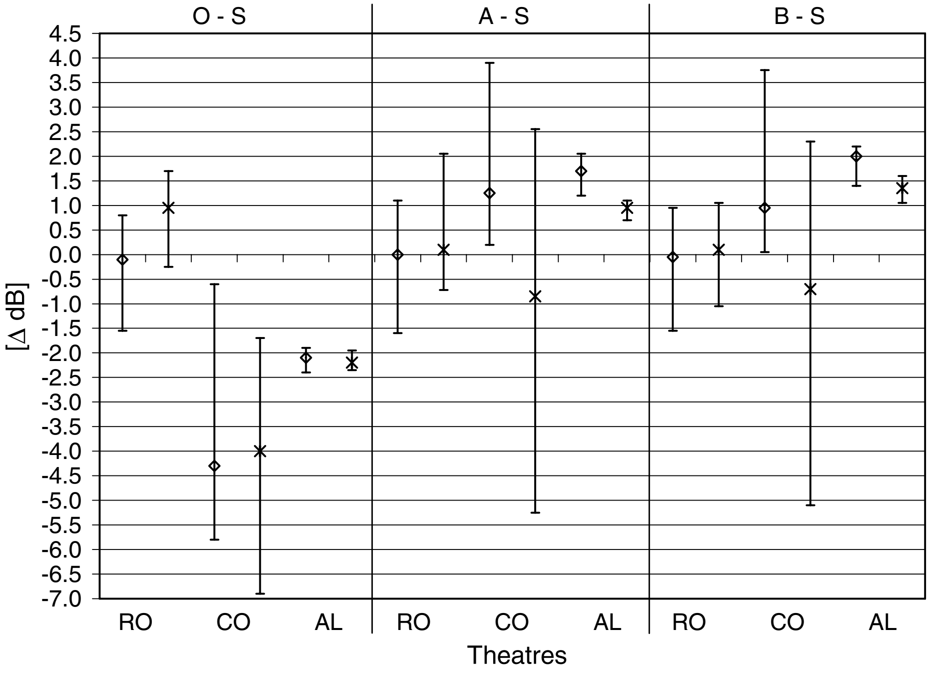


Fig. 11. Differences in the simulated balance as in Fig. 9, but without the stage set.

succession at 0 m, 0.4 m, 0.9 m, 1.5 m and 2 m from the floor of the stalls. The sound level change in the different areas of the theatre due to the increasing rail height was investigated in order to compare with the pit floor changes.

Here it has to be remarked that for the image source/ray tracing algorithm at the basis of Odeon® the simulation of the barrier effect of the pit rail was a challenge. Nevertheless the impact of such limit was limited in the study. This can be ensured firstly by the choice of the frequency range where a more effective screening by the rail is to be expected and secondly by the nature of the simulations, which here, like in the preceding sections, were mainly used for mutual comparisons.

3.2. Results of simulations for the virtual control of balance

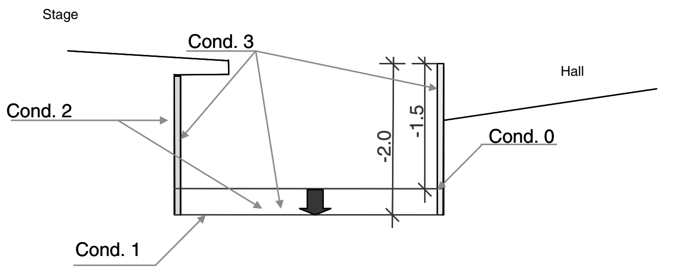
The results are presented in Fig. 12 as single figure averages of the octave bands from 500 Hz to 4 kHz. Though frequency dependent changes were to be expected, it was

Table 3
The sound absorption coefficients employed before and after the acoustical treatment in the pit of RO

Pit surfaces	Frequency [Hz]							
α	63	125	250	500	1k	2k	4k	8k
Back wall	0.12	0.12	0.04	0.06	0.05	0.05	0.05	0.05
Back wall treated	0.37	0.37	0.4	0.65	0.72	0.6	0.53	0.53
Pit rail wall	0.12	0.12	0.04	0.06	0.05	0.05	0.05	0.05
Pit rail wall treated	0.30	0.30	0.20	0.18	0.20	0.28	0.27	0.27

Similar data were used also for CO and AL.

Table 4
A sketch of the geometrical conditions implemented in the orchestra pit during the simulations



Changes applied	Condition
Pit floor at −1.5 m from the edge of the pit rail	Cond. 0
Pit floor at −2 m from the edge of the pit rail	Cond. 1
Cond. 1 + sound absorption treatment of pit back wall	Cond. 2
Cond. 2 + sound absorption treatment of pit rail	Cond. 3

decided to average across frequency in order to have a more direct comparison. The changes in the balance from one condition to the next are reported as differences (i.e. "Cond. 1–Cond. 0" is the difference in the balance values from the respective conditions).

In RO the results show that lowering the pit floor has some 1 dB increase in balance but only in the stalls. No changes can be observed in the balconies. As one might expect when the pit back wall is treated the whole theatre is influenced in favour of the singer. The improvement is between 1.5 dB in the stalls and is more marked (little more than 2 dB) in the balconies. Interestingly treating the pit rail has no effect in the hall whereas it is potentially problematic for the way the singer on stage receives the orchestral sound. Also the last group of data confirm the findings and the joint effectiveness of the back wall and pit floor level changes is assessed at nearly 2.5 dB.

In CO the data show that it is much harder to control the balance with these few elements. In fact stalls and balconies show quite separate trends, and the latter are practically not sensitive to the changes. To have some effect in the stalls it is necessary to implement "Cond. 2" from "Cond. 0" and by doing so a change of 2 dB is observed.

Lastly in AL all of the architectural changes applied have quite little or irrelevant influence on the balance. The biggest change occurs in the stalls when the pit floor is lowered and very interestingly it favours the orchestra instead of the stage. This is probably due to the peculiar pit layout which has a pronounced overhang area. In this case the increase of the volume below the overhang could work in favour of the orchestra. In any case the amount of 1 dB is actually too limited to be an effective design strategy for the balance assessment.

From the above findings some more general considerations can be developed. In particular it is shown that, despite the different plan shape and geometrical details, both CO and AL are less sensitive to the changes in the pit compared to RO.

In RO there are more effective reflections towards the hall from surfaces in the pit or close to it which are clearly less effective in the other halls due to an increased distance from both source and receivers. Moreover more specific geometrical details could also in this case be considered. For instance the scarce changes obtained in the CO balconies

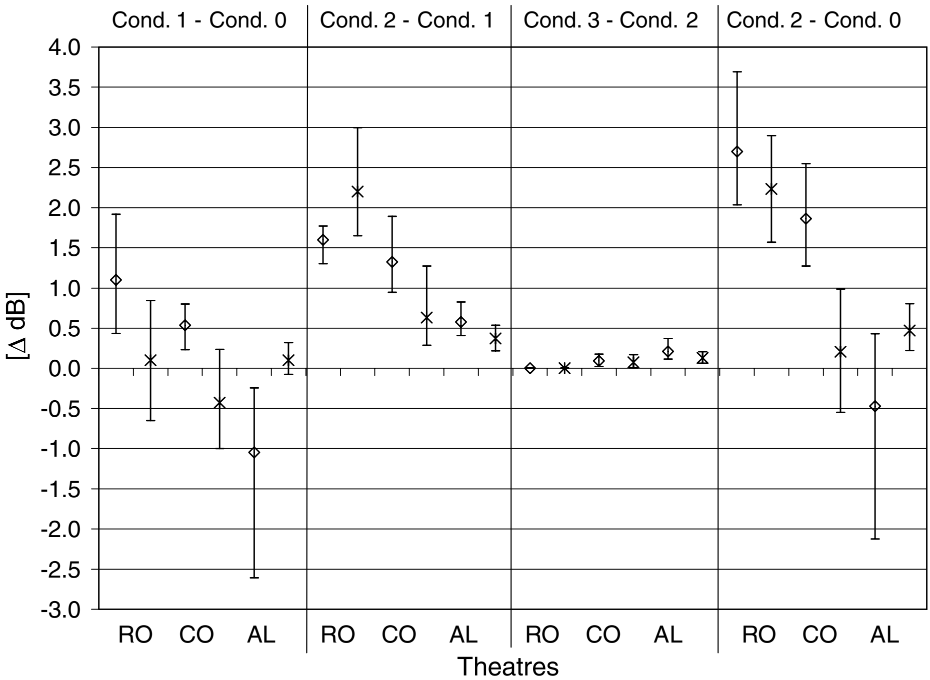
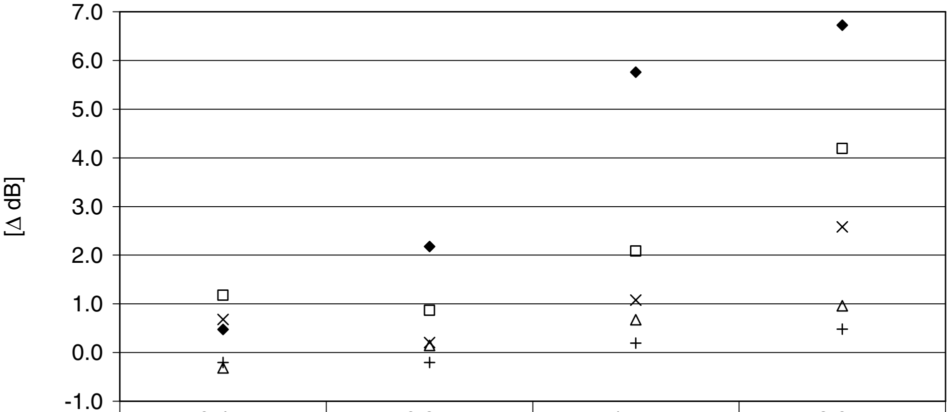


Fig. 12. The effect of the changes in the pit on the balance. Refer to Table 4 and to the text for the description of the conditions. Average values of the octave bands from 500 Hz to 4 kHz. Symbols are: ◇ stalls; × balconies. Max and min bars are also included.

could be traced back to the height of the balconies which makes the pit entirely visible from them despite the changes in the floor level. Also in AL the disposition of the audience on raked planes seems to make it almost independent from the pit details but probably more dependent on the pit opening, which was unaltered in the successive conditions.

As a result of this section of the simulations one concludes that working on the pit only could be probably enough in many historical opera houses, in fact in RO an increase of 2.5 dB was obtained and this can be regarded as an encouraging outcome. On the contrary a more articulated design revision is mandatory in halls whose layout is significantly different in some respect, as both the CO and AL cases show.

The results of the study of the barrier effect of the pit rail in RO is reported in Fig. 13. The graphic shows the transitions from a null pit rail to a 2 m high fence. It can be seen that the IV and III orders of boxes are not as sensitive to the changes as the I order and the stalls. The II order has a behaviour which is a mix between the two groups. The data tell us that the height of the fence has to be set with great care and shall not exceed 1 m in order to control the impact of the barrier effect in the whole hall. This is because when the height passes from 0.9 m to 1.5 m the balance undergoes a different an probably unacceptable change between stalls and boxes. The figure of 3.6 dB in the stalls, according to [4], would in fact shift considerably the perceived balance towards positive values (i.e. in favour of the singer). Furthermore a marked darkening of the sound is to be considered due to the frequency filtering of the barrier itself which, as known, is more effective in the higher



	0.4m	0.9m	1.5m	2.0m
◆ Stalls	0.5	2.2	5.8	6.7
□ I Order	1.2	0.9	2.1	4.2
× II Order	0.7	0.2	1.1	2.6
Δ III Order	-0.3	0.1	0.7	1.0
+ IV Order	-0.2	-0.2	0.2	0.5

Fig. 13. The barrier effect of the pit fence in the different areas of the RO theatre. A: pit fence raised from 0 m to 0.4 m; B: from 0 m to 0.9 m; C: from 0 m to 1.5 m; D: from 0 m to 2 m. Average values of the octave bands from 500 Hz to 4 kHz.

frequency range. A rail height of more than 1 m would also seriously impair the visibility lines and for this reason is practically not possible.

Even if these findings are related to RO it is believed that the above remarks can safely cover a larger ensemble of historical opera houses and especially those whose geometrical characteristics are close to the present case.

4. Conclusions

Investigations on the balance measurements technique and the balance control through architectural elements were the proposed goals of this project. The methodology applied here was based on computer models of three theatres with different plan shapes and layouts, whose dimensions span over a wide range. The models were equipped by virtual sources developed from directivity measurements in an anechoic chamber and a soprano was modelled with the same procedure. Regarding the assessment of the procedure for the qualification of balance it was found that:

- the directional loudspeakers matched the soprano better than the omnidirectional source especially in the 2 kHz and 4 kHz octave bands;
- the presence of the stage setting has a bigger impact on the omnidirectional source even though variability has to be expected: general quantitative conclusions are hardly extracted due to the many design variables involved;
- despite the changes in the directivity and in the layout, the two single-unit directional loudspeakers gave quite matching results.

From the above results, and reminding the findings of [10], it can be concluded that the qualification of balance should be based on directional sources whose layout could be that of single unit full range loudspeakers in a reasonably sized cabinet.

The second goal of this work was to evaluate the architectural elements suitable to control the balance. Changes were applied primarily to the pit layout and finishing. The findings were the following:

- it appeared that RO was more sensitive to changes in the pit whereas CO and AL would require an extended design strategy for balance control;
- the RO data show that the pit floor level and the pit rail level can control the balance in the stalls due to the barrier effect, but limited changes are noted in the balconies;
- when the pit back wall is acoustically treated the effect can be observed all over the hall and is especially effective in the balconies.

Finally the main concern of the work was the design in favour of the singer, since often listeners complain for excessive orchestral sound. In few cases the reverse might be true and the present results could be used with the opposite aim of projecting more sound from the pit into the audience.

In the future further investigations will be devoted to developing some effective tools in order to both predict the balance and to assess its performance in real environments by means of the results of this work.

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