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Review

Acoustics in the restoration of Italian historical opera houses: A review

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A R T I C L E I N F O

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A B S T R A C T

The cultural heritage of Italian historical opera houses is of paramount importance in terms of architecture, music and acoustics. Much is known about the development of their architectural design and the selection of materials that guided the construction of such houses. In fact, traditional technologies are implemented as much as possible when refurbishments are required to ensure the halls maintain their original characteristics. Nevertheless, from an acoustic point of view, the correct approach to safeguard the heritage involves a number of issues which require great insight into the propagation of sound, the interaction with the boundary materials and the occurrence of structural vibrations. Unfortunately, the technical literature on acoustics in the restoration process consists of reports on case histories and provides only limited generalisations. This review develops a comprehensive approach to the topic, covering the most sensitive acoustical issues and their potential impact on the outcome. Together with previous results, fresh data have been added to support the discussion. Moreover, basic and special procedures have been presented to deal with acoustics in the restoration process and, finally, the most important aspects to-be-researched are addressed with special regard to the role of re-radiation from lightweight structures.

1. Research aim

This review deals with the role of acoustics in the context of the renovation of Italian historical opera houses. The basic characteristics of the acoustics of historical theatres are summarised and the main issues related to the preservation of acoustical heritage are discussed. The tools for the appropriate control of the behaviour of materials and volumes are presented and more specific issues related to the orchestra pit and the vibrating structures are outlined. New experimental data are combined with previous data to support the claims, and the need for further developments in the area of vibro-acoustics of lightweight elements is discussed.

2. Introduction

The Italian-style theatre has been considered the most traditional opera house for over three centuries. In fact, from the second half of the 17th century to the early 20th century, theatres in Italy were most often built with rings of boxes piled up on top of each other and a gallery on top. It can be estimated that over 800 historical theatres are still active across the country, varying in seating capacity and hall design (i.e. plan shape, number of box tiers, etc.). All these buildings need restoration, renovation and, in some cases, complete reconstruction, as was the case for the Teatro Petruzzelli in Bari and the Teatro La Fenice in Venice. Both were destroyed by fires in 1991 and in 1996, respectively, and were subsequently rebuilt. These events raised awareness regarding the cultural heritage of the acoustics of historical spaces for opera and music which has to be investigated, protected and enhanced. In fact, it was apparent that the knowledge of the acoustics of the halls could not be left to a fortunate chance like that of the Teatro La Fenice [1], but instead should be systematically retrieved in a standardised way. Some elaborations stemming from the previous disastrous events led to the compiling of the so-called Ferrara Charter [2] and later to the preparation of guidelines for acoustical measurements inside historical opera houses [3], which were conceived as an initial response to the need for effective tools to safeguard the acoustics of such spaces during renovations. In the years to follow, some measurement campaigns were accomplished [4–7], and the accumulated primary data allowed a better description of the acoustics of historical theatres including comparison with modern opera halls [8]. The measurement methods have since been developed to include the visualisation of reflections together with 3D sound [9]. Despite these improvements on data and methodologies, the literature covering the very specific topic of the acoustics in the renovation of historical opera houses is still limited, and

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consists mainly of conference papers on case histories which disregard possible generalisations. Moreover, even for some outstanding theatres, only a descriptive summary of interventions is provided, with few [10] or no acoustical data and no detailed technical account of the strategies, measures and simulations employed to check the acoustics during the complex renovation process. Some more detailed reports can be found, which present a comparison of ante-operam and post-operam acoustics [11–14] or computer simulations and some relevant design details to be implemented in the refurbishments [15–17]. Some other works outline a schedule for the acoustical design in the renovations and focus on possible improvements [18,19] or specific issues such as stage-house enlargement [20,21]. All in all, it appears that a more comprehensive view of the topic is still required although it would be relevant to better programme the interventions. As a partial justification for this, it has to be recalled that acoustics in opera house renovations covers a number of problems, which range from the acoustical characteristics of materials, furniture, seats and fabrics, etc. to the appropriate design of the renovated hall shapes and, as it will be discussed below, the vibro-acoustics response of the different parts is also relevant. In this review, the acoustics in the renovations of Italian historical theatres will be discussed with the aid of specific acoustical data relating to the prominent points of concern. The aim of this work is twofold: (1) to outline the influence the different acoustical issues may have on the final acoustical outcome, and (2) to present methods and tools that are suitable to deal with the above issues. The review is organised as follows: in Section 3 a background of the acoustics of historical opera house acoustics is provided, in Sections 4 and 5 the control operated respectively by means of materials and volumes is presented, while in Section 6 a focus on the problems related to the orchestra pit is developed. Then in Section 7, the crucial role of vibrating structures is discussed with some related points that remain open.

3. The acoustic character of Italian historical opera houses

The listening attributes of Italian historical halls stem from their special design that includes the stalls, which often have a gentle slope, the rings of piled boxes and the gallery (known as the *loggione*) above them. The three-fold layout (stalls, boxes and loggione) has been the basis for design for almost three centuries [22] and was kept even when the rest of Europe had already abandoned the box solution under the influence of Illuminist ideas [23]. Despite its acoustical limitations, the box solution was in fact able to provide a compromise between theatre fruition and management. From the acoustical point of view, such a design has particular implications that can be outlined as follows. The listeners are reached by the sound waves produced on the stage by the singers and the orchestral sound from the pit, which is an open sub-volume inserted at a lower level between the main hall and the stage. Confining the discussion to propagation in air, the reflections that build up the local impulse response at the receiver can be traced back to specific hall surfaces. The most important reflecting surfaces are the ceiling, the proscenium arch with the proscenium box fronts, the lateral wall of the stalls, the closed portion of the box fronts (between 40% and 60% of the surface) and the pit back wall. As a result of the interplay of the reflections, sound in the stalls is often louder and clearer despite some risk of timbre colouration at the back locations for the stage source due to the concave and plain lateral wall. A boost of low frequency is also expected in the stalls for the pit source. This mostly happens since the pit rail acts as a barrier for the higher frequency sound generated in the pit. In the boxes, only the frontal position facing the main hall is recommended since even sitting in the second row usually implies a slight lack of sound [24]. Moreover, the sound field in the box recess is said to be fairly irregular due to the possible influence of standing waves, and corrections have been suggested for this [18]. The reasons for the unique listening experience in the boxes compared to that of the stalls have also been elaborated [25,26]. In particular the box volume, especially when provided with velvet and sound absorbing finishes, seems to act as a resonator for the lower frequency range and as a full absorber for the higher range. There is also a range of listeners' preferences in the boxes [27]. As discussed in [8], much has to do with the tonal balance and the pit rail shading so that the best balance between the pit and stage is found at a certain height (typically at the second or third box ring), and this is primarily correlated with the smoother frequency response of the pit source. This occurrence is perceived as a more naturally sounding orchestra or, in other words, more brilliant in tone. On the other hand, when one goes higher and higher towards the *loggione*, the prevalence of the orchestra is usually manifested, and only better singers can compete with this by means of a strong and focused voice emission. When compared with modern opera halls of a similar volume, the sound inside the Italian historical opera houses was shown to be less reverberant in particular in the higher frequency range, slightly clearer and not quite as loud [8]. Moreover, the dependency of early reverberation on volume is not as marked as expected probably because of the compact geometry [28]. The outline above helps us understand the inextricable mix of geometry, materials and source arrangement that governs the propagation in air. Additionally, as will be shown in Section 7, the role of structural vibrations shall also be considered.

4. Control of reverberation by means of materials

One of the main tasks in the renovation process is to provide a refurbished hall where reverberation time is appropriate and consistent with previous values. This statement has only recently been questioned and the renovation was carried out as an opportunity to partially fulfil the reverberation gap with modern opera halls [9]. For this reason, as a first task, the planning of restoration needs to clarify the philological issues related with the heritage concept that may arise when reverberation time is increased. In any case, the intervention on the sound absorbing surfaces in the main hall is the most critical to reach whatever goal, and comprises stall seats, box furniture with teasers, movable chairs and arm-rests on top of the parapets, curtains and fabric on a large part of the interior walls (i.e. box walls). Moreover, very large acoustically hard or reflecting surfaces such as stuccos and paintings are refreshed, and their acoustical behaviour may change due to the decrease in surface porosity. Keeping track of the acoustical performance of the original single elements is vital and the usage of standardised measures is required either on groups of seats, furniture or the curtains [29]. By so doing, the performance can be assessed and adapted. As an example, in Fig. 1 the stalls seats of the Teatro Zandonai in Rovereto are shown with their original 1923 design [30]. The sound absorption values of the seats prior to renovation measured according to [29] are reported in Fig. 2. The data can be compared within the Beranek rating [31], which is based mostly on modern chairs. Fig. 2 shows that the Zandonai seats do not fit well in the scheme probably because of the original padding material which has a moderate sound absorbing effect. Therefore, their data were found between "lightly upholstered" and "not upholstered". The original padding material and velvet were replaced with similar fireproof materials with similar characteristics. In particular, as is usually done, the acoustical data of new seats were not to deviate by more than 10% from the original ones when the measurements were obtained in the same conditions and in the same laboratory. Since the surface of the seats is by large the most important sound absorbing surface in the main hall, it is obvious that failing to control this

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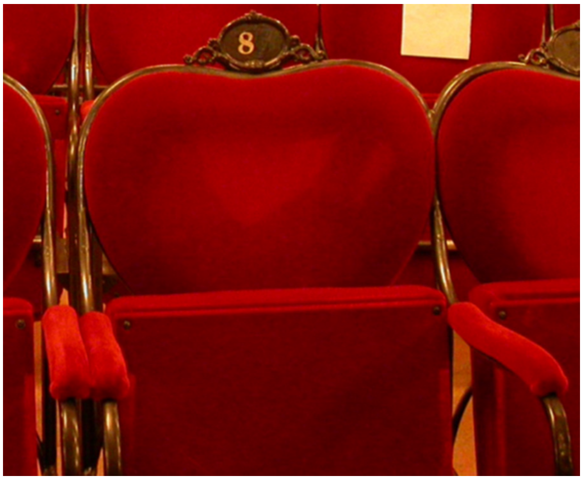

Fig. 1. Cast-iron seats (1923) of the Teatro Zandonai after the refurbishment of 2012. The intervention consisted of the replacement of the velvet and padding with fireproof materials.

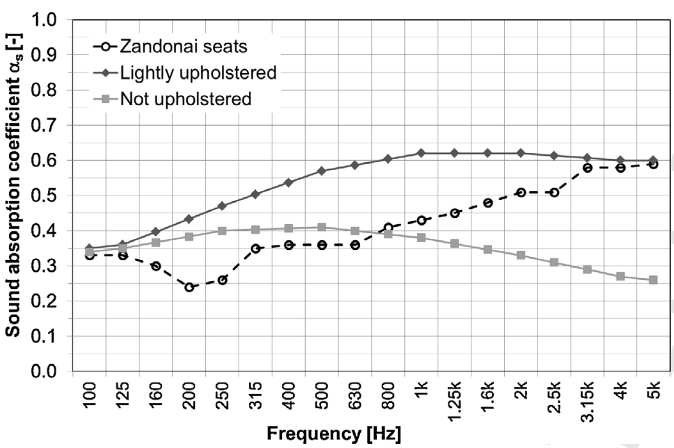

Fig. 2. Sound absorption coefficients of the Zandonai seats measured before the refurbishment. The acoustical data can be used to compare it with the seats category in the conventional Beranek scheme [31]. These data do not fit well in the scheme and lay between "not upholstered" and "lightly upholstered" types.

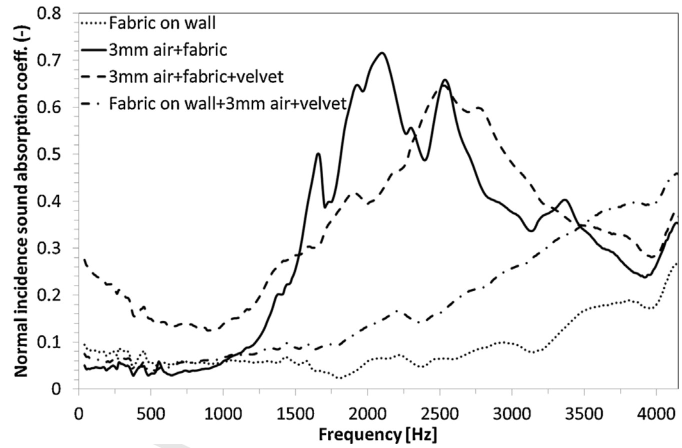

Fig. 3. Normal incidence sound absorption values measured for different treatment hypotheses of the lateral box walls of the Teatro Zandonai.

data would lead to the serious risk of an unacceptable alteration in the acoustics. However, many other larger or smaller surfaces call for control and also the use of acoustical measures on small samples should be implemented [32]. This is particularly helpful during the selection of drapes, curtains, teasers and fabric in general. In particular, this method of operation can resolve conflicts between aesthetics and acoustics that may arise in the definition of interior box surfaces, teasers and curtains. As an example, in Fig. 3, the sound absorption data of several layouts for the box walls inside the Teatro Zandonai are reported. The investigated options included the two layers of tissue (fabric and velvet) with or without a small air gap (3 mm) and with one or both layers directly glued onto the wall. The measured data explained that the sound absorption could vary greatly depending on the air gap and tissue placement, and could reach unacceptably high values. In fact, the behaviour of such a composite system depended on several factors which are not necessarily predictable in the final assembly. It is to be stressed that, although a reliable acoustical prediction can be achieved with conventional theories and software tools (typical details of such tools are found for instance in [33]), direct measurements are necessary to minimise the uncertainties that affect the input data. Controlling the performance of hard surfaces, which have a large extension and thus a non-negligible impact on the acoustics despite a low sound absorption area, is generally more difficult since none of the previous measures can be directly implemented. Moreover in situ measures of sound absorption, based either on the impulsive technique (called the "Adrienne" method) or on other available methods, provide more reliable results only with non-negligible surface absorption, and thus they are not suitable to carefully characterise the almost reflecting theatre surfaces (including paintings, marmorino walls, etc.). In addition, a scan of the literature does not provide a specific estimate of the acoustical data of the hard boundaries to-be-polished and the respective refreshed ones. Acoustical motivations stemming from the decrease in surface porosity and from past experience has led to the conclusion that only high frequencies are affected (>2 kHz), but medium and lower frequencies are untouched by the polishing of hard surfaces. This was confirmed in [13] where a substantial part of the increase in reverberation time in the higher frequency range (the so-called valuable "patina" of sound) was traced back to the above surfaces. In this respect, one can note that such change is mostly welcomed since the sound is more brilliant and vivid, and historical opera houses are almost never abundant in high frequency sound.

5. Control of acoustical coupling between the stage-house and main hall

The renovation of an historical opera house is often an opportunity for a major improvement of the stage machinery. In fact, especially in larger theatres, the requirement of hosting several settings at once has become essential for the theatrical business to remain sustainable. For this reason the stage-house volume is seldom enlarged to a great extent and, if not currently present, a fire curtain is added between the fly-tower and the main hall to protect the latter from fire. Since it is unlikely to find fixed sound absorbing treatment in the stage-house of traditional theatres, the acoustics in this area depends mainly on the number of curtains and the stage setting in general [8,34,35]. When there are no preparations, the resulting reverberation time is thus usually much longer than in the main hall. This implies that, when the fire curtain has been raised, there can be an incongruous match of the two reverberant tails with the reverberant energy from the stage-house exceeding that of the main hall. Recently, the acoustical coupling of the stage-house and main hall has been closely investigated [7] in a set of 11 small- and medium-sized historical theatres. The investigation showed that, under operational conditions, the sound decay has a trend denoting the coupling especially when the sound source is located in the forestage, that is in the location that solo singers take during most of the performance. Moreover, quantitative results for modern opera

Fig. 4. View of the back wall of the former stage tower of the Teatro Zandonai during the acoustical measurements for characterisation of the acoustic coupling. Glass wool strips were hung along the lateral walls to induce a controlled change in the reverberation time.

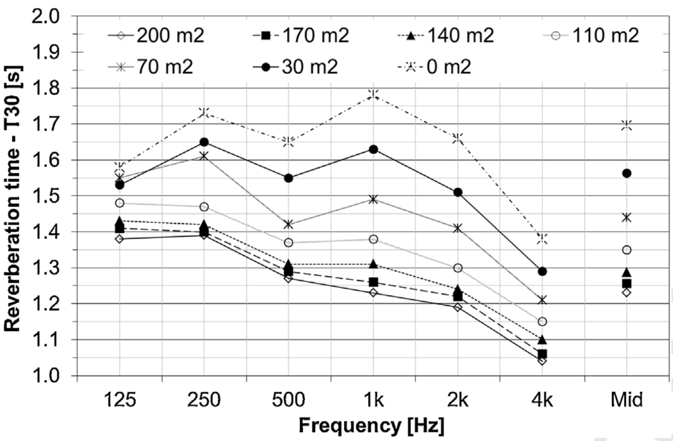

Fig. 5. Reverberation time T30 in the main hall (one central position, sound source on stage) while varying the preparation of the stage-house with a variable amount of sound absorbing glass wool stripes (see Fig. 4). The indication "Mid" refers to the arithmetical average of the values at 500 Hz, 1 kHz and 2 kHz.
Adapted from [20].

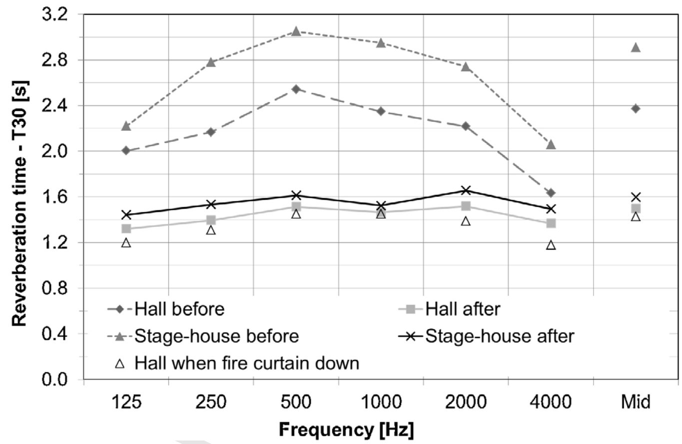

Fig. 6. Reverberation time in the restored hall and in the new stage tower before and after the acoustical treatment. The differences between the coupled and decoupled conditions are within the minimal perceptual difference threshold.
Adapted from [37].

houses were also developed [36], and it has been found that the lateral surfaces and ceiling of the stage-house should typically be more than 50% acoustically absorbent in order to keep the excursion of reverberation time in the main hall below 10% when the stage setting is inserted. It can therefore be understood that when the fly-tower volume of an historical opera house is increased, the risk of overwhelming reverberation from the tower to the hall is even more serious. Dealing with this issue at best requires the qualification of the ante-operam condition of the two separate systems before any numerical modelling can be done. Unfortunately, the more common smaller halls are not often equipped with a fire curtain which, according to the specific guidelines for measurements [3], should provide the required septum to acoustically decouple the two systems (fly-tower and hall) in order to achieve their single responses. A similar problem was resolved practically by resorting to a dynamical characterisation of the coupled system, which was obtained by a series of acoustical measurements taken while changing the amount of sound absorption material installed in the stage-house [20]. Fig. 4 shows how the preparation was realised and Fig. 5 reports the trend of the obtained reverberation times in the main hall. As seen in Fig. 5, the excursion of T30 in the mid frequency range from the most to the least reverberating condition is close to 50%. This means that failing to control the coupling phenomenon would lead to a macroscopic error in the acoustical design. With the previous data available, numerical models can be developed on either a statistical basis or based on acoustic CADs [21]. This technical procedure made it possible to fix the amount of acoustical treatment to be implemented in the stage-house to keep the interplay of the two volumes as stable as possible. After final adjustments to the numerical model, which took it as close to the "as built" fly-tower as possible, the post-operam acoustical measurements confirmed the approach above. In Fig. 6, it is seen that the acoustically treated stage-house and the main hall, once separated by a new fire curtain, have almost the same reverberation time which is half that of the untreated stage-house [37]. Moreover, the discrepancy of reverberation time in the main hall with or without the fire curtain down is within 5%, which is taken as the just noticeable difference for early decay time (EDT) of the parameter in Annex A of the relevant norm for room acoustics measurements [38]. This means that, perceptually, the two conditions should hardly be considered different.

6. Control of acoustical balance between the orchestra pit and stage, and the musicians' aural safety

A distinguishing characteristic of an opera house with respect to a concert hall stems from the presence of two competing sound sources, the singer on the stage and the orchestra in the pit. Seldom pits were added afterwards and sometimes the pit can be enlarged during renovations. To increase the space available for musicians, pits are often provided by an overhang, but open pits are also common (Fig. 7). The geometry of the forestage and the layout of the pit do influence the balance between the singer and orchestra and open pits are more prone to an excess of orchestral sound against the singer [39]. Listening in the pit markedly differs [40] from what can be experienced on a stage platform since the floor surface is usually much less per musician and the lateral walls are quite close, thus providing strong side reflections, especially due to the louder orchestral sections (e.g. brass, percussions). Moreover, the presence of an overhang greatly enhances the risk of longitudinal standing waves that may affect the location of the musicians underneath, and cause aural damage in the long run. Given this complex logistic condition, the acoustical problem of the pit can be considered twofold. Firstly, there is an increased risk of over-exposure of musicians to loud sounds and this has in fact been reported both internationally [41] and nationally related specifically to an historical opera house [42]; secondly, the balance between the pit sound and the singer is critical from the point of view of the listeners in the main hall.

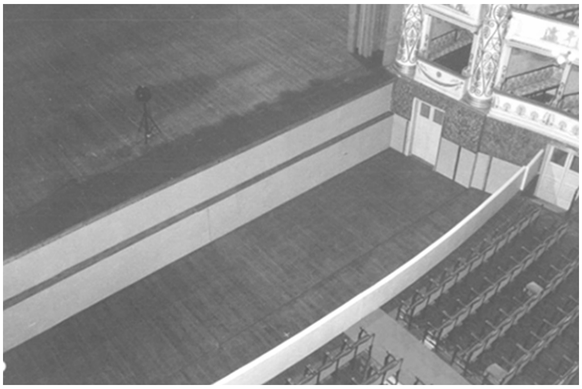

Fig. 7. The open pit in the Teatro Pavarotti in Modena, Italy. The back wall of the pit before renovations was finished with a reflecting surface.

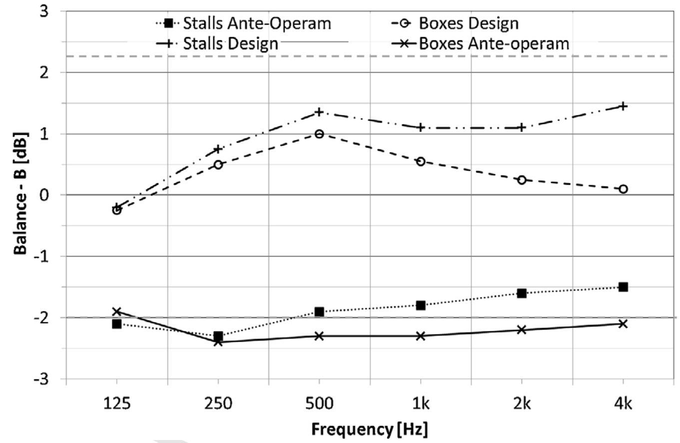

Fig. 8. Design of the acoustical treatment in pit of the Teatro Pavarotti in Modena, Italy. Values of the balance B (arithmetical difference between levels obtained with source on stage and in the pit respectively). Data are compared between the ante-operam and the design phase. It is seen that the former condition suffers from an unfavourable balance whilst the refurbished pit shall provide values consistent with the indicated range of suitability, of which the limits in the figure are reported as grey dashed lines.

The two issues above need specific consideration in the restoration process since the means of control do not entirely coincide. In particular, the control of excess sound to prevent aural damage of musicians requires the implementation of extended sound absorption treatments in the pit, particularly in the low frequency range to reduce the worst impulsive sounds which have the most harmful high peak levels. Strategies have been proposed which are mainly based on fixed low frequency and broadband absorbers which are frequency matched [43], or on movable double-face panels that can be configured depending on the orchestra layout [19]. Fixed diffusing elements [14] on the lateral and back walls and/or under the overhang do help in the mitigation of the above phenomena by smearing the specular reflections to the benefit of a more homogeneous sound level distribution in the pit. On the other hand, the number of musicians in a smaller pit may not be as high as in the bigger pits, so that the overall sound level will tend to decrease and its control in this area can be more effective. Strategies can be implemented to improve the balance between the singer and orchestra, and they are more effective in smaller halls. In particular, it was shown in [44] that the pit back wall is the most important surface to consider as it works on the whole auditorium, whereas the pit height and pit fence height can only control the orchestra sound in the stalls. As a demonstration of such concepts, the intervention on the pit shown in Fig. 7 was proposed to remedy a reported unfavourable balance. The pit back wall was split into two longitudinal stripes which were designed with a specific sound absorbing finishing to best cover the exceeding orchestra sound and, by doing so, to decrease the overall level in the pit to the benefit of the musicians. Predictions of the possible improvements in balance were elaborated by means of acoustical CAD simulations of the whole opera house and the results are reported in Fig. 8. As can be seen, the improvement is relevant for both the stalls and boxes and, in the context of restoration, this may add value to the acoustical quality of the hall without compromising its original character. In fact, the reverberation time and the rest of the standardised parameters [38] obtained in the main hall and in the boxes are only very slightly affected. Moreover, as a consequence of a more appropriate balance, the ease of playing together (orchestra and singer) will be improved and the performance will have a global benefit too.

A further issue related to the pit interventions is the role of the so-called "keel". This is a traditional resonating volume enclosed in a wooden structure placed underneath the pit floor, which was conceived to sustain and blend the orchestra sound. This system was implemented in several historical theatres but, unfortunately, it was often dismissed during renovations, for instance to install a movable pit floor. Compromising the efficiency of the "keel" led to a significant loss of the previous sound. In fact, the effectiveness of such resonator was demonstrated in one case [45] and the results showed an increase in reverberation time for a pit source of around 15–20% with higher values in the lowest octave bands when the "keel" was operating.

7. Vibro-acoustics performance of structural elements

In the restoration process, interventions on structural elements are often implemented to improve fire safety or to substitute damaged parts. If the choice of technical solutions does not respect the structural vibrations, the impact on the final acoustics of the theatre will be seriously at risk. In fact, while the monitoring of sound propagation in air can be pursued with standardised procedures [38,3], the same is not true for the structural vibrations of the many parts which, inside an historical opera house, are subject to transmit and re-radiate sound. More specifically, the traditional design concept was developed with close consideration of the role of vibrations, and this can be verified by the very common presence of extended lightweight or wooden surfaces (e.g. stalls floor, pit fence, pit floor, stage floor, hall suspended ceiling, box surface such as balustrade, floor and ceiling, and often box lateral walls) that were considered to cooperate in the formation of the overall sound [22]. Moreover, the beams carrying the stall floor, the stage floor, the hall ceiling and the whole tiers of boxes were made of wood. Substituting one part with stiffer and fire resistant materials (concrete *in primis*) may compromise the whole system, since vibration paths could be unacceptably distorted or even completely neglected. To prevent this risk, suitable means of controlling the integrity of vibrations in the different parts needs to be specified. This issue was the topic of the earlier work [46] which, to the knowledge of the authors, is the only systematic published contribution presenting an operational scheme to monitor vibrating elements inside historical opera houses. The basic proposal was to investigate the airborne structural vibrations, which are those induced in the structures by the sound emitted by a sound source. This was accomplished by the simultaneous measurement of pressure and acceleration close to the different vibrating target elements. Thanks to the transfer function between the injected (pressure) and re-radiated energy (acceleration), the radiation performance could be ranked and assessed. Further focus could be obtained by weighting the transfer function above by the coherence of the two signals in order to discern the local or remote origin of the vibrations radiating sound back to the hall. With such method, some reference

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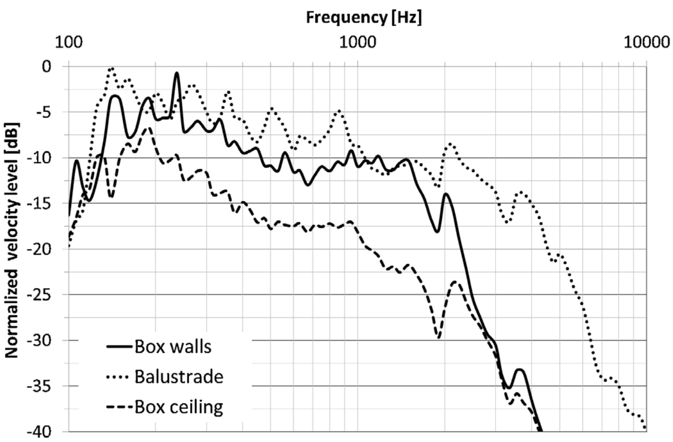

Fig. 9. Normalised vibration velocity measured on the surfaces of a mid-box in the first tier. Values are averages of four source locations on the stage (dodecahedron emitting white noise) and of four receivers on each surface. Depending on the frequency, the standard deviations of the obtained sixteen values are in the ranges [0.9;6.4] dB (box walls); [1.5;8.8] dB (balustrade) and [0.8;5.6] dB (balustrade).

values were also reported for typical elements: for instance the low frequency contribution of the hall ceiling was noted and the outstanding role of the box balustrade was also outlined, but direct comparison with other historical opera houses is hardly possible due to a lack of data and shared procedures. Recently, the approach was used in a simplified version to investigate the vibration of the box balustrade, box ceiling and walls inside the refurbished Teatro Zandonai. The incident sound was provided by a dodecahedron source placed on stage and operating with a white noise signal in the 60 Hz to 18 kHz band. The results for the three surfaces are reported in Fig. 9. The vibration response of lightweight wooden elements in the box is wideband and covers most of the range of interest for the message delivered in the opera. In particular, the balustrade is able to react effectively up to over 3 kHz, which is highly significant in the context of the singing voice since the most relevant formant frequencies appear to be included. Then, the sound is best radiated from the balustrade but effectively from the sidewalls too. The relative loss of power for the balustrade in the useful range is close to 10 dB. The box ceiling is stiffer and not as efficient as a radiator, but the contribution might be non-negligible at least in the lower frequency range. Despite the reliable ranking operated by the measures, which is largely congruent with [46], the quantitative assessment of audibility and of the relevance of re-radiated sound to the overall acoustic quality are topics still-to-be-researched. Clearly, it has to be considered that the distance between vibrating elements and listeners in the box is quite limited and this may be one of the key reasons to motivate audibility and relevance. Together with the air-borne vibrations, the structure-borne vibrations also play a role. For instance, it is well known that the coupling of musical instruments to the wooden stage or pit floor is accomplished, especially for instruments (like cellos and double basses in particular) that directly touch the floor on a point [47,48]. Apart from re-radiation, the structure-borne vibrations are propagated and can cover significant distances especially in the lower frequency range: the clearest example is the enhancement of low frequency perception obtained in the stalls due to the travelling of low frequency vibrations. For this reason, also the most probable structural paths should be validated and kept by dedicated measures. From the above discussion, it is easily understood that much of the timbre character of an opera hall is owed to the structural vibrations. In particular, the structure has its own "sound" and the outcome is how it blends with the sound of the enclosed volume. It must be noted that these vibro-acoustics effects are not taken into account in the acoustical CAD programs used to monitor the acoustics in the renovation process, which are based on a simplified energetic approach considering only sound absorption and scattering coefficients. New tools should be developed and targeted to standardise the characterisation, safeguard and design of vibrating elements.

8. Conclusions

This paper has reviewed the most prominent acoustics issues to be dealt with when renovating Italian historical opera houses. It has to be noted that the sound insulation of the building is crucial in order to provide optimal conditions for the audience in terms of protection from external and internal noise. Similarly, great care is necessary to control ventilation noise (HVAC) and noise from service equipment. These topics were deliberately left outside the scope of this work but are the basis, or pre-requisites, for successful acoustical design in restorations. It has been shown above that the tools for monitoring and predicting the contribution that air propagation gives to the acoustics are nowadays sophisticated and effective; together with dedicated procedures, they can assist the practitioner in the reliable assessment of materials and volume contributions to obtain the outcome. On the contrary, there is a lack of knowledge and tools to deal with air-borne and, even more so, with structure-borne vibrations. Much work needs to be devoted to the analysis and standardisation of procedures tailored for such large scale vibrating structures (hall ceiling, box parapets, box walls, etc.) since this type of evaluation is not properly covered by the relevant technical norms dealing with vibrations in buildings [49]. The scope of those norms is in fact on the one hand to assess the amount of vibrating energy which is potentially harmful for the structure or which may cause aesthetic damage [50] and, on the other hand [51], to rate the disturbance of vibrating structures on people using the buildings. No specific technical document or recommendation is available with the task of evaluating the quality of vibrations, viewed in this case as an essential and necessary constituent of the structural response to enhance air propagation. Some of the issues to be covered by novel technical guidance should include the elaboration of reference source means, its positions, together with those of the acoustical and vibrational receivers. Moreover there is a serious need for the collection of the related expected values, which might help the practitioner to evaluate the state of conservation and thus to comply with structural and acoustical targets in the renovations. Finally, it is hoped that, like in the case of building acoustics [52], also the air-borne and structure-borne vibrations that provoke re-radiation of sound towards the audience could be auralised and included in the analysis tools producing the perceived sound. This may allow for the assessment of the respective importance of the various components in forming the overall impression of acoustic quality and to evaluate the possible alterations introduced during restorations.

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