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Methods to know and preserve a heritage of the Italian historical theatres: the wooden stage

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Abstract

The work treats the refurbishment of a critical part of an historical theatre: the wooden stage. An opera house is characterized by the consistent use of perishable materials, such as the wooden floor, which is at the same time structural and acoustic element. On one hand the theatre geometry and materials are the characteristic heritage of each theatres, on the other hand the utilization of theaters changes over time and therefore modifications are unavoidable. An Italian opera house has been used as a case study: the Alighieri theatre in Ravenna, designed by Tomaso Meduna and his brother (the former architect of La Fenice theatre in Venice). In 2015 the theatre wooden stage was replaced and the authors of this work were asked to study the influence of the wood ageing. A sample of the stage wood has been analyzed using vibro–acoustic techniques in laboratory and the stage has been qualified using musical instruments (cellos, double basses) and measurements. Finally, a model has been proposed in order to quantify the stage radiation.

Keywords: Wood stage, vibration analysis, historical theatre

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1 Introduction

The Charter of Ferrara (1999) stated: “Preserving the acoustical heritage of historical opera houses means first of all being fully aware of it, identifying its presence and getting to know it. Then, it implies making an inventory of it and, finally, introducing legal protection measures to avoid its spoilage.” [1]

The acoustical characteristics of theatres and concert halls are influenced by the surfaces which are present in the hall itself. The absorption properties and the shape of the hall surfaces have a strong impact on the descriptors qualifying the listening space. The stage is one of the biggest surfaces which has to be considered in a planning phase and in numerical simulations of the theatre. However, very few studies take into account the vibro–acoustic behaviour of the stage [3], which reacts to the excitation given, e.g. by the end pin of double basses and cellos and by aerial excitation from the sound produced by the musical instruments. Professional musicians claim that a significant difference can be perceived when playing in a concert hall allowing greater displacement of the stage.

This work aims to quantify the vibration levels obtained using different excitation sources and determine how the vibrations propagate on the stage. Laboratory measurements have initially been carried out in order to determine and compare the acoustical properties of different wooden specimens. Furthermore, the double bass excitation has been studied and measurements were carried out in the Alighieri theatre in Ravenna. The problems arising from this type of excitation are evident: repeated measurements are not possible and therefore no systematic investigations can be made in different theatres. Hence, measurements with an instrumented impact hammer have been carried out in the Alighieri theatre in order to define a method which could be utilized in a measurement campaigns comprehending vast number of case studies. An in-depth study was performed to estimate the radiation efficiency, a crucial parameter that needs to be considered when calculating the sound power radiated from a vibrating structure.

2 The case study: Alighieri theatre of Ravenna

In 1838 Tomaso Meduna, formerly architect of “La Fenice” theatre in Venice, was asked to design the new Opera house in Ravenna. Works began in 1840 and the theatre was inaugurated in 1853.

The original stage was made of fir boards arranged in square blocks measuring 17.30 m by 17.30 m and sloping “nel rapporto di vent’uno di base per uno di altezza” (the ratio by twenty one of one). The stage was renewed a first time in 1893. In 1928 the orchestra pit was built, cutting the proscenium. From 1959 to 1967 the theatre remained closed in order to replace the wooden structures affected by termites. The original wooden structures were replaced by newer ones made by concrete and steel. In 2014 the direction of Alighieri Theatre planned the

Figure 1: **Quasi-longitudinal phase velocity measurement along the x-axis**

renovation of the stage, due to the wood consumption. In order to suggest an adequate wood typology for the refurbishment a measurement campaign was planned. Both laboratory tests and in-situ measurements were done in order to qualify the effects of the wood ageing on the sound properties. Finally in the summer of 2015 the wooden stage was renewed for a third time.

3 Laboratory measurements

A set of measurements carried out in the laboratory allowed to compare different types of wood and determine several relevant parameters related to the acoustical quality of the wood.

Three wooden beams have been analyzed in the laboratory:

1. Original beam from Alighieri Theater in Ravenna (about 50 years aged)
2. A new beam
3. Recent beam 2 years aged

Figure 1 shows how the measurements were performed on the samples. Two accelerometers were fixed at a reference distance d and impulses were generated with an impact hammer in the longitudinal axis (F_y), the tangential axis (F_x) and the radial axis (F_z). The signal acquired from the accelerometers and the impact hammer were then analyzed in order to calculate the wave propagation speed considering the delay of time t from the two signals.

Monaural accelometers Brüel&Kjær 4371V were placed in the propagation plane. The accelerometers were fixed with Ethylene-vinyl acetate (EVA) hot glue and beeswax, whose damping characteristics do not influence the behaviour of the accelerometers in the frequency range that has been analyzed. An instrumented impact hammer APTech AU02 was used as impact source. Three different impact hammer tips (rubber, teflon and steel) were used to evaluate the influence of the material on the wave propagation speed. No significant changes have been observed; consequently for every measurement the softer tip – namely the one made out of rubber – was used to excite the lowest frequency range. A MOTU 896HD audio converter was

Table 1: **Acoustical and properties of the measured samples.**

Sample	ρ [kg/m^2]	c_{ll} [m/s]	c_{tt} [m/s]	c_{lr} [m/s]	c_{tr} [m/s]	E_l [GPa]	z [10^{3}kg/(m^{2}s)]	R [m^4/(kg s)]
new	390	3000	920	900	260	3,4	1170	7,57
2 years aged	400	4570	870	1000	340	8,13	1828	11,2
50 years aged	450	5300	540	800	230	12,8	2385	11,85

set up to 96 kHz, in order to have enough samples to measure the wave propagation inside the material. Arrival times have been measured using a kurtosis–based method. A Matlab code was then created to calculate the wave speed c_{ly} in the longitudinal direction with the impulse generated in the longitudinal direction. Similarly, the quasi-longitudinal wave speed c_{lx} in the tangential direction with the impulse generated in the tangential direction was determined.

The wave propagation speed along different axes was measured in order to compare the three samples characteristics. With the obtained values it was possible to determine the dynamic elastic modulus E from equations:

$$E_l = \rho c_l^2 \tag{1}$$

$$E_t = E_l \left(\frac{c_t}{c_l}\right)^2 \tag{2}$$

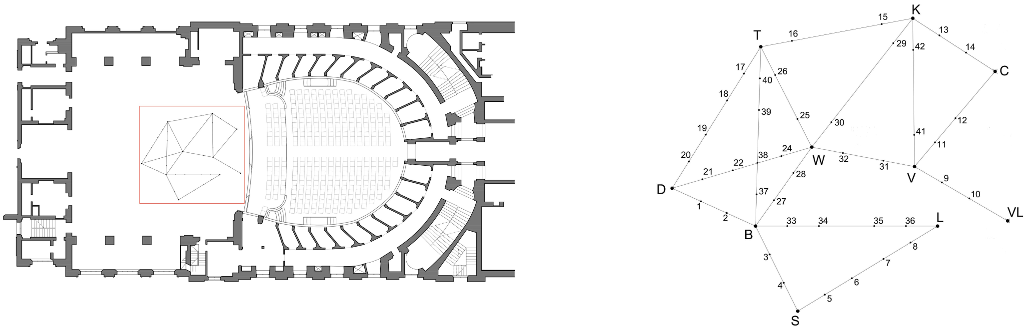
the characteristic impedance is defined as the product of sound velocity c and density ρ [6], [7], [8]:

$$z = \rho c \qquad [kg/(m^2 s)] \tag{3}$$

and, finally, the radiation coefficient R is defined as the square root of the ratio between the elastic modulus E and cubic density ρ^3 [6], [7], [8]:

$$R = \sqrt{E/\rho^3} \qquad [m^4/(kgs)] \tag{4}$$

The results are reported in table 1. The characteristic impedance shows very low values, especially because of the low density of this type of wood. Since lower values of the characteristic impedance allow better sound transmission, the no–aged spruce beam and the two years–aged one show the best properties. Nevertheless, the comparison is more complicated, since also the varnish has an influence which was not taken into account and could explain this difference. Moreover, the trend observed for the three specimens shows that wood ageing increase the values of the characteristic impedance. Furthermore, since the sound radiation coefficient is a parameter which is used to compare the acoustical properties of different wooden species, it is possible to compare the values obtained for the three specimens with the ones found in other studies. The sound radiation coefficient calculated for the three specimens shows values falling in the range of woods for soundboards. As a matter of fact, spruce is a wooden species widely used for instruments' soundboards. This allows to affirm that the wooden species which the



(a) Alighieri theatre (b) Detail of the stage

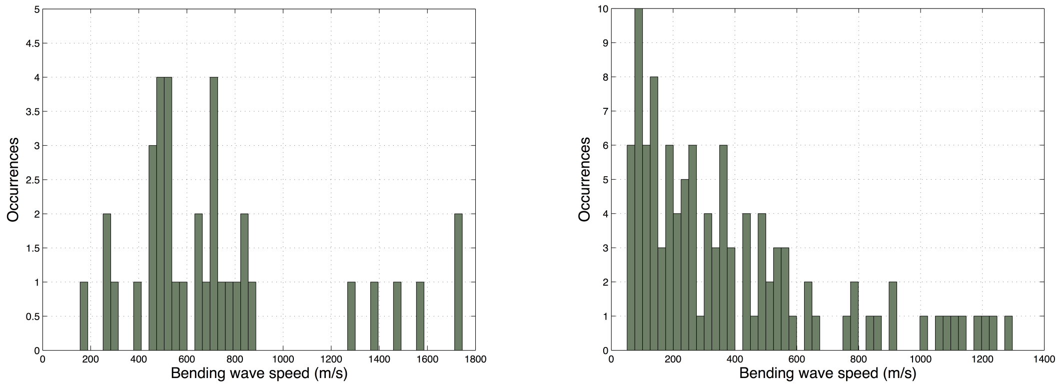
Figure 2: **Sources and receivers positions on the stage of the Alighieri theatre.**

stage is made of will have higher radiated sound power compared to other wood species. The importance of this work is justified because of the high values of the sound radiation coefficient measured for the three specimens.

4 In situ measurements

A set of measurements was carried out to determine the bending phase velocity on the stage of the Alighieri theatre. The positions of the measurement points, shown in figure 2, follow the displacement of the Cherubini Orchestra. The orchestra was founded and directed by Maestro Riccardo Muti and it is the resident orchestra at Alighieri Theatre. With reference to Fig. 2(b) the points B, C, D, K, L, T, S, V, VL and W have been used as sources in the case of hammer excitation, points 1 to 42 have been used as receiver positions for the accelerometers. The method used in this analysis to determine the bending wave speed is the same that was used in the laboratory: two accelerometers were fixed to the stage and an impulse was given either in the longitudinal or in the tangential axis. Considering the delay with which the impulse reaches the accelerometer farther from the source and the distance between the two accelerometers, the wave propagation speed is calculated.

A first analysis considered only the receivers positioned on a line joining two sources and only these two source points have been considered as excitation points (see fig. 4(a)). For instance, considering the receivers 25 and 26, the excitation was given in the points T and W and the bending wave speed was calculated by means of the technique which had also been used in the laboratory. This analysis was extended to every pair of accelerometers on the stage. Interestingly, the mean calculated value of this set of measurements $\mu_{1A} = 770$ m/s is rather similar to the bending phase velocity $c_{by} = 800$ m/s obtained in the laboratory. A more in depth analysis considered also the impulses of the sources not aligned with the receivers' positions (see fig. 4(b)). However, it is rather difficult to interpret the results of this test, since the waves generated from the impulse take two different paths in order to reach the receivers.



(a) aligned couples of receivers only.

(b) all random couples of receivers

Figure 3: **Statistics of the structural sound velocities measured on the stage (occurrences vs velocities).**

The distribution of bending wave speed determined from this analysis is reported in figure 3(b). In this case the mean value is $\mu_2 = 380$ m/s.

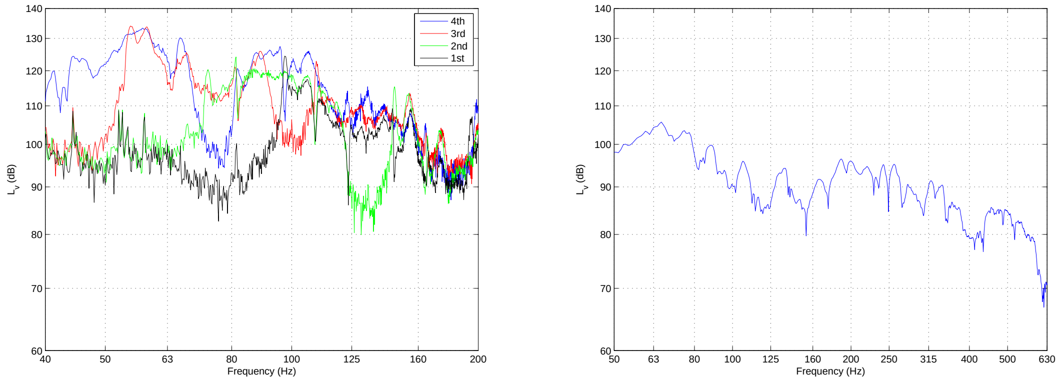
4.1 Comparison between hammer and instrument excitation

It was possible to make measurements in the Alighieri theatre with two professional musicians: a double bass player and a cello player. They were asked to play glissandos and chromatic scales on the four strings, in order to excite the stage in the entire frequency range of the two instruments.

Both instruments were positioned with the end pin on the point K and the responses of the accelerometers were measured at a distance of one metre from the source, i.e. at points 13, 15, 29, 42. The same measurements were taken positioning the end pin of the instruments on point B and the accelerometers in points 2, 3, 27, 33, 37.

The velocities measured with the excitation given by the four double-bass strings have been averaged for the two source points. The velocity levels are expressed in dB (ref. 10^{-9} ms^{-1}). The results are shown in figures 6a and 6b. It can be seen in this graph that every single string is capable of exciting the stage in a particular frequency range.

As in the case of instrument excitation, the same receivers' points were considered in order to determine the velocities in the case of hammer excitation. The mean of the obtained values for the different receiver points is shown in figure 4(b).



(a) Double-bass

(b) Hammer

Figure 4: **Average velocity levels ad a distance of one meter from the source using the excitation of a double bass playing a glissando (a) and hammer (b).**

4.2 Damping measurements

The radiation efficiency is equal to one above the coincidence frequency of the plate, while it has lower values below the coincidence frequency. This happens because of dipole and quadrupole cancellations; therefore, it is of primary importance to determine the radiation efficiency of a structure at low frequencies. The radiation factor increases for higher values of loss factor, since less energy is dissipated in the structure itself.

The total damping loss factor η_{tot} can be considered as the sum of three contributions:

$$\eta_{tot} = \eta_{int} + \eta_{flank} + \eta_{rad} \tag{5}$$

where η_{int} is the internal loss factor, associated with energy dissipation in the structure, η_{flank} is the loss factor associated with energy dissipation by means of flanking transmission and η_{rad} is the loss factor associated with acoustic radiation damping.

The total loss factor has been calculated from the reverberation time T_s and frequency f by means of equation:

$$\eta_{tot} = \frac{2.2}{fT_s} \tag{6}$$

The damping factor of radiation η_{rad} is related to the radiation efficiency σ_{rad}, defined as follows:

$$\sigma_{rad} = \frac{W_{rad}}{\rho_0 c_0 \bar{v}^2} \tag{7}$$

where $\bar{v}^2$ is the temporal averaging of the vibration velocities.

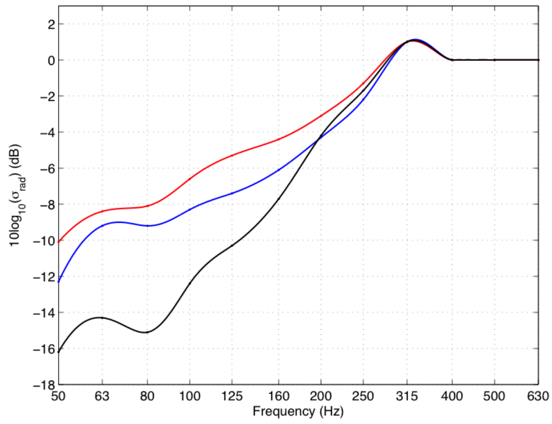


Figure 5: **Radiation efficiencies calculated using analytical method (red line), extimated from measurements (black line). The blue line is the curve used to estimate the sound power levels in eq. 8.**

In the present work the σ_{rad} values have been estimated using both analytical and experimental data (see figure 5).

4.3 Propagation of vibrations on the stage

The signals acquired with the accelerometers allowed to determine the velocities at every measurement point. The intensity of the force used to excite the stage was measured with the instrumented impact hammer. The signals have been averaged, the autospectrum was calculated and a frequency response function was obtained for every couple of source and receiver. This set of measurements permits to determine an area around the excitation point where the levels measured are sufficiently high to generate non negligible sound power levels (see Fig. 7).

5 Sound radiation estimation

Basing on the radiation efficiency σ_{rad} (see figure 5) and the vibration velocities measured on the stage (see figure 6), the sound pressure level may be evaluated using the ISO 10140 formulation [9]:

$$L_w = 10 \log \frac{\rho_0 c_0 \sigma_{rad} \bar{v}^2}{W_0} \qquad (dB) \tag{8}$$

Knowing the sound power levels, the sound pressure levels at musicians' ears have been estimated at 1.2 m height from the stage. The model takes into account:

1. sound power levels from eq. 8

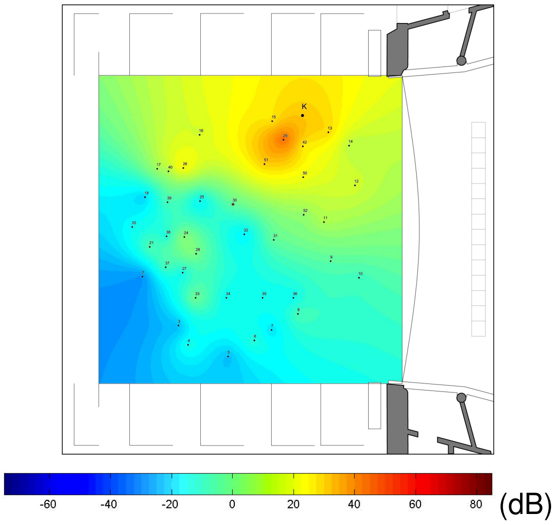


Figure 6: **Frequency response functions (FRF) measured on the stage of the Alighieri theatre excited with an impact hammer in the position of double-basses (K). FRF are expressed in dB and filtered in the third–octave band of 125 Hz.**

2. the instruments as point sources
3. the measurements of the sound velocities of the stage

Figure 7 shows the results of this model for double–bass, taking into account the position of the instruments on the stage of the Alighieri theatre. At low frequencies the sound power levels re-radiated from the stage are comparable to the instrument ones, boosting the warmth of the orchestra. For the position of the double–basses the maximum increasing of the sound pressure level has been estimated in figure 7. The re-radiation of the stage may contribute about + 3 dB for the double–basses in the third-octave band of 80 Hz.

6 Conclusions

The present work collects acoustic considerations about the wooden stage of historical Italian theatres. Analysing the case study of the Alighieri Theatre in Ravenna both acoustic and vibro–acoustic behaviours of the stage have been analyzed. On the occasion of the renovation works of the wooden stage several wood sample having different ageing have been tested, both on laboratory and in situ. A simple theoretical model has been used, by comparing laboratory tests with different boundary conditions and statistical analysis of measurements on the stage. Basing on the laboratory test it has been studied how the ageing changes the wood mechanical properties and which ageing is needed in a refurbishment. Moreover, the results of the laboratory tests have been compared to the ones on the stage in order to validate the used method. Statistical analysis of about 700 measurements on the stage allows to use a

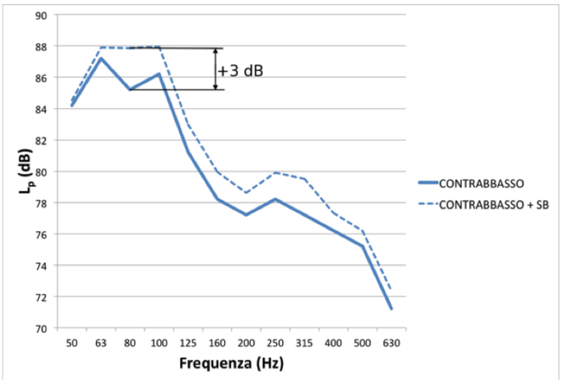


Figure 7: **Increases of sound pressure levels estimated at the double–bass position on the stage when the double–bass is played**

simplified single parameter-based description by taking into account the complex system of axes, supports, wood orthotropicity, etc... The results show that:

1. The results of the laboratory tests on sample beams are in accordance with measurements on the stage.
2. The wood ageing affects the mechanical properties, and consequently the sound radiation. Two-years aged wood shows mechanical properties similar to the original sample of the stage, about 50 years aged.
3. The re-radiation from the sound source contributes to the warmth of the orchestra sound. The maximum of the re-radiation from the stage is in the third-octave band of the 80 Hz, increasing the sound of the instruments which are mechanical coupled to the stage.

The results are in agreement to previous literature [3, 5] as well as they give several details and stimulates further research.

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