TECHNICAL NOTE: SOUND ABSORBING SYSTEMS MADE OF WOOD CROSS SECTIONS PAIRED WITH VOID CAVITIES—A FIRST INVESTIGATION

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Abstract. This study investigates the possibility of exploiting the porous structure of wood for absorbing sound. With this aim, the following system is proposed: 1) the cross section of wood should be exposed to sound waves so that these can activate the vibration of air inside the wood pores; 2) the cross section should be cut to have small thickness to realize a thorough open cell absorber; 3) a void cavity should be left on the back to activate the absorption effect. This setup has been conceived to absorb sound by Helmholtz resonance. To preliminarily assess the effectiveness of the system, cross sections of poplar wood were cut 1 mm thick and paired with rear void cavities 15, 30, and 50 mm thick. The normal sound absorption coefficient α was determined through the impedance tube method. Multiple absorption

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peaks and several α values higher than 0.6-0.7 ($\alpha_{max} = 0.99$) were measured in the medium-low frequency range. Building on these results, further studies are envisaged to model the acoustic behavior of the system and to set the technical aspects relevant to its feasibility in practice.

Keywords: Helmholtz resonance, poplar wood, porous absorbers, sound absorption, wood cross section, wood porosity.

INTRODUCTION

Acoustics strongly affect people in indoor spaces. In offices, classrooms, and similar environments, poor acoustic quality can cause headache, loss of productivity, and other negative effects (Tristán-Hernández et al 2018). The human voice is a major source of noise in the aforementioned spaces, especially when crowded. Therefore, their acoustic correction should be addressed at the frequencies at which the human voice is emitted, in particular within the medium-low frequency range (80-1,600 Hz) (Tang and Chan 1996).

There are three typical methods by which sound can be absorbed by a material. The first method consists of setting the material to damped vibration as a diaphragm paired with a rear cavity. To activate the vibration, the material has to be adequately flexible and arranged in a continuous, thin sheet. This type of absorption is generally notable only at low frequencies (Kuttruff 2007).

In the second method, sound is absorbed by a porous material. Porous absorbers are widely used for acoustic purposes in buildings. They can be defined as solid materials containing voids (cavities, channels, or interstices) through which sound waves can penetrate (Arenas and Crocker 2010; Deshmukh et al 2019). Sound absorption occurs through viscous and thermal effects, which are due to the vibration of the air inside the pores, and through material damping, which is caused by resonance of the pore walls (Cao et al 2018). When pores are isolated from one another, the porosity is called "closed." "Open" pores, in contrast, are continuously connected with the surface of the material and can be "blind" (one open-end) or "thorough" (open at two ends). As a general rule, the higher the possibility of airflow inside the pores, the higher will be the sound absorption.

In the third method, a material with suitable openings (holes) is used to build Helmholtz resonators. These can be described as acoustical mass–spring systems based on two communicating air volumes: the smaller "neck" and the larger "cavity." When hit by sound waves, the air in the neck presses, acting like a mass, the air in the cavity, which reacts by expanding like a spring. This activates a repeated oscillation that is able to absorb high amounts of sound at a specific frequency of resonance, converting energy into heat by internal friction (Kuttruff 2007).

Overall, air is an efficient sound absorber because it is easily put in motion by sound waves, thus dissipating sound energy. Actually, the sound absorbing properties of air are exploited to create different sound absorbing materials, such as porous foams or Helmholtz resonators.

The sound absorption coefficient α indicates the ratio between absorbed and incident sound energy; it ranges from 0, in the case of total reflection of the incident sound, to 1, in the case of complete absorption. Sound absorbing materials commonly used in closed spaces yield α values higher than 0.6-0.7 at the frequencies of interest. By comparison, the sound absorption of longitudinal–radial and –tangential section of wood is limited within the low frequency range (typically $\alpha < 0.20$ below 1,600 Hz, Smardzewski et al 2014; Xu et al 2020). The same is also valid for the cross section of solid wood, which can be considered as a "blind open cell" absorber (typically $\alpha < 0.25$ below 1,600 Hz, for instance, Kang et al 2008; Wang et al 2017).

Given the aforementioned behavior, solid wood, although porous, is usually not considered a porous absorber. Nonetheless, sound absorption properties can be conferred to wooden products to enable their acoustic use in real applications. As an example, wood-based panels are perforated and installed as ceiling coverings, leaving void cavities between them and the rear walls, to provide sound absorption through the Helmholtz resonance effect (Negro et al 2016, 2017).

In this context, this study investigates the possibility of enhancing the sound absorption behavior of the cross section of solid wood. To accomplish this, the following system is proposed: 1) the cross section should be exposed to sound waves so that these can activate the vibration of the air inside the wood pores; 2) the cross section should be cut to have small thickness to activate the Helmholtz resonance effect; 3) a void cavity should be left on the back to activate the absorption effect of the system (Fig 1).

To the best of the authors' knowledge, the system proposed is new to date. Conceivably, it has been overlooked because of limited exposure which cross-sectional surfaces have in most applications of wood-based products. Typically, in fact, the visible surfaces of wooden products are almost entirely obtained by cutting along longitudinal–radial or –tangential sections. Nonetheless, the cross section of wood is important for some applications. A recent example is demonstrated by decorative paneling systems made of cross sections of logs or branches fixed to supporting panels. They can be found as wall coverings in restaurants and public spaces, where they are appreciated for their natural/rustic appearance. Conferring sound absorbing properties to them can result in new value-added products that match aesthetics with acoustic performance.

The present work provides a preliminary assessment of the proposed system. To this purpose, 1-mm-thick cross sections of poplar wood were paired with 15, 30, and 50 mm rear cavities (as outlined in the center of Fig 1). Their sound absorption properties were measured in the low and medium-low frequency range by the impedance tube method according to the standard EN 10534-2 (CEN 2001). Poplar wood was selected because it is highly porous and because its vessels, whose mean tangential diameter is mainly between 50 and 200 µm in *Populus canadensis* (Insidewood 2004; Wheeler 2011), have simple perforation plates, which makes it easier for the air to flow through. Furthermore, the wide availability of poplar wood could support potential manufacturing of the suggested product on a medium to large scale. Overall, the initial findings provided by the present work can lead to future studies on the development of the proposed acoustic system.

MATERIALS AND METHODS

Specimen Preparation

A cylindrical core of poplar wood (*Populus x Canadensis*, clone "I-214") with diameter 101 ± 1 mm was drawn from an industrial peeling process and conditioned until the achievement of 12% equilibrium moisture content (EMC). Subsequently, 1 ± 0.1-mm-thick circular specimens were cross cut perpendicularly to the main geometrical axis of the core, resulting in a series of transversal disks. Thickness was limited to 1 mm to enable the airflow throughout them. The circumference of each specimen was sanded until

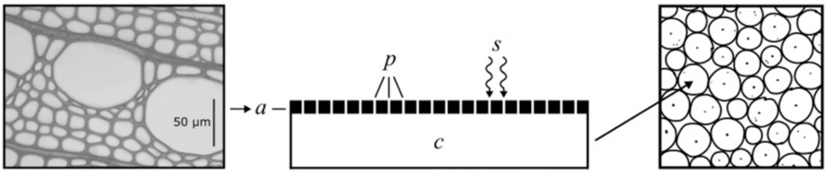

Figure 1. On the left: cross section of poplar wood (image Fragnelli G., modified). In the center: outline of the system proposed, shown in a side view and not in scale for better readability. *a*: thickness of the cross section of solid wood. *p*: the wood pores constitute the necks of the resonator; *c*: the rear cavity is made by the void space between the cross section and is delimited by the surface at the back. *s*: the sound waves hit the air inside the pores, activating the absorption effect. On the right: outline, shown in a front view, of a hypothetic panel realized by arranging several round cross sections of wood: each of them is thin and paired with a rear cavity as in the setup shown in the center.

reaching 100 ± 1 mm in diameter, making it suited to adhere to the inside of the impedance tube used for the acoustic testing. Dimensions were always measured by a digital caliper with accuracy ±0.01 mm. The surface of each specimen was sanded and blown out with compressed air to remove eventual sawdust from inside the wood pores. The specimens were glued on thin plastic rings (100 mm diameter) to enable steady placement inside the tube. Specimens were visually inspected before testing and discarded when considered not suitable, for instance, in the case of an uneven surface. After placing a specimen in testing position inside the tube, its circular edge was sealed with vinyl glue to fill any void that could have remained between it and the inner circumference of the tube. Overall, five specimens were subjected to testing. In addition, a 30-mm-thick specimen, taken as control, was prepared and tested as described earlier to verify the sound absorption properties of the cross section of solid poplar wood.

Normal Sound Absorption Coefficient

The normal sound absorption coefficient α was determined using the impedance tube method according to the standard EN ISO 10534-2. The aforementioned coefficient was measured at 2 Hz intervals in the frequency range of 63-1,600 Hz by means of a large impedance tube (SW422, diameter 100 mm, BSWA Technology Co., Ltd., Beijing, China). Three cavities, of 15, 30, and 50 mm, were left between the specimens and the steel backing of the tube. The testing setup corresponds to the outline shown in the center of Fig 1, where the cavity *c* is delimited by the cylindrical walls of the tube and by its rear steel backing, and the sound waves *s* are generated within the tube. Three repetitions were performed for each specimen/cavity combination and for the 30-mm-thick specimen. Overall, 48 tests were performed (5 specimens × 3 cavities × 3 repetitions + 3 repetitions for the 30-mm-thick specimen).

The tests were carried out at an ambient temperature of 22°C, 50% relative humidity (RH), and an atmospheric pressure of 101.325 kPa. This results in the following values: air density: 1.2 kg/m^3, sound speed: 344.369 m/s, characteristic impedance of air: 405.653 rayl (Pa × s/m).

RESULTS AND DISCUSSION

As shown in Fig 2, the sound absorption coefficient α measured for the 30-mm-thick control specimen resulted always <0.20 (α_{max} = 0.18, $\alpha_{average}$ = 0.10). This confirms the limited sound absorption provided in the low frequency range by wood cross sections, including those of poplar (Wang et al 2017), which can be considered blind open cell structures.

Figure 3 illustrates the sound absorption coefficients measured in the low frequency range for a 1-mm-thick specimen paired with rear cavities 15, 30, and 50 mm thick. Six main absorption peaks can be identified for each curve. As for the 15-mm-thick cavity, the peaks appear not entirely formed, indicating that the rear volume did not properly trigger the absorption effect. By contrast, the 30- and 50-mm-thick cavities fully activated the system and gave rise to various peaks with α values > 0.7, the highest of them (α = 0.99) laying at 550 Hz.

The activation of multiple, successive absorption peaks demonstrates a complex absorption phenomenon. This behavior cannot be attributed to a membrane absorber because the surface of the

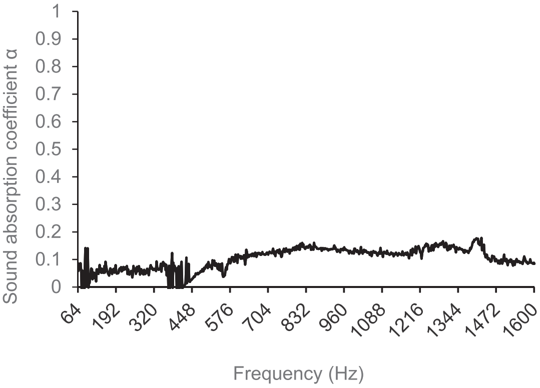

Figure 2. Sound absorption coefficient α measured in the impedance tube for the 30-mm-thick specimen of poplar wood taken as a control.

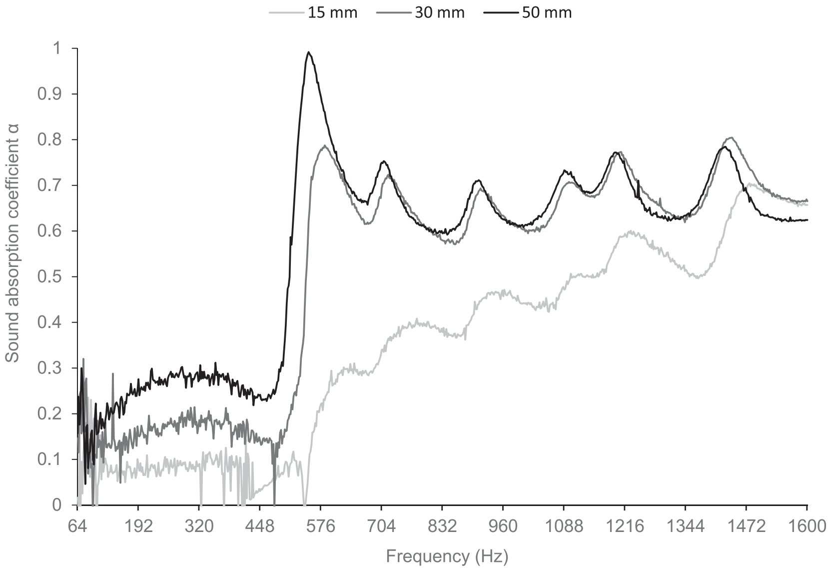

Figure 3. Sound absorption coefficients α in the low frequency range measured for 1-mm-thick specimens paired with rear cavities of 15, 30, and 50 mm.

wood cross section is not continuous but rather has scattered open pores (thorough open cells). The absorption behavior also cannot be caused by the action of a porous absorber placed at a distance from a rear rigid surface. In this case, the absorption should peak at frequencies corresponding to a quarter wavelength from the surface and to its odd multiples (Everest and Pohlmann 2009). This physical law does not hold for the tested specimens (thickness 1 mm). When, for instance, the cavity is 50 mm thick, the corresponding peak frequencies should be about 1,722 Hz and its odd multiples, which do not correspond to the values measured.

The morphology of the system instead suggests the activation of a conventional multiple-hole Helmholtz absorber. Typically, such resonators activate a wide, single absorption peak placed at a specific frequency of resonance. This can be calculated, as is well known in the literature (for instance Cox and D'Antonio 2009), as follows (Eq 1):

$$f_r = \frac{c_0}{2\pi}\sqrt{\frac{\varepsilon}{a'd}}, \qquad (1)$$

where c_0 is the speed of sound in air at the environmental conditions considered (ms^{-1}), ε is the ratio between the overall perforated area and the total area, d is the depth of the rear cavity (m), a is, as shown in Fig 1, the thickness of the cross section of solid wood (m) in which the pores constitute the resonator necks, a' is the length of the resonator necks with "end corrections" to take into account their radiation impedance (typically, $a = a'[1 + 0.85D]$, where D is the diameter of the holes).

Anyway, the action of a conventional multiple-hole Helmholtz absorber must be rejected as well. This is, primarily, because the experimental results did not show a single absorption peak, but several. Furthermore, in the case of the tested system, the outcome of Eq 1 is not in line with the experimental results. For instance, Eq 1 can be solved using the following values: cavity thickness 50 mm, pore diameter 50-200 μm, and perforation 20-100 pores mm^{-2} (common ranges for *Populus canadensis* wood, Insidewood 2004). Using these parameters results in a resonance frequency ranging from 1,370 Hz to 7,700 Hz, which does not match with the experimental data.

Therefore, the conventional multiple-hole Helmholtz absorber does not describe the behavior of the tested system. This can be attributed mainly to two reasons: 1) the geometry of the specimens and the distance of mounting do not satisfy the condition under which Eq 1 is derived (ie the cavity size has to be much smaller than the acoustic wavelength); 2) the microstructures of poplar pores and their relative distances create mutual interactions of the radiation impedances; and thus, the various impedances cannot be assumed to be independent of one another.

Based on the previous considerations, the measured multiple-peak absorption behavior appears to be quite consistent with the action of a microarray of Helmholtz resonators (SangRyul et al 2006). These can be defined as microstructures consisting of a large number of micropores whose diameters and relative distances are much shorter than the wavelengths of the sound under consideration. This type of system is consistent with the microstructure of the wood open pores, where the wood pores act as resonator necks and the rear airspace as a cavity, which results in multiple-peak absorption curves. Developing theoretical models of Helmholtz arrays requires specific studies (Kang and Fuchs 1999; SangRyul et al 2006), and modeling the present system would be particularly complex, given the structure and variability of the anatomical features of poplar wood. Overall, the proposed system requires further investigation by additional experimental measures, like the flow resistivity of the specimens and the longitudinal velocity of radial waves, as well as by developing a theoretical model of sound propagation. In practice, the behavior could be even more complex if wood cross sections have some degree of fold, which can affect placement and size of the absorption peaks.

Figure 3 also shows that increasing the cavity thickness shifted the peaks toward lower frequencies, where the correspondent α values resulted mostly higher (in other words, the curves shifted toward the top left of the graph), for example, considering the leftmost peak of each curve: cavity 15 mm: $\alpha = 0.30$ at 638 Hz; cavity 30 mm: $\alpha = 0.79$ at 584 Hz; cavity 50 mm: $\alpha = 0.99$ at 550 Hz. This phenomenon further confirms that the cross section of wood acted like as a Helmholtz resonator array. In fact, the size of the cavity affects the sound absorption properties: the higher the volume, the lower is the frequency and the higher is the α value (Everest and Pohlmann 2009).

The multiple-peak behavior was found for all specimens tested. Yet, even if similar patterns can be identified, the number of peaks, their frequencies, and heights varied depending on the specimen considered (Fig 4). This can be because of the anatomical differences of the cross sections tested. Wood, in fact, is a highly variable material, and its anatomical features are known to vary depending on the portion of the trunk that is sampled. Furthermore, as a diffuse porous wood, poplar wood includes vessels of several different widths. This can result in absorption peaks laying at different frequencies, depending on the most recurrent vessel sizes. Variation in nominal thickness or in elasticity and folding of specimens could have affected the features of the peaks as well.

In this preliminary study, cross sections of wood were cut 1 mm thick to ensure proper airflow thorough them. However, poplar vessels, which are around 0.6-0.7 mm long (Hacke 2015), constitute continuous ducts longer than 1 mm

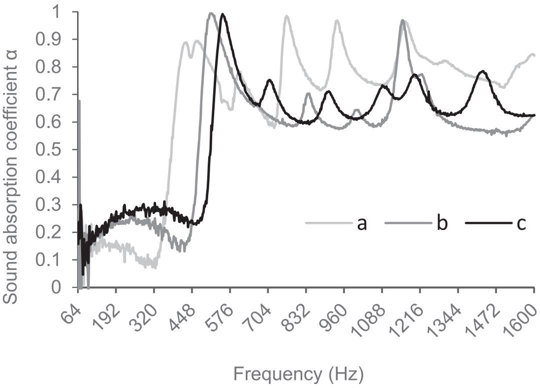

Figure 4. Sound absorption coefficient measured for three different specimens (a, b, and c, where c is the specimen already shown in Fig 3); all specimens were paired with a rear cavity 50 mm thick.

because they are stacked on top of each other and have simple perforation plates. Therefore, the proposed system could work with wood cross sections even thicker than 1 mm, resulting in different resonance frequencies and peak sizes. Differences should be specifically investigated together with the threshold of thickness that enables the functioning of the system. From a practical-productive point of view, thicker cross sections would be easier to realize and manage.

Additional perforations of the cross section could be envisaged to optimize the absorption properties of the system. Based on the physics of Helmholtz arrays, absorption curves would presumably shift toward higher frequencies by additional perforations. Still, artificial perforation would represent an additional processing phase that would only be worthwhile if it were able to considerably enhance the absorption properties. Control of the cavity volume is also relevant to the proper functioning of the system, where bigger cavities would shift the absorption curves toward lower frequencies. The area of each cavity is limited by the area of the continuous, thin solid wood section that can be realized in practice. Therefore, the volumes of the cavities are likely to be regulated mainly by modifying its depth.

In sum, further studies are required to better investigate the variability of acoustic performance within the same trunk, within the same species and between different species.

Nonetheless, the aim of the present work was to study the possibility of exploiting the cross section of wood as a thin sound absorber, which was verified for all specimens tested. In this context, the observed absorption performance resulted to be suitable for practical applications for acoustic improvement of indoor environments. In addition, the variability of wood can turn out to be positive in creating claddings and sidings that absorb sound simultaneously at different frequencies.

CONCLUSIONS

The present work indicates that thin cross sections of wood can be paired with void cavities for absorbing sound effectively through the Helmholtz resonance effect. The sound absorption effect measured for 1-mm-thick cross sections of poplar wood paired with rear cavities 15, 30, and 50 mm thick was considerable, with α values higher than 0.7 ($\alpha_{max} = 0.99$) in the low frequency range.

The performance observed could be used for practical applications. For instance, several elements (wood cross sections paired with cavities) can be arranged to form paneling systems intended as wall coverings, cladding, and sidings with both acoustic and aesthetic functions. Another example is the manufacturing of small acoustic traps, addressed at specific frequencies, to be used in closed spaces that require high acoustic quality.

Starting from the encouraging results of this work, further studies are needed to investigate and model the acoustic performance of the proposed system and to verify its feasibility in practice. In particular, research should focus on modeling its acoustic behavior depending on the wood species and on the thickness of the cross sections. In this vein, the authors intend to test the sound absorption properties of the system realized with cross sections of other wood species having different vessel diameters and porosity patterns. Additional perforations and controls of the cavity volume are also worth studying. Last, further research should investigate aspects related to technical feasibility, including cutting and finishing of the cross sections, maintenance of the final product, and effects of variations in the wood EMC on the sound absorption properties.

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