EQUALIZATION OF WOOD-PANEL LOUDSPEAKERS

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ABSTRACT

This paper studies the acoustic properties of a tree orchestra consisting of four wood-panel loudspeakers and proposes an equalizer (EQ) design for each loudspeaker. Two design strategies for graphic equalization on Bark bands are considered: a single- and a multi-point approach. Asymmetries in the wood-panel speakers cause their magnitude responses to vary so much in different directions that the multi-point averaged EQ gets smoothed and does not have much effect. A single-point EQ, designed based on the frontal response, changes the magnitude response more and improves the overall shape of the response substantially in front of the panels. The magnitude responses at other measurement points are also improved. The EQ does not attenuate the ringing of the wood-panel modes much, thus retaining their resonant quality. The orchestra of equalized wood-panel speakers is used in a science center to showcase acoustic properties of wood.

1. INTRODUCTION

Contrary to the neutral sound of moving-coil cone loudspeakers, a more natural sound has been pursued with unusual types of sound reproduction methods. An example is the panel loudspeaker comprising a wooden board and actuators, which is studied in this work. This can basically be seen as the elemental form of a distributed-mode loudspeaker [1]. Equalization of such speakers is studied in [2]. Other constructions involving wood-induced sound radiation are, for example, wooden boxes used as loudspeakers, and actuators attached to existing wooden surfaces. All these follow the recent trend of hidden or invisible sound [3–5]. Other materials such as glass have also been tested in speakers [6–9].

The sound generation method studied in this paper is called structure-borne sound, which is typically characterized by resonances, an unusual spatial image caused by a large radiating surface, and sound localization behind the radiating surface [10]. Furthermore, when multiple actuators are attached to a panel, a complex superposition of excited modes is obtained [11]. The resulting frequency response thus contains heavy spectral coloration, and depending on the application, equalization may be beneficial.

Sowden and Ampel [6] reported on the development of professional/commercial planar loudspeakers, where they experimented with various types of radiating surfaces. They found that large surfaces typically attenuated the high-frequency response, whereas a light, radiating panel led to better efficiency. The radiating surface acts as a dome radiator, with a frequency-dependent size, i.e., the lower the frequency, the larger the size of the radiating surface. Furthermore, the directivity varied less than with a conventional loudspeaker, but less predictably.

Berndtsson presented measurements on “acoustic walls” [12] and performed a perceptual study with such systems [13]. The acoustic walls consist of pairs of boxes, where the soundboard is made of a specially-treated spruce [12]. A loudspeaker coil driven by a large magnet is attached to the soundboard, and it is fed by a compressed and equalized microphone signal. Since their aim was to improve room acoustics by adding more reverberation, the resonance and sound radiation properties of the acoustic walls were analyzed. The measurements showed that the system deviated from an ideal one, and instead colored the spectra [12]. The acoustic walls were shown to possess complex radiation characteristics, and the resonances can contribute to excessive reverberation times.

Lähdeoja *et al.* presented the measurements of a flat panel speaker constructed of plywood [10]. They measured the plywood, intended as a scenographic element to be viewed and heard from different directions, and designed a finite impulse response (FIR) equalizer (EQ) using the inverse Fourier transform. Due to their application, they opted for an averaged multi-point design procedure that resulted in an acceptable compromise regarding the magnitude responses in different directions. The measurements showed that without the equalization the audio output was heavily dependent on the acoustic properties of the radiation surface and its modes, which led to a heavily colored spectrum with emphasized resonant modes [10]. Other potential problems are the lack of perceived bass, a blurry bass response, and a reduced dynamic range.

Cecchi *et al.* studied the effects of equalization on sound transducers installed on existing surfaces, such as walls, ceilings, or swimming pool walls [5]. They measured different vibrating surfaces in various environments and noted that the resulting magnitude response is not flat in general. Thus, a multi-point equalization procedure was applied to enhance the sound quality. Both objective and subjective tests indicated positive effects: resonances were reduced, the magnitude response became flatter, and the overall audio quality was improved [5].

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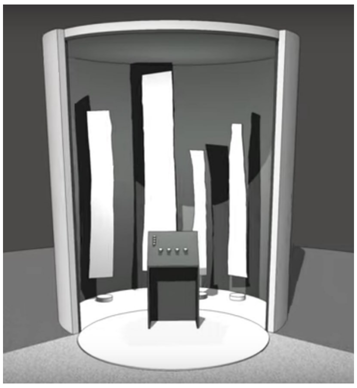

Figure 1. Sketch of the tree orchestra installation at the Finnish Science Center Heureka (used with permission). The control panel in the center allows the user to adjust the volume of each speaker and select the program material.

This paper presents measurements of a “tree orchestra” installation. This project is a commission from Heureka, a science centre in Vantaa, Finland. As part of their 2020 exhibition on wood called Wild Wild Wood, Heureka sought to have an installation showcasing the music-related acoustic properties of wood in an engaging and aesthetically attractive manner. In response to Heureka’s request, our team at the Aalto Acoustics Lab and at the University of the Arts Helsinki, joined by luthier Juhana Nyrhinen, elaborated a design idea for a tree orchestra comprising four wooden panels equipped with structure-borne sound drivers. In order to allow for easy comparison between the different panels, the installation contains audience interaction in the form of playback controls. The work builds on previous research on artistic use of audio-rate vibration in solids [10], involving several sound art installations [14]. As the wood panels have a highly colored response, the use of an EQ is considered helpful to improve the overall sound quality. However, the goal is to retain the characteristic wood resonances.

This paper is organized as follows. Section 2 describes the design principles and the construction of the four wood-panel loudspeakers. Section 3 focuses on the acoustic measurements and the EQ design for the wood-panel speakers, comparing two different equalization strategies: multi-point and single-point. Section 4 analyzes the results and shows how the panels’ sound quality was improved using EQs. Section 5 concludes the paper.

2. DESIGN OF THE TREE ORCHESTRA

The installation is composed of four wood panels cut in longitudinal sections directly from the trees, exposing the tree’s internal structure as well as its contour. The core idea is to play original composed music through the panels, one instrument per panel, following the metaphor of a “tree orchestra”. A sketch of the installation is shown in Fig. 1.

One of the authors (Otso Lähdeoja) composed a set of four musical pieces and recorded them with an instrumental quartet comporting a cello, violin, clarinet, and flute. A central design guideline was to use local Finnish wood traditionally used in lutherie. The overall design targeted strong visual appeal and character combined with optimized audio quality.

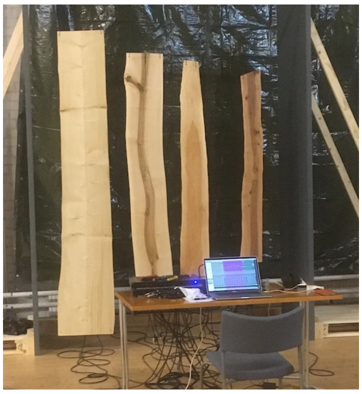

Figure 2. Tree orchestra installation during the mixing of the music program. From left to right: spruce, maple, goat willow (*Salix caprea*), and apple.

The wood and musical instruments were assigned as follows, with the approximate panel size in parenthesis (height, width, depth): Spruce (250 cm × 40 cm × 2 cm) – cello; maple (202 cm × 30 cm × 2 cm) – clarinet; goat willow (183 cm × 22 cm × 1 cm) – violin; apple (161 cm × 16 cm × 1 cm) – flute. The choice of the instrumental ensemble was made on aesthetic grounds, aiming for a light, acoustic ensemble sound. The assignment of the instruments to the different wood panels was decided upon testing how the unprocessed audio recordings translated through each panel. Figure 2 shows the tree orchestra setup during the final mixing of the musical pieces.

The panels are equipped with audio transducers (structure-borne sound driver) for sound output. Each panel has one Tectonic Audio Labs TEAX32C30-4/B transducer [1] and one Fischer Amps Bass Pump 3 [2]. The smaller actuator, TEAX32C30-4/B, has a reported frequency range from 100 Hz to 20 kHz. The bass drivers reportedly respond between 5 and 200 Hz. Thus, the two transducers implement a built-in crossover, and they are treated as one loudspeaker unit in this study.

The low-frequency drivers were placed in the lower half of the panels and the treble drivers were placed in the upper half. Generally, the actuators were placed slightly off the center line to reduce symmetric modes. The distance between the two actuators also affects the generated vibrations in the panels, and in this study, the distance was maximized while at the same time ensuring that they are not placed too close to the top or bottom of the panels. Finally, the exact location of the drivers on each panel was determined by ear due to the non-standard nature of the panels.

The transducers are driven by two Audac EPA104 D-

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[1] `https://www.tectonicaudiolabs.com/wp-content/uploads/2019/04/T-DS-TEAX32C30-4B_Rev-1.1.pdf`

[2] `https://www.fischer-amps.de/drum_section.html#article-253`

(a) Front (b) Rear

Figure 3. Placement of the maple panel loudspeaker in the anechoic chamber: (a) the front and (b) the rear of the loudspeaker, showing the bass actuator below the middle and the treble actuator near the top highlighted with arrows.

class power amplifiers [3]. The audio is played back with a custom-made four-track audio-player program, incorporating an interface allowing the public to mix between tracks and their respective instruments. The audience interaction rationale is to provide the public with an opportunity to engage in active participation by navigating within the musical composition and the instrumentation of the installation as well as to allow for a careful listening of each wood panel's specific sonic qualities.

3. MEASUREMENTS AND EQUALIZER DESIGN

3.1 Measurement Set-up

All the measurements were conducted in the large anechoic chamber in Aalto University's Acoustics Lab. The wood-panel loudspeakers were hung in the middle of the chamber one at a time, as shown in Fig. 3, attached loosely to the net floor in order to keep them still and facing the microphones. This is also the way the wood-panel loudspeakers are positioned in the tree orchestra installation in the science center, as shown in Fig. 1. Furthermore, should the wood-panel loudspeakers be positioned directly in contact with the floor or other hard surface, their frequency response would change due to the altered radiation properties, and their vibrations could be transmitted to the supporting structures. The aim was to create an audio system in which the sound radiates directly from the wood panels and not through any of the supporting structures.

All wood-panel speakers were positioned with the bottom edge about 15 cm above the net floor of the anechoic chamber. The height of the panels varied from 161 to 250 cm, and thus, the midpoint of the speakers in this set-up varied from 99 to 140 cm. Figure 3 shows the placement of the maple-panel speaker during the response measurement.

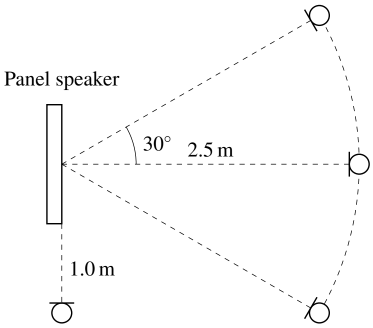

Figure 4. Locations of three microphones in the front sector and one on the side of the panel.

The response of the wood-panel speakers were measured using five G.R.A.S Type 46AF 1/2-inch, free-field microphones. Figure 4 illustrates the placement of the microphones. Four microphones were placed at a height of 1.6 m (those shown in Fig. 4) and one at a height of 1 m, corresponding to an assumed ear height for an adult and a child, respectively. School children and families with small children form a large portion of the visitors to the science center. The four microphones were positioned 2.5 m away from the loudspeaker at angles −30°, 0°, and 30°. These values were selected to approximate the audience position in the installation. The "child" microphone was placed at the 0-degree angle below the "adult" microphone. One microphone was placed at the side of the loudspeaker, at an angle of 90°, in order to verify how a dipole loudspeaker of this type without a baffle radiates sound to the side.

The acoustic measurements were conducted by using a 5-second logarithmic sine sweep [15]. The actuators—two per wood-panel speaker, as seen in Fig. 3(b)—were measured one at a time, as well as simultaneously. The playback level of the sweeps, i.e., the amplifier gain, was kept constant throughout the measurements. Thus, all level differences in the responses are caused by the different types and sizes of the wood panels. The equalization was designed based on these measurements (see Sec. 3.2), after which the equalized wood-panel loudspeakers were remeasured to confirm that the magnitude response of the loudspeaker actually changed as was intended (see Sec. 4).

3.2 Single-Point and Multi-Point Equalizer Design

Based on the first set of measurements, a cascade graphic equalizer (GEQ) was defined to flatten the overall magnitude response of each wood-panel loudspeaker. Since the response of each wood type was measured with multiple microphones, two different procedures were tested: one based on averaged responses of several microphones (multi-point) and another based on a single response (single-point). First, the magnitude responses were smoothed using a one-sixth-octave averaging window in order to decrease the effect of sudden changes in the mag-

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[3] `https://audac.eu/Products/d/epa104---quad-channel-class-d-amplifier-4-x-100w---crossover`

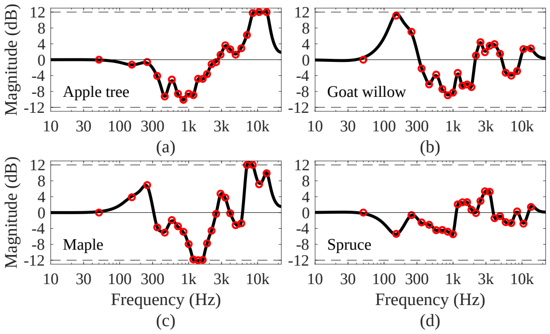


Figure 5. Single-point Bark GEQ responses for the (a) apple tree, (b) goat willow, (c) maple, and (d) spruce panel speakers. The red circles are the command gains, or the estimated corrections needed at each Bark band. The lowest center frequency is 50 Hz and the highest is 13.5 kHz.

nitude response of the EQ. Next, the responses measured with the four microphones in front of the wood-panel loudspeakers were averaged. This was the baseline signal for the multi-point EQ design procedure. For the second procedure, the smoothed response of microphone 1 (distance 2.5 m, height 1.6 m) was used as the baseline.

The EQ design requires only the command gains at the band center frequencies. A recent neural-network controlled Bark-band GEQ [16] comprising 24 bands was used in this project. It was chosen due to its accuracy and low computational load. The command gains for all bands were estimated as follows. The target response was set to be constant (flat) in the passband of the wood-panel speakers, and so the smoothed baseline magnitude responses specified above were additively inverted to determine the gain required for a flat response. That is, the mean value of the baseline response was first subtracted from the baseline response in order to bring it to around 0 dB. Next, the dB values at the Bark center frequencies were picked, and their additive inverse values were stored as command gains. In order to avoid excessive gains, a ±12-dB limit was set for the maximum gain values. Furthermore, the gain for the first band (50 Hz) was always set to zero so as not to overload the bass transducer. This way, two sets of command gains were obtained from the two different design procedures (single-point and multi-point).

The EQ design itself was based on a neural network: the command gains were fed to a four-layer neural network, which selected the optimal band-filter gains by accounting for the interaction between adjacent Bark-band filters [16]. These filter gains were used to design a second-order filter for each Bark band of the GEQ, as described in [16]. The resulting EQ responses for each wood type are shown in Fig. 5 for the single-microphone design method and in Fig. 6 for the multi-point method. The required EQs for the different wood-panel loudspeakers differ from each other, demonstrating the different acoustic behavior of each wood type and panel size. The comparison of Figs. 5 and 6 also reveals that the two design methods produce completely different EQ curves.

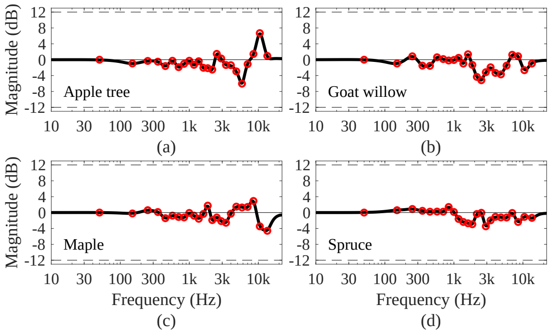


Figure 6. Multi-point EQ responses for the wood-panel loudspeakers, cf. Fig. 5.

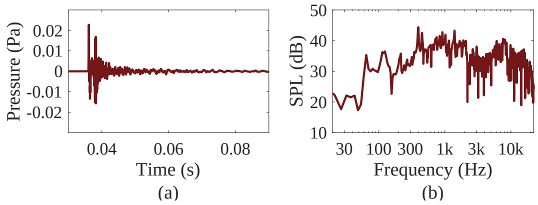


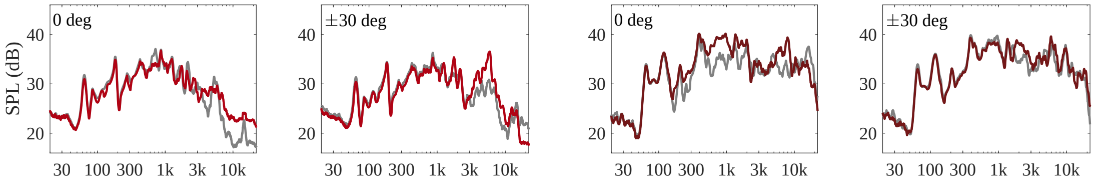
Figure 7. Measured impulse response and the corresponding magnitude response (without smoothing) of the goat willow panel at microphone 1 in front of the speaker.

The most striking difference between Figs. 5 and 6 is in the range of correction: almost all large peaks and dips are missing in the latter. The gains in Fig. 6 mainly range from approximately −6 dB to 7 dB, whereas in Fig. 5, practically the entire range of ±12 dB is used except in the case of the spruce-panel speaker. The explanation for this is that the responses of the wood-panel loudspeakers vary greatly as a function of direction (see the figures in Sec. 4), and thus, when the EQ is designed based on averaged results from different microphones, the effect of extreme values dissolves, and the resulting EQ has little effect.

It was quickly noticed that the EQs in Fig. 5 produce better results especially in the front direction (this is analyzed further in Sec. 4). This is the most important direction for the wood-panel loudspeakers, since they will be exhibited in a rather small enclosure, as shown in Fig. 1, to avoid sound from radiating all over the exhibition space. Thus, only a few listeners can enjoy the speakers at one time, which allows us to concentrate on improving only the sound radiating directly in front of the speakers. This substantiates the choice of the EQs in Fig. 5. Their effect was tested for each wood-panel loudspeaker by listening to the combined effect of the actuators and the EQs to ensure no audible artifacts emerged due to the equalization. Finally, the effect of the EQs was measured to verify their behavior. These results are presented next.

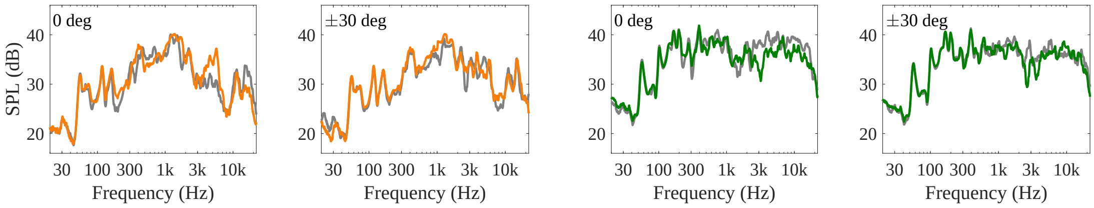
4. RESULTS

This section reports the results for the two sets of measurements: the wood-panel loudspeakers without and with



(a) Apple tree

(b) Goat willow



(c) Maple

(d) Spruce

Figure 8. Unequalized responses for all wood types. For each (a)–(d), the left figure is for 0° at height 1.6 m (color) and 1.0 m (gray) whereas the right one is for ±30° (color and gray, respectively) at height 1.6 m.

the equalization, respectively. As explained in Sec. 2, the loudspeakers are not optimized electroacoustically, i.e., the two actuators are fed with identical signals from two different amplifier output channels without crossover filters or time-alignment. Thus, we consider the combined effects of the two actuators and the wood itself by having one EQ for both channels and by not considering the separate responses measured from one actuator at a time. Furthermore, we acknowledge the possible time differences between the two actuators seen in the measured impulse responses (see an example in Fig. 7(a)), but we ignore them. These time differences range from couple milliseconds to less than ten milliseconds.

Figure 7 shows an example impulse response and a non-smoothed magnitude response obtained with the microphone in front of the speaker at height 1.6 m. Two separate main spikes are seen in the impulse response in Fig. 7(a). This is caused by a time difference between the two actuators, the amount of time each actuator requires to excite the wood, and the difference in distance between the two actuator locations and the microphone. The impulse response is also longer than that of a typical loudspeaker.

The corresponding magnitude response is shown in Fig. 7(b), demonstrating the non-ideal unequalized response. Many peaks are seen corresponding to resonances as well as the general unevenness of the response. Due to the roughness of the obtained responses, in the following, the magnitude response curves are presented after a one-sixth-octave smoothing for better clarity. The GEQ with 24 bands is unable to fully flatten the magnitude response. Thus, important information about the overall shape of the magnitude response is not lost by applying the smoothing.

4.1 Unequalized Responses

The unequalized magnitude responses for each wood-panel loudspeaker are shown in Figs. 8(a)–8(d) for the two microphones at 0° and two others at ±30° (the figures are color-coded across the paper). All frontal responses (0°) in Fig. 8 contain resonances in the upper bass range (between 40 Hz and 200 Hz), which give the wood panels a boxy sound quality [17]. These resonances occur in all curves in Fig. 8 (both at 0° and ±30°) indicating that they arise from properties having quite wide radiation patterns.

From the 0-degree plots in Fig. 8, one sees that the wood-panel loudspeakers, apart from the spruce, mainly radiate middle frequencies (around 1 kHz) well, but the low and high frequencies less effectively. The spruce-panel loudspeaker possesses the flattest overall response aside from and the wide dip around 2 kHz. The flatness is also visible in the EQ curves in Fig. 5(d), where the EQ for the spruce contains the smallest gains, i.e., its overall shape is closest to a flat line. In addition, the responses from the adult and child microphones differ from each other for all wood types: Figs. 8(a)–8(c) show that there is more energy at the higher microphone location, probably due to the small treble actuator being placed high on the wood-panel speakers and being unable to excite the entire panel of wood to radiate sound thus resulting in a high directivity. The spruce-panel speaker differs from the others in this regard.

When observing the ±30-degree plots in Fig. 8, the wood-panel loudspeakers are seen to be asymmetric radiators, since the two curves differ from one another for all wood types. The low-frequency resonances, however, are mostly identical for ±30°. As mentioned, these resonances are also similar here as in the 0-degree figures for the corresponding wood type, whereas the other frequency regions differ between 0-degree and ±30-degree responses. The maple and the spruce panels have the widest radiation patterns, as seen in Fig. 8(c) and Fig. 8(d), since the ±30-degree responses resemble most the ones at 0°. This is logical since these two wood panels are the largest ones. The spruce-panel speaker radiates the flattest magnitude

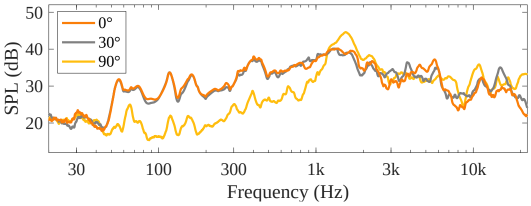


Figure 9. Directivity of a wood-panel loudspeaker (maple).

response in the ±30-degree directions.

4.2 Directivity

Figure 9 presents the measured directivity of the maple panel loudspeaker by showing the magnitude responses in the directions of 0°, 30°, and 90°. The response measured at 90° differs drastically compared to the other two directions, especially below 1 kHz. The attenuation of low frequencies is caused by the cancellation of sound waves radiating forward and backward from the wood-panel speaker in opposite phase. This acoustic short-circuiting is a typical behavior of a dipole radiator. Otherwise, the magnitude levels are similar, especially when observing the curves measured at 0° and 30°. Thus, one can conclude that even though the wood-panel loudspeakers do not radiate ideally due to asymmetries in the wood, the magnitude responses are good in the frontal sector. This analysis applies to all measured wood panels, although only one of them is shown here as an example.

4.3 Equalized Main Frontal Response

After the EQ design based on the initial acoustic measurements, a second set of measurements was conducted to verify that the equalized panels performed as predicted. Here, the results of the second measurement are compared with the first ones for the different panels and microphone locations. Figure 10 shows the effect of the equalization by presenting both the unequalized and the equalized magnitude response for each loudspeaker for the “adult” microphone (0°, height 1.6 m). Note that each curve is normalized by setting the level at 1 kHz to 0 dB.

Figure 10 demonstrates that the EQs produce the desired result for each panel. The magnitude response of the apple-panel speaker originally contained almost 14 dB of variation between 60 Hz and 20 kHz (the −6-dB corner frequencies for the equalized response), whereas after equalization the largest deviations from the normalized level are, naturally, 6 dB for the same frequency range and only approximately 2 dB between 300 Hz and 10 kHz. The resonances of the wooden panel are still visible in the response, but the general level is flat.

The goat-willow-panel loudspeaker response originally contained larger deviations at low frequencies than the apple tree one, but the response at high frequencies behaved better, as shown in Fig. 10. After the equalization, a relatively flat response is observed: before the equalization the largest deviations were approximately 12 dB between 60 Hz and 20 kHz (again, the −6-dB corner frequencies), whereas after the equalization the value is approximately 4 dB for most of the frequency bands. A resonance around 120 Hz is seen to be boosted above the reference level. Not much could have been changed in the EQ response due to the selected frequency division. Furthermore, the stated resonance peak did not affect the sound negatively when listening to the equalized speaker.

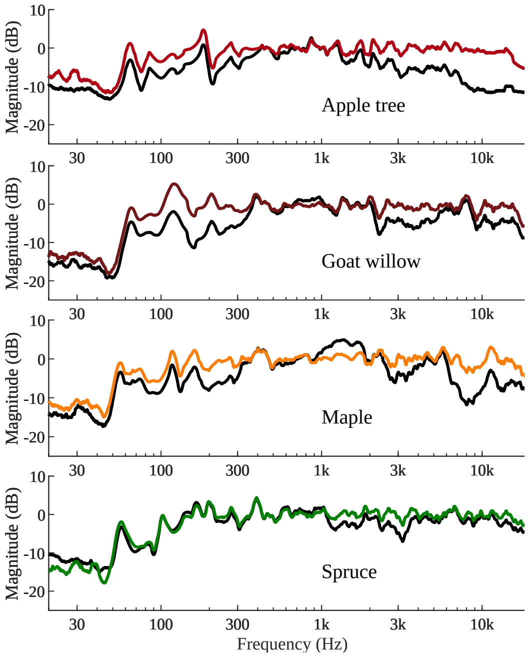
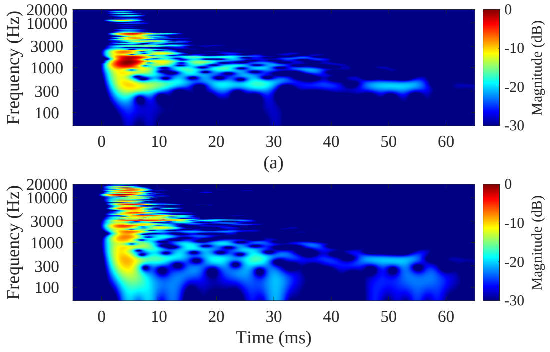


Figure 10. Main frontal magnitude responses of all wood panels before (black line) and after (color line) equalization, one-sixth-octave smoothed.

The unequalized response of the maple-panel speaker in Fig. 10 is similar to that of the apple-tree-panel in that it has a wide peak around 1 kHz. The maple has, however, also other wide peaks, and the largest deviations from the reference level equal approximately 10 dB between the −6-dB corner frequencies of 50 Hz and 19 kHz. After the equalization, the response is much flatter, with the largest deviation being approximately 6 dB at low frequencies and no more than 3 dB at high frequencies.

The unequalized magnitude response of the spruce panel in Fig. 10 is the flattest of the four. Still, the magnitude differs from the normalized level by as much as about 10 dB between 50 Hz and 21 kHz (i.e., the −6-dB corner frequencies of the equalized response). After the equalization, the largest deviation is approximately 9 dB below 100 Hz and less than approximately 4 dB above that. For the equalized spruce-panel loudspeaker, the lowest resonance peak of the magnitude response deviates the most from the rest of the response, so nothing could be done about it with the selected EQ. Between 150 Hz and 400 Hz, three peaks are preserved after the equalization, i.e., the EQ neither boosts nor attenuates them due to the wide bandwidth of the EQ filters relative to the said peaks.



(a)

(b)

Figure 11. Spectrograms of the (a) unequalized and (b) equalized maple-panel speaker's response measured at the front microphone.

4.4 Time-Frequency Analysis of Measured Responses

Finally, spectrograms of the impulse responses on a logarithmic frequency scale were computed to analyze the wood-panel loudspeakers and the effects of equalization. Figure 11(a) shows the spectrogram of the unequalized response of the maple panel, which is computed similarly as in [18]. We use a 10-ms long Blackman window, a hop size of 1 sample, and 256 logarithmically-spaced frequencies to evaluate the discrete-time Fourier transform. The most notable property here is the lack of low frequencies and the temporal spreading of the response at multiple frequencies. Additionally, the main impulse around 5 ms, which corresponds to the magnitude response in Fig. 10, is not of the same color, i.e., the magnitude response is not flat.

The equalized response in Fig. 11(b) contains similar ringing properties to the unequalized one, i.e., the equalization does not cancel the resonances of the wood panels. Now, due to the EQ, the main impulse is closer to having a constant color, i.e., the magnitude is flatter. At the same time, however, the low frequencies introduced by the EQ spread heavily in time. Thus, the log-spectrograms show that it is important to consider both the temporal as well as the frequency-domain properties of loudspeakers. The spectrograms also exemplify the limitations of the minimum-phase EQs in that they cannot repair the non-minimum-phase problems in sound systems [19].

In this application, where non-ideal wood-panel loudspeakers are used, the aim was not to achieve perfection, but improvements to the initial situation. This goal was achieved, as confirmed by informal listening of the panels. The listening comprised the composer listening to the equalized wood-panel speakers and carefully verifying the best panels for each instrument. The spruce-panel speaker produced the most pleasing sound, which is not surprising considering spruce is used in musical instruments.

The final verification occurred when the EQs were applied to the music tracks. The composer noted an improved sound quality and increased clarity for every speaker. In addition, the original characteristics of the wood were not fully lost, and the spatial sound image remained exciting.

4.5 Equalized Responses in Other Directions

The responses measured with the front microphone were discussed above, since that microphone was used for the EQ design. It is, however, interesting to consider the effects of the EQs at other measurement points as well. The responses at 30° at height 1.6 m and 0° at height 1 m are shown in Fig. 12 for every wood type. The responses are offset to improve clarity. Only responses from the $+30$-degree microphone are considered here, but the -30-degree microphone signals show similar trends while also containing some differences in the magnitude responses, as suggested by Fig. 8.

Figure 12(a) shows the magnitude responses at 30° after equalization for apple tree, goat willow, maple, and spruce. Comparing these to the equalized responses in Fig. 10, we notice the following. For the apple tree, the response has a similar flat shape aside from a small level difference and the wide boosted peak around 6 kHz.

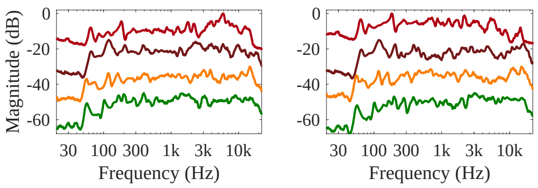
The goat-willow-panel speaker, on the other hand, is flatter overall, and when compared to the front-microphone-response, the response at 30° in Fig. 12(a) is similar with small level differences and slightly changed peak structure. The deviations from a flat curve, however, do not grow much. The response of the maple-panel speaker at 30° resembles its frontal response. The overall response is a flat one with the resonance peaks moving around without their relative levels changing much. Figure 12(a) shows that the spruce-panel loudspeaker radiates a flat response in the 30-degree directions, resembling the 0-degree response with some resonance dips at different frequencies and depths.

Finally, the responses from the "child" microphone, i.e., the microphone below the front microphone at height 1.0 m, are analyzed. Overall, each response in Fig. 12(b) resembles the corresponding equalized magnitude response in Fig. 10, but differs at high frequencies: apple tree, goat willow, and maple radiate less energy in the child listening position, whereas spruce radiates more energy. In addition, there is a wide dip of about 5 dB at about 700 Hz in the equalized goat-willow-panel response in Fig. 10. Thus, although the magnitude responses are not as flat as in the "adult" microphone, children receive an improved sound as a result of the equalization.

Additionally, the responses from the side microphone (90-degree direction) were also analyzed (not shown), but the EQs had little effect on them: the responses are still bad due to destructive interference, and they are omitted here.

5. CONCLUSIONS

This paper presented a tree orchestra installation consisting of four sound-emitting wood panels. The wood panels were measured and equalized to have overall flatter magnitude responses. The aim was not to suppress the modes and resonances of the wood panels, but to reduce the coloration while still retaining the original reverberant characteristics of the panels. Hence, a Bark-band GEQ was utilized. The single-point equalization approach was found to be suitable for this application. The equalized wood-panel speakers were also measured to verify that the actuators



(a) (b)

Figure 12. Effect of the EQs in different directions: (a) +30°, 1.6 m height and (b) 0°, 1.0 m height. From top to bottom: apple, goat willow, maple, spruce. The curves are normalized and offset by -15 dB from each other.

are capable of reproducing the enhanced sound without unwanted artifacts. Example anechoic recordings of the unequalized and equalized wood panels are available online at `http://research.spa.aalto.fi/publications/papers/smc2021-tree-orchestra/`.

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