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Acoustic Properties of Wood-Based and Non-Wood-Based Materials for Piano-Case Making

Akustična svojstva drvnih i nedrvnih materijala za izradu kućišta klavira

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ABSTRACT • *This article presents the possibilities of substituting expensive and scarce wood materials in the construction of piano cases, especially the front panels of upright pianos. Three-layer blockboard, multi-layer plywood, medium-density fibreboard (MDF), and Purenit were selected for the study. These materials were long-time climatised at 20 °C and 50 % relative air humidity. Their frequencies, damping coefficient and relative amplitude were measured. The density* ρ*, sound velocity v, dynamic modulus of elasticity E´, sound impedance* Z_n *and Acoustic Conversion Efficiency (ACE) were calculated. With the materials used to make the front panels of an upright piano, a subjective assessment of the instrument's acoustic response was made. The presence of front panels of any type was found to have a negative effect on the sound except at low frequencies. With panels fitted, the best acoustic properties were achieved by blockboard, followed by plywood, MDF and Purenit panels in that order; this was affirmed by the subjective assessment. The best acoustic performance was achieved by blockboard and plywood. Taking both price and performance into consideration, MDF presented the best compromise. Purenit was ruled out due to its high damping properties.*

KEYWORDS: *composites; acoustic; non-destructive-test; piano case*

SAŽETAK • *U ovom su članku prikazane mogućnosti zamjene skupih i rijetkih drvenih materijala za izradu kućišta klavira, posebice prednjih ploča uspravnih klavira. Za istraživanje su odabrane stolarska ploča, furnirska ploča, srednje gusta ploča vlaknatica (MDF) i purenit ploča. Ti su materijali dugotrajno klimatizirani pri temperaturi 20 °C i 50 %-tnoj relativnoj vlažnosti zraka. Mjerene su njihove frekvencije, koeficijent prigušenja i relativna amplituda. Izračunane su gustoća* ρ*, brzina zvuka v, dinamički modul elastičnosti E´, zvučna impedancija* Z_n *i učinkovitost akustične pretvorbe (ACE). Napravljena je subjektivna procjena akustičkog odziva instrumenta za materijale upotrijebljene za izradu prednjih ploča uspravnog klavira. Utvrđeno je da prednje ploče uspravnih klavira izrađene od bilo koje vrste odabranih ploča imaju negativan utjecaj na zvuk, osim na niskim frekvencijama. Prema subjektivnoj procjeni, najbolja akustična svojstva pokazala je stolarska ploča, zatim furnirska ploča te MDF i purenit ploča. Najbolja akustična svojstva imaju stolarska i furnirska ploča. Uzimajući u obzir cijenu i performanse, MDF je najbolji kompromis. Purenit je isključen zbog jakog prigušivanja zvuka.*

KLJUČNE RIJEČI: *kompoziti; akustičan; nedestruktivno ispitivanje; kućište klavira*

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1 INTRODUCTION
1. UVOD

Wood has been used to produce musical instruments since ancient times because of its availability and workability, especially by hand before power tools were available. Some wood species are more suitable for producing musical instruments than others. For example, European spruce (*Picea abies*) is suitable for making pianos and violin soundboards due to its superb resonance properties (Bucur, 2006). Curly maple (*Acer* sp.) is used for various musical instrument parts, especially guitar back plates, bridges, ribs and necks (Bucur, 2006). The choice often depends on the culture and t region of production. Wood species used for xylophones, a very common subject of research, are black mulberry (*Morus nigra*) (Čulík *et al.*, 2015), padouk (*Pterocarpus soyauxii*) (Straže *et al.*, 2015) and vène (*Pterocarpus erinaceus* Poir) (Traoré *et al.*, 2010).

Bucur (2016) describes three groups of composites – composites with synthetic and natural fibres, nanocomposites, and ceramic-based composites. Fibres are often mentioned as a way of improving musical instrument stability. Synthetic composites include carbon and graphite fibre (Bucur, 2016), used as reinforcing elements in a polymer matrix, usually resin (Bucur, 2016).

The first attempt to replace wood in musical instruments with composite involved plywood (Besnainou, 1998), a panel built up of sheets of wood veneer. Plywood panels contain an odd number of layers – the grain orientations of which alternate at right angles – held together with urea-formaldehyde glue (Ross, 2010). Plywood may be used for small harp soundboards, for example (Waltham and Yoshikawa, 2018; Gunji *et al.*, 2012). In terms of sustainability and environmental friendliness, the tendency is to decrease emissions of formaldehyde from urea-formaldehyde glues (Bilgin and Colakoglu, 2021; Kawalerczyk *et al.*, 2020; Demir *et al.*, 2018).

Medium-density fibreboard (MDF) belongs to a group of fibreboards made from wood fibres using either a wet or dry process. MDF is made by the dry process, in which glue and other additives are applied to the fibres that are pressed and trimmed to standard formats (Ross, 2010). MDF panels are often used in musical instrument construction due to their low price and easy workability. Due to disintegration, MDF has a higher ratio of absorption coefficient than resonance wood, making it suitable for loudspeaker boxes (Sali *et al.*, 2004). Compressing wood before making MDF panels negatively affects dimensional stability (Ayrilmis, 2008). Exposing manufactured MDF panels to heat treatment at 225 °C for 30 minutes decreases surface roughness, thus decreasing wettability and the adhesive bonding strength between the veneer sheet and panel surface (Ayrilmis and Winandy, 2009). Recently, a lot of research has focused on the ecological nature of production. Special attention has been paid to the use of waste in the production of MDF boards (Olgun *et al.*, 2023; Moezzipour and Moezzipour, 2021; Ahmadi *et al.*, 2019) or use of alternative glues instead of Urea-Formaldehyde resins (Savov and Antov, 2020; Sepahvand *et al.*, 2018).

Blockboard is a material made from softwood strip-core with a veneer facing. The central core is made of 25 mm wide strips with vertically arranged growth rings that are interlocked (Böhm *et al.*, 2012). There may be three layers (strip-core and two veneers) or five layers (two strip-cores divided by one veneer and faced with two more). The elements are held together with urea-formaldehyde glue. In this study, a three-layer blockboard was used.

Purenit is a material obtained by recycling polyurethane foams and vehicle interior elements. The colour, structure, and processing parameters of purenit are similar to the properties of particleboards. Purenit is a highly compressed material based on polyurethane rigid foam, commonly used for thermal insulation. It is resistant to moisture and has dimensional stability (Majewski and Smardzewski, 2013). As its acoustic properties have not been tested before, Purenit board was selected as the last material in this study.

Composites made from carbon fibre/epoxy with a balsa core used as a drum shell may be used as a substitute for wood because of their comparable acoustic parameters (Damodaran *et al.*, 2015b).

Some research has been conducted into fibre-reinforced wood (Ono and Isomura, 2004; Ibáñez-Arnal *et al.*, 2019; Ono *et al.*, 2002) as a material for guitar (Ono and Isomura, 2004) and violin soundboards, and the results were evaluated by listeners (Duerinck *et al.*, 2020). These composites may be a good alternative to wood but require further study.

Experiments on natural fibre composites are based on the assumption that natural fibre has a structure similar to wood (Bucur, 2016). The inner part of bark lime or flax (*Linum usitatissimum*) (Bucur, 2016) is often used. The acoustic properties of musical instruments reinforced with natural fibre have been studied – e.g., (Liu *et al.*, 2021; Sun, 2018; Phillips and Lessard, 2009; Daoud *et al.*, 2017). A flax fibre-resin composite may be a good alternative to wood because of its better properties under varying humidity and temperature conditions, its lower variability than that of wood, etc. (Bucur, 2016).

Wollastonite ceramic-based composite has wood-like properties such as good machinability, high sound velocity, and high damping capacity. This material is successfully used in the production of musical instruments (Shimazu *et al.*, 2006).

Petung bamboo (*Dendrocalamus asper*) is a good alternative material for guitar top plates because its fre-

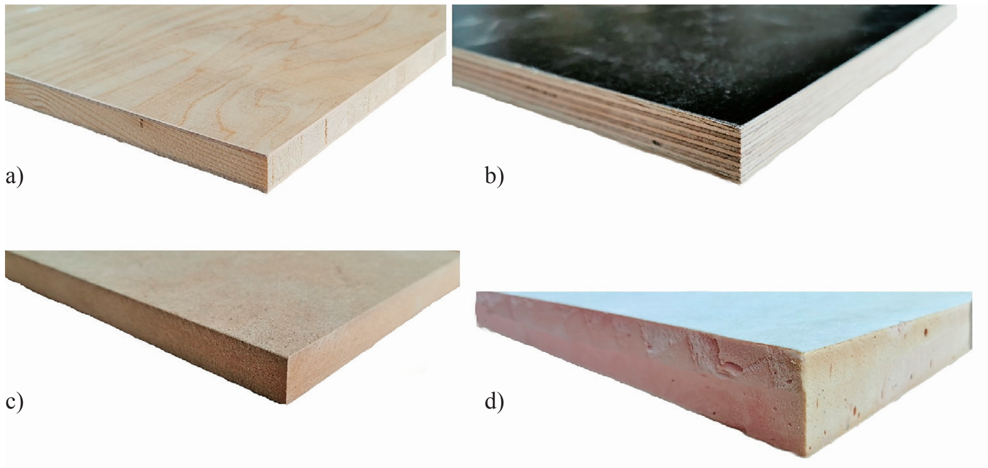

Figure 1 Samples of raw material for making piano panels: a) three-layer blockboard, b) multi-layer plywood, c) medium-density fibreboard (MDF), d) purenit
Slika 1. Uzorci materijala za izradu ploča klavira: a) stolarska ploča, b) furnirska ploča, c) srednje gusta ploča vlaknatica (MDF), d) purenit

quency response function is a fifth that of spruce (Kusumaningtyas *et al.*, 2016).

The main aim of this study was to identify composites which could be used as a substitute for wood in the production of musical instruments, in particular the construction of piano cases.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Four materials were selected for testing – MDF, multi-layer plywood (Multiplex) made from beech (*Fagus sylvatica*, L.) veneers, three-layer blockboard whose core was made from pine (*Pinus* sp.) and face from birch (*Betula pendula*, Roth) veneers and Purenit (Figure 1). Specimens of the dimensions of the front panels of an upright piano were made. Dimensions of specimens were 1400 mm × 435 mm for the upper panel and 1310 mm × 500 mm for the lower panel. The thickness of material was 18 mm for blockboard and MDF panels, 16.5 mm for multiplex, and 21.6 mm for purenit.

The upright piano used in the tests was a P 125 M1 from a Czech manufacturer - Petrof Company. The

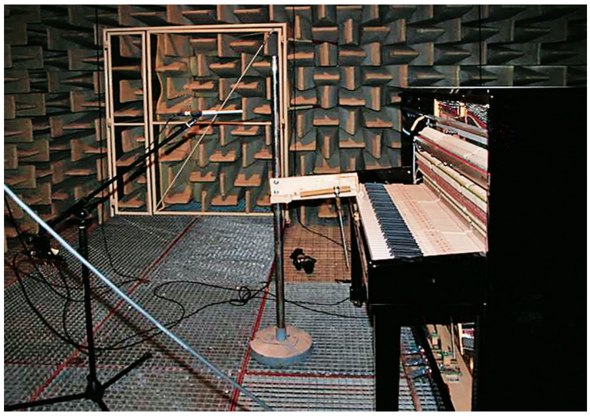

Figure 2 Measuring in anechoic chamber
Slika 2. Mjerenje u anehoičnoj komori

panel specimens were climatised at 20 °C and 50 % relative air humidity for approximately two months, then weighed and placed on soft polyurethane foam pads in an anechoic chamber. The chamber was lined with triangular sound absorption wedges 1,000 mm long, with base dimensions of about 240 mm × 240 mm. The dimensions of the inner space were 8.6 mm × 7.1 mm × 6.6 m. The chamber structure was a concrete

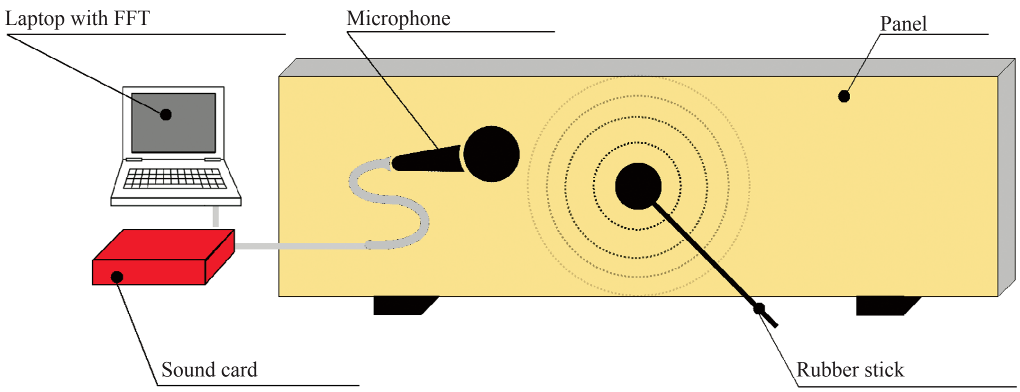

Figure 3 Scheme for measuring acoustic properties
Slika 3. Shema za mjerenje akustičnih svojstava

monolith mounted on springs to absorb vibrations from the surroundings (Figure 2).

Three measurements of acoustic parameters were taken. In the first test, the panels were struck by rubber stick (a small mallet with rubber head) and the resulting vibrations were captured with a condenser microphone (Behringer ECM 8000), connected to an external FireWire sound card Edirol FA101 (Roland, 192 kHz). The position of the struck was selected in the middle of the panels. The measurements were performed as free-free according to (Bucur, 2017). The FFT analyser application (Fakopp Enterprise Bt.) was used for a fast Fourier analysis (Figure 3).

Ten strokes were recorded and edited using a sound editor for the next analysis. The frequencies, amplitudes, and damping coefficient were captured - the five readings were statistically and visually evaluated, based on the sound curves obtained by FFT. Values of frequencies of dominant modes (peaks in the spectrum significantly higher than noise level) were processed in real-time. These points were acoustically evaluated. Acoustic parameters were calculated according to Eq. 1 to 7.

The damping coefficient was derived from logarithmic decrement using Eq.1 (Ghofrani *et al.*, 2016):

$$\tan\delta = \frac{\lambda}{\pi} \qquad (1)$$

Logarithmic decrement λ is derived as a ratio of the amplitudes of two successive peaks using Eq. 2 (Lamarque *et al.*, 2000):

$$\lambda = \frac{1}{n} ln \frac{x(t)}{x(t+nT)} \qquad (2)$$

The parameters describing the acoustic response of materials used in this work were obtained as follows.

Density (Eq. 3) (Glass and Zelinka, 2021):

$$\rho = \frac{m}{V} \qquad (3)$$

Where: ρ is density (kg·m^{-3}), m mass (kg) and V volume (m^{-3})

Sound velocity was calculated from the measured frequency and length of the specimen using Eq. 4 (Kretschmann, 2010):

$$v = f_n \cdot \left(\frac{2 \cdot L_{spec}}{n}\right) \qquad (4)$$

Where: v is sound velocity (m·s^{-1}), L_{spec} is length of specimen (cm), n is mode number of resonance and f_n is measured frequency (Hz)

Dynamic modulus of elasticity calculated using longitudinal waves (without taking into account Poisson´s ratio) (Eq. 5) (Niemz and Mannes, 2012):

$$E' = \rho \cdot v^2 \qquad (5)$$

Where: E' is dynamic modulus of elasticity (MPa), ρ is density (kg·m^{-3}), v is sound velocity (m·s^{-1})

Characteristic sound impedance for any direction (Eq. 6):

$$Z_n = \rho \cdot v \qquad (6)$$

Where: Z_n is sound impedance (kg.m^{-2}.s^{-1}), ρ is density (kg.m^{-3}), v is sound velocity (m.s^{-1})

Acoustic conversion efficiency (ACE) (Eq. 7) (Baar *et al.*, 2016):

$$ACE = \frac{\sqrt{\frac{E'}{\rho^3}}}{\tan\delta} \qquad (7)$$

Where: *ACE* is Acoustic Conversion Efficiency (m^{-4}·kg^{-1}·s^{-1}), E' is dynamic modulus of elasticity (MPa), ρ is density (kg·m^{-3}), and $\tan\delta$ is damping coefficient.

In the second test, the acoustic response of the upright piano was measured while fitted with panels of the materials under investigation. Two microphones

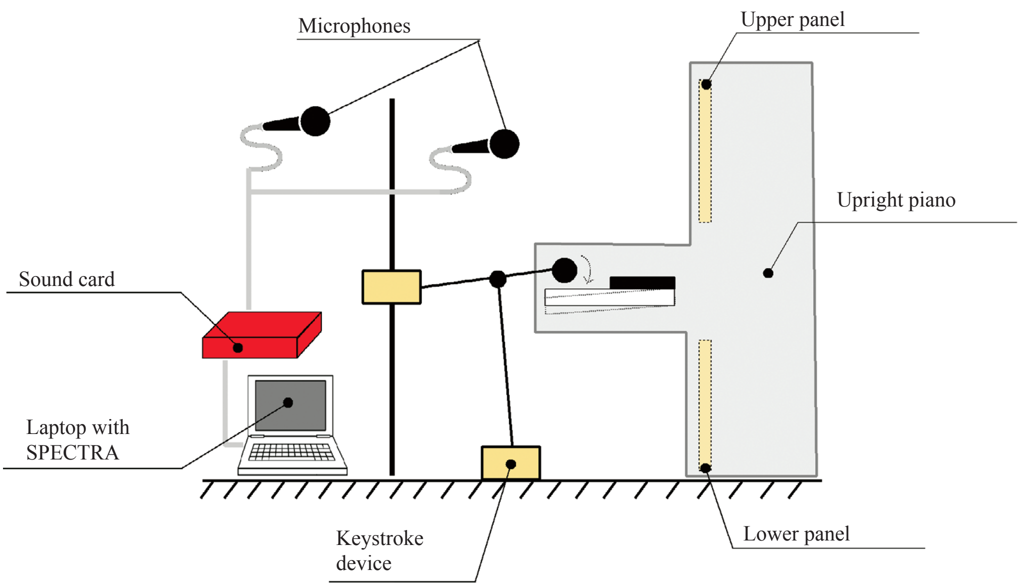

Figure 4 Second test: recording C in each octave
Slika 4. Drugi test: snimanje tona C u svakoj oktavi

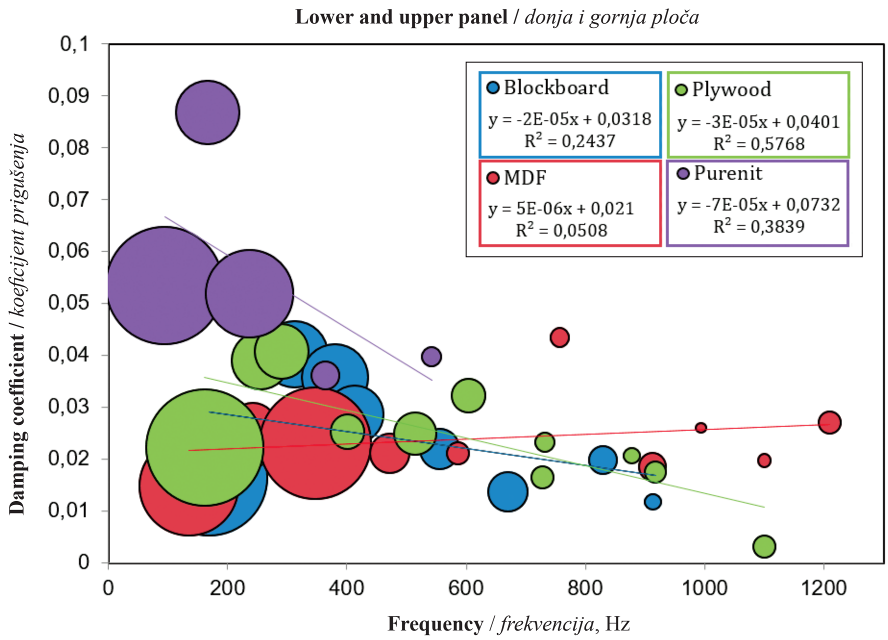

Figure 5 Damping coefficient by frequency for both panels. The area of circles represents relative amplitude.
Slika 5. Koeficijent prigušenja prema frekvenciji za ploče (površine krugova predočuju relativnu amplitudu)

were mounted in front of the piano, the first at approximately the position of the player's head and the second approximately one metre behind the player. A simple device for generating a standard keystroke was built. Eight reference keys on the piano (C in each octave) were selected and a keystroke generated. This procedure was performed with front panels of the test materials, and without panels. All repetitions were recorded and evaluated using SpectraPLUS-SC (Pioneer Hill Software LLC) software (Figure 4).

The third test was a subjective evaluation of the piano fitted with the panels under study. Pieces of music were played on the piano by three experienced players; first without panels, and then after the panels of each material were quickly changed. A committee was set up to assess the sound quality, consisting of intoners, technologists, and employees of the Petrof development department. The committee assessed the sound of the piano without knowing which type of panel was mounted. Members of the committee assessed the quality of the sound on a scale from 1 to 10, where 1 meant the best and 10 the worst result. They also assessed the influence on sound quality of the distance and position of the instrument from the listener.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

An analysis of the frequencies, amplitudes and damping, using an FFT analyser, is shown in Figure 5 for the lower and upper panels of the piano. The values of both panels were averaged because the difference between panels is only in dimensions and support points. The damping coefficient and frequency with relative amplitude of all materials are captured in the graphs. The relative amplitude is indicated by the size of the circles in the plot.

Several points are apparent from the graphs. The data are highly variable, yet some differences are apparent. One difference is between wood-based materi-

Table 1 Comparison of physical and acoustic properties of measured materials
Tablica 1. Usporedba fizikalnih i akustičnih svojstava istraživanih materijala

	Density, kg/m³ *Gustoća,* kg/m³	**Frequency, Hz** *Frekvencija,* Hz	**Sound velocity, m/s** *Brzina zvuka,* m/s	**Dynamic modulus, MPa** *Dinamički modul,* MPa	**Impedance, (kg/m²·s) × 10⁻⁵** *Impedancija,* (kg/m²·s) × 10⁻⁵	***ACE*, m⁻⁴·kg⁻¹·s⁻¹**	**Damping coefficient** *Koeficijent prigušenja*
Plywood *furnirska ploča*	746.0	1,300.5	3,636.2	9,863.7	27.13	206.1	0.0235
Blockboard *stolarska ploča*	640.5	1,389.0	3,883.6	9,661.2	24.88	257.1	0.0234
MDF	859.3	872.5	2,439.5	5,114.1	20.96	103.7	0.0273
Purenit	653.6	400.0	1118.4	817.6	7.31	62.5	0.0536

Table 2 C notes and their frequencies on a standard range piano keyboard
Tablica 2. Tonovi C i njihove frekvencije na klavirskoj tipkovnici standardnog raspona

Note / *Tonovi*	C_1	C	c^1	c^2	c^3	c^4	c^5	c^6
Frequency, Hz *Frekvencije,* Hz	32.7	65.4	130.8	261.6	523.2	1046.4	2092.8	4185.6

als and Purenit boards, whose decrement of damping has higher values. Despite a relatively low regression coefficient, a lower damping coefficient with increasing frequency is noticeable. On average, Purenit achieved the highest damping values (0.0432 and 0.064 for the lower and upper panel, respectively). In the case of the lower panel, plywood and blockboard had almost the same damping coefficient (0.022), while MDF was higher (0.027). In the case of the upper panel, a downward trend was found for wood-based panels – 0.031, 0.024 and 0.019 for plywood, blockboard and MDF, respectively.

Based on the longitudinal frequency, dimensions and weight of the specimens, sound velocity, dynamic modulus of elasticity, characteristic impedance and ACE can be calculated.

Blockboard and plywood have structures closer to natural wood than the other materials and therefore have better acoustic properties, such as *ACE* and sound velocity. Due to the disintegration of wood fibres in MDF panels, this material shows higher damping values than blockboard or plywood. Purenit panels, as expected, gave the lowest frequency, sound velocity impedance and *ACE* due to the different non-wood structure and homogeneity of this material.

Ono and Okuda (2007) and Ono *et al.* (2002) reported acoustic parameters of carbon-fibre reinforced polyurethane foam. This material is closer to the purenit panels. They state that the frequency along the fibres is between 1,433 and 1,860 Hz. Values are higher than those in this article probably because of highly conductive carbon fibres content. Q_r^{-1} factor, which is an alternative to damping coefficient, measured about 0.014. This value is close to resonance spruce damping.

Ghofrani *et al.* (2016) reported damping coefficient between 0.039 – 0.068 for plywood with a rubber core. Due to the damping of rubber core, these values are almost 3 times higher than those of standard plywood.

Bucur (2016) reported the acoustic properties for spruce. He determined the value of longitudinal frequency of 1,405 Hz, which is very close to the measured frequency for the blockboard. The value of damping in longitudinal direction measured 0.009, which is about 2.5× lower than for blockboard. This fact is due to the presence of glue and veneers, which violate the consistency of the grown wood.

Fibreboards are often used as an absorption material. It depends on the density of the material and surface structure (Sharma *et al.*, 2020; Damodaran *et al.*, 2015a). To improve damping parameters, Liu *et al.* (2019) uses the composite made from MDF face and rubber core. They achieved a sound velocity of 594.4 m.s^{-1}, which is much lower compared to our results. The damping coefficient was measured at 0.138, which

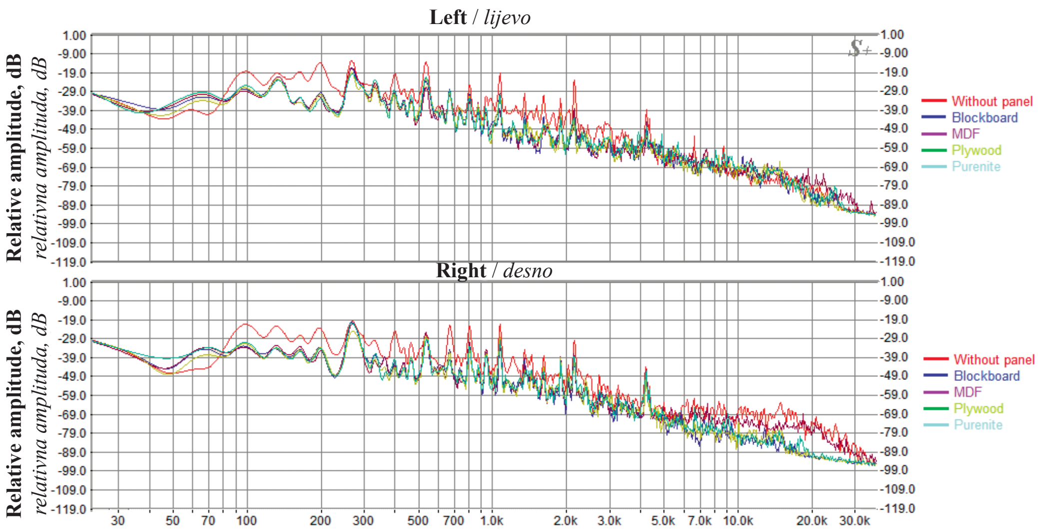

Figure 6 SpectraPLUS-SC output (scale 8000 pts). Red line without panel; blue line blockboard; purple line MDF; green line plywood; light blue line purenit. Top plot: microphone closer to the piano; bottom plot: microphone 1 m behind. Curves represent maximum amplitudes for each note sounded
Slika 6. Izlaz SpectraPLUS-SC (skala 8000 bodova). Crvena linija – bez ploče; plava linija – stolarska ploča; ljubičasta linija – MDF; zelena linija – furnirska ploča; svjetloplava linija – purenit. Gornji graf: mikrofon bliže klaviru; donji graf: mikrofon 1 m iza klavira. Krivulje predočuju maksimalne amplitude za svaki ton.

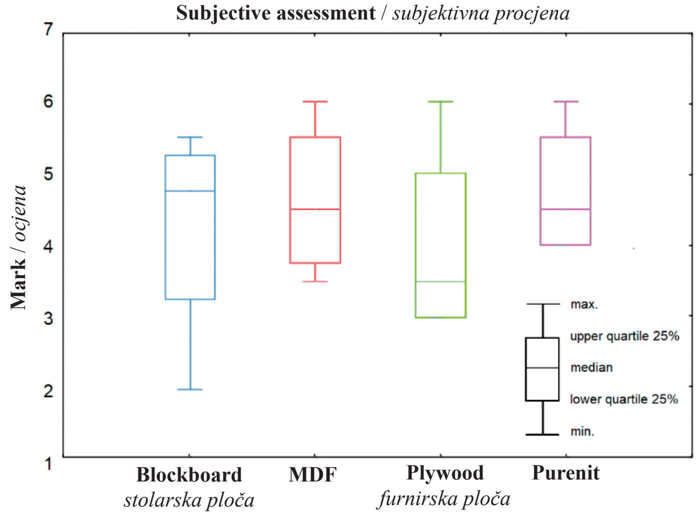

Figure 7 Subjective assessment of test materials
Slika 7. Subjektivna procjena ispitnih materijala

is about 5 times higher than our results. Rubber core makes the material very absorbent.

The second part of this study deals with the acoustic response of the musical instrument. A note C in each octave was generated sequentially one by one with a device designed to make the same stroke repeatedly. Their frequencies are given below.

Outputs from Spectra software are given in Figure 6. The plots represent the maximum amplitude at all described tones.

As can be seen, the red line falls above all others, indicating that the front panels of the piano absorb the sound in most frequencies. The exception is an area of low frequency, which the panels amplify. The amplitudes of other materials overlap considerably; therefore it is not possible to find a statistically significant difference between materials in the case of amplitudes with this measuring equipment.

The last part of the study is a subjective assessment of the piano when fitted with different panels. The best assessment was given for multi-layer plywood, the worst for Purenit, though the results found by ANOVA testing were not statistically significant. The committee found that the presence of panels decreased the acoustic radiation of the instrument. The highest decrement of damping was subjectively registered for the Purenit panel (Figure 7).

When a good acoustic response is required, piano manufacturers choose a high-quality resonance spruce wood (*Picea abies*), in other situations a compromise is struck that takes into consideration the price, availability, workability and acoustic properties of materials. Good acoustic properties of resonance spruce are well known (Zatloukal *et al.*, 2021; Endo *et al.*, 2016). Therefore, four composite materials were selected for testing in this study (three wood-based and one non-wood-based), and the acoustic response of a piano fitted with front panels made of these materials was assessed using straightforward methods. The results show that it is very hard to assess these materials either with simple measuring apparatus or by subjective judgement. The timbre of the sound and its character formed by many small nuances of higher harmonic tones is experimentally almost undetectable in all respects. Therefore, a subjective assessment is very often used, especially with violins – the wealth of research involving the legendary Stradivarius violin (Torres *et al.*, 2020; Invernizzi *et al.*, 2016; Grissino-Mayer *et al.*, 2004) serves as a good example. The fact is that players, when choosing an instrument, select the one that sounds best to them from a range of similar models. Several measurable parameters can support the basic assessment. For the suitability of the different types of material for the front panel of a piano case, the density, frequency response, sound propagation velocity, dynamic Young's modulus, characteristic impedance, and radiation ratio were also added.

In terms of these sound propagation properties, it can be said that the best performance was achieved by blockboard, followed by plywood, MDF, and last by Purenit panels. The subjective assessment made in this work confirmed this ranking.

Blockboard and plywood have a structure closer to natural wood than the other materials. Average resonance spruce achieves a longitudinal sound velocity of 5,600 $m.s^{-1}$ (Bucur, 2006), longitudinal frequency of 6400 Hz (Zatloukal *et al.*, 2021), dynamic Young's modulus of 11000 MPa (Endo *et al.*, 2016), radiation ratio of 12.3 $m^{-4}{\cdot}kg^{-1}{\cdot}s^{-1}$ (Zatloukal *et al.*, 2021), and characteristic impedance of 5.7 $(kg/m^2{\cdot}s){\times}10^{-5}$ (Zatloukal *et al.*, 2021) at an average density of 480 kg/m^3. The comparison of our results with the parameters of

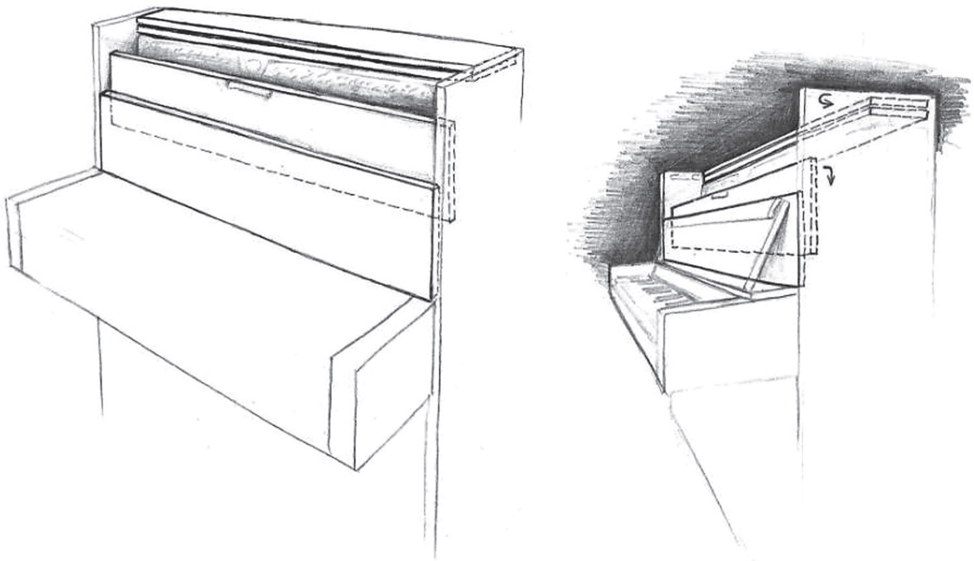

Figure 8 Suggestion of an openable upper panel for better acoustics (F. Šulc)
Slika 8. Prijedlog gornje ploče koja se može otvarati radi bolje akustike (F. Šulc)

resonance spruce, clearly show that these properties were not achieved by the tested materials. MDF panels are used rather than sound absorption panels (Sali *et al.*, 2004; Kang *et al.*, 2005; Lee *et al.*, 2014). Purenit, primarily used as a thermal insulation material, was not expected to have good results of acoustic response.

When considering price and performance, MDF becomes attractive as a material for piano panels because it is less than half the price of plywood and a third that of blockboard, at the time of writing. Despite the measured acoustic properties, the presence of front panels of any type was found to have a negative effect on the acoustics of the piano. Some piano designers acknowledge this and solve the issue by perforating the front panel (this should improve the aesthetics of the instrument as well). Better acoustic performance can be achieved by opening the top board, but this is sometimes impractical. Some manufacturers use an ellipse-shaped constriction in the front panel to improve acoustics (August Förster 125 and Rönisch 132); the panels may be openable in the manner of Venetian blinds; or the front panels may be made thinner than usual (e.g., Zeitter Winkelmann model 36930). A piano with a visible action may make listening more attractive, as used, for example, in the experimental self-playing Edelweiss U49 model. Fig. 8 suggests how to open the front panel and thus decrease damping. A similar solution can be found in the Petrof AP 136. Another example of an openable panel can be found in Feurich Model 123, which has a small window on the front. The problem of piano panels is very complex. Many professional piano players prefer damping panels instead because the sound that comes from an open piano may be too loud. If a quieter sound is desired, then materials with higher damping properties may be considered.

4 CONCLUSIONS
4. ZAKLJUČAK

Four types of front panels for upright piano were vibro-acoustically tested.

Having front panels at all was found to have a negative influence except at low frequencies.

Based on the acoustic parameters, blockboard achieved the best result with a longitudinal frequency of 1,389.0 Hz, sound velocity of 3,883.6 m/s, *ACE* 257.1 $m^{-4}\cdot kg^{-1}\cdot s^{-1}$, and damping coefficient of 0.0234.

Pywood achieved good acoustic with longitudinal frequency 1,300.5 Hz, sound velocity 3,636.2 m/s, *ACE* 206.1 $m^{-4}\cdot kg^{-1}\cdot s^{-1}$, and damping coefficient 0.0235.

MDF panel had the worse acoustic properties with a frequency of 872.5 Hz, sound velocity of 2,439.5 m/s *ACE* 103.7 $m^{-4}\cdot kg^{-1}\cdot s^{-1}$, and damping coefficient 0.0273.

Purenit panels achieved the worst acoustic properties, which was also unanimously confirmed by the committee. The measured frequency was 400.0 Hz, sound velocity 1,118.4 m/s, *ACE* 62.5 $m^{-4}\cdot kg^{-1}\cdot s^{-1}$, and damping coefficient 0.0536 This material was found inappropriate for the construction of the piano.

However, when considering the price-performance ratio, the MDF panels should be a good compromise for making the front panel of the cheaper piano.

Further research could aim to research other materials such as carbon-fibre composites, fibre-reinforced wood, or resonance spruce boards. Various shapes and structural designs of front panels might be acoustically tested.

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