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Analiza zvočnih lastnosti kompozitnih materialov

An Analysis of the Acoustic Properties of Composite Materials

Samo Šali - Uroš Žnidarič - Janez Kopač

Da bi izdelovalcu okrovov zvočnikov olajšali izbiro optimalnega materiala, smo testirali različne vrste plastičnih materialov, oplemenitenih z drobno mletimi lesnimi delci, ter jih primerjali z aluminijem, MDF (srednje gosti komopziti), polistirenom drugega izdelovalca zvočnikov (JVC) in ABS (akrilonitril – butadien – stiren). Vsi preizkušani materiali so bili v obliki plošč z izmerami 150×150 mm, njihova debelina pa je bila 2 mm. Ker so bile v ospredju testov zvočne lastnosti materialov, smo merili njihov relativni zvočni upor, relativno dušenje zvočne radiacije in faktor viskoznega dušenja. Prvi dve veličini sta izpeljani iz gostote in relativnega modula elastičnosti, ki ju lahko dobimo iz meritev frekvenčnega odziva prosto vpetih preizkušancev. Rezultati kažejo, da se s pravilno izbiro drobno mletih lesnih delcev in plastične osnove lahko približamo materialu MDF, ki velja za zelo dobro izbiro pri izdelavi okrova zvočnika.

(Ključne besede: materiali kompozitni, lastnosti akustične, analize modalne, metode preskušanja)

To help select the best material for loudspeaker boxes, we tested various types of polymer materials that are filled with fine, ground wood particles. In addition, we compared these materials with aluminium, MDF (medium-density fiberboard), polystyrene from another producer of loudspeaker boxes (JVC), and ABS (acrylnitril – butadiene – styrene). All the specimens were in the shape of square plates with dimensions 150×150 mm and the thickness 2 mm. Because the analysis was focused on the acoustic properties of the materials, we measured their relative sound-wave resistance, the relative damping of the sound radiation and the viscous-damping factor. The first two parameters are derived from the density and the relative modulus of elasticity, which can be obtained from measurements of the frequency response for free-supported specimens. The results show that a careful selection of fine, ground wood particles and polymer can give a satisfactory approximation to MDF, which is known as one of the best choices for the production of loudspeaker boxes.

(Keywords: composite materials, acoustic properties, modal analysis, testing methods)

0 UVOD

Modalna analiza tankih štirikotnih plošč je razmeroma dobro raziskano področje ([1] do [4]). Poleg vpetja in oblike preizkušancev na njihovo modalno obnašanje vsekakor vpliva tudi gradivo. Modalno obnašanje objekta pomeni amplitudo, dušenje in gibalne oblike pri posameznih frekvencah nihanja tega predmeta. Primerjava zvočnih lastnosti različnih materialov pomeni torej primerjavo modalnega obnašanja preizkušancev z enako obliko in vpetjem, pri čemer je spremenljivka vrsta materiala. V našem primeru smo za določanje zvočnih lastnosti preizkušancev uporabili metodo za prosto vpete, izotropne, tanke štirikotne plošče.

0 INTRODUCTION

The modal analysis of thin, square-shaped plates is relatively well investigated ([1] to [4]). Besides the specimens' shape and the type of support, their modal behaviour depends on the choice of material. The modal behaviour of an object means the amplitude, the damping and the modal shapes at certain frequencies of vibration (oscillation) for this object. A comparison of the acoustic properties of different materials is therefore a comparison of specimens with equal shape and the some type of support, where the only variable is the material. In our case, for a definition of the acoustic properties of the specimens, a method for free-supported, isotropic and thin square-shaped plates was

Podoben postopek je že bil uspešno uporabljen pri meritvah zvočnih lastnosti izrazito izotropnega (ortotropnega) materiala, tj. lesa [5]. Zato predpostavljamo, da morebitna izotropnost preizkušanih materialov ni vplivala na kakovost analize, kar pa bo še podrobneje razloženo. Cilj raziskave je bila metoda za merjenje zvočnih lastnosti kvadratastih tankih plošč ter kriterij za določanje zvočne kakovosti različnih plastičnih materialov z lesnimi vključki, ki so namenjeni za velikoserijsko proizvodnjo brizganih okrovov za srednje kakovostne zvočnike za poslušanje glasbe.

Akustične lastnosti materialov ne moremo definirati enopomensko. Za primer: med najboljše materiale za zvočne plošče lesenih glasbil uvrščamo smreko, medtem ko se ta in podobne vrste lesa sploh ne uporabljajo pri gradnji okrovov za zvočnike. Razlog je seveda v različnosti namena, ki ga imata zvočna plošča glasbila in okrov zvočnika.

Modul elastičnosti E in gostota ρ sta edini veličini, ki določata zvočni upor Z in dušenje zvočnega sevanja ϑ trdnih teles [6]:

applied. A similar approach was already applied during measurements of the acoustic properties of an extremely non-isotropic (orthotropic) material – wood [5]. It is assumed, therefore, that the probable non-isotropy of the tested materials did not affect the analysis, which will be explained in more detail later. The aim of this research was to devise method for measuring the acoustic properties of thin, square-shaped plates and a criterion for determining the acoustic quality of different polymer materials with wood particles. These materials are intended for the large-scale production of middle-quality loudspeaker boxes using injection-moulding technology.

The acoustic properties of materials cannot be defined simply. For example, the best choice for the sound boards of wooden instruments is spruce, whereas this and similar types of wood are not used in the production of loudspeaker boxes. The reason for this lies in the different requirements of a sound board and a loudspeaker box.

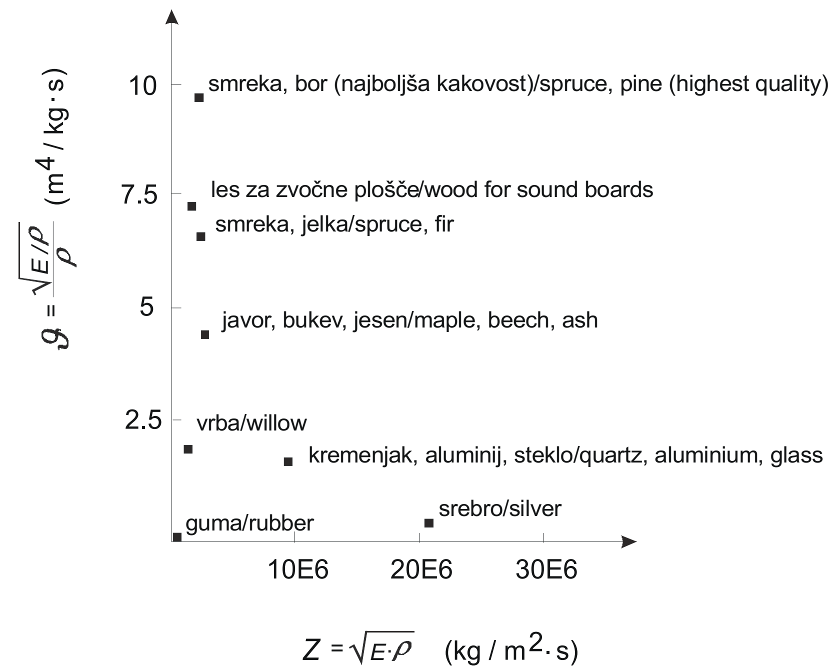
The modulus of elasticity E and the density ρ are the only two variables that denote the sound-wave resistance Z and the damping of the sound radiation ϑ of solids [6]:

$$Z = \sqrt{\rho \cdot E} \tag{1}$$

$$\vartheta = \frac{\sqrt{E/\rho}}{\rho} \tag{2}$$

Razlike v E in ρ se izražajo tudi v spremembi dinamičnega Youngovega modula. Ta modul izraža razmerje togosti in specifične teže preizkušanca. Togost in gostota se lahko primerjata z E in ρ. Slika 1

Variations in E and ρ will also result in changes to the dynamic Young's modulus. This modulus is defined as the ratio of the stiffness to the specific gravity of the specimens. The stiffness and the density can be compared to E



Sl. 1. *Odvisnost dušenja zvočnga sevanja (ϑ) od zvočnega upora (Z) za različne vrste lesa in druga gradiva [6]*

Fig. 1. *Dependence of radiation damping (ϑ) on sound wave resistance (Z) for several types of wood and other materials [6]*

prikazuje odvisnost dušenja zvočnega sevanja od zvočnega upora za različne vrste lesa in nekatera druga gradiva.

Prikazane odvisnosti potrjujejo, da sta pri zvočnih ploščah glasbil zaželena majhen zvočni upor in veliko dušenje zvočnega sevanja. Z drugimi besedami, večji dinamični Youngov modul zvočne plošče je ugodnejši.

Zvočna plošča glasbila mora namreč čim več prejete energije spremeniti v zvočno energijo, izgube zaradi notranjega trenja morajo zato biti čim manjše. Z drugimi besedami, pri čim manjšem faktorju viskoznega dušenja (definicija sledi) mora biti dušenje zvočnega sevanja za zvočne plošče glasbil čim večje. Faktor viskoznega dušenja δ lahko izračunamo na podlagi faktorja kakovosti Q iz enačbe, ki velja za malo dušene sisteme [7]:

and ρ, respectively. Figure 1 shows the dependence of the damping of sound radiation on the sound-wave resistance for different wood species and other materials.

The presented relations confirm that in the sound boards of musical instruments, low sound-wave resistance and high damping of the sound radiation are desirable. In other words, a high rather than a low dynamic Young's modulus of the sound boards is preferred.

The wooden resonant boards of musical instruments should translate most of the input energy into sound radiation. Therefore, losses due to internal friction are not desired. In other words, the factor of viscous damping (definition follows) should be as low as possible, and the damping of the sound radiation should be as high as possible. The viscous-damping factor δ can be calculated from the expression for the quality factor Q, which applies to low-damped systems [7]:

$$Q \cong \frac{1}{2\delta} \cong \frac{f_{0d}}{f_2 - f_1} \qquad (3),$$

kjer je f_{0d} lastna frekvenca modalnega načina, f_1 in f_2 pa pomenita frekvenci, kjer je amplituda frekvenčnega vrha enaka $P/\sqrt{2}$ (sl. 2).

Za primer resonančne frekvence s slike 2, ki pomeni lastni modalni način, je faktor viskoznega dušenja premo sorazmeren koeficientu viskoznega dušenja b in obratno sorazmeren zmnožku modalne mase m in modalne togosti k [7]:

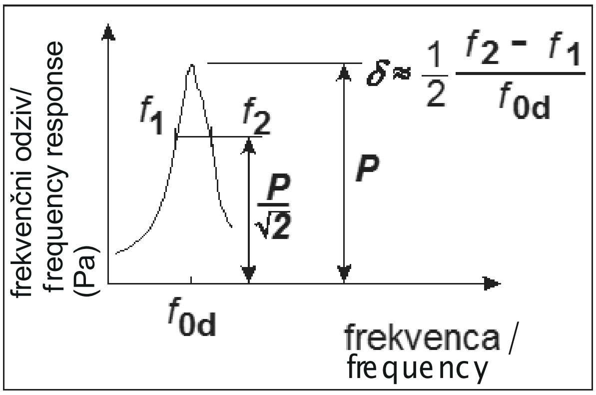
where f_{0d} is the natural frequency, and f_1 and f_2 are frequencies where the amplitude is $P/\sqrt{2}$ (see Figure 2).

In the case of the resonant frequency, which is presented in Figure 2, and which presumably indicates a natural mode, the factor of viscous damping is proportional to the coefficient of viscous damping b, and inversely proportional to the product of the modal mass m and the stiffness k [7]:

$$\delta = \frac{b}{2\sqrt{k \cdot m}} \qquad (4).$$

Podobno razmišljanje velja pri izbiri optimalnega materiala za okrove zvočnikov, namenjenih za poslušanje glasbe. V tem primeru mora okrov preprečevati pojav izrazitih resonanc in odmevov, ki nastanejo zaradi izvira zvoka – vibracij membrane zvočnika. To je logično, saj želimo predvajati le signal, ki prihaja iz elektronskih komponent v mebrano zvočnika, in to brez dodatnih negativnih vplivov, ki bi se utegnili pojaviti zaradi prisotnosti okrova. Po drugi strani okrov zvočnika ne sme imeti pretiranih dušilnih lastnosti, saj bi to pomenilo prevelike izgube zvočne

A similar way of thinking is applied when the selection of the best material for loudspeaker boxes is considered. In this case the box of a loudspeaker has to prevent the phenomenon of distinctive resonances and echoes that appear due to a sound source – vibrations of the loudspeaker diaphragm. Because we wish to produce only a signal from the electronic components into the loudspeaker diaphragm (without any additional and negative effects due to the loudspeaker box), this is logical. On the other hand, the loudspeaker box should not exhibit an excessive damping quality, because this would mean too high sound-energy losses.



Sl. 2. *Definicija amplitude prvega resonančnega vrha in faktorja viskoznega dušenja* δ
Fig. 2. *Definition of both amplitude of the first resonant peak and factor of viscous damping* δ

energije. To bi se lahko poznalo kot opazno zmanjšanje glasnosti ustvarjenega zvoka, kakor tudi preveliko dušenje vseh ali določenih frekvenčnih pasov. Potemtakem dušenje zvočnega sevanja, ki pravzaprav pomeni zmožnost sevanja zvoka v okolico, pri okrovu zvočnikov ne sme biti preveliko, vsekakor pa mora biti bistveno manjše kakor v primeru zvočnih plošč glasbil. Lahko bi rekli, da manjšanje velike stopnje dušenja zvočnega sevanja, ki je značilna za zvočne plošče glasbil, pomeni izboljševanje zvočnih lastnosti gradiva za okrov zvočnika [8].

Z gotovostjo lahko trdimo, da majhen zvočni upor pomeni majhno zvočno impedanco. To se kaže v razmeroma hitrem odvajanju zvočne energije, torej premajhna zvočna impedanca v primeru zvočnih plošč glasbil pomeni glasne, a kratko trajajoče šume brez glasbenega značaja [9]. V primeru okrova zvočnika bi premajhen zvočni upor torej lahko pomenil interferenco takšnih šumov z vibriranjem membrane zvočnika, kar seveda ni zaželeno. Po drugi strani razmeroma velik zvočni upor pomeni preveliko zvočno impedanco, torej pretirano počasno odvajanje zvočne energije v okrov zvočnika. To bi pomenilo možnost pojava stojnega valovanja in odmevov ustvarjenega zvoka znotraj okrova zvočnika, kar vsekakor ne bi prispevalo h kakovosti zvoka.

Zvočni upor je glede na enačbo (1) proporcionalen zmnožku modula elastičnosti in gostote materiala. Ta dva določata velikost modalne togosti k in mase m. Ob predpostavki, da je zvočni upor nespremenljiv, je višji faktor viskoznega dušenja d posledica večjega koeficienta b (enačbi (1) in (4)). Razmeroma veliko (majhno) dušenje δ pomeni torej razmeroma velike (majhne) izgube zvočne energije znotraj okrova zvočnika [8]. Če torej lahko govorimo o neki idealni vrednosti zvočnega upora gradiva, potem za to vrednost obstaja tudi idealna vrednost faktorja viskoznega dušenja δ, ki ne sme biti ne previsoka, ne prenizka, torej mora biti optimalna. Nadalje, razmeroma velike vrednosti zvočnega upora okrova zvočnika pomenijo ob nespremenljivi vrednosti koeficienta b razmeroma majhne vrednosti faktorja viskoznega dušenja, kar pomeni možnost pojava odmeva in stojnega valovanja [9]. Po drugi strani pomeni razmeroma majhna vrednost zvočnega upora pri nespremenljivem koeficientu b veliko vrednost faktorja δ, s tem pa možnost prevelikih zgub zvočne energije od membrane zvočnika v okrov ([8] in [9]).

Veliko okrovov zvočnikov, med njimi tudi zelo kakovostni sistemi, je narejenih iz materiala MDF. Ta je v osnovi podoben iverni plošči, le da gre pri MDF za bolj drobno mlete lesne delce. Primerjava strukture za MDF in klasično iverno ploščo je prikazana na sliki 3.

Z veliko gotovostjo lahko torej trdimo, da so zvočne lastnosti materiala MDF referenčne

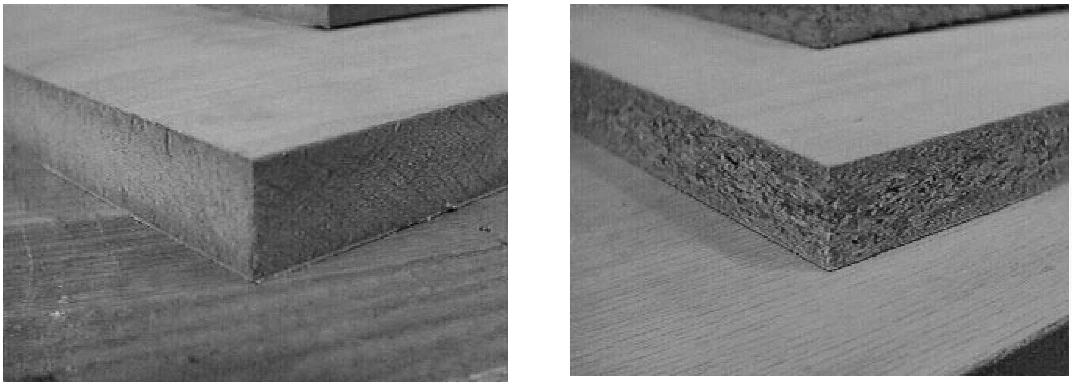
A consequence of this would be a significant decrease in the loudness, as well as too high damping of all, or only certain, frequency ranges. Therefore, the damping of sound radiation, which means the ability to radiate sound energy into the surroundings, must not be too high. In any case, it has to be significantly lower than in the case of the sound boards of musical instruments. One can say that a decrease of the relatively high level of damping of sound radiation, which is typical for musical instruments, indicates an improvement in the acoustic properties of a material for loudspeaker boxes [8].

With great certainty one can say that a low value of sound-wave resistance means low sound impedance. This results in a relatively fast sound-energy drain. Consequently, too low sound impedance of the sound boards results in loud and short-lasting noises without musical character [9]. Therefore, too low sound-wave resistance of a loudspeaker box could cause an interference of these noises with the loudspeaker diaphragm, which of course is not desired. On the other hand, a relatively high sound-wave resistance means too high acoustic impedance, which means that sound-energy drain into the loudspeaker box is too slow. This could result in the appearance of standing waves and echoes of the produced sound inside the loudspeaker box. Of course, this would not contribute to the sound quality in a positive way.

According to expression (1) the sound-wave resistance is proportional to the product of the modulus of elasticity and the material density. These two quantities determine the magnitude of the modal stiffness k and the mass m. Considering that sound-wave resistance is a constant, an increase in the viscous-damping factor δ is a consequence of an increase of coefficient b (see Equations (1) and (4)). A relatively high (low) damping δ therefore means high (low) losses of sound energy inside the loudspeaker box [8]. If we are allowed to speak about an ideal magnitude of sound-wave resistance for a certain material, then for this value there is also an ideal factor of viscous damping δ. This factor should be neither too high nor too low, i.e. it should be optimised. Next, if we assume that coefficient b is a constant, then a relatively high value of sound-wave resistance of the loudspeaker box will result in a relatively low factor of viscous damping. This can lead to the appearance of echoes and standing waves [9]. On the other hand, a relatively low sound-wave resistance, at a constant coefficient b, means a high magnitude of factor δ. This can significantly increase the losses of sound energy from the loudspeaker diaphragm into the box ([8] and [9]).

A lot of loudspeaker boxes, including high-quality systems, are made of MDF (medium-density fibreboard). In comparison to the particle board, MDF consists of smaller wood particles. Figure 3 shows a comparison between the MDF and the particle board structure.

With great certainty we can say that the acoustic properties of MDF are reference in terms of



Sl. 3. *Primerjava med MDF (levo) in iverne plošče (desno)*
Fig.3. *Comparison between MDF (left) and particle board (right)*

lastnosti, če imamo v mislih iskanje optimalnega materiala za okrov zvočnikov. V nadaljevanju je predstavljena metoda za merjenje zvočnih lastnosti kvadratastih tankih plošč iz različnih materialov, predvsem kompozitov s plastično osnovo in z vključki iz drobno mletih lesnih delcev. Pri tej metodi smo torej vrednosti veličin (i) dušenje zvočnega sevanja, (ii) zvočni upor in (iii) faktor viskoznega dušenja, ki so značilni za MDF, označili za želene vrednosti. Te so torej merilo za določanje najboljše kombinacije plastične osnove z drobno mletimi lesnimi delci kot polnilom.

1 METODA

1.1 Priprava preizkušancev

Preizkušanci so bili kvadrataste plošče z dimenzijo 150×150 mm. Oznake ter število preizkušancev v vzorcu (n), njihova debelina (d), gostota (ρ) in sestava oziroma vrsta materiala so prikazani v preglednici 1.

Uporabljena sta bila dva tipa drobno mletih lesnih delcev. V primeru preizkušancev z oznako vz4 so bili to razmeroma veliki delci iz mehkega lesa (smreka), v preostalih preizkušancih pa razmeroma majhni delci iz trdega lesa (bukev). Kakor vidimo iz preglednice 1, se preizkušanci vz1 in vz4 ločijo samo po vsebini lesnih delcev. Razlika med preizkušanci vz2 in vz6 je v tipu polipropilena, sicer pa so masni deleži vseh treh sestavnih komponent (pregl. 1) enaki. Enako velja za preizkušance vz3 in vz5. Polistirenski preizkušanci vz9 so bili narejeni z injekcijskim brizganjem zdrobljenega okrova zvočnikov proizvajalca JVC (tip XV THA35). Polistirenski preizkušanci vz10 so bili narejeni za primerjavo s preizkušanci vz9. Postopek izdelave vseh preizkušancev s plastično osnovo je bilo iztiskanje, torej zvezna predelava plastičnih mas, v katerem se polimerna talina potiska skozi orodje specifičnega profilnega prereza. Material MDF je narejen iz drobno mletih lesnih delcev, ki so zlepljeni med seboj. Postopek lepljenja

the best material for loudspeaker boxes. A method for measuring the acoustic properties of square-shaped and thin plates made of various materials, especially of composites with a polymer matrix and fine, ground wood particles, is presented in the next section. In this method the values of (i) the damping of sound radiation, (ii) the sound-wave resistance, and (iii) the viscous-damping factor, which are typical for MDF are denoted as the desired values. Thus, these values present a criterion for determining the most suitable combination of a polymer material and fine wood particles as filler.

1 METHOD

1.1 Specimens preparation

The specimens were square-shaped plates with dimensions of 150×150 mm. Denotations and the number of specimens in the group (n), their thickness (d), density (ρ), and composition or material type are presented in Table 1.

In the experiments two types of fine, ground wood particles were applied. For specimens vz4 this pulp consisted of relatively coarse particles of softwood (spruce), whereas for other specimens the fine, ground wood particles consisted of relatively small particles of hardwood (beech). As one can see from Table 1, the only difference between specimens vz1 and vz4 is in the content of wood particles. The difference between specimens vz2 and vz6 is in a type of polypropylene, whereas the mass portions of all three main components (see table 1) are the same. The same is true for specimens vz3 and vz5. Specimens based on polystyrene vz9 were made by injection moulding ground loudspeaker boxes JVC (type XV THA35). Specimens vz10 (also based on polystyrene) were used for a comparison with specimens vz9. All the specimens based on polymer were produced by extrusion, which means the continuous manufacturing of polymers, where a polymer melt is pushed through a die with a specific cross-section. MDF is made of fine, ground wood particles that are glued together. The process of gluing is performed at high

Preglednica 1. *Lastnosti preizkušancev*
Table 1. *Properties of specimens*

Oznaka skupine/ Group denotation	*n*	*d* mm	ρ kg/m^3	sestava preizkušancev/ specimen composition
vz1	4	2	1059	polietilen velike gostote + drobno mleti lesni delci (trdi les)/ high density polyethylene + wood pulp (hardwood)
vz2	4	2	1089	polipropilen (tip A*) + drobno mleti lesni delci (trdi les) + kemično spremenjen polipropilen/ polypropylene (type A*) + wood pulp (hardwood) + chemically modified polypropylene
vz3	4	2	1059,5	polipropilen (tip A*) + drobno mleti lesni delci (trdi les) + termoplastični elastomer/ polypropylene (type A*) + wood pulp (hardwood) + thermoplastic elastic material
vz4	4	2	1089	polietilen velike gostote + drobno mleti lesni delci (mehki les)/ high density polyethylene + wood pulp (softwood)
vz5	4	2	1000	polipropilen (tip B**) + drobno mleti lesni delci (trdi les) + termoplastični elastomer/ polypropylene (type B**) + wood pulp (hardwood) + thermoplastic elastic material
vz6	4	2	1020	polipropilen (tip B**) + drobno mleti lesni delci (trdi les) + kemično spremenjen polipropilen/ polypropylene (type B**) + wood pulp (hardwood) + chemically modified polypropylene
vz7	2	4	1046	ABS (akrilonitril – butadien – stiren)/ ABS (acrylnitril - butadien - styren)
vz8	1	2	2761	aluminij/ aluminium
vz9	3	2	1037	polistiren (zvočniki JVC)/ polystyrene (JVC loudspeakers)
vz10	3	2	1056	polistiren/ polystyrene
vz11	3	2	898	MDF/ MDF (medium density fiberboard)

* kopolimer/copolymer
** homopolimer/homopolymer

poteka pri visoki temperaturi in visokem tlaku. V primerjavi z borovim ali smrekovim lesom ima MDF običajno približno dvakrat manjši modul elastičnosti in približno 70% večjo gostoto.

Preglednica 2 kaže mehanske lastnosti preizkušancev vz1 – vz6. Iz neenakih lastnosti v prečni in vzdolžni smeri (glede na smer iztiskanja) vidimo, da so vsi ti preizkušanci anizotropni.

1.2 Meritve zvočnih lastnosti preizkušancev

Slika 4 kaže mesto meritve in merilno opremo. Vsi preizkušanci so bili vpeti na okoli 2 m dolgi elastični vrvici, debeline okoli 0,3 mm. S tem zagotovimo najmanjši vpliv vpetja na dinamično obnašanje preizkušanca. Vzbujanje je bilo opravljeno s posebej izdelano napravo, katere glavni del je piezoelektrični merilnik vzbujevalnega impulza, ki je prikazan na sliki 5. Tipična oblika vzbujevalnega impulza in odzivnega signala je prav tako prikazana na sliki 5. Kakor vidimo, je amplitudna os vzbujevalnega signala prikazana brezrazsežno, saj prikazani vzbujevalnik ni umerjen v

temperature and pressure. In comparison to a fir or spruce wood, the MDF's modulus of elasticity is approximately 100% smaller and its density is approximately 70% higher.

The mechanical properties of specimens vz1 – vz6 are shown in Table 2. Based on unequal properties in the transversal and longitudinal directions (according to the direction of extrusion) one can see that all the specimens are non-isotropic.

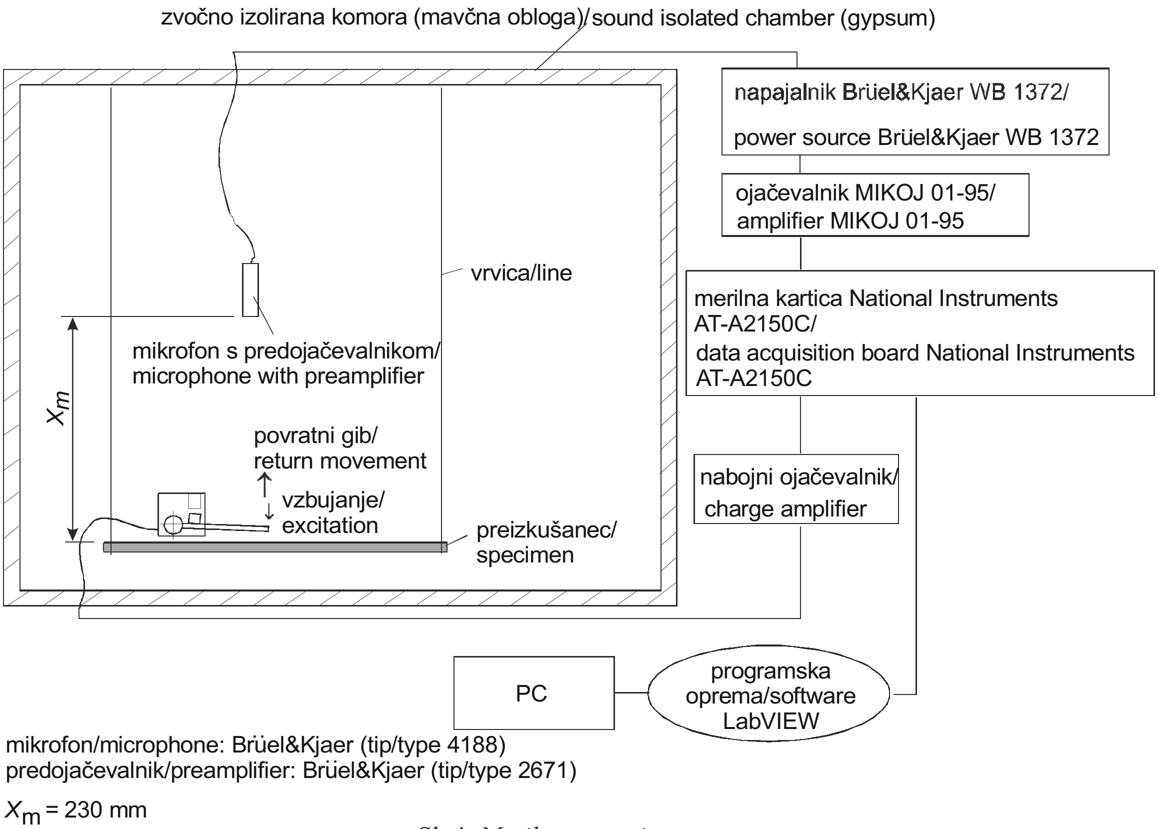
1.2 Measurements of the acoustic properties of the specimens

The measurement arrangement is shown in Figure 4. All the specimens were suspended on approximately 2-m-long (0.3 mm in diameter) nylon line. This ensured a negligible effect of the specimen's support on its dynamic behaviour. A special device with a piezoelectric sensor was used to excite the specimens, as shown in Figure 5. Typical shapes of the excitation and output signals are shown in Figure 5 as well. One can see that the amplitude axis of the input signal is presented on a dimensionless scale. The reason for this is that the excitation device was not calibrated for

Preglednica 2. *Mehanske lastnosti preizkušancev vz1 do vz6*
Table 2. *Mechanical properties of specimens vz1 to vz6*

Preizkušanci/ Specimens	E-modul vzdolžno/ E-modulus longitudinally (MPa)	E-modul prečno/ E-modulus transversally (MPa)	upogibna trdnost vzdolžno/ bending stregth longitudinally (MPa)	upogibna trdnost prečno/ bending stregth transversally (MPa)	MFI* (5kg/190ºC)	natezna trdnost/ tensile strength (MPa)
vz1	3112	2275	46,43	37,38	24,5 g/10 min	24,24
vz2	3819	2675	52,32	40,77	3,90 g/10 min	32,90
vz3	3522	2575	40,80	30,43	3,75 g/10 min	28,92
vz4	3564	2786	40,79	33,47	3,70 g/10 min	23,97
vz5	2804	2398	38,71	30,31	10,8 g/10 min	21,07
vz6	3355	2761	58,96	44,09	16,6 g/10 min	37,21

* indeks tečenja/percolation index



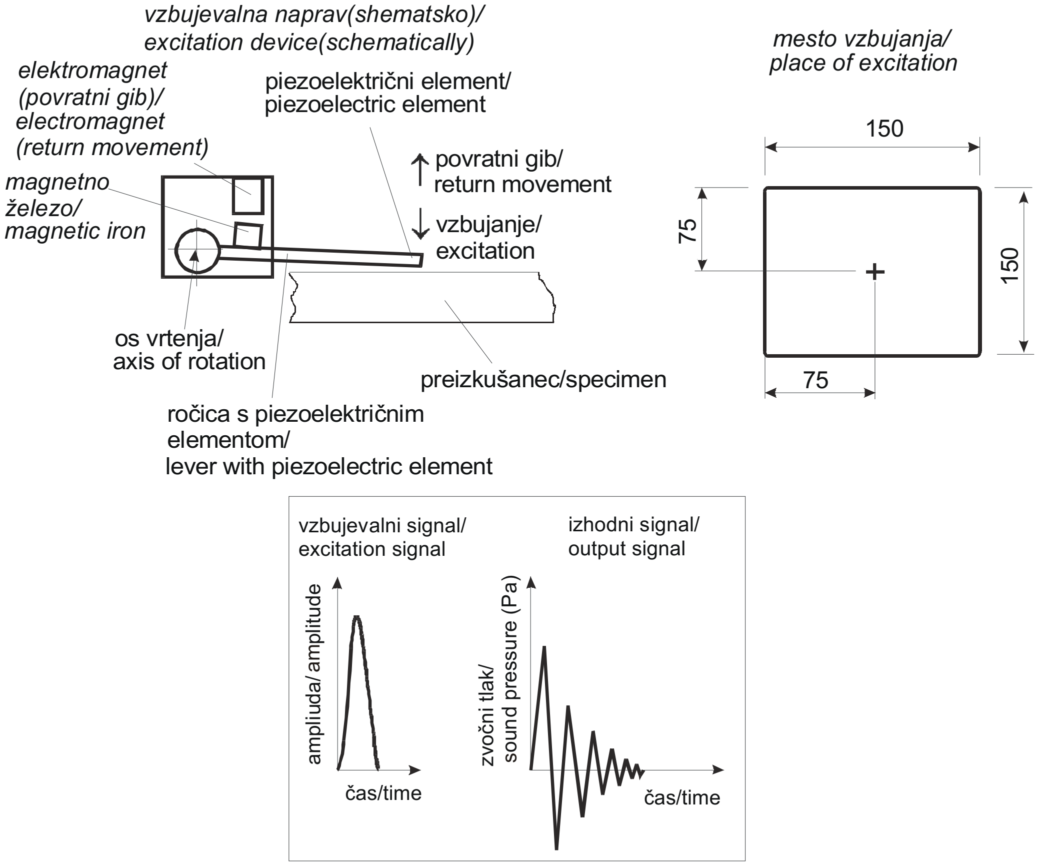
Sl. 4. *Merilno mesto in oprema*
Fig. 4. *Measurement place and arrangement*

fizikalnih enotah. To seveda ne zmanjša njegove uporabnosti, saj je končni cilj meritev t.i. frekvenčni odziv preizkušancev, pri katerem odzivni signal delimo z vzbujevalnim v frekvenčnem področju, torej merimo razmerje med odzivnim signalom ter vzbujevalnim signalom (mehanskim impulzom) [7]. Poleg tega nas niso zanimale absolutne vrednosti frekvenčnih odzivov preizkušancev, temveč le njihova primerjava.

Akustični odziv preizkušanca na mehansko impulzno motnjo (brezrazsežno), merjen s kondenzatorskim mikrofonom, ima enoto Pa, torej je amplituda zveznega frekvenčnega odziva preizkušanca izražena v Pa [7]:

measurements in physical units. This does not affect its applicability because the aim of the measurements is the frequency response of the specimens, which is defined as the ratio of the output to the input signal [7]. In addition, we were interested in a comparison of the different frequency responses of the specimens rather than their absolute values.

The acoustic response of the specimen due to the mechanical impulse (on a dimensionless scale) which is measured with a condenser microphone is defined in Pascal units. Therefore, the amplitude of the continuous frequency-response function of a specimen is defined in Pascal units [7]:



Sl. 5. *Shematski prikaz naprave za vzbujanje preizkušancev, mesto vzbujanja ter oblika vzbujevalnega in odzivnega signala*

Fig. 5. *Schematic representation of excitation device, place of excitation, and both excitation and output signal*

$$H(f)=\left|\frac{\overline{G}_{xy}(f)}{\overline{G}_{xx}(f)}\right| \quad (4),$$

kjer so: $\overline{G}_{xy}(f)$ povprečni križni energijski spekter vhodnega in izhodnega signala, $\overline{G}_{xx}(f)$ povprečni energijski spekter vhodnega signala, f pa frekvenca z izmero Hz. Še nepovprečena spektra izračunamo iz naslednjih enačb [7]:

where $\overline{G}_{xy}(f)$ is an average cross power spectrum of both the input and output signals, $\overline{G}_{xx}(f)$ is an average power spectrum of an input signal, and f is the frequency with dimension Hz. Before the averaging both spectra from expression (4) are [7]:

$$G_{xy}(f)=S_x(f)\cdot S_y{}^*(f) \quad (5)$$

$$G_{xx}(f)=S_x(f)\cdot S_x{}^*(f) \quad (6),$$

kjer so: $S_x(f)$ frekvenčna slika vhodnega in $S_y(f)$ izhodnega časovnega signala, $S_x{}^*(f)$ in $S_y{}^*(f)$ pa njuni konjugirano kompleksni vrednosti. S tako definiranim frekvenčnim odzivom se izognemo napaki zaradi navzočnosti šuma. Pri meritvah frekvenčnega odziva je pomembna koherenčna funkcija, ki je merilo za moč izhodnega signala zaradi vhodnega signala. Če je koherenca 1, potem je bil ves izhodni signal povzročen zaradi vhodnega, če pa je 0, potem izhodni signal ni posledica vhodnega. Koherenčna funkcija γ^2 je [7]:

where $S_x(f)$ and $S_y(f)$ are frequency transformations of the input and output signals, respectively, and $S_x{}^*(f)$ and $S_y{}^*(f)$ are their complex conjugates. Such an approach ensures that a frequency-response function is not influenced by the presence of noise. A criterion of the quality of the measurements is the coherence function, which indicates the power of the output signal due to the input signal. When this function is 1 then all the power of the output signal is a consequence of the input signal. When the coherence was 0 then the output signal was not caused by the input signal. The coherence function γ^2 is [7]:

$$\gamma^{2}(f)=\frac{\overline{G}_{xy}(f)\cdot\overline{G}_{xy}*(f)}{\overline{G}_{xx}(f)\cdot\overline{G}_{yy}*(f)} \qquad (7),$$

kjer je $\overline{G}_{yy}(f)$ povprečni energijski spekter izhodnega signala, * pa označuje kompleksno konjugacijo. Nepovprečeni spekter $G_{yy}(f)$ izračunamo analogno $G_{xx}(f)$ iz enačbe (6), tako da indeks $_x$ nadomestimo z $_y$.

Dejansko so zaradi analogno/digitalne premene z merilno opremo zvezni spektri v izrazih (4) do (7) diskretni. Diskretni amplitudni frekvenčni spekter signala dobimo s hitro Fourierjevo preslikavo signala v časovnem prostoru ([7] in [10]):

where $\overline{G}_{yy}(f)$ is an average power spectrum of the output signal, and * indicates its complex conjugation. A non-averaged spectrum $G_{yy}(f)$ is calculated by analogy to $G_{xx}(f)$ from expression (6), where the index $_x$ is replaced by $_y$.

As a matter of fact, the continuous spectra in expressions (4) to (7) are discrete due to the analogue/digital conversion with the measurement equipment. The discrete amplitude spectrum of a signal is obtained with a fast Fourier transformation of this signal in a time domain ([7] and [10]):

$$FFT(s\cdot\Delta f)=\frac{T}{N}\sum_{n=0}^{N-1}f(n\cdot\Delta t)\cdot e^{-\mathrm{j}2\pi\, sn/N} \qquad (8),$$

kjer so: $s = 0, 1, 2 \ldots N/2$, Δf frekvenčna ločljivost, T čas snemanja, N število diskretnih točk, Δt časovni korak med diskretnimi točkami, $f(n\cdot\Delta t)$ diskretna vrednost signala v n-ti točki in $\mathrm{j}=\sqrt{-1}$. Frekvenca vzorčenja f_s je bila 8 kHz pri številu diskretnih točk N=4096. $FFT(s\cdot\Delta f)$ torej pomeni diskretno Fourierjevo preslikavo digitaliziranega diskretnega signala časovne funkcije $f(n\cdot\Delta t)$. Če velja, da je z $f(n\cdot\Delta t)$ opisan vhodni signal v vzbujani predmet, katerega frekvenčni odziv merimo, velja tudi ([7] in [10]):

where $s = 0, 1, 2 \ldots N/2$, Δf is frequency resolution, T is time of signal recording, N is the number of discrete points, Δt is the time interval between these discrete points, $f(n\cdot\Delta t)$ is a discrete value of the signal in the n-th point, and $\mathrm{j}=\sqrt{-1}$. The sampling frequency f_s was 8 kHz and N was 4096. Thus, $FFT(s\cdot\Delta f)$ indicates a discrete Fourier transformation of a digital discrete signal of a time-dependent function $f(n\cdot\Delta t)$. If $f(n\cdot\Delta t)$ describes the input signal into an object whose frequency response is measured, then the following is true ([7] and [10]):

$$S_x(s\cdot\Delta f)\approx FFT(s\cdot\Delta f)=\frac{T}{N}\sum_{n=0}^{N-1}f(n\cdot\Delta t)\cdot e^{-\mathrm{j}2\pi\, sn/N} \qquad (9),$$

kjer je $S_x(s\cdot\Delta f)$ frekvenčna slika vhodnega signala v diskretni obliki. Podobno lahko rečemo tudi za izhodni signal. Torej, če je z $f(n\cdot\Delta t)$ opisan izhodni signal iz vzbujanega predmeta, katerega frekvenčni odziv merimo, velja tudi ([7] in [10]):

where $S_x(s\cdot\Delta f)$ is the frequency transformation of the input signal in a discrete form. Similarly, if $f(n\cdot\Delta t)$ describes the output signal from the excited object then the following is true ([7] and [10]):

$$S_y(s\cdot\Delta f)\approx FFT(s\cdot\Delta f)=\frac{T}{N}\sum_{n=0}^{N-1}f(n\cdot\Delta t)\cdot e^{-\mathrm{j}2\pi\, sn/N} \qquad (10),$$

kjer je $S_y(s\cdot\Delta f)$ frekvenčna slika izhodnega signala v diskretni obliki.

Dvostranski amplitudni diskretni frekvenčni spekter je ([7] in [10]):

where $S_y(s\cdot\Delta f)$ is a frequency transformation of the output signal in a discrete form.

The two-sided amplitude spectrum in a discrete form is ([7] and [10]):

$$\left|FFT(s\cdot\Delta f)\right|/N \qquad (11).$$

N – število diskretnih točk signala mora biti za natančno Fourierjevo preslikavo 2^n, n=1, 2 ... Izraz (11) predstavlja dvostranski spekter, po množenju z 2 pa dobimo amplitudni frekvenčni spekter, ki pomeni amplitude frekvenčnih komponent signala. Frekvenčne komponente so na frekvenčni osi spektra med seboj oddaljene za Δf (Hz). Zveza med frekvenčno ločljivostjo in trajanjem signala je ([7] in [10]):

For a high-quality Fourier transformation the number of discrete points N has to be 2^n, n=1, 2 ... Expression (11) represents a two-sided spectrum, however after multiplying it by a factor at 2 the result is an amplitude spectrum that represents the amplitudes of the frequency components of a signal. The frequency resolution between neighbouring components of this spectrum is Δf (Hz). The relation between the frequency resolution and the time of recording is ([7] and [10]):

$$\Delta f=1/T \qquad (12).$$

Zaradi poenostavitve naj za nadaljnjo analizo velja, da je vsak izmerjeni frekvenčni odziv obravnavan kot zvezni odziv $H(f)$ iz enačbe (4), četudi je dejansko nezvezen, torej odvisen od diskretnih vrednosti frekvence f z ločljivostjo Δf.

Kakovosten analogno/digitalni pretvornik na merilni kartici z vgrajenim analognim filtrom za odstranitev visokih frekvenc je zagotovilo, da je bil Nyquistov pogoj (frekvenca vzorčenja vsaj 2-krat višja od najvišje frekvence v signalu) vedno izpolnjen. Čas snemanja vstopnega sunka in akustičnega odziva preizkušancev je bil 0,512 s, torej je bila frekvenčna ločljivost spektrov 1,953 Hz (enačba (12)). Snemanje impulza in rezultirajočega zvočnega tlaka je bilo sočasno. Z obdelavo signala s programsko opremo je bilo poskrbljeno, da sta se oba, izhodni in vhodni signal, začela in končala z amplitudo nič. To prispeva h kakovosti frekvenčne analize, dokaz za to pa je bila vrednost koherenčne funkcije med 0,95 in 1,0 za analizirano frekvenčno območje (prvega resonančnega vrha) za vse materiale. Komponente frekvenčnih spektrov so izražene v vrednostih kpk (korena povprečja kvadratov).

Za meritev morebitnih razlik v akustičnem odzivu kvadratastih plošč iz različnih materialov lahko uporabimo enačbo (13). Ta povezuje frekvenco n-tega modalnega načina f_n in mehanske lastnosti homogene, izotropne in prosto vpete kvadrataste plošče [11]:

Due to a simplification let us denote that each measured frequency response function is analysed as a continuous response $H(f)$ from expression (4), although in reality all the spectra were discontinuous, thus they were dependent on discrete values of frequency f with frequency resolution Δf.

A high-quality analogue/digital converter on a data-acquisition board with an anti-aliasing filter ensured that the Nyquist criterion (the sampling frequency has to be at least two times higher than the highest frequency of interest in a signal) was fulfilled. The recording time of the input impulse and the specimen's acoustic response was 0.512 sec. Thus, the frequency resolution of all spectra was 1.953 Hz (see expression (12)). The recording of the mechanical impulse and of the resulting sound pressure was performed simultaneously. Additional processing of both input and output signals was performed in order to set the amplitudes at their beginning and end to zero. This improves the quality of the frequency transformation, which was confirmed with a coherence function higher than 0.95 for the analysed frequency range (first resonant peak). The frequency-spectrum components are expressed in rms values.

To measure eventual differences in the acoustic response of square-shaped plates from various materials we can use expression (13). This includes the frequency of n-th mode f_n and the mechanical properties of homogeneous, isotropic and free-supported square-shaped plates [11]:

$$f_n = C_n \cdot t \cdot \sqrt{\frac{E}{\rho \cdot (1-\nu^2) \cdot l^4}} \quad (13),$$

kjer so C_n konstanta, odvisna od n-tega modalnega načina, t debelina plošče, ν Poissonovo razmerje in l dolžina (širina) plošče. V analizi, ki bo prikazana, je bil analiziran prvi modalni način za vse plošče. Ta modalni način ima največje pomike na sredini vzbujene plošče, proti robovom pa so pomiki postopoma manjši (podobno kakor pri trampolinu) ([11] in [12]). Če torej ploščo vzbudimo v sredini, vzbudimo prvi modalni način v največji možni meri. Veličina f_n je izmerjena, t, l, ν in ρ so točno ali vsaj približno znane. Za prvi modalni način preizkušancev iz enačbe (13) izhaja:

where C_n is a constant that depends on n-th mode, t is the plate thickness, ν is Poisson's ratio, and l is the length (width) of the plate. In the analysis which follows, only the first mode of all specimens was analysed. The largest displacements for this mode are in the middle of the plate. The amplitudes of the displacements diminish towards the plate's edges (like with trampoline) ([11] and [12]). Thus, when the specimen is excited in its geometrical centre, the first mode is excited as much as possible. The quantity f_n is measured, and t, l, ν and ρ are exactly or approximately known. Based on expression (13) for a first mode it follows:

$$E = \frac{1}{C_1} \cdot \frac{f_1 \cdot \rho \cdot (1-\nu^2) \cdot l^4}{t^2} \left[\mathrm{Pa}\right] \quad (14).$$

Z zelo veliko verjetnostjo lahko rečemo, da je Poissonovo razmerje za aluminij 0,3, za MDF med 0,3 in 0,4, za preostale testirane materiale pa približno 0,4 ([13] in [14]), vsekakor pa med 0,3 in 0,5. V nadaljevanju bosta tako pri analizi vseh materialov, razen aluminija, upoštevani spodnja (0,3) in zgornja meja (0,5) Poissonovega razmerja.

With great certainty we can say that Poisson's ratio for aluminium is 0.3, for MDF between 0.3 and 0.4, and for other tested materials about 0.4; in any case between 0.3 and 0.5 ([13] and [14]). Therefore, in the following analysis the lower (0.3) and the upper (0.5) limit for Poisson's ratio are considered.

2 REZULTATI IN ANALIZA

Ker gre v nadaljevanju le za relativno primerjavo veličin, lahko konstanto C_1 in izmere

2 RESULTS AND ANALYSIS

Because in the following analysis only a relative comparison of quantities is presented, it is reason-

Preglednica 3. *Rezultati meritev*
Table 3. *Results of measurements*

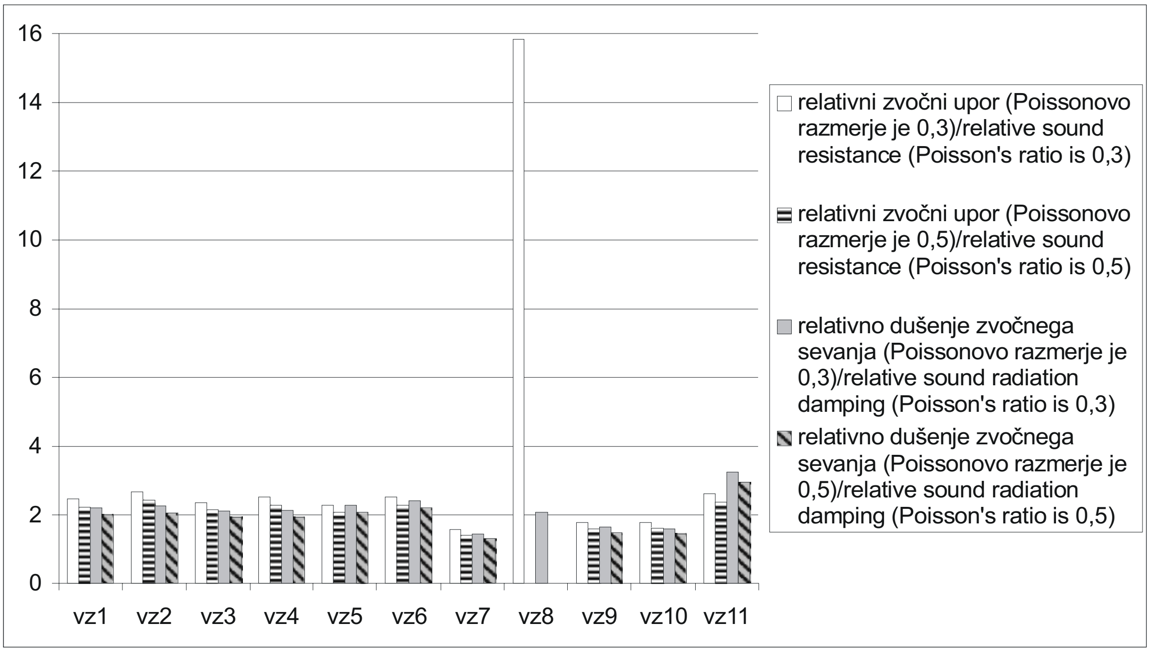
Preizkušanci Specimens	f_{od} Hz	δ	E_{rel} za / for ν=0,3	E_{rel} za / for ν=0,5
vz1	214,3	0,0258	5,68E9	4,68E9
vz2	228,7	0,0214	6,56E9	5,41E9
vz3	207,6	0,0228	5,26E9	4,33E9
vz4	215,1	0,0144	5,81E9	4,79E9
vz5	209,6	0,0263	5,20E9	4,29E9
vz6	228,0	0,0279	6,16E9	5,08E9
vz7	278,3	0,0084	2,33E9	1,92E9
vz8	535,0	0,0028	91,02E9	/
vz9	158,0	0,0132	2,98E9	2,46E9
vz10	156,3	0,0147	2,97E9	2,45E9
vz11	259,0	0,0142	7,64E9	6,29E9

vseh veličin iz enačbe (14) izvzamemo. Tako namesto veličine E dobimo brezrazsežni modul elastičnosti E_{rel}. Preglednica 3 prikazuje zbrane rezultate meritev za vse testirane plošče. Prikazane so srednje vrednosti frekvenc in faktorjev viskoznega dušenja prvega modalnega načina ter relativnih modulov elastičnosti.

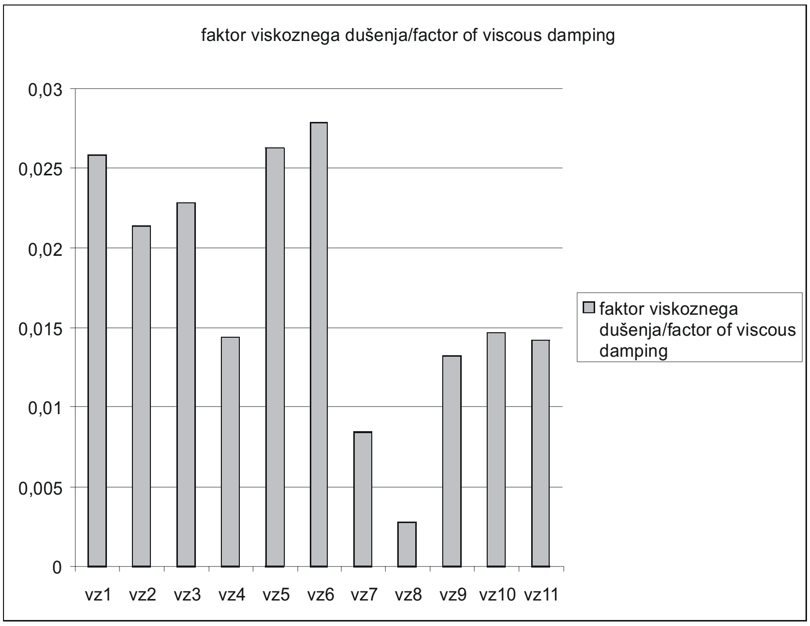
Če v enačbah (1) in (2) namesto veličine E upoštevamo E_{rel}, in če za gostoto ne upoštevamo izmer, dobimo namesto veličine Z t.i. relativni zvočni upor Z_{rel} in namesto veličine ϑ relativno dušenje zvočnega sevanja ϑ_{rel}. Obe relativni veličini in faktor viskoznega dušenja so za vse testirane materiale predstavljeni na slikah 6 oziroma 7. Zaradi zelo velike vrednosti relativnega zvočnega upora za aluminij (vz8) so na sliki 8 še enkrat prikazane vrednosti za vse nekovinske materiale.

able to exclude from Equation (14) the constant C_1 and the dimensions of all quantities. Instead of quantity E we consequently obtain the dimensionless modulus of elasticity E_{rel}. The results of the measurements of all the plates are presented in Table 3. More precisely, the mean values of the frequencies and the factors of viscous damping of the first mode, and the relative moduli of elasticity are presented.

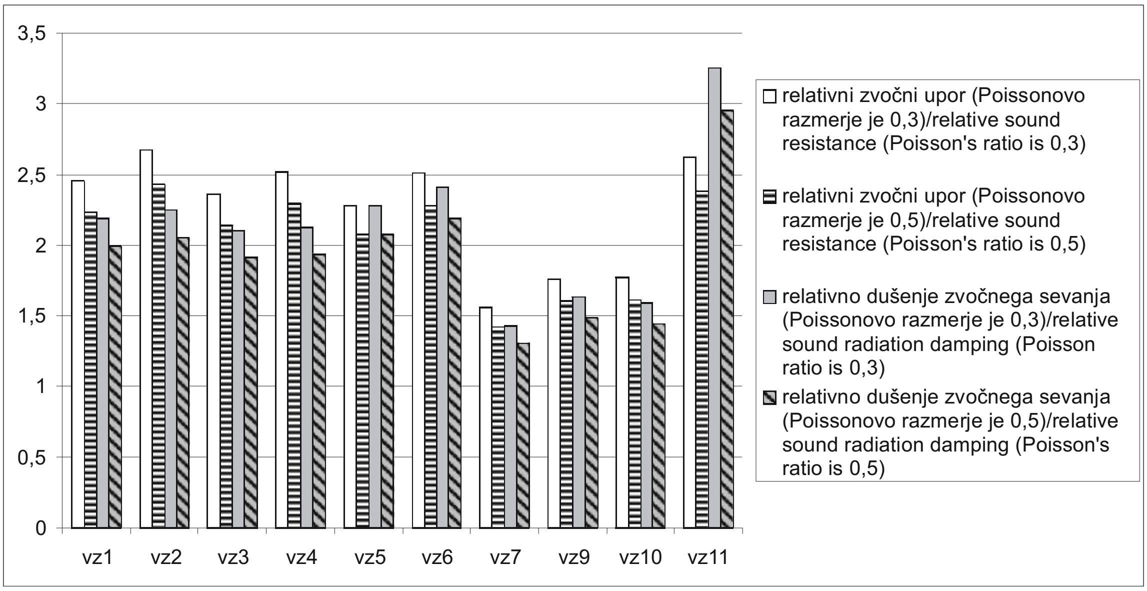
Considering E_{rel} instead of E and ignoring the units for density in Expressions (1) and (2), we obtain a relative sound-wave resistance Z_{rel} instead of Z, and a relative damping of sound radiation ϑ_{rel} instead of ϑ. In addition to the viscous-damping factor, these two quantities are shown in Figures 6 and 7 for all the tested materials. Due to a high value of the relative sound-wave resistance for aluminium (vz8), Figure 8 shows E_{rel}, ϑ_{rel} and δ for all the non-metal materials.



Sl. 6. *Relativni zvočni upor in dušenje zvočnega sevanja (vsi materiali)*
Fig. 6. *Relative sound resistance and sound radiation damping (all materials)*



Sl. 7. *Faktor viskoznega dušenja*
Fig. 7. *Factor of viscous damping*



Sl. 8. *Relativni zvočni upor in dušenje zvočnega sevanja (vsi nekovinski materiali)*
Fig. 8. *Relative sound resistance and sound radiation damping (all non-metal materials)*

S slik 6 do 8 je razvidno, da imajo materiali vz4, vz9 in vz10 vse tri analizirane veličine (zvočni upor, dušenje zvočnega sevanja in faktor viskoznega dušenja) podobne tistim za referenčni material MDF. Pri tem velja, da imajo faktor viskoznega dušenja skoraj identičen tistemu za MDF. Med temi tremi materiali je vz4 v splošnem najbliže MDF, saj ima večji zvočni upor in dušenje zvočnega sevanja kakor materiala vz9 in vz10. Iz pregl. 1 je razvidno, da ima samo material vz4 drobno mlete lesne delce iz mehkega lesa. Vpliv drobno mletih lesnih delcev (trdi oziroma mehki les) je razviden iz primerjave materialov vz1 in vz4.

One can see from Figures 6 to 8 that materials vz4, vz9 and vz10 indicate similar acoustic properties (sound-wave resistance, damping of sound radiation and viscous-damping factor) to the reference material MDF. In addition, their factor of viscous damping is almost identical to that of MDF. Among all three materials the closest to MDF is vz4, because it has a higher sound-wave resistance and a higher damping of sound radiation than materials vz9 and vz10. It is evident from Table 1 that only fine, ground wood particles in vz4 are made of softwood. The influence of fine, ground wood particles (hardwood, softwood) is evident from a comparison between materials vz1 and vz4. It seems that

Kakor kaže je ta vpliv precej značilen, saj je faktor viskoznega dušenja za material vz1 za približno 80% večji od tistega za vz4, medtem ko sta za oba materiala zvočni upor in dušenje zvočnega sevanja primerljiva.

this influence is quite significant because the viscous-damping factor for material vz1 is approximately 80% higher than that one for vz4, whereas both the sound-wave resistance and the damping of sound radiation for these two materials are comparable.

3 SKLEP

Eden najbolj razširjenih materialov za tudi najbolj kakovostne okrove zvočnikov je t.i. MDF. Zato smo zvočne lastnosti, ki jih ima ta material, definirali za referenčne. Zvočne lastnosti gradiva so definirane z (i) zvočnim uporom, (ii) dušenjem zvočnega sevanja in (iii) faktorjem viskoznega dušenja. V primerjavi z zvočnimi ploščami glasbil, ki morajo čim več vibracijske energije sevati v okolico (pri čim manjših notranjih izgubah), je funkcija okrova zvočnikov drugačna. Podrobneje, dušenje zvočnega sevanja mora biti za zvočne plošče glasbil razmeroma veliko, zvočni upor pa majhen. Energija tresenja membrane zvočnika se mora pravilno absorbirati, pri tem pa stopnja absorpcije ne sme biti prevelika ali premajhna. Rečemo lahko torej, da mora biti zvočni upor materiala za okrov zvočnikov razmeroma velik, da se ne ojačujejo resonančne frekvence zvočnika kot celote. Dušenje zvočnega sevanja, torej sevanje zvoka v okolico, pa mora biti razmeroma majhno. Vendar bi previsok zvočni upor pomenil slabo prehajanje zvočne energije v okrov zvočnika, kar pomeni veliko možnost pojava odmevov in stojnega valovanja. Lep primer tega je velika vrednost zvočnega upora za aluminij (sl. 6). Ni si težko predstavljati, da bi se aluminijski okrov zvočnika kazal v nezaželenih stranskih pojavih, na primer stojno valovanje in posledično resonančna nihanja membrane zvočnika. Logično je namreč, da namen okrova zvočnika ni poudarjati določenih frekvenc, temveč prav nasprotno, takšne pojave mora preprečiti. Po drugi strani je majhen zvočni upor materiala povezan z razmeroma majhno zvočno impedanco in hitrim odvajanjem zvočne energije v okrov zvočnika, kar se lahko kaže v kratko trajajočih, a izrazitih resonančnih frekvencah okrova zvočnika. To lahko pomeni velike izgube zvočne energije, sploh če se razmeroma majhen zvočni upor pojavi v kombinaciji z razmeroma visokim faktorjem viskoznega dušenja (velike izgube zaradi notranjega trenja).

Smiselno je skleniti, da so zvočne lastnosti, ki smo jih izmerili na materialu MDF, optimalne. Tako lahko rečemo, da je material vz4 med vsemi testiranimi materiali najbolj primeren za okrove zvočnikov. Ker sta oba, dušenje zvočnega sevanja in zvočni upor za ta material nekoliko manjša v primerjavi z MDF, se pojavi vprašanje, kako obe veličini povečati, ne da bi bistveno spremenili faktor viskoznega dušenja, ki se zelo dobro ujema s tistim za MDF.

3 CONCLUSION

One of the most common materials for loudspeaker boxes, including high-quality products, is MDF (medium-density fibreboard). Therefore, we denoted the acoustic properties that are significant for this material as the reference properties. The acoustic properties of a material are defined by (i) the sound-wave resistance, (ii) the damping of sound radiation, and (iii) the viscous damping factor. In comparison to the sound boards of musical instruments, which should radiate their vibration energy into the surroundings as much as possible (in addition to minimal internal losses), the function of loudspeaker boxes is different. More precisely, the damping of sound radiation for the sound boards of musical instruments has to be relatively high, and the sound-wave resistance should be low. The energy contained in the vibrations of a loudspeaker diaphragm has to be absorbed in a proper way, which means that the intensity of the absorption should be neither too high nor too low. We can say that the sound-wave resistance of a material for loudspeaker boxes has to be relatively high in order not to amplify the resonant frequencies of a whole loudspeaker. The damping of the sound radiation, and thus the radiating of sound into the surroundings, has to be relatively low. However, too high sound-wave resistance means an insufficient transition of acoustic energy into the loudspeaker box, which can result in phenomena like echoes and standing waves. A nice example of this is the high value of sound-wave resistance for aluminium (see Figure 6). It is not hard to understand that an aluminium loudspeaker box would result in undesired effects like standing waves and, consequently, resonant vibrations of the loudspeaker diaphragm. It is logical that the purpose of a loudspeaker box is not to emphasize certain frequencies, but on the contrary, to prevent this phenomenon. On the other hand, too low sound-wave resistance correlates with a relatively low sound impedance and fast sound-energy drain into the loudspeaker box. This can result in short-lasting but distinctive resonant frequencies of the loudspeaker box. Finally, this can lead to high sound-energy losses, especially if relatively low sound-wave resistance appears together with a relatively high factor of viscous damping (high losses due to internal friction).

It is reasonable to conclude that the acoustic properties measured for MDF are the best ones. Thus, one can say that the most suitable material for loudspeaker boxes among the tested materials is vz4. Because both the damping of sound radiation and the sound-wave resistance for this material are slightly lower in comparison to MDF, the question is how to increase these two parameters and not significantly affect the viscous-damping factor that corresponds to that for MDF.

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Naslova avtorjev: mag. Samo Šali
prof.dr. Janez Kopač
Univerza v Ljubljani
Fakulteta za strojništvo
1000 Ljubljana

Uroš Žnidarič
ISOKON. d.o.o.
Mestni trg 5a
3210 Slovenske Konjice

Authors' Addresses: Mag. Samo Šali
Prof.Dr. Janez Kopač
University of Ljubljana
Facaulty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia

Uroš Žnidarič
ISOKON. d.o.o.
Mestni trg 5a
3210 Slovenske Konjice, Slovenia

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