Experimental and Numerical Approach in the Acoustical Behaviour of Kefalonian Traditional Instruments Made from Different Materials

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Abstract: ***The present investigation deals with two types of traditional Kefalonian musical instruments, 'anakarí' and 'skortsámpouno' respectively. Within the present research, static and dynamic mechanical properties, as well as the water uptake of several wood types as candidate construction materials for 'anakarí' and 'skortsámpouno' were evaluated, with the purpose to select the most appropriate ones from both structural and acoustic viewpoints. Further on, a numerical study by FEM was performed to investigate the production of (non-) differential sound quality, depending on the construction material. Based on the experimental results, several 'anakarí' instruments were designed and manufactured (i) traditionally from two wood types and (ii) by using modern materials and techniques - 3D printing of poly lactic acid (PLA). Finally, acoustical measurements were carried out using BIAS software and studio recording processing of "skortsámpouno" and "anakarí", in order to compare the acoustical behavior depending on the construction material. The conducted analysis revealed small divergence of the sound quality in correlation with the different materials used for the construction of the tube. On the contrary, the use of different materials for the construction of the bell resulted in significant divergence in the sound quality of both instruments.***

Keywords: Kefalonian traditional instruments, wood in wind musical instruments construction, acoustic behaviour of wind instruments

1. Introduction

Musical instruments are mechanical constructions related to music, art, culture, technology and the science of acoustics. The modern shapes of the wind instruments are usually the result of empirical modifications that have resulted in musical instruments with good acoustics, ergonomics and volume. Musical instrument manufacturers must be able to construct a mechanical structure that meets the following requirements: (i) From the point of view of acoustic science, it should be possible for the wind instrument to produce a range of notes blurred to a predetermined scale by generating stationary waves inside it; (ii) The instrument should be made of a material suitable to withstand environmental conditions and (iii) After the stationary sound generating waves are produced inside it, a good melodic effect should be released from the instrument, that allows the instrumentalist to play his repertoire. These requirements have been encountered by the older generations of manufacturers and continue to challenge scientists and fabricators in the industry of music nowadays. [Fletcher, 1998]

The island of Kefalonia in Greece is known for its music tradition and cultural heritage, being a leader in this sense in the Ionian Islands. Kefalonia's music is divided into three categories (excluding Ecclesiastical music): (a) Western-style music, which either comes directly from Italy and other Western countries, or its influences on local musicians and their creations; (b) Urban music, the well-known arriets and cadets who are folk-urban genres as well as the exploitation and promotion of the band as a medium of popular musical expression in all facets of city life and (c) rural music; that is, local folk music that is either table or dance. The instruments involved in the music production of Kefalonia, are mainly classical instruments of Western origin. Specifically, in (a) and (b) categories of Kefalonian music the classical instruments of the violin, guitar, mandolin, tuba, clarinet and other string and woodwind musical instruments of the band takes apart. In category (c), the violin has a predominant role. It can be found either playing solo or in combination with the guitar, or other strings. In the category of traditional wind instruments, the so called 'anakarí' and 'skortsámpouno', which are the subject of the present research, are used in Kefalonian folk music. These instruments are not particularly widespread in Kefalonia; they are rarely found in specific areas of the island. They have been introduced in Greece by other countries and used to appear sporadically and in special occasions, e.g. weddings, religious festivals. The 'skortsámpouno' belongs to the category of bagpipes, which is found throughout Europe and the Mediterranean countries. Bagpipres generally consist of an air tank (bag), and one or more double-reeds. The 'anakarí' belongs to the category of woodwind instruments. It is alike with zurna with tonal holes and mouthpiece and it uses a short cylindrical reed that is tied to a conical brass tube on the end, flattened to a narrow slit on the other end, as source of sound. [Baines, 1991]

The present investigation deals with the two types of traditional Kefalonian musical instruments, 'anakarí' and 'skortsámpouno' respectively. Very few scientific sources are published about these two instruments, only in Greek language. Both 'anakarí' and 'skortsámpouno' musical instruments were used mainly by shepherds in the rural areas of Kefalonia and were key instruments at festivals and folk festivals. The 'skortsámpouno' is a kind of bagpipe, that is a traditional wind instrument in Europe, North Africa and the Middle East, consisting of a bag and a wooden part. The bagpipe consists of the bag, the mouthpiece and the audio section. The latter consists of two separate chanters: one, short with holes, produces the melody, and the other, long without holes, produces a tone that holds equal. The pibroch came to Greece from Asia in between the 1st and the 2nd century B.C. and it can be found in two forms: the 'tsampoúna' (in the islands) and the 'gáida' (in Macedonia and Thrace). [Anogiannakis, 1991] The manufacturer of the 'skortsámpouno' is the player himself. In the fabrication, he uses processed baby goat skin for the bag and wood or bone for the mouthpiece. These two organs, although an integral part of the island's tangible and intangible cultural heritage, have not been scientifically studied until now. Technologically, they are mechanical systems, where an initial oscillation in the mouthpiece propagates in an air column, which is defined by the geometrical characteristics of the pipe (inner cylinder dimensions) and causes the generation of sound waves. The present study seeks to analyze their construction and function through experimental studies (e.g.: design, construction methods, measurement of acoustic impedance, mechanical characterization of materials, etc.). The results of the studies will help to evaluate ways of construction and their place in the local cultural heritage. Also, an attempt will be made to detect the sound spectrum that the instruments can produce in order to correlate them with Kefalonian music and to identify their relationship with instruments from other Greek and / or Italian areas belonging to the same family.

Finally, the influence of materials on the acoustic effect of the two aforementioned Kefalonian musical instruments will be presented.

2. Materials and Methods

2.1 Materials

The main investigated material was wood. Traditionally, instrument makers used pieces of tree that had been naturally dried. Otherwise, they cut the piece of wood and left it for a long time in a sealed place for at least 6 months to dry. This tradition was respected within the present study, since a eucalyptus tree had been dried for over 2 years near by the laboratory where the research and experiments were carried out, in Kefalonia. The team decided to use it as a manufacturing wood of the 'anakarí'. On the other hand, other local wood was involved in the study: walnut, eucalyptus, beech tree, cherry tree, mulberry. The wood species were chosen since they are available in the island of Kefalonia. Three material categories were used for the construction of the components of the musical instruments: wood, plastic and metal. Modern instruments made of new materials and construction procedures are being tested nowadays; in this context, a 3D printed 'anakarí' made by PLA provided from Innofil3D was manufactured for the present study.

2.2 Investigation of static and dynamic mechanical properties and water uptake

Tensile testing and dynamic mechanical analysis were performed for the evaluation of the wood specimens. Emphasis added on the elasticity modulus and the tensile strength. In order to the tensile testing evaluation, specimens were prepared according to ASTMD198-15. For the calculation of the elasticity modulus along the direction perpendicular to the wood fibers, DIN-52188 standard has been used [Bachtiar, 2017]. Furthermore, the wood specimens with the highest values of static mechanical properties, were evaluated in a dynamic testing analyser. The E', E", tanδ of walnut, eucalyptus and beech tree were measured and calculated. For this test, the dimensions of the tested specimens were 50x10x4mm. A DMA machine type Artemis by Netzsch has been used for the measurements. 15 specimens were used for each wood type to minimize errors in the results. The samples were tested in 3-point bending, and with applied frequencies 1,5 to 50 Hz. A dehumidifier has been used in the testing room, in order to maintain constant humidity: 65% Relative Humidity RH, 200C).

The water absorption of four types of wood samples have been investigated: eucalyptus tree with longitudinal fibers (codes P1 and P2), eucalyptus tree with transverse fibers (codes S3 and S4), beech tree with longitudinal fibers (codes P3 and P4) and beech tree with transverse fibers (codes S1 and S2). Immersion times were 1, 2, 3, 18, 20, 80 and 96 hours, at 23.50 C. Before immersion in water, specimens were prepared according to ASTM-D143 standard; they were dried in an oven for 24 hours, at 1030 C. The mean value of the following parameters of the specimens has been calculated: thickness, width, length, surface and volume of dry and wet specimens. Finally, the water uptake of all specimens has been calculated and results were plotted.

2.3 Design & Structural Analysis

The structure in relation to the acoustic feedback of the two musical instruments ('skortsámpouno' and 'anakarí') was investigated. AutoCad and a Finite Element Model and software were used in order to achieve the analysis of the acoustic behaviour by the numerical study of air vibration along the column of the musical instrument (pipe), as well as in the bag and in the whole system, in the case of the 'skortsámpouno'. The effect of the selected materials on the acoustic performance of the musical instruments has been studied using virtual experiment approaches. In order to build the virtual musical instruments, the input data obtained after the mechanical characterization of the selected construction materials have been introduced.

2.4 Instruments Manufacturing and Acoustic Measurements

Three types of wood: walnut, eucalyptus and the beech tree respectively, were used for the manufacture of the real model musical instruments. Walnut wood was used to manufacture the 'zournás'" and eucalyptus was used to manufacture the 'anakarí'. Modern 3D printing technology was used to print an 'anakarí' made of PLA thermoplastic. A 3DISON AEP desktop 3D printer based on Fused Filament Fabrication (FFF) was used to print the PLA 'anakarí'. With respect to the 'skortsámpouno', its largest part is the bag, which is traditionally made of goat skin. The other parts of the 'skortsámpouno' are generally made of wood and in this case, walnut was used. Finally, two types of materials were used for the bell construction: copper and spruce wood.

Two players were involved in the studio recordings in order to avoid the recording errors, associated to their personal particularities (how he holds the instrument, blowing strength etc.) Acoustical measurements of the recording room were made in order, to calculate the reverberation time. The acoustical behavior in the room was calculated before, during and after the musical instrument recordings, using a Sound Meter Level, Bruel & Kjaer type 2250 placed in the center of the room where the performers stood as well. The microphone type was Neumann U87 and two Millenia STT-1 amplifiers were also installed. Pro Tools software was used for the recording. Praat program was used to calculate the tone pitches and the intensity contours and Audacity software saw used for editing the recording files (FFT).

Furthermore, for the analysis of the acoustic behavior of the musical instruments, BIAS- Diagnosis and Therapy for Musical Instruments (www.artim.at) software has been used, to manage acoustic impedance measurements.

3. Results and Discussion

3.1 Statics and dynamic mechanical characterization

Luthiers know they have to adapt to the wood they choose, and that resonance may be achieved differently depending on its quality. A heavy wood can be thinned down, while a soft wood must stay thick. A heavy and soft wood is not recommended, while a light springy piece can give better results. Compromises are necessary to achieve the best possible instruments, or musical instruments parts. [Fouilhe, 2012]. On the other hand, the engineering properties of wood are extremely variable naturally. Same type of trees which are growing up in different places, generally result in dissimilar mechanical material properties under tensile and torsional load types. [Günay, 2003]. When studying materials for the construction of musical instruments, it is important to know that Young's modulus, together with the wood's density, determines most acoustical properties [Wegst, 2006].

Wood is a cellular solid and its macroscopic physico-mechanical properties depend on the arrangement of the cells and on the properties of the cells [Gibson, 1997]. Research claims that measuring acoustic or mechanical properties of wood can aid in selecting the 'singing timber'. Measuring the dynamic Young's modulus (stiffness of an elastic material) can distinguish between suitable and unsuitable wood material for sound boards for pianos [Fukada, 1950]. Also, lower angles of cellulose microfibrils in wood cell walls of spruce trees result in higher Young's modulus and it is generally accepted that a reduction in the internal friction of wood improves the quality of soundboards [Ono, 1984, Trifkovica, 2016]. With regards to the strength of the wood, it has been found that the tension strengths in longitudinal directions are higher by a factor of 1.5 and 2.1 for walnut and cherry wood compared to the compression strengths. Moisture content influences the orthotropic material strength properties of these woods. If moisture content is less than the fiber saturation point, the strength properties decrease [Bachtiar, 2018]. A top candidate material in musical instruments manufacturing is the beech wood which besides being widely available, it also has excellent mechanical properties, significantly higher than those of the common softwoods used for structural purposes [Ehrhart, 2018].

The tensile properties of wood have been the subject of numerous studies. mostly from the point of view of its performance as a structural material. A number of these investigations examine wood strength as a function of such variables as moisture content and temperature. It was shown that the strain-temperature curve remains linear up to about 250C, at which point it begins to level off, reaching a maximum value at about 1250C. It is interesting to note that the maximum rate of decrease in fracture energy corresponds to the same temperature range (from 250 to 1250C) [Koran, 1979]. For this reason, room temperature is considered appropriate when evaluating the static mechanical properties of wood.

As seen in Fig. 1(a), the highest value of the elasticity modulus between the tested wood specimens was detected in the case of the eucalyptus. Very close value to it was the beech tree and on the third place the walnut. This finding places the eucalyptus, which is commonly found in Kefalonia, on the first position between the candidate materials for traditional instrument manufacturing. The tensile strength of eucalyptus is slightly higher than the ones of the beech tree and the walnut. These three wood materials with highest values of static mechanical properties were further tested in a dynamic mechanical analyser (DMA).

International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2019): 7.583

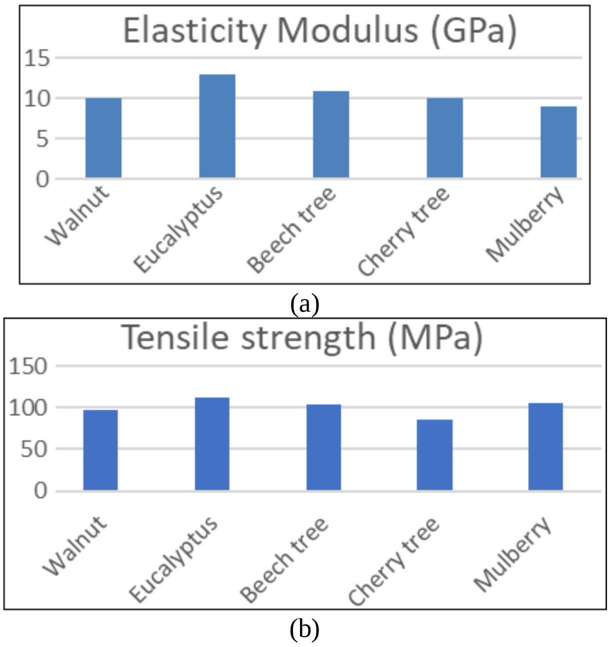


Figure 1: Static mechanical properties of some wood types: (a) Elasticity Modulus and (b) Tensile Strength

Both static and dynamic mechanical properties of wood for instrument construction are key factors influencing the quality of the sound. Developments in wooden percussion instruments depend upon many of the intrinsic properties of wood, particularly that is fairly consistent in elastic properties from one piece to another of the same species and quite low in internal damping so that the sound would not decay too quickly [Fletcher, 2012]. The dynamic mechanical behavior of wood is strongly related to its biochemical composition, more than to its structure. In previous research, two transitions temperatures (between 400C and 900C) were detected in green wood and ascribed to the softening of hemicelluloses and lignin, in that order. However, this degree of strain far exceeds the wood linear viscoelastic response region, and so these transitions probably reflect something other than the simple Tg of hemicellulose and lignin. It has been reported that the hemicellulose Tg in water-saturated wood is below ambient temperatures [Sun, 2007]. However, given that the musical instruments are normally used in an environment at room temperature or in between some normal temperature limits that the human being can outstand, room temperature is adequate to perform mechanical testing and extract the appropriate information regarding wood mechanical behavior.

The vibration damping coefficient (tanδ) of wood is an important property for acoustical uses, including musical instruments. Current difficulties in the availability of some of the preferred species call for diversification, but this comes up against the lack of systematic damping coefficient data [Bremaud, 2010]. One way of studying the viscoelastic properties of wood is through vibrational analysis. A simple harmonic stress results in a phase difference between stress and strain. The specific modulus, that is the ratio of dynamic Young's modulus (E') to specific gravity (γ), and internal friction (tanδ) measurements can be used to study the viscoelastic nature of wood. The E'/γ ratio is related to sound velocity and the tanδ to sound absorption or damping within the wood. For musical instruments, manufacturers are looking for wood materials with high storage modulus and low damping coefficient. As observed in Fig.2(a), the highest storage modulus of the beech three, is followed by the walnut and, with a great difference of more than 1000 MPa, by the eucalyptus. As seen in Fig. 2(b), the loss modulus of walnut is highest between the three wood types. However, the ratio between the loss and the storage modulus determines the final property of interest (tanδ) of the materials. As observed in Fig.2(c), the highest (tanδ) is expressed in the case of walnut. The material with lowest (tanδ) is the eucalyptus; this wood type remains the favorite one for musical instrument construction within the present research, due to good static and dynamic mechanical behavior comparing to the other wood types.

While the difference of values between Young's Modulus of eucalyptus and the other wood types is almost insignificant, the difference in (tanδ) is considerable. Due to its high value of Young's Modulus and low value of tanδ, the specific modulus will have an appropriate value, because of a good sound velocity and sound absorption.

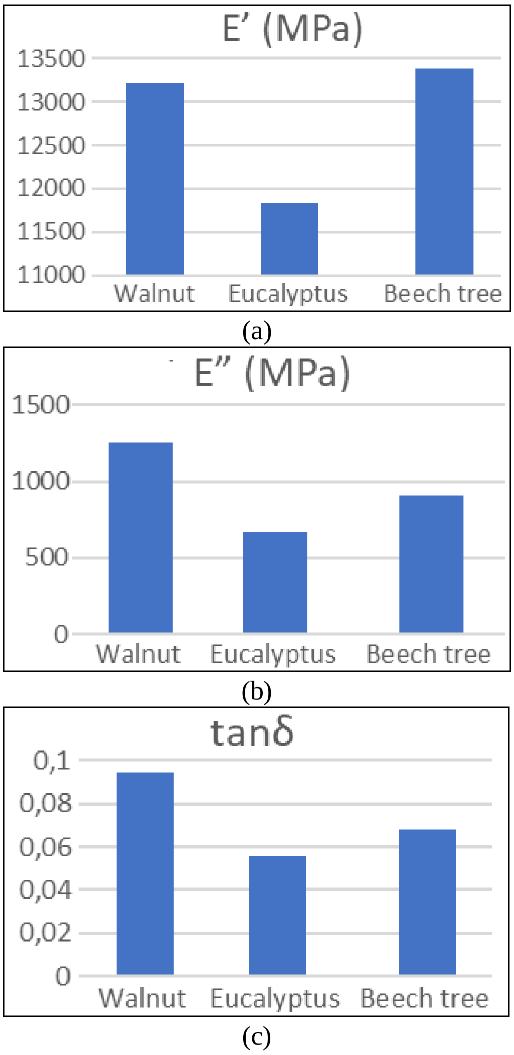


Figure 2: The dynamic mechanical properties of several wood types: (a) Storage modulus; (b) Loss modulus and (c) Damping coefficient

3.2 Water Absorption

Wood, like many natural materials, is hygroscopic; it takes on moisture from the surrounding environment. Moisture exchange between wood and air depends on the relative humidity and temperature of the air and the current amount of water in the wood. This moisture relationship has an important influence on wood properties and performance. Many of the challenges of using wood as an engineering material arise from changes in moisture content or an abundance of moisture within the wood. The mechanism of water absorption is called capillary action or wicking. Water interacts strongly with the wood cell wall and forms a concave meniscus (curved surface) within the lumen. This interaction combined with the water–air surface tension creates a pressure that draws water up the lumina. The rate of liquid water absorption in wood depends on several factors. The rate of absorption is most rapid in the longitudinal direction (that is, when the transverse section or end grain is exposed to water) [Glass, 2010]. Besides decrease of sound quality, the water absorption in wood may lead to other unwanted effects. The periodic water absorption has a negative effect on wood quality. The ability of microorganisms to attack wood depends on the moisture content of the wood cell wall [Khazaei, 2008]. Unlike mold and stain fungi, wood-destroying (decay) fungi seriously reduce strength by metabolizing the cellulose fraction of wood that gives wood its strength [Kretschmann, 2010]. Early stages of decay are virtually impossible to detect. For example, brown-rot fungi may reduce mechanical properties in excess of 10% before a measurable weight loss is observed and before decay is visible. When weight loss reaches 5% to 10%, mechanical properties are reduced from 20% to 80%. Decay has the greatest effect on toughness, impact bending, and work to maximum load in bending, the least effect on shear and hardness, and an intermediate effect on other properties.

Although fiber often constitutes the majority of woody tissue, general fiber is not considered as important as vessels in primary liquid flow. However, fiber permeability may influence the subsequent spreading of liquid from vessels or other cells connecting them to pits. Comparing fibers to vessels, non-perforated ones are thick walled with relatively small pits that are not adapted for efficient liquid conduction [Okoh, 2014]. The beech tree (Fagus sylvatika) belongs semi-diffuse-porous hardwoods. In previous research, significantly higher water uptake was observed in the diffuse-porous and the semi-diffuse-porous group. Water uptake varied among the species; nevertheless, tangential section was more permeable in general. Ring-porous species had low rate of earlywood and low water uptake, whereas diffuse-porous and semi-diffuse-porous hardwoods had high rate of earlywood and high-water uptake. Relation between water uptake and microstructure of wood was observed [Michalec, 2006]. As in the case of the mechanical properties, the water absorption process in wood is strongly influenced by its biochemistry. A biochemical cycle is formed, where the control of water uptake may lead to control of some mechanical properties. The lignin content and lignin structure exert a great influence on softening of wood. Lignin is a branched polymer made up of phenylpropane units. The softening temperature of wood, noted Tg, increases with the degree of cross-linking of the lignin. Methoxyl groups hamper crosslinking of the aromatic units. Their presence in abundance in typical hardwoods, and this fact results in a more flexible network with lower Tg. As water acts as a plasticizing agent for wood, the moisture content also affects the Tg [Obataya, 2001]. In the present study, water uptake of two wood types (beech and eucalyptus) was studied; the two wood types were chosen based on their internal structure which is known to have high rate of water uptake, which may lead to the decay in acoustic quality of a musical instrument. Tables 1 and 2 show the measurements of the dimensions and volumes of dry spruce and beech woods and the calculation of the percentage of change, while Tables 3 and 4 show the calculation of the change in percentage of the volume of specimens that were immersed in water, for 24 hours, at a temperature of 23.50C. In the case of wood, first hours are considered most important due to the fact that it is highly hydrophilic and a high rate of water uptake exists immediately after immersion.

Table 1: Dimensions and volume of dry spruce specimens

Fiber orientation	Mean thickness (mm)	Mean Width (mm)	Mean Length (mm)	Mean Surface (mm^2)	Mean Volume (V_0) (mm^3)
Longitudinal	2.016	10.270	50.74	521.1	1050.54
Longitudinal	2.040	9.943	49.84	495.56	1010.94
Transverse	1.996	10.490	49.90	523.45	1044.81
Transverse	2.126	10.420	49.87	519.64	1104.76

Table 2: Dimensions and volume of dry beech specimens

Fiber orientation	Mean thickness (mm)	Mean Width (mm)	Mean Length (mm)	Mean Surface (mm^2)	Mean Volume (V_0) (mm^3)
Transverse	2.143	9.870	48.74	481.06	1030.92
Transverse	2.116	10.333	48.96	505.90	1070.49
Longitudinal	2.103	9.466	44.56	421.80	887.05
Longitudinal	2.023	9.840	49.92	491.21	993.72

Table 3: Dimensions and volume of wet spruce specimens after 24 hours immersion in water

	Mean thickness (mm)	Mean Width (mm)	Mean Length (mm)	Mean Surface (mm^2)	Mean Volume (V_i) (mm^3)	ΔV/V (%) $[(V_i-V_0)/V_0]$ x100
Longitudinal	2.113	10.590	50.93	539.34	1139.64	+8.48
Transverse	2.246	10.453	51.69	540.31	1213.55	+9.85

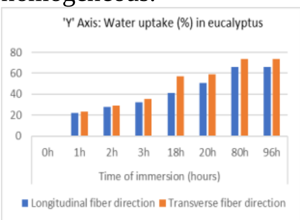
Table 4: Dimensions and volume of wet beech specimens after 24 hours immersion in water

	Mean thickness (mm)	Mean Width (mm)	Mean Length (mm)	Mean Surface (mm^2)	Mean Volume (V_i) (mm^3)	ΔV/V (%) $[(V_i-V_0)/V_0]$ x100
Transverse	2.260	10.086	50.04	504.70	1140.63	+10.64
Longitudinal	2.100	10.143	50.28	509.99	1070.98	+7.77

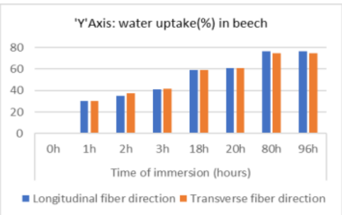
Finally, the water absorption (%) of eucalyptus and beech woods after several immersion time periods can be seen in

Paper ID: SR20504173104 DOI: 10.21275/SR20504173104

the diagrams in Figure 3, for both transverse and longitudinal fibers directions. As seen in Fig. 3(a), there is no significant difference of water uptake percentage in the case of the longitudinal direction of the fibres comparing to the transverse one, in eucalyptus. This is because eucalyptus internal structure is not porously isotopic, given its rectangular cell type. On the other hand, the percentage uptake in the transverse direction is slightly higher, showing that the eucalyptus overall porosity plays more important role in water diffusion than the fibres. As observed, the water uptake within the first day of immersion is much more significant than in the case of longer periods. This shows the pronounced hydrophilic character of the eucalyptus wood. Almost the same observations can be made in the case of beech tree (Fig.3b). The water uptake in longitudinal and transverse directions is almost similar. Almost undistinguishable difference, with higher amount of water uptake in specimens with longitudinal fibre direction may be observed at 80 and 96 hours of immersion time. Finally, from the point of view of water absorption capacity along the longitudinal and transverse directions, both eucalyptus and beech may be considered relatively homogeneous.



(a)



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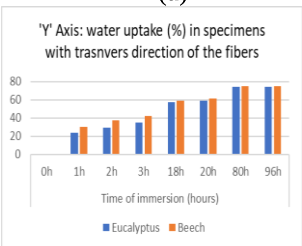
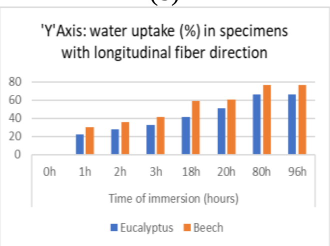


(c)



(d)

Figure 3: Water uptake after several immersion times in: (a) Eucalyptus specimens with longitudinal and transverse directions of the fibers; (b) Beech specimens with longitudinal and transverse directions of the fibers; (c) Spruce and beech specimens with longitudinal direction of the fibers and (d) Eucalyptus and beech specimens with transverse direction of the fibers.

Analyzing Fig3(c) one may see that for specimens with longitudinal fiber direction, the water uptake is much higher in the beech tree comparing to the eucalyptus. For the transverse direction (Fig.3d), the case is not the same. At 20 hours of immersion, the water uptake is almost the same for eucalyptus as for beech tree.

Regarding water absorption, between the tested specimens, the spruce tree with longitudinal fiber direction is the most efficient as it absorbs less amount of water.

3.3 Numerical investigation

The design and structural analysis of the 'skortsámpouno' and 'anakarí' were performed. More precisely, the structure in relation to the acoustic feedback of the two musical instruments was investigated. A Finite Element Model and AutoCad software were used in order to achieve the analysis of the acoustic behaviour by the numerical study of air vibration along the column of the musical instrument (pipe), as well as in the bag and in the whole system, in the case of the 'skortsámpouno'.

The meshing method in FEM has been used to numerically study the air vibration in the musical instruments made of eucalyptus, PLA and walnut. Representative results may be seen in Figure 3. The FEM model has been developed using the COMSOL software; 2D shell elements with dimensions 1x1 mm were used in the processing.

Figure 4a and 4b shows the designs in a virtual computing environment, for the 'anakari' and the 'skortsámpouno'. In the case of 'skortsámpouno', only the tsampouna (sound generator) was designed, because the bag plays the role of introducing air into the musical instrument, rather than producing sound.

During the modeling process the above drawings were meshed and numerical studies of the air propagation due to the musical instruments column (pipe) were performed. The peculiarities and oscillations of the eucalyptus, PLA and walnut musical instruments were calculated. Indicative results are shown in the following figures 4c, 4d, 4e and 4f.

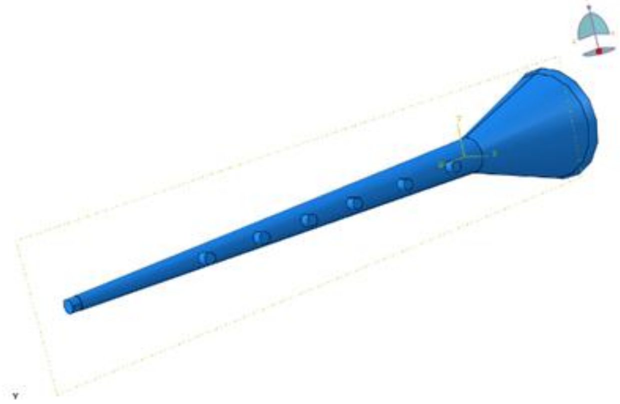


Figure 4a: "Anakari" 3D Rendering

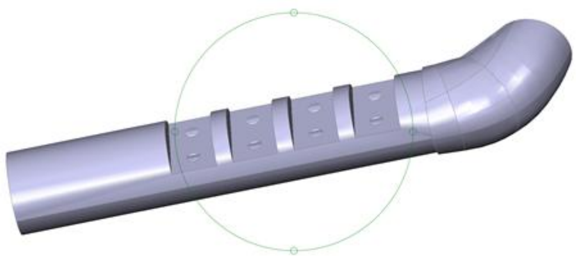


Figure 4b: "Skortsámpouno" 3D Rendering (tsampouna)

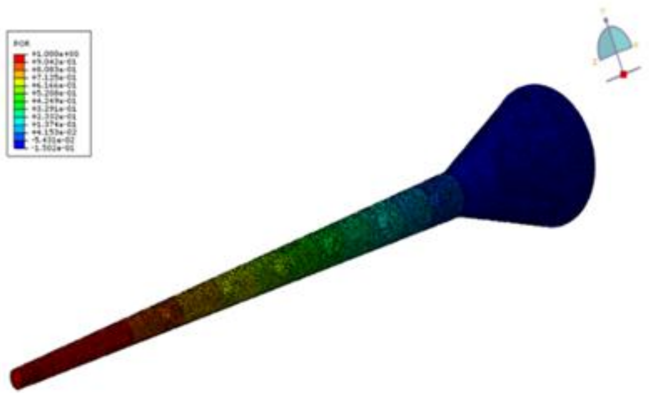


Figure 4c: Air column "Anakari" FEM Analysis

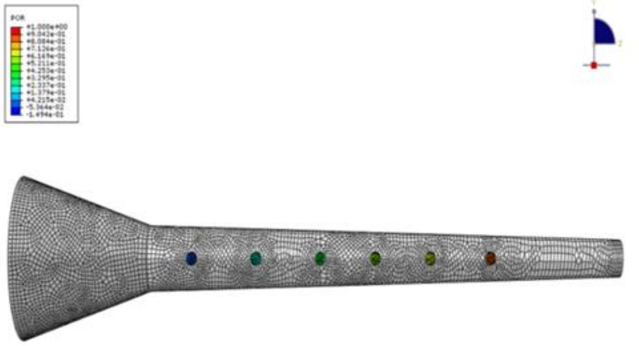


Figure 4d: Natural Frequencies in "anakari"

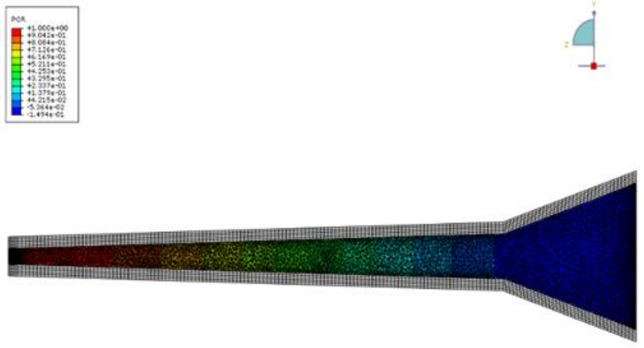


Figure 4e: Natural Frequencies in "anakari" (section)

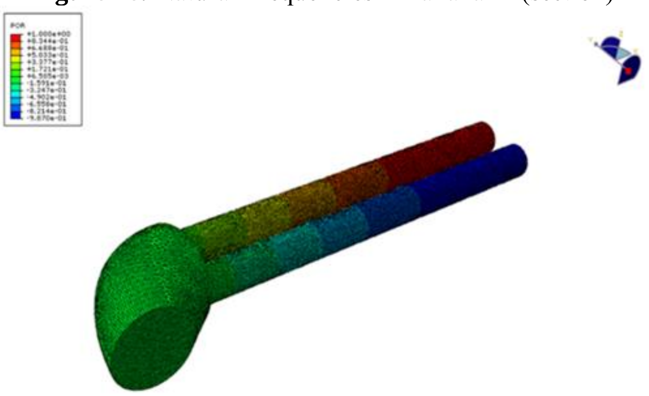


Figure 4f: Vibrations in "skortsámpouno"

3.4 Manufacturing of real model instruments

Traditionally, reeds have been made from sections of cane, but nowadays more and more players use synthetic ones. Plastic is a promising material for the construction of reeds, because it is less dependent on moisture levels, high temperatures and ageing; tuning of the instruments is, therefore, more stable. On the other hand, according to some musicians, the timber of instruments would be altered by plastic-made reeds [24]

The two wind instruments, 'anakarí and 'skortsámpouno' were manufactured as shows in Figure 5a-5d. The constructed models were based on traditional instruments that exist since decades in Kefalonia. In Kefalonia, the 'skortsámpouno' players have always been the constructors of their instrument; in this case specialized knowledge is not require. Therefore, the construction of the instrument makes use of empirical knowledge that has passed down from generation to generation. This musical instrument is common to traditional pastoral societies where the use of materials for construction comes from nature, whether fauna or flora, in the Kefalonia region. An attempt has been made in order to maintain the traditional prototypes. Particularly, for the manufacturing of the bagpipe of the 'skortsámpouno', the procedure has been difficult in terms of the preparation of the bag made of animal skin. It is important to note at this point, that the general concept of the construction of the musical instrument is related to the different materials available in a specific region.

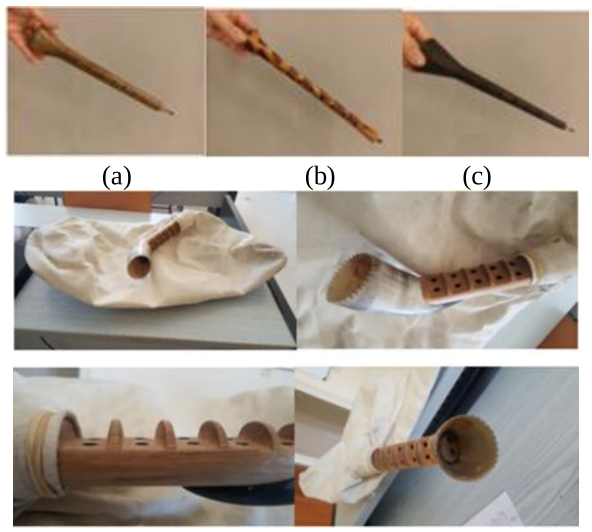


Figure 5: (a) "Anakari" made of eucalyptus, (b) Zurna made of walnut, (c) 3D printed PLA "anakari" (d) "Skortsámpouno" made of walnut and goat skin (bag)

3.5 Acoustic measurements and analysis

The principles of function of wind instruments are well known since the early 20th century and are relatively simple: the human lips open and close like a valve (440 times per second for an a1) and push overpressure pulses into the mouthpiece. These pulses form a sound wave with many harmonics and travel down inside the tube of the instrument to the bell. At the bell 90-94% of the energy is reflected, travels back to the mouthpiece and forms a "standing wave" with the original sound wave. The rest is radiated into the room and represents the sound of the instrument. This works only if the time span of the opening

and closing of the lips exactly matches (or is an integer part of) the time required by the sound wave for its round trip from the mouthpiece to the bell and back. [Widholm, 2012]
Previous investigations lead to very interesting conclusions related to the 'tsampouna'. A significant finding was that humidity created in the musical instrument by the player's breath, plays a huge role in the acoustic outcome. Another significant result was that the musical instrument can never create the same acoustic result. The uniqueness of tsampouna comes from the special features of each of its parts, which come from organic matter, which consequently can never be alike. The above is also due to the anisotropy of the wood. [Liari, 2016]

The construction of a large database of impedance measurements of a wide variety of instruments would be valuable, particularly if it can be combined with the evaluations of professional players. Ideally, one will be able to obtain a reliable method of predicting how a musician will judge an instrument based on its impedance curve [Braden, 2006]. Impedance is defined as the complex ratio of the pressure difference across a section of pipe over the volume flow rate through it. The acoustic impedance plays a central role when it comes to describing the propagation of sound waves in pipes of various shapes. Impedance is a complex quantity, both mathematically and in the more general sense. In the case of a pipe with a flared bell, it turns out to be quite simple to measure the impedance. However, comparison with the impedance of a standard cylindrical pipe of the same length reveals the effect that the flared bell has on the resonances of the pipe. [Dalmont, 2001]

Previous comparison between vibroacoustic properties of wood, plastic, and metal bars gave some clues. An important quality criterion for instrument woods is the frequency characteristic of acoustic radiation. Tap tones from sample plates or bars will indicate the significant differences between tone woods, frame woods, plastics, and metals. The radiation characteristics of tap tones from sample plates of Sitka spruce, maple, and aluminum, a large difference is observed above around 2 kHz that is attributed to the relative strength of shear and bending deformations in flexural vibrations. This shear effect causes an appreciable increase in the loss factor at higher frequencies. The stronger shear effect in Sitka spruce than in maple and aluminum seems to be relevant to soundboards because its low-pass filter effect with a cut off frequency of about 2 kHz tends to lend the radiated sound a desired softness [Yoshikawa, 2014].

The effect of wall vibration has been studied with brass instruments. It has been shown that mechanical wall resonances were excited when a simple wind instrument, consisting of a mouthpiece and section of metal piping, was artificially blown. The materials of the pipe affected the position of the structural modes and its response to a particular note. It was found that the sound level associated with unannealed brass flares was higher in the 1-3 kHz range than with the annealed brass bell flares, whereas the opposite was observed for nickel-silver bell flares [Paquier, 2016].

For the audio measurements, four instruments were involved: (1) an 'anakarí' made of eucalyptus; (2) an 'anakarí' made of PLA; (3) a 'skortsámpouno' manufactured within this research and (4) a 'skortsámpouno' belonging to a folklore music band of Kefaloniá. Additionally, considering that 'skortsámpouno' has a lot in common with the Ikárian 'tsampouna', recordings of both instruments were subject to contrastive analysis. All instruments were played by two local musicians. Figure 6 shows the tonal heights (Spectral Pitch Display) for all fingerings for the 'anakari' made of PLA. Corresponding charts were also created for the rest of the musical instruments after the studio recordings were processed. Data were extracted from the recorded files including waveforms, pitches, and intensity contours. The Praat program (http://www.fon.hum.uva.nl/praat/) was used to calculate the abovementioned.

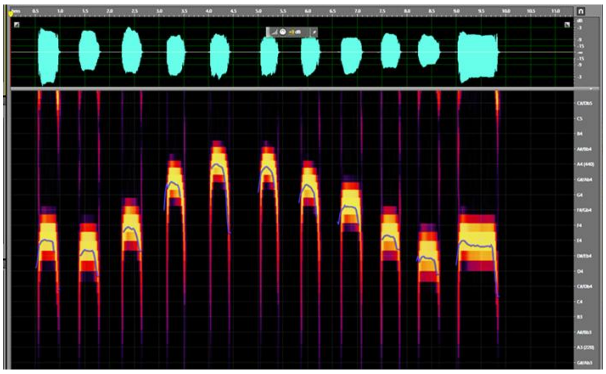
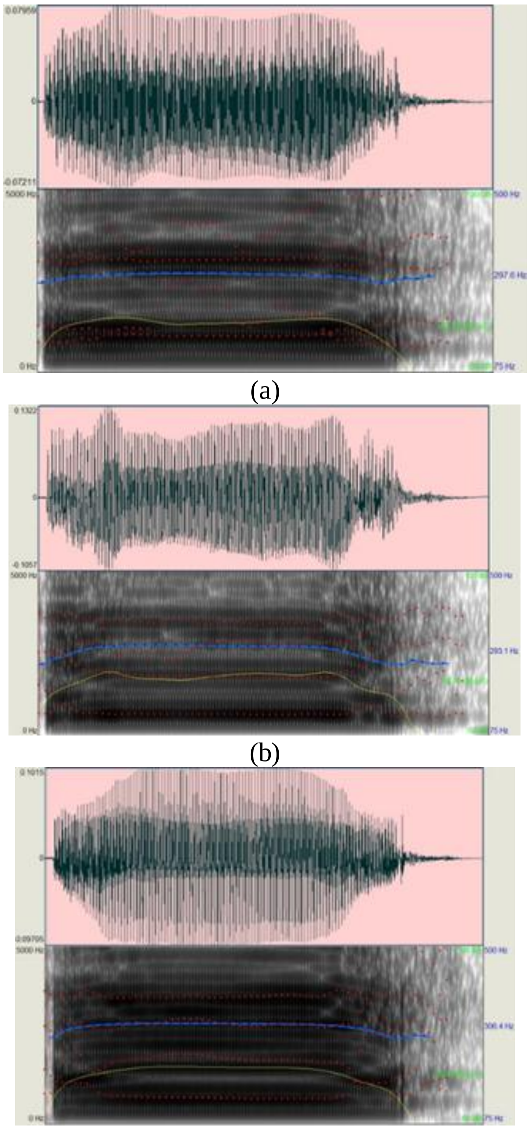


Figure 6: 3D printed "Anakari's" Spectral Pitch Display

In order to investigate the effect on the sound color of the column endings (bells) the above-mentioned procedures and methods were followed, along with the parametrization the bell of the instrument. For this purpose, bells were made of different materials and in different shapes, according to the traditional practice and the musical instruments (3d printed 'anakari', eucalyptus 'anakari', zurnas, 'skortsámpouno') were recorded by adding bells of different materials each time. Copper and spruce wooden bells were used, in addition to the bell of the instrument each time.

The study of the effect on the sound color of the musical instruments by adding bells of different materials, as a result of these changes, is shown in Figures 7a, 7b and 7c below. The results confirm that the bell acts as an acoustic impedance transformer and increases the efficiency of sound propagation while also affecting the frequency spectrum of the sound being transmitted.



(a)

(b)

(c)

Figure 7: Amplitude, spectrogram, pitch (mean value)and intensity for "anakari" made of eucalyptus. (a)"Anakari", (b) "Anakari"+ spruce wooden bell, (c) "Anakari"+ copper bell

Modal analysis showed that the eigenfrequencies seem to change when wood (spruce) or metal (copper) bells are added. In the case of 'anakari' we notice the oscillation frequency being 296.6Hz. The addition of a soft wood bell like the spruce, results in decreasing the frequency to 293.1Hz, which in turn lends more bass tone to the musical instrument. Conversely, the addition of metal to the bell results in sharpening the sound to 306.4Hz. Similar results were observed in the other musical instruments. Among them 'skortsámpouno" showed smaller deviations when adding bells, especially compared to the 'anakari". As already mentioned, two sets of bells of different cylindrical shapes were fitted to all the instruments, made of wood and copper.

4. Conclusions

The static and dynamic mechanical properties, as well as water absorption of several wood materials have been investigated with the purpose to evaluate their perspectives in the construction of traditional Kefalonian musical instruments. Two types of Kefalonian instruments were selected: the 'anakarí' and the 'skortsámpouno'. In between the several types of wood, the walnut, the eucalyptus, the beech tree was found appropriate for the specific application. The materials with highest elasticity modulus and tensile strength were the walnut the beech tree and the eucalyptus, which also presented good dynamic mechanical behaviour. Among them, eucalyptus displays the best mechanical behaviour, has high Young's Modulus and low damping coefficient, that will assure adequate sound velocity and sound absorption. A dry piece of an eucalyptus, lying in the entrance of the building of our laboratory, proved ideal for the construction of musical instruments and the specimens of this research.

No significant difference in water absorption along the longitudinal and transvers direction of both eucalyptus and beech existed, which shows some of the advantages and disadvantages of using these woods in musical instrument construction. The wave propagation will be homogeneous, which may be considered an advantage in the case of room concerts. When outdoor, maintenance of wood quality including its dryness is extremely important and the direction of its fibres may also have a key role in the performance, which should be studied in future investigations. The present study showed that beech tree absorbed less water in specimens with longitudinal direction comparing to all the other specimens.

The 'anakari' made of eucalyptus and the 3D printed made of PLA, constructed identically, but the zurna (walnut) had a slight difference in its dimensions relative to the other two. The 'skortsámpouno' manufactured within the project and the musician's one recorded during this study, showed almost identical acoustic impedance while the two 'anakari' and the zurna, had quite a difference in acoustic impedance. The 'tsampounas' (sound generator) of the two 'skortsámpouno'were dimensionally alike and were made of the same material (walnut). 'Anakari' and zurna were made of different material and zurna was not alike with the other two.

During the acoustic study of the aforementioned musical instruments and after editing the audio files created, it was observed that the musical instruments sound almost the same. The FFT charts showed slight differences in eigenfrequencies for the same note by the same performer each time for the musical instrument regardless of the construction material. With the addition of a soft wood bell lends more bass tone to the musical instrument, while the addition of metal to the bell results in sharpening the sound. Similar results were observed in the other musical instruments, with the 'skortsámpouno' having smaller deviations when adding the bells, compared to the 'anakari'.

In general, we could argue that when the wind musical instruments are of close mechanical properties and the dimensions of the instruments are no different, there is no change in the sound produced. Changing the instrument's bell, changes the sound produced. Although there are many studies that suggest that it is possible to 3D-print wind musical instruments, the 3D printed 'anakari' made of PLA of the present work, didn't succeed because it had a lot of differences in the sound it produced compared with its replica made of eucalyptus. The above is probably due to the large differences in the mechanical properties of the construction materials. According to the FEM analysis, it appears that in a wind instrument made of soft material the air is absorbed into the tube creating assuming a metamaterial, although this is in need of further research.

5. Acknowledgements

This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning 2014- 2020» in the context of the project "Traditional wind musical instruments of Kefalonia – Approach through mechanical research and acoustic investigations" (MIS 5006690).

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