STRUCTURAL AND ACOUSTICAL RESEARCH OF TRADITIONAL KEFALONIAN WIND INSTRUMENTS (BAGPIPE AND PIPE)

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ABSTRACT

The structural and acoustical characteristics of two Kefalonian traditional wind musical instruments are investigated. The first one is a bagpipe called 'skortsámpouno' which is, from a constructional perspective, alike the Greek 'tsampoúna' (alike to gaida). The second one is another wind instrument called 'anakarí', which is alike the well-known 'zournás'. Tensile testing, dynamic mechanical testing (DMA), water absorption experiments and mechanical modeling were carried out for the purposes of this paper. The degradation of the properties of different construction materials was evaluated. Three different materials were used for the construction of parts of the two instruments (wood, plastic, metal), which in turn were subjected to acoustic and structural analysis in order to evaluate the production of (non-) differential sound quality. Acoustical experiments 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.

1. INTRODUCTION

The construction of musical instruments is a multi-step process, even in the case of seemingly simple instruments such as flutes. Opinions vary among musicians, acousticians and musical instrument makers regarding the influence of materials on the sound of instruments. When sound is generated by the body of the instrument (a violin for example), the choice of materials can be essential [1]. In the temperate climates of Europe, where the instruments of the Western symphony orchestra were developed and perfected, instrument makers still primarily take advantage of the unique property combination and the aesthetic appeal of wood. On the other hand, over centuries previous generations of luthiers all over the world discovered what seemed to be the most appropriate materials for increasingly complex acoustical applications. Nowadays, the plethora of novel materials and manufacturing technologies allow the introduction of totally new products on the musical market. Despite that, since the degradation of material properties in time play an important role in the overall performance and in the handling of a musical instrument, innovative in-depth studies towards this direction are essential.

In previously reported studies, measurements on the humidity influence on the psychoacoustic performance of bagpipes showed minor changes in the values of the studied properties, enough however to affect significantly the sound quality [2, 3]. It is worth mentioning the study by Carral et al [4], reporting on the performance of Scottish Border bagpipe chanter. Results revealed that variations in the relative humidity of the air around the reed affected the moisture content and thus the physical parameters of the instrument, and finally the produced sound. Mass, stiffness, mechanical response and damping factor were measured as a function of relative humidity. The stiffness measurements were inconclusive; however, according to the above-mentioned study, the damping factor remained constant and unaffected by the humidity, while the resonance frequency showed a decreasing trend with the increasing of the relative humidity.

In the case of flute, its construction material is generally thought to affect the sound quality of the resulting instrument. Nevertheless, there exist studies reporting that players and listeners of the flute cannot distinguish between flutes made from a variety of different materials. Coltman compared keyless flutes made of silver, copper and grenadilla wood, each of them played with the same head joint made of Delrin plastic [5]. Widholm et al. compared entire flutes of identical design made of solid silver, 9 carat gold, 14 carat gold, 24 carat gold and solid platinum, as well as platinum plated and silver-plated flutes [6]. According to Coltman, 'no statistically significant correlation between the listeners' scores and the material of the instrument body was attested. Moreover, Widholm et al. conclude that there is 'no evidence that the material has any appreciable effect on the sound color or dynamic range of the instrument'. In any case, the bore surface of wooden instruments can change over time with playing and this change may affect the acoustic impedance, and therefore the playing quality. Lastly, there is common consensus on the fact that materials which are highly porous or cannot be machined sufficiently smooth, will produce instruments of inferior quality [7].

In traditional musical instrument making, the potential of merging traditional designs and methods with the ability of introducing new technologies has always been a major challenge. The complex relationship among design, sound, and playability lies in the centre of instrument manufacturing: in many cases, sound and playability are limited owing to the constraints of the instrument design, imposed by the new fabrication technologies. A study by Zoran [8] elaborates on the controversy of modern acoustic instruments, which may have come to an evolutionary impasse, due to its high standardization that makes it difficult to explore design modifications. 3D printing has the potential to influence new designs, and to lead to new acoustics and ergonomic innovations. While 3D printing technologies still have significant drawbacks—such as resolution, material quality, and stability—limiting their use for manufacturing (instead of prototyping)—we can easily envision the way future digital fabrication technologies may play a major role in paving the way for new acoustic instrument designs. When technology evolves further, digital design and fabrication tools will enable the implementation of designs and modifications that cannot be achieved otherwise. To take maximum advantage of such modern technologies, the performance of a wide variety of materials under different conditions should be investigated. Research on musical instruments may open a wide range of interdisciplinary endeavors, since technology offers today a great range of possibilities for exploring both the component materials and the physical phenomena around them.

The present research focuses on the study of two traditional wind musical instruments made of various materials. Traditional and modern materials (wood, plastic, metals) were used for the construction of ‘skortsámpouno’ and **‘**anakarí**’**, focusing on the study of the mechanical and acoustical characteristics of various wood species, materials used for 3D printing and metals. Structural investigation and acoustic measurements of the musical instruments made of the aforementioned materials, are also presented.

2. MATERIALS AND METHODS

2.1. Materials

Three different materials were used for the mechanical testing and the manufacturing of the ‘skortsámpouno’ and ‘anakarí’; these were: wood, plastic and metal. Several wood species were used for the purposes of the study in order to compare their elasticity modulus: walnut, eucalyptus, beech tree, cherry tree, mulberry. The abovementioned wood species were chosen on the basis of their availability on the island of Kefalonia. However, emphasis was placed on the two wood materials with the highest elasticity modulus, walnut and eucalyptus respectively. For the 3D printing of the ‘anakarí’, PLA was provided from Innofil3D.

2.2. Mechanical Evaluation

The mechanical evaluation included tensile testing and dynamic mechanical analysis. Testing machines and specimens’ dimensions are described below.

a. Static mechanical testing

The static mechanical properties of the selected wood types were evaluated (elasticity modulus and strength). Elasticity modulus was calculated along the direction parallel to the wood fibers. Specimens were repared 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 [9].

Dynamic mechanical analysis (DMA)

The dynamic mechanical properties (E’, E”, tanδ) of walnut, eucalyptus and beech tree were measured and calculated. 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 using 1,5 to 50 Hz frequencies.

A dehumidifier has been used in the testing room, in order to maintain constant humidity: 65% Relative Humidity RH, 20^0C).

2.3. Design & Structural Analysis

The design and structural analysis of the ‘skortsámpouno’ and ‘anakarí’ were performed. More specifically, the structure in relation to the acoustic characteristics of the two musical instruments was investigated. To this end, , a Finite Element Model and AutoCad software were used to achieve the analysis of the acoustic behaviour by the numerical study of air vibration along the column of the musical instrument (blow stick), 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 organs, the input data obtained after the mechanical characterization of the selected construction materials have been introduced.

2.4. Water Absorption

The water absorption of four types of wood samples have been investigated (Table 1), after 1, 2, 3, 18, 20, 80 and 96 hours of immersion, at 23.5^0 C. Before immersion in water, specimens were prepared according to ASTM-D143 standard; they were dried in an oven for 24 hours, at 103^0 C.

Wood name	Fibers	Specimen

	orientation	code
Spruce tree	Longitudinal	P1, P2
Spruce tree	Transverse	S3, S4
Beech tree	Longitudinal	P3, P4
Beech tree	Transverse	S1, S2

Table 1. Wood species involved in the investigation of water absorption.

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.

2.5. Instruments Manufacturing

Three types of wood: walnut, eucalyptus and the beech tree respectively, were used for the manufacturing 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'. As far as 'skortsámpouno' is concerned, its largest part is the bag, which is traditionally made of goat skin. The other parts of the 'skortsámpouno' are generally made of wood; walnut was used for the purposes of this study. The 'anakarí' was made of beech tree. Finally, two types of materials were used for the bell construction: copper and spruce wood. The detailed description of the instruments components and the manufacturing steps are presented in the section of *Results and Discussion*.

2.6. Acoustic Testing

, 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. Two Millenia STT-1 amplifiers were also installed. Pro Tools software was used for the recordings. Praat program was used to calculate the tone pitches and the intensity contours and Audacity software was 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. Mechanical Characterization

In Table 2, the values of the elasticity modulus and the tensile strength of different wood species, calculated after the tensile tests can be observed.

Wood type	Elasticity Modulus (GPa)	Tensile strength (MPa)
Walnut	10,81±1,8	98,8±12
Eucalyptus	13,9±2,4	112±14
Beech tree	11,68±1,7	104±8
Cherry tree	10,25±1,3	85±19
Mulberry	9,1±2.8	105±16

Table 2. Elasticity modulus and the tensile strength of the tested wood specimens.

Our results align with those of previous studies, for each wood type [9]. The storage modulus ($E^{'}$), and the damping factor of the materials with highest found values of the elasticity modulus and tensile strength (walnut, eucalyptus and beech tree) were measured. Calculated values of $E^{'}$, $E^{''}$ and tanδ are given in **Table 3**.

Specimen (mean value)	E' (MPa)	E" (MPa)	tanδ
Walnut	13212.21	1251.35	0.094
Eucalyptus	11836.16	672.72	0.056
Beech tree	13381.98	908.92	0.068

Table 3. Values of dynamic mechanical properties for the three types of wood (walnut, eucalyptus, beech tree)

3.2. Structural analysis

In Figure 1 and 2, the AutoCad design of 'anakarí'and 'skortsámpouno' may be seen. In the case of 'skortsámpouno', only the blow pipe has been designed, because the bag plays the role to maintain the air in the instrument; is does produce sound.

The meshing method in FEM has been used to numerically study 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 during processing.

During modeling, the selection of the type of elements that are taken into consideration was based on the fact, that the bearing structure of the instrument is a thin wall structure with a proportionally small thickness compared to the main dimension, having both membrane stiffness and flexure. To this end, shell elements are preferred over the volume elements in the following cases:

- Considering ‘h’ as the thickness of the structure and ‘L’ as the standard length, the ‘h/L’ ratio is indicative of the type of element to be selected for the analysis. When the h / L ratio is high, shear deformation is of major importance and therefore volume data is used. On the other hand, for small h/L ratio, cross-shear deformation is considered negligible and shell elements are the most appropriate choice.
- Shell elements can efficiently approach curved surfaces.
- Shell elements are less demanding in terms of resolution time
- Shell elements are less susceptible to negative Jacobian errors that may occur when using thin volume elements

A total of 23,286 shell elements with 5 mm thickness were used to model the construction.

Two types of materials were selected for the analysis: walnut and eucalyptus. These materials are considered orthotropic, having different and independent properties in the three transverse plane directions. The longitudinal direction (longitudinal-1) is parallel to the fiber direction, the tangential-2 perpendicular to the fiber direction and the radial-3 perpendicular to the tangential. The properties of the two materials are summarized in the table below:

Property	Walnut	Eucalyptus
Elasticity Modulus (MPa), E_{11}	9800	12000
Elasticity Modulus (MPa), E_{22}	548.8	516
Poisson ratio, v_{12}	0.632	0.467
Shear Modulus (MPa), G_{12}	606.7	732
Shear Modulus (MPa), G_{23}	205.8	36
Shear Modulus (MPa), G_{13}	833	768
Density (kg/m^3), ρ	610	470

Table 4. Properties of the two materials used in FEA.

For the analysis of frequencies, a theory has been applied, according to which the dynamic response of a finite element system is mathematically expressed by the following equation:

$$[M]\ddot{X} + [K]X = 0 \qquad (1)$$

Where [M] is the mass, [K] the stiffness and X is the vector indicating the degrees of freedom node of the system.

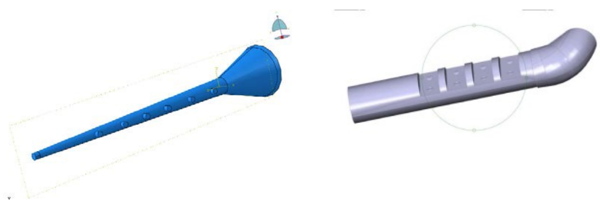
Considering solutions of the form $\mathbf{X(t)} = \boldsymbol{\varphi}\mathbf{sin}(\boldsymbol{\omega}\mathbf{t} + \boldsymbol{\varphi})$ we have the following equation:

$$([K] - \omega^2[M]) * \varphi = 0 \qquad (2)$$

According this, the frequencies characterizing the system are derived:

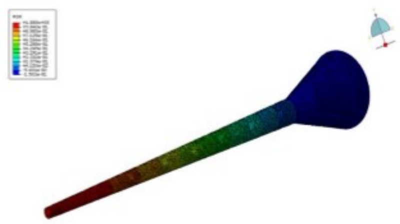
$$det([K] - \omega^2[M]) = 0 \qquad (3)$$

Equation (3) is solved numerically by the Lanzcos method. Table 5 summarizes the resulting frequencies for the two types of materials.



(a) (b)

Figure 1. Design of (a) ‘anakari’ and (b) ‘skortsámpouno’ in AutoCad.



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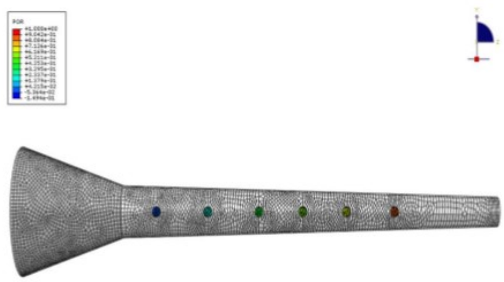

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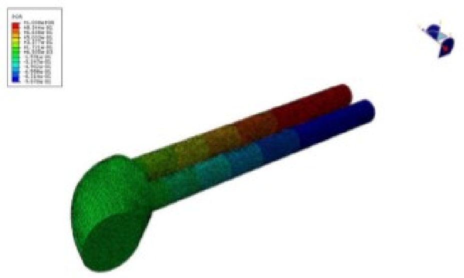


(c)

Figure 2. FEM analysis of: (a) the air column, (b) Natural frequencies in ‘anakarí’ and (c) Vibrations in ‘skortsámpouno’.

Frequency (Hz)	Walnut	Spruce
1st	838.84	670.55
2nd	897.01	716.04
3rd	1760.78	1411.64
4th	1955.48	1576.83
5th	2025.56	1633.24

Table 5. Frequencies of the musical system made of walnut and spruce.

3.3. Water absorption

Some of the tested wood specimens that have been immersed in water, with parallel or perpendicular fibers in relation to the longitudinal axis may are depicted in Figure 3. A diagram of water absorption vs immersion time can be seen in Figure 4.

Figure 3. Wood specimens with parallel (P1, P2) and perpendicular (S3, S4) fibers in relation to the longitudinal axis.

The highest water uptake has been detected in the beech tree, for specimens with fibers in the longitudinal direction, followed by the specimen of the beech tree with fibers on the transverse direction. On the other hand, in the case of the eucalyptus specimens the phenomenon was inversed. The opposite behavior between the two types of wood is attributed to their internal structure that involves different mechanisms of water absorption.

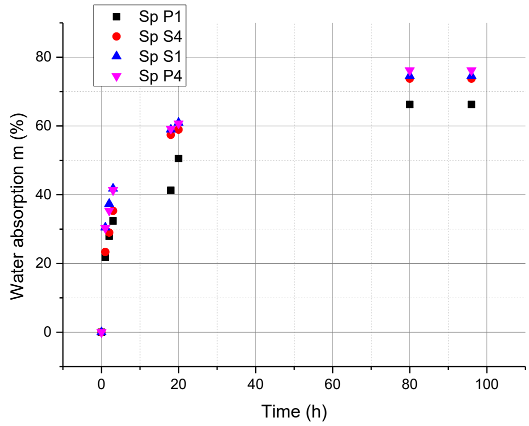


Figure 4. Water absorption of different specimens in time.

3.4. Musical instruments manufacturing

The two wind instruments, ‘anakarí and ‘skortsámpouno’ were manufactured. The constructed models are replicaes based on original instruments forming part of the Kefalonian musical tradition. For the manufacturing of the bagpipe of the ‘skortsámpouno’ in particular, the procedure has been difficult in what concerns 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. In Kefalonia, the ‘skortsámpouno’ players have always been the constructors of their instrument; in this case specialized knowledge is not required. Therefore, the construction of the instrument benefits from the empirical knowledge that has passed down from generation to generation. This type of musical instrument is common to traditional pastoral societies where the use of materials for construction comes from nature, whether fauna or flora of the Kefalonia region.

a. The construction of ‘anakarí’ & ‘zournás’

Eucalyptus wood was used for the construction of the ‘anakari’, while the ‘zournás’ was built from walnut. A modern ‘anakarí’ was also 3D printed with PLA plastic. The main parts of the ‘anakarí’, including the ‘zournás’ are listed below:

Zournás:

This is the main part of the ‘anakarí’. It is a conical tube that ends in the bell which, in combination with the double reed, is responsible for pronounced and permeable sound. ‘Anakarí’ displays 6 holes, ‘zournás’ displays 7 (+ 1 holes at the bottom of its bell) while similar instruments attested across Europe or in the wider

Mediterannean area may display a somewhat smaller or bigger number thereof (e.g. the Armenian or the Turkish 'zournás'). These extra holes are never pressed and remain open, but they have little impact on the instrument's tone and sound quality. The holes are circularly mounted on the bell and their number and position depend on the manufacturer. The hole made on the back of 'zournás' is called by manufacturers 'soul'. Its differentiation from the front holes lies in that with its opening and closing, it shifts tonal height in relation to other given notes, within a certain period of time. When opened, the instrument plays at its highest tones.

***Kléftis or the 'thief'*:**

'Kléftis' (literally the 'thief') as named on the island of Kefalonia, is the detachable part of 'anakarí' and may have divergent dimensions, depending on the length of 'anakarí'. 'Thief' must be well installed so that it doesn't allow air to go out during blowing.

'Kanéli':

"kaneli" is the thin, cylindrical tube - usually of 2 different diameters welded at the upper end of the instrument where the double reed ('tsampoúna') is tied up with a resistant thread. Its construction material is usually copper or other cylindrical piece of metal, allowing for an easy change of its conical shape. When the double reed blows, the two parts vibrate and produce sound. The dimensions of the components of the 'anakarí' are playing an important role in the type and quality of the produced sound. A smaller 'anakarí' should have a smaller reed while a bigger one, a bigger reed. the constructive material of the reed plays also an important role in the quality of the produced sound. The plastic reed is stiffer comparing to the traditional cane, which results in a reduced number of harmonics but, on the other hand in being more resistant. Another parameter worth noting is the cummulation of saliva in the reed, which constitutes an impediment for the production of a clear sound. Musicians overcome this problem by using a supplementary sugar cane reed which absorbs a large amount of fluid that normally enters the instrument while playing. Alternatively, the 'kaneli' can be removed and cleaned periodically.

b. **The construction of 'skortsámpouno'**

The most important part of 'skortsámpouno' is the sounds generator (reeds) for which, beyond the right choice of the materials, good knowledge of technical details is also necessary. The sound generator consists of a grooved base, and two pipes (made of sugar cane) mounted in the base. The pipes play an important role in the production of a a good quality of sound which is a result of the side holes, similarly as in the woodwind instruments. The use of two pipes allows one to play the main tune while the other operates concurrently (drone, ruchilo, ison); both play always at the same time. Empirically and following tradition, manufacturers have created five holes in the two chanter pipes. Depending on the music of the region, the cane pipe may have a different number of holes, e.g. 1, 3 or 5. The most common number of holes is five. The grooved base results in a hopper which can be made as an extension of the base itself or as prolongation using animal horns. The bull horn is most popularily used, as it has the most desirable shape. Finally, the blow pipe is made of wood or bone. Admittedly, material variations are always related to the availability of the area. It should be noted that the length of the mouthpiece varies according to the preference of the performer. Due to the complexity of the manufacturing procedures and the limited length of the manuscript, further details will be reported in a complementary study. Photos of the two manufactured 'anakarí' made of eucalyptus forrowing traditional methods vs. one made of PLA using a modern technology (3D printing) may be seen in Figure 5, while photos of the manufactured 'skortsámpouno' can be observed in Figure 6.

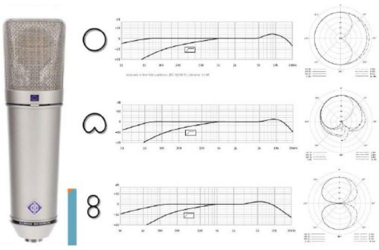
1.1 **(a)**

1.2 **(b)**

Figure 5. (**a**) Eucalyptus 'Anakari', (**b**) PLA 'Anakari'

3.5. Acoustic measurements

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 7(a) shows the characteristic frequency of the microphone, as well as its polar diagram. Figure 7(b) illustrates the recording of the waves produced by the ’anakarí’ made of eucalyptus In Figure 8a the acoustic behavior (processed with BIAS software) of the ‘anakarí’ made of eucalyptus, the ‘anakarí’ made of PLA, and the‘zournás’ made of walnut is shown while in Figure 8b, the same diagram for ‘skortsámpouno’ is shown.



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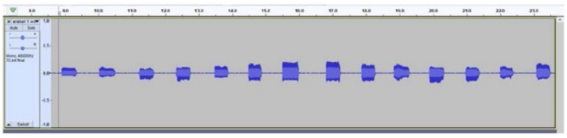

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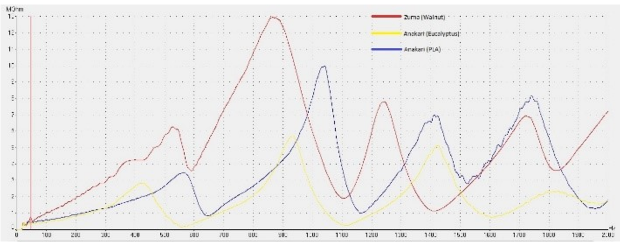
Figure 7. Diagram showing: (a) Frequencies of the microphone Neumann U87 and (b) ‘Anakarí’ recording and processing with Audacity system.



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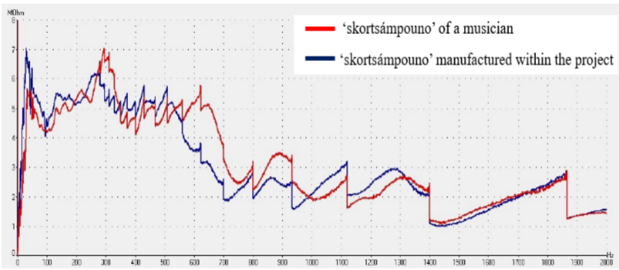

(b)

Figure 8. Measurement of the acoustic impedance of: **(a)** the two manufactured ’anakarí’ and ‘zournás’ and **(b)** the manufactured ‘skortsámpouno’ and the one belonging to a local band.

The detailed description of all manufacturing steps is quite complex and does not fall within the purposes of this paper.

4. CONCLUSION

In this paper the mechanical properties of a number of 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’. Among the several types of wood, the walnut, the eucalyptus and the beech tree were chosen as more appropriate for the specific application, since they display high elasticity modulus and tensile strength good dynamic mechanical behavior.

Moreover, contrastive investigation of the water absorption of the wood with parallel and perpendicular fibers in relation to the length of the specimens, revealed that the highest water uptake is detected in the beech tree, for specimens with fibers in the longitudinal direction, followed by the specimen of the beech tree with fibers on the transverse direction. On the other hand, in the case of the eucalyptus specimens the phenomenon was inversed.

The anakari made of eucalyptus and the 3D printed made of PLA were constructed based on the same (Autocad) blueprint. Walnut zurna, on the other hand, has a slight difference in its dimensions compared to the other two. The ‘skortsampouno’ manufactured within the project and the musician’s one recorded during this study, showed almost identical acoustic impedance, while the two anakaris and the zurna, show divergence in their acoustic impedance. The sound generator (tsampounas) of the two ‘skortsampouna’ are dimensionally alike and are made of the same material (walmut), while ‘anakari’ and zurna are made of different materials.

During the acoustic study of the afore mentioned musical instruments, processing of the recorded audio files, revealed that the two sets of ‘anakari’ and ‘skortsampouno’ sound almost the same. The FFT charts showed slight differences in eigenfrequencies for the same note by the same performer each time.

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