

## ACOUSTIC PROPERTIES IN ARIZONA CYPRESS LOGS: A TOOL TO SELECT WOOD FOR SOUNDING BOARD

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In this study, variation in acoustic properties of Arizona cypress wood was monitored from pith to bark as affected by tapering of the growth ring width. Specific modulus of elasticity, acoustic coefficient, damping, and acoustic conversion efficiency were calculated. It was shown that the outer parts of the stem, close to the bark containing narrower growth rings, exhibited lower damping due to internal friction and higher sound radiation. Our finding theoretically justified the luthier craftsmen's traditional preference toward timbers with narrow growth rings to make sounding boards in musical instruments.

*Keywords:* Acoustic properties; Arizona cypress; Damping; Modulus of elasticity; Pith to bark; Variation

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### INTRODUCTION

The process of selecting appropriate quarter-sawn timber to make a sounding board for any resonator is often delicate and difficult, even for an experienced professional luthier. However, selection can be assisted by employing a suitable acoustical description, which may be available to help the luthier to identify the pith-to-bark variation of acoustic properties, utilizing a nondestructive procedure. In an acoustic procedure, when a sound wave reaches the wood, part of its acoustic energy is reflected, and the other part penetrates into the wood mass. However, as wood vibrates, the initial sound is either intensified or partially or totally absorbed. Similar phenomena happen when wood is used in any resonator (Tsoumis 1991).

In general, when wood is used as a resonator in stringed musical instruments, features such as its modulus of elasticity and density will receive higher value and attention, but qualities such as straight grain, quarter-sawn, homogenous structure, growth rings with optimum width of 2 mm, age (130 to 150 years), log diameters of 400 millimeters or larger, and last but not least the absence of compression wood should not be ignored (Tsoumis 1991; Bucur 2006). Among all, the specific modulus of elasticity, the acoustic coefficient, and the speed of sound propagation are considered as being critical and essential for the musical instrument industry (Krzysik 1967; Tsoumis 1991; Barlow 1997; Wegst 2006; Yoshikawa 2007).

In the equations that follow  $E_{sp}$  is the specific modulus of elasticity ( $\text{Pa}\cdot\text{m}^3/\text{kg}$ ) indicating the square value of speed ( $V$ ) of sound propagation (m/s);  $K$  is the acoustic coefficient (sound radiation coefficient);  $E$  is the longitudinal modulus of elasticity (Pa), and  $\rho$  is the air-dried density ( $\text{kg}/\text{m}^3$ ). Wood density, modulus of elasticity, moisture

content, and temperature can affect the magnitude of acoustic coefficients (Tsoumis 1991) and must be kept constant at specified standard values during the experiments.

$$E_{sp} = \frac{E}{\rho}, \quad V = \sqrt{\frac{E}{\rho}} \quad (1)$$

$$K = \sqrt{\frac{E}{\rho^3}} \quad (2)$$

Only part of the acoustic energy that enters the mass may be absorbed due to repeated refractions of sound waves. Friction between the molecules in the bulk of the wood, which is initiated by sound, causes the variation and converts the acoustic energy to thermal energy (Tsoumis 1991). The sound waves absorbed by wood are subject to gradual damping due to a phenomenon called vibration decay. Another part of acoustic energy is dissipated by radiation to the atmosphere or by wood internal friction.

Wood species, moisture content, direction of vibration (i.e. longitudinal, transverse, torsional), and mode of vibration initiates variations in damping (Tsoumis 1991). Sound radiation is largely dependent upon the magnitude of the acoustic coefficient, which has occasionally been called sound radiation coefficient (Wegst 2006; Yoshikawa 2007; Brémaud 2008). In musical instruments (e.g. sounding boards of guitars or violins), relatively lower damping due to wood internal friction and absolutely higher sound radiation coefficient is desirable. Vibration damping ( $\tan \delta$ ) due to internal friction in a temporal field is calculated from logarithmic decrement,  $\lambda$  (Bodig and Jayne 1982; Bremaud 2008; Roohnia et al. 2011).

$$\tan \delta = \frac{\lambda}{\pi} \quad (3)$$

By combining the damping and acoustic coefficients, a new indicator called the Acoustic Conversion Efficiency (ACE), Eq. 4, is derived (Aizawa 1998; Obataya 2000; Yano 1992; Rujinirun 2005):

$$ACE = \frac{K}{\tan \delta} \quad (4)$$

This new parameter is a useful measure when both the internal friction and sound radiation coefficient are important, and it is usually used to evaluate the acoustical priority of wood, e.g. in sounding boards for musical instruments.

Acoustical properties of wood have been reported relative to musical instruments, with consideration of dynamic mechanical evaluations, the viscoelastic properties of wood used for musical instruments (Aoki and Yamada 1973), and the importance of high specific modulus of elasticity and low  $\tan \delta$  values of wood for sounding board of pianos,

guitars, and violins (Norimoto 1982). An excellent correlation between  $\tan\delta E_{sp}$  and  $E_{sp}$  of 25 softwood species was observed, and based on that data it was concluded that “the suitability of wood for musical instruments can be evaluated by specific modulus of elasticity” (Ono and Norimoto 1983). The impact of annual ring widths on structural and vibration properties of wood was identified, showing that variation in annual ring width and latewood content causes strong anisotropy and shear in radial vibration (Yoshitaka 1997). Shen (2006) introduced wood with proper anisotropy, fine toughness, and weak shear in longitudinal and radial vibration as being suitable for musical instrument industries. Matsunaga et al. (1996) and Matsunaga and Minato (1998) identified both physical and mechanical properties required for material to be used for violin bow. Two acoustical indicators, the relative acoustic conversion efficiency and the anisotropy of hundred spruce wood specimens used for sounding boards, were both measured, and the results revealed the effects of chemical treatment on these indicators, both experimentally and theoretically (Obataya 2000). It was suggested that these parameters cannot be improved simultaneously by any chemical treatment. Rujinirun et al. (2005) determined the important acoustic properties of wood for making Thai xylophone bars and the resonator box. Consequently, they tried to apply some chemical treatments to modify the acoustical properties of the wood. Acoustic conversion efficiency was used as an important acoustical property in their study. Shen et al. (2005) showed that wood with an even growth ring width exhibits good vibration character, which helps to explain the effect of growth ring variations on the vibration property of wood used to make musical instruments. Wegst (2006) described the most important acoustic properties of wood and their impacts on a variety of musical instruments, including their acoustical coefficient (radiation coefficient) and damping coefficient (internal friction). Spycher et al. (2008) assessed the importance of the wood quality, including density, modulus of elasticity, sound velocity, acoustic coefficient, acoustic conversion efficiency, and loudness index in a musical instrument. Specific modulus of elasticity, damping, and acoustic conversion efficiency were also taken into account as important acoustical properties of wood in musical instruments by Sedik et al. (2010). Extractives of muirapiranga (*Brosimum sp.*) and its effects on the vibrational properties of wood were investigated, and suitable extractives to impregnate other woods and modify the acoustical properties of resonance woods were selected (Minato et al. 2010). Bremaud et al. (2010) studied the effect of extractives on vibrational properties of African padauk, taking into account the specific modulus of elasticity and damping.

In this study, the pith to bark variation of acoustical properties was examined in Arizona Cypress lumber, selecting the samples from four locations to find out the justification behind the preference of luthier’s selection of the lumbers with narrower annual growth rings in making the musical instruments sounding boards. This article investigates new highlights beyond those considered in previous published articles in justification of acoustical anisotropy in different locations from pith to bark of Arizona Cypress logs in musical instruments. Different methodologies and instrumentation were applied as reported by Roohnia et al. (2011). *Cupressus arizonica*, which is an exotic tree adapted successfully in Iran, which is considered here, may be regarded as a potential source of wood for the musical instruments industry due to its proper density.

## MATERIALS

Arizona cypress lumber pieces used in this study were harvested from a plantation 30 km west of Tehran, Iran. Three 38 years-old trees were selected, and the sampling locations were marked in the southwest side at breast height of the clear, defect-, and reaction-wood-free stem. Four sampling locations from pith to bark were named as the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, and 4<sup>th</sup> quarters, respectively (Fig. 1). For each clear log, four contiguous thin bars were cut from each sampling location, dimension of 14×2×150 mm (R×T×L), then conditioned at 65% relative humidity and 22°C for two weeks starting from the green condition. As the sound boards are always produced from quarter-sawn timbers, the specimens for this study were also quarter-sawn cut (Fig. 2).

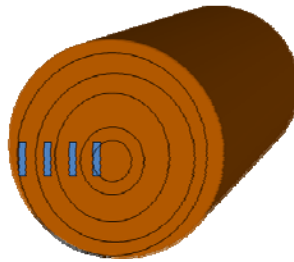


Fig. 1. Sampling locations from pith (1<sup>st</sup> location) to the bark (4<sup>th</sup> location)

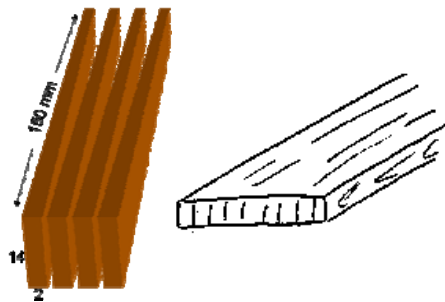


Fig. 2. Quarter sawn specimens in the forced vibration test

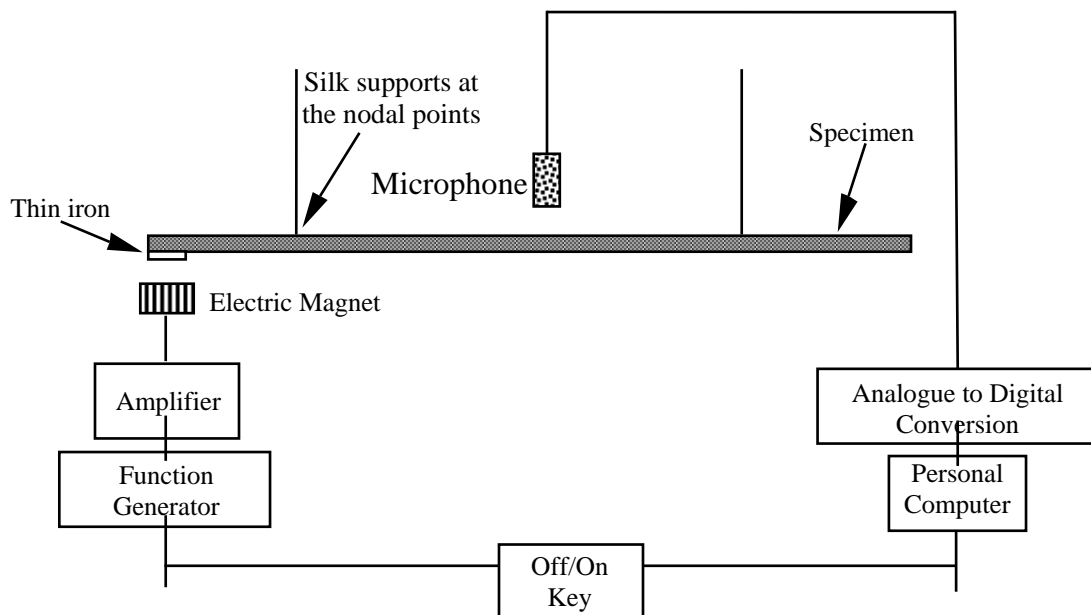
## EXPERIMENTAL

The longitudinal modulus of elasticity, acoustic coefficient, and specific modulus were determined using non-contact forced vibration setup in a free-free bar as introduced by Obataya (2000) and Bremaud (2006) (Fig. 3) followed by the Fast Fourier Transform analysis to reach the modal frequencies (sampling rate = 44100 Hz). ASTM C1548-02 standard test for flexural vibration of a free-free bar were used to derive the dynamic longitudinal modulus from the fundamental frequency, as given in Eq. 5 and Eq. 6.

$$E_d = \left( \frac{mf_f^2}{b} \right) \left( \frac{L^3}{h^3} \right) T_1 \quad (5)$$

$$T_1 = \left( 1.000 + 6.585 \left( \frac{h}{L} \right)^2 \right) \quad (6)$$

In these equations  $E_d$  is longitudinal dynamic modulus (Pa),  $f_f$  is the fundamental frequency of flexural vibration, and  $m$ ,  $b$ ,  $h$ , and  $L$  are the mass (kg), width, height, and length (m) of the specimen, respectively.  $T_1$  is the height to length correction factor and is appropriate for sufficiently long beams ( $L/h > 20$ ) similar to the specimens in this study. This setup, which was reconstructed in accordance with a previous publication (Bremaud 2006), as well as its diverse programming, software, and accessories have been introduced as the "Vibra-Force" ndt system (Roohnia et al. 2010), resembling the forced vibration method.



**Fig. 3.** Schematic setup of non-contact forced vibration of a free-free bar

Using four sampling locations in any log, the pith-to-bark variation of the acoustic properties was monitored in terms of correlation between damping due to internal friction and sound radiation of the logs. Statistical analysis was used to find the effects of four sampling locations with different ring width on acoustic properties such as acoustic coefficient, acoustic conversion efficiency, specific modulus of elasticity, and damping factor, applying analyses of variances (ANOVA). In cases where differences between the averages were observed, Duncan multi-comparison tests were used for ranking the averages considering the homogeneity in three Arizona cypress logs and in four similar specimens obtained from each sampling location.

RESULTS AND DISCUSSION

The pith to bark variation of acoustical properties due to ring width tapering in Arizona cypress is plotted in Figs. 4 to 7. For each log, 12 replications and four similar contiguous specimens from each sampling location were evaluated. The effect of four neighbouring samples in three identical trees (totally 12 replications) on the acoustic properties was not statistically significant, which indicates that the pith to bark variations in acoustic properties were due to the effects of sampling locations relative to the tree diameter.

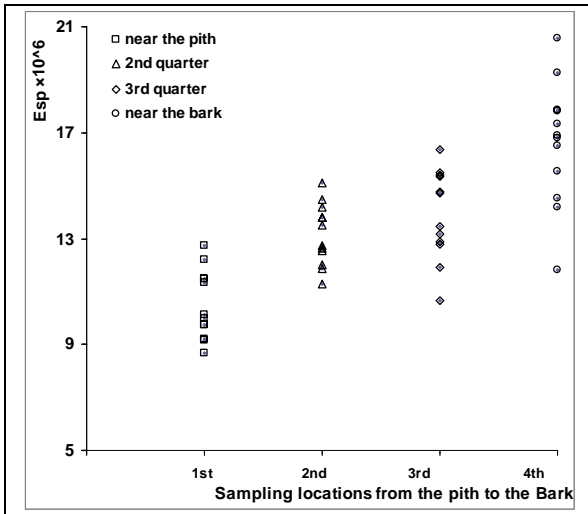


Fig. 4. Pith to bark variation of longitudinal specific modulus of elasticity (Pa.m<sup>3</sup>/Kg) from four locations in three Arizona cypress timbers

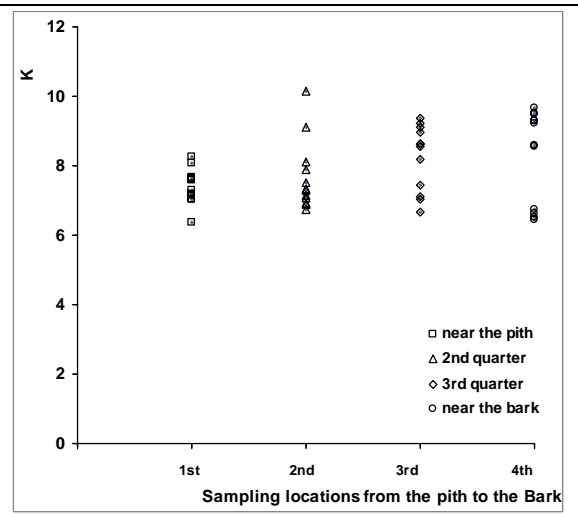


Fig. 5. Pith to bark variation of Acoustic coefficient (m<sup>4</sup>/s·Kg) from four locations in three Arizona cypress timbers

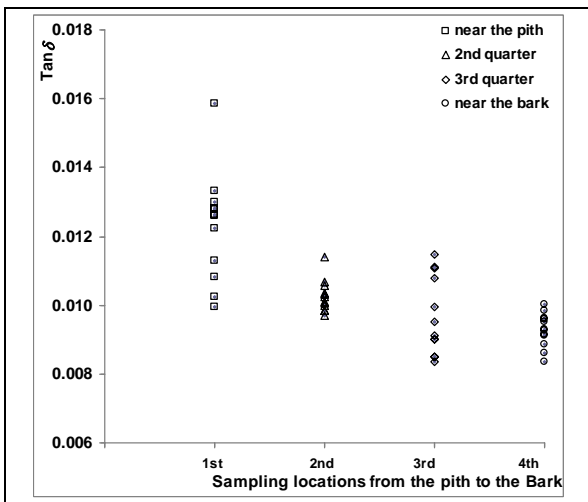


Fig. 6. Pith to bark variation in damping (tan δ) from four locations in three Arizona cypress timbers

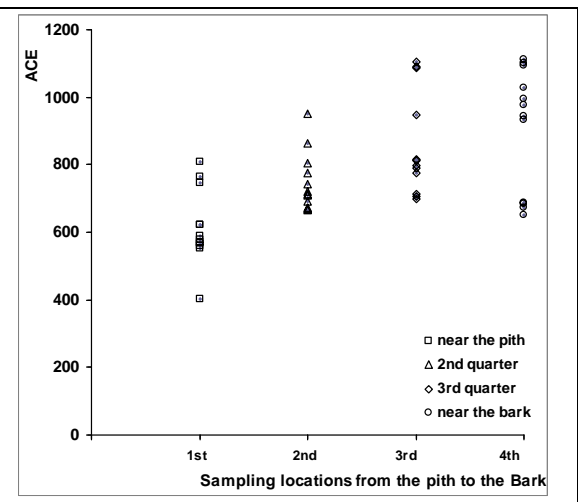


Fig. 7. Pith to bark variation in acoustic conversion efficiency from four locations in three Arizona cypress timbers

The variations in specific modulus of elasticity across the tree diameter are shown in Fig. 4, demonstrating that the highest value corresponded with the 4<sup>th</sup> quarter, close to the bark. The effects of sampling location on the specific modulus of elasticity were statistically significant at the 0.01 level of probability (Table 1 and 2). However, in the direction from pith to bark, the specific modulus of elasticity increased, and the 2<sup>nd</sup> and the 3<sup>rd</sup> quarter values were almost identical in terms of specific modulus.

**Table 1.** Analysis of Variances for the Pith-to-Bark Variation in Acoustic Properties in Four Sampling Locations

Property	Source	df	F	p value
<i>Specific modulus of elasticity</i> (Pa.m <sup>3</sup> /Kg)	Between Groups	3	26.411	< 0.001**
	Within Groups	44		
<i>Acoustic Coefficient</i> (m <sup>4</sup> /s.Kg)	Between Groups	3	2.398	0.081
	Within Groups	44		
<i>Tanδ</i>	Between Groups	3	20.000	< 0.001**
	Within Groups	44		
<i>Acoustic Conversion Efficiency</i>	Between Groups	3	10.599	< 0.001**
	Within Groups	44		
<i>Density</i> (gr/cm <sup>3</sup> )	Between Groups	3	2.965	0.042*
	Within Groups	44		

\* Significant at the 0.05 level

\*\* Significant at the 0.01 level

**Table 2.** Duncan<sup>a</sup> Multi-Comparison Tests for Specific Modulus of Elasticity (Pa.m<sup>3</sup>/Kg)

Sampling locations from pith to bark	Ring width mm	Subset for alpha = 0.05		
		1	2	3
1	6.66	10,485,805		
2	5.43		13,158,039	
3	2.67		13,909,715	
4	2.28			16,594,093

Means for groups in homogeneous subsets are displayed.

a Uses harmonic mean sample size = 12

Figure 5 indicates that significant differences in acoustic coefficients did not exist in the four sampling locations (Table 1). However weak acoustic properties of the 1<sup>st</sup> quarter, close to the pith, were detected (Fig. 6), because of the higher damping (internal friction) in this location. Notable reduction in damping was observed as the sampling location was varied from pith to bark (Tables 1 and 3).

**Table 3.** Duncan<sup>a</sup> Multiple Comparison Tests of  $\text{Tan}\delta$ 

Sampling locations from pith to bark	Ring width mm	Subset for alpha = 0.05		
		1	2	3
1	6.66			0.0093
2	5.43		0.0097	0.0097
3	2.67		0.0103	
4	2.28	0.0123		

Means for groups in homogeneous subsets are displayed.

a Uses harmonic mean sample size = 12

The concept of acoustic conversion efficiency, (*ACE*) in terms of variation in acoustical properties is displayed in Fig. 7. The *ACE* is regarded as an intended acoustical property (Eq. 4) due to combining internal friction to the sound radiation coefficient; it appears to be a better criterion for the suitability of wood in terms of its acoustic performance. Statistical analysis confirmed that the lowest *ACE*s were measured from the first quarter samples close to pith. The 2<sup>nd</sup> and the 3<sup>rd</sup> quarters seemed to behave similarly, and the 4<sup>th</sup> quarter showed the highest *ACE* values (Tables 1 and 4). Though Arizona cypress wood at the defined age in this study is not recommended as the best resonance wood of sounding boards, the observed variations in acoustic properties in different cross directions might lead to promising results in similar resonance woods or in older specimens.

**Table 4.** Duncan<sup>a</sup> Multi-Comparison Tests for Acoustic Conversion Efficiency

Sampling locations from pith to bark	Ring width mm	Subset for alpha = 0.05		
		1	2	3
1	6.66	615		
2	5.43		748	
3	2.67		862	862
4	2.28			907

Means for groups in homogeneous subsets are displayed.

a Uses harmonic mean sample size = 12

**Table 5.** Duncan<sup>a</sup> Multi-Comparison Tests for Density ( $\text{g/cm}^3$ )

Sampling locations from pith to bark	Ring width mm	Subset for alpha = 0.05	
		1	2
1	6.66	0.437	
2	5.43	0.458	0.458
3	2.67	0.477	0.477
4	2.28		0.496

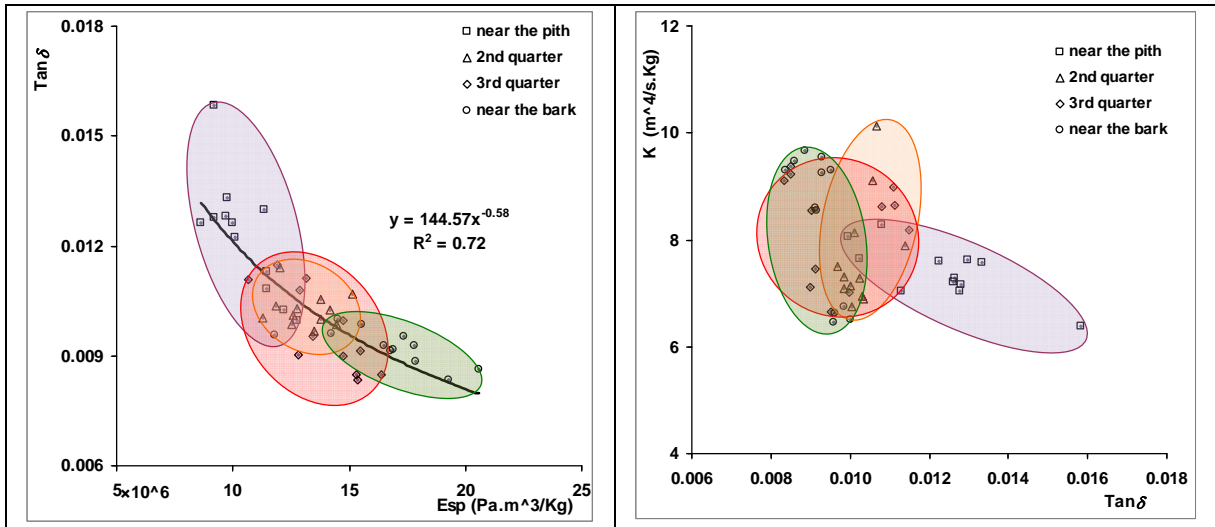
Means for groups in homogeneous subsets are displayed.

a Uses harmonic mean sample size = 12



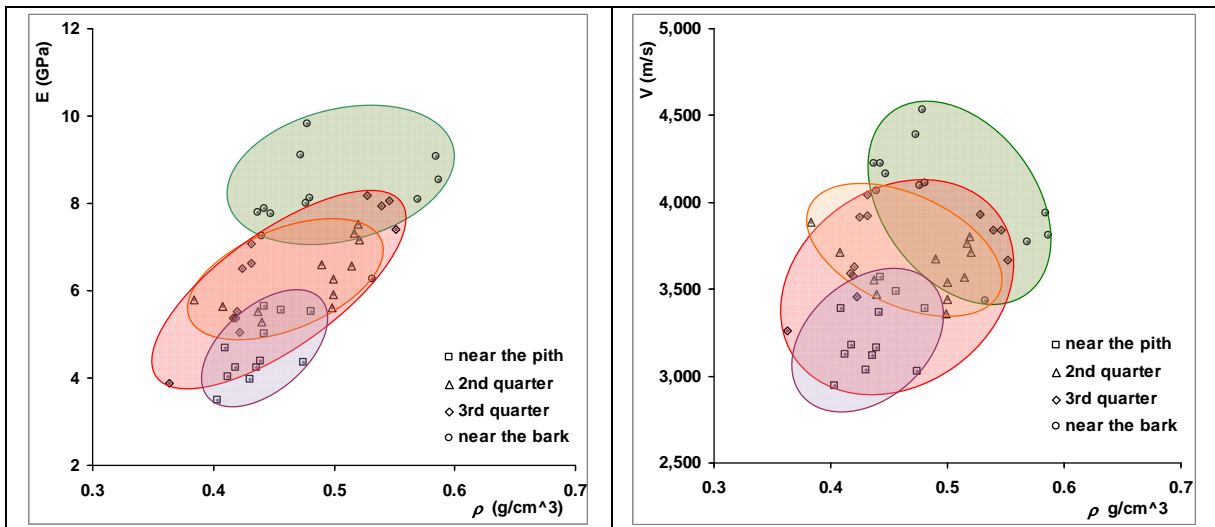
A comparison of the acoustical properties of Arizona cypress wood with the criteria and qualifications reported in the literature (Wegst 2006) for sounding boards of stringed musical instruments is shown in Figs. 8 to 13. Figure 8 illustrates the correlation coefficients between damping (internal friction) and specific modulus of elasticity. As observed in most of specimens, wood samples obtained from inner parts exhibited higher damping and lower specific modulus of elasticity. However samples from the outer quarters rehabilitated these undesirable properties, which helps us to acknowledge that wood from the 4<sup>th</sup> quarter might be an appropriate material for sounding board (Norimoto 1982). Figure 9 reveals that damping due to internal friction and sound radiation coefficient of the Arizona cypress wood were not correlated, which might properly demonstrate the weakness of the inner parts in the 1<sup>st</sup> quarter samples for acoustic performance in comparison with the outer parts. The outer parts close to bark exhibited lower damping, to support the fact that in Arizona cypress lumbers, the 4<sup>th</sup> quarter close to bark possesses lower internal friction with relatively proper sound radiation (at least some of them). However, based on the quality criteria introduced by Wegst (2006), most of the specimens from this location show the potential to qualify for sounding board. Modulus of elasticity and density are almost linearly correlated, and the 4<sup>th</sup> quarter samples exhibited the greater modulus of elasticity (Fig. 10). The plot of speed of sound propagation parallel to the grain (almost equal to the root of longitudinal specific modulus of elasticity) against density demonstrates that the sound speed in most of the specimens from the outer quarter at identical density with the inner quarters was higher (Fig. 11). This is also another indication of the suitability of some of the specimens from 4<sup>th</sup> quarter for sounding board manufacture based on the criteria provided by Wegst (2006) and Spycher et al. (2008). The outer quarter showed relatively higher modulus of elasticity and lower damping (Fig. 12), and if there is any qualified specimen for sounding boards, it can be found in the 4<sup>th</sup> quarter, representing the higher acoustic conversion efficiency (Fig. 13). This demonstrates that the specimens with higher acoustic coefficient and lower damping (internal friction) are not visually selected specimens from the outer quarter of the stem lead to a similar result as an important byproduct in terms of sampling locations. In comparison with the previous article, the present research that was done on similar but separate samples, both the modulus of elasticity (ASTM C1548-02) and damping. This finding might be taken into account as reconsiderations to a previous approach in justifying the sound velocity ratio (acoustical anisotropy) in musical instrument industry (Roohnia et al. 2011), which eventually lead to a similar result as an important byproduct in terms of sampling locations. In comparison with the previous article, the present research that was done on similar but separate samples. Both the modulus of elasticity (ASTM C1548-02) and damping factor were evaluated from a single small thin specimen (absolute absence of defects could be visually assured) in a proper replication using the newly reconstructed setup. However there were two different kinds of large and small specimens, adjacent, for modulus of elasticity (in accordance with Timoshenko theory) and damping factor evaluations, respectively, in the previously mentioned approach. Meanwhile, the traditional choices of wood pieces with narrower rings for use in sounding boards were confirmed scientifically here due to their priority in damping and acoustical conversion efficiency. The growth ring variations across four sampling locations are shown in Tables 2 to 5. The specimens

with narrower growth rings exhibit lower damping, higher modulus of elasticity, and higher speed of sound (higher specific modulus of elasticity), which makes such samples suitable for sounding board manufacture.



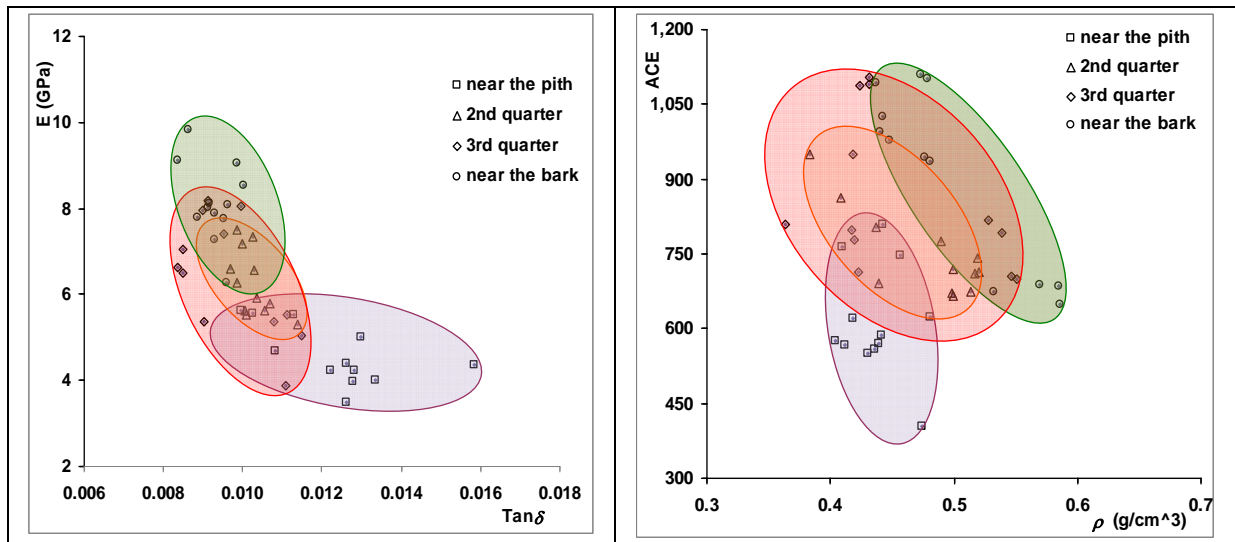
**Fig. 8.** Damping vs. specific modulus of elasticity. Circles are for better recognition of the sampling locations

**Fig. 9.** A material property chart for plotting the acoustic coefficient against tan  $\delta$ .



**Fig. 10.** A material property chart for plotting longitudinal modulus of elasticity, E, against density

**Fig. 11.** A material property chart for plotting the speed of sound, V, resembling root of specific modulus of elasticity, against density



**Fig. 12.** A material property chart for plotting modulus of elasticity against  $\tan \delta$

**Fig. 13.** A material property chart for plotting The acoustic conversion efficiency against  $\tan \delta$

Luthier craftsmen and wood scientists both have provided a good wealth of information on visual specifications and evidence to help selection of suitable resonance wood. However, only few have been able to acknowledge any unified description or satisfactory justification for such case. Wood as an engineering material usually requires a given strength in acoustical behavior to satisfy the needs of a sounding board to compliment visual characterization. Therefore it is necessary to mention that due to inherent characteristics, there are many uncertainties in visual characterization of wood.

After the acceptance of this article for publication, a reviewer pointed out to the authors that it would be useful to consider the influence of juvenile wood vs. mature wood on the present results. The authors plan to address this and related issues in a future publication.

## CONCLUSIONS

It has been mentioned that a piece of wood with growth rings of less than 2 mm width (Tsoumis 1991; Bucur 2006) is appropriate for making musical instruments sounding board. In this study, we were able to acoustically verify that narrow growth rings close to bark in the 4<sup>th</sup> quarter across the defined sampling locations exhibited lower internal friction, occasionally higher sound radiation, and higher acoustic conversion efficiency. These results provide reasonable engineering verification of the fact that acoustic properties of wood can be a good measure of its applicability for such purposes. There was no significant correlation between damping due to internal friction and sound radiation of the wood under the study. It was proved that the 1<sup>st</sup> quarter close to pith with wider growth rings was the most unfavorable sampling location for a resonator sounding board. Consequently, we can conclude that the qualified specimens for sounding board

are found in 4<sup>th</sup> quarters, representing the higher acoustic conversion efficiency (Wegst 2006).

The relationship between damping due to internal friction and sound radiation is still unknown and requires further work in the field. The research to reach more verification to support lifelong visual or anatomical propositions in acoustic properties of wood, leads to a better understanding in this valuable engineering material.

It can be concluded that visual inspection is not a reliable and efficient methodology to select an appropriate piece of wood to provide acoustical performances required. Even though all of the specimens in the study were selected from sound and clear lumbers, and each sampling location exhibited identical visually graded samples, it was demonstrated that such samples did not show similar acoustical properties. From a repertory of 12 visually selected sound and clear pieces of 4<sup>th</sup> quarter specimens, approximately 6 pieces were qualified as being suitable for sounding boards (Wegst 2006). It is believed that the ring width in visual grading of the wood for the sounding boards is important, but it is not a sufficient criterion by itself. Therefore, cross-checking the acoustical properties, particularly the acoustic conversion efficiency followed by the visual inspection of raw materials is suggested as obligatory in selection of the appropriate wood for sounding boards manufacture.

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