Original Research Article

Acoustic Properties of *Gmelina arborea* Wood

ABSTRACT

G. arborea wood is a preferred choice for making musical instrument in Nigeria. However, its utilization is solely dependent on indigenous knowledge. Meanwhile, for optimum acoustic performance there is need to study acoustic properties of wood. Thus, this work aim to study the acoustic properties of *G.arborea* wood. Three trees of *G. arborea* with 25 ± 2cm in diameter at breast height (DBH) were obtained. From each tree, bolts of 60cm in length were collected axially, and wood sample of $20 \times 20 \times 300\ mm^3$ (R x T x L) were obtained radially from each bolts. The samples were then prepared for testing. Fundamental frequency longitudinal vibration method was used to determine acoustic properties of the wood. Hence, necessary model and equations were used to calculate other acoustic parameters. The fundamental frequency, velocity of sound, longitudinal elastic modulus, specific longitudinal elastic modulus, damping factor, acoustic coefficient (K), sound quality, acoustic conversion efficiency, and impedance obtained in this study were 1095.02 ± 20Hz, 4848.58 ± 77m/s, 9.34 ± 0.35GPa, 23.57 ± 0.74GPa, 0.0039 ± 0.00, 12.30 ± 0.29$m^4kg^{-1}s^{-1}$, 279.64 ± 21.64, 3435.66 ± 278$m^4kg^{-1}s^{-1}$, 1.9119 x 10^6 ± 4.8 x $10^3$$kg/m^2s$ respectively. Meanwhile, no significant differences were recorded for acoustic variables tested axially and radially, except for K. Furthermore, values obtained in this work compared favorably with some known acoustic species. Conclusively, this work was able to conduct a study on some acoustic properties of *Gmelina arborea* wood and thus found G. arborea wood suitable for acoustic purpose. However, selection of wood for acoustic function should be purpose driven.

Keywords: Acoustic, Gmelina arborea, Wood, Sound

1.0 INTRODUCTION

Wood can produce sound (by direct striking) and can amplify or absorb sound waves originating from other bodies. When sound waves of extrinsic origin strike wood, they are partly absorbed and partly reflected, and the wood is set in vibration. For these reasons, it is a unique material for musical instruments and other acoustic applications.

In spite of recent advances in material science, wood remains the preferred construction material for musical instruments worldwide. Some distinguishing features of wood such as light weight, and workability are easily noticed if wood properties is compared with plastic (acrylic), and metal (aluminum). Woods common in musical instruments (strings, woodwinds, and percussions) are typically (with notable exceptions) softwoods, hardwoods and monocots [1]. Sound energy loss as a result of friction is also significantly low in woods due to its lightness and structure. Because of such properties, wood is extensively used in musical instruments [2].

Some wood are acoustic in nature and has the ability to produce sound effect. Because of this unique property, wood is used as a musical instrument as well as in producing a number of musical instruments such as guitar, violin, piano, xylophone and percussion. However, the pitch of sound produced depends on the frequency of vibration [3].

However, poor selection of wood species has hindered optimal performance of wood for acoustic purposes, such as for making musical instrument in Nigeria. A major contributory factor is little or no scientific information about the acoustic properties of choice species, hence trial and error methods, and indigenous knowledge are adopted.

To abort this practice and recommend wood species for optimal acoustic performance, there is need to study the acoustic properties of wood species. Thus, this work aims to study the acoustic properties of *G. arborea* wood.

Gmelina arborea is considered as one of the most widely cultivated and distributed exotic wood species in Nigeria and many people have benefited from the wood.

2.0 MATERIALS AND METHOD

Five trees of *G. arborea* with 25 ± 2cm in diameter at breast height (DBH) were obtained from Gambari Forest Reserve, Nigeria - This is to avoid the influence of site factor or age on results. From each tree, bolts of 60cm in length were collected from the top and base wood, hence, wood samples of $20 \times 20 \times 300\ mm^3$ (R x T x L) were obtained radially (core wood and outer wood) from each bolts using circular machine and planning machine. 10 samples were collected from each portion of the bolts. Thus, a total of 200 wood samples were used in this study. The samples were oven-dried and kept at room temperature and relative humidity for a month prior testing. Figure 1 shows the sample collection procedure.

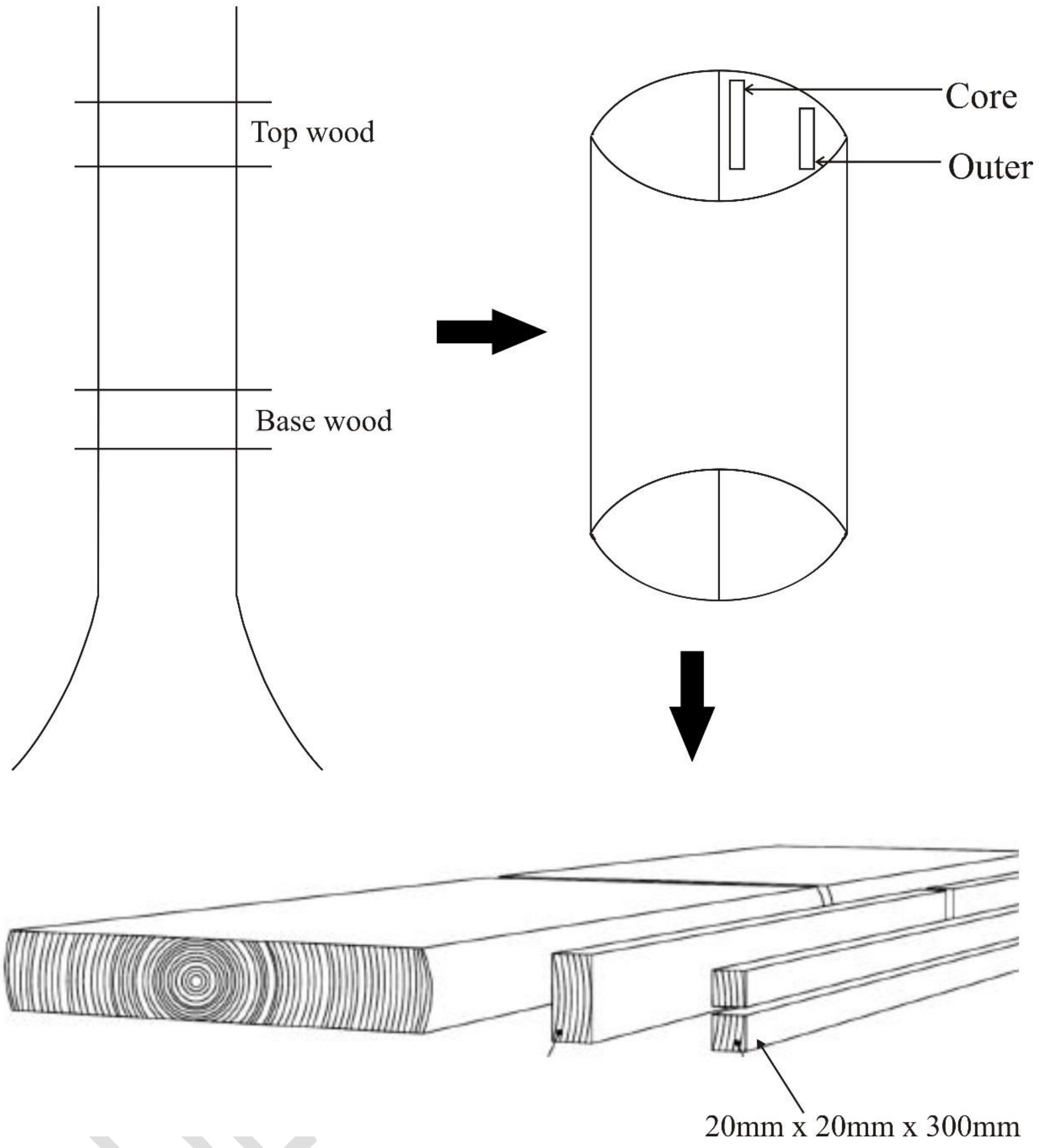

Fig. 1: sample collection positions

2.1 Acoustic property test

Free vibration method - Fundamental Frequency Method

The acoustic property test was conducted according to [4]. This type of acoustic test method is known as the longitudinal vibration method. Each sample was suspended as shown in figure 2; this is done to ensure no external sound is produced during testing. A wooden hammer was used to hit the wood sample from one end while the 1st bending natural frequency (fundamental frequency) and resonance frequency were obtained immediately from the other end using a Fast Fourier Transform (FFT) spectrum analyzer, and the response vibrating sound was recorded in a wave format file using a recording software (Audacity). From the recorded sound, parameters of damping factors were retrieved. Hence, follow-up equations were used to estimate other acoustic properties.

$$\rho = Density = \frac{oven\ dried\ mass}{green\ volume} \qquad (1)$$

Longitudinal modulus of elasticity (E) [5];

$$E = \left(\frac{2f_n}{\gamma_n \pi}\right)^2 \frac{mL^3}{I} \qquad (2)$$

Where m is the specimen weight, f_n is the 1st bending natural (fundamental) frequency, n is the mode number, L is the length of the sample. γ_n is for the first mode 2.267, and *I* is inertia.

$$I = \frac{(bh^3)}{12}$$

Where b is the width and h is the thickness of the specimen

Having obtained dynamic elastic modulus from method 1 and 2, equation 8-15 were used to calculate other selected acoustic parameters. Note that the experiment was conducted in an enclosed place at room temperature having ensured a total silence, and the FFT analyzer showing no sign of sound signal.

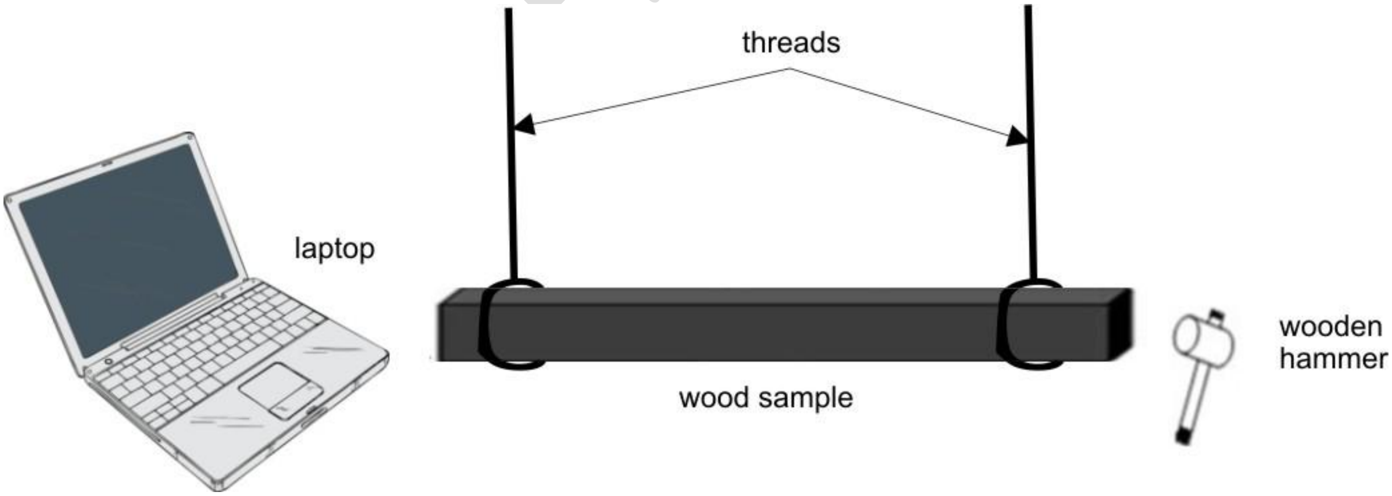

Fig. 2: The set-up of longitudinal free vibration test

Specific longitudinal elastic modulus (Es);

$$Es = \frac{E}{\rho_s} \qquad (3)$$

where $\rho_s = Relative\ Density\ (Specific\ gravity)$

$$\rho_s = \frac{\frac{oven\ dried\ mass}{green\ volume}}{density\ of\ water} \qquad (4)$$

To calculate Acoustic co-efficient of the vibrating body (K) [4];

$$K = \left(\frac{E}{{\rho_s}^3}\right)^{0.5} \qquad (5)$$

$where\ E = longitudinal\ elastic\ modulus, and\ \rho_s = specific\ gravity$

$$Damping\ factor\ due\ to\ internal\ friction\ (tan\delta) = \frac{\lambda'}{\pi} \qquad (6)$$

$where$

$\lambda^1 = logarithmic\ vibrating\ decrement\ factor$ [4]

$$\lambda^1 = \left(\frac{1}{n}\right) ln\left(\frac{X_1}{X_{n+1}}\right) \qquad (7)$$

$where\ n = number\ of\ successive\ peaks,$

$X_1\ and\ X_{n+1}\ are\ the\ first\ and\ (n+1)th\ amplitude\ of\ vibration\ respectively$

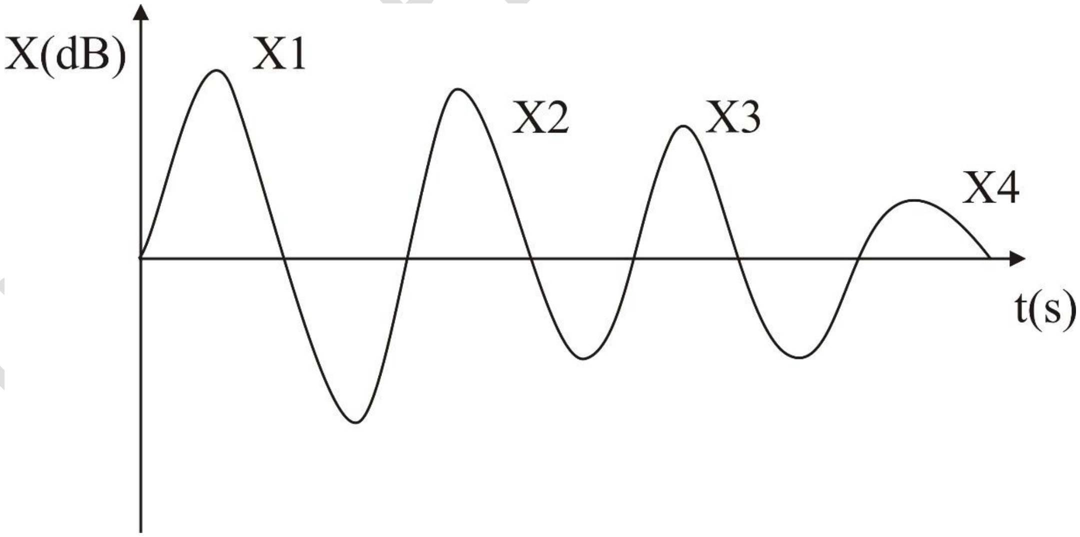

Fig 3. The schematic view of amplitude decrement of the first mode of vibration through time

To calculate sound quality factor (Q) and acoustic conversion efficiency (ACE) [6];

$$Q = \frac{1}{tan\delta} \qquad (8)$$

$$ACE = \frac{K}{tan\delta} \qquad (14)$$

$where\ K\ is\ the\ acoustic\ coefficient\ of\ the\ vibrating\ body$

$$z = c\rho \quad z = impedance, c = velocity \qquad (9)$$

Descriptive statistics and analysis of variance were used to analyze results obtained.

3.0 RESULTS AND DISCUSSION

Axial and radial variation of acoustic properties of *G.arborea* wood were shown in Table 1 and 2 respectively while analysis of variance done was shown in Table 3, and Table 4 shows comparism of acoustic properties of the wood species with other selected wood species. Axially, top wood had values higher than base wood in many of the acoustic properties tested, whereas outer wood had higher value than core wood radially.

3.1 DISCUSSION

Sound frequency of a material is measured by the number of whole cycle of a vibration per second produced as a result of particle disturbance in the travel medium [7]. Therefore, since RF at base wood and core wood of *G.arborea* wood had a higher resonance frequency compared with the top wood and core wood respectively, higher sound pitch is expected provided the FF is constant. On the other hand, FF at top wood and outer wood was higher axially and radially. Thus, this implies that provided resonance frequency remain constant, top wood and outer wood would have the highest pitch of sound. Meaning, top wood as well as outer wood would be expected to best support any musical instrument requiring a high pitch of sound with which it was used to manufacture.

However, Analysis of Variance (ANOVA) done for FF and RF indicated that results obtained axially and radially were not significantly different. For this reason, FF and RF obtained in this study axially and radially are the same, and as such none has performed better than the other.

The velocity of sound which may also be referred to as the speed of sound is defined as the distanced travelled per unit time by a sound wave as it propagates through elastic medium. Therefore, sound velocity is an essential parameter to consider before recommending a material acoustically suitable, especially for making musical instrument. Thus, a higher value of velocity of sound is essential for making a better choice. Although top wood and outer wood had higher values along and across the bole respectively, however analysis of variance shows no significant differences. Therefore these values are assumed the same.

Meanwhile, the mean velocity for *G.arborea* obtained in this study is within estimated range of velocity of sound for wood (3300m/s – 5000m/s) [8]. However, [9] reported 3068.66m/s for this same species. It is thus evident that *G.arborea* wood considered in this study had a higher velocity of sound than [9]. While the variation in values with that of [9] was not investigated in this study, this variation may have resulted due to some site quality factors or age difference.

Also, sound velocity of *G.arborea* wood in this work was higher than *Brachystegia eurycoma* (3712.35m/s) [9], *A. robusta* (3711.46m/s) [10]. In addition, selected wood species reviewed in Table 4 highlighted that values of sound velocity for *G.arborea* was higher than Amboyna wood, Walnut wood, and Bamboo. Inferentially, *G.arborea* can be considered as one of the suitable wood species for acoustic purposes where higher sound velocity is required.

Furthermore, modulus of elasticity influences energy propagation and dissipation throughout a sample material, so, higher E leads to lower loss of vibration energy [11], and since loss of vibration means loss of sound, then a high E should be sourced after for a better acoustic. Therefore, values of E obtained in this study showed that base wood lost a higher vibration energy owing to its lower value of E, and top wood the least loss of vibration energy. Meanwhile, samples tested radially highlighted the outer wood as a better choice owing to its higher value of E.

In the work of [12], mean MOE of *G.arborea* wood was 6.91 GPa, 9.61 GPa, and 10.24 GPa for 18, 28, and 36 years old respectively. These values were relatively the same with what was obtained in this study for the same species, while it was relatively lower when compared with other selected wood species under review; (Afzelia sp. - 12.5GPa, Milletia sp. – 15.8GPa, Bamboo – 11.5GPa, Amboyna wood –

12.5GPa, and Walnut – 8.8 GPa). This pose a limitation to *G.arborea* wood among the committee of wood species that can be selected for acoustic purpose as far as longitudinal elastic modulus is concerned.

On the other hand, [13] reiterated that a high specific modulus of elasticity should ensure sufficient radiation at lower frequencies. Therefore, the need for a high Es is essential. From the result obtained for Es in this study, it can thus be concluded that it is high enough when compared with other selected wood species. Since ANOVA shows no significant difference for E and Es in axially and radially plane, then values obtained are thus the same.

[14] reported that the average dampening factor value of a wood for a good acoustic property is 0.006. Therefore, wood with value ≤ 0.006 are considered to be in the category of a lower dampening material. Since low dampening factor of a material is a required trait for better acoustic performance. Therefore, *G.arborea* wood with the lowest value of dampening factor amongst the wood species compared with it implies that it is the best and most suitable choice.

Furthermore, [15] reported that the more the quality factor of a wood, the lesser its wave dampening. This therefore means that a material with high dampening factor can be associated with a poor acoustic quality. Thus, *G.arborea* wood had a better sound quality.

Acoustic coefficient ‘K’ describes the average amplitude or loudness and it’s also used an indice to estimate ACE. Whereas, ACE represents the peak response of a material to vibration energy, while Z is related to the transmission of vibration from one medium to another [16; 17). Also, [18] and [19] defined ACE as the efficiency with which vibrational energy is converted into sonic energy and that it should be accepted as an overall estimation of acoustic properties.

In comparison, *G.arborea* had an excellent ACE (3365.28 $m^4kg^{-1}s^{-1}$/3435.66 $m^4kg^{-1}s^{-1}$) when compared with other selected wood species (*Afzelia sp.* - 649 $m^4kg^{-1}s^{-1}$, *Instia sp.* - 687 $m^4kg^{-1}s^{-1}$, *Astronium sp.* - 704 $m^4kg^{-1}s^{-1}$, and *millettia sp.* 883 $m^4kg^{-1}s^{-1}$) [5], thereby making it the most suitable for acoustic functions.

Acoustic impedance of a medium is the rate of resistance of a medium to sound flow travelling through it [20]. As such, higher value of Z higher sound reflection and in turn louder sound. So, high value of Z is advantageous. Thus, top wood and outer wood of *G.arborea* is a better choice for acoustic where louder sound is needed.

Inferentially, top wood is better than base wood axially while outer wood is better than core wood. The question is – what characteristics can be attributed to outer wood and top wood? Since outer wood is characterized with sapwood while top wood is characterized with juvenile wood, then, better acoustic performance recorded for outer wood over core wood may be referenced to its higher sapwood contents, while that of top wood associated with its juvenile wood. Acoustically, *G.arborea* wood performed better than other selected wood species compared with it in this study.

Table 1: Axial variation of acoustic properties of *G.arborea* wood

	Top			**Base**			**P. mean**
	Core	Outer	Mean	Core	Outer	Mean	
γ	0.39	0.41	0.40	0.36	0.42	0.39	**0.40**
			± 0.01			± 0.04	**± 0.03**
tan δ	0.005	0.003	0.004	0.004	0.004	0.004	**0.004**
			± 0.001			± 0.001	**± 0.001**
Q	222.08	344.97	283.53	275.28	276.22	275.75	**279.64**
			± 83.16			± 73.61	**± 74.99**
FF (Hz)	1122.47	1130.98	1126.73	1059.46	1067.17	1063.32	**1095.02**
			± 72.92			± 53.35	**± 69.33**
RF Hz)	2170.75	2066.48	2118.62	2350.27	2429.53	2389.90	**2254.26**
			± 336.23			± 128.62	**± 281.03**
E (GPa)	9.52	10.12	9.82	8.47	9.24	8.86	**9.34**
			± 0.93			± 1.35	**± 1.22**
Es (GPa)	24.23	24.67	24.45	23.2	22.2	22.7	**23.58**
			± 2.09			± 2.90	**± 2.58**

K	12.51	12.11	12.31 ± 0.60	13.27	11.29	12.28 ± 1.36	**12.30** **± 1.00**
V (m/s)	4917.69	4964.01	4940.85 ± 209.80	4809.64	4702.99	4756.32 ± 304.62	**4848.58** **± 267.35**
ACE ($m^4kg^{-1}s^{-1}$)	2754.29	4172.93	3463.61 ± 944.38	3650.79	3164.6	3407.70 ± 1071.98	**3435.65** **± 963.63**
Z($x10^6$) ($kgm^{-2}s^{-1}$)	1.93	2.04	1.99 ± 0.11	1.75	1.96	1.86 ± 0.20	**1.92** **± 0.17**

Mean ± S.D

Table 2: Radial variation of acoustic properties of *G.arborea* wood

	Core			**Outer**			**P. mean**
	top	Base	Mean	Top	Base	Mean	
γ	0.39	0.36	0.38 ± 0.03	0.41	0.42	0.42 ± 0.01	**0.40** **± 0.03**
tan δ	0.005	0.004	0.005 ± 0.001	0.003	0.004	0.004 ± 0.001	**0.004** **± 0.001**
Q	222.08	275.28	248.68 ± 70.08	344.97	276.22	310.60 ± 71.83	**279.64** **± 74.99**
FF (Hz)	1122.47	1059.46	1090.97 ± 79.11	1130.98	1067.17	1099.08 ± 65.41	**1095.02** **± 69.33**
RF Hz)	2170.75	2350.27	2260.51 ± 3125.05	2066.48	2429.53	2248.01 ± 272.77	**2254.26** **± 281.03**
E (GPa)	9.52	8.47	9.00 ± 1.30	10.12	9.24	9.68 ± 1.13	**9.34** **± 1.22**
Es (GPa)	24.23	23.20	23.72 ± 2.61	24.67	22.20	23.44 ± 2.78	**23.58** **± 2.58**
K	12.51	13.27	12.89	12.11	11.29	11.70	**12.30**

			± 0.89			± 0.79	**± 1.00**
V (m/s)	4917.69	4809.64	4863.67 ± 267.50	4964.01	4702.99	4833.50 ± 291.80	**4848.58 ± 267.35**
ACE ($m^4kg^{-1}s^{-1}$)	2754.29	3650.79	3202.54 ± 961.65	4172.93	3164.60	3668.77 ± 993.83	**3435.65 ± 963.63**
Z($x10^6$) ($kgm^{-2}s^{-1}$)	1.93	1.75	1.84 ± 0.18	2.04	1.96	2.00 ± 0.12	**1.92 ± 0.17**

Mean ± S.D

Table 3: Analysis of Variance showing *P*-values for acoustic properties of *G.arborea* wood

S of V	**Df**	**FF**	**RF**	**V**	**γ**	**E**	**tan*δ***	**Es**	**K**	**Q**	**ACE**	**Z**
Axial	1	0.162	0.131	0.299	0.258	0.207	0.913	0.308	0.957	0.852	0.919	0.173
Radial	1	0.849	0.940	0.861	0.006*	0.360	0.182	0.865	0.031*	0.163	0.408	0.112
A*R	1	0.992	0.584	0.658	0.092	0.908	0.214	0.664	0.123	0.169	0.112	0.564
Error	8											
Total	11											

S of V – sources of variance Df – degree of freedom RF – Resonance frequency FF- Fundamental frequency * - significant at *P* ≤ 0.05

Table 4: Acoustic properties of *G.arborea* wood compared with selected wood species

	G.arborea	*Afzelia sp.*	*Millettia sp.*	Bamboo	Amboyna wood	Walnut wood
γ	0.39	0.754	0.835	0.7	0.87	NA

E (GPa)	9.34	12.5	15.8	11.5	12.5	8.8
V (m/s)	4848.58	NA	NA	4600	4800	4037
tan δ	0.0039	0.0075	0.0061	0.0071	0.0065	0.0083
Es (GPa)	23.57	16.6	18.9	15	20	16.3
Q	279.64	133.33	163.93	140	155	120.5
ACE ($m^4kg^{-1}s^{-1}$)	3435.66	649	883	920	855	NA

Source: Yoshikawa and Waltham (2014); Mohammad *et al.,* (2014); and Baar *et al.,* (2016). NA – Not Available.

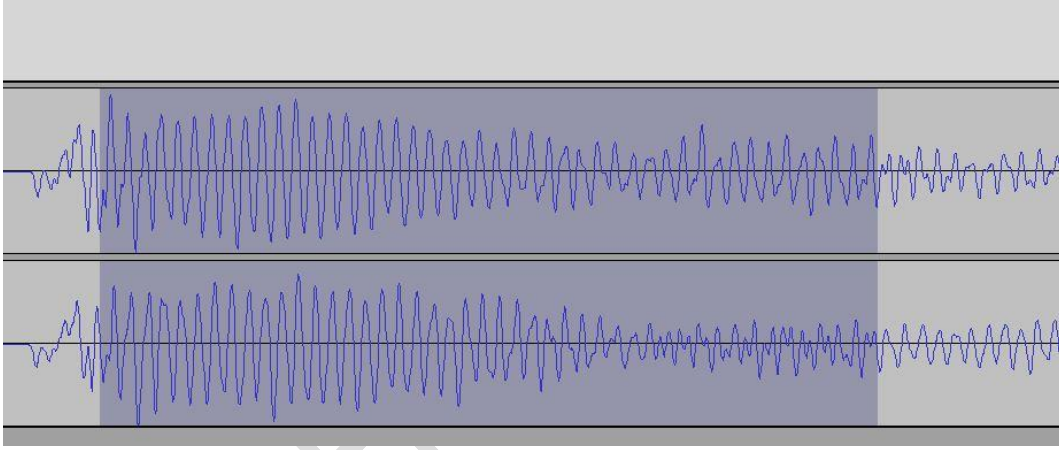

Fig 4: Sample of measured graph of amplitude decrement of the mode of vibration through time.

4. CONCLUSIONS

This study shows how to determine the acoustic properties of *G.arborea* wood, and thus concluded that *G.arborea* wood is a good choice for acoustic purposes especially for musical instrument. It also compared favourably with other wood species considered for acoustic purposes. However, precaution should be taken when selection of wood species on the basis of its acoustic properties for acoustic functions is to be done. This is because some acoustic traits of wood are needed to be higher for making certain shell; such as sound boxes and sound boards for musical instruments, but these traits may be needed to be lower when considering the same wood species for frame board or construction of musical studio. For this reason, selection of wood species for acoustic functions should be purpose driven.

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