Acoustic Characteristics of Bamboo-based Guitar – A Case Study

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Bamboo is a fast-growing plant easily obtained in Malaysia. It is commonly used for constructing various solid structures including the guitar. Its unique sound quality makes it different from the traditional wooden guitar. The Yamaha guitar sound was used as reference for the generally preferred guitar characteristics. This work focused on the acoustic characteristics easily obtained using the frequency spectrum analysis *via* a PicoScope oscilloscope and spectrogram using Adobe Audition. A microphone was used for recording the string sound and yielding the frequency response function. The Fast Fourier Transform (FFT) spectra showed that the Yamaha guitar had less partials compared to the bamboo guitar, except string 4. Strings 1, 2, and 3 showed a regular signal from the Yamaha guitar whereas the bamboo guitar showed an irregular pattern with significant overtone. The intensity of the partials in the bamboo guitar displayed a recognizable pattern, *i.e.*, a reduction of partial intensity amplitude proportional to increasing frequency in strings 4, 5, and 6. Some random partials appeared between the harmonics in string 1, 2, and 3 from bamboo guitar whereas the absence of partials in the Yamaha guitar could be due to the higher radiation coefficient of wood, which displays a different timbre.

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INTRODUCTION

Bamboo grows widely in Malaysia. Bamboo has been used for many purposes by locals, including for musical instruments. As a fast-growing plant, bamboo is expected to be used as an alternative in the future economically. This paper describes a bamboo guitar that has been manufactured by locals as an approach of substituting wood in the instrument. The resonator and other components were manufactured from a pressed, 14 cm diameter bamboo tube. Despite having a similar tune, in general, a bamboo guitar has a unique quality compared with a wooden guitar. Other chordophones (strings instruments) using bamboo resonator are the pratuokng (Hamdan *et al.* 2024a), and tongkungon (Hamdan *et al.* 2024b). Compared with other common materials, bamboo is considered a good soundboard material (Wegst 2008). The sound radiation coefficient is high, approximately close enough to that of soundboard materials and back plate materials. Impedance matching from the strings and soundboard can be done carefully, because the impedance is proportional to the material's characteristic impedance and the soundboard's thickness. Therefore, bamboo can be considered as an alternative for guitar resonator. Kusumaningtyas *et al.* (2016) used glued bamboo board for guitar soundboard.

The sound generation of guitar is produced by plucking the tuned strings, which defines the desired pitch. Guitar sound spectra obtained by several different researchers, including Richardson (1982), Meyer (1983), Jansson (1983), Ross and Rossing (1979), and Ross (1979) show individual differences. All of them show strong peaks around 100 and 200 Hz, several peaks in the 400 to 700 Hz region, and a broad set of peaks above 1.5 kHz (Rossing 2010). These sound spectra show the radiated sound level when a sinusoidal force of constant amplitude is applied perpendicular to the bridge. The strong peaks around 100, 200, and 400 Hz, which stem from resonances of the guitar body, do much to determine the low-frequency tonal characteristics of the guitar. Meyer (1983) found that the peak level of the resonance near 400 Hz correlates especially well with the quality rating of the guitar by listeners.

In this paper, the acoustics characteristics of a bamboo-based guitar were analyzed using Fast Fourier Transform (FFT) *via* PicoScope and spectrogram *via* Adobe Audition. The fundamental frequency along with the overtones defines the pitch and the sensation of timbre. The work used a wooden Yamaha guitar model FG-251B as a reference. Solid spruce tops are popular for acoustic guitars because they may provide a bright, clear, balanced tone with good resonance and projection. This is also the case with the Yamaha FG-251B. Usually constructed from laminated tone woods such as mahogany or nato, the back and sides of the guitar add to its warmth and robustness. Additionally, constructed of mahogany or nato, the neck offers stability and a pleasurable playing experience. In fact, the Yamaha FG-251B is an excellent representation of a typical mid-range acoustic guitar. It is a good point of comparison because of its playability, good sound quality, and well-made construction. Regarding acoustic qualities, the FG-251B holds up well compared to other guitars in this range, including those made by Guild, Takamine, Seagull, and Alvarez. As such, it can be regarded as a wise choice to use as a reference in this work. It is possible to assess the locally produced bamboo guitar by comparing it to a dependable and easily identifiable benchmark, such as the FG-251B. This decision guarantees that the comparison makes sense and is pertinent to the guitar community and knowledgeable listeners.

Spruce (*Picea* sp.) is a common wood for the top plates of acoustic guitars (Wegst 2006) due to its ability to produce high quality sound and beautiful wood grain. However, it is not available in Malaysia. Therefore, Malaysian guitar luthiers sought an alternative for the top plate materials. The mechanical, acoustic, and vibrational properties of various types of woods characterize a musical instrument (Haines 1979; Ono *et al.* 1983; Barlow 1997; Bucur 2006). Many works have been published about the speed of sound, the characteristic impedance, the sound radiation coefficient, and the loss coefficient for various woods (Wegst 2006; Bremaud 2012). Based on these works, certain species of wood are preferred to others for different types of musical instruments and parts. Many researchers have investigated the string musical instruments made of wood, acoustical and vibrational characteristics (Wright 1996; Bollousa 2002; French 2008; Paiva *et al.* 2014).

When compared to bamboo, wood for acoustic guitars is matured in 30 to 40 years, whereas bamboo can be harvested after 3 to 5 years. Bamboo can be used in its original cylindrical form or made into splits. Wegst (2008) stated that bamboo is the only material worldwide, with a mechanical and acoustic property profile that simultaneously satisfies all design criteria and functional requirements of all classes of musical instruments. However, further discussion on the influence of bamboo on the properties of soundboards was not given. In this work, ‘Semantan’ bamboo (*Gigantochloa scortechinii* Gamble) was used for the manufacturing of bamboo acoustic guitars. These characteristics were compared to the acoustics of the Yamaha guitar.

EXPERIMENTAL

The ‘Semantan’ bamboo (*Gigantochloa scortechinii* Gamble) used is shown in Fig. 1. The green and fresh ‘Semantan’ bamboos are taken from the forest around Gerik, Kedah, Malaysia. This guitar used 90% bamboo as the basic construction material including bracing, neck, fingerboard, and bridge except for equipment such as tuning pegs, saddles and nuts that use materials other than bamboo. Laminated ‘Semantan’ bamboo plank had the hardness 4.5kN, modulus of rupture (MOR) 146.8 MPa and compression 71.3 MPa (Ong *et al.* 2023). The European Spruce (Norway Spruce) wood (*Picea abies*) had the hardness 1.5kN, MOR 60 MPa and compression 41.0 MPa (George 1991). Sound reduction index for laminated bamboo and spruce at 2500 Hz is 60dB and 30dB respectively. (Kong *et al.* 2023). It grows primarily in the wet tropical biome with erect culms up to 20 m tall. Lanceolate leaves have a petiole-like connection to the culm and a hairy underside. The size and feature of the bamboo guitar almost fully imitated the common wooden guitar. The specific dimensions of the bamboo and Yamaha guitars are:

1. Head and neck measurements are 17 cm and 36 cm long, respectively.
2. Body, upper and lower bout are 51 cm, 12 cm and 17cm long, respectively.
3. Bridge length and thickness are 10 mm and 3 mm, respectively.
4. The thickness of the top and back plates is both 3 mm.
5. The 6 strings used for both bamboo and Yamaha guitars are D’addario.

Figure 2 shows the front, back and side view of the upper and lower bout of the bamboo guitar. In this work, the experiment was done by plucking the strings by a professional player to ensure the same plucking parameters were applied for both bamboo and Yamaha guitars. To ensure uniformity in the plucking parameters for the Yamaha and bamboo guitars, the experiment was carried out by an expert guitarist. With every attempt, the guitarist employed the same method, applying the same amount of force and angle to the pluck. To minimize variances, the guitarist thoroughly rehearsed the precise plucking motions before the recordings. This methodological rigor reduces the impact of human variability, enhancing the reproducibility and reliability of the experimental outcomes.

The notes at strings 1, 2, 3, 4, 5, and 6 are E5 (659 Hz), B4 (494 Hz), G4 (392 Hz), D4 (294 Hz), A3 (220 Hz), and E3 (165 Hz). The radiated sound was measured with an omni directional microphone placed 20 cm above the guitar and was done in an anechoic chamber.

Fig. 1. The ‘Semantan’ bamboo (*Gigantochloa Scortechinii* Gamble)

Fig. 2. The bamboo guitar

The time signals obtained from PicoScope oscilloscopes and data recorders for real-time signal acquisition were viewed and analyzed using the PicoScope computer software (Pico Technology, 3000 series, Eaton Socon, UK). The PicoScope program facilitates analysis through the utilization of FFT, a spectrum analyzer, voltage-based triggers, and the capability to save and retrieve waveforms. A schematic diagram of the experimental setup is depicted in Fig. 3. The placement of the guitar was strategically chosen to optimize sound collection while minimizing interference. To provide a fair comparison, the Yamaha FG-251B and the bamboo guitar built locally were both played in the customary sitting position. This position promotes natural sound output and resonance and is most indicative of normal playing circumstances. To capture the authentic acoustic qualities of each guitar, a microphone was positioned in front the guitar at a constant distance and angle during the recording process. This arrangement makes sure that the recordings accurately capture the tonal qualities of both guitars without adding distortion or bias from different microphone positions.

The sound capture was sufficiently loud to be detected by the signal converter, facilitated by the amplifier (Behringer Powerplay Pro XL, Behringer, Zhongshan, Guangdong, China). The sound spectra were acquired by measurements conducted using a PicoScope. Following the capture and recording of the sound data, the FFT was analyzed using Adobe Audition to determine the dominant frequency for each tone at a certain moment. Fourier transformation is a mathematical technique used to identify fundamentals, harmonics, and subharmonics. The Yamaha FG-251B is a well-regarded mid-range guitar known for its consistent quality and sound. Its use as a reference model is justified because it represents a standard in acoustic guitar construction, making it an ideal benchmark for comparing with the locally made bamboo guitar. To ensure durability and dependability, sound data for the Yamaha FG-251B and the locally built bamboo guitar were gathered in numerous rounds. Each guitar was played and recorded under identical settings to minimize any abnormalities or deviations. The two guitars were played in their customary sitting position, and microphones were positioned at the same height and angle in front the player to guarantee that the recordings accurately captured the acoustic qualities of each instrument without adding any bias. Following this, the recordings from these several iterations were averaged to smooth out irregularities and produce a more trustworthy comparison that gave a thorough and accurate depiction of the acoustic characteristics of both guitars.

By utilizing multiple rounds of data collection and averaging the results, we ensure that our comparison is robust and reliable. This detailed methodology strengthens the validity of the present findings and provides a clear and accurate comparison between the Yamaha FG-251B and the locally made bamboo guitar.

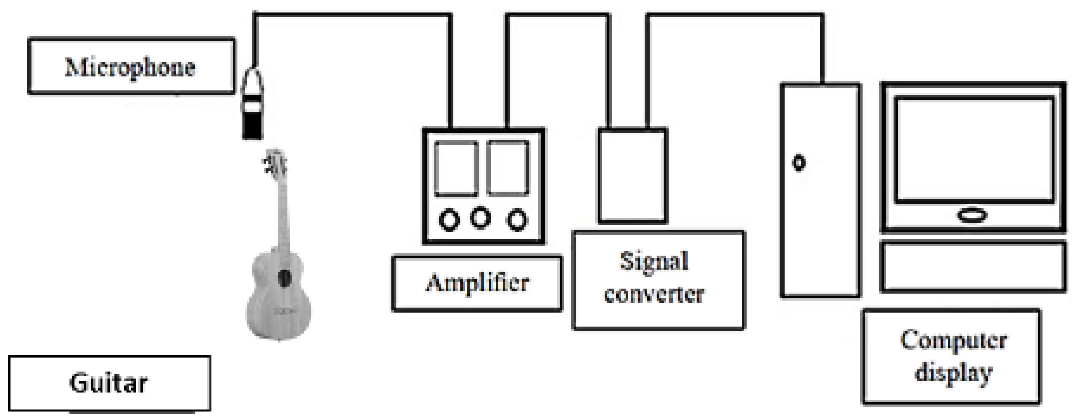


Fig. 3. Schematic diagram of the experimental setup

RESULTS AND DISCUSSION

Figure 4 shows the FFT spectra from strings 1 to 6 (E5 (659 Hz), B4 (494 Hz), G4 (392 Hz), D4 (294 Hz), A3 (220 Hz), and E3 (165 Hz)) for bamboo and Yamaha guitar. String 1 had non-harmonic at 0.94 kHz in bamboo guitar and at 0.68 kHz in Yamaha guitar. String 2 had 4 harmonics in bamboo guitar but only 3 harmonics in Yamaha guitar. Strings 3 had 4 harmonics in bamboo guitar and 3 harmonics with 1 non-harmonic (0.68 kHz) in the Yamaha guitar. String 4 had 6 and 9 partials in the bamboo guitar and Yamaha guitar, respectively. String 5 from both bamboo guitar and Yamaha guitar had 8 harmonics. String 6 had 11 and 8 partials from bamboo guitar and Yamaha guitar, respectively. From Fig. 4, the FFT spectra showed that the Yamaha guitar had less partials compared to the bamboo guitar, except string 4. Strings 1, 2, and 3 showed a regular signal from the Yamaha guitar, whereas the bamboo guitar showed an irregular pattern with significant overtone. The intensity of the partials in bamboo guitar displayed a recognizable pattern, *i.e.*, a reduction of intensity amplitudes proportional to increasing frequency in strings 4, 5, and 6. The intensity of the Yamaha guitar did not respond with this peculiar pattern.

The wood as a rigid body allows the sound of the string to sustain directly on the sound box. In contrast to the bamboo guitar, the sound of the strings decreased gradually on the sound box in the lateral direction. This happens due to higher flexibility of the bamboo top plate in the lateral direction because lateral properties are lower than the longitudinal properties. The bamboo top plate is glued to make it one piece of laminate, whereas the wood top plate is from one piece of wood laminate. The frequency response function of the bamboo guitar is generally shorter than the Yamaha guitar. Although both guitars had the same thickness at the top and back part, the Yamaha guitar had higher radiation coefficient than the bamboo guitar. The Yamaha guitar had a smaller loss coefficient compared to the bamboo guitar, because the loss coefficient effect was more emphasized in high frequency. The figure shows more damp in bamboo guitar frequency response function because the bamboo absorbed more sound. In Fig. 4, some random partials appeared between the harmonics in strings 1, 2, and 3 from bamboo guitar. These absences of partials in Yamaha guitar can be due to the higher radiation coefficient of wood that displays the different timbre.

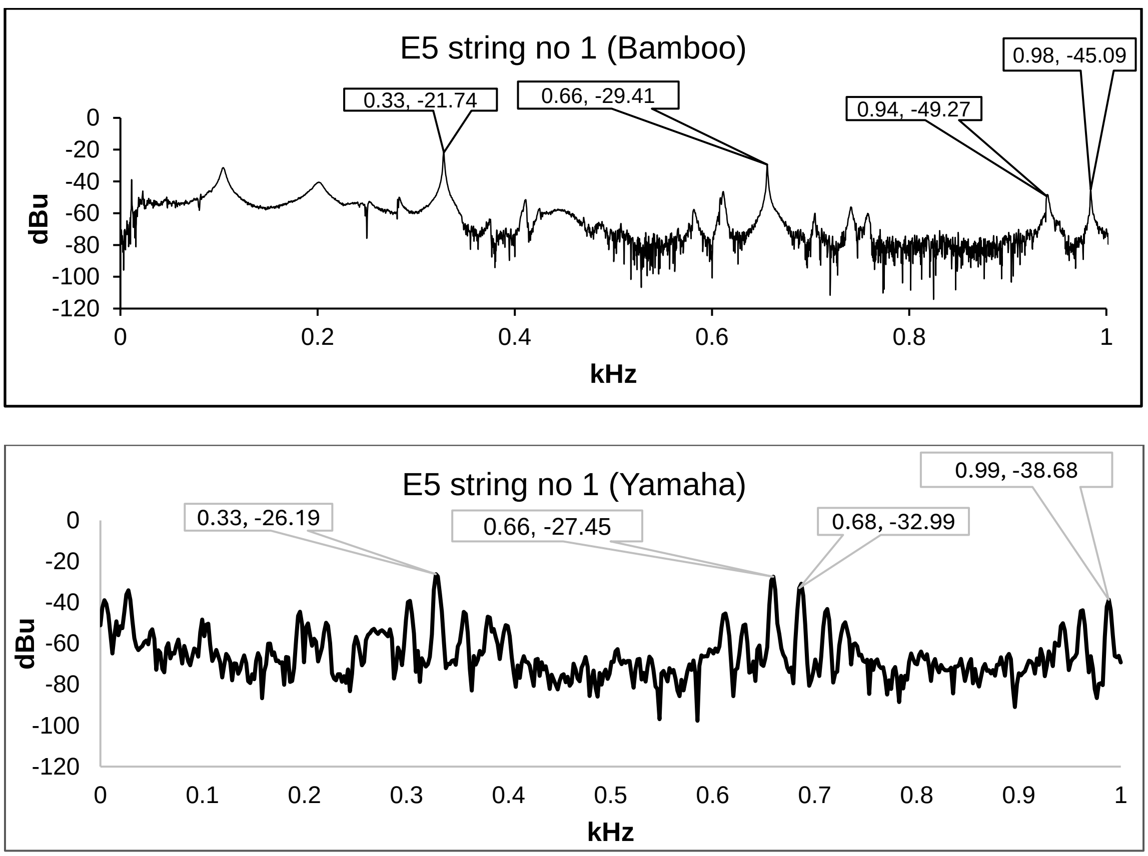


Fig. 4a. String no 1, E5 (659 Hz) from bamboo guitar and Yamaha guitar

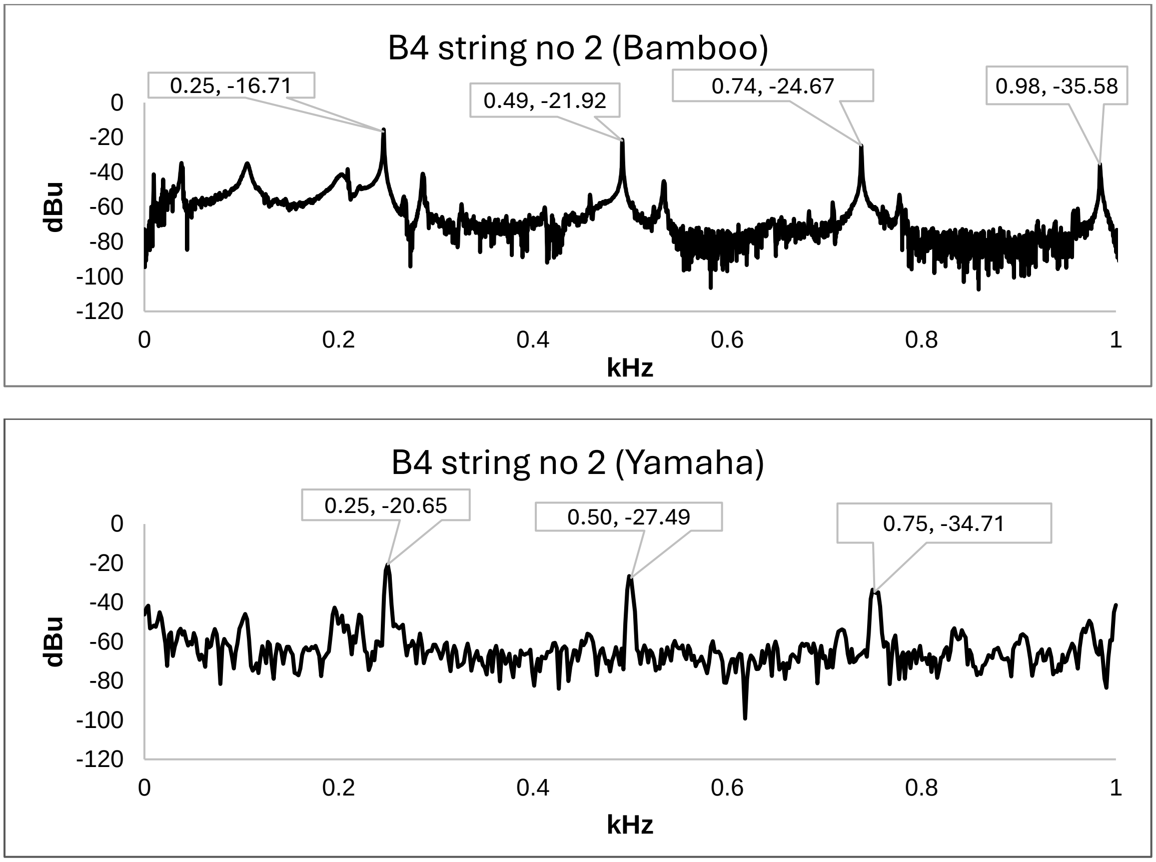
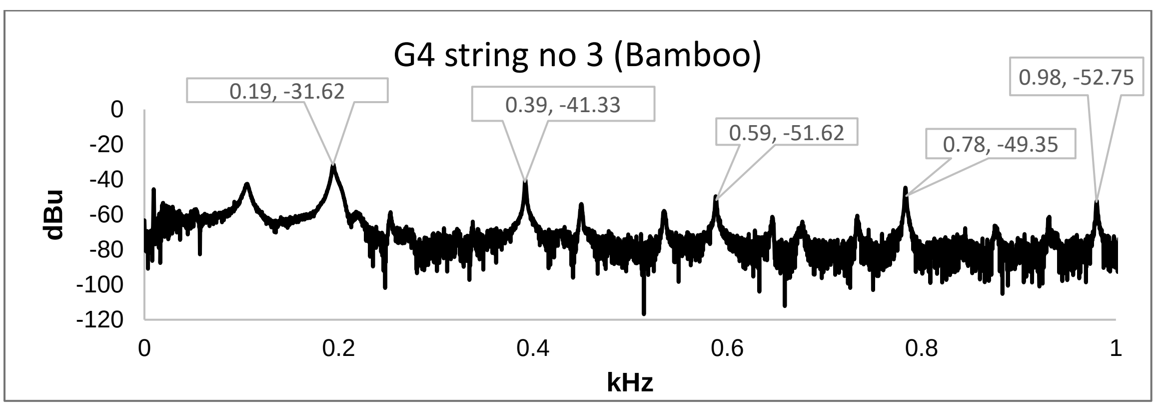


Fig. 4b. String no 2, B4 (494 Hz) from bamboo guitar and Yamaha guitar



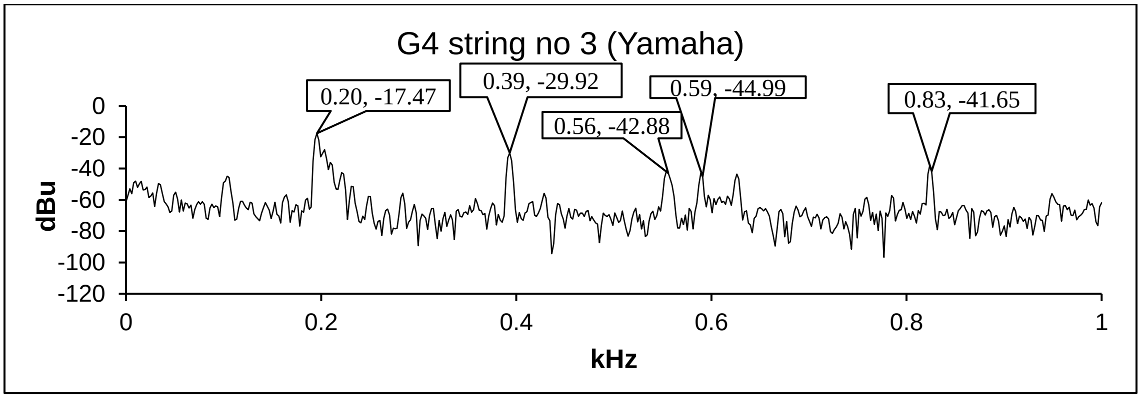


Fig. 4c. String no 3, G4 (392 Hz) from bamboo guitar and Yamaha guitar

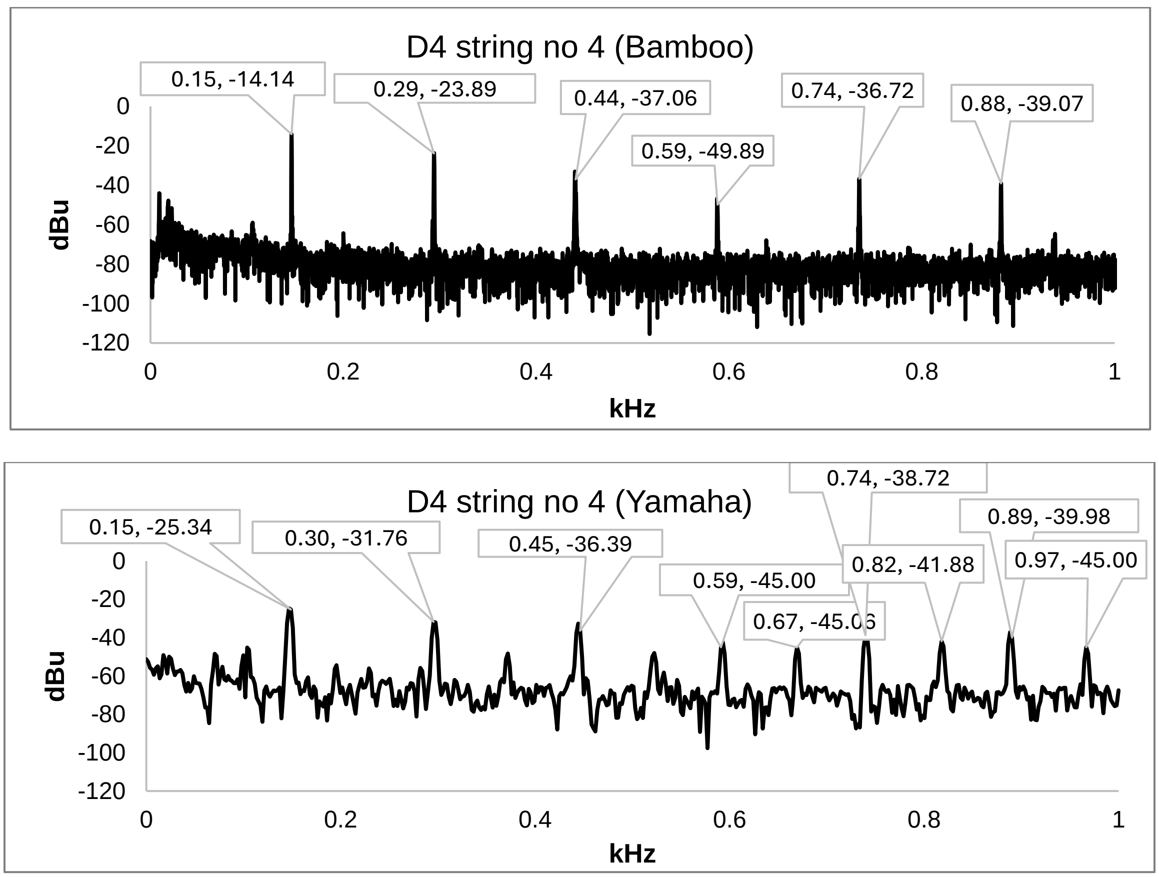


Fig. 4d. String no 4, D4 (294 Hz) from bamboo guitar and Yamaha guitar

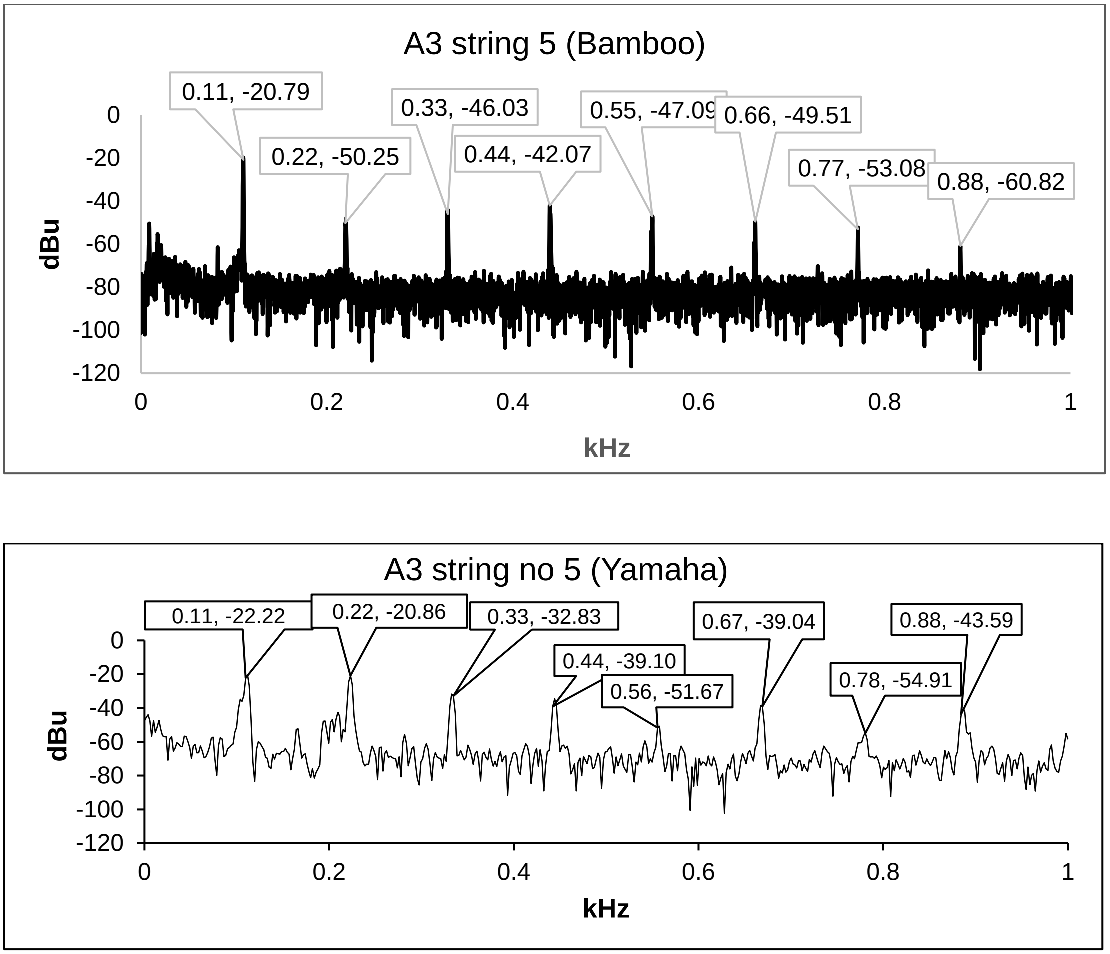
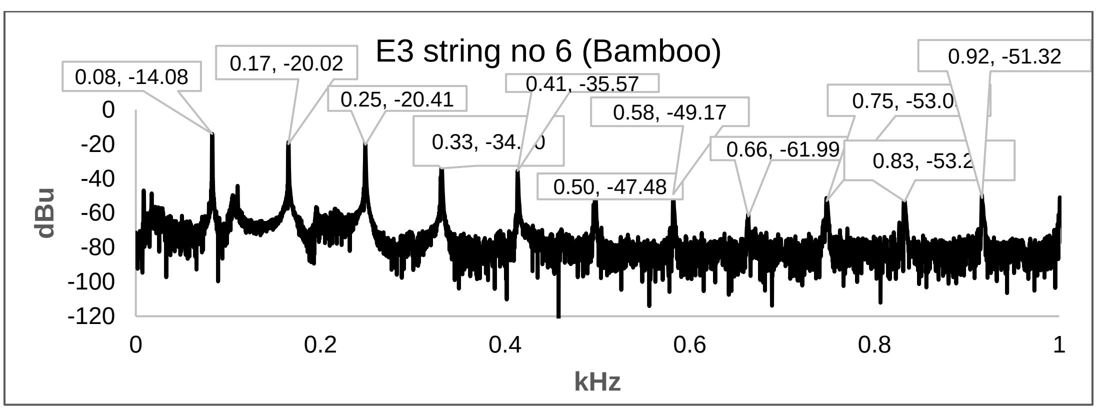


Fig. 4e. String no 5, A3 (220 Hz) from bamboo guitar and Yamaha guitar



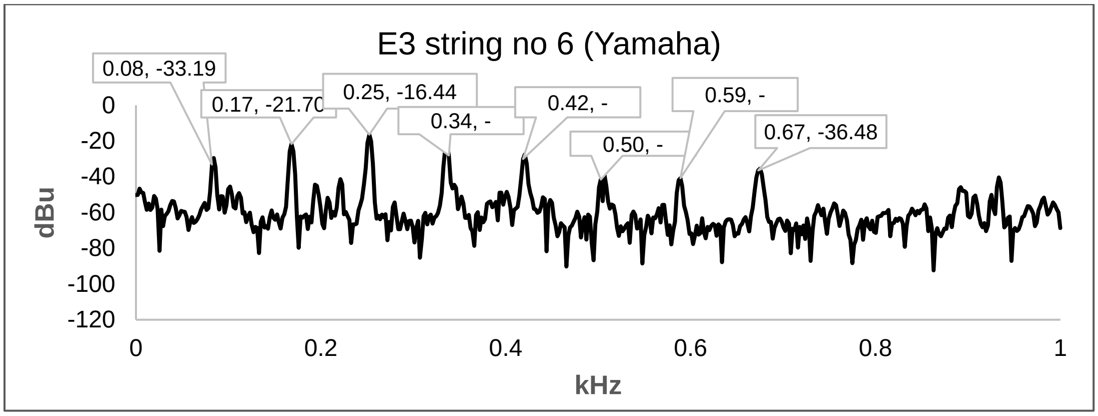


Fig. 4f. String no 6, E3 (165 Hz) from bamboo guitar and Yamaha guitar

Table 2 shows that the bamboo guitar and Yamaha guitar radiated the same pitch as the fundamental frequencies. The first and second partials of each string from both guitars matched with each other. The number of partials varied with different amplitudes. The partials of the overtones confirmed the typical sound quality of both guitars. The Yamaha guitar had less partials compared to the bamboo guitar. Even though the bamboo guitar had similar pitches, with the sensation of a wooden guitar-like sound, the bamboo guitar displayed different timbre from Yamaha guitar, as shown in Fig. 5. From Fig. 5, the spectrogram showed that the Yamaha guitar had a bright sound compared to the bamboo guitar.

Table 2. The Fundamental, First, and Second Partials from Bamboo Guitar and Yamaha Guitar

	Bamboo Guitar (kHz)			Yamaha Guitar (kHz)		
String no	Fundamental	1st partial	2nd partial	Fundamental	1st partial	2nd partial
1	0.66	0.33	0.98	0.66	0.33	0.99
2	0.49	0.25	0.74	0.50	0.25	0.75
3	0.39	0.19	0.59	0.39	0.20	0.59
4	0.29	0.15	0.44	0.30	0.15	0.45
5	0.22	0.11	0.33	0.22	0.11	0.33
6	0.17	0.08	0.25	0.17	0.08	0.25

The intensities of the overtones for both guitars varied, which can cause different timbres. Because the two materials components are very different, the major contributor for the different timbres is the resonator. Psychoacoustic testing and listener evaluations were used in our work to include subjective measurements of sound quality. Both the bamboo guitar built locally and the Yamaha FG-251B were played in a controlled atmosphere by a skilled guitarist. Professional listeners assessed the timbre, projection, resonance, and playability of the sound. Qualitative information about each guitar's perceived sound qualities was obtained from the evaluations. Psychoacoustic research was also done to find out how each guitar's sound was perceived by the human ear. This includes evaluations of pitch perception, loudness, and metrics related to sound quality, such as sharpness and fluctuation strength. A thorough and comprehensive comparison of the acoustic qualities and perceived sound quality of both guitars was made possible by combining the technical information from the FFT spectra and spectrogram analyses with the findings from these subjective assessments and psychoacoustic tests.

The Yamaha FG-251B is a delight because of its flawless fretboard and well-balanced neck. The motion is usually perfect immediately out of the box, so it is possible to start playing immediately without worrying about any quick adjustments. It is designed to be playable and comfortable, which makes extended practice sessions a breeze. The bamboo guitar had its unique atmosphere, although it surely had some peculiarities compared to the Yamaha. Although the fundamental harmonics were the same, the timbre was not as rich. Each string's overall character was impacted by the less noticeable sustain and notes that did not quite reach their full sound spectrum. Because it was composed of bonded bamboo pieces, the bamboo resonator tended to produce a more subdued sound as opposed to the bright projection of Yamaha's solid wood construction. Therefore, although playing both guitars was enjoyable, the Yamaha had a deeper, more resonant sound.

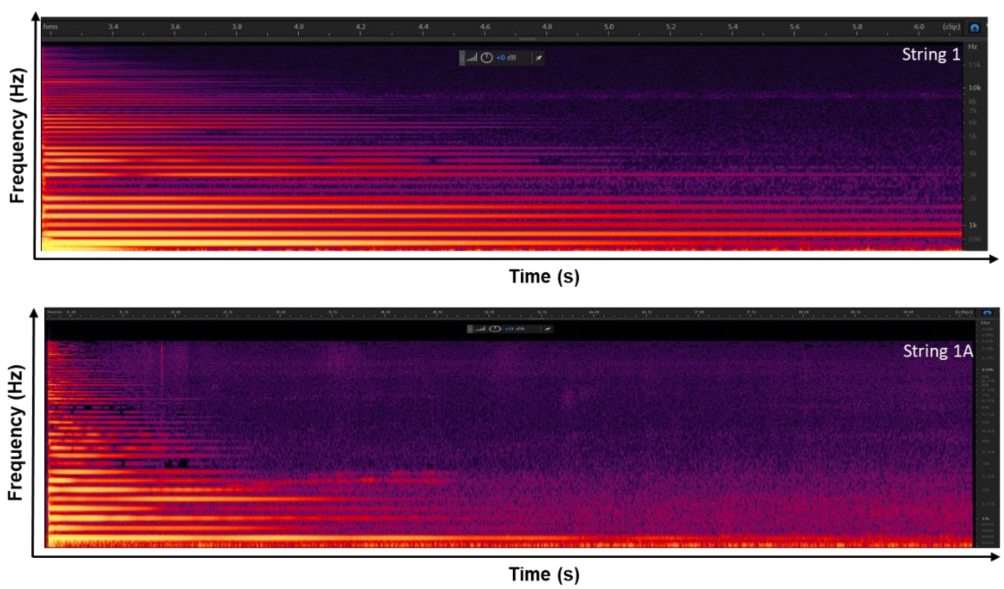
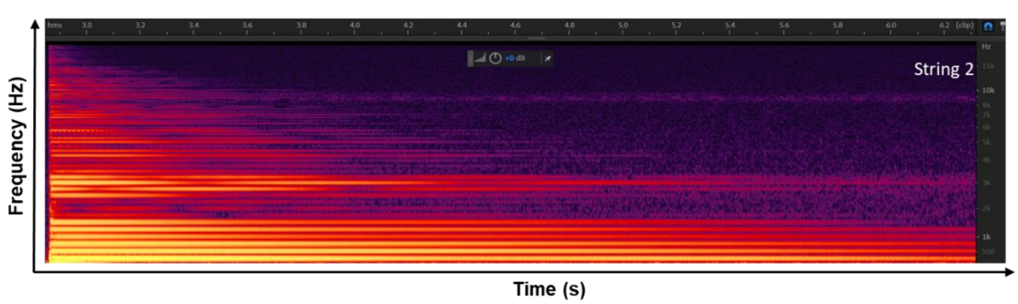


Fig. 5a. String no 1, E5 (659) Bamboo guitar (String1) and Yamaha guitar (String1A)



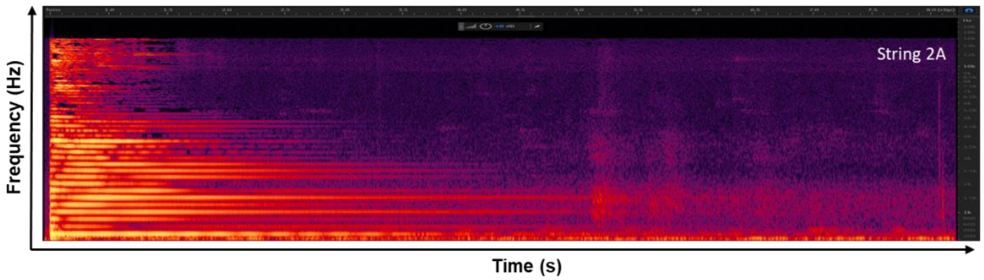


Fig. 5b. String no 2, B4 (494) Bamboo guitar (String2) and Yamaha guitar (String2A)

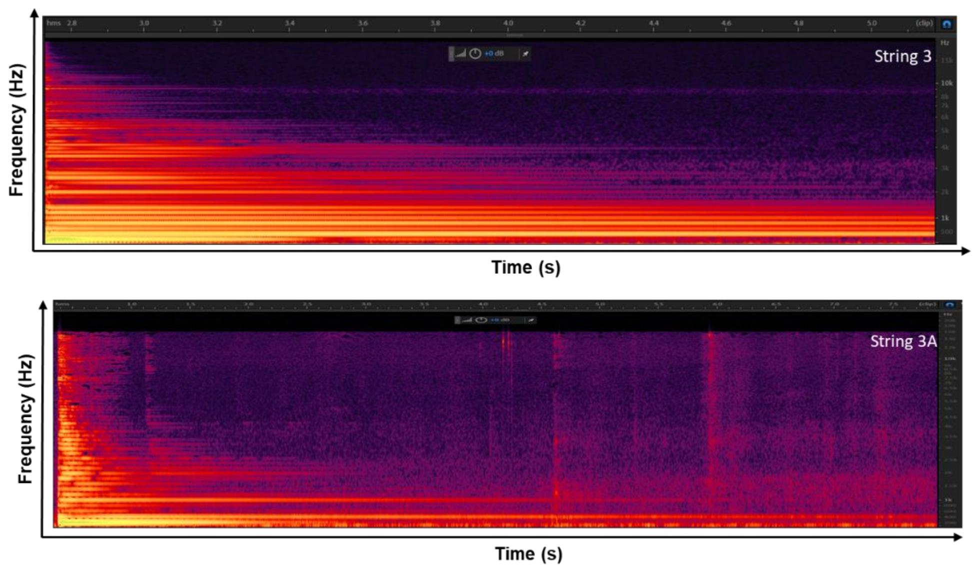


Fig. 5c. String no 3, G4 (392) Bamboo guitar (String3) and Yamaha guitar (String3A)

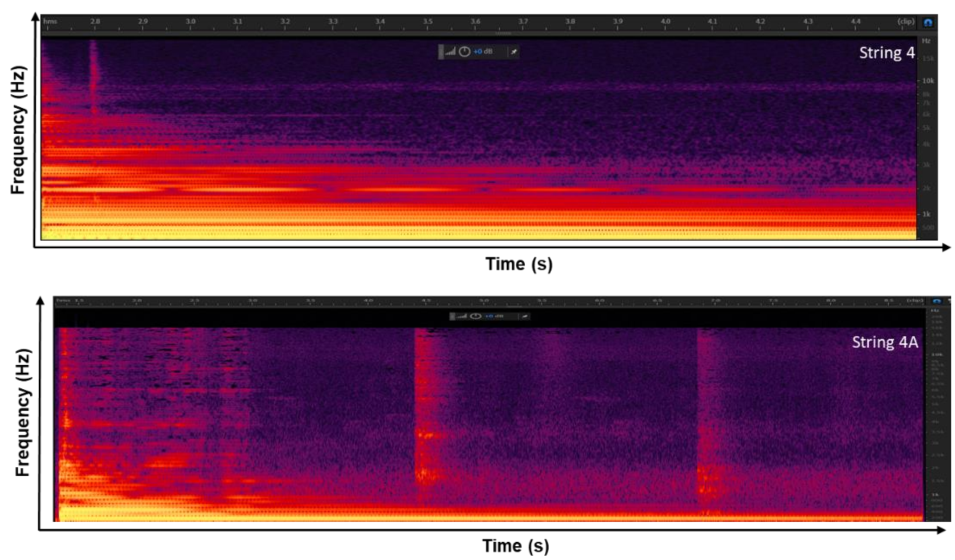


Fig. 5d. String no 4, D4 (294) Bamboo guitar (String4) and Yamaha guitar (String4A)

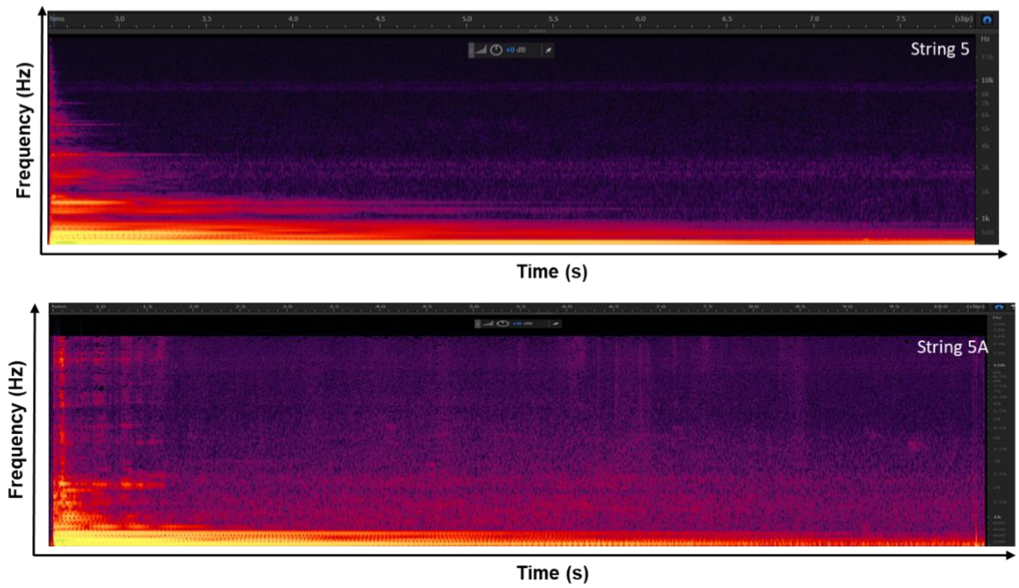


Fig. 5e. String no 5, A3 (220) Bamboo guitar (String5) and Yamaha guitar (String5A)

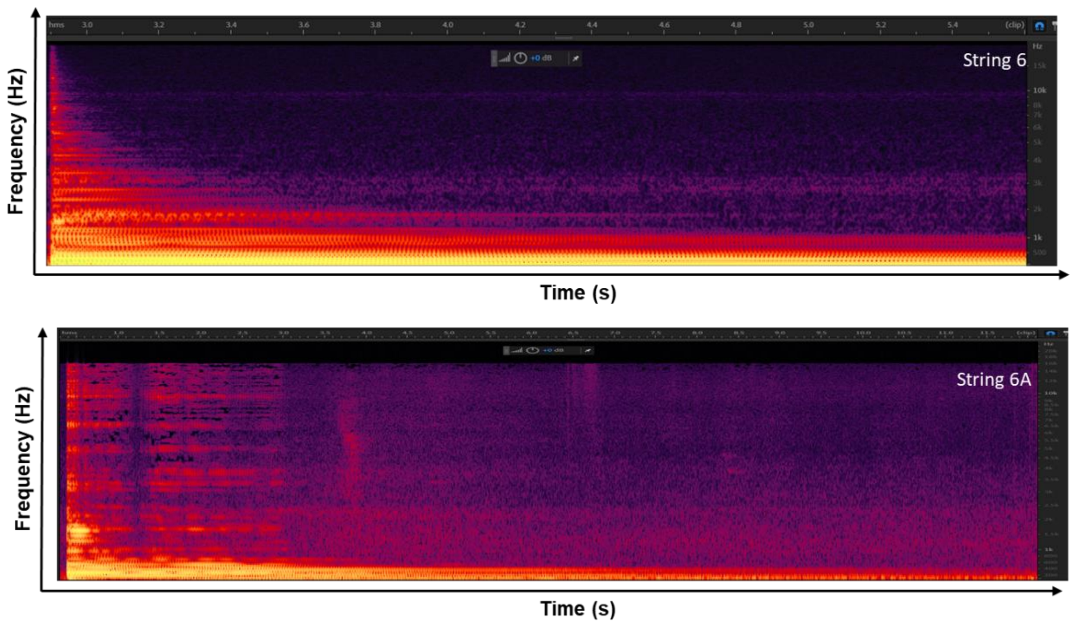


Fig. 5f. String no 6, E3 (165) Bamboo guitar (String6) and Yamaha guitar (String6A)

CONCLUSIONS

1. The pitch and timbre of a bamboo guitar was compared with a conventional wood-constructed Yamaha guitar in this work. Though the pitch and harmonics sound characteristic were similar, the bamboo guitar exhibited a different timbre compared to the Yamaha guitar.
2. The resonator used the longitudinal grain in both guitars. The bamboo guitar resonator showed less radiative and more damp behavior than the Yamaha guitar

resonator. In addition, there were some decreasing amplitudes in the integer overtones in bamboo guitar (although produced the same harmonics frequency with Yamaha guitar). In summary, the bamboo guitar resonator exhibited a peculiar pattern of amplitude intensities compared with Yamaha guitar.

3. The differences were attributed to the fact that the bamboo guitar resonator was made from split bamboo pieces, which were glued together. The Yamaha guitar showed more radiation coefficient due to the one piece of wood used (not glued from split of wood).
4. The only comparable output from the two guitars was the fundamental, first, and second overtone frequencies of the bamboo guitar. These features can be regarded as the main harmonics but not the timbre.

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REFERENCE CITED

Barlow, C. (1997). "Material selection for musical instruments," *Proc. Inst. Acoust.* 19, 69-78.

Bollousa, R. R. (2002). "Vibration measurements in the classical guitar," *Applied Acoustics* 63(3), 311-322. DOI: 10.1016/S0003-682X (01)00037-8

Bremaud, I. (2012). "Acoustical properties of wood in string instruments soundboards and tuned idio-phones: Biological and cultural diversity," *The Journal of the Acoustical Society of America* 131(1), 807-818. DOI: 10.1121/1.3651233

Bucur, V. (2006). "Wood and wood-based materials in architectural acoustics," in *Acoustics of Wood*, V. Bucur (ed.), Springer-Verlag, Berlin, Germany, pp. 21-36. DOI: 10.1007/3-540-30594-7.

French, M. N. (2008). "Response variation in a group of acoustic guitars," *Sound and Vibration* 42(1), 18-23.

George Tsoumis, Science and Technology of Wood: Structure, Properties, Utilization, Van Nostrand Reinhold, (1991).

Haines, D.W. (1979). "On musical instrument wood. Guide to the Catgut Acoustical Society Newsletter," *Online Archive of California* 1, 23-32.

Hamdan, S., Mohamad Said, K. A., Faudzi Musib, A., Rahman, M. R., Sawawi, M., and Sinin, A. E. (2024a). "Pratuokng: The Borneo bamboo zither of Bidayuh Sarawak," *BioResources* 19(1), 1305-1315. 10.15376/biores.19.1.1305-1315

Hamdan, S., Said, K. A. M., Kipli, K., Duin, E. A. M., and Sinin, A. E. (2024b). "The Tongkungon: A traditional Kadazan Dusun music instrument from Sabah, Malaysia," *BioResources* (Accepted, In Press).

Kong, Y., Wen, J., Huang, A., Zhou, L., and Xiao, Y. (2023). "Acoustic properties of glued laminated bamboo and spruce-pine-fir," *Wood Material Science & Engineering* 18(5), 1765–1779. DOI: 10.1080/17480272.2023.2187318

Kusumaningtyas, I., Yordaniansyah, H., and Purwanto, T. A. (2016). "Acoustical properties of petung bamboo for the top plate of guitars," *Applied Acoustics* 112, 123-130. DOI: 10.1016/j.apacoust.2016.05.016

Ong, C. B., Khairul A., and Che Muhammad Farid, C. S. (2023). "Mechanical properties of Semantan laminated bamboo plank for structural application," FRIM Timber Technology Bulletin No. 127.

Ono, T., and Norimoto, M. (1983). "Study on Young's modulus and internal friction of wood in relation to the evaluation of wood for musical instrument," *Japan Journal of Applied Physics* 22, 611-614. DOI: 10.1143/JJAP.22.611

Paiva, G., and Dos Santos, J. M. C. (2014). "Vibration measurements in the classical guitar," in: *Proceeding International Symposium on Music Acoustics 2014,* Le Mans, France, pp. 233-239. DOI: 10.1016/S0003-682X (01)00037-8

Rossing, T.D. (2010). "Plucked Sstrings," in *The Science of String Instruments*, T. D. Rossing (ed.), Springer, New York, NY, USA.

Wegst, U. G. K. (2006). "Wood for sound," *American Journal of Botany* 93(10), 1439-1458. DOI: 10.3732/ajb.93.10.1439

Wegst, U. G. K. (2008). "Bamboo and wood in musical instruments," *Annual Reviews in Material Research* 38, 323-349. DOI: 10.1146/annurev.matsci.38.060407.132459

Wright, H. (1996). *The Acoustics and Psychoacoustics of the Guitar,* Ph.D. Thesis, University of Wales, College of Cardiff, Cardiff, Wales.

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