Study on Vibro-acoustic Characteristics of Bamboo-based Angklung Instrument

Sinin Hamdan,[a] Md Rezaur Rahman,[a,]* Ana Sakura Zainal Abidin,[a] and
Ahmad Fauzi Musib [b]

The frequency (or pitch) content of bamboo angklung musical instruments was analyzed. The pitch of the rattle tubes was determined *via* a Pico oscilloscope recording both the time and frequency spectrum. Fast Fourier transform analysis identified the fundamentals and overtones of the individual tubes, which were compared with the calculated theoretical resonance frequency. The pitch, due to the coupling effects of two rattle tubes, slightly varied from the pitch of the individual rattle tubes. Although both rattle tubes (played simultaneously) displayed the fundamental frequencies in both tubes, the individual tubes played separately did not produce the exact frequency obtained from both tubes played simultaneously. The spectrum of both tubes produced sound output from the individual tube, which is shown by two prominent peaks, corresponding to the pitch of the individual tube. Although the long and short tube show an individual fundamental frequency of 528 Hz and 1095 Hz, respectively, for C5 tube (when played separately), the coupling of both tubes produced the first and second peaks (when played simultaneously) at 546 Hz and 1093 Hz. Due to the disparity of the fundamental frequency, the inner diameter and length of the tube was utilized for the theoretical resonance frequency calculation.

DOI: 10.15376/biores.17.1.1670-1679

Keywords: Bamboo angklung; Pitch; Rattle tubes; Resonance frequency; Fat Fourier transform (FFT)

Contact information: a: Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan 94300 Sarawak, Malaysia; b: Department of Music, Universiti Putra Malaysia, Selangor 43400 Malaysia;
** Corresponding author: rmrezaur@unimas.my*

INTRODUCTION

Bamboo is one of the most widely used materials in musical instruments, including string instruments and percussion as well as wind instruments. Bamboo has been used to make musical instruments for thousands of years, probably as a percussion instrument at first, but later also for wind instruments and stringed instruments. Bamboo pipe walls are complex, composed of a layered structure of fibers. The pipe walls exhibit non-uniformity in terms of the radial structure and density, and there is a considerable difference between the elastic moduli parallel to and perpendicular to the bamboo fibers. Its natural hollow form makes bamboo an obvious choice for many traditional instruments, *e.g.*, a wide variety of flutes. This paper presents a summary of the results of using bamboo as a material for angklung musical instruments. In addition, these results are presented along with calculated values. Bamboo is frequently used for wind and percussion instruments. Figure 1 plots Young’s modulus against the density of bamboo and other woods parallel to the grain (Wegst 2008). The figure shows the analysis and explanation as to why angklung is manufactured from bamboo.

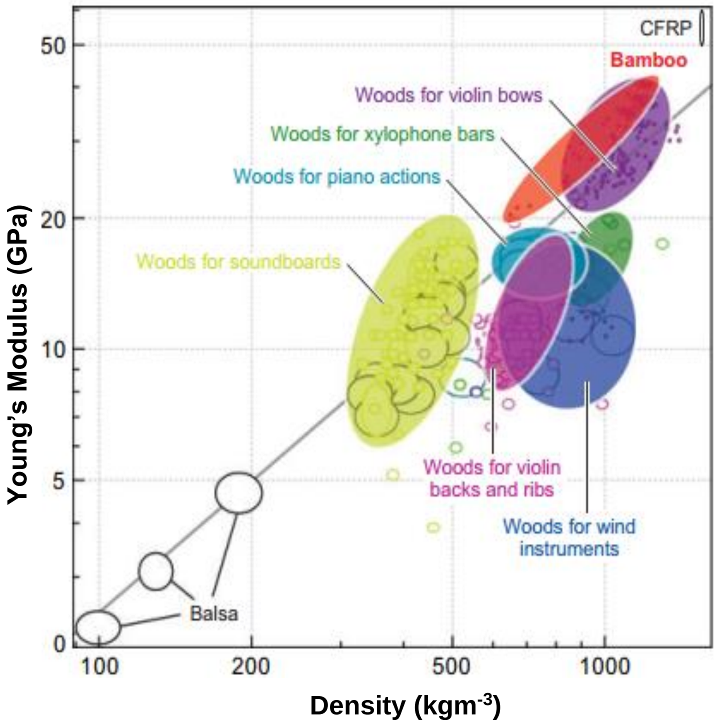


Fig. 1. Young modulus against the density of bamboo and other woods parallel to the grain (Wegst 2008)

The density, Young's modulus, and loss coefficient can be used to characterize the vibrations of the material and acoustical performance. The speed (related to the modulus of elasticity and density), the intensity of sound, impedance, sound radiations, and loss coefficient in a material are determined by these properties. As shown in Fig. 1, the mechanical properties determines the color and quality of the sound. Due to the orthotropic nature of bamboo, these mechanical properties vary in the three directions. The sound speed across the grain is approximately 20% to 30% of the longitudinal value because the transverse Young's modulus is approximately 1/20 to 1/10 that of the longitudinal value. The air that radiates and transmits determines the pitch of a musical instrument as well as the spectrum frequencies. As such, bamboo became the choice for musical instruments because of its excellent sound applications (Richter 1988; Bucur 2006; Wegst 2006).

Angklung instruments are a shaken idiophone with its principal operation by sliding rattle tubes. The upper parts are cut open with a tongue shape, while the lower parts are closed with a node. The tubes rattle by swinging in the frame, and the rattling mechanism is produced from within its body structure. The Western diatonic scale was introduced by a musician, Daeng Sutigna of Bandung (Widjaja 1980). This work analyzed the primary frequencies that make up the unique pitch of the angklung rattle tube. The results will help to understand the theoretical calculation of instrument resonance frequency. The air column resonance frequency was calculated according to Eq. 1,

$$f_n = \frac{nv}{(L+0.305d)} \tag{1}$$

where f is the air column resonance frequency (Hz), n=1,2…, v is the velocity of air (340 m/s), L is the length (in meters), and d the diameter (in meter) of the tube.

EXPERIMENTAL

The bamboo species known for angklung are *Bambusa vulgaris* Schrad. ex J.C. Wendl. var. *maculata* Widjaja, Gigantochloa aff. atter (Hassk.) Kurz ex Munro and *Gigantochloa apus* Bl. ex Schultes f., (Widjaja 2006). Figure 2 shows the front view of the C5 angklung rattle tube.

Fig. 2. Front view of the C5 angklung rattle tubes

Figure 2 shows the frame and rattle tubes of an angklung. The tubes are suspended vertically in the frame. The tubes have one closed end, which generates the main sound. The open end forms the tongue of the tube. The tongue length determines the sharpness or flatness of the pitch of the frequency. A tine is a pair of small protuberances at the closed end that can slide easily inside the slits at the bottom frame (Zainal *et al.* 2005). Holding the frame with one hand and shaking the bottom frame sideways with the other hand causes the tine to strike the end of their respective slits and thus vibrate the tubes. There are 8 pairs of rattle tubes, labeled C5, D5, E5, F5, G5, A5, B5, and C6. Each pair of tubes matches the pitch of a particular musical note (long tube equates to a lower pitch) with its second tube (short tube equates to a higher pitch) an octave higher. Figure 3 showed the experimental set up for the experimental method. Excitation was achieved by shaking the frame by an expert player. The angklung is played by holding the upper frame and shaking the bottom frame sideways.

The microphone was held above the top surface along the axis of symmetry at distance of approximately 20 cm. In this study, the audio signal derived from the striking by an expert player was recorded. The audio signal was recorded in mono, at a 24-bit resolution and a 48 kHz sampling rate. The audio signal was recorded with the aid of a digital audio interface in a .wav format. To ensure the recorded audio signal was at the optimum level, audio signal calibration of the recording system was carried out. A test tone of a 1 kHz sine wave was used to calibrate the recording system. In this study, the 'unity' calibration level was at +4 dBu or -10 dBV and was read by the recording device as '0 VU'.

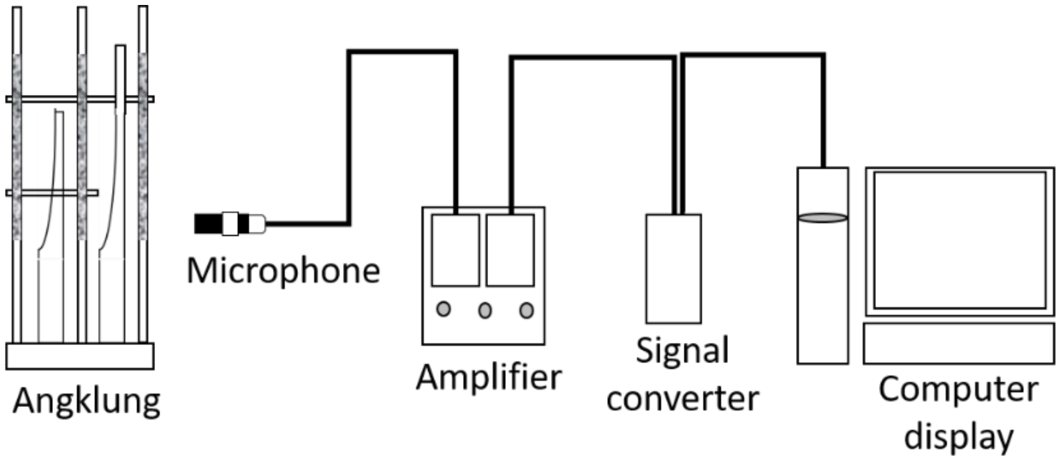


Fig. 3. Schematic diagram of the experimental setups

In this regard, the European Broadcasting Union (EBU) recommended the digital equivalent of 0 VU; *i.e.*, the test tone generated for the recording device of the experimentation was recorded at -18 dBFS (Digital) or +4 dBu (Analog), which was equivalent to 0 VU. During this thorough calibration procedure, no devices were unknowingly boosted, or its amplitude unknowingly attenuated in the signal chain at the time the recording was carried out. The recording apparatus was a Steinberg UR22 mkII audio interface, Audio-Technica AT4050 microphone, XLR cable (balance), with the microphone position on an axis (less than 20 cm), and the microphone setting with low cut (flat) 0 dB. PicoScope computer software (Pico Technology, 3000 series, Eaton Socon, United Kingdom) was used to view and analyze the time signals from the PicoScope oscilloscopes (Pico Technology, 3000 series, Eaton Socon, United Kingdom) and data loggers for real time signal acquisition. The PicoScope software enables analysis using fast Fourier transform (FFT), a spectrum analyzer, voltage-based triggers, and the ability to save/load waveforms to a disk. The amplifier (Behringer Powerplay Pro XL, Behringer, China) ensured that the sound capture was loud enough to be detected by the signal converter. The resonance frequency (Hz) of the air column in the long and short tubes were calculated using the length and diameter of the rattle tube.

RESULTS AND DISCUSSION

The rattle sound was produced by striking the tubes once only. The signal was captured for almost 50 ms to ensure that all the high frequencies from the signal (Fig. 4) are displayed in the frequency spectrum (Fig. 5). The typical voltage-time signals and the prominent frequency from the C5 tubes analyzed using FFT for both the long and short tubes are shown in Figs. 4 and 5, respectively. Note that the wavelength of the voltage-time signal from the long tube was shorter than the wavelength of the short tube. The coupling effects for both tubes create an irregular amplitude envelope sound output, as shown in Fig. 4. Each tube displays a single prominent fundamental with very weak or non-existent harmonics. The wobble effect was due to improper shaking of the tube. To avoid the wobble effect, the tube needs to be shaken very quickly and strongly. By doing so, the wobble effect disappeared, as shown in Part C of Fig. 4.

As shown in Fig. 5, it is clear that the 2 primary peaks in both tubes are at 546 Hz and 1093 Hz, respectively. Whereas the long and short rattle tube (when played separately) showed an individual fundamental frequency of 528 and 1095 Hz, respectively. The pitch, due to the coupling effects of the two rattle tubes, were not identical to the pitch of the individual rattle tubes. Although both rattle tubes played simultaneously displayed the fundamental frequencies of air resonance in both tubes, the individual tubes played separately did not produce the exact frequency obtained from both rattle tubes played simultaneously. The coupling effects of the pair of tubes yielded a higher total amplitude compared to the individual tube amplitude.

The spectrum of both rattle tubes was a mixture of each of its individual rattles, which is shown by two prominent peaks (each peak corresponds to the pitch of each tube). Although the long and short rattle tubes (when played separately) showed an individual fundamental frequency of 528 and 1095 Hz, respectively, for the C5 tube; the coupling of both rattle tubes produced a fundamental frequency of 546 and 1093 Hz for the first and second peaks from the spectrum, respectively. Due to the disparity of the fundamental frequency, the pitch of the tube was calculated using the length and diameter of each rattle tube. Figure 6 shows the frequency spectrum of tube C5 to C6.

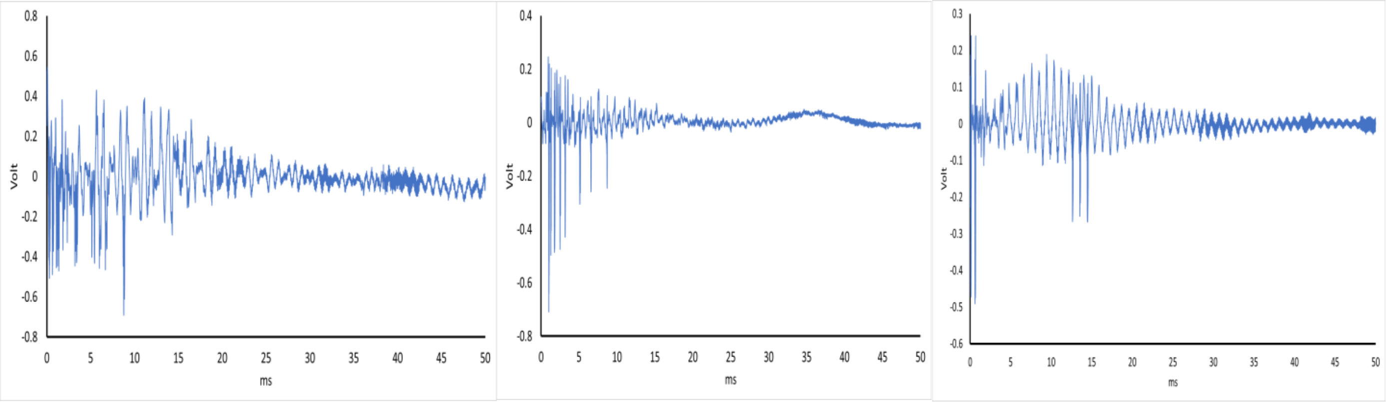


Fig. 4. The voltage-time signal of: (a) both C5 tubes; (b) the long C5 tube; and (c) the short C5 tube

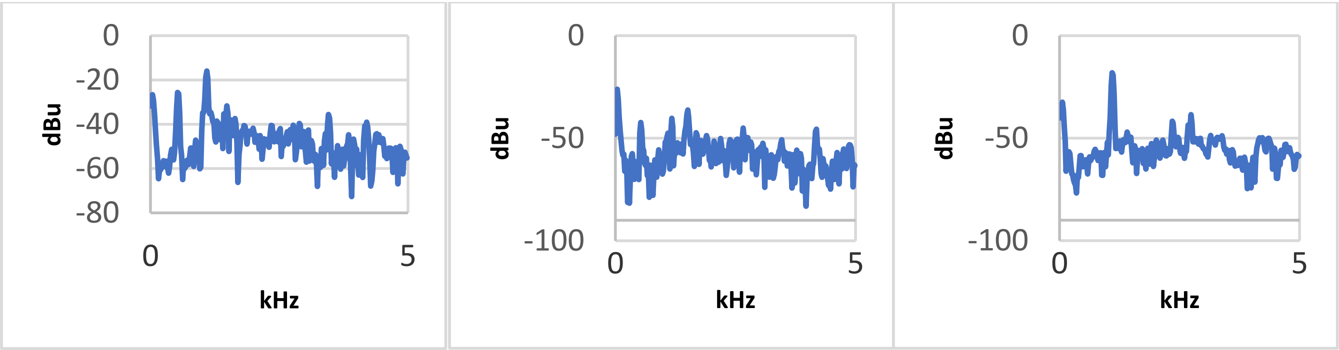
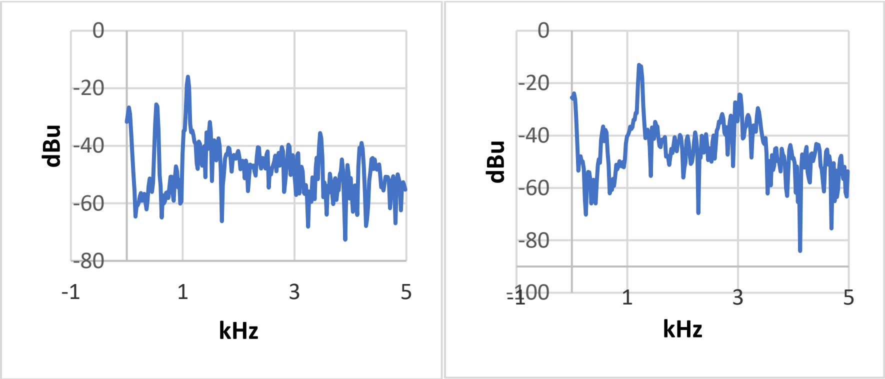
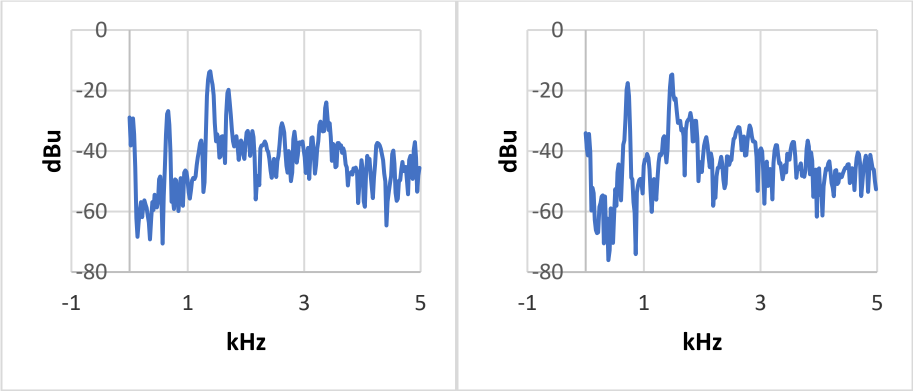


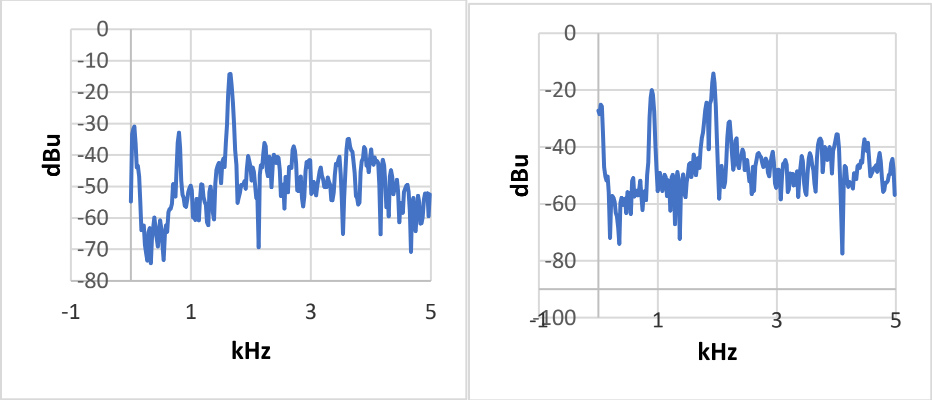
Fig. 5. Frequency spectrum of : (a) both C5 tubes; (b) the long C5 tube; and (c) the short C5 tube



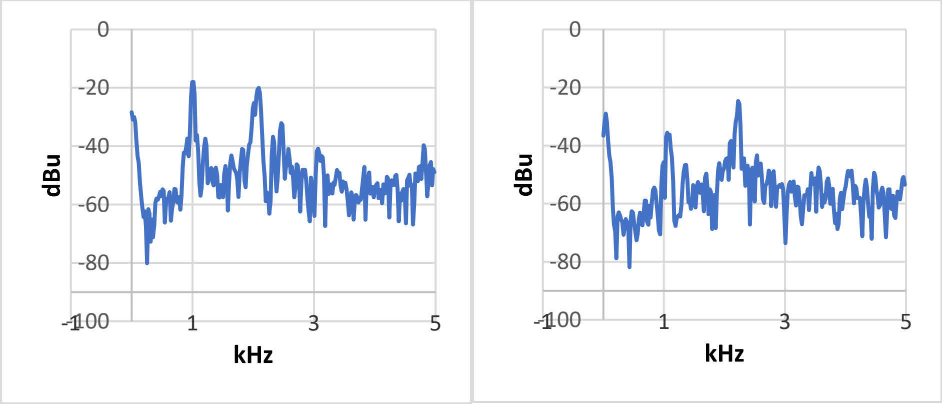
Tube C5 (546 Hz 1093 Hz) Tube D5 (625 Hz 1269 Hz)



Tube E5 (644 Hz 1406 Hz) Tube F5 (703 Hz 1484 Hz)



Tube G5 (800 Hz 1660 Hz) Tube A5 (917 Hz 1953 Hz)



Tube B5 (1015 Hz 2109 Hz) Tube C6 (1093 Hz 2246 Hz)

Fig. 6. Frequency spectrum of tubes C5 to C6

The long and short tubes displayed two primary peaks. Both peaks did not display their respective partial because of its proximity. Table 1 shows the calculated resonances for the long and short tubes compared with the equal tempered scale. Table 2 shows the pitch from both tubes, the long tube, and the short tube, along with data from Zainal *et al.* (2009) and the equal tempered scale for comparisons. The pitch of the angklung played with both tubes was not exactly equal to the long tube and short tube pitches individually. The long tube is considered as being the pitch of the angklung. Since the short tubes are tuned to be twice the long tube, the short tube appears to be the second harmonic of the first pitch (from the long tube). The sound of the angklung is a mixture of its individual tubes. The pitch when playing the angklung with only one of its tubes is slightly different from when playing the angklung with both rattle tubes. The variation between both tubes and the separate tubes are due to unsteady state of the waveform. The vibration cannot settle at a stable frequency before it fully dissipates.

In Priangan (between Bogor and Tasikmalaya and between Sukabumi and Cirebon), the tone systems are often called pelog and salendro. In this region the salendro tone system is an equidistant pentatonic system that is 5 tones in each octave. The interval between each pair of consecutive notes is just more than two Western semitones, or 240 cent) (van Zanten 2021a). The pelog tone system also consists of five major notes. The intervals between the consecutive pairs of notes are different, ranging from about one to four Western semitones or from 100 to 400 cent (van Zanten 2021b). The tunings of the instruments of three angklung ensembles confirm that these ensembles use the salendro tone system. The diatonic angklung was played in Bandung and Baduy angklung refers to an ensemble of 9 bamboo idiophones. Each idiophone consists of three tubes in a frame that is shaken, and each such instrument on its own is also called angklung. The three tubes within the frame are tuned in octaves, resulting in an interval of two octaves between the lowest and the highest tube. The intervals between consecutive notes produced by the different Baduy angklung instruments are approximately equidistant and there are five equidistant intervals within one octave.

In general, the long tube amplitude (fundamental pitch) was lower than the amplitude of the short tube (second harmonic pitch), except for tube B5 (as shown in Fig. 6). Note that the waveform from the long tube is shorter than the waveform from the short tube and thus also produced a lower amplitude in the spectrum (as shown in Fig. 6). The higher pitch (from the short tube) showed harmonic partial characteristics (with respects to the long tube) at 2.00 to 2.18 times the lower pitch and had a higher magnitude than the lower pitch, except for B5. The phenomenon is not common, since the harmonic partial magnitude is usually lower than the fundamental. Since the harmonic partial magnitude is higher than the fundamental, the harmonic partial (higher pitch) can be classified as the pitch of the rattle tube. The fundamental frequency (Hz) for the long and short tube was calculated based on the length and diameter of a closed cylinder. The results for both tubes and the separate tubes, along with the calculated resonance pitch, are shown in Table 2. The ratio between the second peak and the first peak and the ratio between the short tube and the long tube are given in bold values. The calculated resonances are given in italic values. In addition, the results for both tubes, the long tube, and the short tube from the study by Zainal *et al.* (2009), as well as the equal tempered scale, are included for comparison in Table 2.

Table 1. Calculated Resonances for the Long and Short Tubes Compared with the Equal Tempered Scale

Rattle Tubes	Diameter (mm)	Length (mm)	Frequency (Hz)	Equal Tempered Scale (Hz)
C5 short tube	24	60	1263.703	
C5 long tube	30	145	551.881	523.25
D5 short tube	23	50	1492.107	
D5 long tube	33	120	654.077	587.33
E5 short tube	22	46	1613.973	
E5 long tube	28	118	672.297	659.26
F5 short tube	21	40	1833.262	
F5 long tube	30	97	801.437	698.46
G5 short tube	20	35	2069.891	
G5 long tube	27	87	893.29	783.99
A5 short tube	18	30	2397.084	
A5 long tube	25	75	1029.622	880.00
B5 short tube	17	30	2417.863	
B5 long tube	26	60	1252.355	987.77
C6 short tube	11	25	3000.265	
C6 long tube	23	60	1269.455	1046.5

Table 2. Peak Frequencies from Both Tube, Long Tube, and Short Tube

	Both tubes			Separate			Zainal *et al.* (2009)			
Tube	1st peak	2nd peak	Ratio 2nd/1st	Long tube	Short tube	Short to long tube ratio	Both tube (range)	Long tube	Short tube	Equal tempered scale
C5	546	1093	**2.00**	528 *552*	1095 *1264*	**2.07**	521.44 to 526.28	521.51 to 524.20	1068.59 to 1079.35	523.25
D5	625	1269	**2.03**	586 *654*	1231 *1492*	**2.10**	585.30 to 591.07	583.42 to 595.53	1175.58 to 1193.07	587.33
E5	644	1406	**2.18**	665 *672*	1380 *1614*	**2.08**	660.78 to 673.11	659.45 to 666.18	1337.75 to 1344.48	659.26
F5	703	1484	**2.11**	710 *801*	1442 *1833*	**2.03**	700.08 to 706.58	699.83 to 707.90	1396.29 to 1413.12	698.46
G5	800	1660	**2.08**	797 *893*	1645 *2069*	**2.06**	788.99 to 802.78	787.98 to 797.40	1587.40 to 1597.49	783.99
A5	917	1953	**2.12**	896 *1029*	1922 *2397*	**2.14**	875.44 to 881.53	894.30 to 904.39	1779.85 to 1781.20	880.00
B5	1015	2109	**2.08**	1012 *1252*	2059 *2417*	**2.03**	1003.88 to 1011.44	983.13 to 1000.20	1779.85 to 1781.20	987.77
C6	1093	2246	**2.05**	1095 *2417*	2212 *3000*	**2.02**	1046.50 to 1059.88	1061.18 to 1081.37	2102.18 to 2116.98	1046.5

Note: The ratio between the second peak and the first peak and the ratio between the short tube and the long tube are typed in the bold values; the calculated resonances are typed in the italic values. The frequencies from Mohd Zainal et al. and the equal tempered scale for comparisons purposes.

CONCLUSIONS

1. The fundamental and second harmonic of an angklung set were determined. The fundamental frequency of each rattle tube was calculated using the diameter and the length of the tube.
2. The calculated fundamental frequency was compared with the pitch from the respective tube. The calculated fundamental frequency of the air resonance in the tube cannot estimate the pitch of an angklung due to the non-uniformity of the open end attached to the tongue of the tube. This caused the effective length to only be a rough estimation, whereas the diameter is considered as an ideal open cylinder.
3. The pitch for both tubes was also simultaneously analyzed with two major primary features observed. The sound output of every angklung with a pair of rattle tubes will have two primary peaks with each peak corresponding to the pitch of each rattle tube. Both peaks are harmonic partials with the second peak being 2.00 to 2.18 times the first peak frequency.
4. Although the crafter tuned the angklung manually, it seems that mother nature had proved that the crafter produces a partial very close to an octave interval.

ACKNOWLEDGMENTS

The authors are grateful to Universiti Malaysia Sarawak for the technical support.

REFERENCES CITED

Bucur, V. (2006). *Acoustics of Wood*, Springer, Berlin, Heidelberg, Germany.

Richter, H. G. (1988). *Holz als Rohstoff für den Musikinstrumentenbau* [*Wood as a Raw Material for Making Musical Instruments*], Moeck, Celle, Germany.

van Zanten, W. (2021a). “Tone systems, angklung, keromong, dancing and gender aspects,” in: *Music of the Baduy People of Western Java*, chapter 5, pp. 135-180, Brill. Stable URL: https://www.jstor.org/stable/10.1163/j.ctv1sr6k5w.12

van Zanten, W. (2021b). “Seasons for music and major rituals dancing and gender aspects,” in: *Music of the Baduy People of Western Java*, chapter 4, pp. 107-134, Brill. (2021) Stable URL: https://www.jstor.org/stable/10.1163/j.ctv1sr6k5w.12

Wegst, U. G. K. (2006). “Wood for sound,” *American Journal of Botany* 93(10), 1439-1448. DOI: 10.3732/ajb.93.10.1439

Wegst, U. G. K. (2008). “Bamboo and wood in musical instruments,” *Annual Review of Materials Research* 38(1), 323-349. DOI: 10.1146/annurev.matsci.38.060407.132459

Widjaja, E. A. (1980). “Angklung and other West Javanese bamboo musical instruments,” in: *Bamboo Research in Asia: Proceedings of a Workshop Held in Singapore, 28-30 May 1980*, G. Lessard, and A. Chouinard (ed.), International Development Research Centre, Ottawa, Ontario, Canada, pp. 201-204.

Zainal, M. R. M., Samad, S. A., and Hussain, A. (2005). "Sound analysis of angklung: A traditional musical instrument," in: *Proceedings of the MMU International Symposium on Information and Communications Technologies*, Putra Jaya, Malaysia, pp. 9-12.

Zainal, M. R. M., Samad, S. A., Hussain, A., and Azhari, C. H. (2009). "Pitch and timbre determination of the angklung," *American Journal of Applied Sciences* 6(1), 24-29. DOI: 10.3844/ajassp.2009.24.29

Article submitted: October 17, 2021; Peer review completed: December 19, 2021; Revised version received and accepted: January 14, 2022; Published: January 20, 2022.
DOI: 10.15376/biores.17.1.1670-1679