The Khene: A Lao Mouth Organ of the Isan Region of Thailand

Ahmad Faudzi Musib,[a,]* Aaliyawani E. Sinin,[b] Sinin Hamdan,[c] Khairul A. M. Said [c] and Ezra A. M. Duin [d]

*Corresponding author: faudzimusib@upm.edu.my

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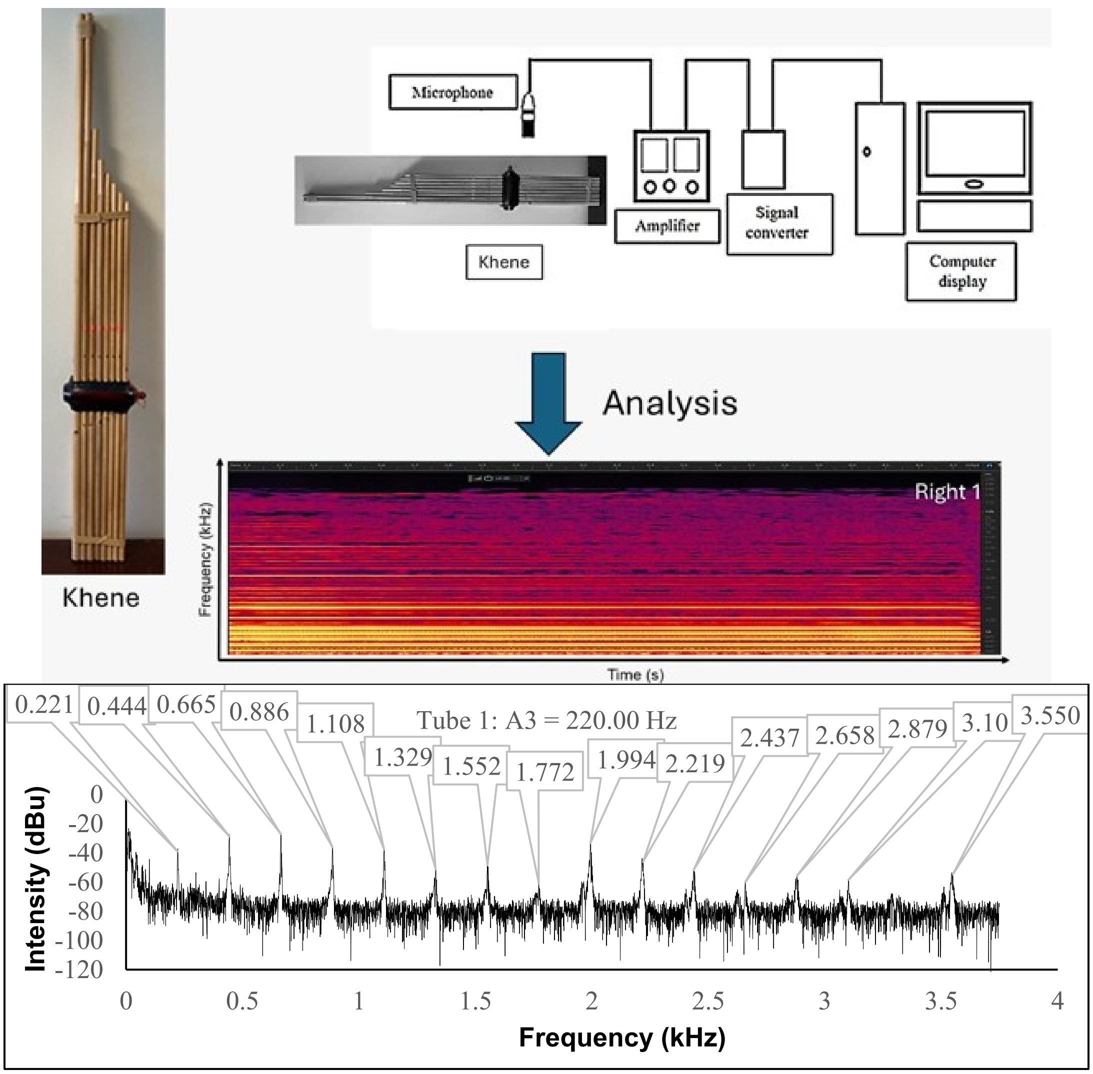
GRAPHICAL ABSTRACT



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The khene is a musical instrument from Thailand's Isan region (the Thai term for Northeastern Thailand and its local Thai inhabitants). The Fast Fourier Transform (FFT) of khene signal was determined *via* a Pico oscilloscope. Tubes 1, 2, 3, 4, 5, 6, 7, and 8 on the right and left side produced the fundamental frequency (in hertz) as 221(A3 = 220), 255(C4 = 261), 384(G4 = 394), 443(A4 = 440), 499(B4 = 493), 591(D5 = 587), 672(E5 = 659), and 887(A5 = 880) and as 519(C5 = 523), 247(B3 = 247), 293D4(293), 329(E4 = 331), 342(F4 = 349), 395(G4 = 392), 683(F5 = 698), and 781(G5 = 783), respectively. The standard deviations of the fundamental pitch from the equal tempered scale (ETS) for tube 1, 2, 3, 4, 5, 6, 7, and 8 on the right and left side were ± 1, ± 6, ± 10, ± 3, ± 6, ± 4, ± 13, ± 7 and ± 4, ± 0, ± 0, ± 2, ± 7, ± 3, ± 15, ± 2 Hz, respectively. The tunings were remarkably similar with the diatonic scale of ETS. The linear equation for the partial frequency *versus* harmonic number for tube 1 to 8 from the right and the left side is given by y1 = 220x + 1.31, y2 = 255x + 0.34, y3 = 384x + 0.77, y4 = 443x + 0.19, y5 = 499x - 0.13, y6 = 591x + 1.82, y7 = 672.x + 2.35, and y8 = 887x, and y1 = 519x + 0.14, y2 = 247x - 0.07, y3 = 293x + 0.40, y4 = 331x - 5.49, y5 = 341x + 1.70, y6 = 395x + 0.38, y7 = 683x - 0.4, and y8 = 782x - 0.50, respectively. The harmonic number of tubes 1 to 8 on the right and left side were 16, 14, 9, 8, 7, 6, 5, 7, and 7, 14, 10, 10, 11, 9, 5, 4, respectively.

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Keywords: Khene; Isan (Northeastern Thailand); Fast Fourier Transform (FFT); Harmonics

Contact information: a: Faculty of Human Ecology, Universiti Putra Malaysia, 43400, Serdang, Selangor Darul Ehsan, Malaysia, b: Department of Science and Technology, Faculty of Humanities, Management and Science Universiti Putra Malaysia Bintulu Campus, 97008 Bintulu, Sarawak, Malaysia; c: Faculty of Engineering, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia; d: Faculty of Applied and Creative Art, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak, Malaysia;
** Corresponding author: faudzimusib@upm.edu.my*

INTRODUCTION

The khene mouth organ is an aerophone that is used by both Thai and Lao people both in Thailand and in the neighboring country of Laos. The khene is the national instrument of Laos (Whitaker 1972). The instrument represents the Lao identity, particularly in relation to rituals, folk music, and communal life. The bamboo tubes of the khene (spelled khaen, ken, khen) (Shepherd *et al.* 2003) or ken in English (Martin and Mihalka 2020) are attached to a little, hollowed-out hardwood reservoir that air is blown into. The UNESCO Representative List of the Intangible Cultural Heritage of Humanity (UNESCO 2021) now includes khene music, a crucial part of Lao culture that promotes social and familial togetherness (Yap 2018). The khene uses a free reed made of brass or silver. Five different lai (or pentatonic modes) with different drone pitches make up the two families (Thang San and Thang Yao) that make up the khene. Lai sutsanaen (G, A, C, D, E), lai po sai (C, D, F, G, A), and lai soi (D, E, G, A, B) are members of the Thang San family, whereas lai yai (A, C, D, E, G) and lai noi (D, F, G, A, C) are members of the Thang Yao family. Lai sutsanaen is regarded as the father of the Lai Khaen, while Lai po sai is the oldest of the modes. The Lao Khaen Chet utilize 14 tubes, the Khmu use a version with only 12 tubes, and the Thai employ a 16-tube variant, depending on local customs. There are several sizes and variations of the khene. A skilled khene player, sometimes referred to as a mo khene, needs to be able to perform each song in at least eighteen distinct ways. It is one of the few Asian free reed instruments for which an instruction book in English has been written, according to Miller (1980).

Since its 2017 inclusion on UNESCO's Representative List of the Intangible Cultural Heritage of Humanity, interest in conserving, teaching, and adapting the khene has grown significantly. The following elaborates on its performance practice, regional variants, and socio-cultural role. The khene typically consists of 14 to 18 bamboo pipes arranged in two parallel rows. Each pipe contains a finger hole and a free reed. Sound is produced by blowing through a mouthpiece while manipulating the finger holes to create polyphonic textures, combining melody and drone. Regional variations influence the tuning system, with pentatonic and heptatonic scales being most common. Traditionally, the khene plays a central role in *lam* or *mor lam*-a poetic form of musical storytelling. It is performed solo, in duets, or in ensembles, particularly during ceremonial events. Performers often improvise within fixed modal systems such as *lai soi* and *lai yai*. Since UNESCO's recognition, formal teaching methods, including written notation, have supplemented oral traditions. Contemporary fusion styles now integrate the khene with jazz, techno, and classical music, gaining exposure through international festivals and digital platforms, which also engage the diaspora. Though the instrument is most closely associated with Laos and Northeastern Thailand, related versions exist throughout Southeast Asia. The Lao khene is used in rituals and courtship and is tied to Buddhist and Animist traditions. The Isan (the Thai term for Northeastern Thailand and its local Thai inhabitants) variant, which shares linguistic and cultural ties with Laos, has adapted tuning systems to ensure compatibility with Western instruments in popular *mor lam* performances. In Vietnam, Tai-speaking communities in the highlands use similar mouth organs, whereas in Cambodia, related instruments are found among upland groups but are not part of mainstream Khmer culture. The UNESCO listing has also encouraged the standardization of instrument-making, with modern materials such as epoxy wind chests and plastic reeds now used to enhance durability and support mass production for educational use. Historically, the khene has been an essential part of Lao cultural life, performed at weddings, funerals, temple festivals, and community gatherings, symbolizing ethnic identity and serving as a traditional medium for musical courtship. Following its recognition by UNESCO, national pride and institutional support have increased, leading to the integration of khene instruction into both community programs and formal education, particularly among urban youth. Among the Lao and Isan diasporas in countries such as the U.S., France, and Australia, the khene continues to function as a key cultural marker, with performances featured at multicultural festivals and widely shared on platforms such as YouTube and TikTok. Additionally, both Laos and Thailand have used the khene in cultural diplomacy, showcasing it at international expos, ASEAN summits, and embassy events as a symbol of regional heritage and resilience. The khene is more than an instrument. Rather, it is a living emblem of identity, continuity, and memory. UNESCO's recognition has elevated its profile, fostering both preservation and creative innovation. Balancing authenticity with adaptability remains key to ensuring its relevance in contemporary cultural life.

The UNESCO inscription of Lao khene music in December 2017 has had a considerable impact on khene pedagogy and new repertoire production. The UNESCO ruling specifically urged the government of Laos to promote transmission at the local and national levels through formal and informal education. Since then, the Ministry of Information, Culture, and Tourism has collaborated with regional cultural organizations to include khene instruction into pilot school programs and community cultural centers, especially in rural areas where khene customs are most prevalent. These educational initiatives are supported by inventory procedures and action plans. Following inscription, workshops, youth training, and intergenerational gatherings were expanded by local organizations such as the Association of Khene Arts. They provide structured courses on notation systems, musical theory, instrument construction, and technique. All throughout Laos, these non-formal education programs are taking place in local cultural centers and villages. Efforts include generating guideline publications, digital archives of repertoire and practices, and pedagogical guides to facilitate standardized teaching and preservation. Some university research programs now offer scholarships and systematic training to young khene makers and players, incorporating parts of Western notation and assessment stages for learners. Young composers and groups have been urged by academics and professionals to create new works for khene that combine regional traditions with classic Lao idioms. Particularly in international and regional ensemble situations, Christopher Adler's (2023) works and recommendations for composers employing khene have grown to be significant resources. Particularly in Isan and university-based contexts, workshops that blend Thai classical music and Western musical structures with khene method have become popular. Students are experimenting with fusion works that incorporate elements from other traditions, as well as harmonies and tuning. Since inscription, the government's action plan and cultural financing have encouraged national festivals to commission new khene compositions or choreographed performances that combine traditional lam traditions with contemporary staging.

The origins and evolution of these musical instruments are examined in James Cottingham's 2023 study (Cottingham 2023). The study looks at the construction, functionality, and cultural importance of the wide variety of free reed instruments that can be found across East and Southeast Asia. In a study of Thai ritual and popular sound worlds, Pierre Prouteau focuses on the intersections between free reed traditions and twin horns, processional sound systems, and musical technology (Prouteau (2022–2023)). An Isan or Lao vocalist can play khene solo (dio khene), in an ensemble (khene wong and wong pong lang), or as a soloist's accompaniment (mor lam). It is commonly played on the traditional fretted plucked lute known as the phin (Hamdan *et al.* in press). Figure 1 shows a 16 tube khene. Typically, a finger covering the tube's hole produces sound. Most instruments feature a diatonic scale, which is a musical scale consisting of two half steps, five whole steps, and seven notes. C, D, E, F, G, A, and B) for the left-hand side and chromatic additions or duplets form the foundation of Western music. A duplet is a pair of equal notes played in time of three, or a set of two notes played in the time typically allowed to three notes of the same value. Compound time signatures, such as 6/8, where each beat is inherently divided into three pieces, are common places to find duplets. All 12 pitches are included within an octave in a chromatic scale, which is a musical scale with the right-hand side semitones separating each pitch. This basic tonal scale-which includes C, C#, D, D# E, F, F#, G, G#, A, A#, and B-is frequently employed in Western music.

(a)

(b)

Fig. 1. A 16-bamboo tube khene as seen from the (a) right-hand and (b) left-hand side view

Layers of pentatonic scale elements make up the chords that the khene produces. Two holes are waxed to provide steady drones that act as a basement for the melodies, which are also closely linked to the scales of the lai, depending on the mode of the instrument. A stiff, fibrous grass called yah nang connects the khene's tubes, and kissoot, also called khisut, a black insect wax, holds them in place. Inside each tube is a little free reed made of old coins that have been hammered into very thin sheets (Fig. 2).

Fig. 2. A tiny free reed composed of worn coins that have been pounded into extremely thin sheets is placed inside each tube

Inside the frame is a thin, flexible metal reed that is fashioned from hammered coins. The reed vibrates back and forth due to airflow, which permits air to flow around it. The reed is referred to as free since it vibrates without touching or colliding with any solid surface. This permits constant airflow and sustained vibration. The note has a particular timbre, and the second harmonic is firmly supported by the reeds, which are positioned exactly at the quarter-point of the tube's effective length. Frequencies that are integer multiples of the fundamental frequency are also referred to as harmonics. The fundamental frequency is also called the first harmonic. Non-harmonic in music refers to having nothing to do with harmony or a harmonic. The reed in the tube affects the harmonics or overtones together with the fundamental. The inward-facing side of each bamboo tube typically has a tuning slot consisting of a small rectangular or oval hole that is carved into the tube. These tuning slots are crucial for fine-tuning the pitch of each pipe. The slot affects the resonating length of the air column inside the bamboo pipe. By adjusting the size or position of the slot, makers can raise or lower the pitch of the note produced by that pipe. Often, a bit of beeswax or resin is added to the slot to adjust tuning precisely, allowing the maker to fine-tune the instrument after carving. This feature makes the khene both simple in construction yet highly precise in sound production. It is one of the reasons why the khene can play complex traditional scales and harmonies despite its seemingly modest build. A clear image of a khene pipe assembly, showing the inward-facing tuning slots is shown in Fig. 3. Notice that each bamboo pipe also has a finger hole on its outer side**,** which the player covers to allow that reed-pipe to sound. The tuning slot (rectangular opening) alters the acoustic length, tuning the tube to match its reed's frequency for harmonious vibration. This system allows adjustments even after assembly.

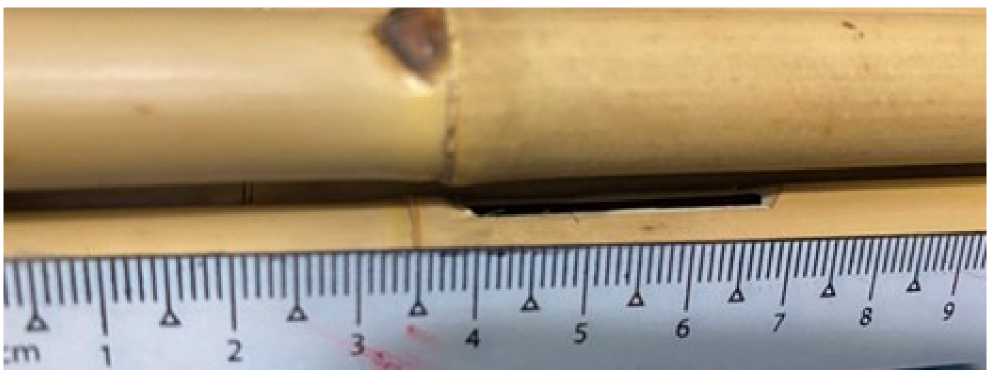


Fig. 3. A rectangular holes on the interior surface of each bamboo tube-these tuning slots are carved into the pipes.

The scale of this particular instrument is comparable to a two-octave A minor scale, and five pentatonic modes are commonly used: C, D, F, G, A, C; D, E, G, A, B, D; D, F, G, A, C, D; A, C, D, E, G, A and G, A, C, D, E, G. Although it is technically conceivable, the sixth mode-E, G, A, B, D, E-is rarely used due to its challenging gameplay. The khene has seven tones per octave, which are A, B, C, D, E, F, and G, just as the western diatonic natural A-minor scale. A khene can be built in a certain key after the reed is in place and the tubes are cut. The notes A2, B2, C3, and C4 are produced by the instrument's four longest tubes, which are all the same physical length. However, most of the tubes do not resonate all the way through. This is because a rectangular hole is bored in the wall of each tube to establish its acoustical length, which is always shorter than its physical length. It seems that the tube' meticulously graduated external lengths were selected for aesthetic rather than practical reasons because these holes are concealed. Through an aperture at one end of the wind chest, the instrument can be breathed and expelled, allowing it to be played continuously for long periods of time. The sixteen tubes (two of which are set to the same pitch, G3) generate a diatonic scale that includes two octaves from A2 to A4 (A2, B2, C3, D3, E3, F3, G3, A3, B3, C4, D4, E4, F4, G4, and A4). Instead of being in scalar order, the pitches are spread out throughout the two rows of reeds to accommodate conventional fingering patterns. Depending on the mode (lai), two tubes are used as drones in the instrument's top register for any given piece. They are kept playing continuously by plugging their fingerholes with small beeswax beads at intervals of an octave, a fifth, or a fourth. The performer's ten fingers are left to produce a tune against the drone by successively covering particular fingerholes. A diatonic interval is created by combining two notes from a diatonic scale. A chromatic interval is a non-diatonic interval composed of two notes from a chromatic scale.

EXPERIMENTAL

The wind chest of the khene is a small, hollowed-out wooden reservoir that is blown into bamboo tubes. The instrument considered here is made up of sixteen bamboo tubes, eight on each side, that are joined by a kind of beeswax inside a hardwood reservoir that has been hollowed out. The individual tubes that emit sound when the hole is closed are displayed in Fig. 4. The bamboo is about the same length on both sides. Tubes 1 and 2 have a physical length of 100 cm each, whereas tubes 3, 4, 5, 6, 7, and 8 have physical lengths of 80, 75, 72.5, 70.5, 68.5, and 67 cm, respectively. The inner and outer diameters of each tube are 10.5 mm and 12.6 mm, respectively. The second, third, and fourth fingers are used to cover tubes 2, 3, 4, 5, 6, and 7, while the fifth finger of the right and left hands is used to regulate the sounds in tube 8. Tube 1 has holes at the front tube, allowing both thumbs to control the front-positioned holes on tube 1. The opening at the bottom of tube 8 is the only one that is covered by the fifth finger (Fig. 4b and 4c). The instrument is often held by using both palms to grab the hardwood reservoir, which acts as the wind chest. The tubes' perforations are closed to chosen notes.

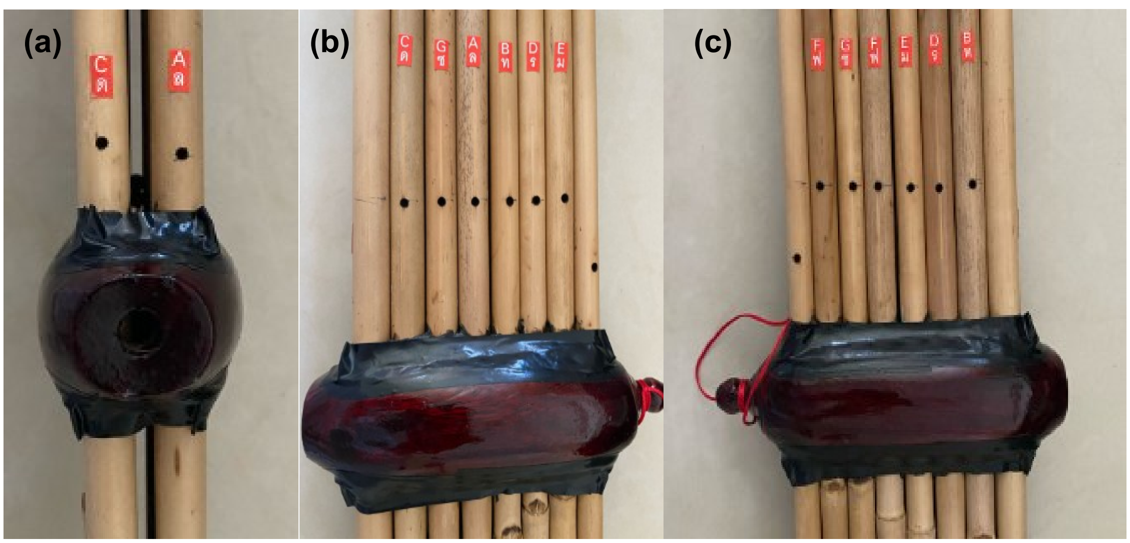


Fig. 4. (a) Front view with A and C on the right and left-hand side, respectively, (b) right view with A (hole at the side near the blowing point for the thumb position) and C, G, A, B, D, E, and A (with no label) on right-hand side tube; (c) Left view with C (hole at the side near the blowing point for the thumb position) and B, D, E, F, G, F, and G (with no label) on left-hand side tube

The bamboo species that is suitable for the tubes is *Schizostachyum pilosum.* The stalks are trimmed into different lengths and then let to dry. After connecting the bamboo tubes (eight on one side) with a dried bamboo strip, beeswax is used to further seal them. This dried bamboo strip is used as a string to bind the bamboo tubes together to create a two-layered raft. The Trigona bee, one of the biggest genera of stingless bees, is the source of beeswax, which is used to seal the gaps between the bamboo tubes and the wind chest. The wind chest is a hollowed-out hardwood reservoir made of teak wood. A simple diatonic scale (from low to high) is used to present the notes. The goal of the study was to determine the key of the instrument and identify the notes in each tube. This study is distinct and noteworthy because there has not been much investigation into whether the results align with the notes written on the tubes. It displayed the 16 notes from the separate tubes as well as the musical key.

The frequency was measured at the studio hall of Universiti Malaysia Sarawak (UNIMAS). The audio signal was recorded in mono, at 24-bit resolution, and 48 kHz sampling rate. The signal was calibrated using a 1 kHz sine wave. The signal was recorded using the Steinberg UR22mkII (audio interface), Audio-Technica AT4050 (microphone) and XLR cable (balance). To ensure a fair comparison, the khene was played in the conventional seated position. In order to capture the true acoustic qualities of the sound, this posture is most indicative of normal playing settings and promotes natural sound output and resonance throughout the recording process. This arrangement guarantees that the recordings accurately capture the tonal qualities of the sound without adding bias or distortion from different microphone positions. The model of the PicoScope was PicoScope 4224, 2 Channel, USB powered, 12-bit resolution and 20 MHz bandwidth. PicoScope software (Pico Technology, 3000 Series, Eaton Socon, UK) was utilized to visualize and analyze time signals from PicoScope oscilloscopes and data recorders for real-time signal capture. The PicoScope software facilitates analysis using Fast Fourier Transform (FFT), a spectrum analyzer, voltage-based triggers, and the capability to store and load waveforms to a disk. Figure 5 illustrates the schematic diagram of the experimental apparatus.

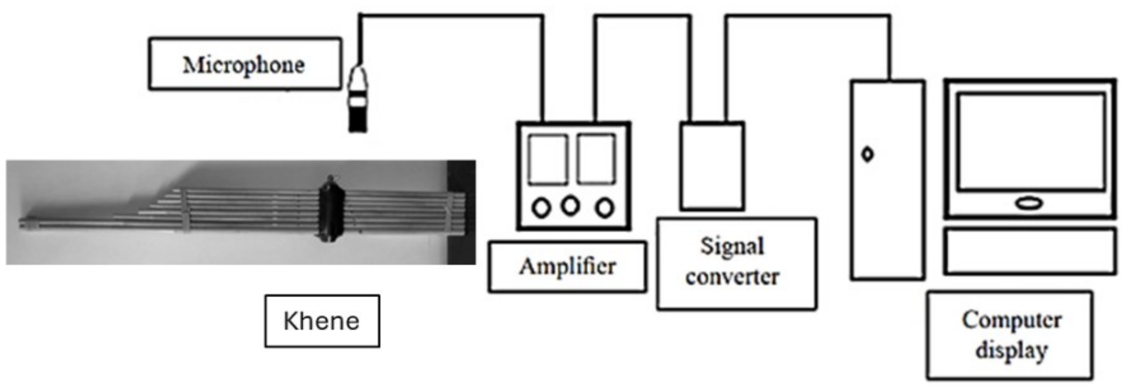


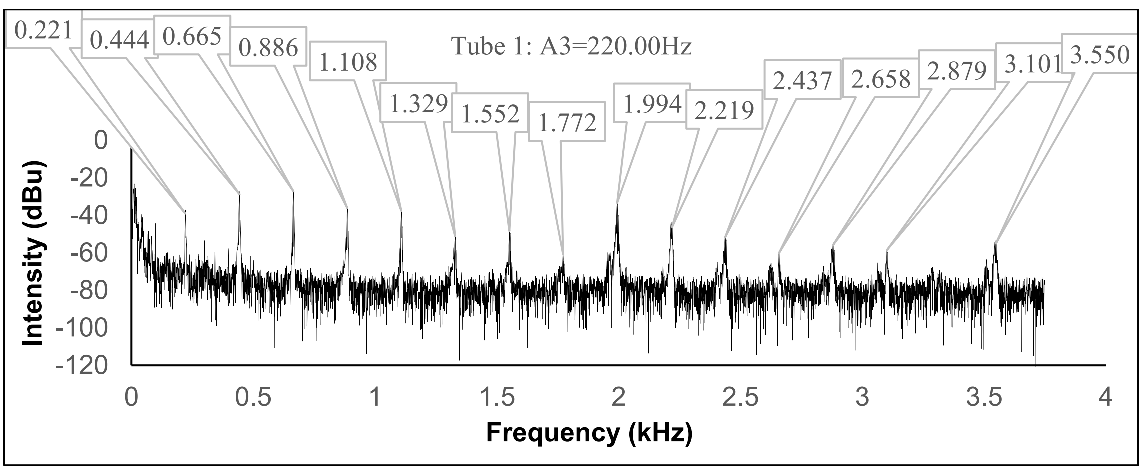
Fig. 5. Schematic diagram of microphone data acquisitions

The khene was positioned to record sound with little interference. The Behringer Powerplay Pro XL amplifier (Behringer, Zhongshan, Guangdong, China) guaranteed that the sound capture was sufficiently loud for detection by the signal converter. The sound spectra are derived from PicoScope readings. Subsequent to the acquisition and recording of the data sound, the FFT was evaluated utilizing Adobe Audition to ascertain the dominant frequency for each tone at designated intervals. The Fourier transformation identifies fundamentals, harmonics, and subharmonics.

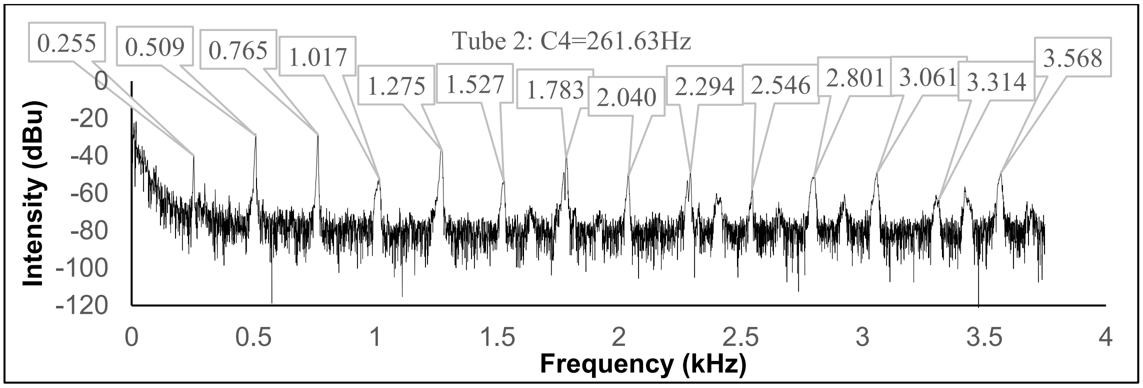
The microphone was positioned 20 cm from the tube, as shown in Fig. 5. This 20 cm microphone position promotes natural sound generation and resonance and is most realistic of normal playing situations. To capture the authentic acoustic qualities, the microphone was positioned in front the khene at a constant distance and angle during the recording process to guarantee that the recordings accurately captured the acoustic qualities of the instrument without adding any bias. With this setup, distortion is avoided and the recordings are guaranteed to accurately capture the tonal qualities. The instrument was played and recorded under identical circumstances to minimize any anomalies or variations. Each tube's pitch was determined using a Pico oscilloscope recording of the time and frequency spectrum. The fundamental and overtones of each tube were then determined using FFT analysis. The experimental conditions in the lab were established at 25 °C and 60% relative humidity. The frequency of each tube's sound was determined by shutting off the tubes that created the desired sound. The frequency of each tube was recorded three times. The Time Frequency Analysis (TFA) was performed in Adobe Audition utilizing measurements in seconds, concentrating on the exact intensity in hertz to distinguish the power of partial frequencies. The fundamental partial, which is the lowest frequency and significantly influences the perceived pitch, is one of the partials that contribute to the overall sound. Partials can be either harmonic (whole number multiples of the fundamental) or inharmonic (frequencies without simple ratios). The data were found to be similar for every run. Therefore, the statistical variance was zero. The data were always consistent regardless of how many experiments were conducted. Therefore, the mean is similar to the data with no standard deviations.

RESULTS AND DISCUSSION

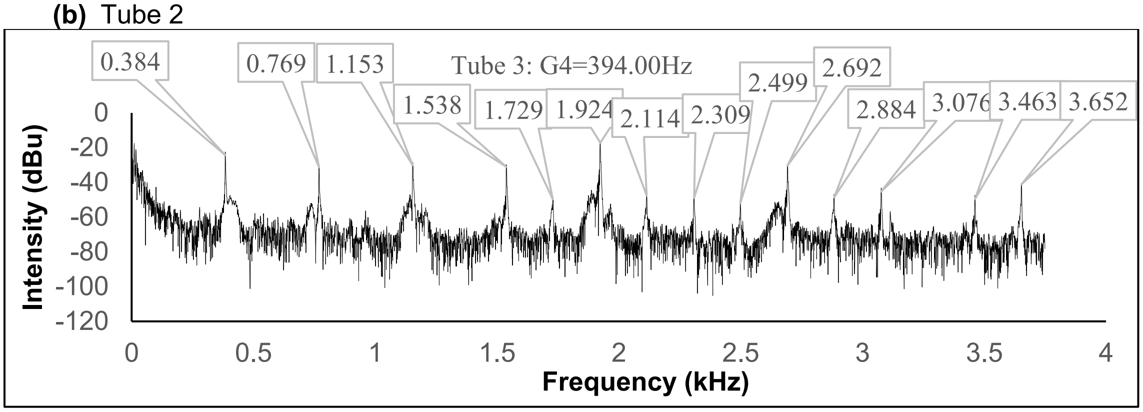
Figure 6 shows the FFT spectra from tubes 1 to 8 from the right-hand side. The reeds are positioned precisely at the quarter-point of the tube's effective length, giving the note a specific timbre and firmly supporting the second harmonic (except for tubes 3 and 6).



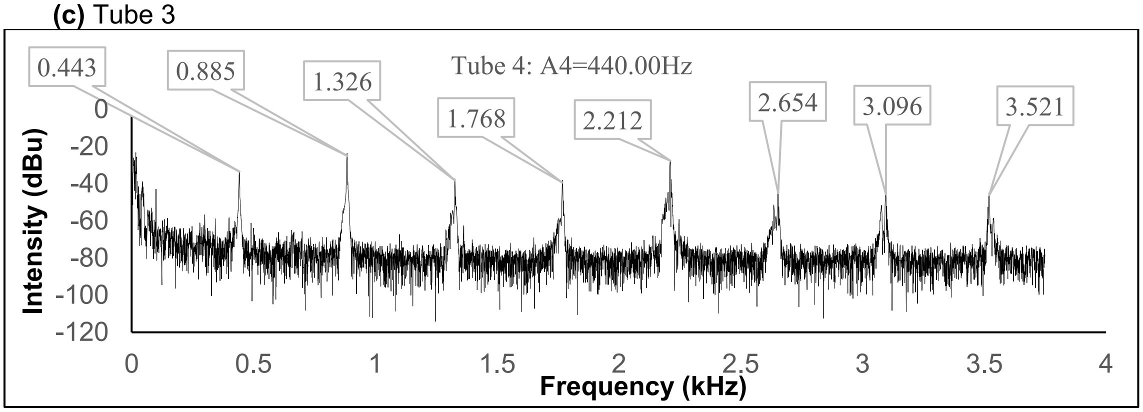
(a) Tube 1



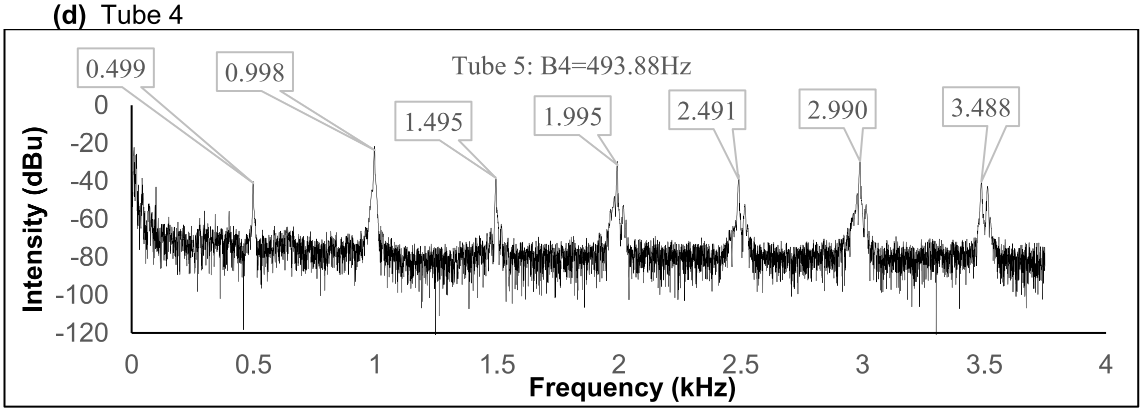
(b) Tube 2



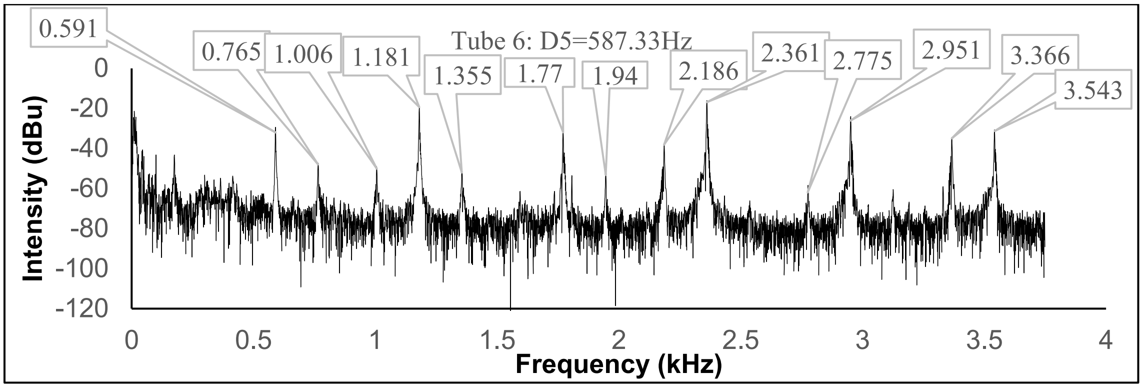
(c) Tube 3



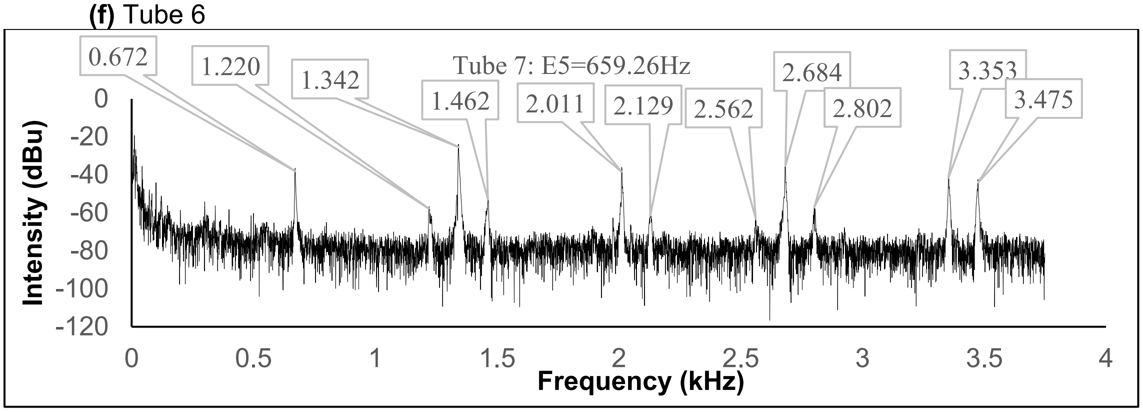
(d) Tube 4



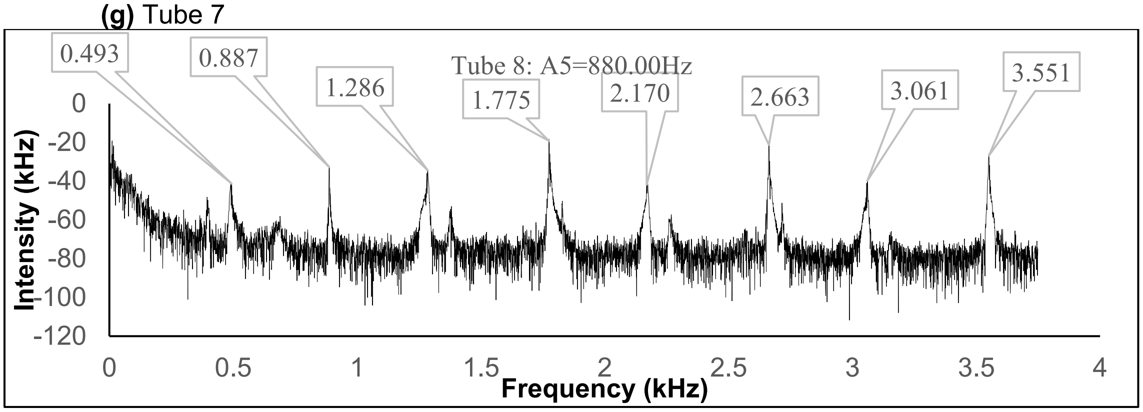
(e) Tube 5



(f) Tube 6



(g) Tube 7



(h) Tube 8

Fig. 6. The FFT spectra (intensity *versus* frequency) from tubes 1 to 8 from the right-hand side

The tunings are in the tonal relationships for the eight pitches as shown in Table 1, which displays the fundamental and higher partial frequencies for tubes 1 to 8 from the right-hand side. From Table 1, Fig. 7 was plotted to show the changes in partial frequencies *versus* the harmonic number (harmonic number=1 is for fundamental frequency).

Table 1. Fundamental and Higher Partial Frequencies for Tubes 1 to 8 from the Right-hand Side

Harmonic Number	Tube 1(A3)	Tube 2(C4)	Tube 3(G4)	Tube 4A4)	Tube 5(B4)	Tube 6(D5)	Tube 7(E5)	Tube 8(A5)
F1	221	255	384	443	499	591	672	493
F2	444	509	769	885	998	1181	1342	887
F3	665	765	1153	1326	1495	1771	2011	1286

F4	886	1017	1538	1768	1995	2361	2684	1775
F5	1108	1275	1924	2212	2491	2951	3353	2663
F6	1329	1527	2309	2654	2990	3543		3061
F7	1552	1783	2692	3096	3488			3551
F8	1772	2040	3076	3521				
F9	1994	2294	3463					
F10	2219	2546						
F11	2437	2801						
F12	2658	3061						
F13	2879	3314						
F14	3101	3568						
F15	-							
F16	3550							

Due to the fabrication error, the instrument's frequencies fluctuated somewhat even though the pitch relationships stayed the same. The standard deviations of the fundamental pitch from the diatonic pitch for tubes 1 to 8 were due to the disparity during fabrication. The fundamental frequency (in hertz) of the individual tubes 1, 2, 3, 4, 5, 6, 7, and 8 on the right-side is 221(A3 = 220), 255(C4 = 261), 384(G4 = 394), 443(A4 = 440), 499(B4 = 493), 591(D5 = 587), 672(E5 = 659), and 887(A5 = 880) respectively. The standard deviations of the fundamental pitch from the equal tempered scale (ETS) for tube 1, 2, 3, 4, 5, 6, 7, and 8 on the right-side were ± 1, ± 6, ± 10, ± 3, ± 6, ± 4, ± 13, and ± 7 Hz, respectively, from the diatonic scale. The tunings were remarkably similar in tonal relationships with standard ETS. The harmonic numbers of tubes 1 to 8 are 16, 14, 9, 8, 7, 6, 5, and 7 respectively.

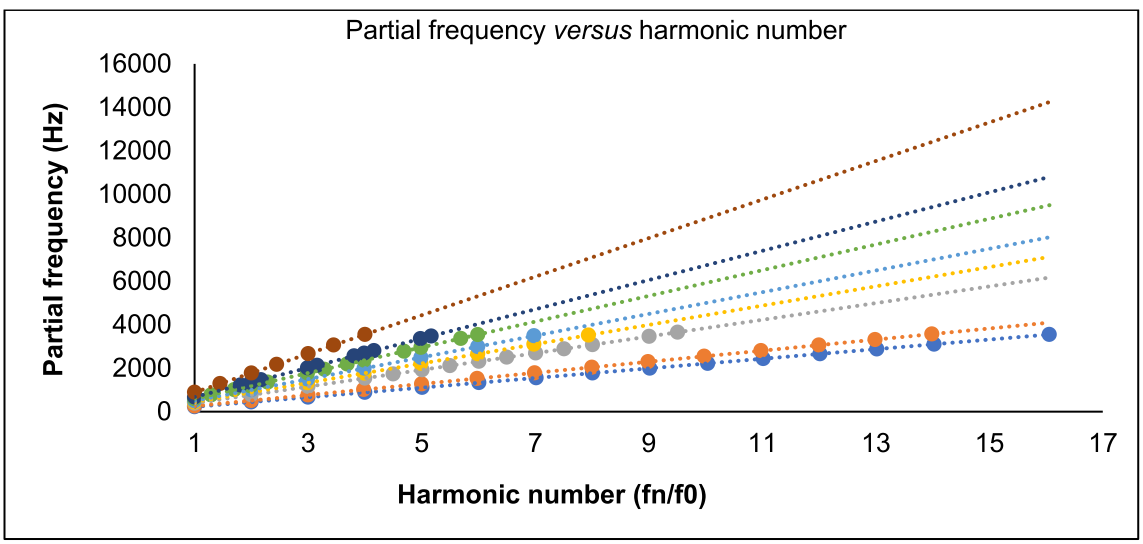


Fig. 7. The partial frequency (Hz) *versus* the harmonic number (fn/f0) from the right-hand side (harmonic number = 1 is for fundamental frequency)

The linear equation (eq. 1 to 8) for the partial frequency *versus* the harmonic number for tubes 1 to 8 from the right side is given as follows:

$y1 = 220.97x+1.3126$ for tube 1: (221 = A3) eq. 1

$y2 = 255.06x+0.3496$ for tube 2: (255 = C4) eq. 2

y3 = 384.05x+0.7795 for tube 3: (384 = G4) eq. 3

y4 = 443.33x+0.1993 for tube 4: (443 = A4) eq. 4

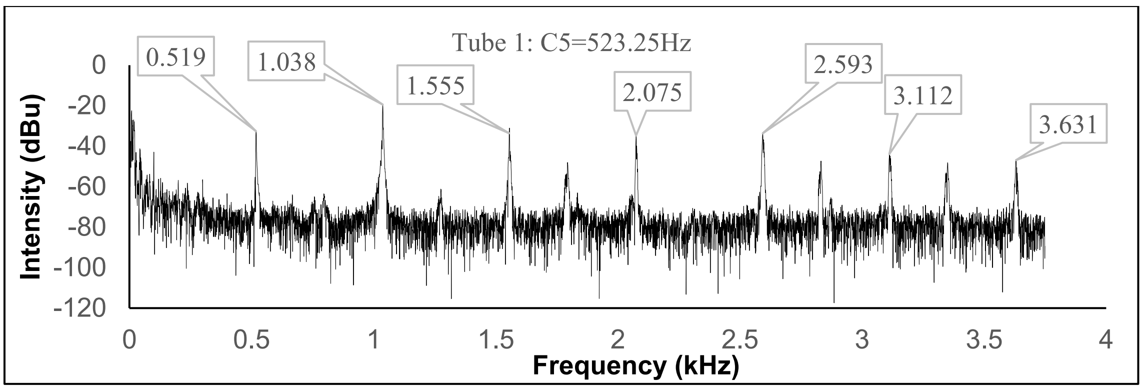
y5 = 499.53x-0.1376 for tube 5: (499 = B4) eq. 5

y6 = 591.26x+1.8292 for tube 6: (591 = D5) eq. 6

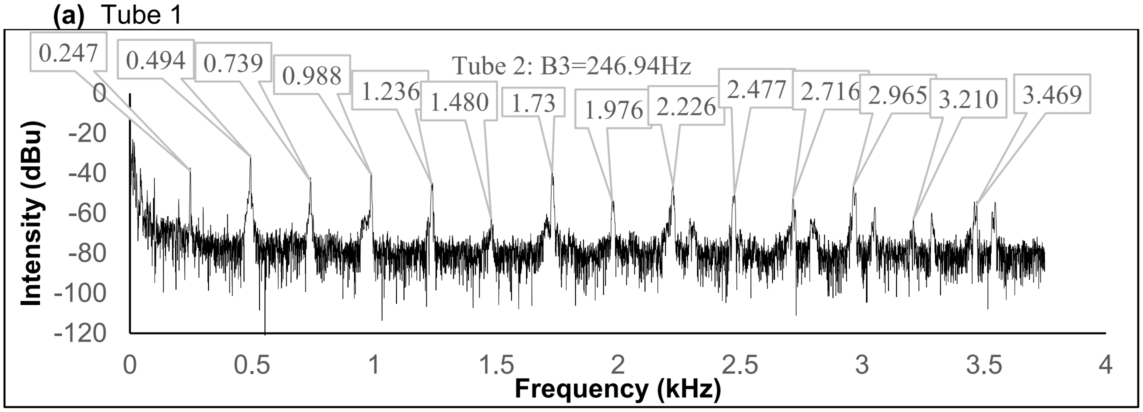
y7 = 672.31x+2.3548 for tube 7: (672 = E5) eq. 7

y8 = 887x-2E-12 for tube 8: (887 = A5) eq. 8

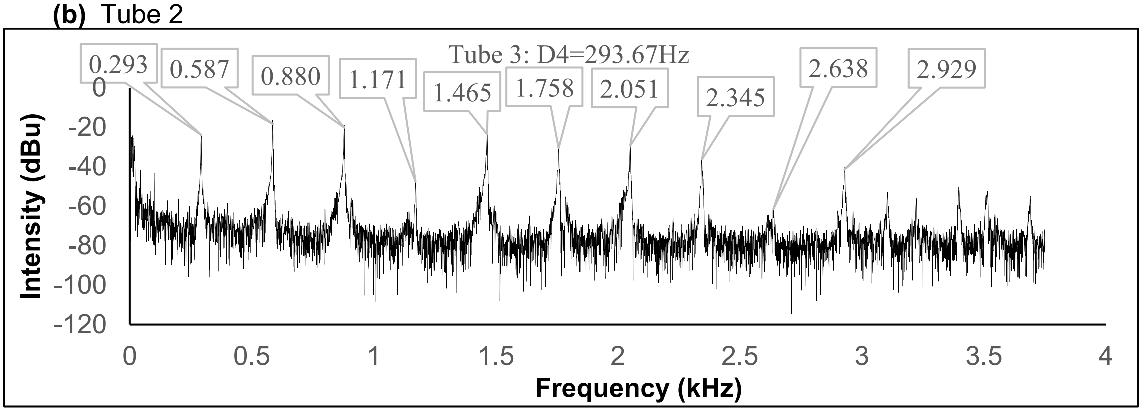
Figure 8 shows the FFT spectra from tubes 1 to 8 from the left side. Table 2 displays the fundamental and higher partial frequencies for tubes 1 to 8 from the left side. Figure 9 shows the partial frequency *versus* the harmonic number. Table 3 shows the note arrangement for the tubes 1 to 8 for the left side and right-side tubes.



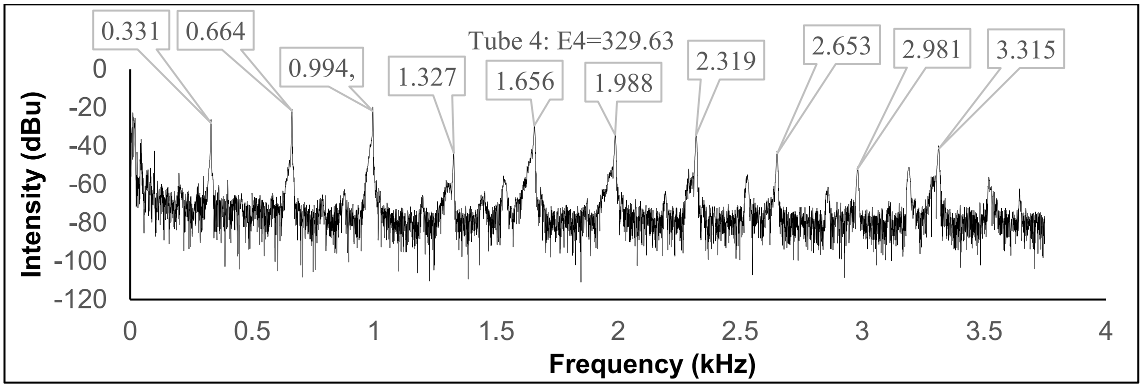
(a) Tube 1



(b) Tube 2



(c) Tube 3



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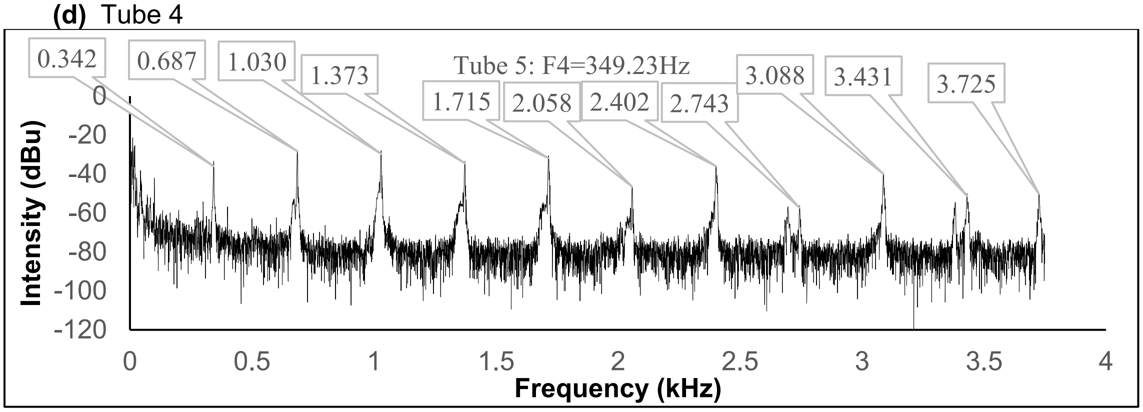
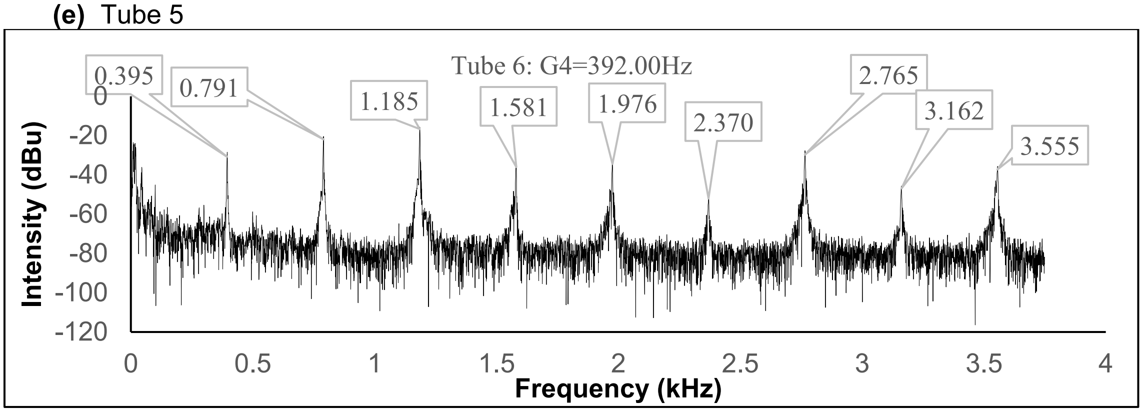
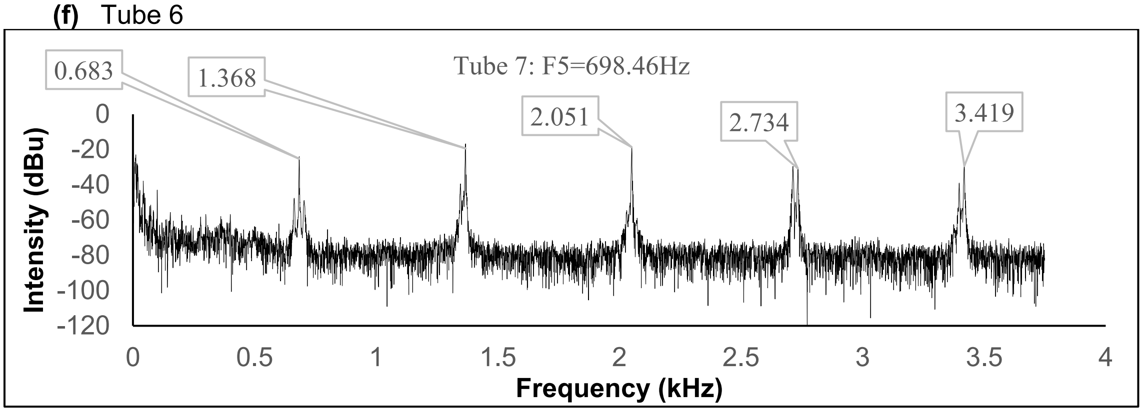


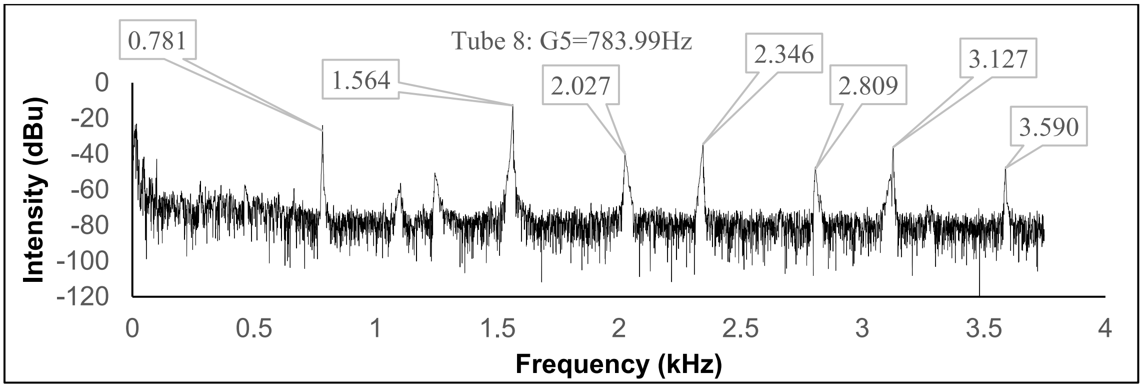
(e) Tube 5



(f) Tube 6



(g) Tube 7



(h) Tube 8

Fig. 8. The FFT spectra (intensity *versus* frequency) from tubes 1 to 8 from the left-hand side

Table 2. Fundamental and Higher Partial Frequencies for Tubes 1 to 8 from the Left-hand Side

Harmonic Number	Tube 1(C5)	Tube 2(B3)	Tube 3(D4)	Tube 4(E4)	Tube 5(F4)	Tube 6(G4)	Tube 7(F5)	Tube 8(G5)
1	519	247	293	331	342	395	683	781
2	1038	494	587	664	687	791	1368	1564
3	1555	739	880	994	1031	1185	2051	2346
4	2075	988	1171	1327	1373	1581	2734	3127
5	2593	1236	1465	1656	1715	1976	3419	
6	3112	1480	1758	1988	2058	2370		
7	3631	1730	2051	2319	2402	2765		
8		1976	2345	2653	2743	3162		
9		2226	2638	2981	3088	3555		
10		2477	2929	3315	3431			
11		2716			3725			
12		2965						
13		3210						
14		3469						

The fundamental frequency (in hertz) of the individual tubes 1, 2, 3, 4, 5, 6, 7, and 8 on the left side was 519(C5 = 523), 247(B3 = 247), 293D4(293), 329(E4 = 331), 342(F4 = 349), 395(G4 = 392), 683(F5 = 698), and 781(G5 = 783), respectively. The standard deviations of the fundamental pitch from the ETS for tubes 1, 2, 3, 4, 5, 6, 7, and 8 on left side were ± 4, ± 0, ± 0, ± 2, ± 7, ± 3, ± 15, and ± 2 Hz, respectively, from the diatonic scale. The tunings were remarkably similar in tonal relationships with standard ETS. The harmonic numbers of tubes 1 to 8 are 7, 14, 10, 10, 11, 9, 5, and 4 respectively.

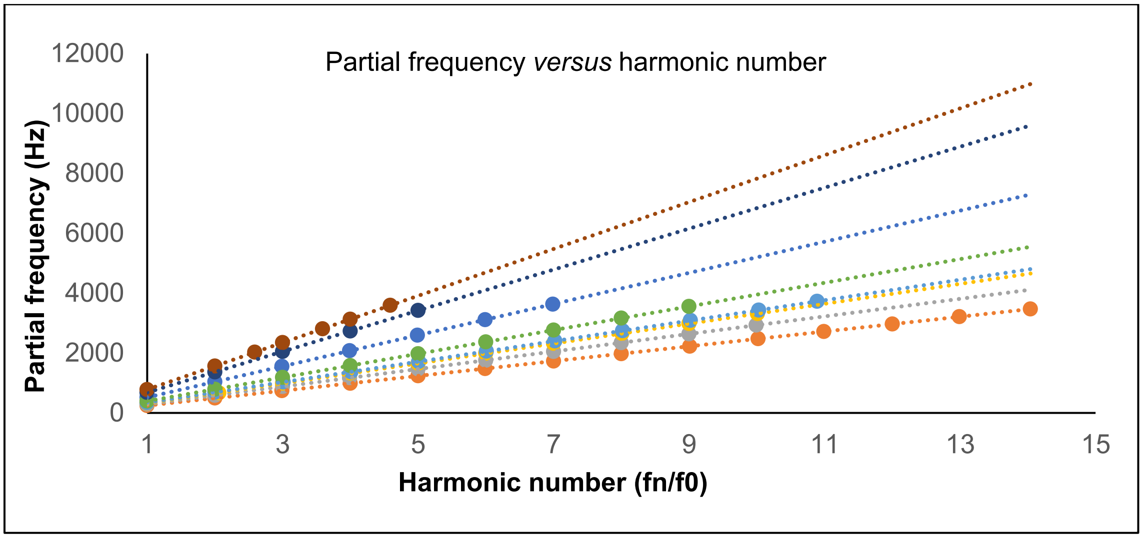


Fig. 9. The partial frequency (Hz) *versus* harmonic number (fn/f0) from the left-hand side (harmonic number = 1 is for fundamental frequency)

The linear equation (eq. 9 to 16) for the partial frequency *versus* the harmonic number for tube 1 to 8 from the left side is given as follows:

y1 = 519.57x+0.1457 for tube 1: (519 = C5) (9)

y2 = 247.11x-0.0713 for tube 2: (247 = B3) (10)

y3 = 293.07x+0.4014 for tube 3: (293 = D4) (11)

y4 = 331.93x-5.4947 for tube 4: (331 = E4) (12)

y5 = 341.96x+1.7093 for tube 5: (342 = F4) (13)

y6 = 395.03x+0.3889 for tube 6: (395 = G4) (14)

y7 = 683.8x-0.4 for tube 7: (683 = F5) (15)

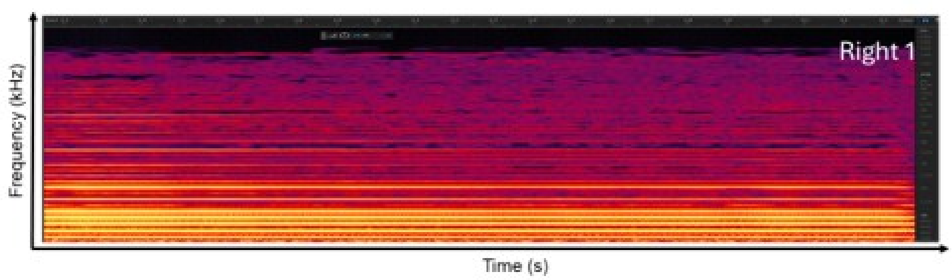
y8 = 782.26x-0.5021 for tube 8: (781 = G5) (16)

Table 3. The Note Arrangement for Tubes 1 to 8 for the Left and Right-hand Side

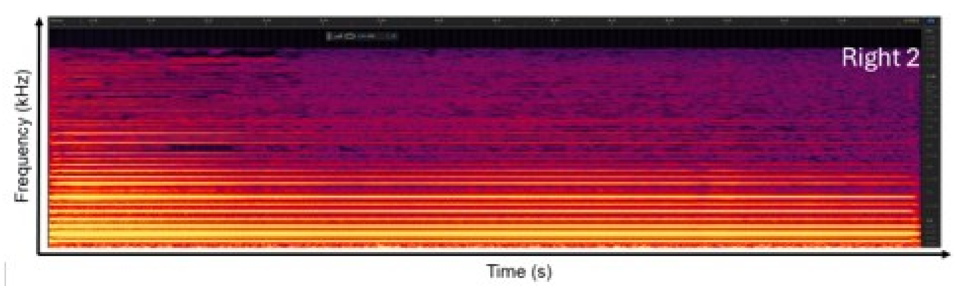
Tube	Note (Left-hand Side)	Note (Right-hand Side)
8(Little finger)	G5	A5
7	F5	E5
6	G4	D5
5	F4	B4
4	E4	A4
3	D4	G4
2	B3	C4
1 (Thumb)	C5	A3

The note on the right-hand side (A3, C4, G4, A4, B4, D5, E5, and A5) and on the left-hand side (C5, B3, D4, E4, F4, G4, F5, and G5) on tubes 1, 2, 3, 4, 5, 6, 7, and 8 can be represented as (C, D, E, G, A, and B) and (C, D, E, F, G, and B) respectively. The right thumb starts with A3 and runs gradually to A5. The left thumb starts with C5 and runs gradually from B3 to G5. When both sides of the tubes are combined, the notes run from A3, C4, G4, A4, B4, D5, E5, A5, and C5, B3, D4, E4, F4, G4, F5, G5 from the right-hand and left-hand side. The notes arrangement for both tubes are A3 (R1), B3 (L2), C4 (R2), D4 (L3), E4 (L4), F4(L5), G4 (L6), G4 (R3), A4 (R4), B4 (R5), C5 (L1), D5 (R6), E5 (R7), F5 (L7), G5 (L8), and A5 (R8), *i.e.*, encompassing two octaves from A3 to A5, with tube 3 on the right (R3) and tube 6 on the left (L6) tuned to the same pitch G4. The number in the brackets indicate the tube number where R and L mean right and left tube, respectively. The G4 appears twice, *i.e.*, reeds are duplicated to support drone and melody textures. One G4 may be used as a constant drone, while the other G4 is freely fingered for melodic variation. Both A3 (R1) and C5 (L1), which are played using the thumb, are from tube 1 on the right-hand and left-hand side, respectively. Both A5 (R8) and G5 (L8) are from tube 8 on the right-hand and left-hand side, respectively, are played using the little finger. The other notes are played using the index, middle and ring fingers. The pitches are dispersed over the two rows of tubes rather than in scalar order to allow for traditional fingering patterns.

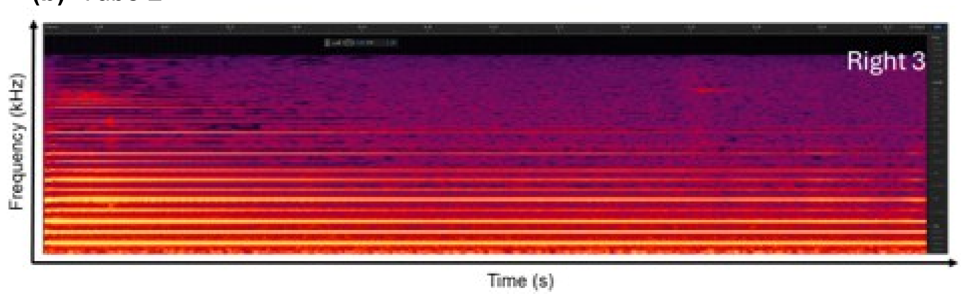
Figure 10 shows the Adobe Audition from the right-hand side. From Fig. 10 it is clear that the partials in Tubes 1 and 2 are very dense. This is reflected by the 16 and 14 partials from Tubes 1 and 2, respectively (see Table 1). Tubes 3 to 8 show a clear and distinct partial, whereas tubes 7 and 8 display a very bright second harmonic.



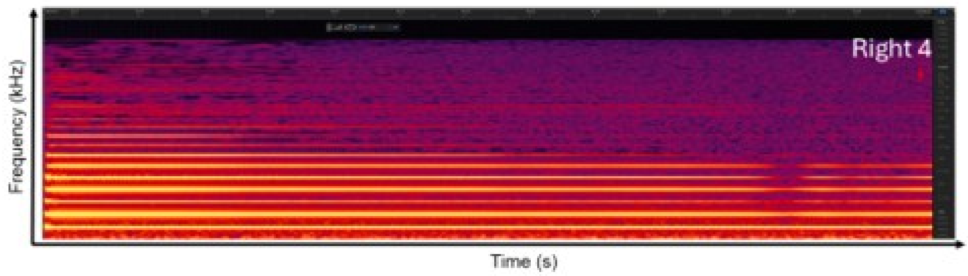
(a) Tube 1



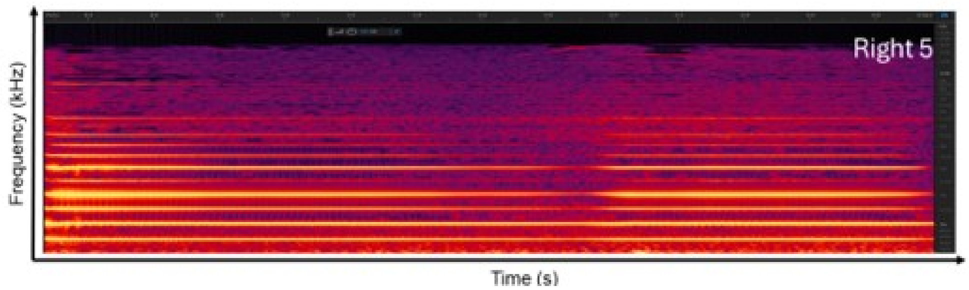
(b) Tube 2



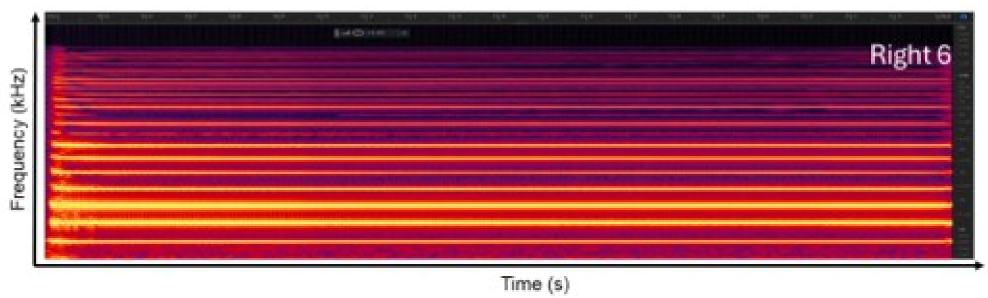
(c) Tube 3



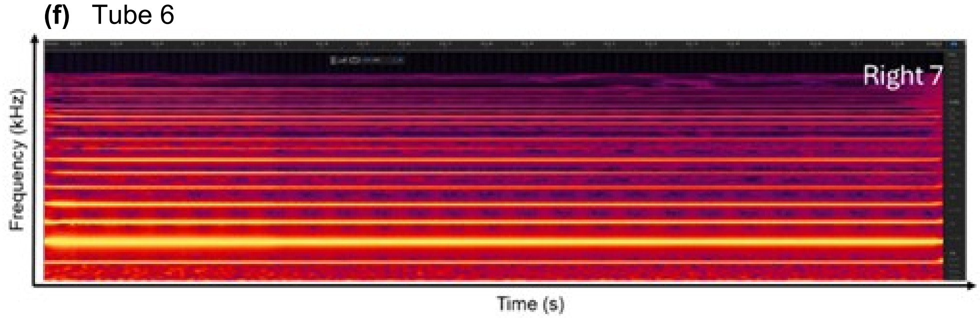
(d) Tube 4



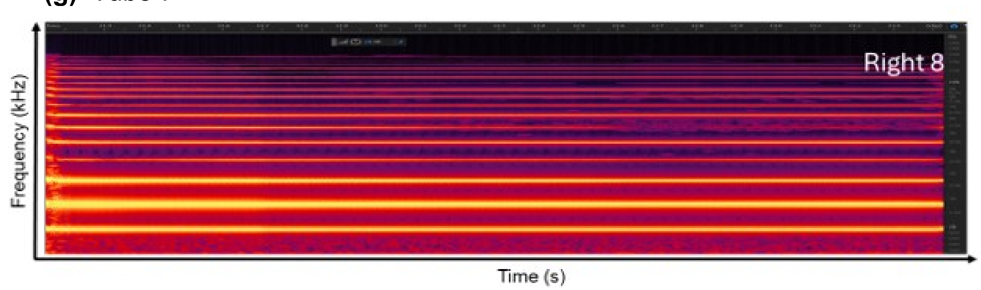
(e) Tube 5



(f) Tube 6



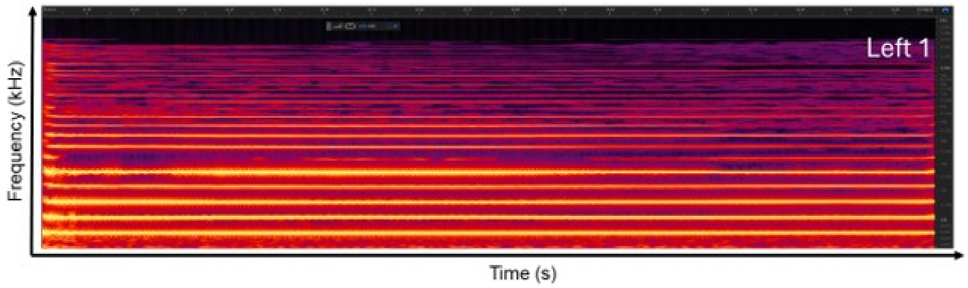
(g) Tube 7



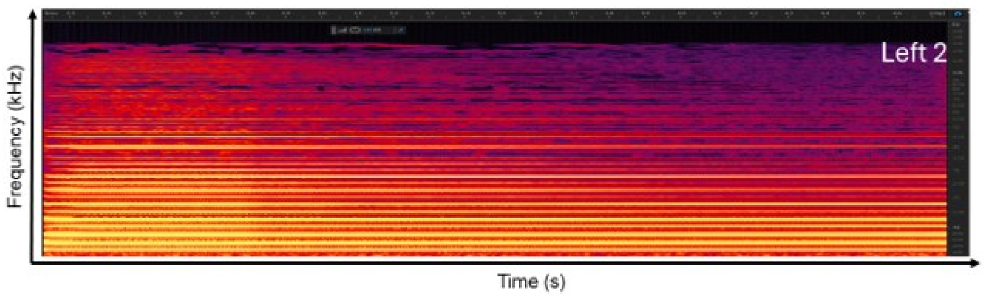
(h) Tube 8

Fig. 10. Adobe Audition for the right-hand side tubes

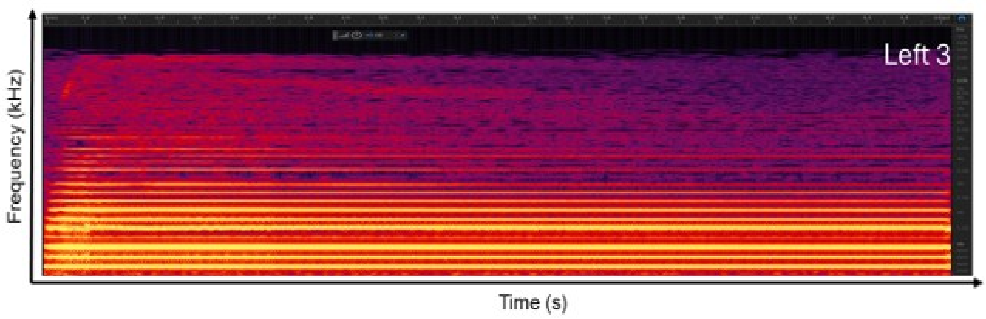
Figure 11 shows the Adobe Audition from the left-hand side. Unlike tube 1 in Fig. 10 (the right-hand side), tube 1 in Fig. 11 (the left -hand side) shows a clear and distinct partial. Similar to Fig. 10 (the right-hand side), tubes 7 and 8 in Fig. 11 (the left-hand side) shows clear and distinct partials.



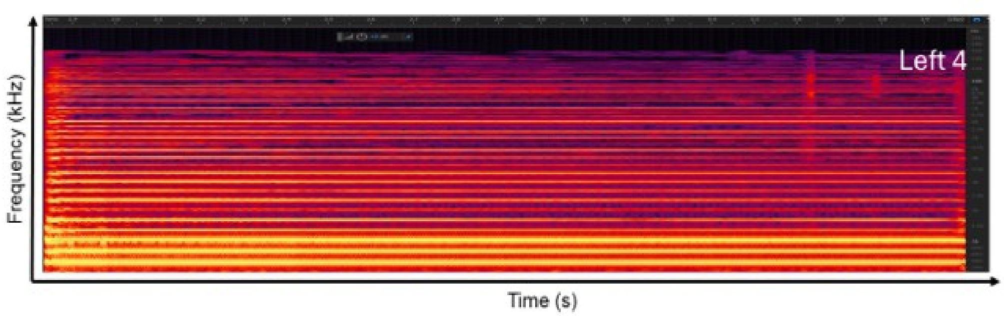
(a) Tube 1



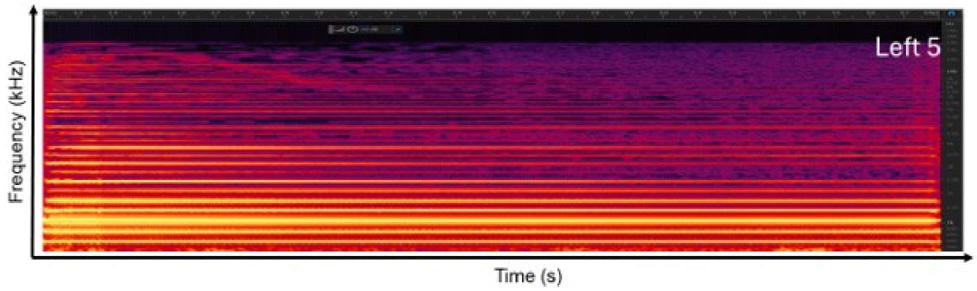
(b) Tube 2



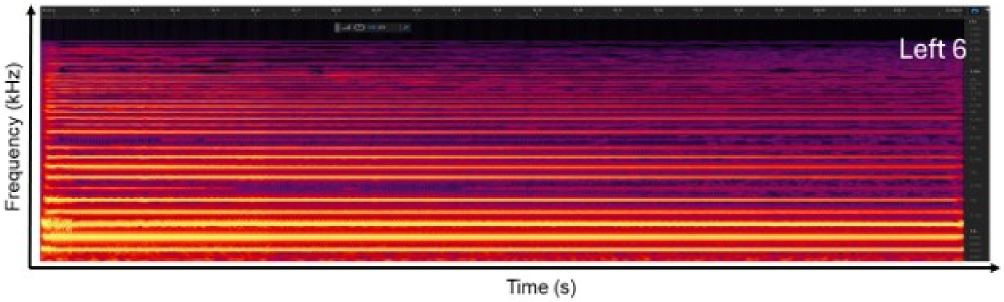
(c) Tube 3



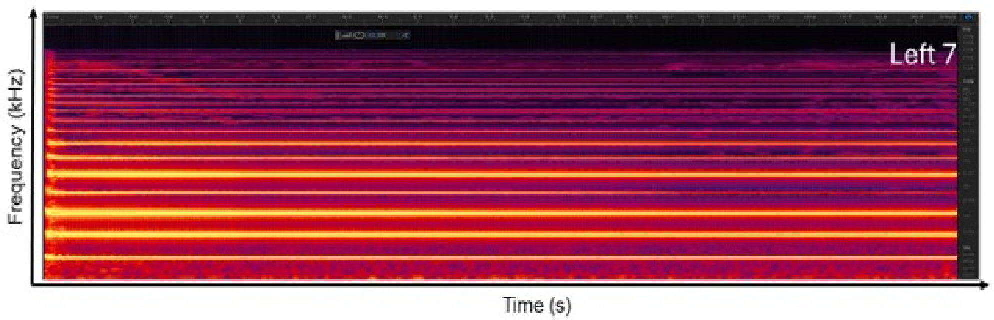
(d) Tube 4



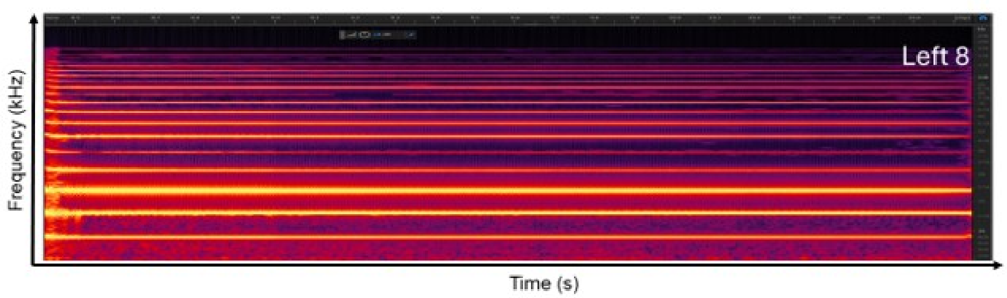
(e) Tube 5



(f) Tube 6



(g) Tube 7



(h) Tube 8

Fig. 11. Adobe Audition for the left-hand side tubes

CONCLUSIONS

1. Tubes 1, 2, 3, 4, 5, 6, 7, and 8 on the right and left side produced the fundamental frequency (in hertz) as follows: 519(C5 = 523), 247(B3 = 247), 293D4(293), 329(E4 = 331), 342(F4 = 349), 395(G4 = 392), 683(F5 = 698), and 781(G5 = 783); and 221(A3

= 220), 255(C4 = 261), 384(G4 = 394), 443(A4 = 440), 499(B4 = 493), 591(D5 = 587), 672(E5 = 659), and 887(A5 = 880).

2. The G4 appears twice, *i.e*., reeds are duplicated to support drone and melody textures. One G4 may be used as a constant drone, while the other G4 is freely fingered for melodic variation.
3. The standard deviations of the fundamental pitch from the equal tempered scale (ETS) for tube 1, 2, 3, 4, 5, 6, 7, and 8 on the right and left side were ± 1, ± 6, ± 10, ± 3, ± 6, ± 4, ± 13, and ± 7, and ± 4, ± 0, ± 0, ± 2, ± 7, ± 3, ± 15, and ± 2 Hz, respectively.
4. The harmonic numbers of tubes 1 to 8 on the right and left side were 16, 14, 9, 8, 7, 6, 5, and 7, and 7, 14, 10, 10, 11, 9, 5, and 4, respectively.

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