Acoustics of the Guzheng: Chinese Plucked Zither

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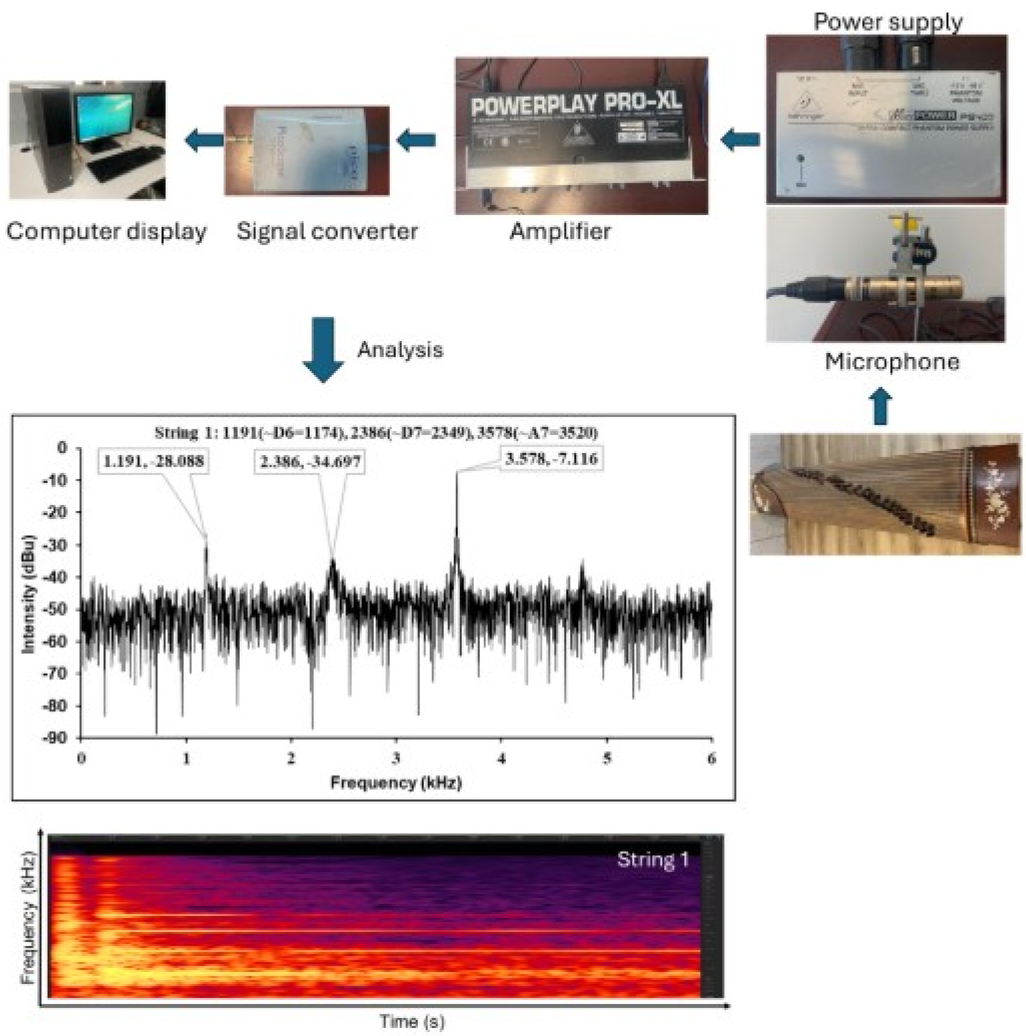
GRAPHICAL ABSTRACT



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The main goal of this study was to evaluate the frequency spectrum and the time frequency analysis of *guzheng*, a Chinese plucked zither. The progressing note for string 21 to string 1 are from D2=73.41 Hz to D6=1174.7 Hz. The G major pentatonic scale consists of the first, second third, fifth, and sixth degrees: D, E, F♯, A, and B. For strings 21 to 2, the notes are arranged as follows: (D2, E2, F♯2, A2, B2), (D3, E3, F♯3, A3, B3), (D4, E4, F♯4, A4, B4), (D5, E5, F♯5, A5, B5). The partials harmonic increased gradually with the harmonic number except for strings 2, 6, 7, 10, 11, 12, 14, 15, and 16 where some partials are not harmonic. The time frequency analysis (TFA) for high pitch string shows distinct partial frequency, whereas the low pitch string shows diffused partial frequency.

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Keywords: Guzheng; Fast Fourier Transform (FFT); Harmonics, Pentatonic scale

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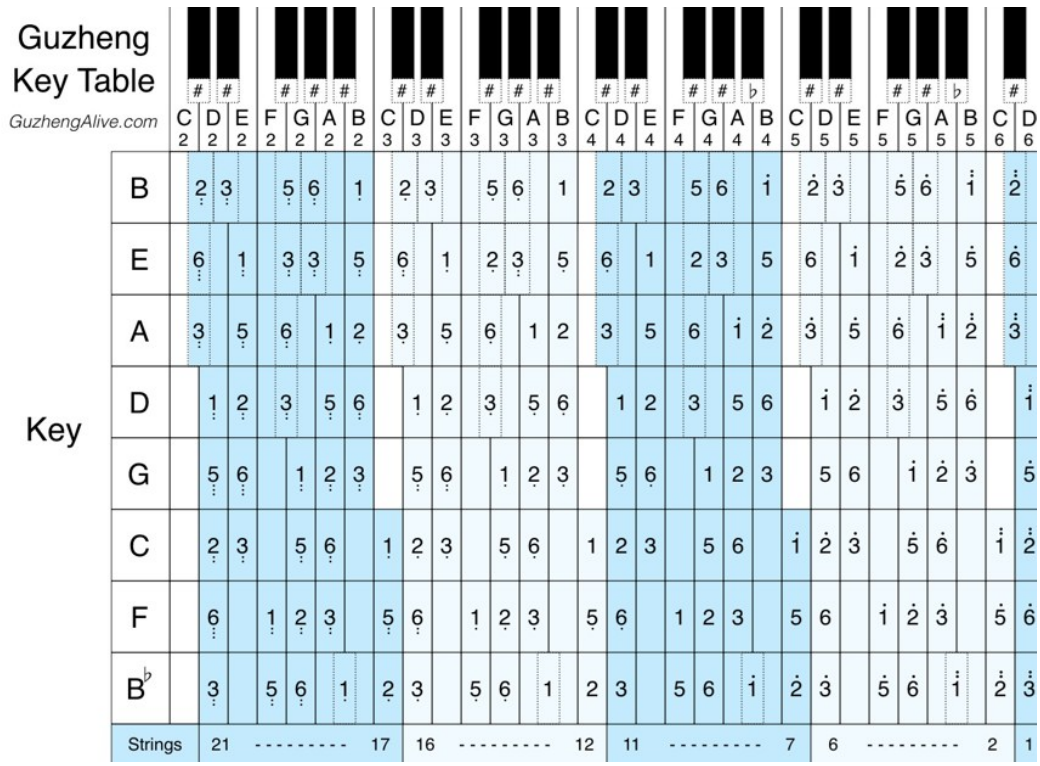
INTRODUCTION

A *guzheng* is a Chinese plucked zither. The modern *guzheng* is typically 1.6 m long, tuned in a major pentatonic scale and contains 21, 25, or 26 strings. A musical scale with five notes per octave is called a pentatonic scale. Known for its simplicity and pleasant tone, this scale is often employed in many different musical genres. Because they are consonant, pentatonic scales are frequently utilized for soloing and improvisation in music from all around the world. The major pentatonic scale consists of the first, second, third, fifth, and sixth degrees of the major scale. The minor pentatonic scale consists of the first, flat third, fourth, fifth, and flat seventh degrees. The notes C, D, E, G, and A make up the C major pentatonic scale. The notes A, C, D, E, and G make up the A minor pentatonic scale. Because A minor is the relative minor of C major, these two scales have identical notes. Half step intervals are eliminated in the pentatonic scale. It eliminates the fourth and seventh scale degrees in a major scale, which are half a step from the first and third. As opposed to heptatonic scales, which contain seven notes per octave, pentatonic scales have five notes per octave. Many ancient civilizations independently invented pentatonic scales, which are still employed today in a variety of musical genres. The *guzheng* features a large, *Paulownia* wood soundboard. For structural or aesthetic purposes, other parts are frequently constructed from other types of wood. *Guzheng* musicians frequently use one or both hands to hold a fingerpick composed of plastic, resin, tortoise-shell, or ivory. In accordance with the genre, it may have steel, nylon, or silk strings. There are 21 strings on the most popular *guzheng*. The *guzheng's* low-pitched strings are on the other side, while its high-pitched strings are near the player. The strings are arranged from 1 to 21 from inside to outside. A number of other Asian zithers, including the Vietnamese *đàn tranh,* the Korean *gayageum* and *ajaeng,* the Mongolian *yatga*, and the Japanese *koto*, are descended from the *guzheng*. Table 1 shows the *guzheng* keys.

Table 1. *Guzheng* Key Table



Paulownia fortunei and closely related species, such as *P. tomentosa*, are prized for their distinctive acoustic qualities, which include low density, strong resonance, and superior sound conductivity. These characteristics make it a popular tone-wood for musical instruments, especially traditional Asian instruments like the *Koto* (Sinin *et al.* 2026) and increasingly for contemporary guitar bodies. High resonance and tone are important physical and auditory characteristics, a sonorous and rich tone is frequently produced, musicians and manufacturers characterize the sound as bright, clear, and strong. It is sometimes thought to have a sound profile that falls between that of swamp ash and alder, with clear low and warm mids. A low and warm mids sound is referred as rich, thick, and non-fatiguing audio profile with robust, deep bass and prominent lower-midrange frequencies, often with relaxed or rolled-off treble. With an air-dry density of about 285 to 340 kg/m³, its high stiffness and low density make it extremely light, enabling resonant, lightweight instrument bodies (such as electric guitars). It keeps good stiffness-to-weight ratios in spite of this. Soundboards can benefit from the wood's well-known propensity to transmit sound. Its overall structure makes it extremely resonant, even though some research suggests that it absorbs less sound than other low-density woods because tyloses obstruct vessels. Because of its extremely low shrinkage and swelling, instruments are kept in tune and are unlikely to warp or shatter.

This study aimed to investigate the acoustic characteristics by studying its tonal and spectral properties. The research specifically sought to analyze the frequency spectrum and timbre using Fast Fourier Transform (FFT) and spectrogram analysis through PicoScope and Adobe Audition software. Additionally, it evaluated the *guzheng* body's sound radiation, tonal clarity, and harmonic structure. This study also assessed the viability in the manufacturing of musical instruments, particularly based on measurable acoustic performance and sound quality. Ultimately, the findings aimed to provide a valuable comparative reference for local instrument makers and researchers interested in adopting *Paulownia fortunei* as a sustainable and accessible material in musical instrument construction.

Through scientific documentation and spectral analysis, this study aimed to maintain the acoustic uniqueness of the *guzheng*. Original tunings and materials run the risk of being lost due to modernity and deteriorating craftsmanship. In order to assist AI-driven sound reconstruction and virtual learning platforms for traditional instrument preservation, this project recorded empirical frequency data and overtone behavior into a digital archive. This study contributes to three main areas:

1. Acoustic documentation; as a scientific record for preservation, it offers an accurate, empirical dataset of the *guzheng's* harmonic structure and tuning.

2. Digital sound preservation; AI sound models that can mimic or replicate the real sound of conventional instruments can be integrated with the frequency and FFT data.

3. Future instrument design; using AI-assisted modeling and AR/VR immersive technologies for education and heritage distribution, the study provides fundamental data for creating sustainable, plant-based musical instruments whose resonance and tuning may be improved.

This research has potential for a substantial impact because it advances both scientific knowledge and cultural preservation. Scientifically speaking, the study offers empirical *guzheng* acoustic data captured by high-resolution digital instruments. This closes a gap in ethnomusicological documentation by analyzing historic tuning systems with the accuracy of contemporary waveform and FFT tools. In addition to revealing the *guzheng*'s tuning behavior, the data maps its overtone patterns and provides a baseline for future comparisons between Western tempered systems and traditional Chinese systems. The results are extremely important for traditional music heritage from a cultural and preservation standpoint. The *guzheng*'s sound identity may be digitally conserved and recreated in virtual environments thanks to the documentation of its spectral properties, protecting it against loss brought on by material deterioration or generational discontinuity. The outcomes can be utilized to teach AI-based sound modeling systems, making it possible for AR/VR cultural simulations, digital museums, and educational applications to replicate real Chinese musical tones. This ensures the *guzheng*'s acoustic identity survives in changing digital environments by building a bridge between traditional craftsmanship and contemporary technology.

By offering a scientific framework for tuning calibration, restoration, and the creation of new instruments utilizing sustainable, plant-based materials, the study's findings have an impact on traditional music. This promotes environmental sustainability while allowing traditional performance practices to continue. Traditional instrument manufacturers can more precisely duplicate or restore the *guzheng*, preserving its cultural integrity, by recording the precise spectral and frequency characteristics of each string.

Additionally, by enabling traditional timbres to coexist with current production circumstances, digital sound libraries based on this research could enhance contemporary Chinese compositions. This contributes to the revival of intangible heritage through contemporary methods of distribution and reaffirms the cultural significance of traditional instruments within contemporary creative enterprises.

Jang and Kang (2021) studied three species of low-density hardwood, *i.e.,* binuang, balsa, and paulownia, which are known for their ability to absorb sound. Paulownia clearly showed the lowest sound absorption of the three species, whereas the other two had higher sound absorption. Despite having a high porosity, paulownia exhibited poor sound absorption capacity because the majority of its vessels are clogged by tyloses. This study showed that gas permeability increased with pore porosity, improving sound absorption performance. Shi (2014) aimed to improve and develop the *guzheng* by expanding its sound capabilities through the use of technology. In order to increase the instrument's capabilities, the research discussed current transformation, modeling, recording, and production procedures. The *guzheng*'s acoustic properties were captured in recordings that include the instrument's impulse response measurement. *Guzheng* tones were simulated in Max/MSP using an additive synthesis model and a physical modeling synthesis model. Yu Zhou Chang Wan, a well-known traditional *Guzheng* tune, was produced using *Guzheng* recordings and synthetic outcomes. The goal of the research by Shi (2014) was to aid in the *guzheng*'s development and inheritance. *Guzheng* compositions and performances can be made more varied by expanding their timbre and pitch range.

EXPERIMENTAL

MATERIAL

The primary wood used in contemporary soundboards is *Paulownia fortunei*. Hard timbers with a high density are used to make movable bridges because they transmit sound more effectively. The most prevalent species are *Dalbergia melanoxylon* (African blackwood), *Dalbergia cochinchinensis* (Thailand Rosewood), and *Pterocarpus santalinus* (Zitan wood). There are references to bridges composed of jade or ivory, but wood is still the most frequent bridge material, though there are current attempts to develop hollow ceramic bridges and low-end instruments with plastic. A brand new *guzheng* is used in this study (see Fig. 1).

The primary soundboard, which is hollow and somewhat bent, is typically 1.6 meters long. Although traditional silk strings are occasionally used for a softer and more conventional sound, steel cores are typically covered in nylon for greater durability and a brighter tone. Each string is supported by a movable bridge, and the pitch is determined by their placement beneath each string. The strings are held in place by the fixed, S-shaped, curved wooden blocks at both ends of the instrument. This is commonly referred to as the mountain bridge in front and the tail bridge in rear. The tuning pins and peg box, which are used to adjust the tension of each string, are situated inside a compartment at the head of the instrument. The head and the tail are frequently decorated with carvings. The strings are numbered from 1 to 21, with the highest pitch being closest to the musician and the lowest pitch being farthest. To pluck the strings, players wear artificial nails, composed of plastic. For the frame, rosewood, sandalwood, or nanmu (hardwoods) are commonly chosen to improve both aesthetics and sound quality.

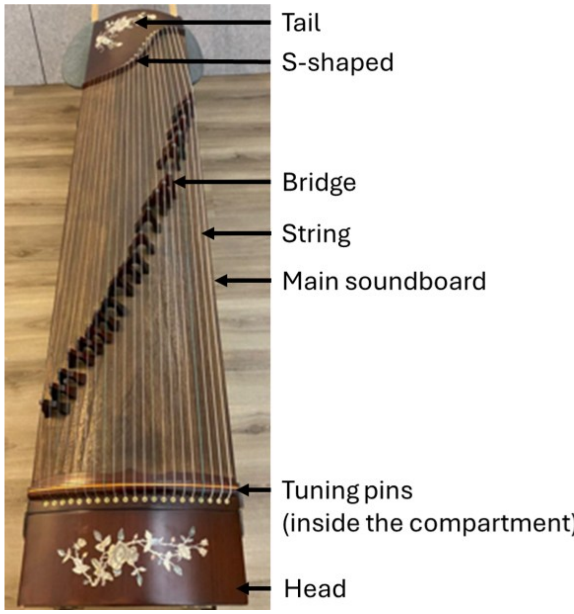


Fig. 1. The 21 strings *guzheng* with the labels

METHOD

All recordings were conducted in an anechoic chamber to eliminate external sound reflections. An omnidirectional polar pattern microphone was positioned 20 cm in front the *guzheng* to capture the radiated sound. It was plucked in a conventional seated position to replicate typical playing conditions and ensure optimal sound resonance. The sound signals were captured in real time using a PicoScope 3000 series oscilloscope and accompanying data recorder (Pico Technology, Eaton Socon, UK). The PicoScope software enabled waveform viewing, Fast Fourier Transform (FFT) analysis, spectrum visualization, and voltage-based triggering. The apparatus used in the experimental setup is provided in Fig. 2.

Fig. 2. The apparatus used in the experimental setup

To prevent distortion or bias, the *guzheng* was recorded under identical conditions, including a fixed microphone position and orientation. The signal was amplified using a Behringer Powerplay Pro XL amplifier (Zhongshan, Guangdong, China) before being processed by the PicoScope. The resulting sound spectra were analyzed in Adobe Audition, where FFT analysis was used to extract dominant frequencies and evaluate tonal characteristics. The FFT enabled identification of fundamentals, harmonics, and subharmonics in the recorded waveforms. Sound data from the *guzheng* was collected in multiple trials. Each iteration was recorded under the same conditions, and the resulting waveforms were averaged to reduce variability and noise. This approach ensured a robust and meaningful acoustic comparison. By employing controlled plucking, consistent recording parameters, and multiple rounds of measurement with averaged data, the methodology ensures a clear, accurate, and scientifically valid comparison of the acoustic performance of the *guzheng*. To ensure accurate and repeatable sound production, a skilled player performed the plucking on the *guzheng*. Consistency was ensured by maintaining the same technique and force for each attempt. Prior to recording, the player rehearsed the precise motions multiple times to minimize human variability and enhance the reliability of the sound comparison.

RESULTS AND DISCUSSION

Figure 3 displays the typical intensity *versus* frequency from string 1. The intensity *versus* frequency for string 2 to 21 is attached in the Appendix. The progressing note running from the lowest pitch (string 21) to highest pitch (string 1) is D2=73.41, E2=82.40, F2#=92.499, A2=110.00, B2=123.47, D3=146.83, E3=164.81 F3#=185.00, A3=220.00, B3=246.94, D4=293.67, E4=329.63, F4#=369.99, A4=440.00, B4=493.88, D5=587.33, E5=659.26, F5#=739.99, A5=880.00, B5=987.77, and D6=1174.7 Hz.

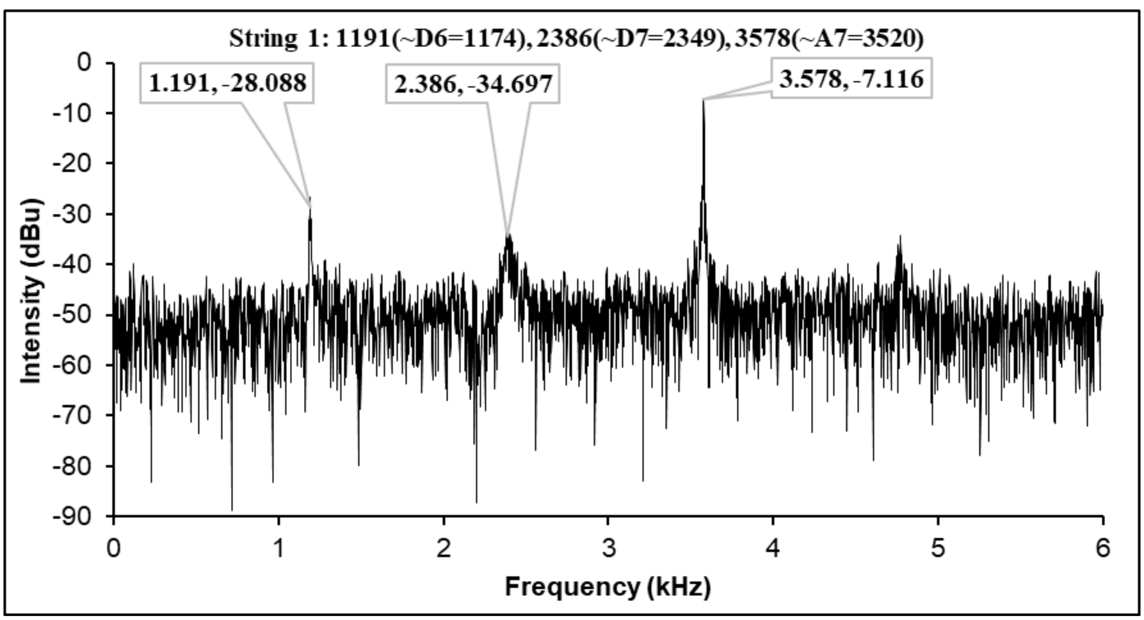


Fig. 3. Example of typical intensity *versus* frequency (string 1)

Table 2 shows the notes from the individual partials from strings 1 to 21. Strings 21 to 17 are in the range D2 to B2 whereas strings 16 to 12 are in the range D3 to B3. Both are in accordance with Table 1 above. Strings 11 to 7 are in the range D4 to B4 and strings 6 to 2 are in the range D5 to B5. Lastly, string 1 is D6. This is also according to Table 1 above. The notes D (first degree), E (second degree), F# (third degree), A (fifth degree), and B (sixth degree) make up the G major pentatonic scale as follows:

Strings 21 to 17: D2, E2, F2#, A2, B2,

Strings 16 to 12: D3, E3, F3#, A3, B3,

Strings 11 to 7: D4, E4, F4#, A4, B4,

Strings 6 to 2: D5, E5, F5#, A5, B5,

String 1: D6.

Table 2. The Notes from the Individual Partials from Strings 1 to 21

String	1st	2nd	3rd	4th	5th
1	D6	D7	A7	-	-
2	B5	C7	F4#	C8	-
3	A5	A6	E7	A7	-
4	F5#	F6#	C7#	F7#	A7#
5	E5	E6	B6	E7	G7#
6	D5	D6	A6#	C7	D7
7	B4	G6	C7	D7#	G7
8	A4	A5	F6	A6#	C7#
9	F4#	F5#	C6#	G6	A6#
10	E4	F5	E6	G6#	B6
11	D4	D5	D6	F6#	A6
12	B3	C6	D6#	F6#	A6
13	A3	A4	E5	C6#	E6
14	F3#	F4#	C5#	C6#	E6
15	E3	E4	B4	E5	G5#
16	D3	D4	A4	F5#	C6
17	B2	B3	F4#	F6	G6#
18	A2	A3	E4	A4	E5
19	F2#	F3#	C4#	F4#	G4#
20	E2	B2	B3	D4#	G4
21	D2	D3	A3	D4	F4#

Table 3 shows the partials frequency and harmonics from strings 1 to 21. From Table 3 the partials frequency *versus* harmonics number is plotted for strings 1 to 10 (Fig. 4) and for strings 11 to 21 (Fig. 5).

Table 3. The Partials Frequency and Harmonics from Strings 1 to 21

String	Partial	Frequency (Hz)	fn/f0	String	Partial	Frequency (Hz)	fn/f0
1	1	1174.7	1	12	1	246.94	1
	2	2349.3	1.99		2	1046.5	4.23
	3	3520	2.99		3	1244.5	5.03
2	1	987.77	1		4	1480	5.99
	2	2093	2.11		5	1760	7.12
	3	2960	2.99	13	1	220	1
	4	4186	4.23		2	440	2
3	1	880	1		3	659.26	2.99
	2	1760	2		4	1108.7	5.03
	3	2637	2.99		5	1318.5	5.99
	4	3520	4	14	1	185	1
4	1	739.99	1		2	369.99	1.99
	2	1480	2		3	554.37	2.99
	3	2217.5	2.99		4	1108.7	5.99
	4	2960	4		5	1318.5	7.12
	5	3729.3	5.03	15	1	164.81	1
5	1	659.26	1		2	329.63	2
	2	1318.5	1.99		3	493.99	2.99
	3	1975.5	2.99		4	659.26	4
	4	2637	3.99		5	830.61	5.03
	5	3322.4	5.03	16	1	146.83	1
6	1	587.33	1		2	293.67	2
	2	1174.7	2		3	440	2.99
	3	1864.7	3.17		4	739.99	5.03
	4	2093	3.56		5	1046.5	7.12
	5	2349.3	3.99	17	1	123.47	1
7	1	493.88	1		2	246.94	2
	2	1568	3.17		3	369.99	2.99
	3	2093	4.23	18	1	110	1
	4	2489	5.03		2	220	2
	5	3136	6.34		3	329.63	2.99
8	1	440	1		4	440	4
	2	880	2		5	659.26	5.99
	3	1396.9	3.17	19	1	92.499	1
	4	1864.7	4.23		2	185	2
	5	2217.5	5.03		3	277.18	2.99
9	1	369.99	1		4	369.99	3.99
	2	739.99	2		5	415.3	4.48
	3	1108.7	2.99	20	1	82.4	1
	4	1568	4.23		2	123.47	1.49
	5	1864.7	5.03		3	246.94	2.99
10	1	329.63	1		4	311.13	3.77
	2	698.46	2.11		5	392	4.75
	3	1318.5	3.99	21	1	73.41	1
	4	1661.2	5.03		2	146.83	2
	5	1975.5	5.99		3	220	2.99
11	1	293.67	1		4	293.67	4
	2	587.33	1.99		5	369.99	5.04
	3	1174.7	4				
	4	1480	5.03				
	5	1760	5.99				

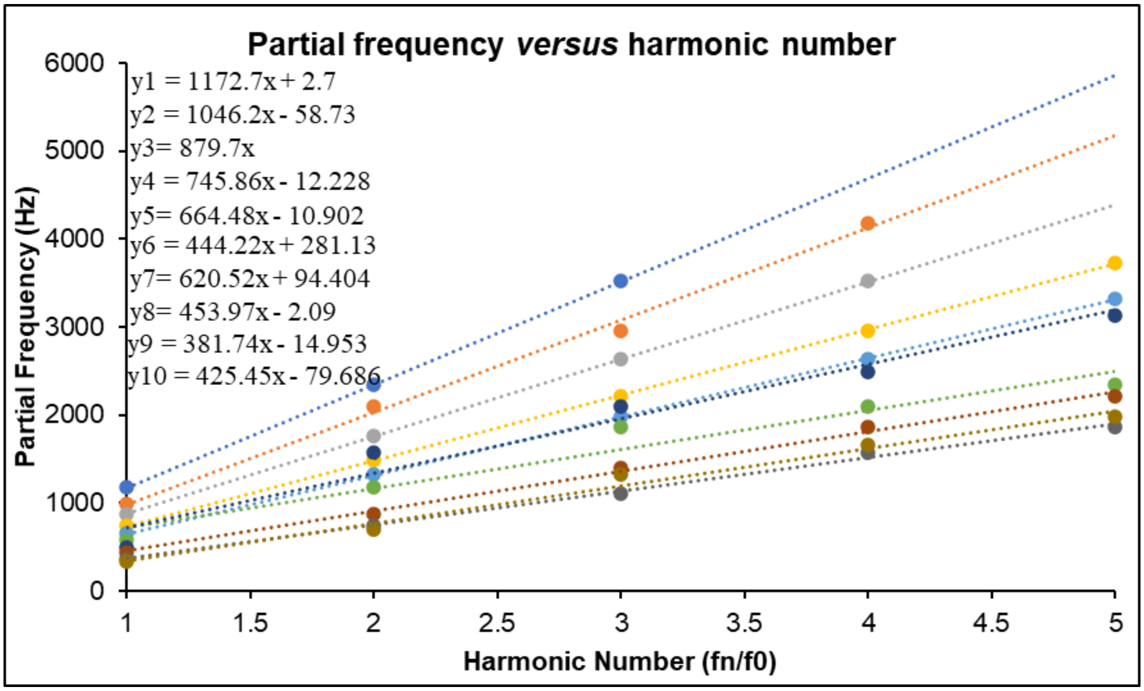


Fig. 4. Partial frequency (Hz) *versus* the harmonic number (fn/f0) for strings 1 to 10 (harmonic number = 1 is for fundamental frequency f0)

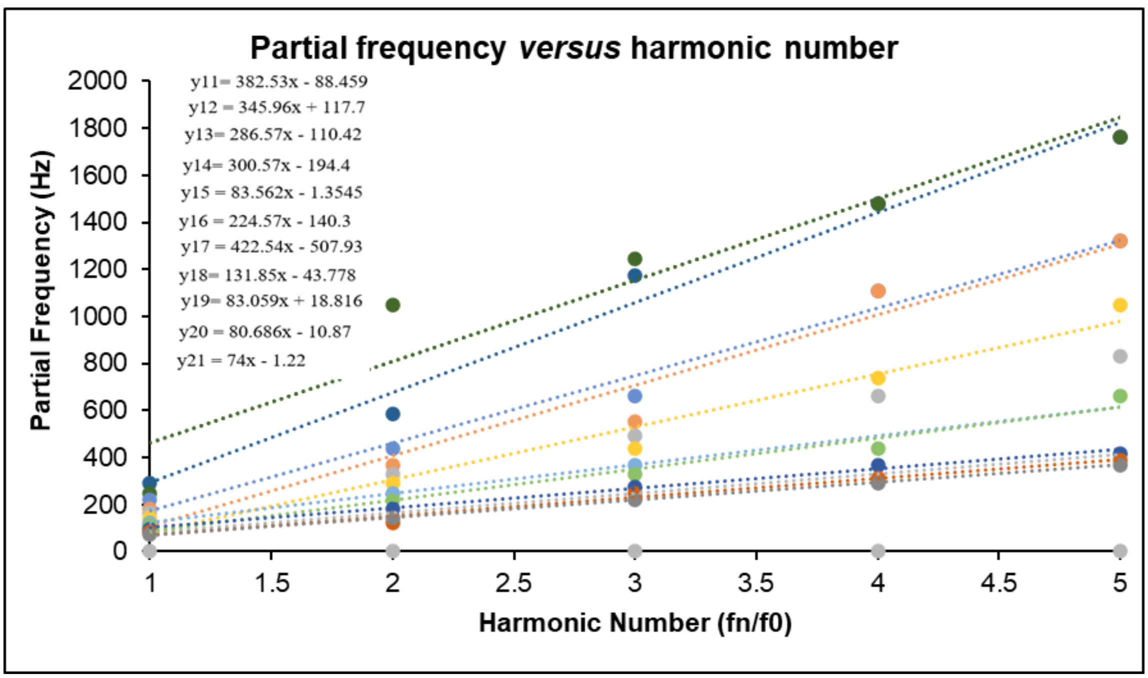


Fig. 5. Partial frequency (Hz) *versus* the harmonic number (fn/f0) for strings 11 to 21. (harmonic number = 1 is for fundamental frequency f0)

The linear equation (Eqs. 1 to 21) for the partial frequency *versus* the harmonic number is given as follows:

$$y1= 1172.7x + 2.7 \quad (1174=D6) \tag{1}$$

$$y2= 1046.2x - 58.73 \quad (987=B5) \tag{2}$$

$$y3= 879.7x \quad (880=A6) \tag{3}$$

y4= 745.86x - 12.22 (730=F5#) (4)
y5= 664.48x - 10.90 (659=E5) (5)
y6= 444.22x + 281.13 (587=D5) (6)
y7= 620.52x + 94.40 (493=B4) (7)
y8= 453.97x - 2.09 (440=A4) (8)
y9= 381.74x - 14.95 (370=F4#) (9)
y10= 425.45x - 79.68 (330=E4) (10)
y 11= 382.53x - 88.45 (293=D4) (11)
y12= 345.96x + 117.7 (247=B3) (12)
y13= 286.57x - 110.42 (220=A3) (13)
y14= 300.57x - 194.4 (185=F3#) (14)
y15= 83.562x - 1.35 (164=E3) (15)
y16= 224.57x - 140.3 (146=D3) (16)
y17= 123.26x + 0.28 (123=B2) (17)
y18= 131.85x - 43.77 (110=A2) (18)
y19= 83.059x + 18.81 (93=F2#) (19)
y20 = 80.686x - 10.87 (82=E2) (20)
y21 = 74x - 1.22 (73=D2) (21)

The number in the bracket (Eqs. 1 to 21) indicates the fundamental frequency and the note. The similarity between the gradient of the equations with the fundamental frequency in the bracket showed that the partials frequency increased linearly with the harmonic number. The big difference between the gradient of the equations and the fundamental frequency (in strings 2, 6, 7, 10, 11, 12, 14, 15, and 16) indicated that some partials frequency did not occur at the harmonic interval where the gradient for:

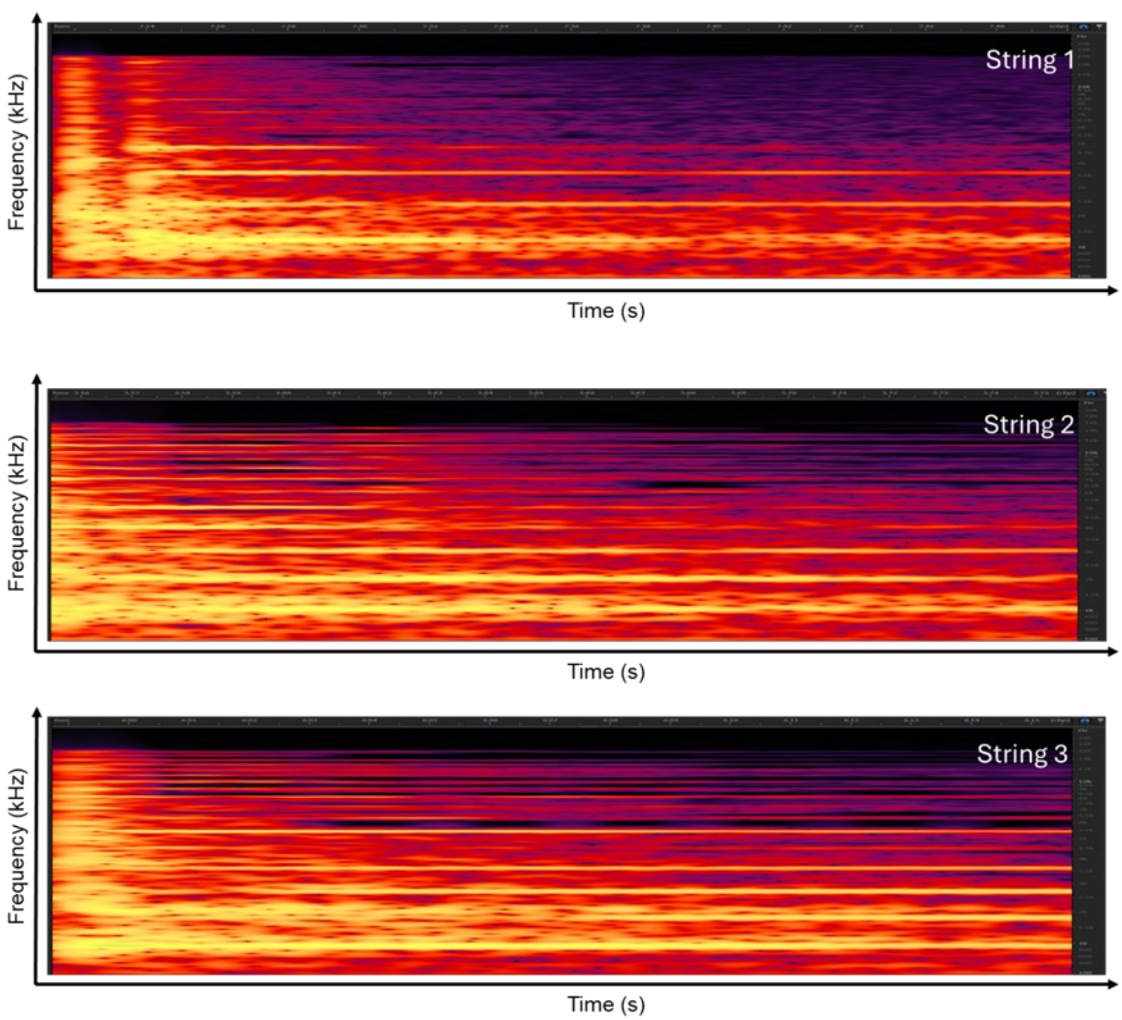
y2 is 1046 and f0=987 (different=59Hz),
y6 is 444 and f0=587 (different=143Hz),
y7 is 620 and f0=493 (different=127Hz),
y10 is 425 and f0=330 (different=95Hz),
y11 is 382 and f0=293 (different=89Hz),
y12 is 345 and f0=247 (different=98Hz),
y14 is 300 and f0=185 (different=115Hz),
y15 is 83 and f0=164 (different=81Hz),
y16 is 224 and f0=146 (different=78Hz)

In string 21 the 150 Hz peak (~D3=146) was more significant than the 70 Hz peak (~D2=73), in string 18 the 223 Hz peak (~A3=220) was more significant than the 121 Hz peak (~A2=110), in string 17 the 249 Hz peak (~B3=246) was more significant than the126 Hz peak (~B2=123), in string 16 the 299 Hz peak (~D4=293) was more significant than the 149 Hz peak (~D3=146), in string 8 the 907 Hz peak (~A5=880) was more significant than the 451Hz peak (~A4=440), in string 6 the 1204 Hz peak (~D6=1174) was more significant than the 598 Hz peak (~D5=587), in string 5 the 1343 Hz peak (~E6=1318) was more significant than the 671 Hz peak (~E5=659), in string 3 the 1793 Hz peak (~A6=1760) was more significant than the 895 Hz peak (~A5=880).

This phenomenon where the listener claimed the note was D2, but the PicoScope measured a frequency corresponding to D3 can be explained by psychoacoustic effects, harmonic confusion, or octave perception errors.

Human ears sometimes hear the fundamental pitch even when it is not physically present. If the sound contains strong harmonics of D2 (*e.g.*, D3, D4 *etc.*), the brain may infer D2 as the fundamental. The PicoScope shows the actual frequencies, while the ear interprets the pattern. For example, in string 21, if D3 (146.8 Hz) is present as a high peak, the listener may perceive D2 because the harmonics also belong to D2 (73.4 Hz). People occasionally misjudge the octave of a tone, especially with low-frequency notes. A D3 note could be mistakenly identified as D2 due to lack of reference pitches and the listener being accustomed to instruments that emphasize lower fundamentals. Some instruments produce strong overtones that can mask or overshadow the fundamental. If D3 is dominant and D2 is weak or implied, a listener might perceive the lower pitch even if it is not acoustically dominant.

The phenomenon where the listener claimed to recognize the note D2 when they hear D3, is the famous phenomenon of the 'missing fundamental'. Figure 6 shows the time frequency analysis (TFA) from Adobe Audition.



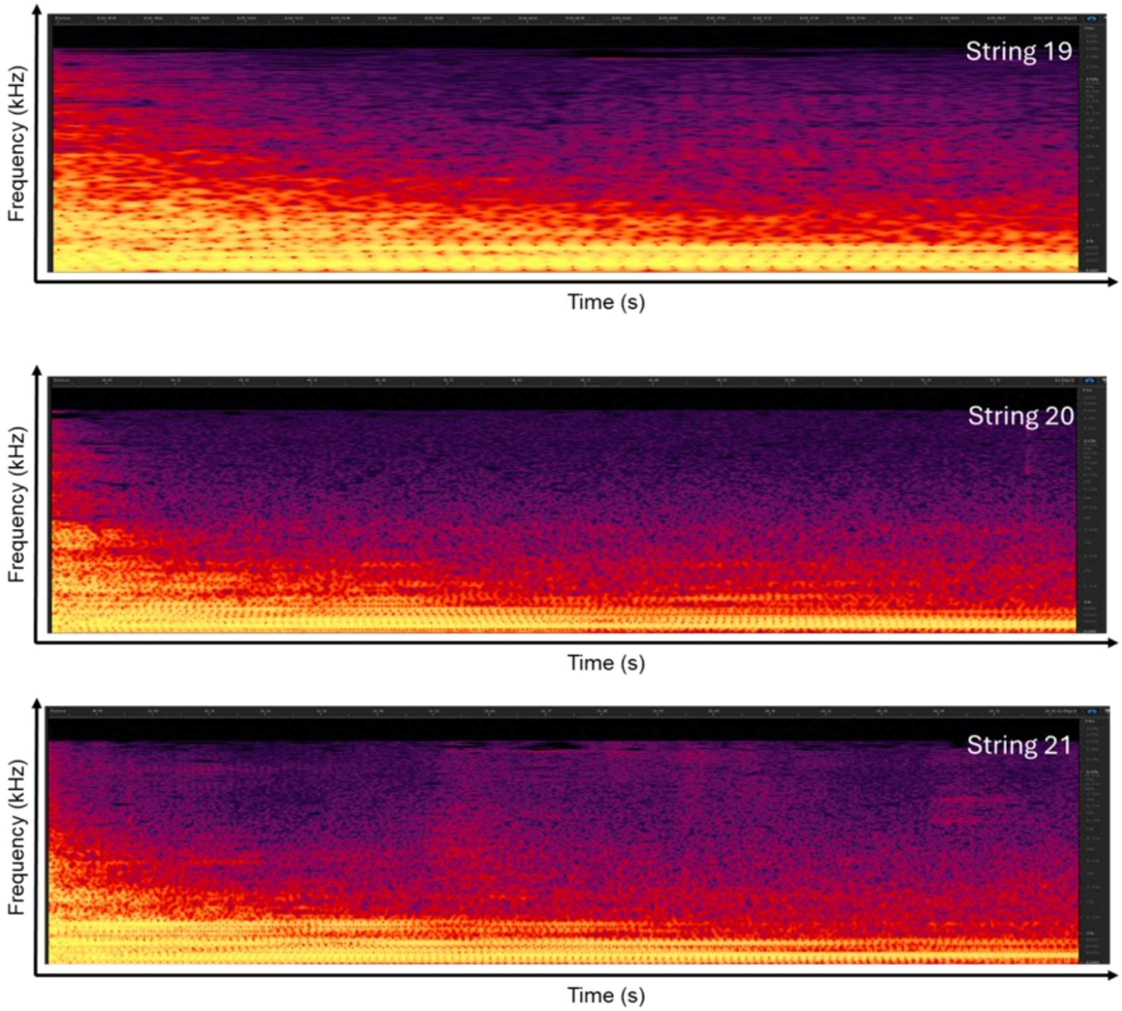


Fig. 6. The time frequency analysis (TFA) from adobe audition

Strings 1, 2, and 3 (the highest pitch) showed distinct partial frequency whereas strings 19, 20, and 21 (the lowest pitch) showed diffused partial low frequency (bassy sound). The term bassy sound was described based on visual analysis of the spectrogram, where yellow region were more prominent intensities appeared in the lower frequency range (typically between 40 and 250 Hz). These yellow bands indicated stronger energy concentration in the low-end spectrum, commonly associated with a bassy tonal character. The Adobe Audition spectrogram uses a brightness scale where darker regions reflect higher amplitude across that frequency band. Yellow indicates the low frequency spectrum, red indicates the medium frequency spectrum, and violet indicates the high frequency spectrum.

CONCLUSIONS

1. The progressing note running from the lowest pitch (string 21) to highest pitch (string 1) is D2=73.41, E2=82.40, F2#=92.499, A2=110.00, B2=123.47, D3=146.83, E3=164.81, F3#=185.00, A3=220.00, B3=246.94, D4=293.67, E4=329.63,

F4#=369.99, A4=440.00, B4=493.88, D5=587.33, E5=659.26, F5#=739.99, A5=880.00, B5=987.77, and D6=1174.7.

2. The notes D (first degree), E (second degree), F# (third degree), A (fifth degree) and B (sixth degree) make up the G major pentatonic scale as follows: (D2, E2, F2#, A2, B2), (D3, E3, F3#, A3, B3), (D4, E4, F4#, A4, B4), (D5, E5, F5#, A5, B5), (D5, E5, F5#, A5, B5).
3. The partial frequency increased linearly with the harmonic number except string 2, 6, 7, 10, 11, 12, 14, 15, and 16 where some partial frequencies do not occur at the harmonic interval.
4. The high pitch string shows distinct partial frequency whereas the low pitch string shows diffused partial frequency.

ACKNOWLEDGMENTS

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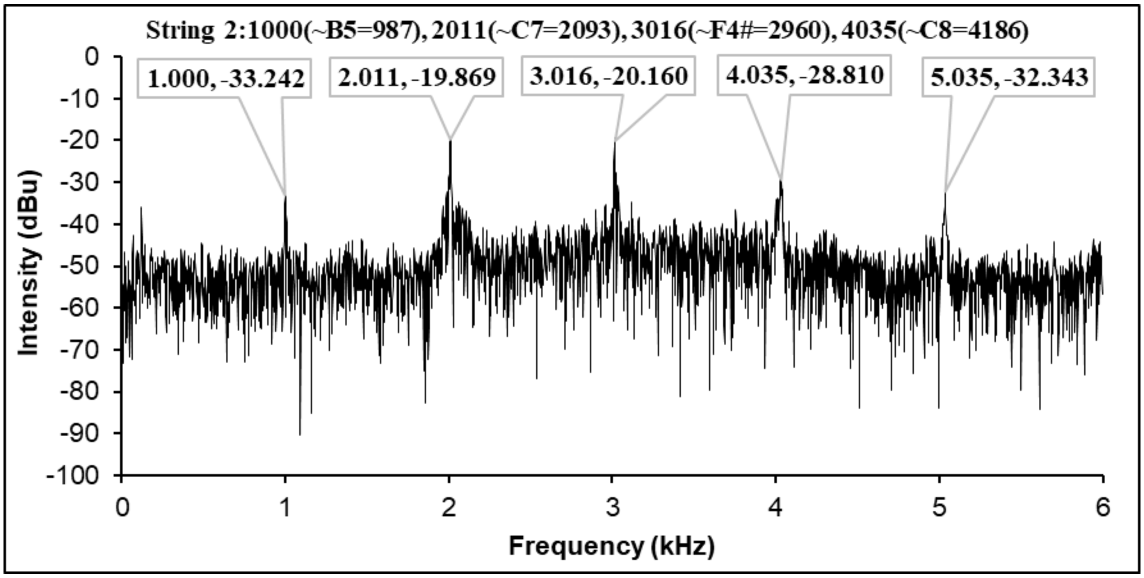
DOI: 10.15376/biores.21.2.5306-5328

APPENDIX

The intensity *versus* frequency for the string 2 to 21 are attached as follows:



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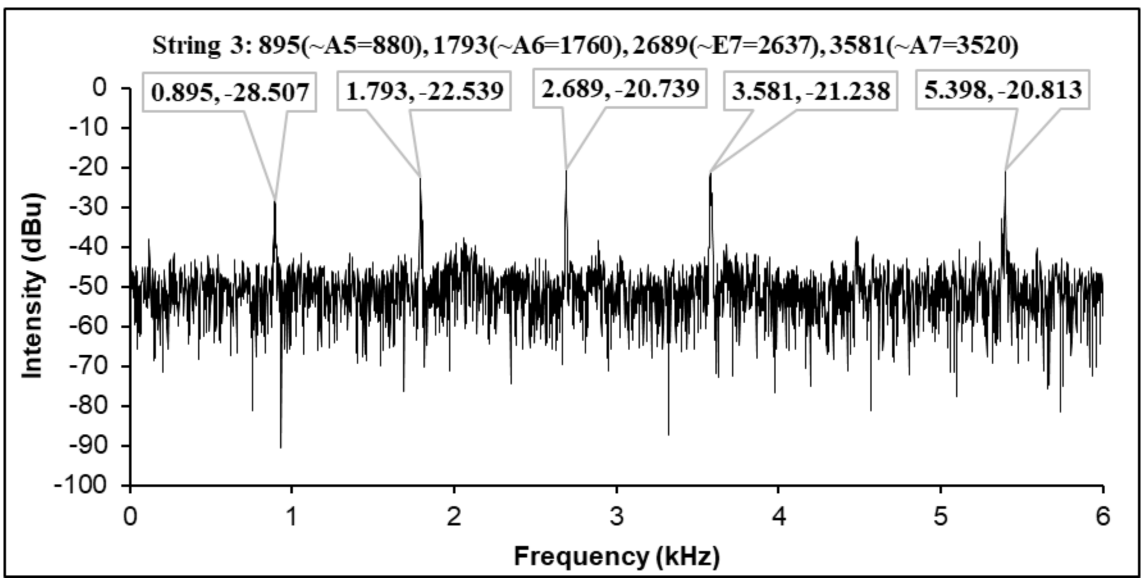

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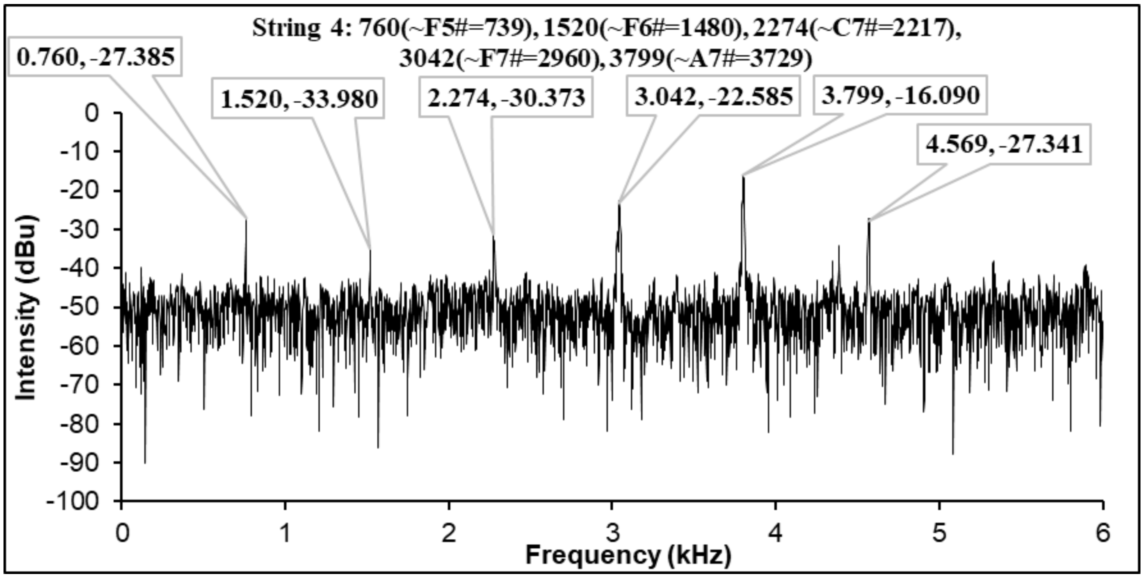

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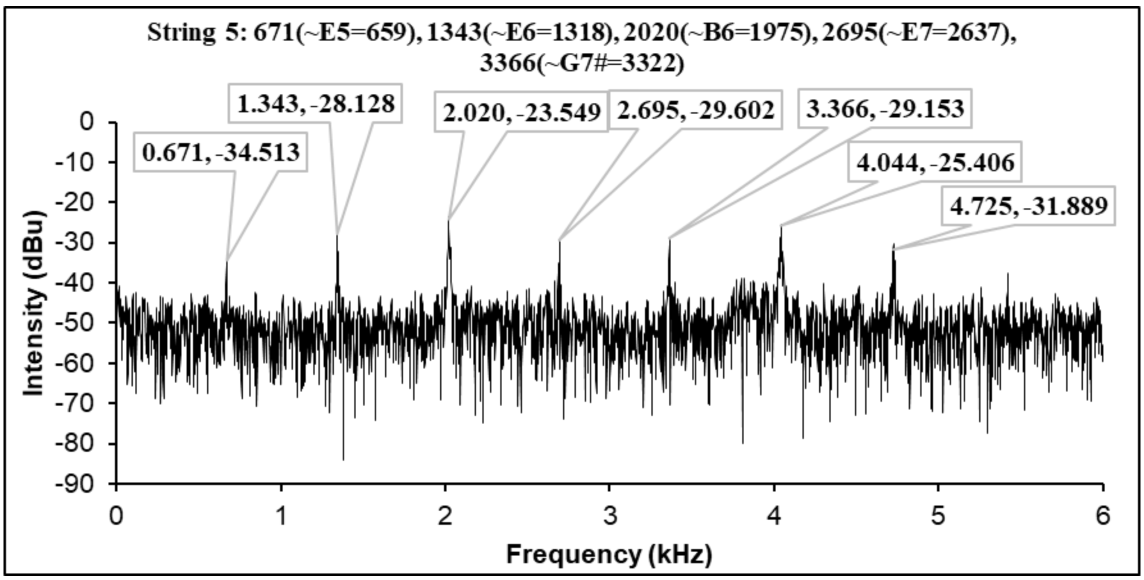

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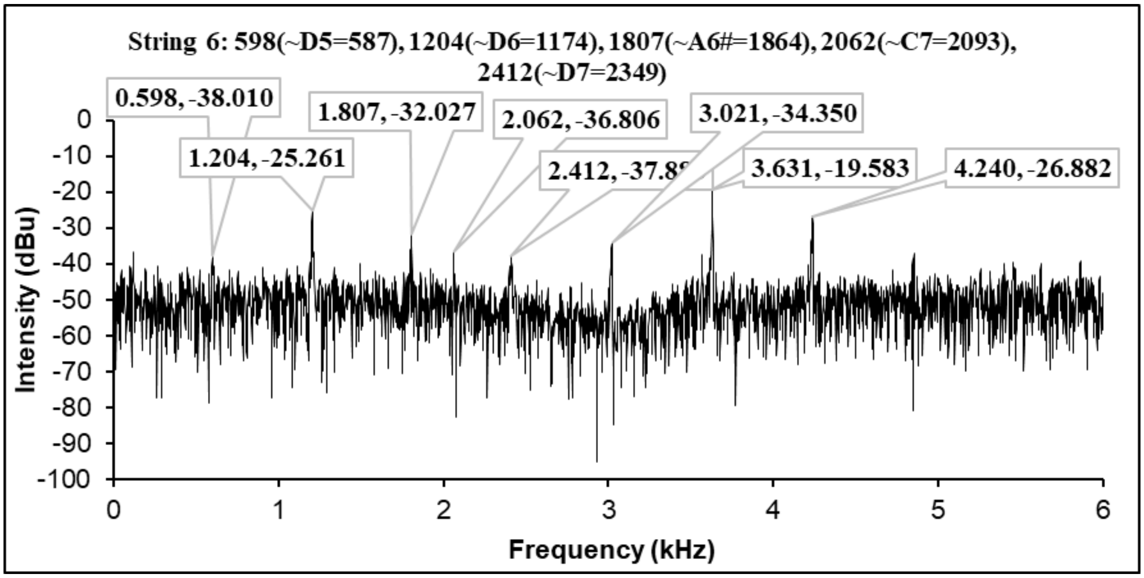

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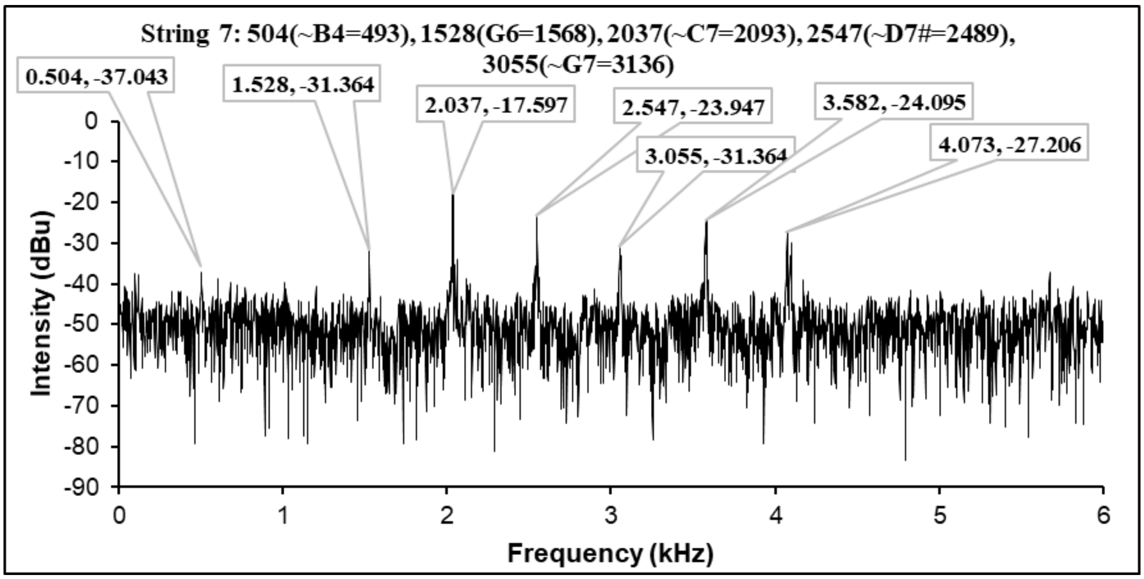

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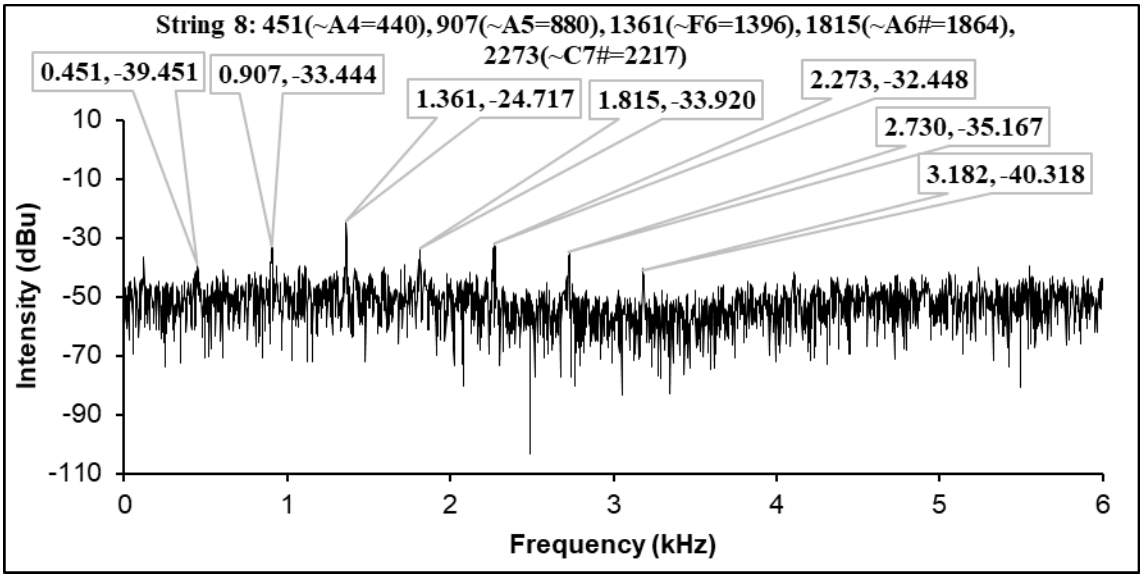

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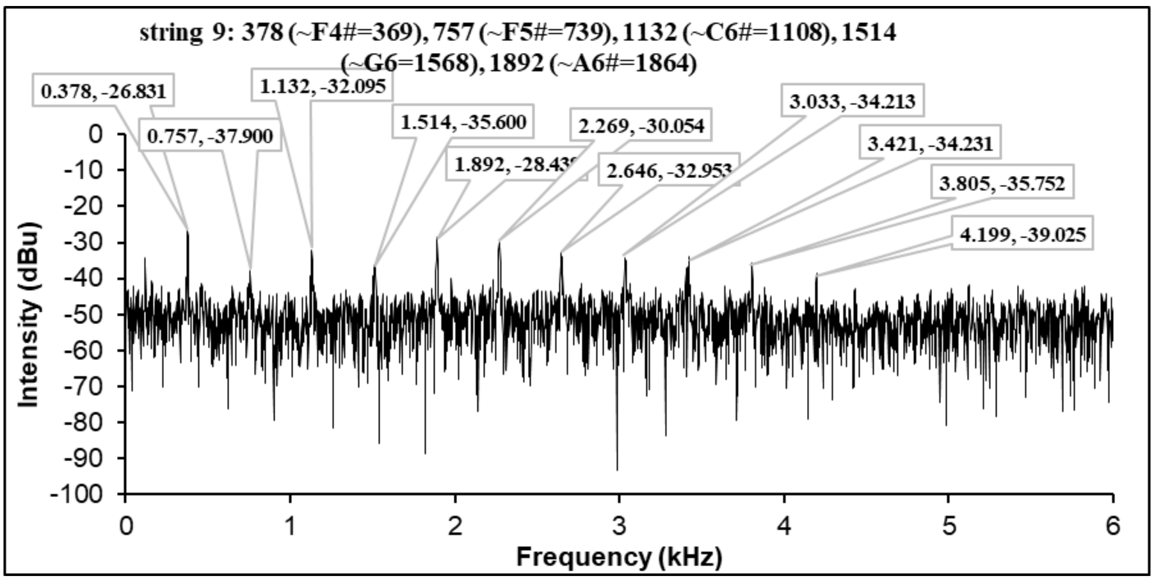

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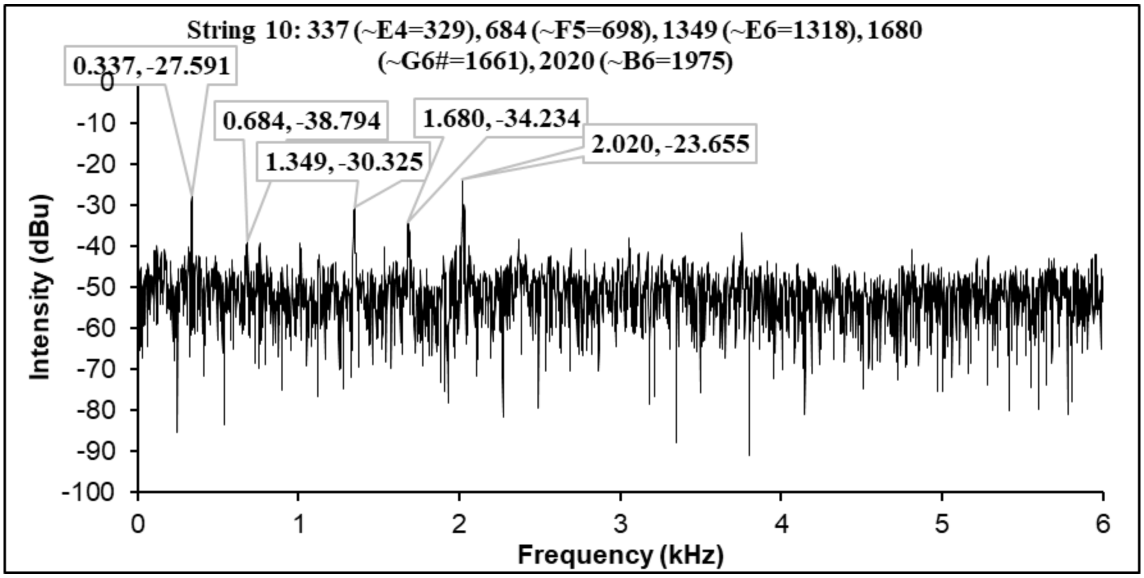

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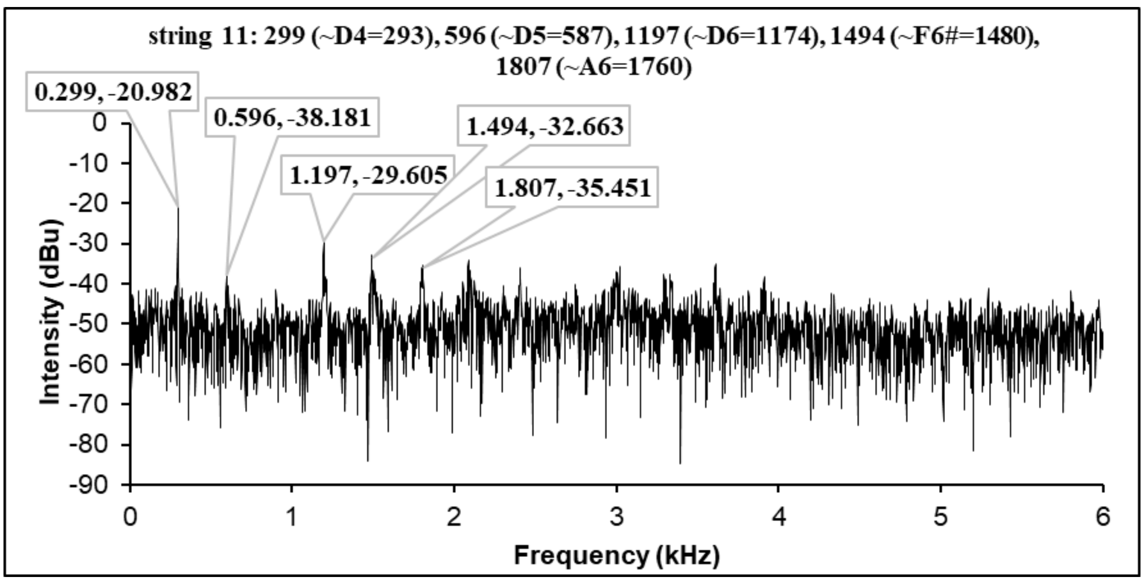

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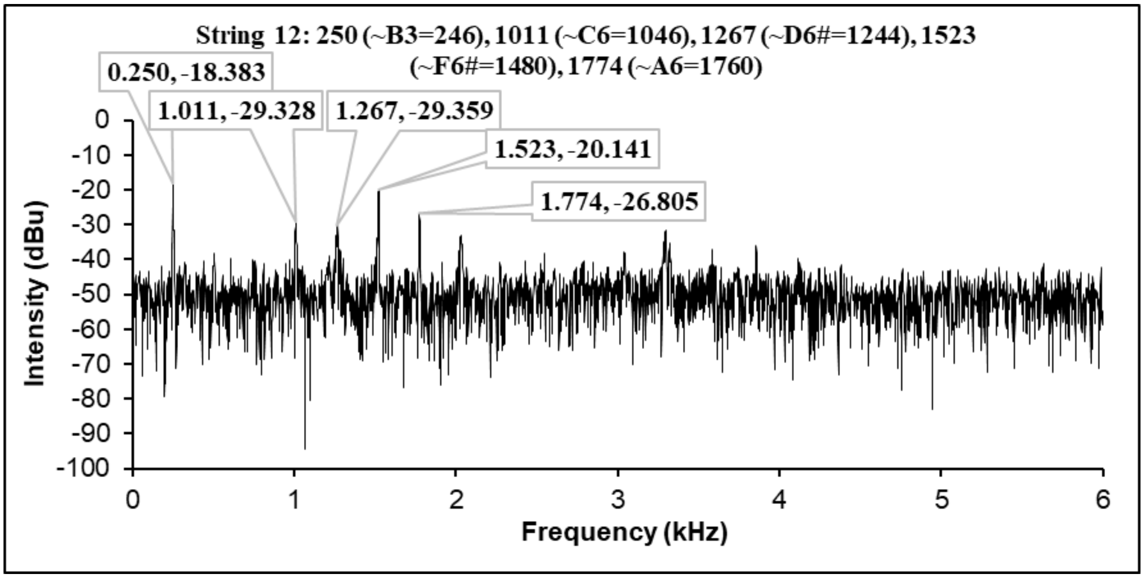

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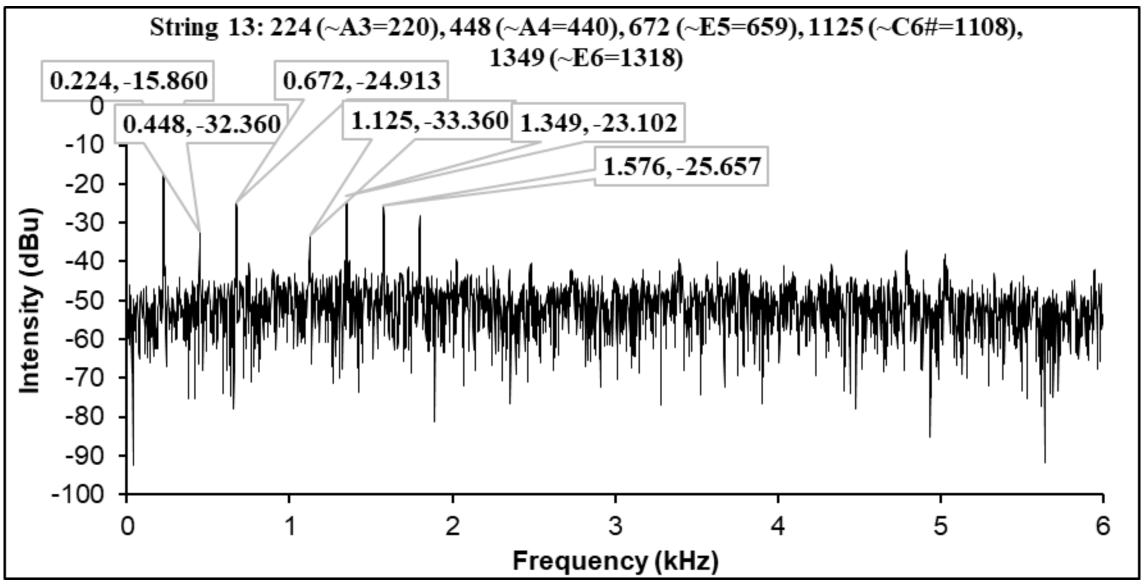

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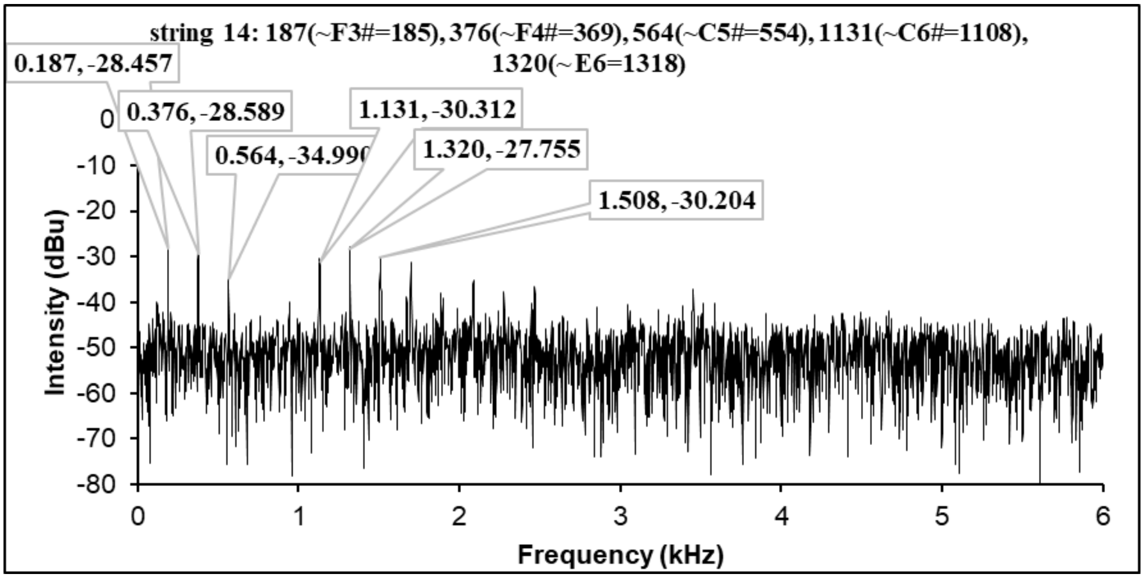

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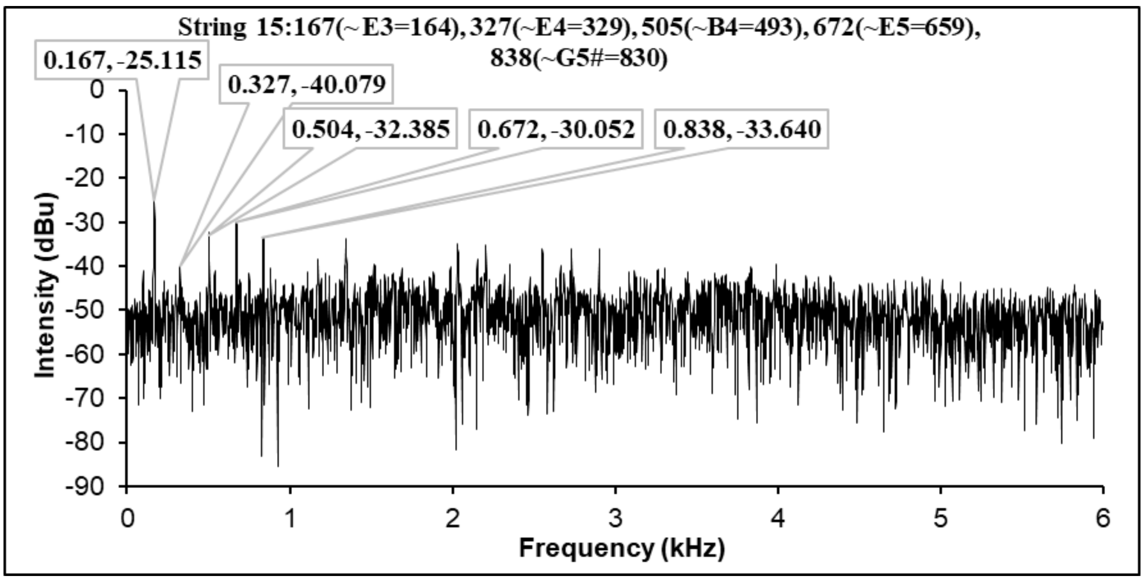

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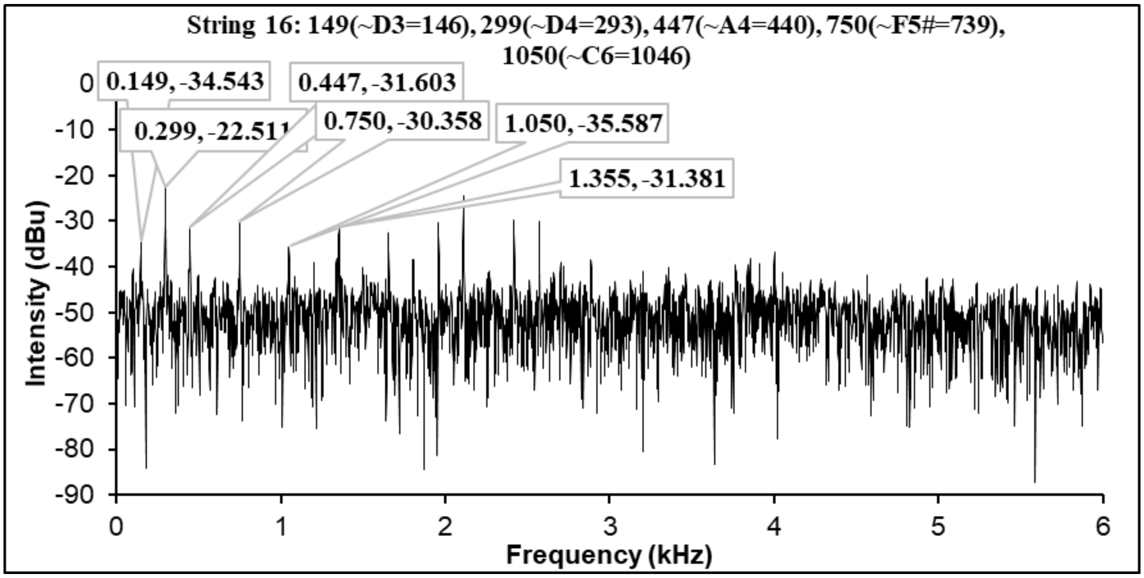

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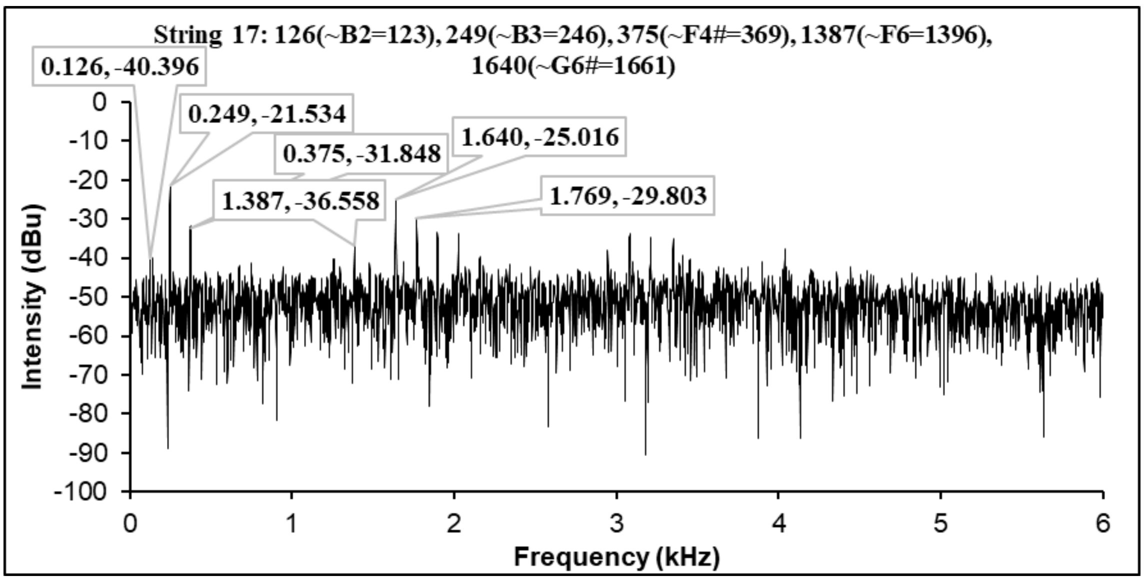

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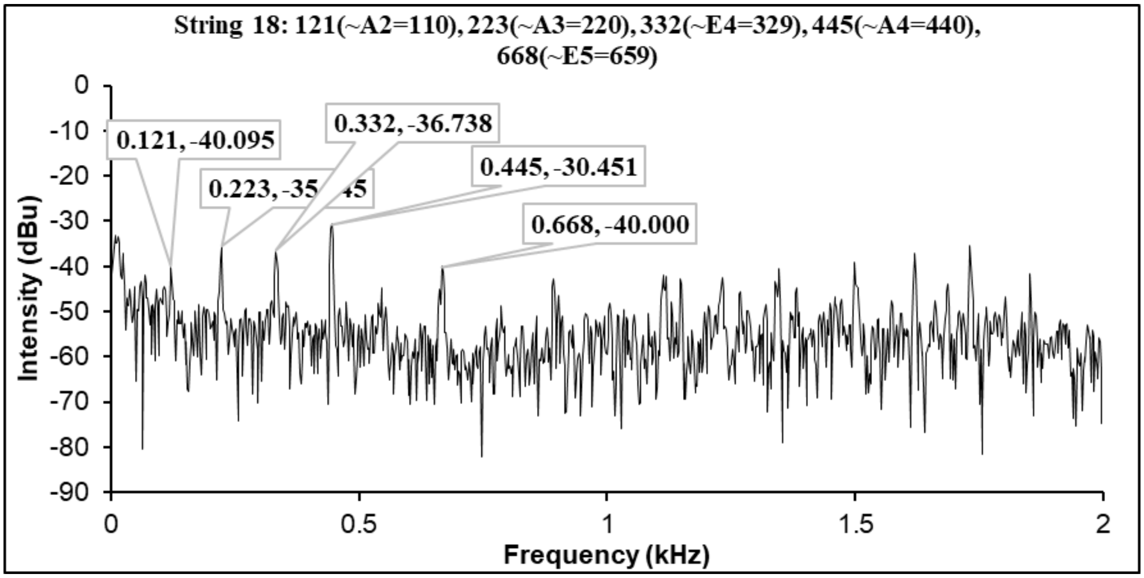

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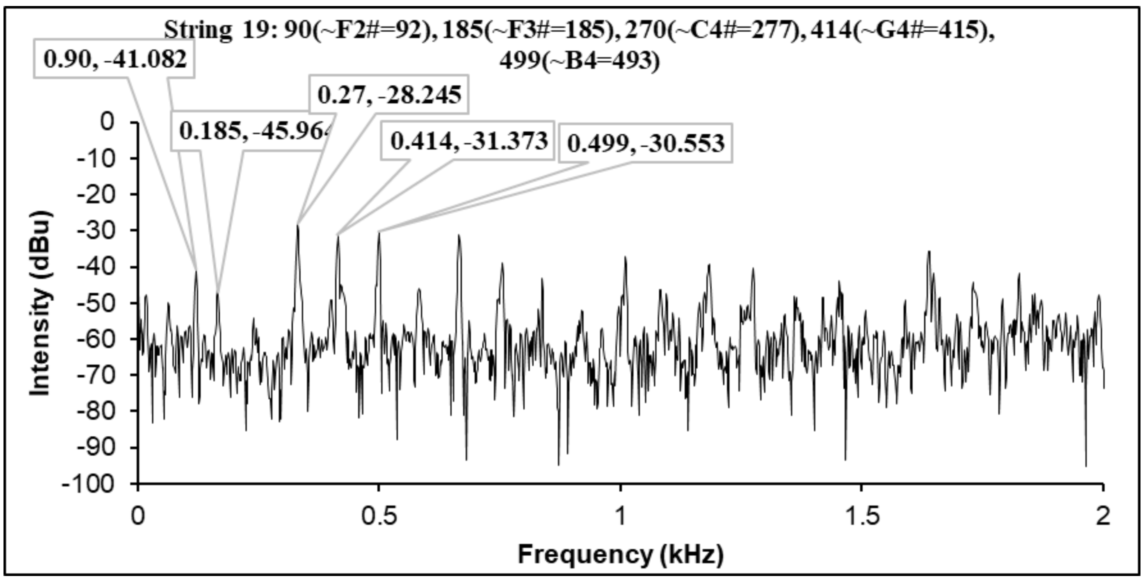

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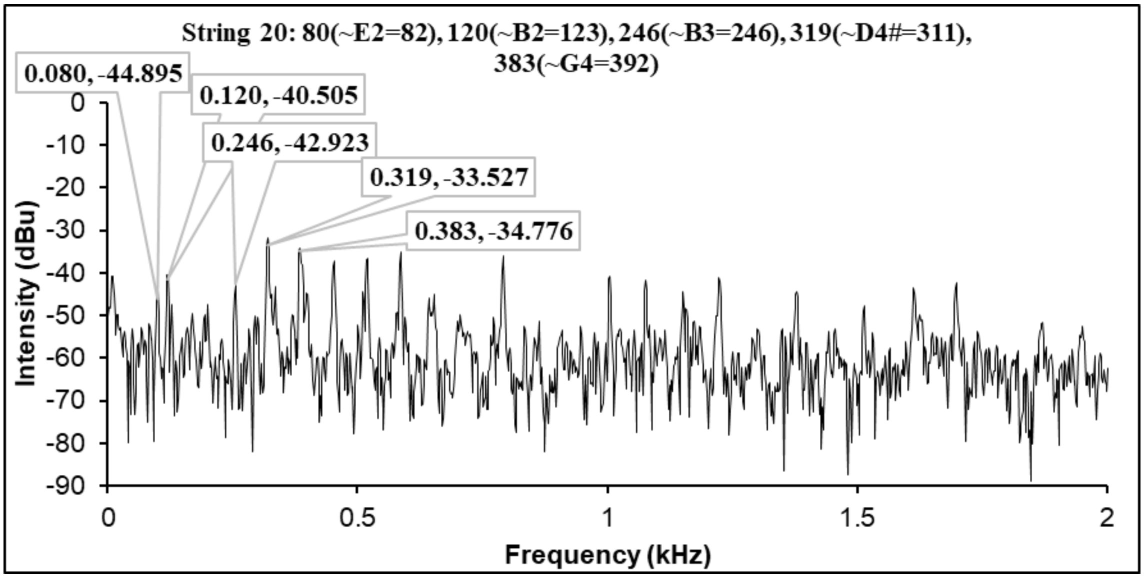

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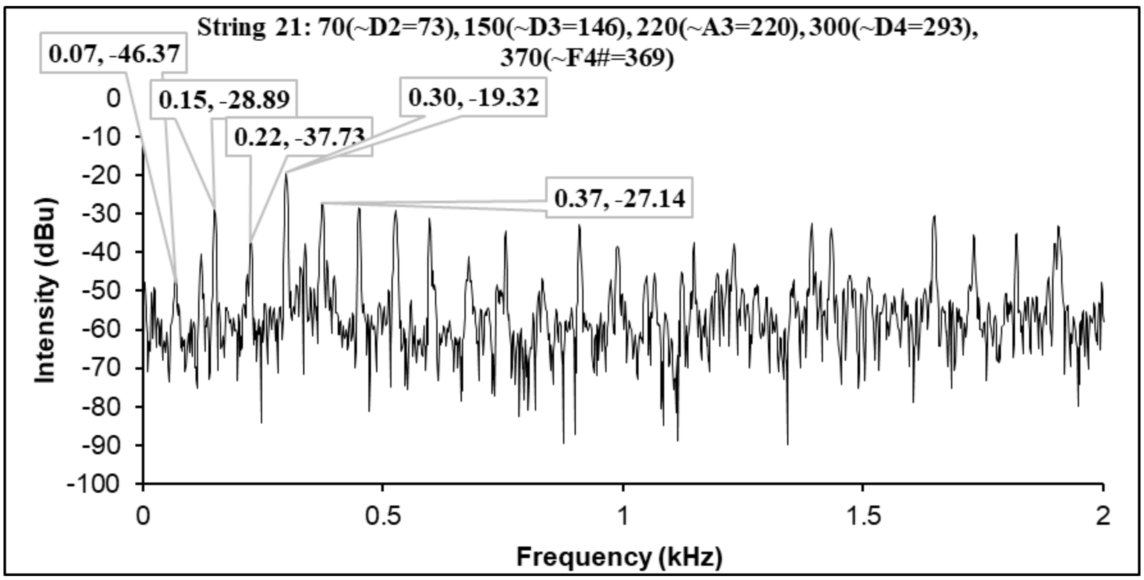

String 21