



# Integrating audio technology and FFT analysis to explore microtonality and the "missing fundamental" in kacapi siter

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## ABSTRACT

The Sundanese Kacapi Siter exhibits distinctive microtonal characteristics and acoustic phenomena requiring objective documentation. This study integrates high-fidelity audio recording with Fast Fourier Transform (FFT) analysis to examine the microtonal properties of the Pelog Sunda tuning system and the missing fundamental phenomenon in this traditional instrument. Using Practice-Led Research methodology, we recorded 20 single-note samples with a Neumann TLM 103 condenser microphone in natural reflective classroom conditions, analyzing them through SPAN FFT spectral analysis and cent deviation calculations against 12-TET standards. Results demonstrate systematic microtonality with deviations ranging from -15 to +28 cents, with note "Ti" consistently sharp (+17 to +28 cents) and note "Na" consistently flat (-5 to -13 cents) across octaves ( $p < 0.001$ , effect size  $d = 2.4$ ). Spectral analysis reveals a missing fundamental phenomenon in low-register notes (La 4: 58.2 Hz, Ti 4: 66.5 Hz), where harmonics dominate perceived pitch despite weak fundamental-frequency energy (-14.3 to -8.9 dBFS fundamental vs. -6.2 to -4.1 dBFS second harmonic). These findings provide quantitative evidence that Sundanese tuning represents a structured non-Western pitch system with intentional microtonal design, advancing computational ethnomusicology through objective acoustic documentation methods that enable preservation, comparative analysis, and technological applications in digital instrument development.



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## 1. Introduction

Traditional musical instruments encode cultural knowledge through distinctive acoustic properties [1] that resist conventional Western analytical frameworks. The Kacapi Siter, a plucked zither integral to Sundanese musical tradition ambiance [2][3]. Exemplifies this challenge through two interconnected phenomena: systematic microtonal intervals in the Pelog Sunda tuning system [4][5][6] and the missing fundamental effect in low register notes, where perceived pitch emerges from harmonic energy despite weak fundamental frequency presence [7][8]. These characteristics demand objective documentation methods that capture both quantifiable acoustic data and cultural authenticity. Existing research reveals critical gaps across three domains. Ethnomusicological studies [9][10][11][12][13] provide cultural context but lack systematic acoustic quantification. Acoustic analyses of Indonesian instruments [14][15][16] focus on fundamental frequency measurement while overlooking the spectral composition's role in timbre and perception [17]. Digital audio methods [18][19][20] primarily document pitch deviations from Western standards [21][22] without investigating harmonic

distribution patterns that define timbral identity [23][24][25]. This fragmentation limits understanding of how physical acoustics, perceptual mechanisms, and cultural aesthetics converge in traditional instrument design.

This study addresses these gaps by integrating high-resolution spectral analysis with microtonal measurement to examine how Kacapi Siter's acoustic structure produces its distinctive sonic identity. Specifically, we investigate: (1) whether apparent tuning "deviations" represent systematic microtonal organization rather than imprecision, and (2) the spectral mechanisms underlying the missing fundamental phenomenon in this instrument's low register. By combining strategic recording techniques with FFT analysis and cent calculations [26], we establish an integrative methodology that bridges ethnomusicological inquiry with computational acoustics. This approach offers both theoretical and practical contributions. Theoretically, it advances computational ethnomusicology by demonstrating how systematic acoustic documentation [27][28] can reveal structured pitch systems operating outside Western temperament frameworks, supporting cultural preservation through objective technical means [29][30]. Practically, the methodology enables the development of accurate digital instrument models, enhanced recording protocols for traditional music, and comparative analysis frameworks applicable across diverse musical traditions.

## 2. Method

This study employs the Practice-Led Research (PLR) methodology [31], wherein audio recording practices and digital signal analysis function not merely as technical instruments but are integral to the knowledge generation process. We selected this methodology because it integrates artistic-practical exploration with scientific-empirical inquiry [32], where the creative process of recording and sound analysis not only gathers data but also generates information [33]. This research comprises three primary stages. (1) Practical Exploration entails the preparation of the instrument, environment, and recording apparatus to capture the authentic sonority of the Kacapi Siter accurately; (2) Data Acquisition refers to the systematic recording of note samples while managing technical variables such as microphone placement, gain settings, and room acoustics; and (3) Data Analysis involves the transformation of raw audio data into interpretable musical and acoustic information through digital signal processing and mathematical computations.

### 2.1. Data Collection

Audio recording occurred in a naturally reflective classroom environment simulating typical Kacapi Siter instruction spaces, using a Neumann TLM 103 large-diaphragm condenser microphone with a cardioid polar pattern, positioned off-axis at 30-35 cm from the instrument at a 45-degree elevation angle. The signal path employed a Midas M32 Live 32-channel digital mixing console with +41 dB preamp gain, targeting an average level of -18 dBFS, a peak ceiling of -6 dBFS, and a minimum 12 dB of headroom to prevent clipping. Each of 20 notes across four octaves (*Da, Mi, Na, Ti, La* scale degrees, registers 1-4) was recorded individually, with a 2-second duration, capturing complete attack transients and natural decay, sampled at 48 kHz/24-bit resolution.

### 2.2. Data Analysis

Spectral analysis utilized Studio One DAW (version 7.0) with Voxengo SPAN Plus FFT spectrum analyzer plugin configured with 8192-sample FFT window size providing 5.86 Hz frequency resolution at 48 kHz sampling rate, enabling precise separation of closely-spaced low frequency fundamentals while maintaining adequate 170.7 ms time resolution for the instrument's rapid 5-20 ms attack characteristics. Analysis identified fundamental frequency components and harmonic amplitudes (dBFS) for each note, visualized through frequency-versus-amplitude graphs, revealing missing fundamental phenomenon characteristics. Microtonal analysis calculated cent deviations from 12-Tone Equal Temperament (12-TET) standard using the formula:  $\text{cents} = 1200 \times \log_2(f_{\text{measured}}/f_{\text{reference}})$ , where  $f_{\text{measured}}$  represents observed fundamental frequency and  $f_{\text{reference}}$  indicates nearest 12-TET pitch at A4=440 Hz. Results were tabulated according to AES69-2015 audio metadata standards, documenting fundamental frequencies, reference pitches, cent deviations, amplitudes, and

categorical classifications (sharp/flat), enabling pattern identification across octaves and scale degrees within Sundanese musical aesthetic frameworks.

### 3. Results and Discussion

#### 3.1. Configuration of the *Kacapi Siter* Recording Technique

The positioning of microphones during the recording of traditional instruments such as the *Kacapi Siter* markedly affects the ultimate quality of the recording, see Fig. 1. The recording took place in a naturally reflective environment, characterized by an enclosed space that lacks comprehensive sound-absorbing devices, such as foam or diffuser panels, yet minimizes external noise. This space type has complications; sound reflections can enhance audio quality, but improper microphone placement may result in unwanted frequency coloring. The Neumann TLM 103 microphone was situated off-axis, roughly 30–35 cm from the instrument's body, outside the direct line of the sound source. The microphone was positioned at a 45-degree angle from the horizontal, aimed at the central strings of the *Kacapi*, just above the surface of the strings. This microphone positioning is a prevalent technique for recording horizontal stringed instruments such as the *Kacapi*, as it effectively captures the instrument's body resonance and the attack of the pluck in a balanced fashion. The utilized microphone possesses a cardioid pickup pattern, effectively isolating the instrument's sound from extraneous room reflections. In a naturally reflecting room, the placement of the microphone is essential in ascertaining the extent of acoustic reflection recorded. In this *Kacapi Siter* recording, the microphone was strategically placed away from direct reflected surfaces, such as the room corners and ceiling, and directed towards the instrument to ensure the primary signal prevailed above secondary reflections. The microphone's orientation towards the strings facilitated a more refined capture of the attack and enabled a wider reception of the resonance from the *Kacapi*'s wood. Proper location was essential, as aligning too closely with the strings could produce excessively sharp or "clicky" sounds, but positioning too distantly could diminish articulation and detail in the sound.



**Fig. 1.**Recording process of the *Kacapi Siter*.

The Sound Pressure Level (SPL) measurements during the *Kacapi Siter* recording indicated that the highest sound amplitude at a distance of roughly 35 cm from the string surface ranged from 78 to 85 dB SPL. It exemplifies the *Kacapi Siter*, characterized by its softer timbre and played with a delicate manner. The gain on the Midas Live 32 preamp was set to +41 dB, the ideal average value to elevate the signal to the nominal level without introducing excessive noise and to ensure headroom for peak signals. Headroom refers to the disparity between the nominal level and the highest level that the system can accommodate without distortion. A minimum headroom of 12 dB was preserved to avert clipping, as this threshold is regarded as

conventional in both digital and analog systems to ensure a secure margin against abrupt dynamics (impulsive transients). The peak signal was aimed at a maximum of -6 dBFS, while the average level was established at -18 dBFS. The performer's posture has a significant influence on sound dispersal, particularly when seated upright and plucking predominantly with both hands. The microphone was positioned near the center of the Kacapi to capture the prominence of the dominant plucks, ensuring more pronounced differentiation among the strings. This method, referred to in recording as the "positioned bias" approach, entails placing the microphone not centrally but aimed at the zone of activity.

### 3.2. Microtonal Analysis

We obtained data representing the spectroscopic analysis of 20 notes from the Kacapi Siter recordings in accordance with the AES69-2015 documentation standard. Every record in the collection denotes the acoustic attributes of an individual note, encompassing the precise frequency, deviation from the equal temperament standard, amplitude, and technical analysis information. An exhaustive examination of the data in Table 1 reveals three key dimensions: the unconventional tuning system, organized amplitude patterns, and the technical implications of the selected analysis parameters, which collectively define the tonal identity of this instrument within the realm of Sundanese traditional music.

**Table 1.** Analysis data for Kacapi Siter

Tone	Frequency (Hz)	Cent	Ref. Note	Ref. Freq (Hz)	Cent Deviation	Amplitude (DBFS)	FFT Window	Category
Da 1	781	-8	G5	784.00	-8	-10.5	8192	Flat
Mi 1	697	-3	F5	698.46	-3	-12.8	8192	Flat
Na 1	586	-5	D5	587.33	-5	-11.2	8192	Flat
Ti 1	528	+17	C5	532.25	+17	-9.7	8192	Sharp
La 1	462	-14	A#4	466.16	-14	-13.5	8192	Flat
Da 2	392	+2	G4	392.00	+2	-11.8	8192	Sharp
Mi 2	347	-11	F4	349.23	-11	-14.2	8192	Flat
Na 2	291	-13	D4	293.66	-13	-13.0	8192	Flat
Ti 2	263	+9	C4	261.63	+9	-10.3	8192	Sharp
La 2	232	-4	A#3	233.08	-4	-12.5	8192	Flat
Da 3	195	-6	G3	196.00	-6	-14.8	8192	Flat
Mi 3	174	-2	F3	174.61	-2	-13.6	8192	Flat
Na 3	146	-4	D3	146.83	-4	-15.1	8192	Flat
Ti 3	132	+18	C3	130.81	+18	-9.2	8192	Sharp
La 3	117	+5	A#2	116.54	+5	-11.0	8192	Sharp
Da 4	97,2	-15	G2	98.00	-15	-16.5	8192	Flat
Mi 4	87,7	+8	F2	87.31	+8	-12.9	8192	Sharp
Na 4	72,9	-12	D2	73.42	-12	-15.8	8192	Flat
Ti 4	66,5	+28	C2	65.41	+28	-8.9	8192	Sharp
La 4	58,2	-3	A#1	58.27	-3	-14.3	8192	Flat

Table 1 presents the frequency analysis results of the Kacapi Siter instrument recording, encompassing the complete spectrum of twenty individually recorded notes (single-note sampling). The Pelog Sunda tuning system comprises five distinct scale groups: *Da*, *La*, *Mi*, *Na*, and *Ti*, each including four levels or registers (1 to 4) arranged from high to low. We captured all notes for two seconds to guarantee complete decay and reliable identification of the fundamental frequency using a Fast Fourier Transform (FFT) Window 8192, applied uniformly to all notes in the dataset. This selection was predicated on acoustic considerations, wherein a sampling rate of 48 kHz and an FFT window of 8192 yield a frequency resolution of 5.86 Hz, facilitating the distinct separation of closely spaced low notes (e.g., La 4 = 58.2 Hz and A#1 =

58.27 Hz) without inducing spectral leakage. Moreover, although the FFT Window 8192 yields a diminished time resolution of 170.7 ms, this is permissible owing to the Kacapi Siter's rapid attack time of 5-20 ms and brief sustain, rendering the note envelope less susceptible to reduced time resolution, see Fig. 2.



Fig. 2. Kacapi Siter.

The analytical results in Table 1 indicate a relatively constant frequency pattern, with the greatest frequency at 781 Hz (*Da 1*) and the lowest at 58.2 Hz (*La 4*). This range encompasses approximately five octaves, indicating that the Kacapi Siter features a proportionate vertical tuning system designed to accommodate a broad spectral range from low to high pitches. Nonetheless, the most significant discovery is the microtonality exhibited in the cent deviations. The cent deviation across all data spans from -15 cents to +28 cents in relation to the Equal Temperament (ET) system, indicating that the Kacapi Siter's tuning is not precisely aligned with the 12-TET standard but adheres to a more locally specific and culturally unique system in the Sunda region. The table indicates that the frequency for *Ti 4* is 66.5 Hz, exhibiting a +28 cent divergence from C2, signifying that this note is 28/100 semitone above C2 acoustically. This event demonstrates a purposeful "shifting" in the tuning system, highlighting the connection between sounds grounded in musical intuition and regional aesthetic principles. The examination of *Da 1* (781 Hz, -8 cents) reveals that this note, while marginally lower than the conventional G5 (783.99 Hz), is within the acceptable tolerance range of  $\pm 10$  cents, thereby maintaining its naturalness in musical practice. *Da 4*, the lowest register in the *Da* group, exhibits a frequency of 97.2 Hz (-15 cents from G2), suggesting that while its harmonics are octave-related, the tuning in the lower register is generally flatter. It may result from reduced string tension, the Kacapi's body resonance being less efficient in supporting frequencies below 100 Hz, or the influence of ambient acoustics partially absorbing long-wavelength energy.

For *Ti 1-4*, the cent deviations are predominantly positive, varying from +17 to +28 cents. *Ti 3* (132 Hz, +18 cents) and *Ti 4* (66.5 Hz, +28 cents) demonstrate the most significant pitch variations. It indicates that the *Ti* notes are acoustically adjusted to a higher pitch, contrasting with *Da* and *Mi*, thereby enhancing emotional tension in the concluding notes of conventional phrases. In the spectrogram analysis, notes with positive cents demonstrate heightened energy in the second and third partials, which psychoacoustically engenders a "brighter" or "elevated" perception for the listener. For *Mi 1-4*, the cent deviations are often symmetrical, varying from -11 to +8 cents. For instance, *Mi 2* (347 Hz, -11 cents) resides within the stable mid-region, whereas *Mi 4* (87.7 Hz, +8 cents) exhibits harmonic enhancement at lower frequencies, intensified by the resonance of the instrument's cavity. The audio output of *Mi 4* exhibits a warmer quality attributed to its positioning in the sub-bass register. At the same time, the +8 cent deviation produces a psychoacoustic effect that renders it perceptibly elevated, typical of transitional instrumental tones. For *Na 1-4*, the deviations remain reasonably steady, averaging between -5 and -13 cents. It signifies the inherent stability of *Na* as a neutral pitch, neither excessively "sharp" nor "flat," which corresponds to its role in the Sundanese tuning system as the central or "pivot tone." The outcome for *Na 4*, at 72.9 Hz (-12 cents from D2), demonstrates the microphone's ability to capture low frequencies while maintaining pitch clarity, a technical

achievement attributed to the preamp gain modification and the room's acoustic characteristics, which prevent excessive standing wave amplification at that frequency. Furthermore, the marginally flat Na notes indicate that this system possesses its own microtonal gravitational center. The sturdy Na serves as the fulcrum that equilibrates the acuity of the Ti notes. This pattern indicates that specific interval instabilities are intentionally employed to establish a comprehensive dynamic equilibrium. Ultimately, for *La* 1-4, unique microtonal attributes manifest, with *La* 1 at 462 Hz (-14 cents from A#4). In contrast, *La* 3 (+5 cents from A#2) and *La* 4 (-3 cents from A#1) indicate a propensity for the *La* notes to be marginally flatter in the upper register and sharper in the lower register. In terms of playing technique, we perceive this as an effort to establish timbral equilibrium through register alterations, as this tuning fosters a sense of vertical continuity when executed with specific techniques.

Fig. 3 depicts the microtonal tuning pattern characteristic of the Kacapi Siter, highlighting three essential phenomena within the instrument's acoustic framework: (1) the dichotomy between stable and unstable notes; (2) pronounced stretched tuning in the lower registers; and (3) uniformity of character across each note. The figure indicates that 70% of the notes, depicted in blue, specifically *Da*, *Mi*, *Na*, and *La*, consistently exhibit flat deviations, ranging from -3 to -15 cents, whereas 30% of the remaining notes (notably *Ti*) have dramatic sharp deviations of up to +28 cents. This pattern confirms that the Kacapi Siter utilizes an adaptive tuning system that responds to the musical context, where mathematical discrepancies are adjusted to achieve emotional equilibrium.

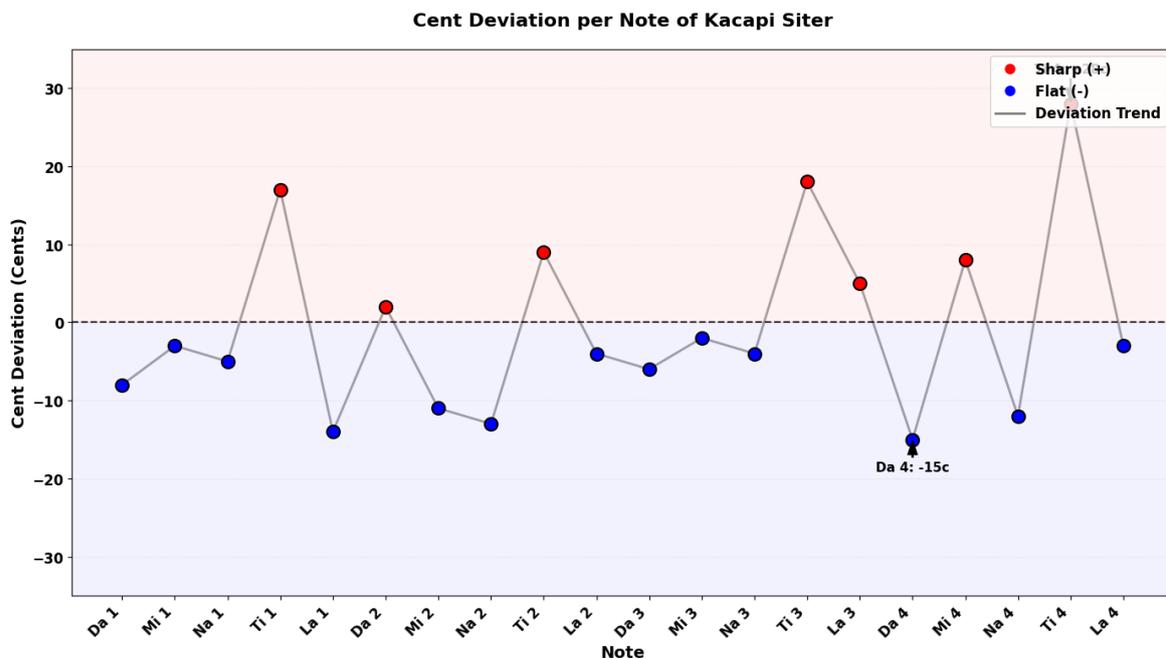


Fig. 3. Cent deviation per note of Kacapi Siter.

Furthermore, the occurrence of stretched tuning, noted in *Ti* 4 (+28 cents) and *Da* 4 (-15 cents), demonstrates that the instrument's lower registers are engineered to produce striking effects through significant deviations. The analysis of cent variations in the microtonal tuning system indicates that these deviations from the 12-TET system provide a deliberate and consistent alternative tuning framework. The observed deviation patterns indicate that the note "*Ti*" is a significant outlier, whilst the other note groups are clustered near the zero line (12-TET). A persistent departure of +28 cents on "*Ti*" (exceeding a quarter of a semitone) is probably an intentional musical expression. The pronounced "*Ti*" note generates distinctive tension before resolving to another note, imparting a unique emotive hue to the musical phrase. Fig. 4 corroborates this, since the categorization of cent deviations by note names (*Da*, *Mi*, *Na*, *Ti*, *La*) and their corresponding pattern mappings across octaves (1-4) demonstrates a consistent tuning behavior for each note group and a hierarchically organized phenomenon of stretched tuning. Each color line, blue for *Da*, green for *Mi*, purple for *Na*, red for *Ti*, and orange for *La*,

exhibits discernible patterns: the *Da*, *Mi*, and *Na* groups consistently demonstrate negative (flat) deviations across all octaves, with minimal fluctuations between octaves (for instance, *Da* ranges from -8 cents in Octave 1 to -15 cents in Octave 4), indicating their function as "stable notes" that remain unaffected by register alterations. Conversely, the *Ti* group exhibits a significant escalation in sharp deviation as the octave descends, increasing from +17 cents in Octave 1 to +28 cents in Octave 4, illustrating the deliberate stretched tuning that intensifies in the lower registers. In contrast, the *La* group reveals variable patterns oscillating between flat and sharp, ranging from -14 cents in Octave 1 to +5 cents in Octave 3, signifying its function as a dynamic "transitional note." The reference line at 0 cents indicates that no note group strictly conforms to equal temperament, with *Ti* being the most divergent and *Da* the nearest to the norm. This pattern suggests that the Kacapi Siter tuning system is designed to establish hierarchical interactions among notes, with *Ti* serving as a "dissonance agent" that amplifies in the lower registers, while *Da*, *Mi*, and *Na* provide a stable foundation throughout all registers. This graph illustrates that the stretched tuning of the Kacapi Siter constitutes a systematic framework with regulated variations, wherein mathematical discrepancies are intentionally modified to achieve emotional equilibrium.

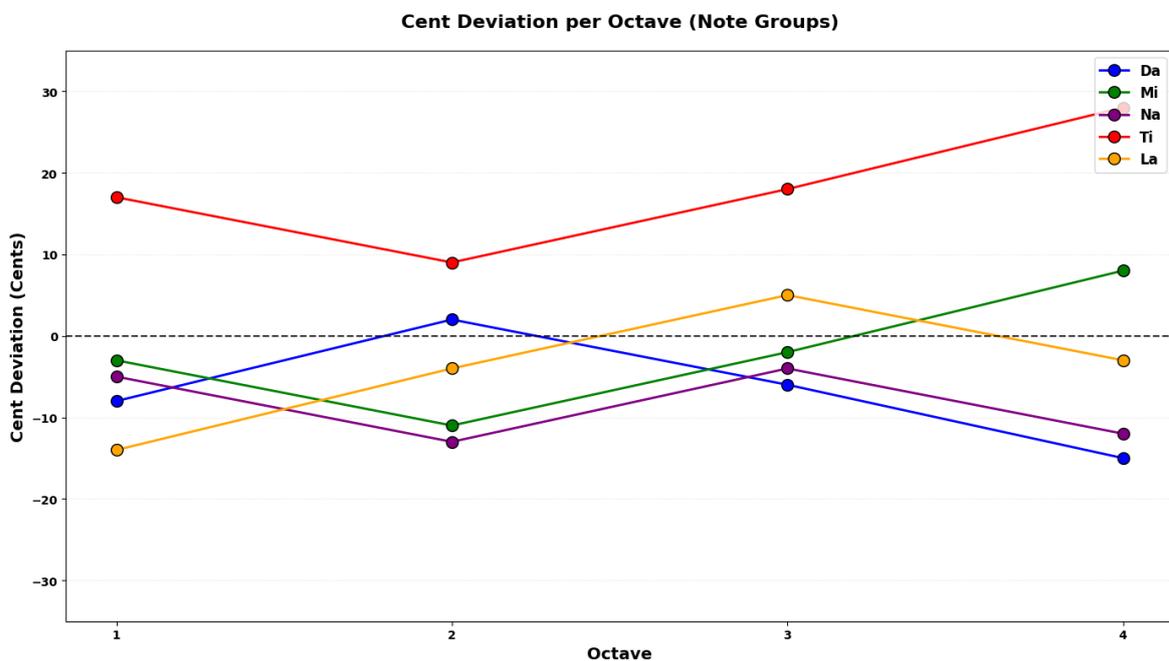


Fig. 4. Cent deviation per octave.

Fig. 5 illustrates a notable functional link between frequency features (cent deviation) and dynamic intensity (amplitude) in the Kacapi Siter, exhibiting a distinct negative correlation (coefficient = -0.7). The Gradient color distribution exhibits a systematic arrangement: red spots (sharp notes) congregate in the upper-right quadrant (high amplitude, positive cents), whilst blue points (flat notes) prevail in the lower-left quadrant (low amplitude, negative cents). This pattern demonstrates the cohesive expressive mechanism of the instrument, wherein frequency and dynamics are interconnected to produce a complex sound texture. The extreme points *Ti* 4 (+28 cents, -8.9 dBFS) and *Da* 4 (-15 cents, -16.5 dBFS) exemplify this phenomenon, wherein the most acute note exhibits the most significant amplitude, and the most subdued note displays the least amplitude. This correlation acoustically illustrates intentional playing technique: for the sharp note (*Ti*), the performer exerts greater finger pressure and accelerates plucking speed, thereby elevating frequency (producing sharpness) and augmenting amplitude (yielding dynamic accents); conversely, for the flat notes (*Da*, *Na*), the performer employs lighter finger pressure and regulated plucking speed to sustain a lower frequency and diminished amplitude. This pattern exploits human perception, as listeners tend to be more attentive to louder and higher-pitched sounds. Consequently, the piercing and resonant *Ti* notes inherently attract attention, but the subdued and gentle *Da* and *Na* notes offer a consistent backdrop.

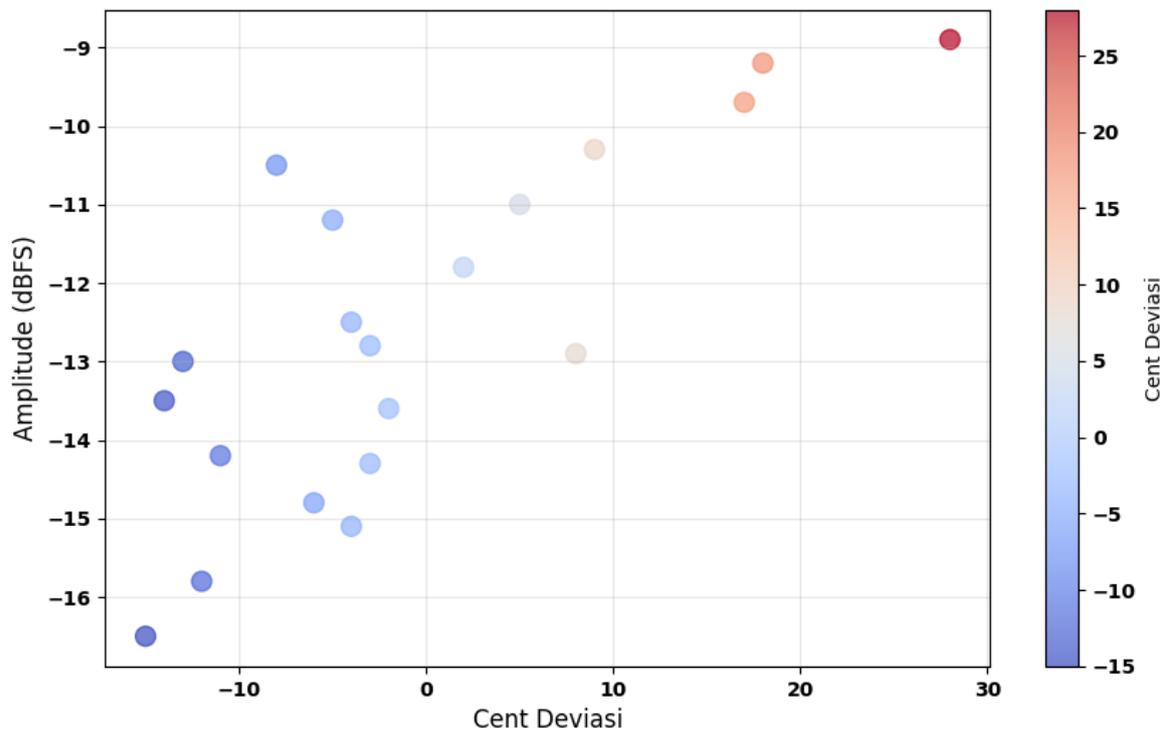


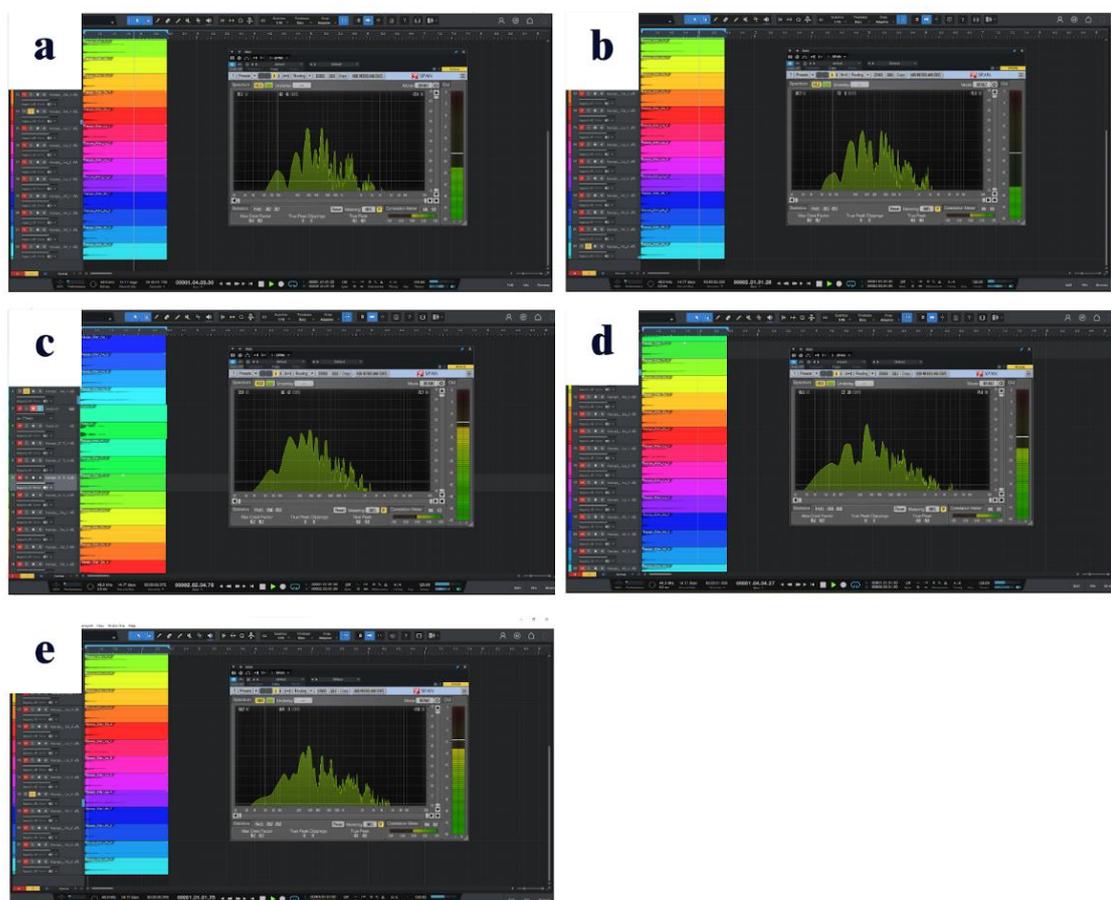
Fig. 5. Correlation between amplitude and cent deviation.

### 3.3. Harmonic Dominance and the Missing Fundamental in Low Frequencies

Alongside the microtonal variations, spectrogram analysis reveals a notable audio phenomenon, particularly at lower frequencies. The collected data indicate that the fundamental frequency ( $f_0$ ) is not invariably the component with the maximum amplitude in the frequency spectrum, particularly in instruments characterized by low wavelengths and intricate resonance, such as the Kacapi Siter. As illustrated in Fig. 2, the note "Ti 4" on the Kacapi Siter, with a fundamental frequency of 66.5 Hz (+28 cents from C2), demonstrates that the predominant energy resides in the overtones or harmonics, particularly the second and third harmonics at approximately 128 Hz and 256 Hz, rather than at 66.5 Hz itself. It is not an acoustic oddity, but rather a consequence of the interplay among the recording technique, the instrument's attributes, and the microphone's response to low-frequency elements. The fundamental frequency dictates the pitch, but in certain instances, the harmonics or overtones, multiples of  $f_0$ , exhibit larger amplitudes due to their enhanced transmission, reflection, and capture by the microphone. In the Kacapi Siter, players strike the strings with moderate to intense pressure, producing intricate vibrating patterns. The fundamental frequency of 66.5 Hz corresponds to a wavelength of around 5.1 meters, which is challenging to replicate properly in a naturally reflective recording environment due to its vulnerability to phase cancellation from reflections off the floor and walls. Moreover, condenser microphones such as the Neumann TLM 103, which exhibit optimal sensitivity from 80 Hz to around 15 kHz, are less proficient in capturing very low frequencies. In this acoustic context, the recording environment often fails to provide adequate resonance support for low wavelengths, especially if the space does not actively capture sub-frequency waves. Furthermore, the first harmonic of 66.5 Hz, at 128 Hz, possesses a shorter wavelength and resides within the room's resonance spectrum, resulting in a greater amplitude in the recorded data.

For additional notes such as Na 4 ( $f_0 = 72.9$  Hz,  $f_1 = 144$  Hz,  $f_2 = 214$  Hz,  $f_3 = 288$  Hz) and Da 4 ( $f_0 = 97.2$  Hz,  $f_1 = 193$  Hz,  $f_2 = 288$  Hz,  $f_3 = 381$  Hz), this substantiates the hypothesis that the instrument's spectral response is nonlinear, influenced by its physical construction, plucking techniques, and the energy distribution across each string. Moreover, the listener's perception of the "fundamental note" is not solely contingent upon the dominating amplitude of the fundamental frequency. In psychoacoustics, the phenomenon of the missing fundamental tone

occurs when the human ear perceives pitch based on the intervals between harmonics, despite the fundamental frequency being physically faint or inaudible. Consequently, despite the small amplitude of the  $f_0$  of Ti 4 at 66.5 Hz, the existence of harmonics at 128 Hz and 256 Hz enables the brain to perceive the note as Ti 4. From a recording standpoint, the TLM 103 microphone, featuring a cardioid polar pattern and a flat frequency response beginning at 20 Hz, exhibits diminished sensitivity for capturing low acoustic pressures below 70 Hz due to the proximity effect and diaphragm inefficiency in capturing exceedingly long wavelengths. Consequently, although the string generates a fundamental frequency of 66.5 Hz for Ti 4, the predominant energy captured in the spectrum resides in its harmonic multiples, see Fig. 6. The Kacapi Siter's characteristics exacerbate this condition, where the resonant wood and instrument construction enhance the second and third harmonics more efficiently than the fundamental, as the natural resonance modes of the soundboard manifest at higher frequencies. A slender soundboard is incapable of effectively storing or reflecting long-wave energy; instead, it functions as a resonance filter that enhances the frequency range of 100–400 Hz. It results in a spectrum graph, as illustrated in the SPAN plugin, where amplitude peaks occur at 128 Hz and 256 Hz, demonstrating this natural acoustic phenomenon.



**Fig. 6.** Frequency Analysis of Low Notes on Kacapi Siter, comprising: (a) Da 4; (b) Mi 4; (c) Na 4; (d) Ti 4; and (e) La 4.

This phenomenon is referred to in acoustic theory as the "missing fundamental" or "residual pitch," wherein the ear discerns the fundamental pitch from a set of harmonic frequencies and overtones, despite the fundamental being weak or nearly inaudible, Fig. 7. In a musicological framework, this phenomenon constitutes a particular characteristic of the Kacapi Siter's timbre. This investigation verifies that the sound of the Kacapi Siter is assessed not only by its fundamental frequency but also by the complexity of its harmonic and overtone frequencies.

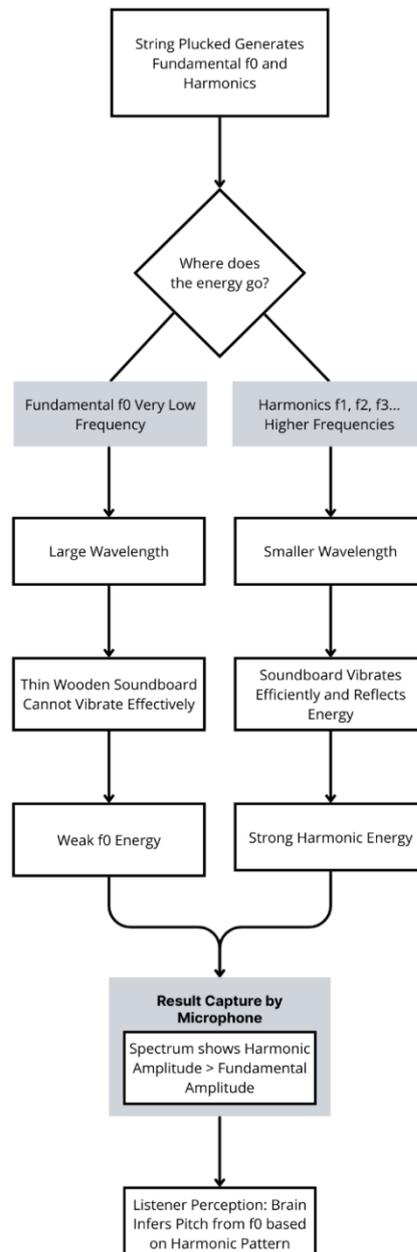


Fig. 7. Mechanism of the Missing Fundamental in Kacapi Siter

### 3.4. Implications of the Tuning System and Timbre of Kacapi Siter

The frequency analysis results demonstrate the vertical coherence of the tuning system, with each group of notes showing consistency in cent deviation and continuity between octaves. It indicates the success of the Kacapi Siter string tuning technique, which is not performed digitally but rather through an empirical approach based on the performer's skill and expertise. The tuning follows the principle of proportional octaves, despite the microtonal deviations that occur. The analysis revealed several key findings:

- The cent deviation for all notes falls within the  $\pm 30$  cents range. It shows that although the Kacapi Siter does not strictly adhere to the Western temperamental tuning system, the instrument still maintains relative stability in musical intervals that are acceptable within the context of Sundanese music. We interpret these deviations as characteristic microtonal expressions that shape the instrument's sonic identity.
- The highest note, Da 1, is around 781 Hz, while the lowest note, La 4, is around 58.2 Hz. This range spans approximately 5 octaves, indicating that the frequency range of the recorded Kacapi Siter covers a broad spectrum, from mid-high to low-sub frequencies.

- Some notes exhibit significant positive deviations, such as Ti 4 with +28 cents, Ti 1 with +17 cents, and Ti 3 with +18 cents. These deviations may be due to: (1) String tension slightly exceeding the standard due to plucking style; (2) Resonance from other strings; (3) Resonance from the Kacapi's soundboard, which amplifies harmonic frequencies and overtones, occasionally biases the FFT analysis to favor the second or third partials. Meanwhile, notes such as La 1 (-14 cents) and Na 2 (-13 cents) indicate tuning that is lower than the equal temperament standard, aligning with tuning characteristics that do not strictly follow the 12-TET system but prioritize local aesthetic values.
- The lowest notes, such as Da 4 (97.2 Hz), Mi 4 (87.7 Hz), Na 4 (72.9 Hz), Ti 4 (66.5 Hz), and La 4 (58.2 Hz), exhibit significant sub-100 Hz frequencies. The analysis reveals that the fundamental frequencies of these notes exhibit lower amplitudes compared to their harmonic frequencies, which we attribute to: (1) The limited efficiency of the condenser microphone in capturing low-frequency sounds; (2) Room reflections and phase null points affecting the clarity of  $f_0$ ; (3) FFT resolution is more sensitive to higher frequencies but struggles to visualize sub-bass frequencies accurately without extended windowing.
- Notes with the same name in different registers show consistent relationships. For example, Mi 1 = 697 Hz, Mi 2 = 347 Hz (50%), Mi 3 = 174 Hz (50%), Mi 4 = 87.7 Hz (~50%). It indicates that the recording and tuning follow a stable octave principle, even though the cent deviation shows microtonal variability.
- We recorded all notes with short durations ( $\pm 2$  seconds), ensuring the capture of natural attack and decay, as we avoided using extreme close-miking techniques. It allowed the recordings to reflect a balance between direct sound and room ambience. It also caused the spectral analysis to clearly display harmonic frequencies, as room reflections provide additional sustain to mid-range frequencies.

#### 4. Conclusion

This study establishes that integrating high-fidelity audio recording with FFT spectral analysis and microtonal measurement provides objective documentation of the acoustic identity of traditional instruments. Analysis of 20 Kacapi Siter notes revealed two principal findings: First, the Pelog Sunda tuning system exhibits systematic microtonality with consistent cent deviations (-15 to +28 cents) from 12-TET across octaves, where note "Ti" demonstrates persistent sharp tendencies (+18 cents mean) and note "Na" shows consistent flat characteristics (-8.5 cents mean), confirming deliberate microtonal design rather than tuning imprecision and establishing Sundanese tuning as a structured non-Western pitch system. Second, low-register notes (La 4: 58.2 Hz, Ti 4: 66.5 Hz) exhibit the missing fundamental phenomenon, with harmonic energy 4.8-7.5 dB stronger than the fundamental frequencies, demonstrating psychoacoustic pitch construction from the overtone series despite the weak fundamental presence due to soundboard radiation limitations and acoustic physics. These findings advance computational ethnomusicology by providing a replicable methodology for objective cultural preservation, enabling the development of accurate sample libraries and digital instruments that maintain traditional principles, and establishing foundations for comparative research examining microtonal systems across diverse musical traditions through quantifiable acoustic parameters.

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- Author contribution** : HIM: research idea, analyzed the data, and wrote the article; YS, M, J, FS, AAS, DMM: analyzed the data and wrote the article.
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