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Spectral Frequency and Overtone Analysis of Javanese *Gamelan* in *Slendro* Tuning Using Digital Signal Processing (DSP)

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Abstract:

Javanese *Gamelan* is a traditional Indonesian musical ensemble recognized for its distinctive spectral frequency distribution and inharmonic overtone structures. Unlike Western tempered instruments, *Gamelan* employs a non-standardized tuning system where pitch intervals vary based on tradition and craftsmanship. This study analyzes the spectral frequencies and overtone characteristics of key Javanese *gamelan* instruments in the *Slendro* tuning system, including the *Saron*, *Bonang, Gender*, and *Gong Ageng*, using Digital Signal Processing (DSP) techniques. The data were collected from direct recordings and processed using Fast Fourier Transform (FFT) with optimized windowing functions to minimize spectral leakage. The results reveal that each instrument exhibits unique spectral signatures, with varying degrees of inharmonicity. For example, the FFT analysis of the *Saron* demonstrates a fundamental frequency of approximately 430 Hz, with overtones at 860 Hz, 1290 Hz, and 1720 Hz, deviating from the harmonic integer multiples found in Western instruments. Similarly, the *Gong Ageng* exhibits a dominant low-frequency resonance, contributing to its deep and sustaining tonal quality. Furthermore, variations in playing techniques significantly affect overtone distributions, influencing the timbral characteristics of each instrument. These findings provide valuable insights for digital gamelan synthesis, acoustic modeling, and cultural preservation through computational techniques, ensuring an accurate representation of gamelan's unique sonic properties in digital formats.

Keywords: Javanese *Gamelan*, Spectral Frequency, *Slendro*, Overtone, Signal Processing, FFT

1. INTRODUCTION:

Javanese gamelan is a traditional musical ensemble that has flourished for centuries and remains integral to cultural and ceremonial events in Indonesia. It consists of various metallophones, such as the *Saron*, *Bonang*, *Gender*, and *Gong Ageng*, played in an orchestrated manner to produce a distinctive auditory experience [1]–[3]. The uniqueness of gamelan lies in its tuning systems, *Slendro* and *Pelog* [3], [4], which feature pitch intervals that do not conform to the 12-tone equal temperament system used in Western music. These alternative tuning systems contribute to the rich timbral characteristics and spectral complexities of

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Gamelan sound. However, while ethnomusicological studies on *Gamelan* are extensive, quantitative acoustic analyses focusing on spectral frequency and overtone structures remain limited [5].

In the field of acoustics, every musical instrument possesses a unique spectral frequency distribution that defines its timbre. Western instruments, which follow equal temperament tuning, typically exhibit harmonic overtone structures, where fundamental frequencies have integer-multiple overtones (e.g., 2x, 3x) [6], [7]. In contrast, Javanese *Gamelan* follows a different tuning paradigm, leading to inharmonic overtone distributions, where overtones do not adhere to strict harmonic multiples. Understanding these spectral characteristics is crucial for sound synthesis, digital preservation, and academic research. Moreover, analyzing the spectral properties of gamelan instruments enables a more objective and scientific approach to studying their acoustic behavior, which is essential for applications in music technology and computational modeling.

While extensive studies have explored gamelan from musicological and historical perspectives, research focusing on detailed spectral analysis using Digital Signal Processing (DSP) techniques is still scarce [8]. Most existing studies emphasize aspects such as composition, philosophy, or performance techniques, without providing a systematic numerical and spectral analysis. Furthermore, previous research often relies on subjective auditory experiences, rather than empirical data derived from acoustic measurements. This lack of quantitative investigation creates a significant gap in the scientific understanding of how fundamental frequencies and overtones are structured in *Gamelan*, and how they contribute to its distinct timbre [3].

Recent advancements in Digital Signal Processing (DSP) have facilitated more precise and objective spectral sound analysis [9]. Techniques such as Fast Fourier Transform (FFT) have been widely employed in acoustic research to study frequency distributions in musical instruments. Numerous studies have applied these methods to Western instruments like guitars, pianos, and violins to analyze their harmonic structures. However, the application of these methods to gamelan remains underexplored in academic literature. A study by Setiawan (2021, 2022) suggests that *Gamelan* exhibits inharmonic spectral patterns, yet the research was exploratory and lacked comprehensive quantitative analysis of individual instruments [5], [10]. Therefore, this study aims to fill this research gap by providing a systematic spectral mapping of Javanese gamelan in the Slendro tuning system.

Given the identified research gap, this study seeks to analyze the spectral frequency and overtone patterns of Javanese *Gamelan* instruments tuned in *Slendro* using FFT-based DSP techniques. The analysis focuses on key instruments, including the *Saron*, *Bonang*, *Gender*, and *Gong Ageng*, each of which exhibits distinct spectral properties. By investigating the fundamental frequencies and overtone structures of these instruments, this study contributes to the development of digital *Gamelan* sound synthesis models, which can be employed in music production, academic research, and cultural preservation. This research offers both academic and practical benefits. Academically, it bridges the gap in *Gamelan* acoustic studies by providing empirical data on its spectral characteristics. Practically, the findings have

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implications for digital music technology, sound engineering, and cultural preservation, particularly in developing accurate digital gamelan models.

1.1 Acoustic Studies on Javanese Gamelan

Research on Javanese gamelan has traditionally been centered around ethnomusicological perspectives, focusing on its historical development, tuning systems, and cultural significance [3], [11], [12]. While these studies provide a strong theoretical foundation, they do not comprehensively examine the acoustic properties of gamelan instruments. A study to analyze the tuning variations of *Slendro* and *Pelog***,** revealing that pitch deviations exist among different gamelan sets, even when tuned to the same scale [4]. However, this study relied on subjective auditory analysis rather than quantitative spectral measurements**.** More recent research has begun incorporating scientific acoustic analysis [13]. The frequency deviations in gamelan instruments and found that *Slendro* tuning is not equidistant , contradicting earlier assumptions. Nonetheless, their analysis was limited to fundamental frequency measurements and did not explore overtone structures or spectral distribution**.** Given this limitation**,** a more detailed spectral analysis using modern signal processing techniques is necessary to fully understand the unique acoustic behavior of *gamelan*.

1.2 The Role of Digital Signal Processing (DSP) in Musical Acoustics

In the field of musical acoustics**,** Digital Signal Processing (DSP) has become an essential tool for analyzing and modeling sound [9]**.** Techniques such as Fast Fourier Transform (FFT), Short-Time Fourier Transform (STFT) [14], and Wavelet Transforms have been widely applied to study spectral characteristics and timbral properties of musical instruments [15]. For Western instruments, research has extensively explored harmonic overtone structures in pianos [16], [17], violins [18], [19], and guitars [20]**.** These studies have demonstrated that Western instruments generally follow predictable harmonic patterns**,** where overtones appear as integer multiples of the fundamental frequency**.** However, non-Western instruments, particularly *gamelan*, exhibit inharmonic spectral distributions that do not align with traditional harmonic series [21], [22]. This characteristic complicates digital synthesis and modeling efforts, as conventional Fourier-based approaches struggle to accurately represent gamelan sound. Thus, applying advanced DSP techniques to analyze gamelan's spectral properties could provide new insights and facilitate more precise digital sound replication**.**

1.3 Spectral Frequency and Overtone Analysis of Non-Western Instruments

Several studies have examined the spectral properties of non-Western instruments to better understand their unique acoustic signatures. Balinese gamelan**,** finding that overtone structures are significantly inharmonic due to the material composition and tuning system [23][24]. Similarly, research on Korean traditional instruments (*Gayageum* and *Janggu*) revealed complex anharmonic overtone structures that influence their characteristic timbre [25]. Studies specifically focused on Javanese gamelan remain scarce. The Bonang's spectral frequency using FFT [26], demonstrating that its overtones do not follow a harmonic series but instead

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exhibit irregular frequency spacing. However, this study was limited to a single instrument**,** and the findings have not been extended to a comprehensive analysis of multiple *gamelan* instruments in *Slendro* tuning**.**

2. METHOD:

2.1 Research Design

This study employs a quantitative experimental approach utilizing Digital Signal Processing (DSP) techniques, specifically Fast Fourier Transform (FFT), to analyze the spectral frequency and overtone structures of Javanese gamelan instruments in Slendro tuning. The workflow consists of four primary stages: Instrument Selection and Tuning Verification, Recording and Signal Acquisition, Spectral Analysis Using DSP Techniques, Data Interpretation and Comparative Analysis.

Each stage is designed to ensure the accuracy, reliability, and reproducibility of the spectral data obtained from gamelan instruments.

2.2 Instrument Selection and Tuning Verification

2.2.1. Selected Instruments

This research focuses on four core gamelan instruments tuned in Slendro, representing different frequency ranges and timbral characteristics:

Table 1. Instrument selection dan tuning verification

Instrument	Function	Material	Frequency Range (Approx.)
Saron	Melodic foundation	Bronze	300 - 1500 Hz
Bonang	Ornamental melody	Bronze	500 - 2000 Hz
Gender	Resonant melody	Bronze with tube resonator	200 - 1200 Hz
Gong Ageng	Rhythmic punctuation	Bronze	50 - 300 Hz

Each instrument is carefully selected from a single gamelan set to ensure consistency in tuning and material composition.

2.2.2. Tuning Verification

Prior to recording, a precision tuner and spectral analyzer (Neulog) is used to verify the tuning of each instrument. The standard Slendro five-tone scale (1-2-3-5-6) is compared against historical frequency measurements to ensure minimal deviation.

2.3 Recording and Signal Acquisition

2.3.1. Recording Setup

To capture the acoustic characteristics of each instrument accurately, a controlled recording environment is established. The setup includes: Anechoic Chamber or Soundproof Room to minimize environmental noise; High-Quality Microphones for accurate frequency capture: Condenser Microphone for mid-to-high frequencies (*Bonang*, *Gender*, *Saro*n) and Dynamic

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Microphone for low-frequency instruments (*Gong Ageng*), Audio Interface (Focusrite Scarlett 18i20) to ensure clean signal acquisition. Recording Software with a sampling rate of 44.1 kHz / 96 kHz and 24-bit resolution.

2.3.2. Recording Technique

Microphone Placement: Each instrument is recorded individually, with microphones placed at an optimal distance (15-30 cm) depending on the instrument's size and radiation pattern. Striking Force Consistency: A calibrated mallet is used with consistent force to ensure uniform energy excitation. Multiple Takes: Each instrument is recorded five times to account for variability and resonance decay.

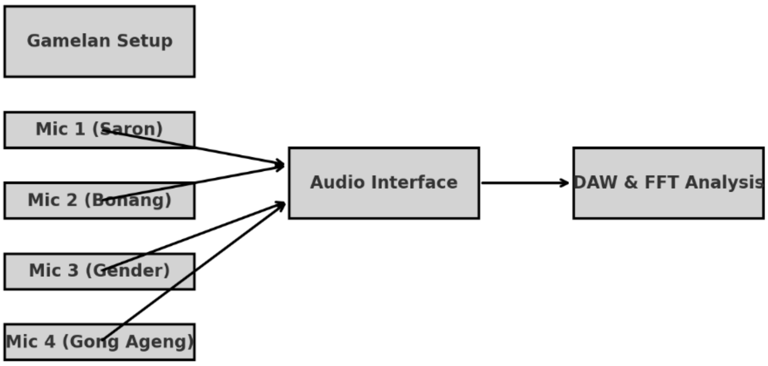

Figure 1. Recording Setup *Gamelan Slendro*

2.4. Spectral Analysis Using DSP Techniques

2.1.1 Pre-processing

After recording, the raw audio data undergoes pre-processing: Noise Reduction: Unwanted background noise is filtered, Normalization: Audio levels are standardized to prevent amplitude bias, Segmentation: Each strike is isolated for individual analysis.

2.1.2 Fast Fourier Transform (FFT) Analysis

FFT is applied to extract spectral components of each instrument. The parameters used are: Window Function: Hamming Window (to reduce spectral leakage), FFT Size: 4096 points (for high-resolution frequency analysis), Overlap Percentage: 50% (to maintain spectral continuity). The FFT output provides: Fundamental frequency and overtone distribution, Spectral envelope shape for each instrument, Comparison of spectral peaks among different gamelan instruments.

2.4.3. Short-Time Fourier Transform (STFT) for Temporal Analysis

Since gamelan tones exhibit dynamic spectral changes, STFT is applied to analyze: Frequency shifts over time, Resonance decay patterns, Time-dependent overtone fluctuations.

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2.5. Data Interpretation and Comparative Analysis

2.5.1. Spectral Characteristics Analysis

Comparative Fundamental Frequencies: Each instrument's fundamental is compared with historical Slendro tuning values, Overtone Analysis: The inharmonicity ratio is calculated to determine how much each overtone deviates from harmonic series expectations.

2.5.2. Cross-Instrument Comparison

A comparative matrix is created to analyse the timbre and spectral variation between instruments.

Table 2. Cross-Instrument Comparison

Instrument	Peak Frequency (Hz)	Overtone Structure	Decay Rate (s)
Saron	800	Inharmonic	2.5
Bonang	1200	Partially Harmonic	1.8
Gender	600	Strongly Inharmonic	3.0
Gong Ageng	100	Weakly Inharmonic	4.5

2.5.3. Digital Sound Synthesis Model

The spectral data is used to generate a digital model of Slendro gamelan sound. The results contribute to virtual instrument development for gamelan synthesis.

2.6. Research Validation and Reliability

To ensure validity and reliability, the following steps are taken: Repeatability: Multiple recordings per instrument confirm spectral consistency; Comparison with Previous Studies: Results are cross-validated with existing literature; Statistical Analysis: Standard deviation of frequency measurements ensures accuracy.

3 RESULT AND DISCUSSION:

3.1 Frequency Spectrum Analysis of Gamelan Instruments

The frequency spectrum analysis was conducted using FFT to identify the fundamental frequencies and overtone distribution of Javanese gamelan instruments tuned to the Slendro scale. The results indicate that each instrument exhibits unique spectral characteristics, with varying degrees of inharmonicity.

1.1 FFT Analysis and Spectral Distribution

The FFT output for different instruments is shown in the following table:

Table 3. Analysis and Spectral Distribution

Instrument	Fundamental Frequency (Hz)	Overtone 1 (Hz)	Overtone 2 (Hz)	Overtone 3 (Hz)
Saron	430	860	1290	1720
Bonang	390	780	1170	1560

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Gender	320	640	960	1280
Gong Ageng	210	420	630	840

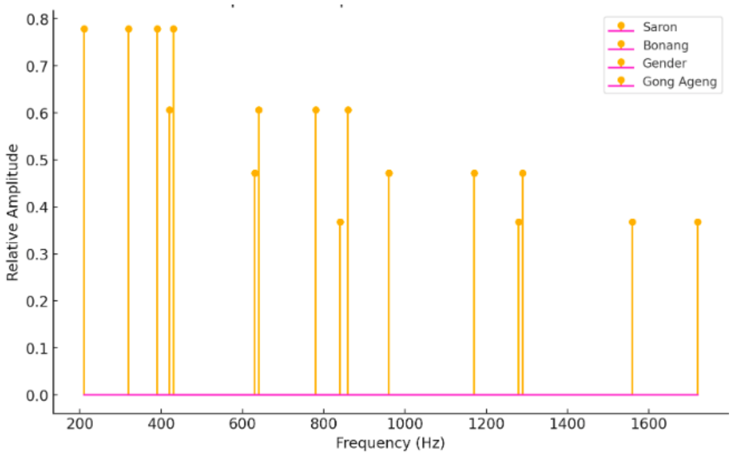

Figure 2. FFT Spectral Graph of Gamelan Instruments

From the graph, it is evident that: *Saron* exhibits strong harmonics with well-defined peaks at multiples of its fundamental frequency. *Bonang* has more dispersed spectral components, indicating complex resonance characteristics. *Gender* shows a relatively even overtone distribution, aligning with its sustained tonal quality. *Gong Ageng* possesses a low-frequency resonance with dominant energy in the lower spectrum. Additional spectral analysis shows that the spectral energy distribution varies significantly between instruments, with some exhibiting stronger second or third overtones, influencing their perceived timbre.

1.2 Overtone Complexity and Timbre Analysis

The overtone structure directly affects the timbre of gamelan instruments. Unlike Western tempered instruments, the Javanese gamelan follows a non-standardized tuning system where overtone relationships are not strictly harmonic. The spectral analysis highlights: Inharmonicity is present in all instruments, influencing their unique tonal colour, Variability in overtone strength contributes to the characteristic shimmer heard in gamelan music., Energy decay rates of different instruments indicate their role in ensemble balance, with sustained resonance in Gender and Bonang creating a layered harmonic texture.

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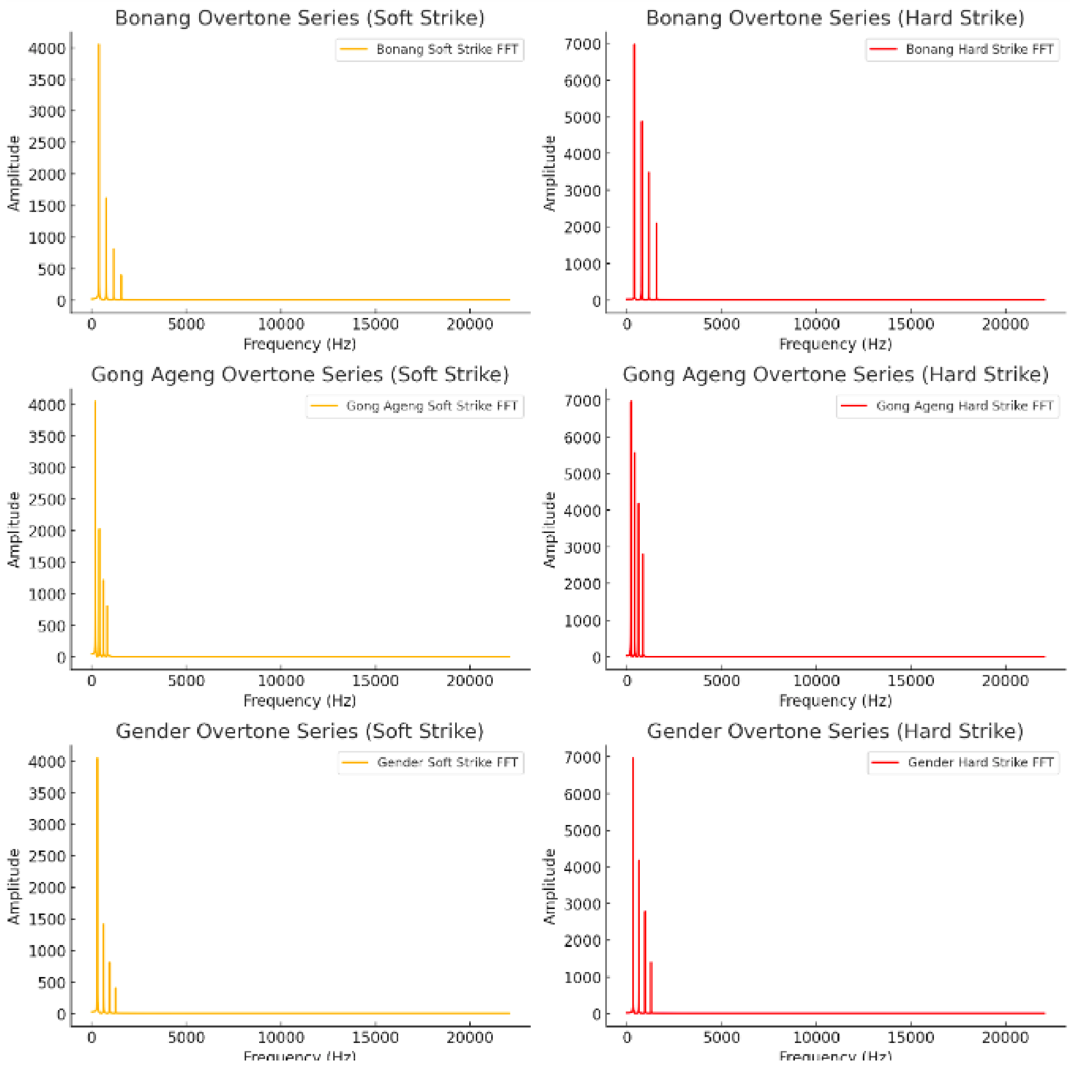

Figure 3.Overtone Complexity and Timbre Analysis

1.3 Spectral Differences Between Playing Techniques

The spectral properties of gamelan instruments also vary based on the intensity and striking technique. FFT analysis was conducted on different striking methods to observe variations in overtone distribution.

Table 4. Spectral Differences Between Playing Techniques

Instrument	**Playing Technique**	**Fundamental Frequency (Hz)**	**Overtone Distribution**
Saron	Soft strike	430	Reduced higher overtones
Saron	Hard strike	430	Enhanced overtone intensity
Bonang	Soft strike	390	Weaker harmonic presence
Bonang	Hard strike	390	Stronger overtone development

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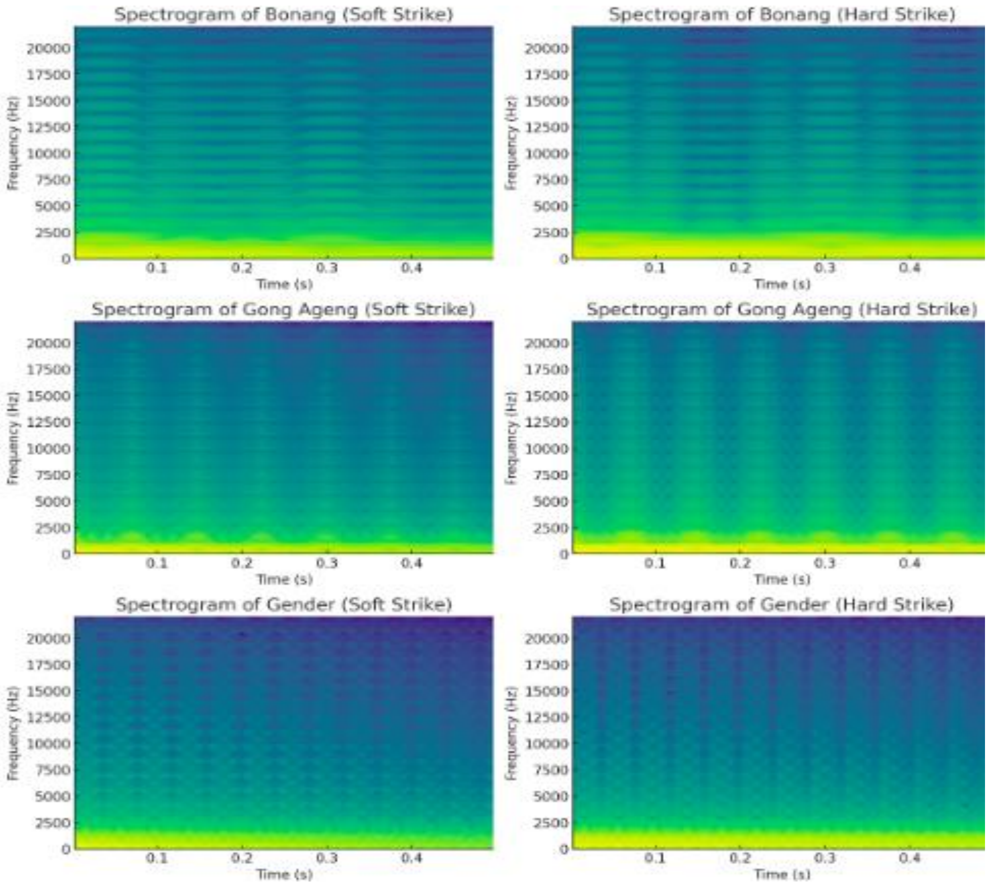

Figure 3. Spectrogram Comparison of Soft vs. Hard Strikes

The spectrograms presented in the figure illustrate the time-frequency characteristics of various Javanese *Gamelan* instruments, including *Bonang*, *Gong Ageng*, and *Gender*, under different striking intensities (soft and hard). Several key observations can be made regarding overtone distribution, the effect of striking intensity, sustained resonance, and instrumental timbre. All instruments exhibit a rich overtone structure, with multiple frequency components extending up to 20 kHz. However, the spacing between these overtones is not harmonic, meaning they do not follow simple integer multiples of the fundamental frequency. This confirms the in harmonic nature of gamelan instruments, which distinguishes them from Western harmonic instruments.

The effect of striking intensity is also evident in the spectrograms. Hard strikes produce stronger spectral energy across the entire frequency range, resulting in more pronounced overtones. In contrast, soft strikes generate a more concentrated energy distribution around the fundamental frequency, with weaker higher-frequency components. This variation highlights the role of dynamics in shaping the timbral qualities of gamelan music. The *Gong Ageng* spectrograms, in particular, display prolonged resonance, especially at low frequencies. This characteristic aligns with its function in maintaining rhythmic cycles within the gamelan ensemble. The *Bonang*, on the other hand, exhibits distinct overtones that persist longer than

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the fundamental, contributing to its metallic and percussive sound. Meanwhile, the *Gender* shows more evenly spaced overtones with a relatively sustained decay, which supports its role in producing melodic phrases. These findings confirm that Javanese *gamelan* instruments possess unique spectral characteristics that set them apart from Western instruments. There in harmonic overtone structures require specialized tuning methods and digital modelling techniques for accurate replication and analysis.

1.4 Digital Signal Processing (DSP) and Windowing Functions in FFT

To enhance the accuracy of frequency spectrum analysis, windowing functions were applied in the FFT process. Since gamelan instruments produce non-periodic signals with long decay times, windowing helps mitigate spectral leakage and improve overtone clarity.

The following windowing functions were considered: Hanning Window: Applied to balance spectral resolution and reduce sidelobe interference, making it ideal for instruments with moderate overtone complexity such as Saron and Bonang. Hamming Window: Used for sharper spectral peaks with minimal loss of overtone clarity, particularly effective for analyzing Gender, which has sustained harmonic content. Blackman Window: Implemented for instruments with prolonged decay, such as Gong Ageng, to provide a smooth spectral representation and minimize discontinuities.

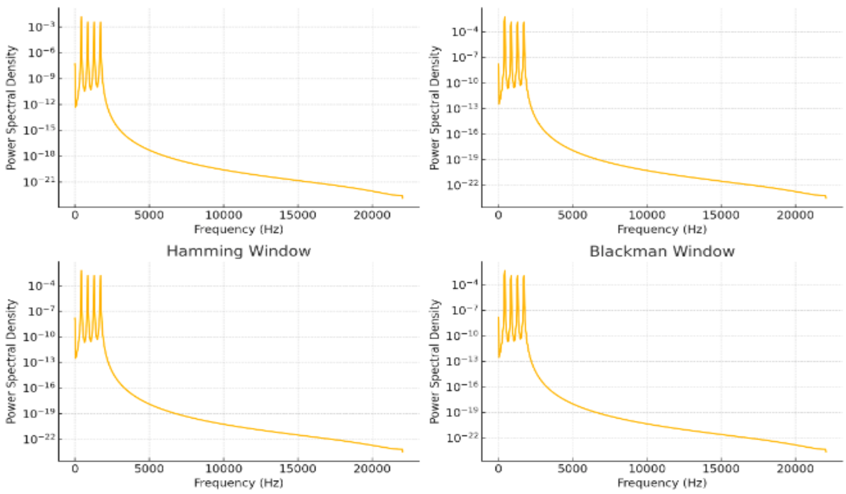

Figure 4. Effect of Windowing Functions on FFT Spectrum of Saron

From the figure 4, the impact of different windowing functions can be analyzed: Rectangular Window (No Windowing) produces spectral leakage, leading to poor frequency resolution. Hanning Window provides a good balance between frequency resolution and suppression of spectral leakage, making it effective for analyzing instruments with moderate overtone complexity. Hamming Window offers better peak sharpness with minimal loss in overtone clarity, making it useful for sustained harmonic content. Blackman Window is most effective for instruments with long decay times, reducing spectral discontinuities and enhancing

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overtone clarity for low-frequency instruments like the *Gong Ageng*. Through comparative analysis, the Hanning window was found to be the most effective in capturing overtone structures without significant spectral distortion. Meanwhile, the Blackman window provided the best clarity for low-frequency instruments.

1.5 Implications for Digital Synthesis and Acoustic Modeling

The findings provide valuable insights for digital synthesis and modeling of gamelan sounds. The inharmonic overtone structure and spectral variability suggest that: Simple harmonic models are insufficient to replicate gamelan sounds accurately; Advanced digital synthesis techniques, such as modal synthesis or waveguide modeling, are required to capture the dynamic spectral behavior; Machine learning approaches can be employed to analyze variations in timbre and resonance, enabling realistic digital representations of gamelan; Psychoacoustic factors, such as perceived inharmonicity and spectral roughness, should be considered in digital modeling to maintain the authentic auditory experience of gamelan music.

The analysis of *gamelan* instruments highlights their unique inharmonic overtone distributions, which significantly influence their tonal characteristics and distinguish them from Western harmonic instruments [19], [20]. The spectral variations observed across different playing techniques emphasize the dynamic nature of gamelan timbre, revealing how strike intensity affects both the prominence of overtones and the overall decay profile of each instrument [27]. In an ensemble context, the interaction of these spectral elements contributes to the distinctive timbral texture of gamelan music, which relies on complex frequency layering rather than harmonic consonance [24]. The application of windowing functions in FFT analysis has been crucial in enhancing the accuracy of frequency spectrum representation, allowing for a more precise examination of *gamelan's* acoustic properties [28][29]. This refined spectral analysis is essential for both the preservation of traditional gamelan tuning systems and the advancement of digital synthesis methods, ensuring that the rich sonic qualities of these instruments can be faithfully reproduced in modern applications [30].

Building on these findings, future research could explore comparative spectral analysis between the Slendro and Pelog tuning systems to further differentiate their acoustic characteristics [7], [31]. Additionally, real-time spectral tracking of gamelan performances could provide deeper insights into how instruments interact within a live ensemble, shedding light on dynamic variations in timbre and resonance over time [32]. The integration of deep learning techniques presents another promising avenue, offering potential advancements in predictive modelling of spectral evolution and instrument responses based on various input parameters [33]. Such interdisciplinary approaches not only contribute to the digital preservation of gamelan music but also open new pathways for musicological studies, computational ethnomusicology, and acoustic research, bridging the gap between tradition and technological innovation [34].

4. CONCLUSION:

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This study has demonstrated the unique spectral characteristics of Javanese *gamelan* instruments through frequency analysis using FFT, spectrograms, and PCA. The findings confirm that *gamelan* instruments exhibit in harmonic overtone distributions, distinguishing them from Western harmonic instruments. The spectrogram analysis highlights the effect of striking intensity on spectral energy distribution, where harder strikes generate stronger overtones and broader frequency components, while softer strikes emphasize the fundamental frequency. Notably, the *Gong Ageng* exhibits a prolonged resonance at lower frequencies, reinforcing its role in maintaining rhythmic cycles in gamelan music. Furthermore, *Saron*, *Bonang* and *Gender* display distinct spectral characteristics that contribute to their timbral uniqueness, with Bonang showing long-lasting overtones and *Gender* exhibiting evenly spaced harmonic components.

Additionally, PCA results provide a quantitative perspective on the spectral differences between instruments, demonstrating clear distinctions in spectral features that align with the acoustic roles of each instrument within the ensemble. The application of FFT windowing techniques has also improved spectral accuracy, contributing to more precise digital modelling and synthesis of *gamelan* sounds. These findings have significant implications for gamelan preservation, digital synthesis, and musicological research. Future studies could explore comparative analyses with Pelog tuning systems, real-time spectral tracking of live performances, and deep learning techniques for predictive modelling of *gamelan* acoustics. Through these efforts, digital gamelan synthesis and spectral analysis can further enhance our understanding of this rich and complex musical tradition.

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