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COMPARING SHORT-TIME FOURIER TRANSFORM (STFT) AND CONSTANT-Q TRANSFORM (QCT) FOR SPECTRAL ANALYSIS OF THE REBANA, MALAY TRADITIONAL MUSIC INSTRUMENT

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Abstract

This study compares the Short-Time Fourier Transform (STFT) and Constant-Q Transform (CQT) techniques in capturing the intricate spectral characteristics of the rebana, a traditional Malay frame drum known for its rich harmonic content and transient attacks. High-quality audio recordings were obtained in a controlled studio environment using a Shure SM57 microphone placed six inches from the drumhead, ensuring minimal noise interference. The analyses were conducted in MATLAB utilising the MIRToolbox, enabling robust computation of time-frequency representations and related spectral parameters. While STFT provides a relatively straightforward and computationally efficient method, its linear frequency resolution can limit the clarity of lower harmonic details, especially for instruments like the rebana that exhibit a broad range of tonal nuances. In contrast, CQT's logarithmic frequency scaling aligns closely with human pitch perception, revealing more detailed harmonic structures and subtle timbral variations. Although this approach demands increased computational resources, the resulting representations offer valuable insights into the instrument's acoustic complexity. These findings suggest that CQT may be better suited for in-depth harmonic analysis and ethnomusicological research, whereas STFT remains a practical choice for applications emphasising transient behaviour or requiring real-time processing. Future work could explore hybrid strategies that combine the strengths of both transforms, yielding a more comprehensive toolkit for analysing traditional percussion instruments and informing efforts in cultural preservation, pedagogy, and performance practice.

Keywords: *Rebana, Spectral Analysis, Short-Time Fourier Transform (STFT), Constant-Q Transform (CQT), Malay musical instrument, acoustic profiling, ethnomusicological tools*

INTRODUCTION

Spectral analysis is a cornerstone in the study of audio signal processing, particularly for musical instruments whose tonal and harmonic complexity demands sophisticated analytical approaches. Among traditional instruments, the rebana—a Malay drum integral to ceremonial and cultural performances—presents a unique acoustic profile characterized by transient-rich percussive attacks, resonant overtones, and dynamic frequency responses. While the rebana is traditionally revered for its cultural significance, its acoustic properties remain underexplored in scientific literature, especially in the context of modern signal analysis techniques. This study addresses this gap by examining the spectral characteristics of the rebana through the lens of two widely utilized spectral analysis methods: the Short-Time Fourier Transform (STFT) and the Constant-Q Transform (CQT).

Background on the Rebana

The rebana has a long history in Malay musical traditions, often played during religious ceremonies, festive occasions, and cultural gatherings. It typically consists of a wooden frame with a single drumhead made from goat or buffalo skin, tightly stretched over the frame. The tension of the skin, as well as the diameter and depth of the frame, influences its tonal qualities. The rebana can vary in size, leading to a range of pitches and timbral characteristics across different types of rebanas. In community contexts, ensembles of rebana players synchronize complex rhythmic patterns, creating a rich tapestry of sound. Despite its prominence, formal documentation of its acoustic profile is comparatively scarce, often limited to cursory descriptions or anecdotal observations rather than rigorous spectral analysis.

Importance of Spectral Analysis

Spectral analysis is essential for understanding how different frequencies—ranging from fundamental frequencies to higher overtones—combine to produce an instrument's unique sound. For percussion instruments like the rebana, transient attacks and complex resonances are particularly vital elements of the overall timbre. Such attributes demand careful examination using methods that can effectively capture the time and frequency domains.

Short-Time Fourier Transform (STFT) and the Constant-Q Transform (CQT).

The STFT has been extensively utilized in audio signal processing because it provides time-frequency signals representations. By dividing signals into overlapping windows, the STFT generates spectrograms that offer insights into transient behaviour and frequency components. However, its fixed time-frequency resolution poses limitations in capturing the intricate harmonic structures of musical signals (Mateo & Talavera, 2020). These limitations have motivated the exploration of advanced methods like the Constant-Q Transform.

The CQT addresses the resolution challenges inherent in STFT by employing a logarithmic frequency scale, which aligns closely with human auditory perception. This innovative approach enables higher resolution at lower frequencies, making it particularly suitable for capturing the harmonic richness of traditional instruments such as the rebana. The development of the CQT and its applications in music signal analysis have been extensively discussed in the works of Brown (1991) and Schörkhuber and Klapuri (2010).

Scope of Research

The rebana's acoustic characteristics pose unique challenges and opportunities for spectral analysis. Its rich harmonic content and complex transient behaviour require analytical methods that balance precision and computational efficiency. By comparing the performance of STFT and CQT in analysing rebana recordings, this study seeks to illuminate the practical implications of these methods. MATLAB and the MIRToolbox were employed to facilitate robust spectral analysis, ensuring the accuracy of computed representations.

The recordings were performed using miking techniques commonly adopted for the rebana, as demonstrated in professional audio practices and instructional videos (Wayang Legend 2020; Pa'ang Zaman 2020; Faris Alfanso 2023). These established methods ensure that the captured audio represents the instrument's authentic sound profile. Understanding the spectral representation of the rebana also contributes to preserving and advancing the cultural heritage of Malay music by providing a scientific framework for documenting its unique acoustic properties. This ensures that traditional techniques and sounds are accurately archived, fostering their appreciation and integration into contemporary music practices.

This research builds on existing knowledge of traditional percussion instruments, such as studies on snare drum acoustics (Rossing et al., 1992) and microphone placement techniques for capturing tonal quality (Muddeen and Copeland, 2013). These insights provide a framework for evaluating the spectral characteristics of the rebana in both theoretical and practical contexts, offering applications in music production, where accurate spectral representations can inform mixing decisions and sound design for modern compositions.

These insights can be used in educational tools to create interactive learning modules that demonstrate the rebana's unique acoustic features, fostering a deeper appreciation for traditional Malay instruments. Additionally, in ethnomusicology, such analyses contribute to understanding and preserving the acoustic traditions of Malay music by supporting digital archiving and heritage projects.

Objectives

The objectives of this study are threefold:

1. To investigate how STFT and CQT capture the spectral characteristics of the rebana.
2. To evaluate the strengths and limitations of each method in resolving harmonic and transient features.
3. To provide practical guidance for the analysis and recording of traditional instruments.

By addressing these objectives, this study advances the field of music signal processing and underscores the importance of integrating technical precision with cultural sensitivity. The comparative analysis presented here aims to inform future studies on traditional instruments and their adaptation to modern audio processing paradigms.

LITERATURE REVIEW

Spectral analysis has been extensively applied in music signal processing to understand various instruments' tonal and harmonic characteristics. The STFT has been a cornerstone among these techniques due to its simplicity and ability to capture transient-rich signals. However, its fixed resolution poses challenges for instruments with complex harmonics, as Mateo and Talavera (2020) outlined. The CQT was introduced to address these limitations, offering a logarithmic frequency scale better suited for musical signals (Brown, 1991; Schörkhuber & Klapuri, 2010). Despite advancements in these methods, the application of spectral analysis to traditional percussion instruments like the rebana remains underexplored.

Studies on Material Properties and Instrument Timbre

Recent studies have highlighted the importance of material properties in shaping the acoustic profiles of musical instruments. For instance, Sinin et al. (2025) investigated the spectral characteristics of bamboo-based guitars compared to conventional wooden guitars. The study used Fast Fourier Transform (FFT) and spectrogram analyses to reveal that bamboo guitars exhibit unique overtone patterns and a distinct timbral richness. These findings underscore how alternative materials can significantly influence an instrument's tonal and harmonic content. By drawing parallels to the rebana, such studies emphasise the role of spectral analysis in uncovering the acoustic character of musical instruments. This body of work reinforces the need to adapt analytical techniques like STFT and CQT to capture the nuanced characteristics of traditional instruments. Understanding these spectral features enhances the documentation process and contributes to the broader field of ethnomusicology and instrument design.

Short-Time Fourier Transform (STFT)

The STFT is widely recognized as one of the most fundamental tools in spectral analysis. It works by segmenting an audio signal into overlapping windows, enabling the examination of both time and frequency components simultaneously. Studies, such as those by Mateo and Talavera (2020), have highlighted its utility in capturing transient-rich signals. However, its fixed time-frequency resolution limits its ability to analyse complex harmonic structures, particularly in instruments like the rebana. This trade-off between time and frequency resolution has driven the development of alternative methods, including the CQT, which better addresses the intricate demands of musical signals.

Constant-Q Transform (CQT)

The CQT offers a logarithmic frequency resolution that closely aligns with human auditory perception, making it especially valuable in the analysis of musical instruments. Brown's pioneering work (1991) established the mathematical foundation for the CQT, while subsequent research by Schörkhuber and Klapuri (2010) refined its computational implementation.

The CQT's ability to provide high resolution at lower frequencies is particularly advantageous for instruments like the rebana, whose rich harmonic content requires detailed spectral analysis. This method has been widely applied in music information retrieval tasks, demonstrating its utility in both academic and practical contexts.

Spectral Analysis of Musical Instruments

Various studies have investigated the acoustic properties of percussion instruments, including the rebana. Rossing et al. (1992) investigated the acoustics of snare drums, providing insights into how vibrational modes influence tonal characteristics. These findings are directly applicable to the study of the rebana, as both instruments share complex vibrational behaviours that contribute to their distinctive tonal qualities. Understanding these modes can inform techniques for analysing the rebana's transient responses and resonances, enhancing the accuracy of its spectral documentation.

Similarly, Muddeen and Copeland (2013) explored microphone placement techniques for tenor pans, emphasizing the importance of capturing authentic tonal quality. Comparable techniques could potentially be adapted for the rebana, although adjustments may be necessary to account for its unique acoustic properties and cultural performance contexts.

Furthermore, Zhang and Wu (2017) emphasize the role of timbral factors such as brightness in culturally unique instruments, which provides valuable insights for documenting the rebana's timbre. These findings can inform the selection of analytical methods and recording techniques to accurately capture the instrument's unique tonal properties.

Additionally, Jannereth and Esch (2021) demonstrate how quantitative methods, such as FFT, can complement spectral analysis techniques by offering an alternative approach to timbre quantification. While FFT provides a foundation for analysing harmonic structures, it lacks the resolution flexibility offered by STFT and the logarithmic frequency scale of CQT.

These features make STFT and CQT better suited for capturing the intricate harmonic and transient characteristics of traditional instruments like the rebana, thereby aligning more closely with the objectives of this study.

Traditional Instruments and Acoustic Documentation

Traditional musical instruments like the rebana are invaluable for their cultural and musical significance. Acoustic analysis provides a scientific approach to documenting their unique tonal characteristics, complementing broader cultural preservation efforts. This study leverages modern spectral analysis techniques, such as STFT and CQT, to explore the rebana's acoustic properties and ensure their accurate representation in contemporary musical contexts.

While this research does not focus on ethnomusicology exclusively, it aligns with global efforts to document and preserve the acoustic identity of traditional instruments, bridging cultural heritage and modern technology. Advanced machine learning techniques have also been shown to enhance traditional spectral analysis, demonstrating their relevance for complex instruments like the rebana (Parimala, Munibhadrayya, & Sudhindra, 2017). Moreover, spectral attributes such as centroid and envelope shape are critical in identifying instrument characteristics, aligning with the objectives of this study (Siedenburg, Jacobsen, & Reuter, 2021).

Knowledge Gap and Study Motivation

Despite the extensive application of spectral analysis methods in modern music signal processing, the rebana's unique acoustic profile remains underexplored. Existing studies have largely focused on Western instruments or generalized applications of STFT and CQT, leaving a gap in the literature concerning traditional Malay instruments. This study bridges that gap by examining how STFT and CQT capture the rebana's spectral characteristics, providing both academically significant and practically relevant insights.

THEORETICAL AND CONCEPTUAL FRAMEWORK

The study of the rebana's spectral characteristics requires a robust framework to connect timbre perception theories with advanced spectral analysis methodologies. As an instrument central to Malay culture, the rebana's preservation through accurate documentation reflects its historical and musical significance, emphasizing the role of spectral methods in safeguarding intangible heritage.

Theoretical Framework

Timbre perception theories provide a critical foundation for understanding the unique acoustic properties of the rebana, as they address how spectral and temporal attributes influence the perception of sound. These theories are particularly suited for traditional instruments like the rebana because they encapsulate the intricate interplay of tonal richness, harmonic content, and transient features, which are central to preserving the instrument's acoustic identity. The spectral centroid, a key timbral attribute, represents the "centre of mass" of a sound's spectrum and is closely associated with perceived brightness (Grey, 1977). Grey's analysis emphasizes the influence of spectral energy distribution on timbre perception, underscoring its relevance for examining the rebana's tonal richness.

Instruments with higher spectral centroid values tend to sound brighter, making this attribute essential for understanding the tonal quality of the rebana. Transient characteristics, including attack and decay envelopes, are also pivotal in shaping timbre perception (McAdams & Giordano, 2008).

For the rebana, its percussive attack and resonant decay are distinctive features that demand detailed analysis. Additionally, the balance between harmonic (tonal) and inharmonic (noise-like) content contributes significantly to the complexity of its timbre. Peeters (2003) highlights the importance of spectral features in defining timbral identities, offering a solid basis for exploring the rebana's unique acoustic profile.

Building on these theoretical insights, the study compares STFT and CQT. This transition from theoretical principles to practical methodologies bridges the gap between understanding timbral characteristics and their accurate representation in spectral analysis.

This comparison has practical implications for audio production, where accurate spectral representation informs mixing and mastering decisions, as well as for cultural archiving, ensuring the rebana's unique sound is preserved with precision for future generations. As Grey (1977) and Peeters (2003) discussed, these methods are assessed for their analytical precision and alignment with perceptual dimensions of timbre.

The STFT is particularly effective for analysing transient characteristics, making it ideal for capturing the rebana's percussive attack and time-dependent harmonic features (Schörkhuber & Klapuri, 2010). However, its fixed resolution can limit the accuracy of low-frequency harmonic representation.

In contrast, the CQT employs logarithmic frequency scaling, aligning closely with human auditory perception and providing detailed insights into tonal richness and harmonic structures (Schörkhuber & Klapuri, 2010). The comparison of STFT's uniform resolution with CQT's frequency-dependent scaling aims to identify the method that offers a more perceptually accurate representation of the rebana's spectral content.

Conceptual Framework

The conceptual framework integrates STFT and CQT to address key research questions about the rebana's spectral profile. These questions include how harmonic and transient features define the instrument's sound, how STFT and CQT differ in their representation of these features, and which method provides the most accurate and perceptually relevant analysis. The framework ensures a comprehensive approach to capturing the rebana's time-dependent and frequency-dependent acoustic properties by employing both techniques.

This framework supports cultural preservation by enabling the precise archival of the rebana's unique sound profile, safeguarding its heritage through informed spectral analysis. These efforts align with broader ethnomusicological goals and international cultural preservation initiatives, such as those supported by UNESCO. Detailed spectral profiles of the rebana contribute to the accurate archiving of its sound, safeguarding its unique characteristics, such as its tonal richness, rhythmic clarity, and distinctive percussive attack, for future generations. This analysis also supports broader ethnomusicological goals, enabling the integration of traditional instruments into contemporary music practices while respecting their cultural origins. Furthermore, the comparative findings will inform best practices for spectral analysis in the study of traditional instruments, ensuring methodological rigour and cultural sensitivity.

Expanding the Framework to Other Instruments

Although the primary focus here is the rebana, the principles outlined in this theoretical and conceptual framework broadly apply to various traditional instruments. For instance, other Southeast Asian percussion instruments, such as the gendang, also exhibit complex transient and harmonic behaviour that could be elucidated by using STFT and CQT. Even beyond percussion, various stringed and wind instruments from diverse cultural traditions may benefit from a similar analytical approach, especially those whose timbral characteristics are not well-documented in Western scientific literature.

Conclusion of Theoretical and Conceptual Framework

This theoretical and conceptual framework underscores the significance of integrating timbre perception theories with advanced spectral analysis techniques while also providing insights into how these methods can be applied to other traditional instruments. For instance, the STFT and CQT could be utilised to analyse the spectral characteristics of the gamelan, focusing on its harmonic overtones and unique resonance patterns, which are integral to its role in traditional Southeast Asian musical ensembles.

Similarly, these methods could aid in documenting the spectral nuances of the tabla, emphasizing its rhythmic clarity and transient-rich attacks, pivotal to its expressive versatility in Indian classical and contemporary music. By focusing on the comparative evaluation of STFT and CQT, the study ensures a methodologically sound and culturally sensitive approach to documenting the rebana's spectral characteristics. This framework provides a robust foundation for bridging acoustic analysis's technical and cultural dimensions, offering valuable insights into the most effective analytical methods for traditional instruments.

METHODOLOGY

This study employs a systematic approach to analyzing the rebana's spectral characteristics using both the STFT and the CQT. The methodology is structured into three key phases: data acquisition, spectral analysis, and comparative evaluation.

Data Acquisition

High-quality audio recordings of the rebana were obtained in a controlled studio environment to ensure optimal recording conditions. The signal captured by the Shure SM57 microphone was sent to an audio interface and recorded using a Digital Audio Workstation (DAW) called Logic Pro. The sample rate was set to 44.1kHz with a bit depth of 24-bit, ensuring high fidelity and detailed sound capture. A Shure SM57 microphone was positioned six inches from the drumhead, capturing the instrument's sound with minimal noise interference (Figure 1 and Figure 2).

The SM57 was chosen for its versatility and reliability in capturing percussive instruments, as it effectively isolates the main sound source while minimizing background noise (Shure, n.d.). Its durability and consistent performance have made it a staple in many recording studios, further supporting its suitability for this study (Huber & Runstein, 2017). This placement was selected based on established miking techniques for percussive instruments, ensuring the authenticity of the rebana's acoustic profile.

Additional Recording Considerations

To capture a range of dynamics and performance techniques, multiple strikes and drumming patterns were recorded. Each performance included various intensity levels, from soft strokes to more forceful hits, as well as different hand and finger placements on the drumhead. This variety aimed to simulate the range of tonal colours and transient behaviours the rebana can produce in real-world performance contexts. All recording sessions took place in a sound-treated studio environment with acoustic treatments designed to minimize reflections and external noise. These conditions ensured that the audio captured would be primarily reflective of the rebana itself rather than confounding room acoustics.

Figure 1: Microphone placed in front of rebana and recorded in Logic Pro
(Source: author).

Figure 2: Microphone placed 6 inches from drumhead
(Source: author).

Spectral Analysis

The recorded audio signals were analysed using MATLAB and the MIRToolbox, which provided robust tools for time-frequency representation and spectral parameter computation. The STFT and the CQT were applied separately to the same dataset to compare their effectiveness directly.

STFT Implementation Details

- **Windowing**: Hanning windows of 1024 samples (approximately 23 ms at a 44.1kHz sample rate) were used, with 50% overlap between segments. This window size was chosen to balance frequency resolution with time resolution.
- **Spectrogram Generation**: The STFT spectrograms were computed, displaying amplitude (or magnitude) as a colour scale. Brighter regions indicate stronger energy in specific frequency bins at given time frames.
- **Parameter Extraction**: Key spectral parameters such as spectral centroid, roll-off, and harmonic-to-noise ratio were computed. Sharp increases in energy across consecutive frames were identified for transient analysis.

CQT Implementation Details

- **Logarithmic Frequency Bins**: The CQT was configured to cover a frequency range from approximately 50 Hz to 8 kHz, encompassing the fundamental and most significant overtone regions of the rebana.
- **Q-Factor Settings**: A moderate Q-factor (quality factor) was used to control the filter bandwidth, balancing frequency resolution with computational efficiency.
- **Spectrogram Generation**: The resulting CQT spectrogram featured a logarithmic frequency axis, highlighting harmonic structures more distinctly than a linear scale.
- **Parameter Extraction**: Similar to the STFT approach, parameters like spectral centroid and harmonic-to-noise ratio were computed. However, the logarithmic scaling allowed for more detailed observation of harmonic partials in lower frequency ranges.

Comparative Evaluation

The results from the STFT and CQT analyses were systematically compared to evaluate their effectiveness in capturing the rebana's spectral characteristics. Specific parameters such as spectral centroid, harmonic-to-noise ratio, and transient dynamics were assessed to determine each method's strengths and limitations. The comparative findings aim to identify the method most suited for analysing traditional instruments like the rebana while considering applications in music production, education, and cultural preservation.

Criteria for Comparison

- **Harmonic Resolution**: The clarity with which each method depicts fundamental frequencies and overtones.
- **Transient Clarity**: The level of detail observed during rapid changes in amplitude, such as percussive attacks.
- **Perceptual Alignment**: How closely the spectrogram correlates with subjective experiences of listening (e.g., capturing brightness, perceived loudness, timbral nuances).

By integrating these methodologies, the study ensures a comprehensive approach to documenting the rebana's unique acoustic features, contributing to technical advancements in spectral analysis and preserving Malay musical heritage.

FINDINGS AND ANALYSIS

This section first introduces the utility of spectrograms in capturing the rebana's acoustic properties, followed by a comparative analysis of the STFT and CQT methods. We then discuss the implications of each method for cultural preservation and other practical applications.

Spectral Analysis Findings

Spectrograms visually represent sound, showing how its frequency content changes over time. Brighter regions on the spectrogram indicate stronger sound energy at specific frequencies and times. In this study, spectrograms generated using the STFT and the CQT were analyzed to evaluate their suitability for documenting the spectral characteristics of the rebana. For instance, the CQT spectrogram emphasizes harmonic richness by resolving lower frequencies with higher clarity, while the STFT spectrogram highlights transient details, such as the percussive attacks of the instrument.

CQT Analysis

The CQT spectrogram (Figure 3) demonstrated significant advantages in capturing the harmonic richness of the rebana. Its logarithmic frequency scaling provided higher resolution across lower and mid-frequency bands while distinctly representing frequencies above 1 kHz. For instance, prominent harmonic structures around the fundamental frequency (~200 Hz) and subsequent overtones (~400 Hz, ~600 Hz, etc.) were clearly visible, highlighting the tonal richness and resonant qualities that define the rebana's unique sound profile. This capability makes the CQT particularly effective for ethnomusicological studies and efforts in cultural preservation.

The CQT's emphasis on harmonic content was further evident in its clear delineation of sustained overtones, even at lower frequencies. These features are critical for documenting the rebana's full tonal spectrum and capturing the subtle timbral variations that characterise traditional instruments. Additionally, the CQT effectively visualised finer details of harmonic content above 1 kHz, with harmonics appearing more pronounced and spread out compared to the STFT spectrogram. This detailed representation underscores the CQT's suitability for analysing the tonal complexity and subtleties of the rebana's acoustic profile.

However, the CQT's focus on frequency resolution comes at the expense of temporal precision. This is evident in the spectrogram, where the sharp percussive attacks of the rebana appear less distinct compared to the STFT spectrogram. For example, in the CQT visualisation, the onset of a drum hit is represented as a slightly smeared or spread-out burst of energy, whereas the STFT captures this same event as a sharper, more concentrated signal around the fundamental frequency. This difference underscores the STFT's advantage in accurately representing time-dependent behaviours such as transients.

This trade-off highlights the importance of selecting an analytical method based on the specific focus of the study, whether harmonic richness or transient dynamics. For instance, in cultural documentation, the CQT's ability to capture detailed harmonic structures can preserve the tonal identity of traditional instruments like the rebana. Conversely, in music production, where precise timing and clarity of transients are critical, the STFT's superior temporal precision ensures that percussive elements are accurately represented.

STFT Analysis

The STFT spectrogram (Figure 4) excelled at capturing the rebana's transient behaviors, such as the sharp percussive attacks characteristic of its drum hits. These are visible in the spectrogram as distinct, concentrated bursts of energy that sharply define the attack onset, reflecting the STFT's precision in time-dependent representation. These transients appeared as concentrated energy peaks in the time domain, showcasing the STFT's capacity to accurately capture the timing and intensity of dynamic events such as drum strikes.

For instance, the onset of a drum hit is clearly represented, demonstrating the method's temporal precision. The uniform frequency resolution across the spectrum ensured that the temporal dynamics of each strike were well-represented, making the STFT particularly effective for analysing rhythmic clarity and percussive sharpness.

However, the linear scaling of the STFT limited its ability to resolve harmonic details effectively, particularly in the higher frequency ranges. In the spectrogram, harmonics above 1 kHz appear less distinct and more blended compared to the CQT's representation, highlighting the trade-off between temporal and frequency resolution.

Spectral content above 1 kHz appeared less pronounced in the STFT spectrogram compared to the CQT, reflecting the STFT's emphasis on temporal precision over detailed frequency resolution. This limitation may affect applications requiring detailed harmonic analysis, such as tonal studies, but proves advantageous for analyzing rhythmic clarity and transient events.

DISCUSSION

The findings indicate that while the CQT is better suited for detailed harmonic analysis, particularly in capturing tonal richness and resolving higher frequencies, the STFT offers superior capabilities in analysing transient and time-dependent behaviours. For applications emphasising harmonic complexity, such as cultural preservation or tonal studies, the CQT provides a more detailed representation. Its ability to clearly visualise harmonic structures and overtones allows researchers to document the subtle timbral characteristics of the rebana, contributing to ethnomusicological archives and cultural heritage projects.

In contrast, the STFT's precision in capturing sharp transients makes it ideal for rhythmic analysis, live performance studies, or music production applications. Its ability to distinctly represent the onset of percussive strikes ensures that rhythmic clarity and timing are accurately preserved, which is critical in both recording and performance contexts.

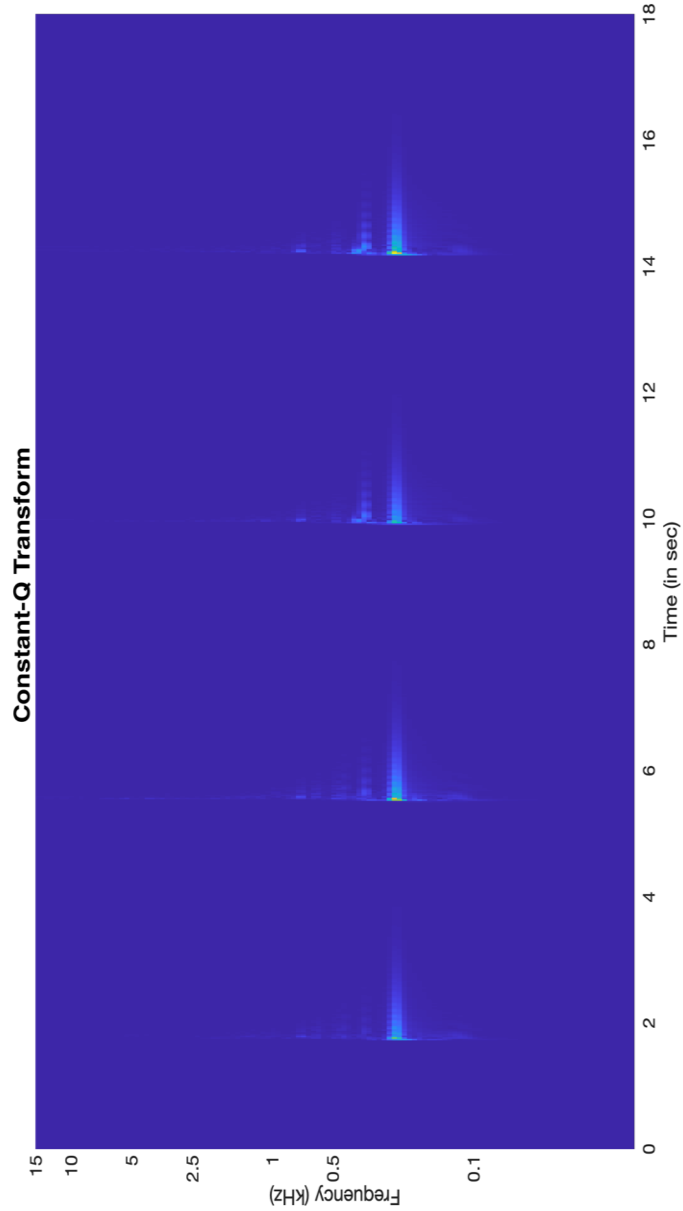

Figure 3: CQT spectrogram of the rebana, highlighting harmonic richness and tonal complexity, with distinct fundamental frequencies and overtones

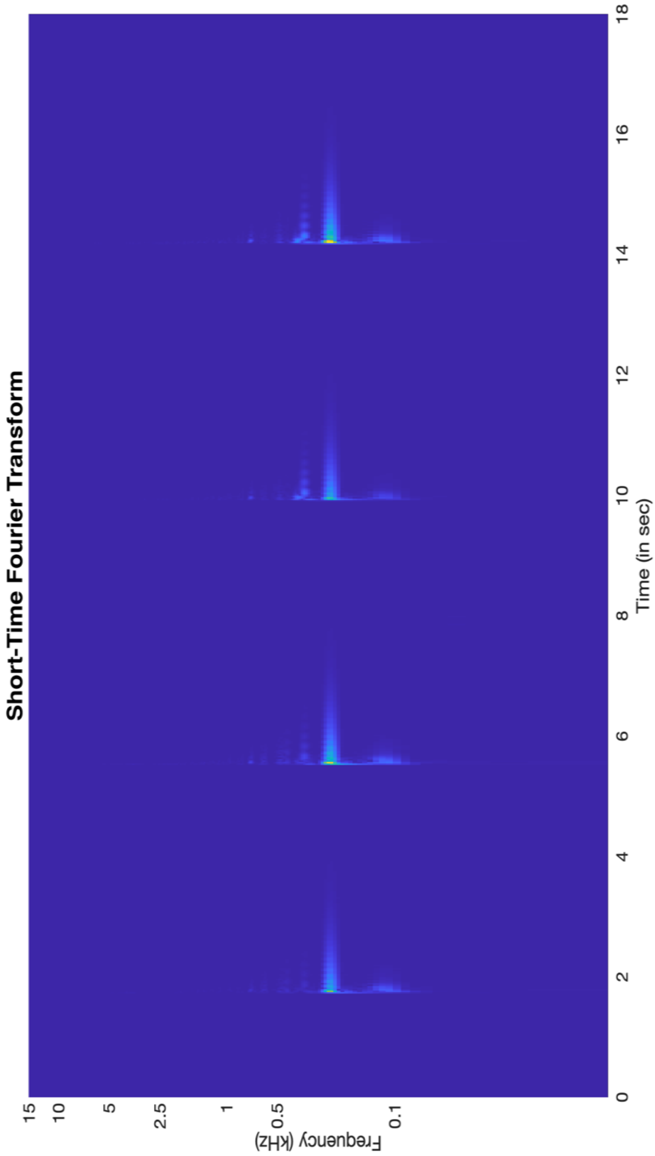

Figure 4: STFT spectrogram of the rebana, emphasising transient behaviours and rhythmic clarity through sharp percussive attacks.

Cultural Preservation Implications

Cultural preservation initiatives often require highly detailed documentation of traditional instruments to ensure their sonic traits are accurately captured for posterity. Given the rebana's importance in Malay traditions, the clarity and resolution offered by CQT in the harmonic domain can be particularly valuable. Digital archives incorporating CQT-based spectrograms could store detailed representations of the rebana's timbre, which would be accessible for future research or revitalisation efforts. This level of detail is vital for maintaining the authenticity of cultural performances, especially if younger generations or cross-cultural musicians wish to study and replicate the rebana's distinctive sound.

Music Production and Education

Engineers frequently deal with percussive elements that require precise transient handling in music production. The STFT's temporal resolution becomes indispensable in such scenarios, where even minor shifts in the timing or intensity of a drum hit can influence the final mix. Consequently, selecting the STFT for transient-oriented analysis can guide mixing decisions that maintain the rebana's percussive energy. Additionally, in educational contexts—such as interactive software or e-learning platforms—developers can employ STFT visualisations to illustrate how quickly the rebana's energy changes over time, offering students a more intuitive grasp of drumming techniques and rhythmic patterns.

Selecting the Analytical Method

Practical recommendations based on the findings of this study provide valuable insights for both analysis and recording of traditional instruments like the rebana. When choosing the right analytical method, researchers should consider their objectives:

Table: Considerations for Choosing Analytical Methods

	Use Case	*Advantages*	*Limitations*
CQT Spectrogram	Cultural documentation, harmonic analysis, timbral research.	Captures tonal richness, identifies subtle overtones, aligns well with human auditory perception in low- and mid-frequency ranges.	Less accurate for transient events, can be computationally more intensive.
STFT Spectrogram	Rhythmic analysis, transient clarity, time-sensitive studies such as live performances.	Superior temporal resolution, clearly identifies the onset of drum hits and short percussive events, relatively straightforward to implement.	Reduced frequency resolution for low and mid-frequency harmonic detail, harmonics above 1 kHz can appear blended.

Recording Techniques

Maintaining a consistent microphone placement is essential. Using a Shure SM57 microphone at a distance of six inches from the drumhead ensures accurate sound capture while minimizing interference. The recording setup should align with the intended analysis; harmonic studies require settings that enhance spectral resolution, while transient-focused recordings prioritise temporal accuracy.

- **Room Acoustics**: For harmonic-focused research, a more controlled acoustic environment with minimal reverberation helps isolate the drum's tonal characteristics.
- **Microphone Selection**: While the SM57 is versatile for percussive instruments, alternative microphones with broader frequency responses might be considered if capturing very high overtones is a priority.
- **Performance Variation**: Including soft, moderate, and loud strikes can enrich the dataset, providing a comprehensive overview of the instrument's dynamic range.

Applications Beyond Analysis

The implications of these methods extend beyond analysis into cultural preservation and music production. CQT-derived spectral profiles can be integrated into digital archives, providing future researchers and musicians with access to high-quality representations of traditional sounds. This approach safeguards the rebana's unique acoustic heritage and supports educational initiatives by showcasing its harmonic and transient characteristics.

In music production, insights from STFT analysis can refine mixing and mastering processes, emphasising rhythmic clarity and transient sharpness. Similarly, the harmonic richness captured by CQT can inspire sound design in compositions blending traditional and modern elements, ensuring the rebana's tonal qualities are preserved and enhanced.

CONCLUSION AND RECOMMENDATIONS

This study set out with three primary objectives: (1) to investigate how the STFT and the CQT capture the spectral characteristics of the rebana; (2) to evaluate the strengths and limitations of each method in resolving harmonic and transient features; and (3) to provide practical guidance for the analysis and recording of traditional instruments.

By systematically comparing the STFT and CQT, we have demonstrated how the CQT excels in revealing the rebana's harmonic richness and tonal complexity, whereas the STFT provides superior temporal resolution for capturing transient behaviours and rhythmic clarity.

In addressing the first objective, the study highlights specific spectral traits associated with each transform, confirming that the rebana's robust harmonic profile is more accurately represented via CQT's logarithmic frequency scaling. Meanwhile, the STFT effectively captures percussive elements critical to the rebana's performance style.

Concerning the second objective, our findings underscore each method's respective limitations—namely, the CQT's reduced temporal precision and the STFT's limited ability to resolve complex overtones above 1 kHz—reinforcing the importance of selecting an analytical approach aligned with specific research or production goals.

Finally, in fulfilling the last objective, the practical guidance derived from this research—covering both recording best practices and transform selection—offers a framework that can be adapted to the study of other traditional instruments.

Beyond these analytical insights, this research carries broader implications for cultural heritage. Detailed spectral analysis is more than a technical exercise; it underpins efforts to preserve traditional instruments like the rebana by accurately archiving their unique sound signatures for future generations. In ethnomusicological contexts, the ability to document an instrument's full tonal richness and transient nuances facilitates knowledge transfer, fosters cultural appreciation, and aids in safeguarding intangible heritage.

When coupled with robust recording methodologies, this study's comparative approach allows researchers and practitioners to establish comprehensive digital archives. These archives enable a deeper understanding of the rebana's acoustic identity, support innovative applications in modern music production, and ultimately strengthen global awareness of the Malay cultural legacy.

This study underscores the comparative advantages of STFT and CQT in analyzing the spectral characteristics of the rebana, offering a methodologically rigorous approach that bridges cultural preservation and technical analysis. The findings contribute to a deeper understanding of how spectral analysis methods can document and preserve traditional instruments, ensuring their relevance in contemporary music practices.

Moreover, this research provides a foundation for further exploration into the acoustic profiles of traditional instruments, fostering cross-disciplinary innovation in music production, sound design, and digital heritage archiving. Future studies could integrate hybrid methods or machine learning algorithms to address the trade-offs identified, enhancing the analytical capabilities for ethnomusicology, instrument design, and audio technology education.

Future Research Directions

The trade-offs between STFT and CQT highlight the need for hybrid approaches that integrate their strengths while mitigating their limitations. For instance, a method combining STFT's temporal precision with CQT's harmonic richness could provide a more balanced analysis of instruments with complex acoustic profiles.

Machine learning algorithms, particularly deep learning models, could also play a role in automating and enhancing spectral analysis, offering more nuanced insights into the transient and harmonic behaviours of instruments.

Extending this research to other traditional instruments, such as the gamelan or tabla, could further validate these methods, fostering a more inclusive understanding of global musical heritage. Furthermore, incorporating these findings into educational software or interactive platforms could bridge the gap between academic research and practical applications, democratising access to advanced analytical tools.

Hybrid Strategies

Future studies could explore hybrid approaches that integrate the advantages of both techniques. One such approach might involve segmenting the analysis timeline to apply CQT for sections requiring detailed harmonic insight and STFT for transient-rich passages. Alternatively, applying wavelet transforms or newer time-frequency analysis methods like variable-Q transforms could bridge the gap between STFT and CQT, achieving a balance of time and frequency resolution.

Machine Learning Integration

The integration of machine learning techniques, particularly deep learning, is another promising avenue. Neural networks trained on a large dataset of rebana recordings might learn to predict harmonic structures or transient characteristics more effectively by fusing STFT and CQT features. This approach could automate various aspects of spectral analysis, potentially revealing intricate patterns that manual methods might overlook. These automated analyses could then be integrated into interactive software for music education or digital archiving projects, broadening access to advanced analytical tools.

Application to Other Traditional Instruments

While this study focuses on the rebana, the methods and findings are relevant to a wide range of traditional instruments across different cultures. Future research could replicate similar analyses on instruments such as the gendang, kompang, or gamelan ensembles to build a comprehensive library of Southeast Asian percussion sounds. This broader initiative could foster cultural exchange, preserve intangible heritage, and inspire new compositions that merge traditional and contemporary elements.

Cultural and Ethnomusicological Research

Beyond technical considerations, future research could delve deeper into ethnomusicological questions. Scholars might investigate how particular spectral traits of the rebana influence or reflect cultural practices, community identity, and performance contexts. Cross-comparisons with recordings of rebanas in different regions or from different historical periods could shed light on evolving performance traditions. Coupling spectral analysis with ethnographic methods—such as interviews or observations—would yield a more holistic understanding of the rebana's role in Malay culture.

Further Exploration of Recording Techniques

Given that microphone placement, room acoustics, and performance style significantly impact spectral data, additional studies could systematically vary these factors to understand their effects on the rebana's recorded sound. This might include testing different microphone polar patterns, preamp settings, or post-processing workflows, thereby refining best practices for capturing traditional percussion instruments.

FINAL REMARKS

Ultimately, the choice between STFT and CQT is not mutually exclusive; both methods have roles to play in capturing the multi-faceted sound of the rebana. By tailoring the analysis to specific research or production goals, scholars and practitioners can leverage these tools to gain a deeper understanding of an instrument that holds significant cultural and musical value.

Cultural preservation benefits from analyses highlighting the rich harmonic structure of the rebana, ensuring that this instrument's unique sonic signature endures for future generations. Music production can capitalize on the STFT's superior transient analysis, helping to achieve accurate and lively drum tracks in modern recordings. Meanwhile, education and research can harness both methods to build comprehensive, interactive learning materials that demonstrate how scientific approaches to sound can illuminate cultural artefacts.

This research confirms that advanced spectral analysis offers more than technical insights; it fosters cross-disciplinary dialogue, bridging the gap between musicologists, audio engineers, cultural historians, and the communities who play and cherish the rebana. By documenting and analysing its spectral characteristics, we also champion the rebana's continued vibrancy in both traditional settings and contemporary creative explorations.

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