

Acoustic Measurement and Modeling of the Traditional Chinese Instrument Guzheng in Digital Transformation: A Case Study of Spectral and Resonance Analysis of Standard Pitch A440

Ning Li, Dandan Li

Division of Arts, Shenzhen University, Shenzhen, China

Email: ron916@naver.com

How to cite this paper: Li, N. and Li, D. (2024) Acoustic Measurement and Modeling of the Traditional Chinese Instrument Guzheng in Digital Transformation: A Case Study of Spectral and Resonance Analysis of Standard Pitch A440. *Open Journal of Acoustics*, 12, 17-30.

<https://doi.org/10.4236/oja.2024.122002>

Received: April 5, 2024

Accepted: June 27, 2024

Published: June 30, 2024

Copyright © 2024 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

This paper aims to explore the acoustic measurement and modeling of the traditional Chinese instrument, the guzheng, in the context of digital transformation, focusing on the spectral and resonance analysis of the standard pitch A440. By employing various tools to conduct detailed analyses of the frequency response and resonance characteristics of guzheng audio, the study clarifies the performance of its timbre across different frequency bands and the distribution of resonance peaks. This research reveals the complexities of guzheng's timbre, and the challenges posed by digital transformation, proposing solutions for optimizing spectral models and resonance data processing. The findings provide theoretical support and technical guidance for digital recording, music creation, preservation, and transmission of the guzheng.

Keywords

Guzheng, Digital Transformation, Spectral Analysis, Resonance Characteristics, Acoustic Measurement

1. Introduction

The guzheng, a traditional Chinese instrument with a rich historical background [1], occupies a significant position in Chinese musical culture [2]. With approximately 2500 years of history [3], the guzheng was named during the Eastern Han Dynasty by Liu Xi, who noted its high-pitched and urgent characteristics [4]. Its timbre and structural design bear resemblance to that of the harp [5], producing

a deep, elegant sound with remarkable artistic expressiveness. The guzheng is characterized not only by complex playing techniques [6] but also by its rich tonal layers. The subtle resonance and harmonic variations produced by each string during performance distinguish it in the realm of traditional Chinese music. Over time, the guzheng has become a vital symbol of Chinese instrumental culture [7], undergoing extensive transmission and innovation.

In light of the rapid advancements in digital technology, the effective digital transformation of traditional instruments, while preserving their unique timbre and resonance characteristics, has emerged as a crucial topic in music research and technological innovation. Digitalizing traditional instruments serves not only to preserve cultural heritage but also to enhance possibilities for modern music production, education, and dissemination. The thriving development of digital music has accelerated the digitalization process of instruments, enabling precise capture, analysis, and reproduction of the guzheng's sound within a digital environment, thus offering musicians a broader palette for tonal choices and expressive means. However, the complexity and uniqueness of the guzheng's timbre present substantial challenges in this process.

The timbre of the guzheng is not a singular sound; its complexity is manifested in its multidimensional tonal qualities and resonance characteristics. Each string is supported by a bridge, and its vibration is influenced not only by the player's technique but also by factors such as string length, tension, and the structure of the resonating body. The interaction between the strings and the resonating box during performance generates a rich array of harmonics and resonances [8], allowing the guzheng to produce distinctly different timbral characteristics under various playing techniques. This rich variability in timbre necessitates more refined acoustic modeling and spectral analysis during the digitalization process.

In the digital transformation of the guzheng, spectral analysis and resonance measurement are two key acoustic research methods. Spectral analysis assists in understanding the distribution of frequency components in the audio signal when the guzheng is played at different pitches, which is crucial for accurately capturing the fundamental frequency, harmonics, and their interrelations. Meanwhile, resonance characteristic analysis reveals changes in the instrument's resonance and vibration properties under various playing techniques and sound production conditions. Through in-depth research of these acoustic characteristics, researchers can construct more precise digital models of guzheng timbre.

The digital transformation of the guzheng encompasses not only technical challenges but also profound cultural significance. Digitalization provides new avenues for the preservation and dissemination of the guzheng's timbre while expanding its applications in contemporary music creation. The diverse tonal demands in digital music production enable this traditional instrument to participate in modern compositions, facilitating a fusion of tradition and innovation. Additionally, digital technology offers new possibilities for innovative guzheng education [9], allowing students to more easily learn and experience the instrument's sound. Even in the absence of a physical instrument, virtual instrument

technology can simulate the guzheng playing experience [10]. The application of such technological transformations not only promotes the popularity and development of the guzheng but also enhances the international influence of traditional Chinese music.

In conclusion, the digital transformation of the guzheng is a complex process involving interdisciplinary intersections of acoustics, computer science, and musicology. Through acoustic measurement and modeling techniques, we can better understand the guzheng's timbre characteristics and resonance mechanisms, laying the foundation for constructing digital timbre models. In modern music production, the digitalization of the guzheng not only provides musicians with a richer creative resource but also offers listeners a more diverse musical experience. Moreover, this process provides technical support for the protection and transmission of guzheng culture, enabling this traditional instrument to thrive in the digital age.

This study focuses on the standard note A of the guzheng, employing a combination of spectral analysis and resonance characteristic measurements to investigate the core attributes of the instrument's timbre and the critical elements for its digital transformation. High-precision spectral analysis tools were used to sample the audio signal of the guzheng's standard note A, with a particular emphasis on analyzing its spectral distribution, resonance peak locations, and frequency attenuation characteristics. Concurrently, the acoustic properties of the guzheng's soundboard were examined to evaluate the influence of resonance on its overall tonal quality. During the experiments, the recording environment was carefully controlled to minimize noise interference, ensuring the accuracy of the measurement data. By integrating multiple sets of sampling data, the study further explored how different playing techniques impact the dynamic variations in the guzheng's timbre, providing a theoretical foundation for its digital transformation.

2. Acoustic Measurement and Modeling of the Guzheng

The guzheng, as a traditional Chinese instrument, derives its unique timbre from the intricate interaction between string vibrations and the resonating body. This complexity makes the measurement and modeling of its acoustic characteristics a challenging task. To achieve the digital transformation of the guzheng's timbre, precise acoustic measurement and modeling techniques are essential, including in-depth analyses of its spectrum, resonance characteristics, and harmonic structures. Through these methods, subtle variations in the guzheng's timbre can be captured, enabling high-fidelity reproduction in digital environments. Acoustic measurement and modeling provide not only scientific support for the digital preservation of the guzheng but also offer technical assistance for virtual instrument modeling and timbre design in modern music production.

2.1. Basic Theories and Methods of Acoustic Measurement

Acoustic measurement is one of the core techniques for studying an instrument's

timbre. By analyzing the physical properties of the sound produced by the instrument, researchers can gain a deeper understanding of its compositional elements. For the digital transformation of the guzheng, commonly used acoustic measurement methods include spectral analysis, resonance characteristic analysis, and Fourier transform.

First, spectral analysis is a foundational technique in acoustic measurement. It decomposes sound signals into their various frequency components, helping us understand the distribution of the fundamental frequency and its harmonics within the timbre. The guzheng's timbre is complex and rich, encompassing multiple harmonics and noise components. Through spectral analysis, we can accurately capture the guzheng's spectral characteristics under different pitches and playing techniques. Especially in digital modeling, spectral analysis is a critical tool for capturing the details of the guzheng's timbre, facilitating its accurate reproduction in a digital environment.

Second, resonance characteristics are a crucial factor in the generation of the guzheng's sound. These characteristics are closely related to the instrument's physical structure, materials, and shape, reflecting its vibrational response to external stimuli. For the guzheng, the vibrations of the strings are transmitted through the bridge to the resonating body, resulting in complex resonance phenomena. By measuring the resonance characteristics of the guzheng at different frequencies, we can understand the vibrational modes of both the body and the strings. This knowledge is vital for digital modeling, as subtle differences in resonance can significantly affect the final generated timbre.

Additionally, the Fourier transform is another important analytical tool used to convert time-domain signals into frequency-domain signals [11]. By applying the Fourier transform, the complex sound waves of the guzheng can be decomposed into various frequency components, providing crucial information for understanding its harmonic structure. In digital modeling, the Fourier transform is widely used for timbre decomposition and synthesis. By processing the original audio data, it allows for the extraction of fundamental frequencies, harmonics, and noise components, enabling the reconstruction of these sound characteristics in a digital environment.

2.2. Common Acoustic Methods in Instrument Digital Modeling

In the process of instrument digital modeling, acoustic measurement methods not only help us capture subtle details of timbre but also ensure accurate reproduction of these details in digital environments. For the guzheng, an instrument with a complex resonance structure, digital modeling presents numerous challenges, including how to faithfully reproduce its multidimensional timbre characteristics and dynamic variations.

First, Physical Modeling Synthesis is a commonly used digital modeling technique for instruments [12]. This method simulates the sound production mechanisms of instruments based on physical laws. With a long-standing history [13],

physical modeling synthesis relies on the physical characteristics of the guzheng, such as string tension, material elasticity, and the vibration modes of the resonating body. By employing physical modeling, the vibration characteristics of the guzheng can be accurately simulated, allowing its complex timbre to be reproduced in digital environments. The advantage of physical modeling lies in its ability to capture subtle acoustic features, resulting in a more authentic timbre simulation, particularly in terms of harmonics and resonance characteristics.

Second, Additive Synthesis is another technique used for instrument modeling [14]. This method generates complex timbres by layering multiple sine waves. The key to additive synthesis is the precise capture and reproduction of the guzheng's harmonic structure. Through spectral analysis, the fundamental frequency and the intensity and frequency distribution of higher harmonics in the guzheng's timbre can be identified, allowing for the simulation of these components using additive synthesis. Although additive synthesis simplifies the sound generation process, it offers advantages in accuracy and flexibility for timbre reconstruction, particularly suitable for simulating instruments with complex harmonic structures.

Third, Convolution Reverb technology is primarily used to recreate the spatial resonance characteristics of instruments [15]. One significant aspect of the guzheng's timbre is its rich resonance, which is closely related not only to the string vibrations but also to the acoustic characteristics of the performance environment. Convolution reverb allows for the combination of acoustic features from real spaces with the guzheng's timbre, simulating the resonance effects of the instrument in different environments. This method is widely used in virtual instruments and modern music production, helping digital instruments present a more natural timbral expression.

In the reproduction of the guzheng's sound, physical modeling synthesis, additive synthesis, and convolution reverb techniques each have their advantages and limitations. Physical modeling synthesis, through mathematical modeling of the guzheng's string vibrations and the acoustic characteristics of its resonator, offers a highly realistic simulation of the dynamic characteristics and physical behaviors of the instrument. This approach is particularly advantageous in replicating the subtle tonal variations caused by different playing techniques. However, the modeling process is complex, computationally intensive, and demands precise acquisition of acoustic parameters. Additive synthesis, on the other hand, generates sound by superimposing multiple harmonic components. It is relatively straightforward and especially effective for recreating static timbres, but it struggles to capture the guzheng's dynamic tonal changes and intricate resonance characteristics. In contrast, convolution reverb is primarily used to recreate the guzheng's tonal expression in specific acoustic spaces. It effectively captures the spatial response and reverberation effects of the resonator but inherently relies on pre-existing sampled data, making it challenging to independently generate timbre without foundational recordings. Overall, while physical modeling synthesis demonstrates the greatest potential for comprehensively replicating the guzheng's tonal

characteristics, combining it with additive synthesis and convolution reverb techniques can further enhance the realism and expressiveness of the reproduced sound.

2.3. The Impact of Guzheng Structure on Timbre and Challenges in Modeling

The guzheng's structure is intricate, with its timbre influenced not only by the strings but also by the resonating body, bridge materials, and their positioning. The vibrations of the strings are transmitted through the bridge to the resonating body, forming a rich sound field characterized by complex acoustic behavior. Factors such as the size, shape, and material of the guzheng's resonating body significantly affect its timbre. Notably, during performance, the vibration modes of each string can differ, resulting in an extremely complex spectral and harmonic structure.

In the process of digital modeling, capturing and faithfully reproducing these physical details presents a significant challenge. Traditional sampling techniques can capture some characteristics of the guzheng's timbre, but they often struggle to provide sufficient detail and flexibility in the face of dynamic changes and complex resonance. While physical modeling can simulate the relationship between string vibrations and the resonating body, it requires substantial computational resources and complex mathematical models. Another challenge lies in the timbral variations resulting from different playing techniques; techniques such as glissando and vibrato can significantly influence the guzheng's sound, making it a focus and challenge of ongoing research to replicate these subtle changes in digital models.

3. Spectral Analysis and Resonance Characteristics of the Guzheng

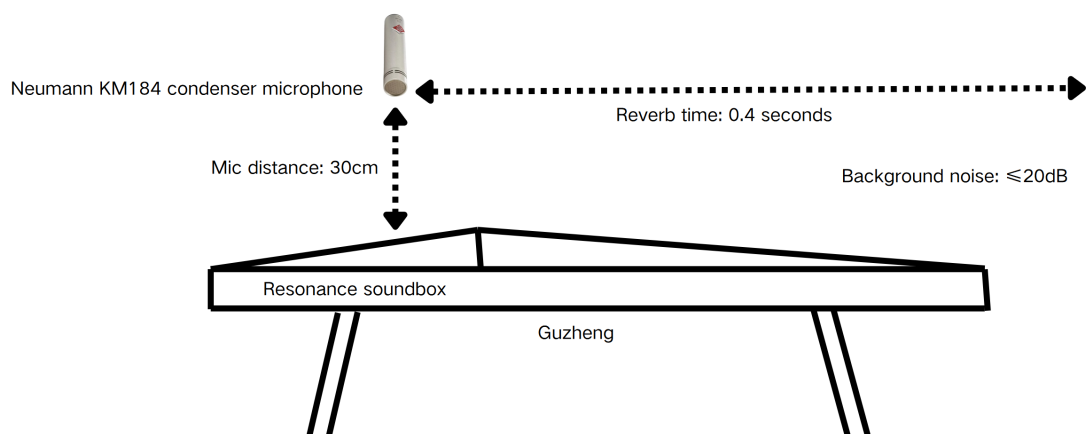


Figure 1. Setup of the recording experiment apparatus.

As a complex string instrument, the guzheng exhibits a rich and variable timbre, especially under different playing techniques, where significant differences in

sound can be observed. Through spectral analysis and the study of resonance characteristics, we can uncover the subtle variations in the guzheng's audio performance and provide a scientific basis for its digital modeling. In this study, a single condenser microphone, the Neumann KM184, was used for mono recording. The microphone was positioned approximately 30 centimeters directly above the guzheng strings to ensure the capture of a comprehensive sound profile, encompassing both the string vibrations and the resonance from the soundboard. To ensure the accuracy of the data collection, the recording was conducted in an acoustically treated professional studio, where the background noise was controlled below 20 dB, and the reverberation time was kept under 0.4 seconds to avoid unwanted reflections interfering with the tonal analysis. (Figure 1)

During the experiment, traditional guzheng plectra were used for consistent plucking, with uniform plucking strength and a consistent angle of attack, ensuring high uniformity and analytical reliability in the collected audio samples. The digital audio workstation employed was Steinberg Cubase Pro 12, with the guzheng audio recorded at a sampling quality of 44.1 kHz and 16-bit resolution. For spectral analysis, iZotope RX 10 was utilized, while FabFilter Pro-Q3 was employed to measure the resonance characteristics of the guzheng.

3.1. Spectral Analysis

The timbre of the guzheng is composed of the fundamental frequency and higher harmonics generated by the vibration of the strings. The persistence and decay characteristics of these frequency components over time significantly determine the expressiveness of the guzheng's sound. To study the spectral characteristics of the guzheng, we selected audio samples of the performance of the standard pitch A and conducted spectral analysis.

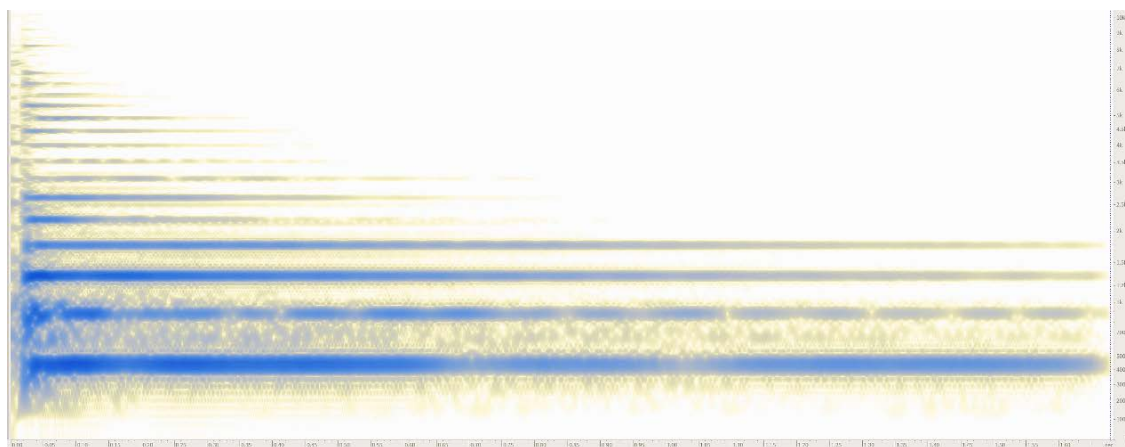


Figure 2. Spectrum chart from 0 to 1.6 seconds after plucking.

In **Figure 2**, we analyze the spectral distribution of the guzheng playing the standard pitch A within the first 0 to 1.6 seconds after the string is struck. The figure shows that within the frequency range of 370 Hz to 520 Hz, the persistence

of the frequencies is relatively strong, with no significant decay observed. This range corresponds to the primary fundamental frequency and lower harmonics of the standard pitch A, indicating that this frequency band is a crucial component of the guzheng's timbre. Additionally, the figure reveals that above 2 kHz, the persistence of frequency components is weaker, with these high-frequency elements rapidly decaying within 0.75 seconds after the string is struck. The quick decay of the high-frequency portion illustrates the soft quality of the guzheng's sound; the sustained resonance of the lower frequencies enhances its lingering timbre, while the rapid decay of high-frequency components reduces the sharpness of the sound, rendering it warmer.

The harmonic distribution of the guzheng's timbre is complex, yet from the spectral analysis, it is evident that the fundamental frequency and lower harmonics dominate the overall structure of the timbre. Particularly, the long-lasting resonance characteristics in the frequency range of 370 Hz to 520 Hz, as shown in the spectral graph for the standard pitch A, provide a foundation for the recognizability of the guzheng's timbre. The persistence of these frequency components allows the guzheng to maintain a clear and soft sound quality even during extended play.

3.2. Dynamic Temporal Changes

In addition to spectral analysis, the dynamic changes of the guzheng's timbre in the time domain are also important aspects of analysis. **Figure 3** displays the dynamic waveform of the guzheng playing the standard pitch A within the first 0 to 0.8 seconds after the string is struck, revealing the amplitude variation characteristics of the guzheng's sound over time. At 0.034 seconds after the string is struck, the amplitude reaches its peak, marking the moment when the string's vibration achieves maximum energy. This peak amplitude indicates the initial vibrational intensity during performance, with the acoustic energy at this moment primarily concentrated in the fundamental frequency and its lower harmonics, providing the foundational structure of the guzheng's timbre.

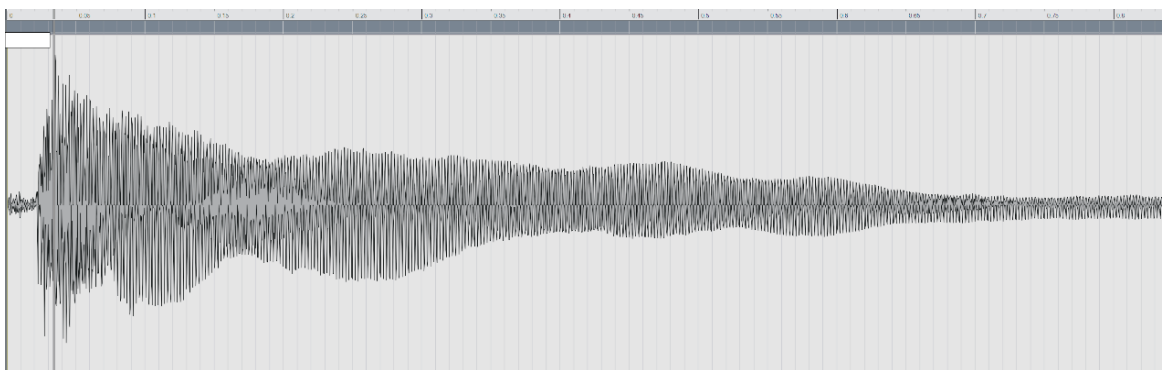


Figure 3. Dynamic time-domain chart from 0 to 0.8 seconds after plucking.

As time progresses, the amplitude gradually decays, but between 0.13 seconds

and 0.24 seconds after striking the string, a phenomenon of sine wave phase interleaving occurs. This phenomenon is typically caused by the multimodal vibrations of the string, where the phase relationships of different frequency components lead to subtle changes in timbre. The phase interleaving results in a “waver-ing” effect in the guzheng’s sound, enhancing the dynamic and spatial qualities of the timbre. Such changes enrich the guzheng’s acoustic characteristics, allowing it to express more complex timbral details under different playing techniques.

Starting from 0.47 seconds after the string is struck, a clear trend of amplitude decay is observed. This gradual decay reflects the dissipation of energy from the string and corresponds to the natural decay of the sound. This process is closely related to the energy transfer between the string vibrations and the resonance box. Accurately capturing these dynamic changes is crucial for the digital transformation of the guzheng’s timbre, as it directly affects the authenticity and spatiality of the sound.

3.3. Frequency Response Analysis

Figure 4 presents the frequency response of the guzheng playing the standard pitch A at the moment when the amplitude reaches its peak at 0.034 seconds after the string is struck. This analysis allows us to gain deeper insight into the frequency distribution of the guzheng’s timbre and the characteristics of its resonance peaks.

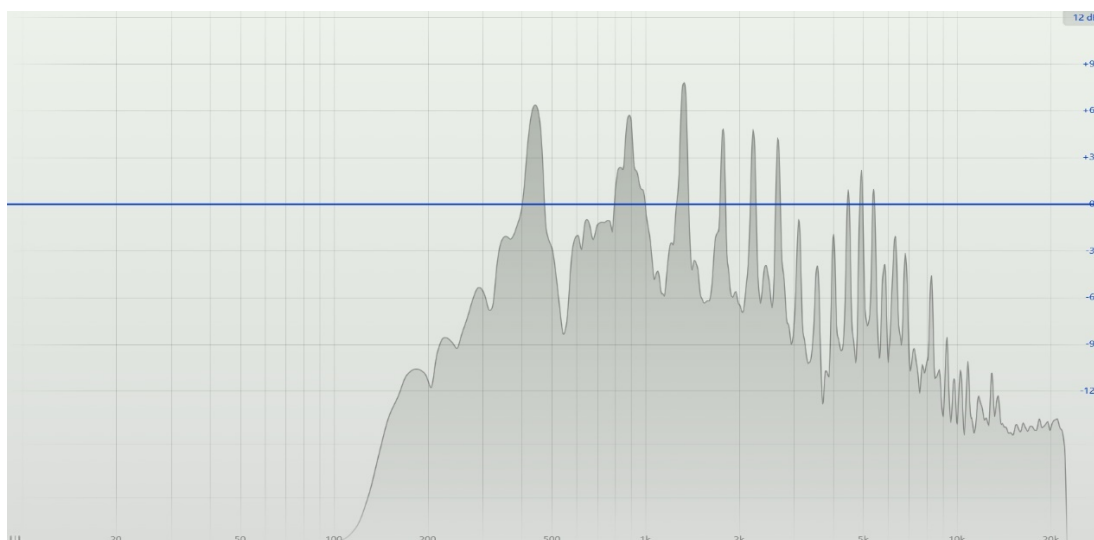


Figure 4. Frequency response chart at 0.034 seconds after plucking.

The figure shows that the guzheng’s standard pitch A exhibits a relatively full frequency response in the frequency range above 100 Hz. Particularly around 440 Hz, the frequency response reaches a high amplitude, corresponding to the fundamental frequency of the guzheng’s standard pitch A. Additionally, other prominent resonance peaks appear at frequencies such as 890 Hz, 1300 Hz, 1800 Hz, 2200 Hz, 2700 Hz, 3100 Hz, and 3600 Hz. These resonance peaks indicate strong

harmonic resonance phenomena in these frequency ranges.

As the frequency increases, the spacing between the resonance peaks becomes denser starting from 3600 Hz, suggesting an increase in harmonic components in the high-frequency region. However, the frequency response amplitude significantly diminishes above 14 kHz, indicating that there is less energy present in the high-frequency range. The rapid decay of high frequencies aligns with the soft and stable characteristics of the guzheng's timbre, while also suggesting that during digital recording, high cut processing above 14 kHz can be applied to eliminate unnecessary high-frequency noise, thereby optimizing the clarity of the timbre.

3.4. Resonance Characteristics of the Guzheng

The resonance characteristics of the guzheng are closely related to its physical structure, influenced by factors such as the material and tension of the strings, as well as the size and shape of the resonance box. Resonance is a crucial element in forming the guzheng's timbre, as the vibrations of the strings are transmitted through the bridge to the resonance box, inducing vibrations in the instrument body. This resonance phenomenon exhibits different vibrational modes at various frequencies. The shape and material of the resonance box determine the vibrational characteristics of the instrument body, while the string tension and vibration modes influence the timbre's sustain and resonance duration. For instance, during the performance of the standard pitch A, low-frequency resonance is more sustained, while high-frequency resonance tends to be brief. This frequency-dependent resonance characteristic gives the guzheng's timbre a unique sense of space and depth.

Through analyzing the guzheng's resonance characteristics, we find that significant frequency changes occur after the string is struck, which not only affects the stability of the fundamental frequency but also enhances the dynamic changes in timbre over time. These resonance characteristics must be accurately captured during the digital transformation of the guzheng's timbre, as they directly determine the authenticity and expressiveness of the digital instrument model.

3.5. Conclusion of Spectral Analysis and Resonance Characteristics Research

Through the spectral analysis and study of resonance characteristics, we can gain a clearer understanding of the complexity of the guzheng's timbre and the key factors involved in its digital transformation. The spectral distribution, temporal dynamic changes, and frequency response of the standard pitch A reveal the core characteristics of the guzheng's timbre. Furthermore, the research on resonance characteristics provides scientific evidence for the timbral variations under different playing techniques. In the process of digital transformation, appropriate low cut and high cut processing based on these research data can optimize the sound quality, ensure minimal noise during recording, and enhance the recognizability of the timbre through EQ adjustments to the resonance peak positions.

4. Challenges and Solutions in the Digital Transformation of the Guzheng

4.1. Challenges Posed by the Complexity of Guzheng Timbre

As a traditional Chinese instrument, the guzheng faces significant challenges during its digital transformation due to its complex timbre. Firstly, the timbre of the guzheng stems from intricate resonance characteristics and multi-layered spectral features, not merely from simple frequency components. This complexity necessitates capturing different string vibration modes, sound wave reflections in the resonance box, and other intricate acoustic phenomena simultaneously during the digital conversion process. Additionally, the guzheng's timbre is highly susceptible to variations in playing techniques. Different plucking methods, finger angles, and pressures can lead to subtle yet complex changes in timbre that are difficult to capture fully through traditional recording or digital transformation methods. For example, while standard sampling can record various frequency components, it often overlooks the unique responses of playing techniques and the resonance box, resulting in a lack of depth and richness compared to live performances.

These complexities in timbre, particularly the nuanced variations under different playing techniques, pose a challenge in faithfully reproducing the sound during digital conversion. In the modeling process, capturing these minute changes is difficult using simple spectral or dynamic range analyses. Therefore, preserving these details becomes a significant challenge.

4.2. Solutions Offered by Acoustic Measurement and Modeling Techniques

To effectively address these challenges, modern acoustic measurement and modeling techniques provide several solutions.

Firstly, optimization of spectral and resonance characteristics. To tackle the complexity of spectral features, more precise spectral analysis tools can be employed for detailed measurement of the guzheng's timbre. Using spectral analysis software, the distribution of resonance peaks across frequency bands can be accurately identified, and frequency adjustments can be made to ensure the integrity of each resonance peak. Furthermore, capturing the sound wave reflection characteristics within the resonance box can optimize the guzheng's resonance performance, allowing the modeling process to not only capture direct sound sources but also reproduce the effects of resonance.

Secondly, multidimensional modeling techniques. Single-dimensional acoustic measurement methods struggle to capture all aspects of the guzheng's timbre. By employing multidimensional modeling techniques, information across frequency, time, and spatial dimensions can be recorded simultaneously. Fourier transforms allow for the tracking of both spectral changes and the temporal evolution of timbre. Additionally, dynamic time-domain measurement tools can better capture the dynamic variations in timbre, thus restoring the authentic performance state during the digital conversion process.

Thirdly, in-depth modeling of resonance data. The resonance characteristics of the guzheng are crucial for sound restoration. By analyzing resonance data and examining the sound wave reflections in different regions of the resonance box, the spectral model can be optimized to closely resemble real sound effects during modeling. For example, resonance box data can be used to adjust the harmonic structure of audio signals, enhancing the fullness and naturalness of the timbre. Moreover, in digital modeling, this data can guide virtual synthesis, making the digital representation of the guzheng more three-dimensional.

Fourthly, the application of augmented reality technologies. Modern digital technologies can also simulate the guzheng's sound performance through virtual or augmented reality (AR) platforms. In this context, acoustic modeling extends beyond two-dimensional audio data to include sound field distribution in three-dimensional space. For instance, spatial acoustic technologies can simulate the sound effects of the guzheng in different environments, bringing the digitized guzheng's timbre closer to that of a real performance setting.

4.3. Future Optimization Directions for Guzheng Digital Transformation

Despite the numerous solutions that modern acoustic measurement and modeling techniques provide for the guzheng's digital transformation, there remains room for further optimization. For example, enhancing the resolution of spectral analysis through more refined acoustic measurement tools could improve timbre restoration fidelity. Additionally, integrating more intelligent algorithms, such as AI generation techniques or deep learning models during the digital modeling process, could automate the capture of changes in guzheng timbre. The development of these technologies will open up greater possibilities for the future digital transformation of the guzheng.

5. Conclusion and Outlook

This study explores the core technologies and application values of acoustic measurement and modeling in the digital transformation of the guzheng through spectral analysis and resonance characteristics of the standard note A. High-precision acoustic measurement tools were primarily employed to analyze the frequency response and dynamic characteristics of guzheng timbre in detail. The spectral analysis and resonance data clarified the main frequency bands, the distribution of resonance peaks, and the dynamic changes under different playing techniques. These analyses provide a solid theoretical foundation for the digital transformation of the guzheng.

The research demonstrates that the guzheng's timbre possesses a unique spectral distribution and complex resonance characteristics. Frequency response analysis indicates that the frequency of the standard note A primarily concentrates above 100 Hz, with noticeable resonance peaks at 890 Hz, 1300 Hz, and 1800 Hz. The significant attenuation of frequency response in the high-frequency range

(above 14 kHz) provides clear guidance for frequency trimming and timbre optimization during digital recording. Additionally, the analysis of resonance characteristics reveals the impact of sine wave phase interleaving on the details of timbre, which is crucial for sound restoration in guzheng digital modeling.

This study clarifies the challenges posed by the complexity of guzheng timbre in digital transformation. While traditional acoustic measurement techniques can capture the basic characteristics of timbre, they still face limitations in faithfully reproducing its rich resonance details. To address these issues, the application of modern acoustic measurement and modeling technologies is essential. For example, optimizing spectral models combined with resonance data can more accurately restore the timbral layers and variations in playing techniques. This not only helps improve the quality of digital recordings but also provides reliable technical support for the dissemination and preservation of guzheng timbre in digital environments.

Looking to the future, the acoustic digital transformation of the guzheng and other traditional Chinese instruments holds broad application prospects. Firstly, in the field of music creation, digital timbre libraries of the guzheng can offer rich creative materials for composers and music producers, promoting the integration of traditional music with modern musical technologies. Secondly, digital technology provides new avenues for the protection and transmission of traditional instruments like the guzheng. Through high-fidelity digital audio capture and storage, the unique timbral characteristics of the guzheng can be preserved intact, avoiding the loss of sound quality due to time or physical deterioration. Furthermore, digital transformation offers new methods for guzheng education. Students can learn and experience guzheng timbre through virtual instruments or audio simulation systems without needing direct contact with physical instruments.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Peirong, W., Yodwised, C. and Panyanan, P. (2023) Development of Guzheng School and Chinese Guzheng Education in China. *Journal of Modern Learning Development*, **8**, 317-325.
- [2] Wu, N. (2018) The Development of Guzheng Playing Technique and Its Application in Teaching. *Proceedings of the 2017 7th International Conference on Education and Management (ICEM 2017)*, Shenyang, 29-31 December 2017, 589-592. <https://doi.org/10.2991/icem-17.2018.118>
- [3] Han, M. (2001) Historical and Contemporary Development of the Chinese Zheng. Ph.D. Thesis, University of British Columbia.
- [4] Li, D. and Choatchamrat, S. (2024) Preservation and Literacy Transmission of Pipa and Guzheng Duets in Pu Dong Style. *International Journal of Education and Literacy Studies*, **12**, 133-139. <https://doi.org/10.7575/aiac.ijels.v12n.1p.133>
- [5] Waltham, C. (2014) An Acoustical Comparison of East Asian and Western String

- Instruments. *Proceedings International Symposium on Musical Acoustics (ISMA 2014)*, Le Mans, 7-12 July 2014, 375-380.
- [6] Li, D., Wu, Y., Li, Q., *et al.* (2022) Playing Technique Detection by Fusing Note Onset Information in Guzheng Performance. arXiv: 2209.08774.
- [7] Kang, Y. and Ariunaa, S. (2024) An Initial Exploration of the Historical Development and Origin of the Guzheng. *Highlights in Art and Design*, **6**, 25-31. <https://doi.org/10.54097/gqgpm010>
- [8] Shi, J. (2014) Extending the Sound of the Guzheng. Ph.D. Thesis, University of York.
- [9] Zhang, S. (2024) The Value and Development Strategy of Guzheng Performing Arts. *Frontiers in Business, Economics and Management*, **16**, 97-101. <https://doi.org/10.54097/hhajqx73>
- [10] Chan, H. (2021) Garage Band's Chinese Instruments—An Overview and Discussion of a Virtual “Ethnic” Instrument. *The Canadian Music Educator*, **62**, 12-19.
- [11] Singh, P. (2016) Time-Frequency Analysis via the Fourier Representation. arXiv: 1604.04992.
- [12] Välimäki, V. (2004) Physics-Based Modeling of Musical Instruments. *Acta Acustica united with Acustica*, **90**, 611-617.
- [13] Bilbao, S., Desvages, C., Ducceschi, M., Hamilton, B., Harrison-Harsley, R., Torin, A., *et al.* (2019) Physical Modeling, Algorithms, and Sound Synthesis: The NESS Project. *Computer Music Journal*, **43**, 15-30. https://doi.org/10.1162/comj_a_00516
- [14] Comerford, P. (1993) Simulating an Organ with Additive Synthesis. *Computer Music Journal*, **17**, 55-65. <https://doi.org/10.2307/3680869>
- [15] Steimel, M. (2019) Implementation of a Hybrid Reverb Algorithm. Master's Thesis, Aalborg University.