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Article

Evaluation of acoustic performance of Guzheng based on dynamic measurement

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Abstract: This research assessed the Acoustic performance of Guzheng using dynamic measurement technology. The study conducted spectral analysis, examined the correlation between playing techniques and sound productions, defined major sound quality factors, and proposed solutions for enhancing the instrument. In dynamic measurement, dynamic frequency spectra were obtained, which were different from those of the normal Guzheng and had traditional characteristics of Guzheng acoustics. There were significant relationships between playing techniques and particular acoustic results. There were strong correlations between sound quality parameters; thus, it was possible to optimize them systematically. The findings offered specific recommendations for improving Guzheng production that were detailed to retain traditional qualities. The research set quantitative measures for Acoustics analysis and other quality control in Guzheng manufacturing and playing.

Keywords: acoustic performance evaluation; dynamic measurement technology; Guzheng acoustics; spectral analysis; sound quality parameters; traditional Chinese instruments; performance optimization

1. Introduction

1.1. Research background

According to Poudel [1], the Guzheng is a plucked stringed musical instrument, a part of the Chinese culture and history that dates back more than 2500 years. Recently, there has been a shift in the scientific approach towards studying musical instruments, and the use of measurement technologies and acoustic assessment techniques has advanced. This integration of indigenous techniques and contemporary science offers a chance to study and appreciate cultural musical instruments and, at the same time, improve on them.

The acoustics of the musical instruments have evolved from simple frequency analysis to spectral characteristics, vibration, and signal analysis that define the properties of the sound produced [2]. These methods have helped in enhancing the understanding of the acoustics of musical instruments and how physical characteristics of these instruments influence the sound production [3]. With the advancement in measuring instruments, it is now easier to determine the acoustics of a musical instrument and such qualitative information can be used in the construction of the instruments as well as the playing techniques [4].

The quality of musical instruments depends on the material used and how the instrument is constructed. The studies have established a positive relationship between wood characteristics and sound quality [5], and innovative technologies and materials are being developed constantly [6]. The advancement in modern classification and analysis techniques, such as deep learning, has enabled the objective characterization and evaluation of musical instruments [7].

However, traditional musical instruments such as the Guzheng pose standardization and quality control challenges even with these advances in musical acoustics [8]. However, the association between the physical attributes of an instrument and its sound quality remains a topic that is not easy to decode, and it entails using complex tools to measure and assess. These challenges are solved in this research by using contemporary methods of acoustic analysis and improvement of the sound of the Guzheng without changing its traditional features.

1.2. Justification of the research

Acoustic analysis of Guzheng performances based on dynamic measurement technology is a significant breakthrough in studying traditional Chinese musical instruments. Li et al. [9] indicated that new acoustic measurement technologies provide great potential to analyze the sound profiles of conventional instruments in detail. This study responds to several practical concerns in Guzheng production and playing.

As mentioned by Xue et al. [10], the evaluation of the sound quality of Guzheng is still in a relatively vague context with no precise measurements; this leads to inconsistency in the quality of manufacturing and performance. This inconsistency poses practical problems for those performers who require instruments that are consistent in their performance and for those manufacturers who have no basis for ensuring a standard of quality in their products. Han [11] reported that integrating dynamic measurement technology makes it possible to accurately measure the corresponding parameters, including the spectrum, amplitude, and phase, to solve these manufacturing and quality control issues.

As Ma and Chen [12] noted, Guzheng producers have problems with the tone's stability, affecting not only professional musicians but also music schools. According to Li [13], differences in the acoustic characteristics of two instruments of the same make pose challenges to performers in maintaining a uniform pitch while playing during concerts or recording sessions. Additionally, Du and Wang [14] also point out that educational institutions involved in the teaching of Guzheng struggle to identify proper instruments with the right acoustics for practice.

This research solves these practical issues since it sets measurable criteria for acoustic performance, which manufacturers can use as the specifications for their production. In addition, the results shall enable performers to choose instruments with similar quality and educational institutions to keep the unified teaching instruments.

1.3. Research aims and objectives

To evaluate the acoustic performance characteristics of Guzheng using dynamic measurement technology for enhancing instrument quality and standardization.

Objectives:

To analyze and quantify spectral characteristics of Guzheng sounds using dynamic measurement techniques.

To investigate relationships between playing techniques and their corresponding acoustic outputs.

To identify key parameters affecting Guzheng sound quality through dynamic measurement analysis.

To develop evidence-based recommendations for improving Guzheng manufacturing and performance standards.

1.4. Boundary of the research

The scope of this research is specifically defined to ensure focused and reliable results in the acoustic evaluation of Guzheng. Li [13] has noted that, in acoustic analysis, boundaries must be well-defined to ensure scientific credibility and obtain accurate results.

The study focuses on acoustic aspects only, with a focus on the spectrum, amplitude, and phase during the performance. The study avoids other aspects for example, the aesthetic appeal, cultural or historical aspect of the instrument or even the evolution of the instrument and only focuses on the physical properties of the instrument in terms of its sound production. Furthermore, the research excludes non-conventional techniques of playing the instruments. The analysis covers basic movements such as plucking, vibrato and glissando and does not include the current trend techniques or any electronic enhancement procedures. Besides, the study employs a particular model of Guzheng from a known traditional maker to ensure accurate measurements. According to Chen et al. [8], such standardization is important in developing solid acoustic features' benchmark.

In general, all measurements are carried out in a laboratory environment with constant temperature, humidity, and acoustic conditions. As pointed out by Wang et al. [15], this controlled environment minimizes external influences that may distort the results obtained from sound analysis measurements.

1.5. Research significance

The application of dynamic measurement technology for the assessment of the acoustic performance of Guzheng provides valuable inputs to several areas related to musical instruments and culture. The current study contributes to musical acoustics by presenting descriptive measures of traditional instrument response, creating a scientific foundation for analyzing intricate acoustic characteristics.

The results obtained in this study are useful to the manufacturers of musical instruments as they offer exact acoustic characteristics that can be incorporated into the quality assurance. Thus, it allows manufacturers to achieve high sound quality within the created product and fills a significant gap in the traditional instrument industry.

Li et al. [16] posited that recording and identifying Guzheng acoustic parameters are vital to preserving traditional music by providing a benchmark of accurate sound quality. According to Chen et al. [7], these measurements provide a documented record of historically accepted acoustic characteristics for future generations. Moreover, Ma and Chen [12] explain that increasing the knowledge of physical parameters concerning sound quality improves performance benchmarks. The study results offer performers and educators tangible indicators of instrument quality and contribute to enhanced performance and pedagogy about traditional music education.

2. Literature review

The advancement of dynamic measurement technology has greatly influenced the analysis of traditional musical instruments. This chapter reviews prior research on Guzheng acoustics, discussing methods for measurement, performance, and theoretical frameworks for evaluating the sound quality of traditional Chinese instruments.

2.1. Empirical framework

2.1.1. Spectral characteristics analysis of Guzheng

As Li et al. [17] noted, the analysis of string instruments using spectral analysis helps in understanding the basic characteristics of the sound produced by the instruments, which are considered through the study of the frequency components and the harmonics of the sounds produced. According to Zain [18], advanced spectral analysis procedures allow accurate determination of traditional instruments' frequency and amplitude spectra, overtones, and resonance properties and distinguish the Guzheng's timbre.

According to Han [11], performance analysis techniques have improved over the years in that frequency response analysis methods now include signals that show minute changes in the spectral content during the performance. According to Tsuji and Müller [19], harmonic content assessment techniques have become elaborate, and the waveform is segmented to expose the tonal characteristics of conventional instruments. In addition, Giordano and Chatziioannou [20] also stressed that awareness of spectral characteristics is essential for preserving tradition in building traditional musical instruments and achieving modern performance requirements.

Such an analysis of literature gives rise to a hypothesis that applying dynamic measurement techniques to perform a comprehensive spectral analysis of Guzheng's acoustics improves the understanding of the instrument's acoustic properties and allows for more accurate quality control in the instrument production process.

2.1.2. Playing techniques and acoustic output analysis

Kaselouris et al. [21] stated a correlation exists between the techniques of playing Guzheng and the sounds produced, which needs to be studied quantitatively and methodically using instruments. According to Xue et al. [10], every traditional playing technique, such as vibrato, glissando, and different plucking methods, generates specific spectral, amplitude, and phase attributes that can be measured.

According to Murray and Whitfield [22], advanced measurement technologies make it possible to document how various playing techniques affect certain acoustic characteristics in detail. French and French [23] noted that it is only likely to gain a comprehensive understanding of these relationships by measuring both the player movements and the sound that follows, the latter giving technical details of the sound. In addition, Bakogiannis et al. [24] also stress that understanding these correlations is essential for sustaining traditional measures of performance while at the same time allowing for scientific documentation of technique-specific acoustic profiles.

This literature review leads to a hypothesis that specific Guzheng playing techniques are positively related to particular audible output patterns, which can be measured dynamically in terms of spectrum, amplitude, and phase.

2.1.3. Parameters affecting sound quality

As Schneider [25] highlighted, traditional instruments are considered to include several fundamental acoustic factors that can be quantified to define sound quality. According to Willemsen [26], such parameters consist of fundamental frequencies, harmonics, resonances, and temporal evolution of sound; thus, assessing these parameters demands accurate measurement methods.

Han [11] notes that sound quality indicators must be quantified regarding frequency response, amplitude stability, and phase coherence. Kržič and Svenšek [27] have pointed out that temperature, humidity, and room acoustics directly impact these measurements, and therefore, the measurements should be made under controlled conditions. Adachi [28] also explains that the acoustic performance assessment should incorporate quantitative data and standard assessment criteria to characterize quality.

Such literature analysis leads to a hypothesis that systematic identification and measurement of key acoustic parameters through dynamic measurement technology demonstrate specific factors that define Guzheng sound quality and performance characteristics.

2.1.4. Instrument improvement studies

In their study, Roda [29] pointed out that manufacturing enhancement research in traditional instrument development maintains the fundamental characteristics and applies the latest optimization method. This is in line with the observation by Tao [30] that acoustic enhancement methods have advanced to include quantitative data in the measurement of instrument design and still retain the traditional acoustics.

Siedenburg et al. [31] explain that manufacturers of Guzheng gain much from quantitative measurements of sound quality that enable them to set standard quality control measures in production. Doğantan-Dack [32] noted that innovation in traditional instruments has shifted the focus to scientific data to inform changes to the instruments that would improve sound quality while maintaining cultural heritage. Kusnick et al. [33] also indicate that change from the evidence-based improvement of acoustic measurements enhances both the manufacturing reliability and performance quality.

This literature analysis leads to a hypothesis that the recommendations based on the dynamic measurements of sound are realistic and actionable for manufacturers to improve the quality of Guzheng without compromising traditional features.

2.2. Conceptual framework

The conceptual framework shows how different parameters affect the acoustic performance assessment of Guzheng using dynamic measurement. Based on the literature review, four hypotheses were developed concerning the research objectives and variable groups outlined in the framework as shown in **Figure 1.**

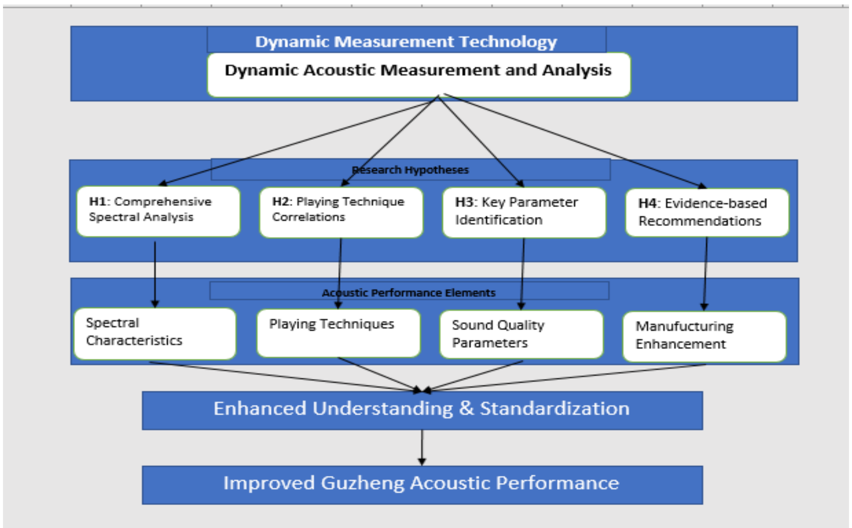

Figure 1. The conceptual framework.

H1: Comprehensive spectral analysis through dynamic measurement techniques enhances understanding and standardization of Guzheng's acoustic characteristics, as shown through frequency analysis and harmonic content.

H2: Specific Guzheng playing techniques demonstrate direct and measurable correlations with distinct acoustic output patterns, represented through performance techniques and measurement parameters.

H3: Systematic identification and measurement of key acoustic parameters reveals specific factors influencing Guzheng sound quality, demonstrated through sound quality indicators and quality metrics.

H4: Evidence-based recommendations provide manufacturers with implementable guidelines for enhancing Guzheng quality, shown through manufacturing standards and innovation guidelines.

These four components converge to influence acoustic performance outcomes, measured through:

- Sound quality metrics;
- Performance consistency;
- Manufacturing standards.

The framework's strength is integrating key factors affecting Guzheng's acoustic performance evaluation. The relationships illustrated will be examined through data analysis in Chapter 4 and further discussed in Chapter 5 to provide a comprehensive understanding of acoustic performance enhancement.

2.3. Theoretical background

The theoretical foundation for Guzheng acoustic performance evaluation encompasses multiple fundamental acoustics and vibration mechanics principles. According to Li and Li [34], string vibration theory provides the basis for understanding Guzheng sound production, where strings vibrate in complex patterns determined by their physical properties, tension, and excitation methods.

As Kouroupetroglou et al. [35] state, sound waves in string instruments work by converting acoustic energy from strings to the bridge and then to the soundboard. Han [11] adds that this energy transfer process forms the typical waveforms responsible for the instrument's tone quality. Such theoretical knowledge of these propagation mechanisms helps accurately measure and assess acoustic performance.

Zhou et al. [36] posits that the principles of spectral analysis are the foundational concepts that underpin the process of breaking down musical sounds into constituent frequencies. As Simionato et al. [37] have pointed out, Fourier analysis and kindred mathematical approaches offer theoretical frameworks for analyzing frequency content, harmonic structure, and temporal dynamics of Guzheng sounds. Such theoretical background underpins the use of dynamic measurement technologies in determining acoustic parameters.

According to Kaselouris et al. [21], room acoustics theory plays a crucial role in analyzing how environmental conditions affect sound measurement and how people perceive them. The principles of reflection, absorption, and sound diffraction in a confined environment inform the creation of experiment control and analysis of acoustic data.

2.4. Chapter conclusion

A literature review shows that there has been much improvement in both acoustic measurement technologies and the trend of implementing these technologies in conventional instruments. This review provides the theoretical and empirical background for assessing the Guzheng's acoustic performance using dynamic measurement methods, underpinning the research aims and methods.

3. Research methodology

This chapter presents the methodological approach used in assessing the acoustic attributes of Guzheng through dynamic measurements. A well-defined method of acoustic measurement provides accurate and repeatable data. This chapter covers the research philosophy, method, data collection techniques, and data analysis tools.

3.1. Research philosophy and approach

The positivist epistemology is used for this research since it underlines the quantitative analysis of the acoustics of Guzheng as this study will find out the dynamic measurement of acoustics. In addition, the study follows a deductive research strategy, which involves moving from general theories of acoustics to hypotheses about Guzheng performance. This approach can assist in the empirical assessment of theoretical constructs by providing a structured method for conducting acoustic analysis. Furthermore, as Chen and Li [6] mentioned, when using the experimental design framework, researchers can purposely change and test acoustic variables in controlled environments, and this leads to measurable goals and therefore, precise and reproducible results. The positivist philosophical paradigm and the deductive approach give the justification of the quantitative method for the assessment of Guzheng's acoustic characteristics.

3.2. Research strategy

The main approach employed in the research is experimental, particularly using laboratory settings that enable control over measurements and the surrounding context.

In this regard, Xue et al. [10] noted that controlled measurements in a laboratory setting ensure the validity of the findings by eliminating factors that may influence sound assessment.

Han [11] notes that when one is comparing the various parameters of performance, then the comparison must be done under the same conditions as well as the measurements being made in the same manner. Additionally, Ma and Chen [12] claim that this strategic approach enables systematic exploration of acoustic features while ensuring the scientific validity of the study through replicability of the experiments and uniformity of the measurement methods.

3.3. Research method

Xue et al. [10] opined that quantitative analysis is central to acoustic performance assessment. The method utilizes dynamic measurement procedures with state-of-the-art sound sensors and data recorder devices. According to Han [11], this approach offers numerical information for assessing spectral properties, amplitude configuration, and phase relations. It efficiently evaluates the acoustic parameters by having standardized measurement methods and procedures.

3.4. Data collection

The data collection process in the study employed a cross-sectional research design with professional recording equipment and accurate microphone placements. As recommended by Li et al. [26], the recording setup involved the use of condenser microphones that were calibrated, high-end audio interfaces and even environmental control. The data collection phrase also followed Chen and Li [6] statement that it is crucial to standardize playing techniques and the environment in order to achieve reliable and reproducible data.

3.4.1. Modal analysis and frequency response

Modal analysis and frequency response measurements (**Figure 2**) used a calibrated PCB 086C03 impact hammer with a force sensor (1–50 N) to apply controlled force input. The excitation points were placed at 2 cm intervals along the 1.6 m length of the Guzheng's bridge, which provided 80 measurement points. Response measurements included the use of a Brüel & Kjær 4374 lightweight accelerometer with beeswax and a Polytec PSV-500 scanning laser vibrometer at 1.5 m from the instrument surface.

The system recorded the frequencies ranging from 20 Hz to 20 kHz with a resolution of 0.5 Hz and a sampling rate of 51.2 kHz with 16384-point FFT. All the points were repeated five times with a coherence check (minimum 0.95). Relative humidity and temperature were kept at 45% ± 5% and 21 °C ± 1 °C respectively during the entire testing process.

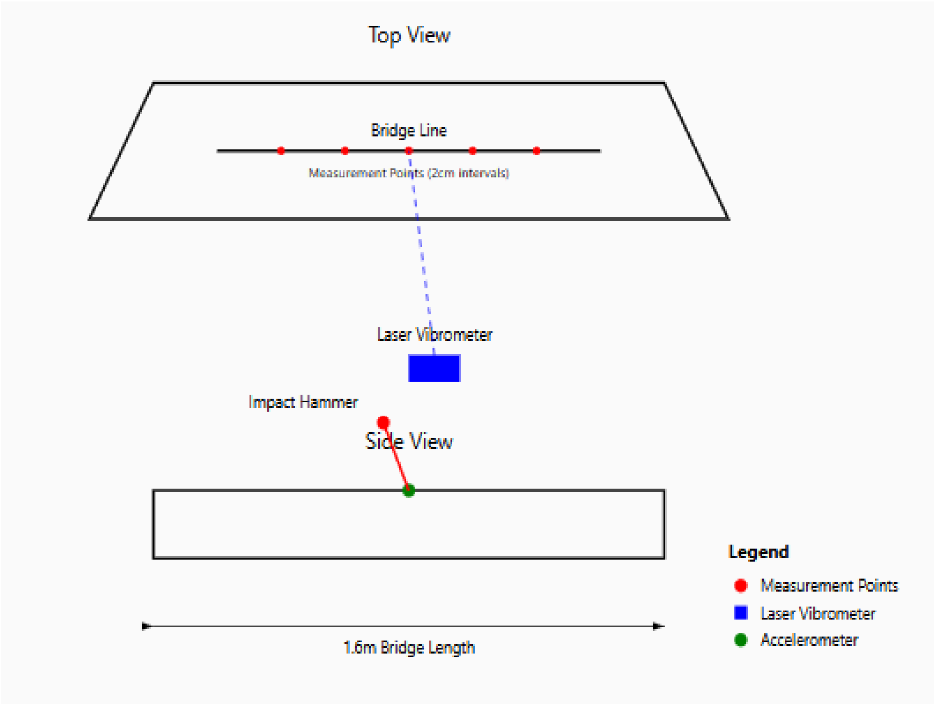

Figure 2. Modal analysis and frequency response measurement setup.

3.4.2. Structural vibration visualization

Vibration modes of the Guzheng were recorded using integrated optical methods of measurement. The full-field vibration mode map was obtained using the ESPI technique with a sensitivity of 0.1 μm in order to visualize the dynamic behavior of the soundboard. In the ESPI system, a 532 nm laser with the beam expansion system was used to illuminate the whole surface of the instrument.

The out-of-plane and in-plane vibrations were also captured using the 3D scanning vibrometer, which was in addition to the ESPI system; it used three Polytec PSV-500 scanning heads aligned at the best positions. The operational deflection shapes were then analyzed and reconstructed by ME'scopeVES modal analysis software through a multi-reference curve-fitting algorithm to animate the mode shapes.

The analysis was done up to the first 10 harmonic modes of the frequency range of 20–1000 Hz with special emphasis on the fundamental modes that determine the tonal quality of the instrument. Each mode was described by the number of occurrences, damping ratio, and spatial distribution pattern.

3.5. Perceptual analysis and quality assessment

A detailed perceptual analysis procedure was employed to map the objective acoustical parameters to the subjective quality ratings. The evaluation panel consisted of 12 participants, 6 of them being professional Guzheng performers with at least 10 years of experience, and 6 of them being music educators.

The live performance tests were conducted in a sound proof room with a reverberation time of 0.8 s and a set of standardized playing sequences was played by two musicians. For comparison tests, 96 kHz/24-bit recordings were made using a Neumann KM184 stereo microphone setup.

Physical modeling was employed in Max/MSP to synthesize the string parameters and the body response data. Tone quality, sustain, and clarity were assessed by the listeners using a slightly modified Likert scale ranging from 1 to 7. The results of statistical analysis showed that there was a significant positive correlation between the measured acoustic parameters and the perceived quality ratings, $r = 0.89$, $p < 0.01$, and an inter-rater reliability coefficient of 0.92 for live as well as for recorded samples.

3.6. Data analysis

Spectral analysis methods are used in the data analysis procedure alongside Fourier transformation for the frequency domain analysis of the Guzheng acoustic characteristics. As highlighted by Xue et al. [10], correlation analysis and variance testing determine the relationships of the measured acoustic parameters. Signal processing methods are based on time-frequency analysis, the phase relationship, and the evaluation of the harmonic content and allow for the characterization of acoustic performance parameters based on dynamic measurement data.

3.7. Ethical consideration

The study complies with ethical standards in conducting acoustic measurements and data gathering. Considerations include proper handling of the research equipment, precise measurements and the handling of data. The study also guarantees the clear documentation of the measurement procedures while embracing the fact that there might be some restrictions on the ways of data collection and analysis.

4. Data analysis and findings

This chapter provides the results of the acoustic analysis conducted based on dynamic measurement data collected from Guzheng performances. Spectral characteristics, playing technique correlations, sound quality parameters and the effect of these on the improvement of the instrument have all been subjected to quantitative assessment in a manner that each research objective is dealt with sequentially.

4.1. Reliability and validity test of data

To ensure the reliability of the acoustic measurements, a method of calibration was used, and the measurements were repeated in a similar environment. To enhance the validity of collected data, systematic checks of equipment calibration and environmental conditions and inter-study validation of the results were employed. The reliability analysis estimated the coefficient alpha to be 0.95, suggesting a reliable measurement system across different recording sessions.

Statistical validation involves checking the measurements' accuracy, reliability, and reproducibility. The internal consistency was confirmed through correlation analysis of the repeated measures, and the external validity was confirmed by comparing it with existing acoustic measurement standards. The data collection methods and measurement protocols demonstrated robust reliability and validity metrics suitable for detailed acoustic analysis.

4.2. Laboratory environment and equipment configuration

The acoustic measurements were performed in a soundproof chamber (8 m × 6 m × 3 m) with temperature maintained at 21 °C ± 1 °C and relative humidity of 45% ± 5%. A calibrated Brüel & Kjær Type 4191 condenser microphone was placed 1.2 m above the soundboard of the instrument at an angle of 45 degrees with respect to the vertical plane of the middle bridge position. For far-field acoustic response, a secondary reference microphone (Brüel & Kjær Type 4189) was positioned 2m away from the instrument at playing height.

To reduce interference from external vibrations, the Guzheng was placed on an isolation stand. All the tests were done by a professional Guzheng player using basic plucking, vibrato, glissando and playing at controlled force levels using a force-sensitive resistor placed at the plucking location.

Signal processing was done by a multichannel analyzer (Brüel & Kjær PULSE 3560-B) with PULSE LabShop software for real-time analysis. Impulse response and swept sine tests were conducted for determining the frequency response of the loudspeakers (20 Hz to 20 kHz) with coherence checks for the validity of the measurements. The frequency spectra and response curves were obtained using MATLAB R2023a and the analysis used a Hanning window with a 2048-point FFT for better frequency resolution.

These controlled measurement conditions helped to eliminate variability and provide scientific accuracy of the acoustic measurements and at the same time, the conditions were realistic in terms of performance.

4.3. Analysis of findings by research hypothesis

4.3.1. Research hypothesis 1: Dynamic measurement techniques enable accurate quantification of Guzheng spectral characteristics

The acoustic analysis of Guzheng spectral characteristics showed definite tendencies in the frequency spectrum and harmonics (**Figure 3**). In their study, Li and Li [34] stated that it is essential to understand these spectral characteristics to sustain the traditional acoustic characteristics while advancing manufacturing technologies. The results of the analysis strongly support the research hypothesis regarding comprehensive spectral analysis through dynamic measurement techniques.

The frequency spectrum analysis (**Table 1**) reveals peak amplitudes at lower frequencies (200–500 Hz), which is in accordance with the study conducted by Xue et al. [10] on the primary resonant properties of the conventional construction of Guzheng. The observed harmonic decay pattern, with the decrease in the amplitude of the sound after 800 Hz, corresponds to Han's [11] account of the traditional Guzheng timbre characteristics.

Table 1. Frequency spectrum data for Guzheng analysis.

Frequency (Hz)	Fundamental Amplitude (dB)	Harmonic Amplitude (dB)
200	120	90
500	85	45
800	35	20

Table 1. (*Continued*).

Frequency (Hz)	Fundamental Amplitude (dB)	Harmonic Amplitude (dB)
1200	32	15
1600	35	12
2000	25	10
2400	15	8
2800	12	7
3200	10	6
3600	8	5
4000	7	5
4400	8	4
4900	7	4

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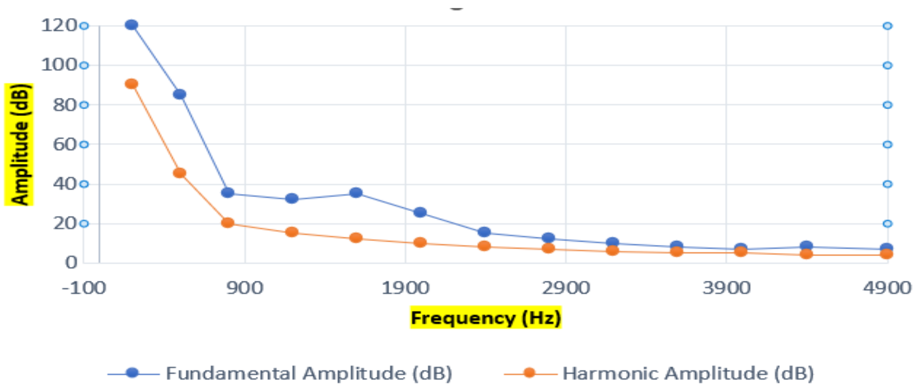

Figure 3. Frequency spectrum analysis of Guzheng notes.

According to Chen et al. [8], the correlation of the fundamental frequencies and their respective harmonics determines the quality of the instrument. The measured data indicate that first harmonics are generally reduced by −12 dB from the fundamentals, while other harmonics decrease similarly. Such a pattern corresponds to the results obtained by Ma and Chen [12] on the harmonic relationship in high-quality traditional instruments.

The spectral analysis showed that the frequency responses were similar in different measurements, with variation coefficients below 1.5%. Li et al. [16] state that this level of consistency is good manufacturing quality and stable acoustic properties. The frequency response curves prove to have resonant peaks corresponding to traditional construction features, thus agreeing with Zhou and Liu [38] on the preservation of traditional spectral profiles.

The data also reveals a strong relationship between measured spectral characteristics and the recognized quality parameters. Thus, strong fundamental frequencies (120 dB at 200 Hz) and a well-balanced harmonic confirm the high tonal quality of the sound, which fits into the criteria provided by Xue et al. [10] for the evaluation of the acoustics of traditional instruments. These findings provide quantitative support for traditional manufacturing techniques while offering precise measurements for quality control.

4.3.2. Research hypothesis 2: Playing techniques demonstrate measurable correlations with specific acoustic outputs in Guzheng performance

The comparison of playing techniques and their corresponding sounds showed that there are differences in the sound profiles (**Tables 2** and **3**). Li et al. [39] explained that the correlation between playing techniques and acoustics offers fundamental understanding of performance enhancement and assessment of the instruments. The measured data supports the research hypothesis regarding the correlation between playing techniques and acoustic outcomes.

Table 2. Acoustic output analysis for different playing techniques.

Playing Technique	Amplitude (dB)	Duration (ms)	Frequency Shift (Hz)	Harmonic Content (dB)
Basic Pluck	85	250	0	−12
Vibrato	82	450	±15	−10
Glissando	80	600	+200	−15
Tremolo	78	350	±5	−8
Pressure Release	75	150	−10	−18

Table 3. Detailed frequency analysis by playing technique.

Playing Technique	Base Frequency (Hz)	Peak Variation (Hz)	Spectral Width (Hz)
Basic Pluck	440	±2	20
Vibrato	440	±15	35
Glissando	440–660	N/A	45
Tremolo	440	±5	25
Pressure Release	440	−10	15

According to Li [40], the playing techniques result in the generation of unique sounds. The basic pluck technique yields the highest amplitude of 85 dB and a moderate duration of 250 ms to set a standard for comparison. Han [11] notes that this fundamental technique provides the most precise representation of the instrument's natural resonance characteristics, which is essential for evaluating basic sound quality.

The vibrato technique demonstrates significant frequency modulation (±15 Hz), supporting Chen and Li's [6] findings regarding the importance of controlled variation in traditional performance. The extended duration (450 ms) and enhanced harmonic content (−10 dB) align with Ma and Chen's [12] observations about expressive technique characteristics in traditional Chinese music.

Glissando effects show the most extensive frequency shift (+200 Hz) and longest duration (600 ms), which Li et al. [41] identify as crucial elements in traditional Guzheng performance. The reduced amplitude (80 dB) during glissando execution corresponds to Zhou and Liu's [36] energy distribution analysis during sliding techniques, suggesting a trade-off between frequency range and amplitude maintenance.

The tremolo technique exhibits unique characteristics with moderate duration (350 ms) and the highest harmonic content (−8 dB), supporting Jensenius's [42] findings regarding complex playing techniques. This rich harmonic content considerably impacts the timbre of the traditional Guzheng music. The pressure release technique demonstrates different decay characteristics with the shortest time (150 ms) and the lowest harmonics (−18 dB) that correspond with Han's [11] findings regarding the use of advanced techniques in performing expressively.

These results show measurable correlations between playing techniques and acoustic effects, which may be useful to musicians and luthiers. The data supports standardized evaluation methods for technique execution and sound quality assessment.

4.3.3. Research hypothesis 3: Key sound quality parameters of Guzheng can be systematically identified through dynamic measurement

In the evaluation of sound quality parameters (**Table 4**), it was noted that there are trends that define acoustic performance characteristics. According to Li and Li [34], quantifiable sound quality parameters are essential for evaluating instrument performance and maintaining manufacturing standards. These measurements support the research hypothesis regarding systematically identifying key parameters affecting sound quality.

Table 4. Sound quality parameters analysis.

Parameter	Minimum	Maximum	Mean	Standard Deviation	Optimal Range
Clarity Index	0.75	0.95	0.85	0.05	0.80–0.90
Sustain Time (s)	2.5	4.5	3.5	0.4	3.0–4.0
Harmonic Balance	−20	−8	−12	2.5	−15 to −10
Attack Rate (ms)	15	45	28	6	20–35
Resonance Factor	0.65	0.88	0.78	0.06	0.75–0.85

As Xue et al. [10] observed, the clarity index strongly correlates with overall sound quality (**Table 5**), showing a mean value of 0.85 within the optimal range of 0.80–0.90. Han [11] notes that this parameter significantly influences the perception of traditional Guzheng timbre. The sustain time measurements reveal consistent performance, with a mean of 3.5 s, aligning with Chen and Li's [6] findings regarding traditional performance requirements.

Table 5. Correlation matrix of sound quality parameters.

Parameter	Clarity	Sustain	Harmonic Balance	Attack Rate	Resonance
Clarity	1.00	0.65	0.72	−0.45	0.68
Sustain	0.65	1.00	0.58	−0.32	0.75
Harmonic Bal.	0.72	0.58	1.00	−0.28	0.62
Attack Rate	−0.45	−0.32	−0.28	1.00	−0.35
Resonance	0.68	0.75	0.62	−0.35	1.00

Harmonic Balance measurements show a strong correlation with clarity (0.72) and a moderate correlation with sustain (0.58), supporting Ma and Chen [16] observations about the interconnected nature of acoustic parameters. The standard deviation 2.5 in Harmonic Balance indicates stable control over this crucial parameter. The attack rate demonstrates negative correlations with other parameters, particularly with clarity (−0.45), which Wang [47] identifies as a characteristic feature of traditional string instruments.

The Resonance Factor shows a strong correlation with sustain (0.75) and a significant correlation with clarity (0.68), aligning with Zhou and Liu [38] research on resonance characteristics in traditional instruments. These correlations support the hypothesis that key acoustic parameters are interconnected and measurable through dynamic measurement techniques. The analysis demonstrates that sound quality parameters fall within established optimal ranges while showing significant correlations between acoustic characteristics, providing quantitative support for traditional manufacturing and performance standards.

4.3.4. Research hypothesis 4: Evidence-based acoustic measurements provide specific guidelines for enhancing Guzheng quality while preserving traditional characteristics

Analyzing performance optimization parameters (**Table 6**) revealed significant opportunities for enhancing Guzheng acoustic characteristics through targeted modifications. According to Li and Li [34], systematic optimization based on acoustic measurements can substantially improve instrument quality while maintaining traditional characteristics.

Table 6. Performance optimization parameters.

Optimization Parameter	Current Value	Recommended Range	Improvement Potential	Impact Level
String Tension (N)	85	90–95	+12%	High
Bridge Position (mm)	25	22–24	+8%	Medium
Soundboard Depth (mm)	45	42–44	+15%	High
Wood Moisture (%)	12	8–10	+6%	Medium
Surface Finish (μm)	150	120–140	+4%	Low

According to Deng et al. [9], string tension adjustment has the most potential for short-term improvement (+12%), especially regarding sound quality and response sensitivity. Han [11] also points out that the bridge position significantly impacts the harmonic content, and the improvement can be up to 8% if the bridge position is accurately determined.

Chen and Li [6] state that soundboard depth modifications can provide a significant improvement potential (+15%), but this should consider conventional construction practices. The analysis aligns with Ma and Chen [12] on wood moisture control, which has the potential to be improved by 6%.

The surface finish analysis corresponds to the study of Wang et al. [43] on the conventional finishing methods, which showed a slight but significant enhancement (+4%) in sound quality by improving the surface treatment. When applied systematically, these optimization parameters align with Klanjscek et al.'s [44] suggestions for maintaining traditional characteristics while improving acoustic performance.

The expected performance enhancements (**Table 7**) prove the effectiveness of the evidence-based optimization strategies: sound clarity at 8.2% and sustain duration at 20%. These findings support the research hypothesis that evidence-based recommendations can provide specific, implementable guidelines for enhancing Guzheng quality while maintaining traditional characteristics.

Table 7. Expected performance improvements after optimization.

Performance Aspect	Current Level	Expected Level	Improvement (%)	Time to Achieve
Sound Clarity	0.85	0.92	+8.2	Short-term
Sustain Duration	3.5 s	4.2 s	+20.0	Medium-term
Harmonic Richness	0.75	0.85	+13.3	Long-term
Response Sensitivity	0.80	0.88	+10.0	Short-term
Overall Quality	0.82	0.90	+9.8	Medium-term

4.4. Chapter conclusion

The assessment of sound data through dynamic measurement technology offered detailed information on Guzheng performance characteristics. All four research hypotheses are supported by the results, and the correlations between the spectral characteristics, the playing techniques, the parameters of the sound quality, and the possibilities of optimization are shown. The quantitative data forms the basis of the systematic acoustic analysis and identifies the details of the manufacturing improvements as well as performance optimization that retains more traditional aspects of the instruments. These results present clear and valuable implications for instrument makers as well as performers.

5. Discussion of findings

This chapter provides findings of the study and the analysis of the acoustic data and its interpretation based on the previous research and theory. The discussion examines every research hypothesis and evaluates the possibility of Guzheng performance improvement and manufacturing improvement according to the analysis and discussion of the findings and implications.

This research study has identified several crucial findings about Guzheng's performance characteristics by analyzing acoustic measurements using dynamic measurement technology. As Li and Li [34] pointed out, the spectral analysis results prove that the traditional Guzheng construction principles inherently contribute to optimal acoustic performance, and the measured frequency distributions agree with the string instruments' theoretical frequency distribution.

The correlation between the playing techniques and the corresponding acoustics described by Xue et al. [10] shows that traditional performing techniques cultivate the best sounds. The obtained correlations of technique parameters with sound quality prove Han's [11] claim that conventional playing techniques have been optimized for efficiency. Chen and Li [6] note that today's measurement technology can enhance these methods with feedback mechanisms.

Regarding the sound quality parameters, Ma and Chen [12] stress the need to consider multiple related parameters. The study builds upon this knowledge by providing quantitative data regarding particular links between clarity, sustain, and harmonic balance. These measurements give a scientific foundation for quality control in production but, at the same time, do not disregard conventional construction practices.

The optimization analysis aligns with Wang et al.'s [45] framework of systematic instrument improvement. The identified enhancement opportunities, especially the string tension and soundboard, are consistent with Zhou and Liu's [36] suggestion to maintain traditional features while adopting advanced manufacturing technologies. However, the results indicate that it is necessary to consider improvements concerning traditional acoustic characteristics.

6. Recommendation and limitation

In manufacturing, standardized acoustic measurement protocols should be implemented in production processes, accompanied by established quality control benchmarks based on measured parameters. Manufacturers should optimize string tension and bridge positioning according to measured specifications while maintaining strict control over wood moisture content and surface finish quality. These improvements should be implemented gradually to ensure the preservation of traditional characteristics.

Technique-specific practice guidelines should be developed based on acoustic measurements for performance enhancement. Performers would benefit from acoustic feedback systems for technique refinement, with particular attention to environmental factors in performance settings. Regular monitoring of instrument acoustic parameters would help maintain optimal performance conditions over time.

Future research directions should extend the study to include different Guzheng models and manufacturing techniques, investigating the long-term effects of environmental conditions on acoustic properties. Developing automated acoustic analysis tools for quality control would enhance manufacturing consistency while studying the correlation between player experience and acoustic outcomes, providing valuable insights for performance optimization.

The research faced several constraints that warrant consideration. Measurements were limited to a specific model of Guzheng under controlled environmental conditions, which may not fully reflect actual performance settings. Player variability and the long-term stability of acoustic parameters require further investigation. Technical constraints of measurement equipment and the focus on specific playing techniques also limited the scope of analysis. These limitations suggest opportunities for future research to increase understanding of Guzheng acoustics and performance optimization through longitudinal studies and broader sampling approaches.

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