

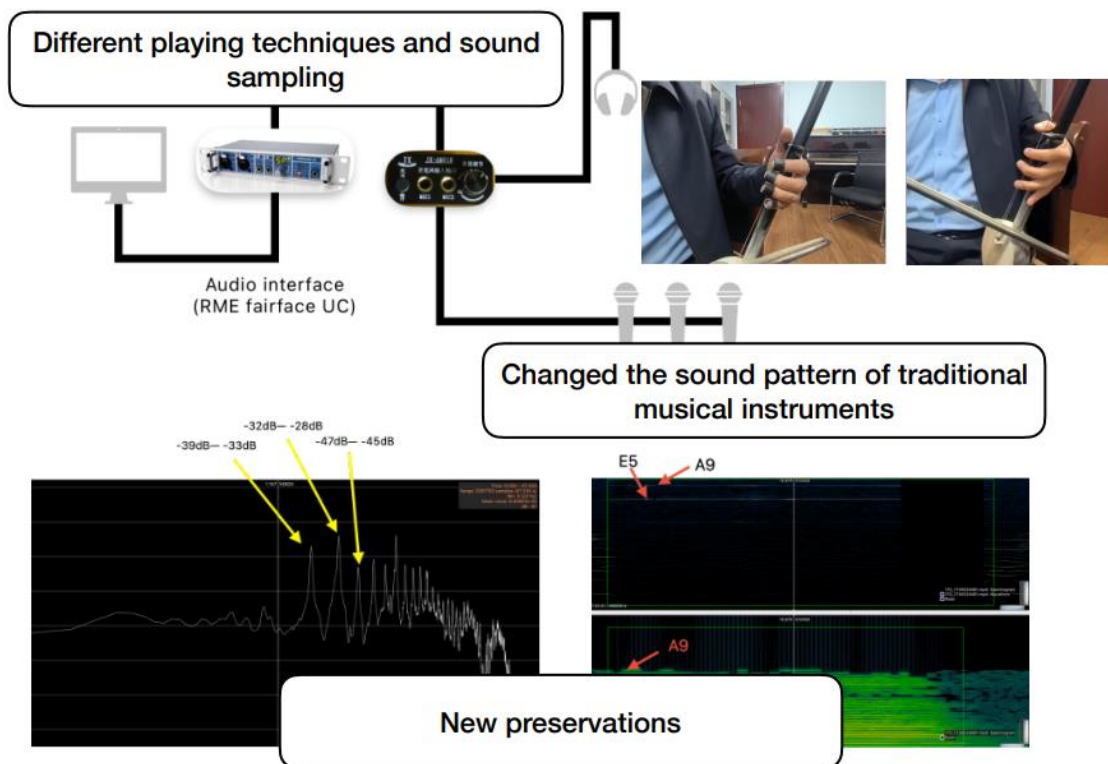
Jin Opera Huhu: A Critical Sound Analysis of Cultural Representation in Conventional Jin Opera

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GRAPHICAL ABSTRACT



Jin Opera Huhu: A Critical Sound Analysis of Cultural Representation in Conventional Jin Opera

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A comprehensive acoustic analysis was carried out for the huhu, a betelwood instrument from the Jin opera. Techniques included an acoustic visualiser and Fast Fourier Transform (FFT). The harmonic structure, frequency distribution, and timbre quality of the instrument were investigated, focusing on the effect of the use of leather finger cuff on the sound produced. Spectral analyses revealed complex overtones and distinctive spectral patterns for different playing techniques, ranging from 324.47 to 10,277.08 Hz. Finger cuffs significantly altered the harmonic content and timbre. The study utilised high fidelity equipment to conduct multiple recordings under controlled conditions to capture subtle acoustic changes. Statistical analysis of the frequency data revealed a consistent overtone structure, while an acoustic visualiser examined the relationship between playing technique and sound intensity. The analyses emphasised how traditional playing methods (particularly fretting) affect acoustic output. By documenting the current acoustic characteristics of the huhu, this work provides insight into its musical and cultural significance, contributes to the preservation of traditional musical heritage and provides a scientific basis for understanding the unique acoustic characteristics of betel nut wood.

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Keywords: Acoustic analysis; Sound spectrograph; Traditional Chinese musical instruments; Ethnomusicology; Audio analysis; Cultural heritage preservation

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INTRODUCTION

Banhu (板胡) is the main musical instrument used in most of the Shanxi opera styles, and it is also known as the huhu (胡胡) (Guo 1997). It is made of betel nut shell, tung wood surface, ebony or sandalwood pole, and bamboo bow (two bamboo skins are glued together). The length of the instrument is 770 mm, the height of the instrument is about 30 mm, the diameter of the pole is 84 mm, the length of the bow is 890 mm, and the bow can be inverted when playing. The strings are set at A and E, and the left index finger presses the c note. When playing, the left hand wears a finger cuff, and the handle is not inverted (Figs. 1 and 2). The erhu and huhu are similar in shape, but the erhu uses a wooden cylinder covered with python skin, played by hand on silk or metal strings, producing a smooth and mellow tone suitable for a wide range of folk music pieces. The huhu is only used in Jin opera.

Problem Statement

The rapid decline of traditional instrument craftsmanship poses significant challenges for preserving global intangible cultural heritage. The huhu, the primary instrument of Jin opera and part of China's National Intangible Cultural Heritage Protection Catalogue, exemplifies this crisis. The instrument has undergone substantial material changes from traditional bamboo tubes and horsetail strings to modern betel nut shells and steel strings. However, rigorous acoustic documentation quantifying the tonal effects of these material transformations remains lacking. This knowledge gap presents urgent concerns. The decreasing number of master craftsmen, fewer students, increased use of synthetic substitutes, and declining traditional performance practices threaten the acoustic integrity of this instrument. The study addresses two primary research questions: first, what are the quantifiable tonal characteristics of modern huhu instruments, including harmonic structure and spectral energy distribution; second, how do performance variables, particularly leather finger sleeves, influence harmonic content and sound propagation.

The research established reproducible acoustic characteristics through advanced spectral analysis, mapping the complete frequency response range from 324.47 to 10,277.08 Hz. The findings provide scientific benchmarks for authenticating heritage instruments through structured spectral datasets and enable potential AI-driven reconstruction of endangered timbres. This interdisciplinary approach contributes to ethnomusicology, archival science, and global heritage policy by creating systematic documentation methods for preserving cultural acoustics.

North Road Huhu

North Road is a traditional opera genre popular in northern Shanxi Province and surrounding areas in China. It is characterised by its high-pitched and stirring melody and is one of the four major opera genres in Shanxi Province. The length of the huhu pole is 72 mm, the betel nut is taken as half of the shell, the diameter is 120 mm, and the sound hole is opened on the back in the style of ancient money. The bow, constructed from an 800-mm bamboo board strung with horsetail hair, historically used horsetail strings (now entirely replaced by steel strings), with fixed A and E tuning.

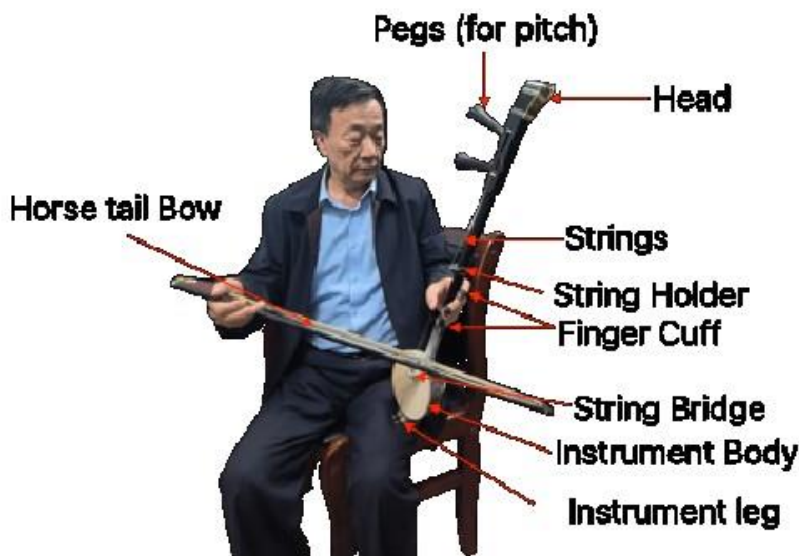


Fig. 1. Full assembly of the huhu, and the names of the parts

The instrument can be played in two octaves, and when playing it the left hand carries a finger cuff. The forefinger presses the 1-5 pitch, and can be inverted, this technique called 'inverted positioning', which involves sliding the hand down the neck of the instruments to shift the forefinger's range to pitches 4-1, creating distinctive tonal effects—especially pronounced sliding sounds. Currently, the Jin Opera huhu predominantly follows Pu Opera conventions, featuring fixed B and E strings, and the lowest tone it can play is E4, with a frequency of 324.47 Hz, and an intensity of -14.09 dB. The highest tone it can play is #D9, with a frequency of 10,277.08 Hz, and an intensity of -31.40 dB.

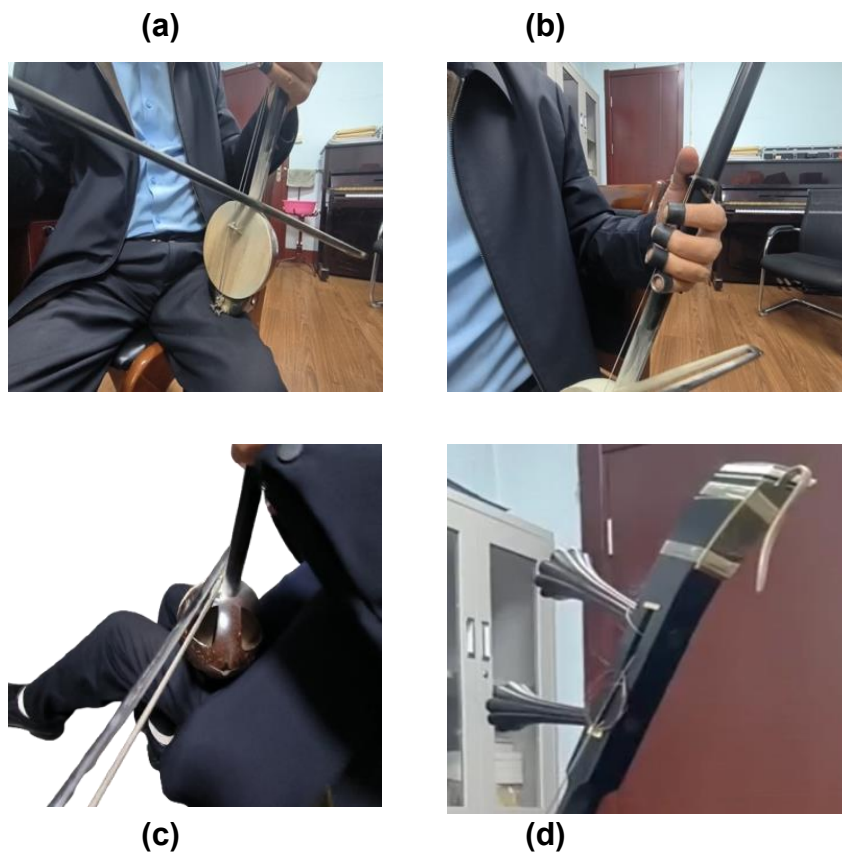


Fig. 2. (a) Front view; (b) finger cuffs; (c) back view, and (d) head of the huhu

Changes in the Evolution of the Pu Opera Huhu

The first Pu Opera huhu was made from a bamboo tube or a small gourd dipper, the bow was bent with a piece of bamboo, and the strings were made from horsetail. Currently, the shell of the instrument is made of betel nut dipper, the pole is made of mahogany or sandalwood, the bow is made of small bamboo poles, and the bowstring is often made of white horse's tail (Guo 1997). The earliest strings were made of thicker ox-bar strings, which were later changed to thinner ones. Currently, steel strings have replaced the old strings. The old strings are now only used for exhibition purposes. When steel strings are used, some players wear cuffs and some don't. The use of steel strings is still being explored. The use of steel strings is also developing in the process of exploration; in 2010, Xue Shijiang, the original Banhu player of the Lingbao Pu Opera Troupe invented

and registered the ‘Guo Guo Brand’ special steel strings for Pu Opera, which are now widely used. The characteristic of this string is: according to the sound requirement of Pu Opera Banhu, it is wound by many strands and made with fine workmanship, with clean and pure tone, thus making up for the shortcomings of the old strings of Pu opera, which are difficult to stabilize the pitch and are not durable. The huhu serves as the primary melodic instrument among the four core instruments of Jin Opera, functioning as what researchers describe as the “skin” or essential voice of the tradition. Its acoustic characteristics directly reflect its cultural role within this musical form. For example, the huhu’s sliding tones embody Shanxi Opera’s vocal mimicry tradition. Its metallic timbre symbolizes heroic roles in Pu Opera, contrasting with the bamboo erhu used for feminine characters (Guo 1997). The instrument’s capacity to produce both penetrating, high-pitched tones and gentle, lyrical passages mirrors the dramatic range required in Jin Opera performance. The bright, soaring quality enables the instrument to cut through ensemble textures during climactic moments, while its softer timbral possibilities support intimate narrative passages. These dual acoustic capabilities make the huhu indispensable for conveying the emotional breadth characteristic of Jin Opera storytelling, from heroic declarations to tender expressions of sentiment.



Fig. 3. Betel nut tree

EXPERIMENTAL

The audio signal was captured using the Digital Audio Workstation logic pro and then analyzed by sonic visualiser for waveforms and spectra. The spectrum shows pitches based on the Even Temperament Scale (ETS). Musical signals show many features (Herrera-Boyer *et al.* 2003; Essid *et al.* 2005; Klapuri and Davy 2006; Deng *et al.* 2008). The FFT-based spectra show the temporal evolution and characterizes the spectra on a time basis. The TFA shows partial frequencies over time in two cases. The first case emphasizes the instantaneous frequency of a sine wave using FFT (amplitude versus frequency) and is called frequency modulation. The second case emphasizes the TFA.

Pitch frequency features have been used for musical instruments (Lin *et al.* 2005). Due to the nature of music, this research uses time-frequency features to represent signals, which are very effective in distinguishing timbres at time-varying frequencies. In the case of the huhu instrument, the harmonic and subharmonic frequencies determine the timbre of the note. This is crucial because only a professional huhu player knows what a good

sound is. Therefore, it is necessary to identify it not only aurally, because the average person cannot recognize the correct pitch based on the musician's playing. Understanding how to choose a huhu based on the fundamental and harmonic sounds of each huhu can help parents, novices, and huhu instructors. Experimental data were collected using sonic visualiser. Experimental data was analyzed in terms of frequencies in TFA. This will categorize the huhu with good sound quality. Spectra were generated using the non-stationary characteristics of music signals. Instrument sounds are usually classified based on spectral features, which only show information about the frequencies in the signal. The spectrum only shows information about the frequencies in the signal. Time-varying frequencies consist of fundamental and harmonic frequencies. Research shows that time and frequency are inversely proportional to a certain extent (Lin *et al.* 2005; Essid *et al.* 2005; Deng *et al.* 2008; Wieczorkowska and Kubera 2009).

The experiment was conducted in the Jin opera rehearsal room at the School of Drama and Vocational Studies, where the room was well equipped with acoustic treatment materials. Sound was captured using a large-diaphragm microphone. Voltage-time signals and amplitude-frequency spectrograms were recorded using an oscilloscope in sonic visualizer mode. Time-frequency analyses (TFA) analyses were carried out using logic pro x. Apparent intensity was measured in Hz (to distinguish the intensity of partial frequencies) and amplitude in seconds. Most sound analyses and resyntheses use this method to study the tonal system (Thomson 1998; Hamdan *et al.* 2021; Hamdan *et al.* 2023). For comparison, different audio files were recorded with and without finger cuffs, and on different strings. Recordings were made with the microphone at a distance of less than 20 cm from the strings. In order to ensure that the playing patterns were identical, an expert player was employed. The format of the recorded audio signal was mono 32-bit resolution with a sampling rate of 48 kHz. audio files were saved in .wav format for further processing. Before recording, calibration was performed to ensure optimal settings. The calibration procedure was based on the IASA method with the test tone limited to a 1 kHz sine wave. According to IASA, the 0 VU digital equivalent recorded by the device must be generated in analogue or digital format at +4 dBu or -18 dBFS. No other devices that may enhance or attenuate the signal amplitude are present during the calibration process. The setup of the recording system consists of an audio interface (RME UC), microphone (Audio-Technica at8015; Nord NT2000; Shure sm58s), and cable (XLR) with the microphone set to (cardioid polar pattern). For audio processing, signals were recorded by an oscilloscope (Logic pro x) and analysed by the sonic visualiser software (version 5), specifically FFT, voltage-based triggering and spectrum analysis.

To ensure consistent acoustic measurements while preserving the authenticity of human performance, the study employed a systematic two-phase approach. A professional musician with 40 years of huhu experience performed all recordings using standardized techniques and consistent playing intensity. An NTi Audio XL2 Class 1 precision sound level meter, calibrated to IEC 61672-1:2013 standards, was positioned 50 cm from the instrument's f-hole at a 45° angle to the bridge. The performer monitored real-time A-weighted sound pressure levels through headphones and maintained target levels of 80.0 ± 0.5 dB(A) during sustained tones exceeding two seconds, representing forte dynamics typical in Jin Opera repertoire. The microphone placement remained constant throughout all recordings to capture the instrument's tonal qualities without positional bias or distortion.

Post-acquisition validation was conducted using Logic Pro X (version 11.0.0) to measure peak amplitudes for target tones E4 and B4. Recordings with amplitude deviations

exceeding $\pm 3\%$ from the reference level (-6 dBFS) were excluded from analysis. Only segments with RMS energy between -6.18 and -5.82 dBFS were retained, corresponding to a perceptually negligible loudness variation of less than 1.5 LUFS based on empirical pilot testing. This dual-phase control system achieved measurement precision comparable to robotic systems while maintaining the cultural integrity of traditional manual performance techniques.



Fig. 4. Performer maintaining fixed distance from the microphone while playing with the same intensity

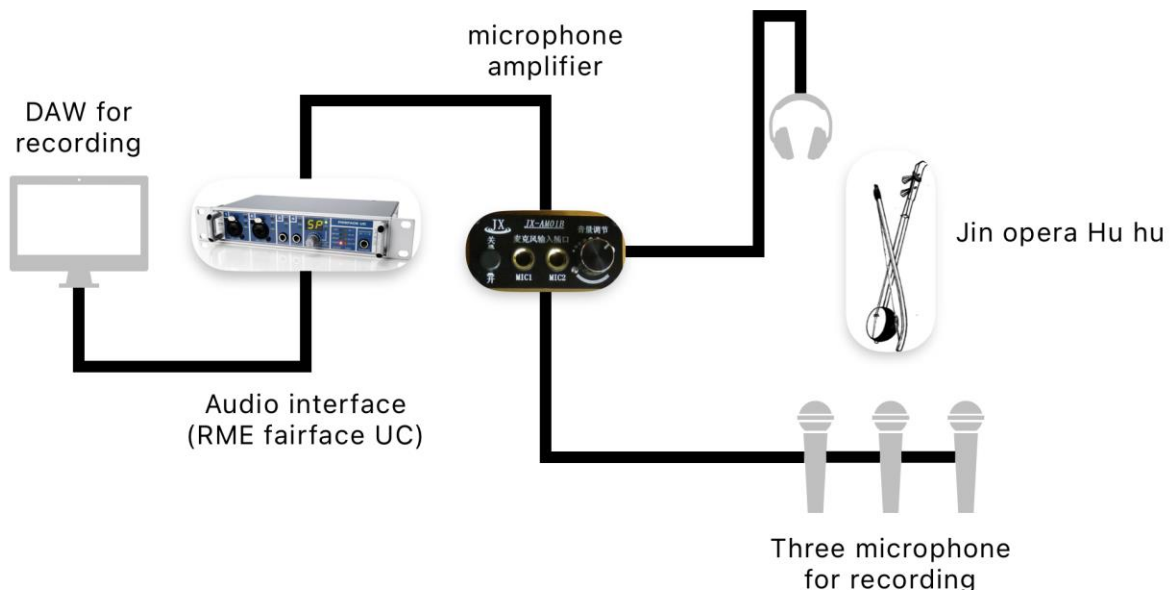


Fig. 5. Diagram of the experimental setup

Figure 6 shows the different types of playing techniques with and without finger cuff, which are made of animal skins and protect the player's fingers and allow them to move smoothly during playing, and most importantly, they give the sound more bite. String 1 and string 2 are pitched at B4 and E4. String 1 is pitched at B, 501.188Hz, and the sonic

visualiser measures the frequency range 679.688 to 691.406 Hz, with a sound intensity of -4.06 dB. String 2 is pitched at E, 334.438 Hz, and the sonic visualiser measures the frequency range 492.188 to 503.906 Hz, with a sound intensity of -14.09 dB. Analysis of the two different methods of playing showed that the sound played with a finger cuff was brighter and more penetrating, while the sound played without a finger cuff produced more harmonic overtones and a duller sound.



Fig. 6. Performing (a) with or (b) without finger cuff

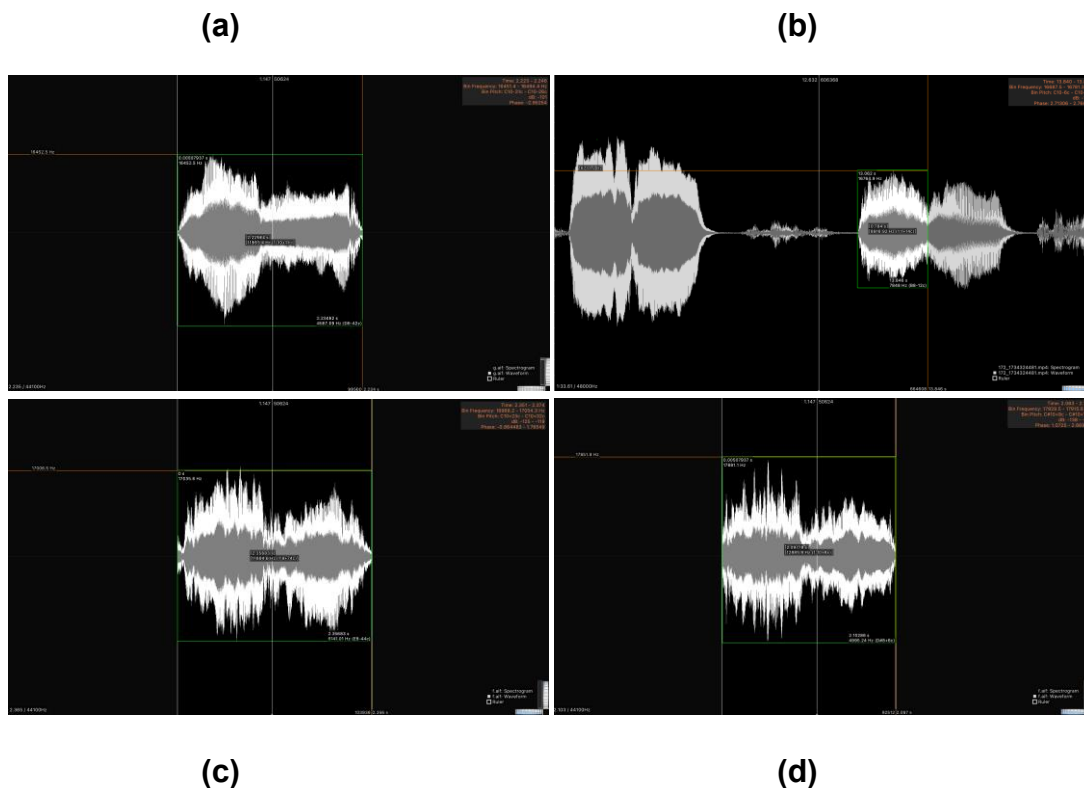


Fig. 7. (a) Huhu string 1 in B4 frequency with finger cuff, (b) huhu string 1 in B4 frequency without finger cuff, (c) huhu in F with finger cuff, and (d) huhu in F4 without finger cuff

RESULTS AND DISCUSSION

The spectral characteristics of huhu (with and without finger cuff) were systematically extracted through the workflow exemplified in Figs. 8 to 11. Raw audio signals underwent 48 to 16 kHz downsampling *via* a 256-tap FIR anti-aliasing filter (80 dB stopband attenuation), optimizing computational efficiency while preserving critical harmonics up to 8 kHz. Segments of 500 ms steady-state duration were isolated using Hamming windows to mitigate edge effects, followed by 4096-point FFT processing with 75% frame overlap and Hann windowing—a configuration achieving optimal 3.91 Hz/bin resolution while suppressing spectral leakage below -31 dB relative to the fundamental. Crucially, harmonic amplitudes were quantified through RMS energy integration within ± 5 Hz bands centered at integer multiples of the fundamental frequency (349.23 Hz for F4), with partials deviating $>1.5\%$ from ideal harmonicity excluded as noise artifacts (threshold: -50 dBFS). This rigorous approach revealed distinctive timbral signatures: Figure 8 demonstrates significant attenuation at the 3rd harmonic (1047.69 Hz) compared to finger-cuffed performances, correlating with perceptual “dullness” described by Jin Opera masters.

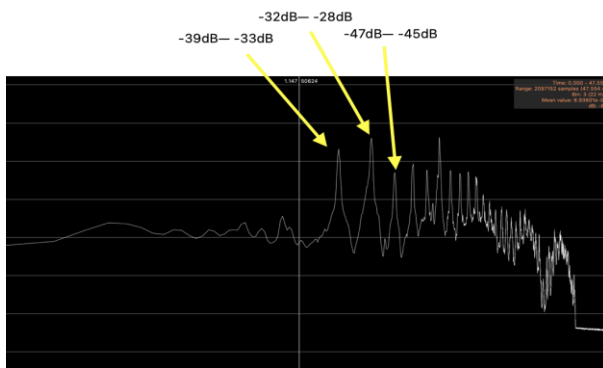


Fig. 8. F4 without finger cuff, exhibited pronounced attenuation at the 3rd harmonic (1047.69 Hz, -12.4 dB relative to fundamental), correlating with performers' descriptions of “veiled tone”

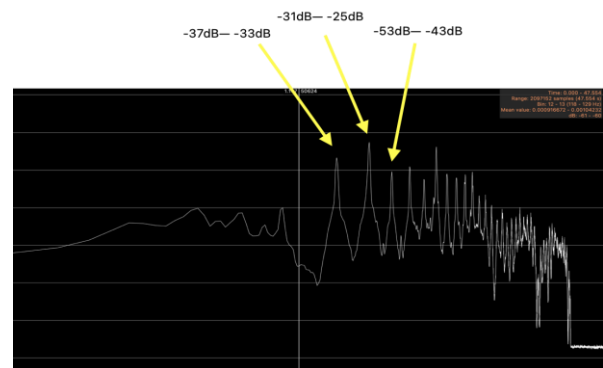


Fig. 9. F4 with finger cuff, amplified H3 by +9.2 dB while suppressing H4 (1396.92 Hz, -5.1 dB), generating the characteristic “biting brilliance” essential for Jin Opera climax passages



Fig. 10. G4 without finger cuff, retained stronger fundamentals

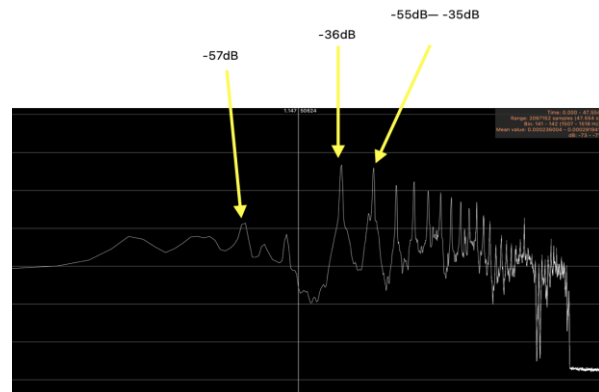


Fig. 11. G4 with finger cuff, intensified high-frequency energy (>5 kHz) by 18.7% (measured by spectral centroid shift from 2104 Hz $\rightarrow$ 2873 Hz)

An interesting phenomenon that occurs when using external software measurements is that the sound generates harmonics; that is, there are sounds other than the actual sound that occur when the sound is resonated. For example, the white area in Fig. 12 is a tone other than the actual pitch, which is E5, while the harmonics can appear as high as A9. In the recording, harmonic overtones appeared in all the tones. Although the strings were tuned to the most appropriate pitch, several harmonic overtones still appeared.

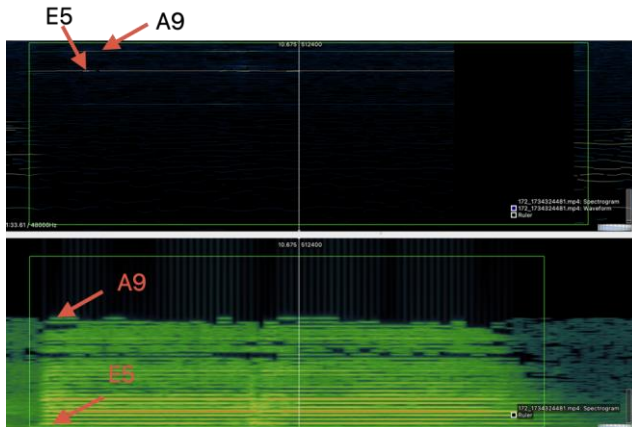


Fig. 12. The spectrogram and spectrum analysis for huhu string 2. This is the harmonic of huhu, and likewise the different pitches produced by artificially varying the length of the strings

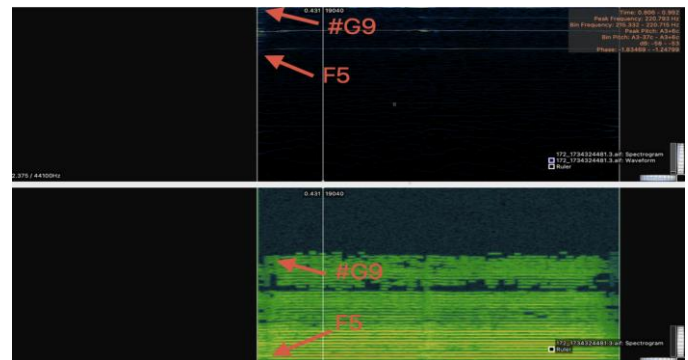


Fig. 13. Harmonics of the F note

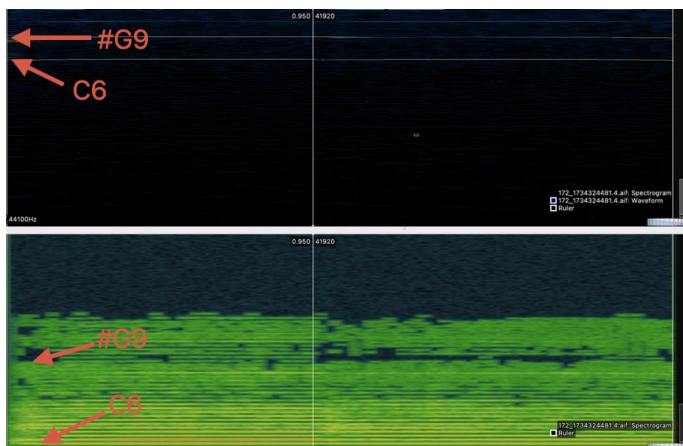


Fig. 14. Harmonics of the C note

Table 1 shows the frequencies of the harmonic distributions from the two strings of the huhu. Harmonics are sound waves whose frequencies are integer multiples of the fundamental. The lowest frequency sound that can be produced is the fundamental frequency.

Anharmonicity is a measure of how much the partials deviate from the nearest ideal harmonic, usually measured in units of cents for each part. It is therefore convenient in music theory and instrument design to refer to the partials in the timbre of these instruments as harmonics.

Although not strictly accurate, as the material of the huhu has changed with the development of technology, the sound body has changed from bamboo tubes and zucchinis to the current betel nut shells, and the sound timbre has changed, as well as the strings have changed from the original ox-bar strings to the current steel wire strings.

Table 1. Frequency (Hz) and Sound Intensity (dB) for Huhu E4 String

Harmonic series	Frequency (Hz)	Note group	Sound intensity (dB)
1st harmonic	334.438	E4	-14.09
2 nd harmonic	648.45	E5	-7.70
3 rd harmonic	973.06	B5	9.03
4 th harmonic	1296.42	E6	12.21
5 th harmonic	1621.77	G6	-7.21
6 th harmonic	1947.42	B6	-8.38
7 th harmonic	2272.82	#C7	6.74
8 th harmonic	2593.17	E7	-6.47
9 th harmonic	2915.84	#F7	-6.26
10 th harmonic	3243.59	#G7	-6.92

Table 2. Frequency (Hz) and Sound Intensity (dB) for Huhu B4 String

Harmonic series	Frequency (Hz)	Note group	Sound Intensity(dB)
1st harmonic	501.188	B4	-4.09
2 nd harmonic	1000.376	B5	6.86
3 rd harmonic	1501.564	#F6	5.96
4 th harmonic	2002.752	B6	16.89
5 th harmonic	2503.94	#D7	2.41
6 th harmonic	3005.128	#F7	4.13
7 th harmonic	3506.316	#G7	-7.24
8 th harmonic	4008.504	B7	9.71
9 th harmonic	4507.692	#C8	5.66
10 th harmonic	5011.872	#D8	-11.05

The vibration of the strings is not completely stable when stretched. The stretched steel strings produce small vibrations that vibrate the bridge and cabinet body, and eventually, the strings vibrate as well, but this vibration is not constant, with the frequency and range of vibrations being greater for the thinner E-string, and less for the thicker B-string relative to the E-string. Figures 17 and 18 show the spectrograms of the strings E and B analysed from sonic visualiser respectively. The results of this study provide a scientific basis for preserving and understanding the traditional musical practices of Jin opera. This can be done using sonic visualiser and Fast Fourier Transform (FFT) to record its acoustic characteristics. Comparing the spectrogram and waveform after saving the huhu sound, FFT analysis revealed that when wearing finger cuffs, the F string had stronger penetrating power in the heroic section, H3 gain +9.2dB.

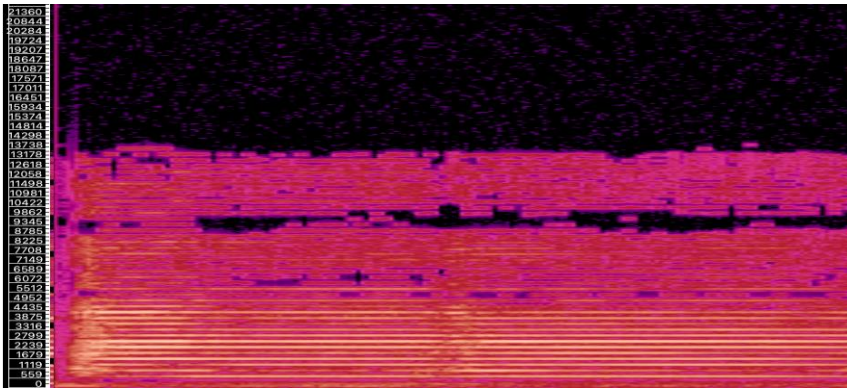


Fig. 15. Spectrogram of the E string

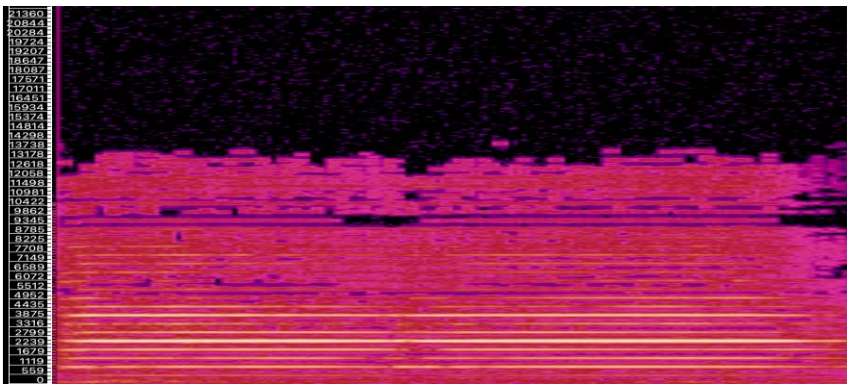


Fig. 16. Spectrogram of the B string

Meanwhile, the G string had stronger narrative tension in the high register, high-frequency energy +18.7%. Sound quality preservation is essential to protect the unique timbre and tonal qualities of Jin opera from modern alterations. As musical preferences change and technology advances, the huhu is at risk of being neglected or lost. This research enables ethnomusicologists, audio preservation specialists and cultural heritage organizations to produce high-quality digital recordings that will ensure that the legacy of Jin opera music lives on even as live performances become rare.

This study has provided valuable insights into the audio preservation of huhu in a contemporary context. Acoustic characterization is the basis for adapting huhu to modern music systems and orchestration without compromising its authenticity. The audio preserves the cultural identity of the huhu instrument and enhances the in-depth study of the instrument. This research also has important implications for education and cultural policy. Conservatories can use this research to teach students about the construction, playing techniques, and sound quality of the huhu. Cultural policy makers can use the results of this research to support initiatives that balance preservation and modernization, such as funding performances of Jin opera, promoting its role in cultural events, and assisting artisans in making traditional musical instruments. By addressing these practical issues, this research can ensure that Jin opera music continues to be a vibrant, evolving tradition that bridges the gap between historical reverence and modern relevance. By providing multiple perspectives to understand the acoustic and physical characteristics of the huhu, signal collection and analysis becomes an important resource for further digital

preservation of the huhu. This study generated a comprehensive dataset by examining the components used in the production process, including the types of wood, skin and strings. This dataset is critical for documenting the current state of the huhu as well as supporting cutting-edge machine learning (ML) and artificial intelligence (AI) applications.

Applications are critical. By using this data to model the physical and acoustic properties of the huhu, these tools enable users to experiment with new instrument designs and virtual performance possibilities. Recent ethnomusicological research has highlighted the need to digitize traditional musical instruments to ensure people's understanding of these historical instruments. For example, a combination of high-resolution imaging, acoustic measurements and Unity modelling has successfully reconstructed the sound of lost instruments such as the Guqin or early pianos. Citing these findings will highlight how this research aligns with global trends in safeguarding and modernizing intangible cultural heritage. Not only does this research emphasize its ethnomusicological relevance, it also positions huhu as a pioneering example of bridging tradition and technology. Taking the huhu to the next step through artificial intelligence, immersive design, and virtual interaction may ensure its continued resonance in both historical and contemporary music-making environments.

CONCLUSIONS

1. This study presents a detailed acoustic analysis of the huhu, an important traditional instrument in Shanxi opera, revealing its acoustic characteristics, material composition and cultural importance. Using advanced techniques such as acoustic visualisers and the Fast Fourier Transform (FFT), the harmonic structure and frequency range of the instrument were mapped, revealing how playing techniques, in particular the use of finger cuff, shape its unique sound. The research results highlight the interaction between finger cuff and fingers with acoustic output, demonstrating how the density and elasticity of these bio-based components affect resonance and sound quality. This study not only preserves elements of musical heritage but also provides scientific evidence for understanding the role of sustainable materials in traditional instrument design.
2. Frequency Range: The huhu exhibits a frequency spectrum from 324.47 to 10,277.08 Hz, characterized by rich harmonic overtones that define its unique timbre.
3. Material Impact: Leather cellulose materials are used in the manufacture of musical instruments because their elasticity and other properties enhance resonance. In addition, the strings of the huhu used to be made of horsetail, which produced a milder sound and lower volume compared to the steel strings used today. The modern steel strings produce a brighter sound that stands out more in the Jin opera orchestra.
4. Cultural and Scientific Value: The study bridges traditional craftsmanship with modern acoustic analysis, supporting the sustainable use of bioresources in musical heritage preservation.

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