Proceedings of CONF-CIAP 2026 Symposium: International Conference on Atomic Magnetometer and Applications
DOI: 10.54254/2753-8818/2026.HZ29758

Physical Modeling Synthesis Development for the Morin Khuur

Yijun Zhu[1*], Sijia Yan[2], Muyuan Zhang[3], Jiale Liang[4]

[1]*Mercersburg Academy, Mercersburg, USA*
[2]*Basis International School Park Lane Harbour, Huizhou, China*
[3]*Jericho High School, Jericho, USA*
[4]*HD Shanghai School, Shanghai, China*
**Corresponding Author. Email: tz3.0@outlook.com*

Abstract. Morin khuur, an old Mongolian bowed string instrument and emblem of rich cultural heritage, with its own distinct timbre, is at risk of being lost to oblivion due to its lack of representation in digital music technology. To counteract this, this study applies physical modeling synthesis to produce a digital version of the instrument that retains its physical features. With a model of the cello in their hands, fundamental parameters and settings are systematically varied to replicate the unique materials, performance, and acoustics of the morin khuur. This piece accounts for specific changes made and follows the process of adapting a Western-biased model to better account for a regional instrument, advancing both its preservation and access in the modern age.

Keywords: morin khuur, physical modeling, spectrum analysis, stereo

1. Introduction

1.1. Background

Humans have been working to digitize sound production for decades. Earlier methods, such as sampling synthesis, relied on stored samples of acoustic instruments, but newer technologies, such as physical modeling synthesis (PMS), offer much greater freedom and responsiveness. PMS achieves this by using mathematical algorithms to simulate not only the surface-level sound of real instruments but also their underlying physical actions—the vibrations of strings and resonances of wooden bodies, the passage of air through woodwinds, or hammering on percussion. This higher level of imitation allows subtle control: an artist can manipulate parameters such as string tension, bow pressure, or brass tube thickness during performance, creating sounds that develop organically in response to performance movements, far beyond the rigid limitations of pre-recorded samples. This essay examines PMS, the core technology of digital music production that not only captures the sound but also the process of the tonal output itself.

Most music technology emphasizes internationally renowned instruments like violins or pianos, often at the expense of regional ones. The morin khuur, a traditional Mongolian instrument, faces this threat due to urbanization and cultural change [1]. By digitally modeling its unique string

DOI: 10.54254/2753-8818/2026.HZ29758

vibrato, bow behaviors, and resonant body characteristics through PMS, we can preserve its authentic sound and share its heritage worldwide. This paper details the creation of a PMS-based morin khuur synthesizer, helping keep its cultural legacy alive in the digital age.

Figure 1. The morin khuur

The morin khuur, or "horsehead fiddle," is a traditional Mongolian bowed string instrument that holds deep cultural meaning as a symbol of nomadic heritage. Its design includes: (1) a trapezoidal soundbox (usually 18 cm for the upper base, 28 cm for the lower base, 35 cm tall, with a 7 cm shell thickness) covered with animal skin (often horse or goat) with f-holes, (2) two horsetail hair strings (50–60 cm long), and (3) a neck without a fingerboard. The strings are played with a horsehair bow, with performers adjusting string tension during play to control the brightness of the sound. While sharing some basic features with Western bowed string instruments, the morin khuur's unique structural traits give it a distinctive timbre, making physical modeling synthesis challenging.

1.2. Literature review

Extensive research has been conducted on the physical modeling of various string instruments, such as violins and cellos. By examining the physical properties of these instruments—such as shape, material characteristics, and vibration modes—researchers can develop mathematical models that simulate their behavior [2]. Due to the complexity of real instruments, simplifications and assumptions are often made to reduce computational demands and enable real-time synthesis. New instrument models can be created by adapting existing models of studied instruments. Luan et al. conducted a physical modeling study of the dizi, a traditional Chinese flute, by considering its unique features compared to the Western flute, such as the dimo membrane. The team developed and modified a physical model of the dizi, enabling more accurate sound generation [3].

The most important part of a string instrument is the string itself. Morse and Ingard modeled an ideal, infinite string based on transverse displacement, with position along the instrument, time, tension, and mass per unit length as parameters. To account for losses and dispersion found in real strings, additional terms can be added [4]. The shape of the wooden body also influences the string's motion and the resulting sound. For bowed string instruments, which require a bow to play, two main factors to consider when determining the produced sounds are the frictional forces between the bow and string and the transverse velocity of the contact point on the string. These factors and their interaction significantly influence the physical model of the instrument [5].

Building on prior physical modeling work for the dizi, we developed a similar approach to create the morin khuur's timbre through parametric adaptation of an existing cello model. The synthesis

DOI: 10.54254/2753-8818/2026.HZ29758

platform used is Sculpture, a physical modeling synthesizer in Logic Pro (Apple's digital audio workstation for macOS), which enables parameter modification for timbral design. The Solo Cello model in Sculpture accurately simulates cello acoustics, serving as our baseline. Our objective is to derive a parameter set that transforms this cello model into a morin khuur timbre through several adjustments, as discussed in the following parts.

2. Method

2.1. Choosing the cello as base model

The cello was chosen as the initial baseline for the morin khuur because of its timbre, technique, ergonomics, and practicality for modeling.

First, both instruments share a resonant mid-range frequency timbre, with the cello having greater low-frequency capability and the morin khuur having greater high-frequency capability. Both instruments resemble the human voice; the cello has historically been identified as the instrument most similar to the human voice [6], while the morin khuur often accompanies singers and occupies a similar range [7].

Second, both instruments share a similar playing style. They are stringed instruments played with a bow hair. The way they produce sound and techniques like vibrato, legato, and dynamics are all similar. Both are also fretless, allowing greater intonation and glissando freedom.

The morin khuur is placed between the player's knees and held almost upright. This position is very similar to the posture used for Baroque cellos. Although modern cellos have endpins, they still closely resemble the posture of the morin khuur, with the right hand on the bow and the left hand on the fingerboard.

Lastly, the morin khuur is a very regional instrument with little academic research on its digitization. Conversely, the cello is a widely popular classical instrument that has been extensively studied by researchers, leading to a more accurate baseline model. This makes the cello an ideal instrument to begin with for adjustments to suit the morin khuur.

The differences between the cello and the morin khuur are the aim of this paper.

2.2. Frequency range & tuning

The cello has four strings with pitches: C2, G2, D3, and A3. The morin khuur differs from this classical arrangement with strings of F2 and Bb2. Although the morin khuur is only a perfect fourth above the cello’s lowest string in traditional tuning, its timbre projects more clearly in the mid-range. In practice, we found that aligning it directly with the cello created a muddy overlap. Therefore, shifting it up by an octave in simulation better reflected its functional role as a brighter, higher-voiced partner. The traditional tuning of the morin khuur also differs from the classical A=440Hz standard. It is usually tuned to around A=437Hz [8]. This can be adjusted in the Tune settings, where the pitch is adjusted in the unit of cent.

2.3. Frequency spectrum – timbre

The timbre is what gives an instrument its unique sound. It is also an essential factor that helps people distinguish between a cello and a flute, even if both play the same note. The timbre is mainly shown in the spectrogram, a frequency–loudness diagram that displays the position and strength of the instrument’s harmonic signature.

DOI: 10.54254/2753-8818/2026.HZ29758

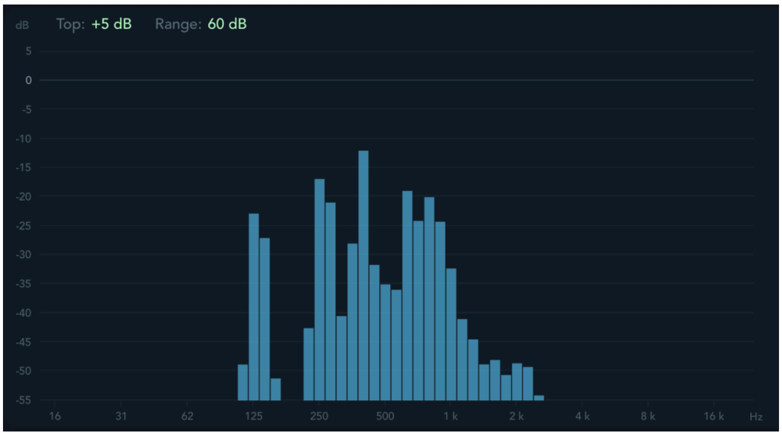

Figure 2. Spectrogram of cello

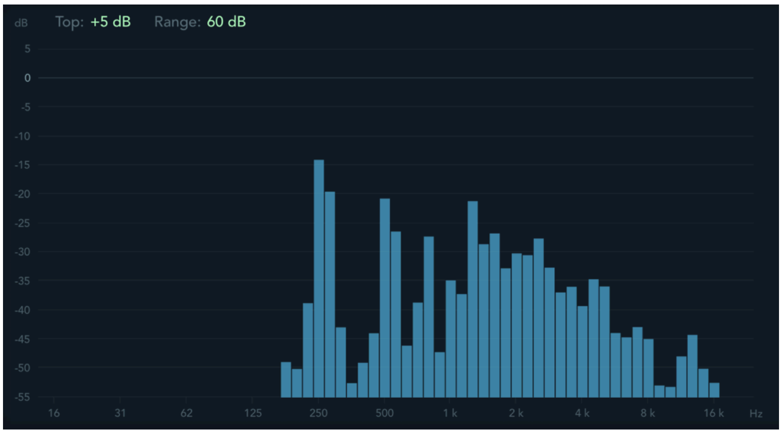

Figure 3. Spectrogram of morin khuur

Figure 1 and Figure 2 show the spectrograms of the cello model compared to the morin khuur sound sample. The cello's first three harmonic peaks gradually increase in intensity, followed by the next two around 600Hz and 800Hz with slightly decreased intensities, then decline significantly. For the morin khuur, the strongest harmonic is at 250Hz, followed by 500Hz, 800Hz, and 1400Hz, with similar intensities, then gradually diminish. It also has a smaller peak at around 14kHz. The higher frequencies of the morin khuur contribute to its raspier tone compared to the smooth tone of the cello. These two patterns represent the harmonic signatures of the instruments and are what make each instrument recognizable.

Our goal is to modify the spectrum pattern of the cello using bow settings, equalization, and filter adjustments to create a shape similar to the morin khuur.

2.4. Envelope – attack & release

An ADSR envelope modulates sound by controlling how quickly the amplitude changes. The attack parameter determines how long it takes for the sound to reach its maximum amplitude, while the release parameter determines how long it takes for the sound to go from the sustained level to zero amplitude.

The morin khuur's strings are lighter and shorter than the cello's strings, around 60 cm for the morin khuur to 70 cm for the cello from nut to bridge. The attack time is directly proportional to

DOI: 10.54254/2753-8818/2026.HZ29758

string length. This means the morin khuur can reach its maximum amplitude faster, resulting in a faster attack time than the cello.

Because the morin khuur's resonant chamber is smaller than the cello's, its sound would decay more quickly. Therefore, the release time should be decreased.

2.5. Additional features

While the cello offers a baseline for modeling the morin khuur due to its acoustic and technical similarities, it does not fully capture the traditional Mongol instrument's playing styles. Specifically, the cello model lacks microtonal inflection and spatial immediacy.

The morin khuur is well known for its extensive use of vibrato and glissando, which the basic model doesn't include. Because vibrato varies in amplitude and speed, the cello model doesn't simulate vibrato. To better replicate the morin khuur, vibrato needs to be added. This is achieved by adjusting the Vibrato settings in the sound design section of the model.

We also added stereo swinging to the physical models to introduce a spatial dimension that pure pitch and amplitude modulation cannot provide. The simulation mimics the slight left-right oscillation of sound waves as if the instrument itself were resonating in a physical space. This spatial movement enhances immersion, makes the tone feel more organic, and counters the often-criticized static quality of synthesized or physically modeled instruments. This effect is achieved by adjusting the Low Frequency Oscillator (LFO) settings for Pickup Panning and Delay.

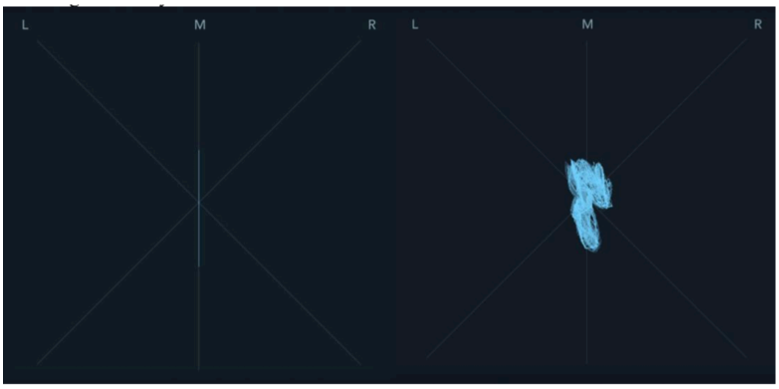

Figure 4. Goniometer of the cello model (left) vs morin khuur sample (right)

Together, these enhancements elevate this model beyond just simulating an instrument's acoustic pattern. They offer users a more effective platform for performance and integration with other User Interfaces.

2.6. Jitter

Jitter simulates the randomness of playing a real instrument to make the sound less synthetic. Jitter on sculpture has three parameters: rate, target, and amount. The rate parameter controls the speed of the modulation signal, influencing how quickly the target changes. A higher rate causes faster changes, making the noise brighter and adding a shimmer to the sound—conversely, a lower rate results in slower changes and wobblier sounds. The target indicates which parameter will have the random fluctuations. At the same time, the amount determines the extent to which the target parameter deviates from the base—a higher amount results in a larger offset. If the amount is too

DOI: 10.54254/2753-8818/2026.HZ29758

low, the sound remains stable and less realistic. The cello base model does not have jitter enabled. To produce more realistic sounds, jitter needs to be added.

3. Experiment

3.1. Octave adjustment & tuning

Transpose: -1oct to None

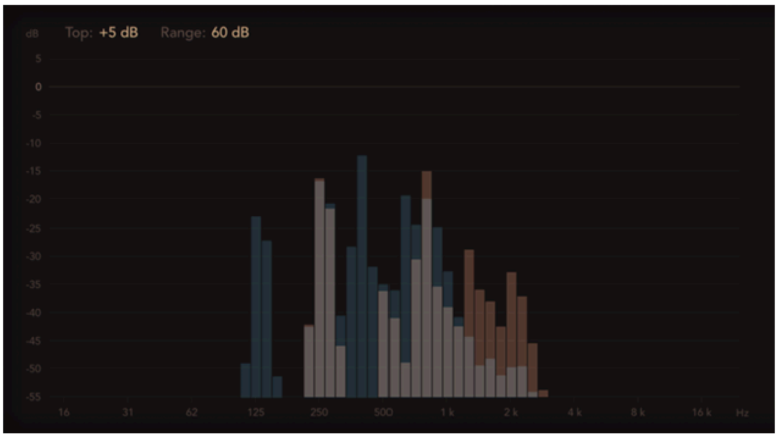

Figure 5. Blue (-1oct) vs red (none)

The cello's original first harmonic is at 125Hz; after the adjustment, it shifts to 250Hz, which is precisely where the morin khuur's first harmonic is located.

Tune: 0cent to -10cent

This fine-tuning adjustment has been modified and tested with a tuner. The morin khuur sample's C4 measured 260Hz, while the cello measured 261.6Hz. After a 10-cent reduction, the cello model reaches C4 at 260Hz, matching the morin khuur tuning.

3.2. Frequency spectrum

3.2.1. Frequency stabilization

LFO1: Off

While trying to match the spectrum of the morin khuur, we found a built-in flaw in the cello model that has been affecting the results. We noticed that specific harmonics of the cello are constantly fluctuating regularly.

DOI: 10.54254/2753-8818/2026.HZ29758

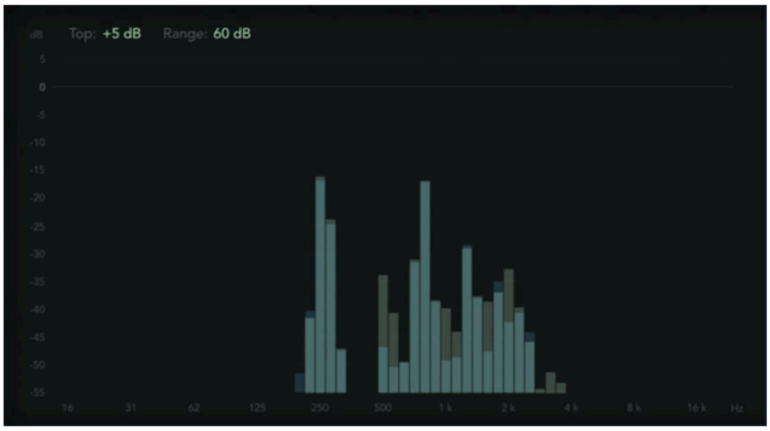

Figure 6. Blue (state 1 – low point) vs green (state 2 – high point)

From the overlaid figure 4, the spectral strength changes significantly from State 1 to State 2, even though the settings remain the same, particularly at the harmonics at 500Hz, 1kHz, and 2kHz, which show notable oscillation. After many debugging attempts, we found the cause to be an LFO controlling the position of sound Pickup A. When this LFO is off, the sound remains steady at State 2.

3.2.2. Bow object – object 1

Strength: 0.5 to 0.55

Position: 0.44 to 0.48

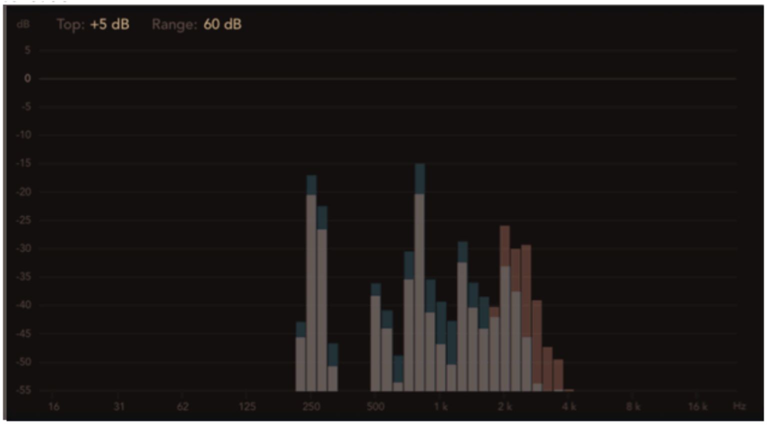

Figure 7. Blue (before) vs red (after)

The primary focus of the frequency spectrum adjustment was to add higher frequencies that were previously missing in the cello. For the morin khuur, the strength decreases almost linearly (according to this graph) from 2kHz to 16kHz. In contrast, the cello model drops off sharply at around 3kHz. By moving the object closer to the bridge, the higher parts of the spectrum were significantly strengthened, especially boosting the harmonic near 2kHz. This also introduced a raspiness that contrasts with the cello's smooth sound and the morin khuur's more distinctive sound. While the higher frequencies were amplified, the lower frequencies were slightly reduced. To compensate for this, bow pressure was increased somewhat to lessen the effect on the first harmonic's strength, which is very prominent in the morin khuur.

DOI: 10.54254/2753-8818/2026.HZ29758

Timbre: -0.31 to 0.17

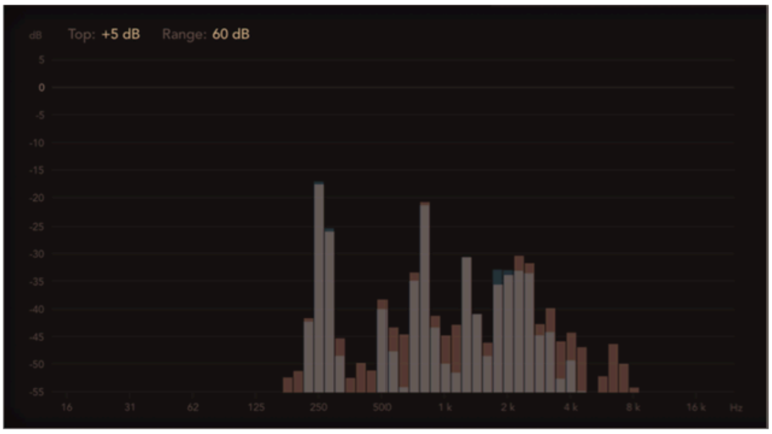

Figure 8. Blue (timbre -0.31) vs red (timbre 0.17)

With the higher frequencies slightly enhanced in the physical aspect, we still miss all higher frequencies entirely. While the morin khuur cuts off at 16kHz, it currently only contains frequencies up to 4kHz. The timbre slider on the bow object helps address this by adding slight static noise across all frequencies, though it is most pronounced in the mid-range and less so at the edges. The effects of this change are most noticeable from 200Hz to 8kHz, where the red bars in those sections are higher than the blue bars.

3.2.3. Body EQ

Lo: +0.56
Mid: -0.33 (Mid Frequency: 0.53)
Hi: +0.82

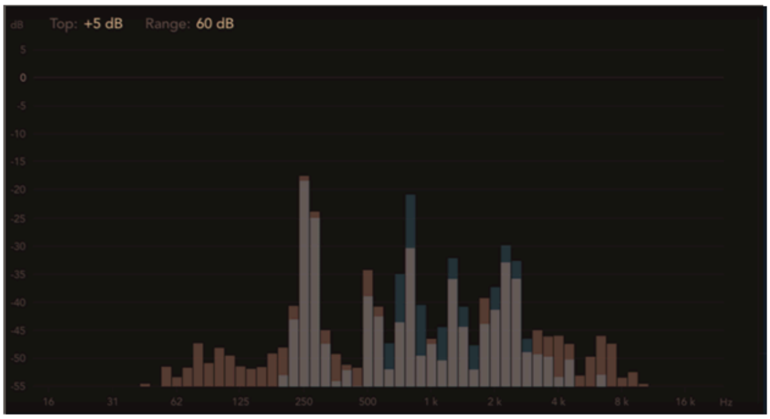

Figure 9. Blue (cello EQ) vs red (custom EQ)

In the previous timbre adjustment of the bow, static was added to the entire frequency spectrum, but the high and low ends weren't shown. Using equalization, we can boost or cut specific frequency ranges to better mimic the instrument's natural tendencies. The EQ tool has three bands: Low, Mid, and High, with an adjustable mid-range midpoint. The morin khuur has a very strong first harmonic followed by three almost equally strong second, third, and fourth harmonics. Previously, the second harmonic was too weak and the third harmonic was too strong.

DOI: 10.54254/2753-8818/2026.HZ29758

To address this issue, the low-range EQ is boosted to enhance the first and second harmonics. The mid-range EQ is cut to diminish the second, third, and fourth harmonics. Finally, the high-range EQ is significantly boosted to add the higher frequencies needed for the sound.

3.2.4. Filter

Filter Type: HiPass

Cutoff: 0.35

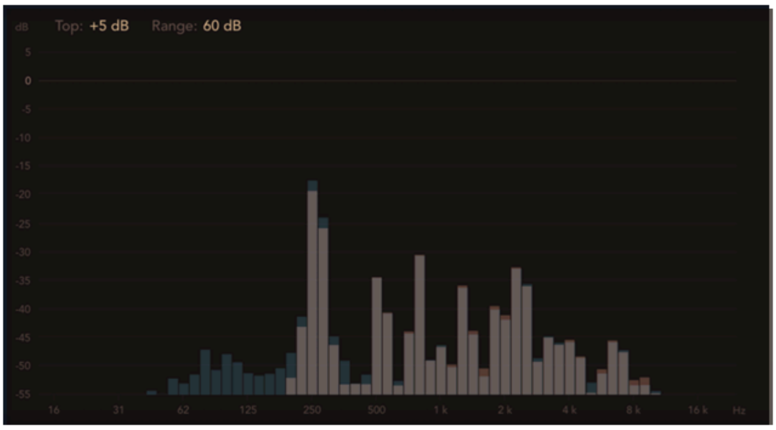

Figure 10. Blue (without filter) vs red (with hipass filter)

Due to the limited bands of the EQ tool, we have some unwanted low-frequency signals below 200Hz. Acoustically, it made the sound of our model too thick for the morin khuur. To remove those low frequencies, a filter can be used.

There are various filter types available, but since we aim to cut frequencies below a certain threshold, a high-pass filter should be used. This is also a pass filter explicitly designed for modeling. While a typical filter remains stable and cuts all signals below a specific point, this filter moves with the pitch of the sound, adjusting its threshold to match the note. In Figure 9, it is clear that the frequencies below 200Hz are eliminated. However, some signal strength is also reduced from the first harmonic. This is an unintended effect caused by the physics of electrical components. A filter has a roll-off and does not cut frequencies instantly. That is why frequencies near the threshold are also affected by the cut.

3.3. Performance effects

3.3.1. Vibrato

Rate: 6Hz to 4.70Hz

Omt: 0 to 0.14

The cello model did not have vibrato enabled, as indicated by the omt (amount) setting, which is 0. It also had a default setting of 6Hz, placing it at the upper limit of vibrato. Calculations are performed by analyzing the sample of the morin khuur using Equation (1):

$$f = \frac{O_b T}{60 B_b} \tag{1}$$

DOI: 10.54254/2753-8818/2026.HZ29758

f : oscillations per second (Hz)
O_b : oscillations per bar
T : tempo (beats per minute)
B_b : beats per bar

For the morin khuur sound sample, an O_b of 9.5 oscillations/bar is counted. Tempo and beats per bar are default settings of 120bpm and 4 beats/bar. 60 is a constant conversion factor from minutes to seconds.

$$f = \frac{9.5 \bullet 120}{60 \bullet 4} = 4.75Hz$$

With that result, we selected the closest available option of 4.70Hz as the vibrato frequency.

3.3.2. LFO2

Rate: 0.05Hz to 4.7Hz
1: Obj3Stren via Off to PickA Pan via Ctrl A
omt: 0.24 to 0.12
2: OFF to PickB Pan via Ctrl B
omt: 0.8

Figure 11. Blue (without panning) vs red (with panning)

The Low Frequency Oscillator (LFO) modulates values periodically at a very low frequency, usually to mimic natural, random changes of the instrument or surroundings. For this modeling, we aimed to add some spatial movement to our audio, so we adjusted the captured sound. Tuned to the same frequency, Pickup A and Pickup B pan left and right to form the elliptical pattern seen on the right of Figure 10.

3.3.3. Delay

Delay Time-10 ms (Free)
Feedback-20%
Wet Level-20%
X-Feed-30%
loCut-200hz

DOI: 10.54254/2753-8818/2026.HZ29758

HiCut-10 khz

GroovePad-

~spread-30%

The cello base model doesn't include stereo, so it produces mono sound. To improve this, we added a standard delay. This delay simulates the hearing difference between left and right channels and widens the sound. The feedback parameter adds a slight resonance and is kept low to prevent noticeable echoes. Additionally, loCut and HiCut are set to eliminate rumble and piercing noises, respectively.

3.4. Envelope

Attack: 260ms-730ms to 15ms-65ms

Release: 470ms to 160ms

The morin khuur has a shorter attack than the cello due to differences in its strings, which makes its sound sharper. To compensate, the attack parameter was lowered. Additionally, because it has a smaller resonating chamber than the cello, the morin khuur's release would also be shorter. It was reduced from 470ms to 160ms.

3.5. Human artistic beauty

Jitter

Jitter 1

Rate: 0.24Hz

1 PickA Pan - -0.14

2 PickB Pan – 0.11

The base cello model does not include jitter. To introduce random variations and make the sound less synthetic, jitter was added to modulate the instrument's recording locations. This adds variation to the captured sound, simulating the randomness found in real instruments.

Jitter 2

Rate: 0.51Hz

1 Obj2 Strength - 0.02

2 Obj1 Strength – 0.01

Variations in playing the string can occur. To account for this, we added jitter targeted to the object's strength. This simulates the variations in applied pressure when playing a real string instrument.

DOI: 10.54254/2753-8818/2026.HZ29758

3.6. Final comparison

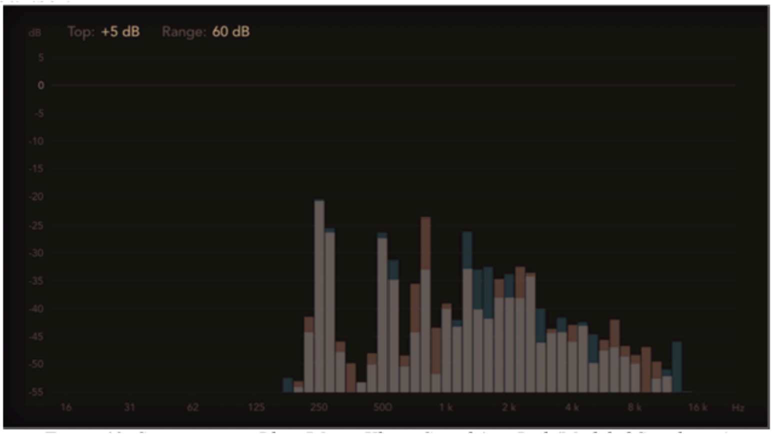

Figure 12. Spectrogram - blue (morin khuur sample) vs red (modeled simulation)

The spectrogram of the sound sample and simulation show many similarities, and trials with real humans confirm that the results are comparable. The low and high sound ranges are very well modeled. The mid-range is slightly lacking in nuance. Frequencies from 600Hz to 1kHz are too prominent, while those from 1.5kHz to 2kHz are too weak. Overall, however, the spectrum aligns well enough to produce a recognizable sound.

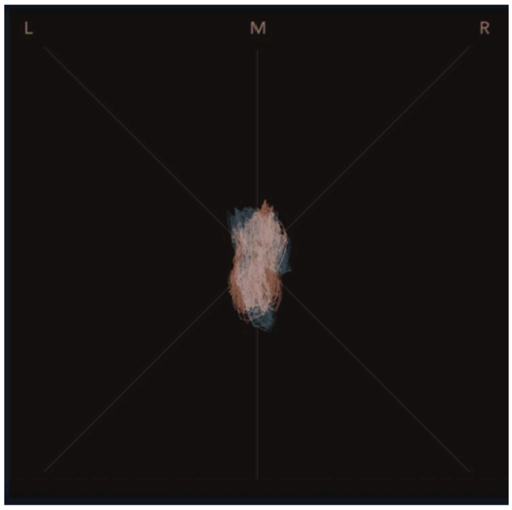

Figure 13. Goniometer - blue (morin khuur sample) vs red (modeled simulation)

We also achieved a good simulation of the stereo effects of the morin khuur sample. Even though the visual shape on the goniometer is slightly different, the swing width and the front and back settings are accurate.

4. Discussion

4.1. Application

Creating a physical modeling synthesizer for the Morin khuur is essential for promoting and preserving traditional music. Even though fewer people are learning to play this traditional

DOI: 10.54254/2753-8818/2026.HZ29758

Mongolian instrument, we are developing a digital version so its unique sound can live on for future generations. Through its digital form, the morin khuur can now be integrated into modern music compositions by musicians and composers worldwide. Other instruments, especially those native to China and East Asia, such as the erhu or guzheng, could also benefit from this technology. Digitizing such instruments helps preserve their cultural identity and introduces them to new markets. Additionally, the synthesizer can be combined with modern music interfaces, such as virtual reality gear or MIDI controllers, to enable innovative performances that blend technology with tradition.

4.2. Limitations & future

Although the Morin khuur was modeled in this project, the current method has limitations. First, the instrument's high-frequency nuances were not precisely replicated by the synthesizer's EQ controls. Second, we only had time to refine this simulation to a single sound source, rather than comparing it to many Morin Khuurs, making it difficult to accurately compare and further develop the model. Future improvements could involve selecting a better base instrument that more closely resembles the Morin khuur and adjusting the harmonics with more advanced EQ software. The model's accuracy would also benefit from working with traditional players to produce high-quality samples. These advancements would lead to even more realistic computer simulations of the Morin khuur and other conventional instruments.

5. Conclusion

Through testing and experimentation, we developed a synthesizer that replicates the unique sound of the morin khuur. This was achieved by modifying the frequency range, tuning the timbre, and simulating playing effects such as vibrato. Although challenges such as parasitic resonance and tuning inconsistency occurred, the complete model manages to preserve the instrument's tone. This project demonstrates the potential of physical modeling synthesis to preserve local music heritage without hindering new artistic applications. By digitizing instruments like the morin khuur, we keep them alive in our modern era. The techniques outlined here also provide a foundation for future research, aimed at achieving greater realism or integrating these sounds into new musical systems. Ultimately, this unites tradition and technology in a circle, offering new ways to listen to and experience cultural heritage.

References

[1] "UNESCO - Traditional Music of the Morin Khuur, " ich.unesco.org. https: //ich.unesco.org/en/RL/traditional-music-of-the-morin-khuur-00068
[2] S. Bilbao et al., "Physical Modeling, Algorithms, and Sound Synthesis: The NESS Project, " Computer Music Journal, vol. 43, no. 2–3, pp. 15–30, 2019, doi: https: //doi.org/10.1162/comj_a_00516.
[3] X. Luan, G. Scavone, S. Wang, and Z. Li, "Exploring the Acoustics of the Chinese Transverse Flute (dizi), " Arxiv.org, Sep. 07, 2024. https: //arxiv.org/html/2409.04853v1 (accessed Aug. 20, 2025).
[4] B. Bank, M. Advisor, and L. Sujbert, "Physics-based Sound Synthesis of Stringed Instruments Including Geometric Nonlinearities Original Contributions of the Ph.D. Thesis, " 2006. Accessed: Aug. 20, 2025. [Online]. Available: https: //home.mit.bme.hu/~bank/phd/tbooklet.pdf
[5] J. Woodhouse, "Physical Modeling of Bowed Strings, " Computer Music Journal, vol. 16, no. 4, pp. 43–43, Jan. 1992, doi: https: //doi.org/10.2307/3680468.
[6] M. Segado, A. Hollinger, J. Thibodeau, V. Penhune, and R. J. Zatorre, "Partially Overlapping Brain Networks for Singing and Cello Playing, " Frontiers in Neuroscience, vol. 12, May 2018, doi: https: //doi.org/10.3389/fnins.2018.00351.

DOI: 10.54254/2753-8818/2026.HZ29758

[7] “Mongolian national musical instrument - Morin khuur, ” MONTSAME News Agency, 2016. https: //montsame.mn/en/read/127341?utm_source (accessed Aug. 17, 2025).
[8] S. Morel, “Into the Morin Huur - #002 - Position, Tuning and Advice (with EN, FR, MN subtitles), ” Youtube.com, May 15, 2020. https: //www.youtube.com/watch?v=_j2VcJa46ZA (accessed Aug. 17, 2025).