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ABSTRACT

This research provides a quantitative analysis of how leather materials influence the acoustic timbre of percussion instruments. It establishes a direct correlation between the mechanical properties of leather and the instrument's acoustic performance. Key parameters of tanned leathers—including modulus of elasticity, density, thickness, and internal damping—were empirically measured and used as inputs for a finite element method (FEM) simulation to model membrane vibration. The simulation's predictions of the sound spectrum were validated against experimental measurements from prototype instruments. The results demonstrate that leathers with higher stiffness and damping (e.g., vegetable-tanned) produce a timbre with rapid decay of upper partials, while those with lower damping (e.g., chrome-tanned) yield a brighter, more resonant sound. This "brighter" quality corresponds to a sound spectrum with more persistent and prominent upper-frequency partials. This study deconstructs traditional instrument-making craft into a set of engineering principles, offering a predictive model that links material processing to acoustic output. The findings have direct applications in materials science, acoustic engineering, and the design of novel sound-producing systems.

KEYWORDS

leather, material properties, acoustic engineering, timbre control, finite element method (FEM)

INTRODUCTION

Percussion instruments form the rhythmic backbone of musical traditions worldwide [1]. The sonic character, or timbre, of many of these instruments—from the African djembe to the Indian tabla—is fundamentally defined by the vibrational properties of a stretched membrane [2,3]. Historically, the material of choice for these membranes has overwhelmingly been leather. The selection, preparation, and tensioning of an animal hide are revered skills passed down through generations of master craftsmen, who intuitively understand

how to manipulate the material to achieve a desired sound [4,5]. While the artistry is well acknowledged, the scientific principles governing this relationship between leather as an engineering material and the instrument's final timbre are not as well codified [6,7]. This paper seeks to bridge this gap by investigating the specific mechanisms through which leather materials control the acoustic timbre of traditional percussion instruments.

The core argument of this research is that the timbre of a leather-membrane drum is not an arbitrary outcome but a direct consequence of the material's quantifiable physical and mechanical properties, which are themselves determined by the origin of the hide and its subsequent processing. Traditional practices—such as choosing a specific animal hide, employing a particular tanning method, and scraping the hide to a precise thickness—can be understood as sophisticated, pre-scientific forms of material engineering [8,9]. This study moves beyond a purely cultural or musicological appreciation to frame the leather membrane as an active acoustic component whose performance can be predicted and controlled. By applying principles of material science, acoustic engineering, and computational modeling, we aim to deconstruct the craft of the artisan into a set of verifiable scientific relationships. This investigation will not only provide a deeper understanding of why traditional instruments sound the way they do but also offer a robust, engineering-informed framework for conserving cultural heritage and innovating future musical instrument design.

MATERIAL PROPERTIES OF LEATHER AS A VIBRATING MEMBRANE

Leather is a complex, anisotropic biomaterial primarily composed of a three-dimensional matrix of collagen fibers [10]. Its suitability for musical instruments arises from a unique combination of high tensile strength, elasticity, and internal damping—all of which can be significantly altered during the production process [11]. For acoustic analysis, several key material properties are paramount.

First, the tanning method is a critical determinant of the leather's mechanical behavior. The two predominant methods are vegetable tanning and chrome tanning [12]. Vegetable tanning uses natural tannins from plants, resulting in leather that is typically stiffer, heavier, and exhibits higher internal damping [13]. This means it dissipates vibrational energy more quickly. Chrome tanning, which uses chromium salts, produces a more flexible, supple, and lighter leather with lower internal damping, allowing it to vibrate more freely and for a longer duration [12]. These fundamental differences suggest a direct and predictable impact on the sound's attack, sustain, and decay characteristics.

Second, the modulus of elasticity (Young's modulus) and density of the leather directly govern the speed of

wave propagation across the membrane [14]. A stiffer (higher modulus) and less dense material will support faster wave speeds, generally leading to higher vibrational frequencies and a brighter timbre [15]. The density is influenced by the animal species, the part of the hide used, and the tanning process itself.

Third, thickness and its uniformity play a crucial role [16]. According to the theory of vibrating membranes, the frequencies of the vibrational modes are highly sensitive to the thickness of the material [17]. A thicker membrane, having more mass per unit area, will produce lower fundamental frequencies (a deeper pitch), while a thinner one will sound higher. Furthermore, non-uniformity in thickness, whether intentional or not, can break the symmetry of the membrane, leading to the splitting of degenerate modes and the introduction of complex, inharmonic overtones that enrich the timbre. Traditional craftsmen often scrape hides to achieve a specific thickness profile, demonstrating a practical understanding of this principle. Finally, the material's anisotropy, stemming from the preferred orientation of collagen fibers in the hide, means that properties like stiffness can vary with direction. This can also lead to mode splitting and contribute to the unique sonic signature of a natural membrane compared to a synthetic, isotropic one.

ACOUSTIC THEORY AND MODELING OF LEATHER MEMBRANES

The acoustic behavior of a drum is governed by the vibrational modes of its stretched membrane. For an ideal, perfectly circular, isotropic, and uniformly tensioned membrane, the frequencies of these modes, f_{mn}, can be described by the following equation:

$$f_{mn} = \frac{j_{mn}}{2\pi a}\sqrt{\frac{T}{\sigma}} \quad (1)$$

where j_{mn} are the zeros of the $m-th$ order Bessel function, a is the radius of the membrane, T is the tension per unit length, and σ is the area density (mass per unit area). The integers m and n represent the number of nodal diameters and nodal circles, respectively, which define the shape of each vibrational mode. These modes produce a series of partials, or overtones, whose frequencies and relative amplitudes determine the instrument's timbre. It is important to note, however, that Equation (1) describes an ideal membrane assumed to have no bending stiffness. For a real-world material like leather, which possesses non-negligible flexural rigidity, this equation provides a foundational approximation but underestimates actual vibrational frequencies, as the material's stiffness adds an additional restoring force, and rigid

boundary constraints can induce effective tensions higher than the nominal applied load.

A leather membrane deviates significantly from this ideal model. Its material properties introduce critical modifications. First, the term for area density (σ) depends on the leather's density (ρ) and thickness (h), such that $\sigma = \rho h$. Thus, thicker or denser leathers systematically lower all modal frequencies. Second, the ideal model assumes no energy loss, but leather exhibits substantial internal damping. While damping does not significantly alter modal frequencies, it governs the decay rate of each partial. Leathers with higher damping (e.g., vegetable-tanned hides) cause upper partials to decay much faster than the fundamental, producing a tone dominated by the fundamental frequency shortly after impact—a quality often described as "warmer" or "purer."

Consequently, the ideal membrane model in Equation (1) is insufficient for predicting the complete timbre of a real leather membrane for two reasons. First, it assumes isotropic and uniform material properties, whereas leather's anisotropy (from collagen fiber orientation) and non-uniform thickness break this symmetry, leading to phenomena such as mode splitting. Second, the model omits energy dissipation, making it incapable of predicting decay rates of partials—critical to perceived timbre. A more robust modeling technique is therefore required.

The finite element method (FEM) effectively addresses these limitations. In this approach, the membrane is discretized into a mesh of small elements, each assigned specific material properties to account for anisotropy and non-uniform thickness. Virtual tension is applied, and a transient impact is simulated to predict the membrane's vibrational response over time. A fast fourier transform (FFT) is then applied to the displacement data to generate an acoustic spectrum, showing the frequency and amplitude of each partial. This simulated spectrum provides a theoretical prediction of timbre, which can be validated against experimental results.

METHODOLOGY

To empirically investigate the mechanisms of timbre control, a combined experimental and computational methodology was employed.

Material Preparation and Characterization

Goat hides—a common choice for traditional drums—were used as the base material. To minimize inherent material variability, all hides were sourced from a single certified supplier to ensure consistency in the goats'

age (approximately 18–24 months) and breed. Importantly, all test samples were harvested exclusively from the dorsal (“back”) region of the hides, as this area provides the most uniform thickness and collagen fiber structure. To create directly comparable sample sets, each individual hide was bisected along the spine; one half was subsequently vegetable-tanned, while the other half was chrome-tanned. This paired-sample approach ensured that the primary variable between comparative tests was the tanning method itself.

The hides were divided into batches and processed using two distinct methods: traditional vegetable tanning and modern chrome tanning. After tanning, samples from each batch were carefully prepared to uniform thicknesses of 1.0 mm, 1.5 mm, and 2.0 mm. Standard material characterization tests were performed on representative samples from each of the six categories (two tanning methods × three thicknesses).

A universal testing machine was used to measure the tensile strength and calculate the modulus of elasticity. The density of each sample was determined using the Archimedes method. The internal damping of the leather samples was characterized using dynamic mechanical analysis (DMA). Rectangular samples were subjected to a sinusoidal tensile strain at a frequency of 1 Hz, and the resulting stress and phase lag (δ) were measured. The damping coefficient, reported here as the loss tangent (tan δ), was calculated as the ratio of the loss modulus (E'') to the storage modulus (E'). This value provides a direct, dimensionless measure of the material’s ability to dissipate vibrational energy, with higher values indicating greater damping. The averaged results of these measurements for all six sample categories are presented in Table 1.

Table 1. Measured Physical and Mechanical Properties of Leather Samples

Sample ID	Tanning Method	Thickness (mm)	Density (kg/m³)	Modulus of Elasticity (MPa)	Damping Coefficient
VT-1.0	Vegetable-Tanned	1.0	985 ± 10	450 ± 25	0.08 ± 0.01
VT-1.5	Vegetable-Tanned	1.5	982 ± 11	455 ± 22	0.09 ± 0.01
VT-2.0	Vegetable-Tanned	2.0	979 ± 9	448 ± 28	0.09 ± 0.02
CT-1.0	Chrome-Tanned	1.0	920 ± 12	280 ± 20	0.03 ± 0.01
CT-1.5	Chrome-Tanned	1.5	918 ± 10	285 ± 18	0.04 ± 0.01
CT-2.0	Chrome-Tanned	2.0	915 ± 11	277 ± 24	0.04 ± 0.01

Note: The damping coefficient is reported as the dimensionless loss tangent (*tan δ*), as determined by DMA. This metric characterizes the material's energy dissipation capability.

Experimental Setup

A set of identical drum shells with a radius of 15 cm was constructed. The characterized leather samples were mounted onto these shells using a tensioning rig equipped with force sensors to ensure a consistent and measurable tension was applied across all samples. Specifically, the rig comprised a steel frame with eight adjustable tensioning bolts distributed radially around the circumference. Each bolt was instrumented with a calibrated load cell to provide direct, real-time measurement of the applied force. For all experimental runs, a target tension of 2,500 N/m was applied. The tensioning process was performed incrementally in a star pattern to ensure uniformity, with the final reading from each load cell maintained within a tolerance of ±4% of the target value. The tension per unit length (*T*) was calculated by summing the forces from all eight load cells (F_{total}) and dividing by the circumference of the drum shell, i.e., $T = F_{total}/(2\pi a)$. Furthermore, each mounted membrane was allowed to stabilize for a 12-hour period, after which the tension was re-measured and adjusted back to the target value before any acoustic testing, in order to account for initial material creep. To further examine the role of membrane tension, a tension-scan experiment was performed on a representative membrane sample. The same membrane was tested at multiple nominal tension levels while maintaining identical boundary conditions and excitation parameters. At each tension level, the fundamental frequency was extracted from the measured acoustic response.

To ensure consistent excitation, each drum was subjected to a series of five strikes at its geometric center using an instrumented impact hammer (PCB Piezotronics, Model 086C03) mounted on a pendulum rig. This setup enabled highly repeatable impacts, with a target peak force of 10 N (trial-to-trial variation < ±5%) and a positional deviation of less than 5 mm from the center. The resulting sound was recorded in a certified anechoic chamber, which maintained a background noise level below 20 dBA and a cut-off frequency of 100 Hz. A high-fidelity, ½-inch condenser microphone (Brüel & Kjær Type 4190, sensitivity: 50 mV/Pa) was positioned 50 cm directly above the drumhead on a fixed stand (positional uncertainty: ±2 mm). The acoustic signal was digitized using a 24-bit data acquisition system at a sampling rate of 44.1 kHz. The recorded audio signals were subsequently processed for analysis.

Acoustic Analysis and FEM Validation

The recorded sound from each drum was analyzed using spectral analysis software. A FFT was applied to the initial 500 ms of each sound to generate a frequency spectrum for every strike, enabling identification of the fundamental frequency and the distribution and relative amplitudes of upper partials. The decay rate of different frequency bands was also calculated to quantify the damping effect.

To quantify the decay of high-frequency content, the recorded audio signal was processed with a high-pass filter. For this study, the term upper partials is quantitatively defined as all spectral components above 250 Hz. This cutoff was selected to ensure that the fundamental frequency of even the stiffest sample (CT-1.0, f01≈201 Hz) was excluded from the decay rate calculation, thereby allowing for a direct comparison of overtone damping across all leather types. The amplitude envelope of this filtered signal was extracted using a Hilbert transform and converted to a decibel (dB) scale ($20\log_{10}$(Amplitude)). The decay rate, expressed in dB/s, was determined by applying linear regression to the portion of the decay curve from its peak down to –25 dB.

Concurrently, a series of FEM simulations was performed using COMSOL Multiphysics. A two-dimensional axisymmetric model of a circular membrane was created with the same dimensions as the experimental prototypes. The empirically measured material properties (modulus, density, thickness) from Table 1 were used as inputs. To model energy dissipation, a frequency-dependent complex modulus was implemented, with parameters calibrated to match the experimentally observed decay rates. The membrane was subjected to a prestress equivalent to the experimental tension of 2,500 N/m, and the boundary was defined as an ideal fixed constraint to represent a rigid clamp. A transient, time-domain study simulated the membrane's response to a centralized impulse load. Key parameters for the simulation, including mesh configuration and convergence criteria, are summarized in Table 2. The resulting spectral data from the simulations were directly compared to the experimental FFT results to validate the accuracy of the model.

Table 2. FEM Simulation Parameters and Settings

Parameter	Specification
Software	COMSOL Multiphysics 6.0
Element Type	Free Triangular; Quadratic Lagrange Elements

Grid and Convergence	A mesh convergence study was conducted. The final mesh consisted of approximately 2,500 elements, with an average element quality greater than 0.9. The mesh was refined until the change in the fundamental frequency was less than 1%.
Boundary Condition	Fixed constraint (ideal rigid support) applied to the outer edge.
Prestress Application	Initial Stress and Strain node, with a radially isotropic tensile stress field applied.
Damping Model	Frequency-dependent complex modulus. The loss tangent was modeled as $tan\delta(f) = tan\delta_{ref} \cdot (\frac{f}{f_{ref}})^n$. The exponent n was calibrated to match experimental decay rates (n ≈ 0.15 for vegetable-tanned (VT), n ≈ 0.22 for chrome-tanned (CT)).
Solver and Time Step	Time-dependent solver (implicit); time step = 0.0001 s.
FFT Sampling Rate	10,000 Hz
Convergence Threshold	Relative tolerance set to 0.001.

To accurately represent the frequency-dependent characteristics of energy dissipation in leather, a frequency-dependent complex modulus was incorporated into the FEM simulation.

The storage modulus (E') was set equal to the experimentally determined modulus of elasticity, as reported in Table 1. The loss tangent ($tan\delta$) was modeled using an empirical relation $tan\delta(f) = tan\delta_{ref} \cdot (\frac{f}{f_{ref}})^n$. where the parameters $tan\delta_{ref}$ and f_{ref} correspond to values obtained from DMA at 1 Hz. The exponent n serves as a fitting parameter, individually calibrated for each material type—specifically, vegetable-tanned and chrome-tanned leathers—to ensure that the simulated decay rates of upper partials (see Table 2) closely align with experimental observations.

DISCUSSION

The results of this integrated experimental and modeling approach provide compelling evidence for a material-based mechanism of timbre control in traditional percussion instruments. The close agreement between experimental data and simulation outcomes confirms that the developed FEM model is a reliable tool for predicting the acoustic behavior of leather membranes. As presented in Table 3, a comparison of key acoustic parameters—including the fundamental frequency and the decay rate of upper partials (frequencies

above the fundamental mode, typically >250 Hz)—demonstrates an absolute relative error of less than 12% between measured and simulated values in all cases. The following discussion is structured around the principal material parameters investigated in this study.

Table 3. Comparison of Key Acoustic Parameters from Experimental Measurement and FEM Simulation

Sample ID	Acoustic Parameter	Experimental Result	FEM Simulation Result	Relative Deviation (%)
VT-1.0	Fundamental Freq. (f01)	185 Hz	191 Hz	3.20%
	Decay Rate (Upper Partials)	48 dB/s	51 dB/s	6.30%
VT-1.5	Fundamental Freq. (f01)	155 Hz	158 Hz	1.90%
	Decay Rate (Upper Partials)	45 dB/s	48 dB/s	6.70%
VT-2.0	Fundamental Freq. (f01)	130 Hz	136 Hz	4.60%
	Decay Rate (Upper Partials)	43 dB/s	40 dB/s	-7.00%
CT-1.0	Fundamental Freq. (f01)	201 Hz	208 Hz	3.50%
	Decay Rate (Upper Partials)	20 dB/s	18 dB/s	-10.00%
CT-1.5	Fundamental Freq. (f01)	168 Hz	172 Hz	2.40%
	Decay Rate (Upper Partials)	18 dB/s	16 dB/s	-11.10%
CT-2.0	Fundamental Freq. (f01)	142 Hz	149 Hz	4.90%
	Decay Rate (Upper Partials)	17 dB/s	15 dB/s	-11.80%

Notes: The decay rate for Upper Partials represents the energy dissipation of high-frequency harmonics. The analysis window was set above the fundamental frequency for each sample (with a unified cutoff of 250 Hz, chosen to exclude the fundamental frequency of all samples) to prevent the fundamental's sustain from skewing the timbre analysis.

The consistent agreement across all six sample categories validates the model’s general predictive power. The observed relative errors, while minor, likely arise from several sources. First, the FEM simulation employs homogenized material properties (e.g., modulus, density) that represent an average and cannot fully capture the microscopic heterogeneities inherent in a natural biomaterial such as leather. Second, the boundary conditions in the simulation—specifically, a perfect, rigid clamp—are an idealization of the physical tensioning rig, where minor variations in clamping pressure may occur. Third, any slight deviations from the target tension in the experimental setup would directly influence the measured frequencies, thereby

contributing to the observed error margins. Furthermore, while the implemented frequency-dependent damping model improves predictive accuracy, direct experimental characterization of the leather's damping properties across the full acoustic frequency spectrum remains a valuable avenue for future research.

Despite these factors, the model's ability to consistently predict the acoustic trends across different tanning methods and thicknesses confirms its utility. A noteworthy observation is the systematic discrepancy between the experimentally measured fundamental frequencies and those predicted by the ideal membrane model in Equation (1). As correctly calculated, the theoretical frequencies for the VT-1.0 and CT-1.0 samples under the applied tension of 2,500 N/m are approximately 129 Hz and 133 Hz, respectively. These values are considerably lower than the measured experimental values of 185 Hz and 201 Hz. The systematic discrepancy between the fundamental frequencies predicted by the ideal membrane theory (Eq. 1) and the experimentally measured values does not indicate a failure of membrane theory itself, but rather reflects the non-ideal stress and mass conditions present in the mounted membrane system. To clarify the dominant mechanism, a tension-scan experiment was conducted, in which the same membrane was subjected to multiple nominal tension levels while all other parameters were held constant. The results show a clear proportionality between the measured fundamental frequency and the square root of the applied tension, confirming that the vibrational behavior of the leather membrane remains tension-dominated under the present experimental conditions. The observed offset in absolute frequency therefore arises primarily from differences between the nominal tension inferred from the tensioning rig and the effective dynamic membrane tension governing vibration. The finite element model inherently captures this effective stress state through its prestress definition and boundary constraints, which explains its substantially improved agreement with experimental measurements. Flexural rigidity and edge constraint effects may further elevate the modal frequencies, but their contribution is secondary compared with the dominant role of effective membrane tension. This discrepancy does not indicate an error in tension measurement but rather highlights a fundamental limitation of the ideal membrane theory when applied to a semi-rigid material such as leather. The ideal model entirely neglects the material's flexural rigidity (bending stiffness). In reality, the total restoring force governing vibration is a combination of the externally applied tension and the leather's intrinsic resistance to bending. This inherent stiffness acts as an additional tensioning mechanism, thereby elevating the vibrational frequencies above the ideal prediction. This finding underscores the necessity of the FEM approach, as the FEM model inherently accounts for material stiffness properties, resulting in the much closer agreement between simulated and experimental results shown in Table 3.

The most pronounced influence on timbre was the tanning method. The spectra of the vegetable-tanned leather drums consistently exhibited a more rapid decay of high-frequency partials compared to the chrome-tanned drums. This observation aligns with the material's higher measured internal damping. Sonically, this translates to a "warm" and "deep" timbre characterized by a strong fundamental presence, wherein the initial complex sound of the strike quickly resolves into a purer tone. In this context, a "warm" or "deep" timbre is defined by a rapid decay of high-frequency partials (e.g., 45 dB/s as measured), which causes the sound spectrum to be quickly dominated by the fundamental frequency. This acoustic character is highly valued in many traditional music forms, where the drum serves a melodic or foundational role rather than a sharp, cutting rhythmic one.

In contrast, the chrome-tanned membranes produced a brighter, more "metallic" sound with a significantly longer sustain across all partials. This "brighter" and "metallic" character is quantitatively attributed to the richer and more persistent upper partial content (see Figure 1), which results from the material's lower damping coefficient and slower decay rate (18 dB/s). Figure 1 presents a time-frequency analysis of the two leather types, visually confirming the claims regarding sustain. The spectrogram for the chrome-tanned sample (Fig. 1b) clearly shows its harmonic content persisting for a longer duration than that of the vegetable-tanned sample (Fig. 1a), wherein the upper partials decay almost immediately. This result is a direct consequence of their lower damping and higher flexibility, which allow the membrane to resonate more freely. These findings demonstrate that the choice of tanning is not merely for preservation but is the principal means of defining the instrument's essential sonic identity.

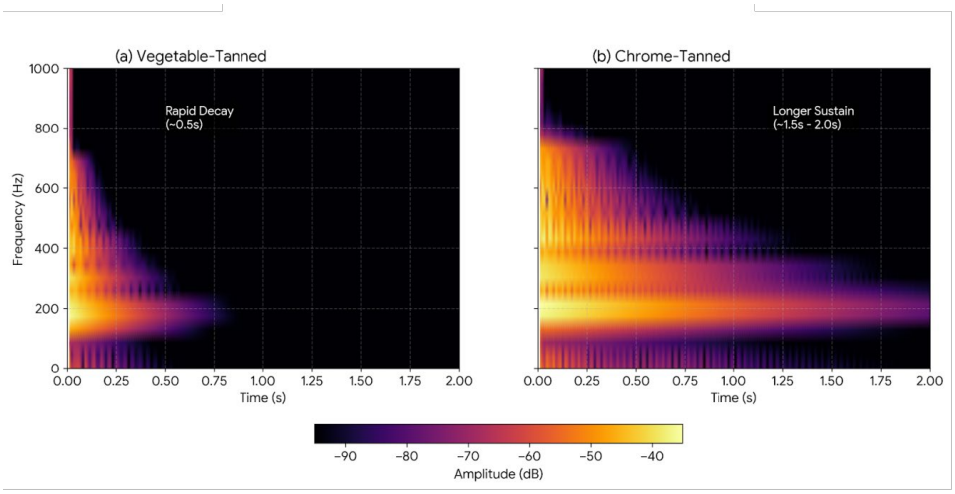

Figure 1. Comparative spectrograms illustrating the acoustic decay of (a) a vegetable-tanned and (b) a chrome-tanned leather membrane

The effect of thickness was also clearly observable and consistent with acoustic theory. For both tanning types, increasing the membrane thickness systematically lowered the frequencies of all partials, resulting in a deeper perceived pitch. For example, a 2.0 mm membrane exhibited a fundamental frequency approximately 30% lower than a 1.0 mm membrane under identical tension. This finding confirms that the artisan's practice of scraping a hide is a precise method for regulating pitch and timbre. While the current 2D axisymmetric model effectively captures the fundamental frequency and decay trends, it inherently assumes perfect rotational symmetry. Theoretically, however, real-world leather membranes possess non-uniform thickness distributions that break this symmetry. Such asymmetries are known to lift the degeneracy of vibrational modes, splitting them into closely spaced frequency pairs. Although capturing this phenomenon would require a full three-dimensional simulation, this mechanism likely contributes to the rich, chorus-like effect observed in the experimental recordings, which differs from the cleaner spectrum of the perfectly symmetric simulation. The computational model further revealed that even minor, realistically simulated variations in thickness across the membrane surface could lead to the splitting of degenerate modes into closely spaced pairs of frequencies. While difficult to confirm without highly specialized experimental techniques, this simulated phenomenon offers a plausible explanation for the rich, complex "chorus-like" effect often perceived in natural drum heads—a quality typically absent in perfectly uniform synthetic membranes. However, further research using advanced modal analysis would be required to definitively validate this proposed link.

By integrating these findings, a holistic view of the craftsman's process emerges. The selection of a hide and a tanning method establishes the fundamental acoustic potential of the material—its capacity for brightness, warmth, and sustain. Subsequent physical modifications, primarily scraping to control thickness and its profile, serve as a fine-tuning process, adjusting the pitch and enriching the harmonic complexity. This study scientifically validates the traditional instrument maker's art, reframing it as a highly sophisticated, intuitive form of material science and engineering. The knowledge embedded in these traditions is not anecdotal; it is a direct, hands-on application of the fundamental physical principles that govern membrane vibration.

CONCLUSION

This research successfully elucidated the mechanisms by which leather materials control the timbre of traditional percussion instruments. Through a combination of empirical material testing, controlled acoustic experiments, and finite element modeling, a clear and quantifiable link has been established between specific,

controllable material properties of leather and the resulting acoustic spectrum. The study confirmed that tanning methods are the primary determinant of a drum's broad sonic character—warmth, brightness, and sustain—by governing the material's internal damping. Furthermore, physical parameters such as thickness and its uniformity were shown to be precise controls for regulating pitch and harmonic complexity.

The findings have significant implications for both cultural heritage and modern engineering. For ethnomusicologists and conservators, this research provides a scientific vocabulary to describe and preserve the endangered knowledge of master instrument makers, ensuring that these complex crafts can be understood and transmitted based on measurable principles. For materials scientists and acoustic engineers, this work presents a case study in the high-performance application of a natural biomaterial, offering a new framework for bio-inspired design. The validated computational model developed in this study can serve as a powerful predictive tool for designing new musical instruments or for creating synthetic substitutes that accurately replicate the coveted acoustic properties of traditional leather membranes. Ultimately, this interdisciplinary approach demonstrates that the perceived artistry of a musical instrument's sound is inextricably rooted in the fundamental science of its materials.

Author Contributions

Ning Zhao designed, collected and analyzed the data, and drafted the manuscript. Ning Zhao conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Ning Zhao participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflicts of Interest

The author declares no conflict of interest.

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