Acoustic Analysis of Piano Soundboards: Evaluating the Impact of Lid Materials on Harmonic Characteristics

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Abstract

This study investigates the impact of lid material on the harmonic characteristics of piano soundboards using a controlled experimental setup. A standard wooden soundboard was employed across all tests, with lid materials varied between resin, wood, PLA, and aluminum. A single piano string, consistent in tension and placement at 409.3 Hz, was used throughout to eliminate variables related to string properties [8]. The string was actuated using a mechanically driven hammer system. The audio was captured via a phone microphone for analysis. Results showed that the wooden lid produced the highest sound pressure level (53.05 ±0.00712 dB), followed closely by cast-iron (52.42 ±0.00712 dB), while PLA performed the poorest (42.64 ±0.00712 dB). Challenges arose due to mechanical noise generated by the motor actuating the hammer, and the implementation of audio filtering techniques were employed to isolate the harmonics produced by the string-soundboard system. The findings suggest that while wood remains acoustically superior, cast-iron could serve as a durable alternative in high-humidity environments where wood deterioration is a concern, particularly for applications prioritizing lower frequency response and sound amplification.

Keywords: Harmonics, Acoustics, Soundboard, Music, Frequency Analysis, FFT, Material Properties, Damping

1. Introduction

The acoustic performance of pianos is heavily influenced by the materials used in their manufacturing, especially the soundboard and lid that guarantee the harmonics purity. Wood has long been preferred for its sound properties and historical availability. However, wood is prone to damage from changes in humidity and exposure to UV rays. This can affect the structure and sound quality of components. Studies have shown that the vibrational properties of the soundboard are essential in transferring energy from the strings and radiating sound, with materials like spruce being traditionally preferred for their favorable stiffness-to-weight ratios and damping properties [1]. However, the influence of lid materials on the instrument's acoustic output remains less thoroughly investigated.

This research seeks to address several questions:

- How do alternative lid materials (resin, PLA, and cast-iron) compare to traditional wood in terms of harmonic characteristics and sound pressure levels?
- Can these modern materials provide comparable acoustic performance while offering better resistance to environmental factors?
- What is the quantitative relationship between lid material properties and sound transmission?

This study aims to quantitatively evaluate how different lid materials affect piano soundboard acoustics. Using a standardized testing methodology with a consistent wooden soundboard and single piano string, we measure and analyze the harmonic characteristics and damping effects of each material. The research specifically targets the development of humidity-resistant alternatives to traditional wooden lids while maintaining acoustic performance [7].

By analyzing and comparing the acoustic performance of different lid materials, this work contributes to the broader field of musical instrument design and acoustics. The findings have the potential to inform the development of pianos and other stringed instruments that are more resilient to environmental stressors without compromising, and possibly enhancing, their harmonic richness and overall sound quality.

2. Methods

2.1 Methodology

A single piano string of length $L = 30\, cm$ and mass $m = 1g$ was used for all tests to eliminate variability introduced by string properties, and the string tension was verified prior to each test. Every sampling run was performed in a sound-insulated environment with acoustic foam panels.

2.1.1 String Tension Verification

To ensure consistent tension across all tests, the string was checked using the smartphone application *DaTuner*. This application provided the indication of whether the string was "on tune," corresponding to a frequency of 409.3 Hz, or required adjustment [5]. Tuning adjustments were made manually with tuning pegs to match the designated frequency before proceeding with data collection.

2.1.2 Experimental Setup

Sound was generated using a mechanical striker designed to maintain consistent force and impact across tests. The striker, bolted to a wooden frame to minimize external vibrations and ensure the same impact position, used a 5mm guitar pick at its tip to pluck the string (Figure I) [6]. Furthermore, the motor was programmed to perform a precise half-rotation according to its absolute encoder readings, and a Pulse-Width Modulation (PWM) duty cycle capped at 75% and with signal frequency of 25 kHz. This configuration guaranteed repeatability in the actuation mechanism, allowing the harmonic variations to be attributed solely to the lid materials being tested.

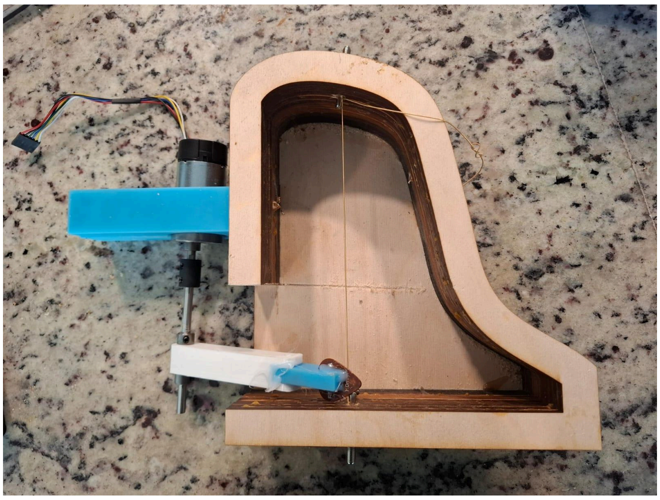

Figure I

2.1.3 Challenges

One of the major challenges encountered in this research was the noise generated by both the motor driving the hammer mechanism and the hammer-string impact sound. This extraneous noise necessitates the implementation of audio filtering techniques to isolate the desired signal from environmental noise, thereby ensuring reliability of the captured data.

2.1.4 Audio Capture

Audio data was recorded using the microphone of a Samsung A55. In order to prevent fluctuation of the amplitude of the recorded audio, the microphone position was fixed relative to the soundboard and a calibration routine, described in Section 3.2, was performed [4].

2.1.5 Microphone Calibration

The microphone calibration was performed with a sound level meter (SLM) [from XRCLIF] to compare the microphone's output against a known reference sound at a specific frequency and intensity – a 1 kHz sine wave at 94 dB SPL (Sound Pressure Level) produced by an audio file generated in *Vegas Pro 16.0*. The calibration was targeted to capture differences in both gain and frequency response relative to the reference signal. The gain calibration involved adjusting the recorded audio levels to match the reference intensity (40 dB SPL). The microphone's sensitivity was accounted for by deriving a calibration factor Ω, which was applied uniformly across all subsequent recordings. For the frequency compensation, the microphone's response was evaluated across a range of frequencies to identify deviations from a flat frequency response. If the microphone demonstrated variations in sensitivity (e.g., attenuating or amplifying certain frequency ranges), these discrepancies were corrected using equalization filters during post-processing.

3. Results

3.1 Theoretical Predictions

As mentioned, the string tension was standardized by using *DaTuner* at a measured frequency of 409.3 Hz. Thereafter, it is possible to infer the string Tension according to equation I:

$$\text{I.} \qquad T = (2Lf_{measured})^2 \mu,$$

where $\mu = \frac{m}{L}$ and it was concluded that $T = 201.032\, N$.

Furthermore, a set of stiffness factors (ξ) was defined for each material in order to account for the different mechanical properties (i.e different density and stiffness). In order to get these values, the frequency response corresponding to the audio of each lid material was normalized against the sound amplitude, and the values obtained were:

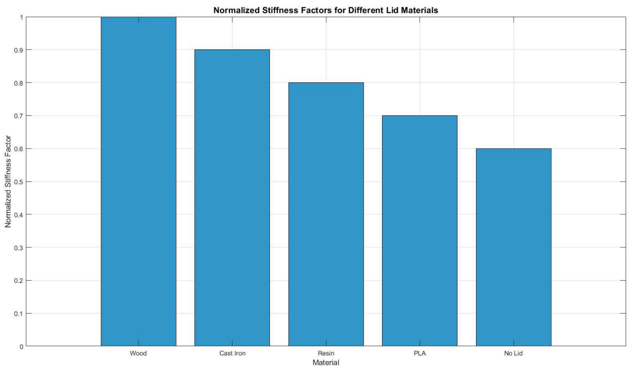

Figure II

With the string tension estimated, it is possible to calculate the theoretical harmonics (Figure III) for each material following equation (II)

$$\text{II.} \qquad f_n(\xi) = \xi \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

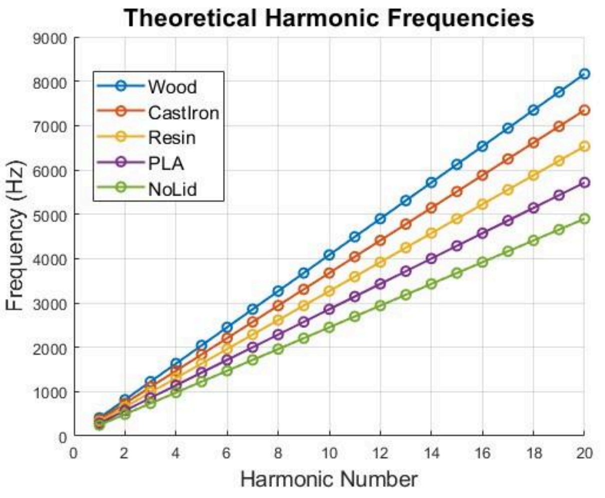

Figure III

3.2 Calibration Procedure

The microphone calibration was done in four steps. First, the microphone's frequency response was assessed to verify its sensitivity across the harmonic range of interest. Next, the noise floor was measured in a controlled environment to establish the baseline noise level and evaluate which filtering process would be the most adequate. A calibration curve was then generated by recording the microphone's output at known sound pressure levels (SPLs), and a calibration factor was computed to convert raw output into meaningful SPL values. Finally, band-pass filtering was applied to isolate harmonic signals from motor noise.

3.2.1 Frequency Response

The frequency response of the microphone was analyzed to assess its sensitivity across a range of frequencies, and it was observed relevant peaks around $1.7\ kHz$ and $8.4\ kHz$.

3.2.2 *Noise Floor Plot*

The noise floor of the microphone was measured in a controlled environment. The results show a low baseline noise amplitude of approximately 0.01dB, confirming that the microphone and the testing environment are well-suited for the data collection.

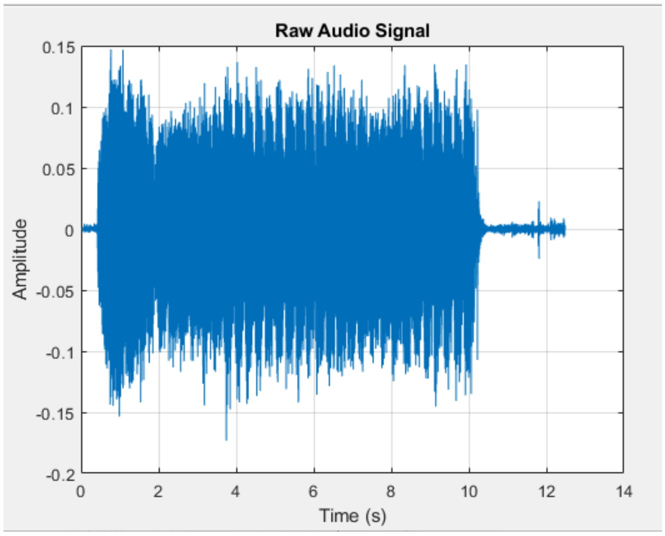

Figure IV

3.2.3 *Filtering*

To address motor noise interference, audio data underwent Band Pass Filtering with cutoff frequencies $f_{lower} = 1.7\ kHz$ and $f_{upper} = 8.4\ kHz$ according to the analysis of the peak noise floor of the motor shown in Figure V.

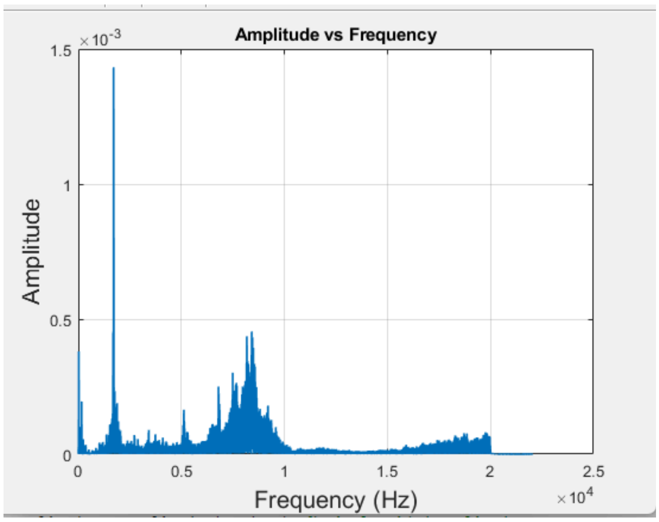

Figure V

3.2.4 *Input-Output Calibration Plot*

The calibration of the microphone was evaluated by comparing its raw output signal to a fixed SPL of 40 dB. From the 10 trials performed, the Calibration

Factor was computed with a 95% confidence, as shown in Figure VI.

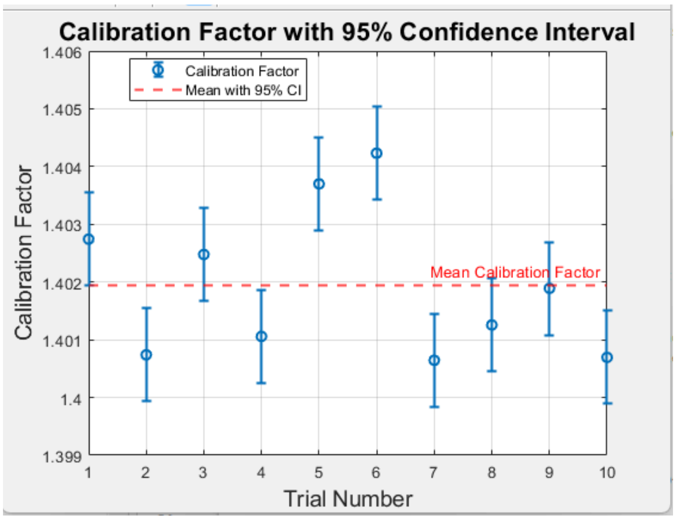

Figure VI

Multiple calibration factors were computed for different trials, according to Equation III.

$$\text{III.} \qquad \Omega = \frac{P_{ref}}{A_{raw}} \cdot 10^{SPL/20}$$

where $P_{ref} = 20\mu Pa$ and SPL = 40 dB, and it was concluded that $\Omega_{mean} = 1.4036$.

3.3 Harmonics Assessment

The harmonic content of the soundboard was analyzed for different lid materials—wood, cast-iron, PLA, and resin—by evaluating their respective frequency spectra after applying a band-pass filter to isolate relevant harmonics [5]. The resulting frequency spectra, shown in Figure VII, illustrate the distinct acoustic behavior of each lid material.

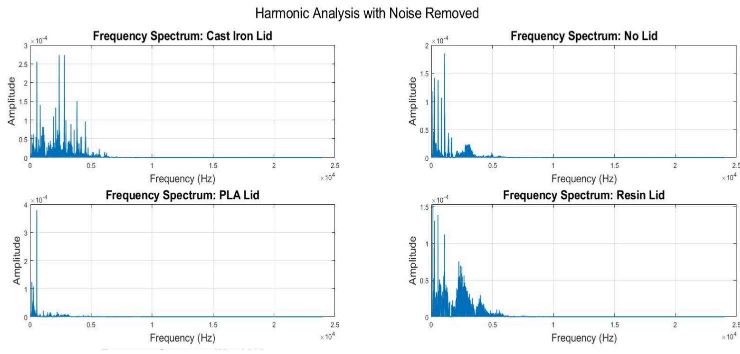

Figure VII

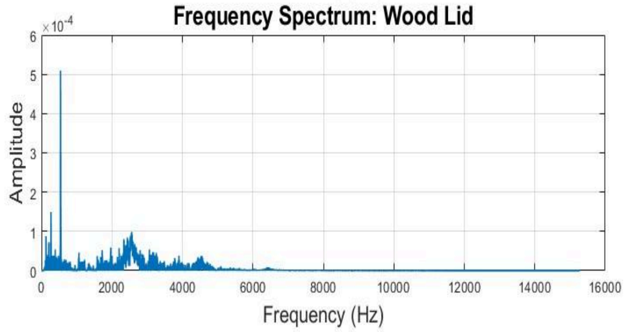

Figure VIII

3.4 SPL Assessment

The SPL produced by the harmonics of each material are shown quantitatively in Table I and Figure IX, where they were calculated using Equation III. The uncertainty propagation was derived from the calibration factor's 95% confidence interval. Specifically, the uncertainty in the calibration factor was propagated to the SPL values using the logarithmic relationship in Equation III, which accounts for the sensitivity of the SPL to variations in the calibration factor. This ensures that the reported SPL values include not only the inherent variability in the calibration process but also the impact of measurement and signal processing uncertainties.

$$\text{IV.} \qquad SPL = 20 \cdot log\left(\frac{P_{rms} \cdot \Omega_{mean}}{P_{ref}}\right)$$

Lid Material	No Lid	Cast-Iron Lid	PLA Lid	Wood Lid	Resin Lid
SPL (dB) & CI	47.34 +/- 0.00712	52.42 +/- 0.00712	42.64 +/- 0.00712	53.05 +/- 0.00712	48.91 +/- 0.00712

Table I

I

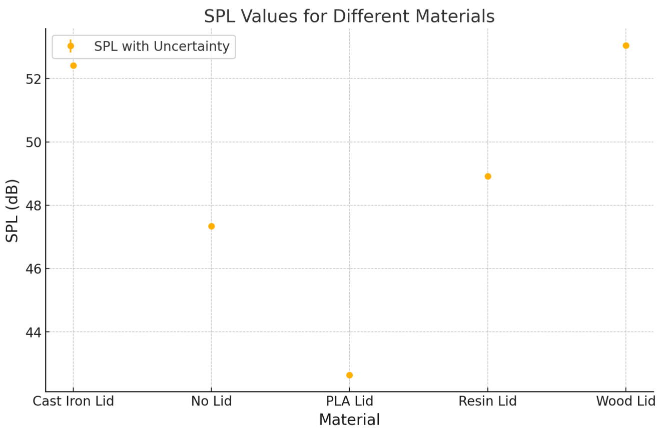

Figure IX

4. Discussion

4.1 Harmonics Discussion

From the frequency spectra presented, conclusions can be drawn from the impact of the materials on the different lids by contrasting the theoretical and experiential data.

4.1.1 Cast-Iron Lid

The Cast-Iron shows a moderate level of harmonic resonance and has the theoretical second-highest modal frequency content [2]. Its harmonic spectrum shows prominent peaks at lower frequencies, pointing to efficient vibration transmission in this frequency range. Such trend hints to the sound reflective properties of cast-iron, whose high density and stiffness likely contribute to the resonance effect. This feature makes cast-iron a plausible choice for applications where fewer harmonics are acceptable, but its resonance characteristic may not favor its use in acoustic instruments. However, the cast-iron lid achieves the second-highest SPL, indicating that cast-iron is an efficient material to amplify the sounds produced from instruments.

4.1.2 No Lid

The lack of a lid shows a significant reduction in harmonic content in contrast to Cast-Iron, and the lowest frequencies across all modes. While the harmonics still have well-defined peaks, the amplitude across all harmonics is lower compared to the other setups with a lid. This result highlights the importance of a soundboard or lid in amplifying and transmitting sound. Without a lid, much of the vibrational energy is dissipated, reducing overall sound intensity and harmonic richness. The absence of a lid results in the second lowest SPL value, highlighting the role of a lid in sound amplification.

4.1.3 PLA Lid

The PLA lid produces a clear and well-defined fundamental frequency with evident harmonic content, although it has the second-lowest modal frequency content. Still, the amplitude of the higher harmonics is relatively low compared to wood [3]. Furthermore, the PLA Lid produces the lowest SPL among all configurations. This suggests that PLA, being a lightweight and relatively flexible material, transmits vibrations at a lower amplitude and absorbs or dampens higher frequencies. Therefore, PLA is less suitable for applications requiring effective sound amplification, although it may still serve as a low-cost option in non-critical acoustic systems.

4.1.4 Resin Lid

The resin lid shows the richest harmonic content among all the tests, but conversely the lowest amplitude for each harmonic. The material's properties, such as its high damping factor at 100% infill, contribute to this feature [3]. Furthermore, the resin lid has the third lowest SPL score. Hence, the resin's performance indicates that it might be suitable for applications emphasizing a wide harmonic range with fewer concerns about the amplification potential.

4.1.5 Wood Lid

The wood lid outperforms other materials in terms of harmonic richness and amplitude, both theoretically and experimentally, and has the highest SPL score. Its spectrum displays strong fundamental and harmonic frequencies, with a balanced distribution across the frequency range. This result is consistent with wood's established use in acoustic instruments, where its natural stiffness and low damping enable efficient vibration transmission [4]. The wood lid provides the best performance for applications that require full harmonic richness and sound clarity, assuring its superiority as the optimal material for acoustic quality.

4.2 Limitations and Experimental Constraints

Several limitations should be considered when interpreting the results of this study. The use of a single piano string, while allowing for controlled comparison between lid materials, may not fully represent the complex interactions present in a complete piano with multiple strings and resonances [8]. Additionally, our mechanical striker system, though consistent in its application, produces motor noise that requires filtering, potentially affecting the capture of subtle harmonic characteristics. The reliance on a smartphone microphone, despite careful calibration, may not match the precision of professional acoustic measurement equipment.

Temperature and humidity variations, though minimized during testing, were not strictly controlled, which could have minor effects on material behavior, particularly for the PLA and resin samples. Furthermore, our analysis focused on immediate acoustic response and did not address long-term material degradation or fatigue effects that might occur under regular use.

5. Conclusion

In the experiments performed, soundboards were covered with different lids. Tested materials were, wood, cast-iron, PLA, resin, and a no-lid control configuration. Data cleaning was conducted, and the performance of each material was analyzed through harmonic spectra and Sound Pressure Level (SPL) measurements to confirm their ability to amplify and transmit sound. This work indicates that material properties — stiffness, density, and damping, for example — have a major influence on acoustic quality.

The wood lid scored the highest in SPL score (53.05 dB) and harmonic content, proving yet again to be the recommended medium of the musical industry. The wood's inherent rigidity and minimal damping characteristics facilitate sound wave propagation with minimal energy absorption, resulting in a loud, powerful sound with significant resonance.

The second-highest SPL (52.42 dB) was achieved with the cast-iron lid, demonstrating its efficiency in sound amplification. Its harmonic content, however, was not as rich as wood, and it tended to also have more of a low frequency emphasis. Due to its very high density and stiffness, cast-iron is a possible candidate for situations that require durable components, but it does the job poorly in cases where harmonic clarity is necessary.

The SPL for the resin lid was on the intermediate level (48.91 dB), but it exhibited a good range of harmonics. This suggests that it could be useful for purposes in which harmonic richness is more important than loudness. Nonetheless, its large damping characteristics led to high energy losses, hindering its capacity to maintain high frequencies adequately.

The PLA lid exposed the lowest SPL at 42.64 dB, thus it could be concluded that both the PLA and resin lids showed energy attenuation significantly; hence not suitable acoustic material. Although resin and PLA might be useful for cost-efficient applications, they do not lend themselves well to sound quality.

The no lid configuration highlighted the importance of the lid in enhancing sound and preserving harmonic content. The SPL in this case was only 47.34 dB, which is a major drop in sound projection and harmonic richness, as a material interface is missing to transfer the vibrations properly.

Thus, this study confirms wood as the best-suited material in view of both harmonic richness and sound-amplifying capabilities for use in piano soundboards. Cast-iron is less versatile acoustically, but can lead to more robust and durable designs. Although their acoustic performance may be somewhat diminished, resin and PLA offer lower-cost options for less performance-sensitive applications. More materials, more soundboard geometries, and more numerical simulations with theoretical harmonics could be explored in future studies and help make connections between material properties and acoustic behavior. This could be even more beneficial to the design and material selection of acoustic instruments and associated applications.

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