String Material Properties' Effect on Sound

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ABSTRACT

Different string materials have been used on string instruments over time, affecting the development of music and its timbre. Focusing on guitars, why do most modern guitarists use metal roundwound bass strings and unison steel or nylon treble strings, while some still opt for flatwound or even gut strings? By testing physical properties of many different string materials through frequency and envelope analysis, this question is answered. The results show that gut and flatwound strings do exhibit different decay and harmonic properties which make them more appropriate for certain musical styles.

1. BACKGROUND

1.1 History

The first ancient stringed instruments used unison strings. Violins and guitars originally used gut strings made from sheep intestines. However, to achieve lower frequencies with a unison string, it is necessary to either increase its length or thickness. Gut strings can be made thicker by twisting several pieces of gut together before drying and polishing. This is however a limiting process. To solve this problem, gut strings overwound with thin metal for violins appeared in Italy in the year 1660. These techniques started to be applied to the bass strings of pianos and harpsichords in late 18th century [1].

In the 19th century metallurgy and wire-making technology was making great strides and metal strings were found to be much cheaper to manufacture than gut strings, longer lasting and louder. However, the instruments of those times were not designed for these strings and would therefore quickly suffer structural damages. The first durable steel string guitars were created by the Larson Brothers and Orville Gibson, both in late 19th century. Nevertheless, these guitars were not widely accepted until the 1930s [2].

In 1874 Hamilton invented flatwound strings. They were initially beneficial for violins because of increasing the contact area with the bow [1], having a smooth surface from being wrapped with a flat wire. Throughout the development of the electric guitar and bass in the 1940s and 1950s, these became the standard strings to use. The roundwound strings that are most common today were not invented until the 1960s. Roundwounds are easier to play cut through surrounding noise while flatwounds have a a softer and warmer sound [3]. There also exists so called "half-wound" strings which are often seen as an intermediate. These strings are made by grinding down roundwounds and polishing them for a smoother feel. Their sound is generally more similar to roundwounds but they feel more like flatwounds [4].

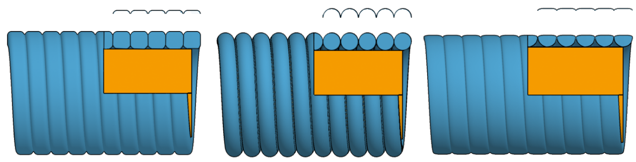

Figure 1: 3D model of flatwound string (left), roundwound string (middle) and half-wound string (right).

It was not until World War II, when the demand for surgical sutures made from gut was high and there was a shortage of gut strings, that classical musicians started looking for alternative types of strings. Andrés Segovia, famous classical guitar player, had problems finding strings for his performances. The synthetic material nylon had been invented in 1935 and Segovia found nylon strings to be perfectly adequate. Together with the instrument maker Albert Augustine they developed the first commercially manufactured nylon strings in 1948 [5]. However, some classical musicians still use gut strings to this day to achieve the right timbre for performing historical pieces. In 1997, the Italian string manufacturer Aquila discovered the synthetic material Nylgut to more adequately replicate the gut timbre by matching the average specific weight and moisture absorption of gut [6].

1.2 Mathematical tools

1.2.1 Fourier Analysis

An arbitrary periodic function can be written as a sum of sine and cosine functions. Through the Fourier Transform, this provides the basis for transformation of time histories into the frequency domain. The Fourier Transform is defined as:

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t}dt,$$

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where $\omega = 2\pi f$ and $X(\omega)$ is a complex-valued function of frequency. When recording an audio signal, it is sampled at the sample rate $f_s = 1/\Delta t$, becoming discontinuous. To perform frequency analysis, one must therefore utilize the Discrete Fourier Transform, defined as:

$$X(k) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) e^{-\frac{i2\pi nk}{N}},$$

where N is the number of samples, k corresponds to frequency and $X(k)$ is a complex function of k. Computing the DFT is however a demanding algorithm, requiring N^2 operations. A faster algorithm that gives the same result is the Fast Fourier Transform. It utilizes the symmetry of trigonometric functions and computes the DFT for the whole signal from a combination of DFTs of parts of the signal. If N is a power of 2, the algorithm is optimized and the number of calculations needed is $N^2 log(N)$ [7].

A similar operation is the Short-Time Fourier Transform. It considers only a short-duration segment of a longer signal and computes its Fourier transform by multiplying the time function $x(n)$ by a window function $w(n)$ that has a shorter length of N_w. This is important for audio signals such as music and speech which are characterized in the ways that frequency components change over time. The STFT is defined as follows:

$$X(n,k) = \sum_{m=n-(N_w-1)}^{n} w(n-m) x(m) e^{-\frac{i2\pi mk}{N}},$$

where n denotes the location of the analysis window along the time axis, k the frequency index and $X(n,k)$ is a function of both time and frequency [8].

1.3 Question Formulation

1. Do flatwound strings sound more like gut/silk strings than roundwound strings do?
2. From a physics standpoint, what characterizes the sounds of different string materials?

2. METHOD

2.1 Data Collection

Data collection was performed at the department of speech, music and hearing at KTH. The setup of the lab included; suspension mechanism for the strings connected to a partial headstock with tuning pegs (utilized from an earlier lab), a condenser microphone, an audio interface and a computer recording the string plucks in the software Audacity. Each string was mounted separately on the suspension mechanism and tuned to either D_2 or D_3 (depending on whether it was wounded) with the help of a mobile tuner application. The microphone was placed about 1.5 cm above the string, a few centimeters from the nut and the plucks where performed at a distance of 1/8th of the suspended string length (65 cm) from the bridge. Each string was plucked at three different dynamics (*mp*, *mf*, *f*), recorded at a sample rate of $44100kHz$ and the plucks were later separated in the DAW Logic Pro. Plucking was performed with a finger. The strings used are:

Unison

- Gut, Nylgut, Nylon, Steel.

Wound

- Silk, Nylgut, Nylon, Roundwound, Flatwound.

2.2 Computer Analysis using Python

The analysis focuses on four main tasks: waveform plotting, spectral analysis, amplitude envelope estimation, and inharmonicity coefficient calculation. Python libraries such as librosa, scipy, and matplotlib were used to facilitate the processing and visualization of audio data.

2.2.1 *Waveform Plotting*

The initial step involves reading the audio file and plotting its waveform. The `librosa.load` function is used to load the audio data and retrieve the sampling rate. A time vector is generated corresponding to the audio length, and the waveform is plotted using `matplotlib`. This visualization provides a clear view of the amplitude variations of the audio signal over time.

2.2.2 *Spectral Analysis (Partial Tones Detection)*

The Short-Time Fourier Transform (STFT) is employed to analyze the frequency content over time. The `scipy.signal.stft` function calculates the STFT, generating frequency bins, time frames, and the complex spectrum. A spectrogram is generated and visualized on a logarithmic frequency scale using `librosa.display.specshow`.

To identify partial tones, specific time frames are selected, and the corresponding magnitude spectrum is extracted. Peaks in the spectrum are detected using `scipy.signal.find_peaks`, representing prominent frequencies at the analyzed moments.

2.2.3 *Amplitude Envelope Estimation*

The third part involves estimating the amplitude envelopes of the detected partial tones. For the data of the two time frames in the previous step, we select the overlapping partials as the reference partials. This step assesses how the amplitude of each partial decays over time, providing valuable information about the damping characteristics of the sound source. Exponential decay models were fitted to the amplitude data at different time frames, and the resulting envelopes were plotted.

$$\mathrm{env}_n(t) = A_n e^{-\gamma_n t}, \quad t \geq 0$$

2.2.4 *Inharmonicity Coefficient Calculation*

The final part of the analysis addresses the inharmonicity of the audio signal. Inharmonicity measures how much the frequencies of overtones deviate from perfect integer multiples of the fundamental frequency. By defining the detected partial frequencies as:

$$f_n = nf_0\sqrt{1+n^2B_n},$$

the following formula for the inharmonicity coefficient can be derived,

$$B_n = \frac{\left(\frac{f_n}{nf_0}\right)^2 - 1}{n^2}.$$

The results, including an average coefficient, were plotted to visualize how inharmonicity varies with harmonic order.

2.3 Computer Analysis using MATLAB

MATLAB and its Signal Processing Toolbox is used to produce envelopes of the audio waveforms and frequency magnitude spectra. Each .wav-file is read using `audioread` and one of the two stereo channels is used for further analysis. The onset of all of the audio files is found by discarding the first values when the signal is less than 10% of its maximum value. All envelopes are calculated by utilizing the `envelope(x, np, 'peak')` function which determines the envelopes using spline interpolation over local maxima seperated by at least `np` samples. `np` in this case represents a resolution of the envelope.

2.3.1 Waveform Envelope

For the waveform envelopes, only one envelope is calculated by choosing the upper envelope of the absolute values of the audio signal. The resolution `np` for each envelope is taken to be $\frac{\text{\# of samples}}{1000} * 20$ so that the resolution is the same for all audio recordings. Further, the envelopes are normalized to be easier to compare by dividing each envelope's elements by the max value of that envelope.

2.3.2 Magnitude Spectrum Envelope

The magnitude spectra are calculated with the function `fft(X,n)` which computes the `n`-point discrete Fourier transform of the signal `X` using a fast Fourier transform algorithm. `n` is taken to be the next power of 2 of the length of the data `X` to optimize the algorithm's performance. The resulting spectrum is scaled by dividing by the chosen value `n` and a correction coefficient to satisfy Parseval's identity. There is a rectangular windowing applied that only analyzes the frequency spectrum of data from onset to the lowest end time of the three audio files of the same string with different dynamics. Further, the magnitudes are presented in a single-sided spectrum in dB by doubling the absolute value of one side of the spectrum and converting it to dB with the function `mag2db`. Each enveloped is placed to start at 0 dB for $0Hz$ for them to be comparable. Only the upper envelope is considered and `np` is taken to be 10 000 for sufficient smoothness.

3. RESULTS

3.1 Waveform and Magnitude Spectrum

First, we use Flatwound as an example to show the drawing of Waveform and Magnitude Spectrum.

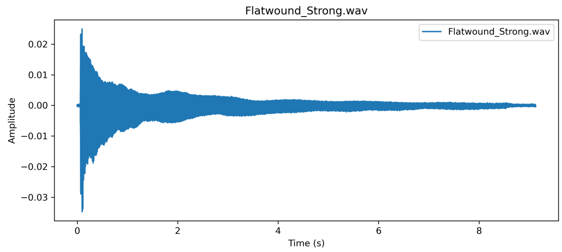

Figure 2: Waveform of the Flatwound Strong pluck.

The quick rise in amplitude corresponds to the plucking action, while the smooth decay reflects the damping characteristics of the flatwound string. The gradual tapering off indicates that the string retains vibration energy for a prolonged period.

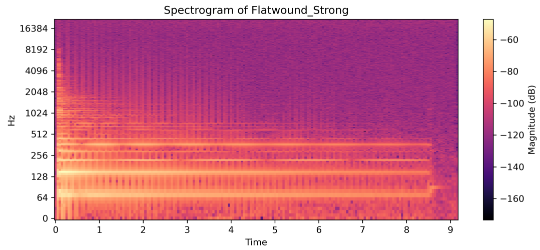

Figure 3: Magnitude Spectrum of the Flatwound Strong pluck.

The spectrogram confirms the harmonic nature of the string vibrations, with the fundamental and first few overtones being the most prominent. The gradual fade of harmonic lines over time aligns with the observed amplitude decay in the waveform. The faster decay of higher harmonics contributes to the mellow sound characteristic of flatwound strings.

3.2 Magnitude Spectra and Amplitude Envelopes of Overtones

3.2.1 Unsion strings

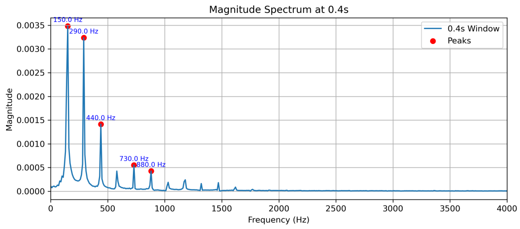

Figure 4: Gut - Magnitude Spectrum

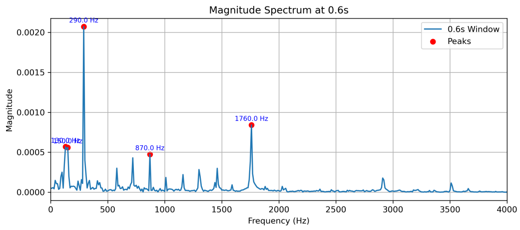

Figure 5: Nylon - Magnitude Spectrum

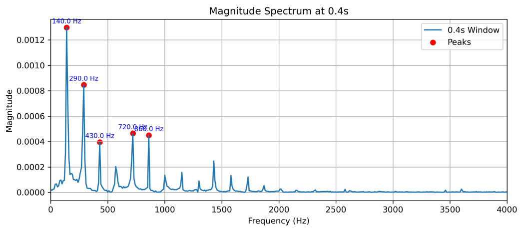

Figure 6: Nylgut - Magnitude Spectrum

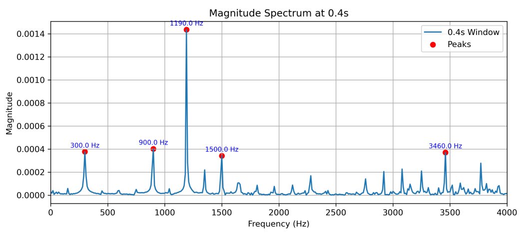

Figure 7: Steel - Magnitude Spectrum

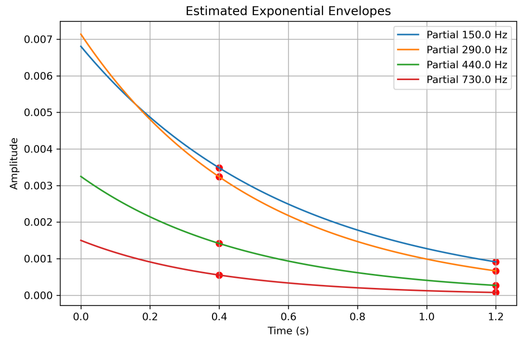

Figure 8: Gut - Amplitude Envelope of Overtones

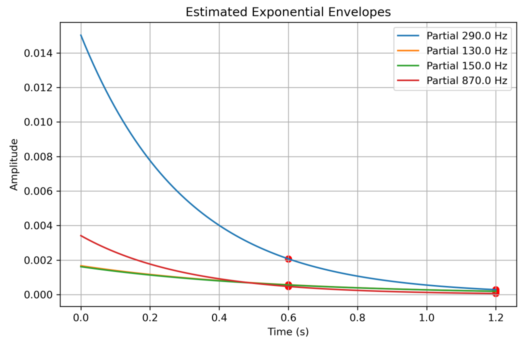

Figure 9: Nylon - Amplitude Envelope of Overtones

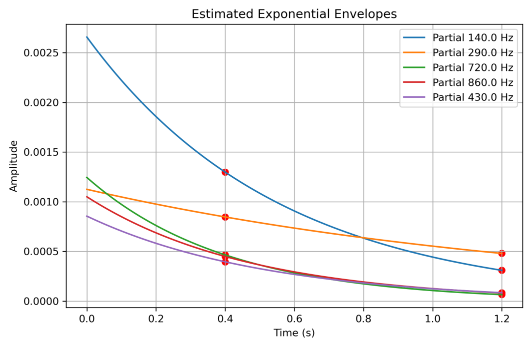

Figure 10: Nylgut - Amplitude Envelope of Overtones

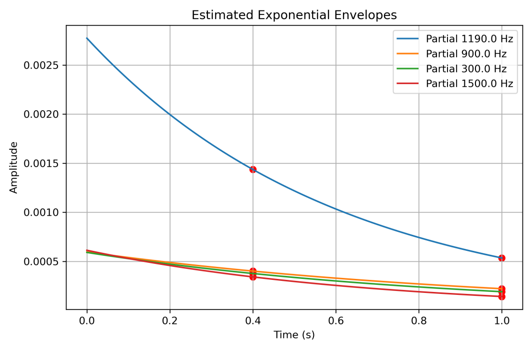

Figure 11: Steel - Amplitude Envelope of Overtones

3.2.2 *Wound strings*

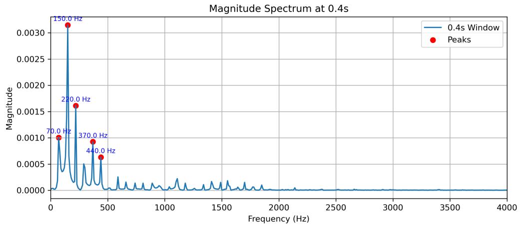

Figure 12: Flatwound - Magnitude Spectrum

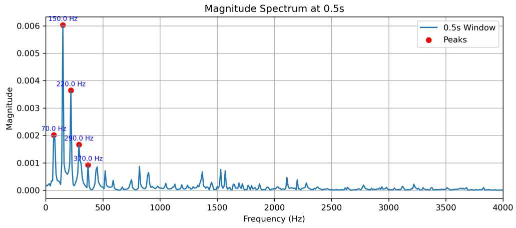

Figure 13: Roundwound - Magnitude Spectrum

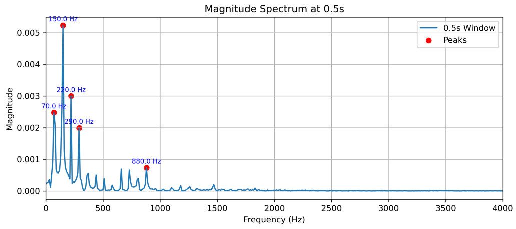

Figure 14: Silk - Magnitude Spectrum

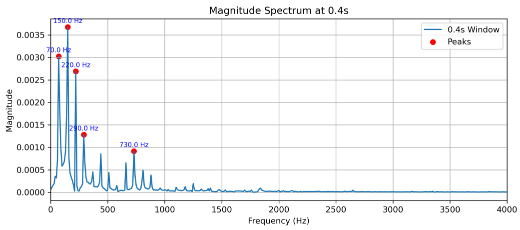

Figure 15: Nylgut (wound) - Magnitude Spectrum

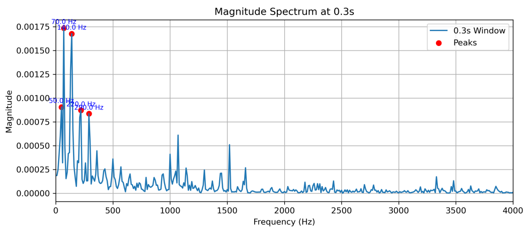

Figure 16: Nylon (wound) - Magnitude Spectrum

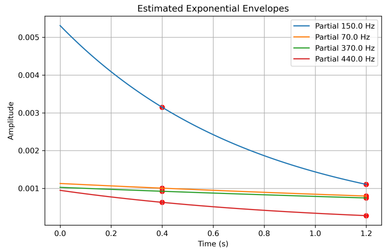

Figure 17: Flatwound - Amplitude Envelope of Overtones

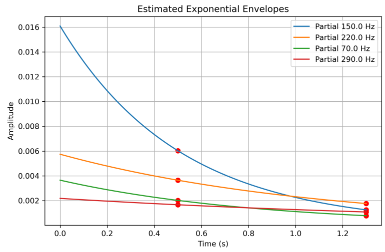

Figure 18: Roundwound - Amplitude Envelope of Overtones

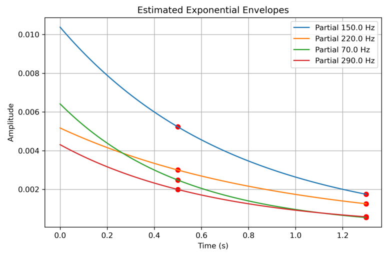

Figure 19: Silk - Amplitude Envelope of Overtones

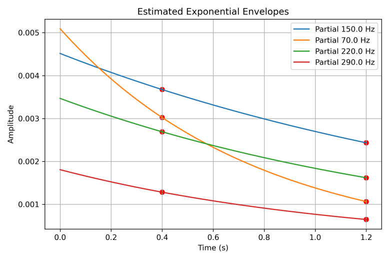

Figure 20: Nylgut (wound) - Amplitude Envelope of Overtones

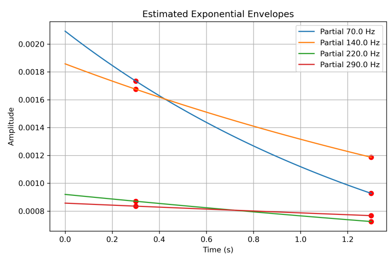

Figure 21: Nylon (wound) - Amplitude Envelope of Overtones

3.2.3 *Wound vs. Unwound Strings*

Wound strings, due to their greater vibrating mass, exhibit longer vibration durations. This results in a slower amplitude decay compared to unwound strings, contributing to a more sustained sound.

3.2.4 *Roundwound vs. Flatwound Strings*

Roundwound strings demonstrate stronger high-frequency content with pronounced spectral peaks beyond 500 Hz, indicating a brighter tone and richer harmonic content. In contrast, Flatwound strings display smoother spectra with fewer high-frequency components, resulting in a warmer and mellower sound.

3.2.5 *Material Influence*

Material properties significantly affect tonal characteristics. Steel strings produce the strongest initial peaks with rapid decay in higher harmonics, creating a bright but short-sustained tone. Conversely, materials like Nylgut (wound) and Silk (wound) show more consistent decay across partials, offering a balanced tonal quality with moderate sustain and warmth.

3.3 Analysis of Inharmonicity Coefficients (B-values) Across Harmonic Numbers

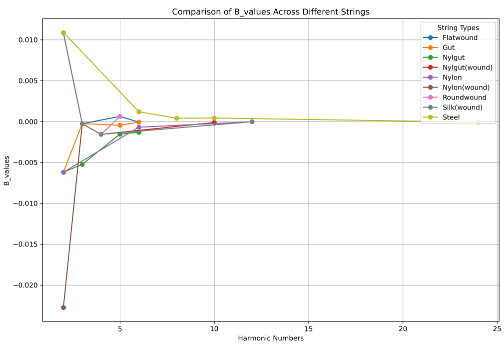

Figure 22: Inharmonicity Coefficients Across Harmonic Numbers

The plot illustrates the variation of inharmonicity coefficients (B-values) for nine different string types as a function of harmonic numbers. Each curve corresponds to a specific string type, showing how the B-values change with increasing harmonic order. Most string types exhibit B-values that decrease and approach zero as the harmonic number increases. This trend aligns with the expected behavior where higher harmonics are less influenced by inharmonicity due to diminishing vibrational amplitude.

- The Steel string:
  It consistently shows the highest positive B-values, particularly at the lower harmonic numbers. This indicates significant inharmonicity, which can be attributed to the steel string's high stiffness and tension.
- Silk (Wound) and Roundwound Strings:
  These strings also demonstrate positive B-values, though not as pronounced as the Steel string. Contributing to a slightly metallic but warmer tone compared to steel.
- Nylon (Wound) and Nylgut (Wound):
  Both wound strings show mild negative B-values at the first few harmonics, potentially due to measurement uncertainties or variations in string construction. However, as harmonic numbers increase, their B-values converge toward zero, indicating improved harmonicity in higher overtones.
- Flatwound, Gut, and Nylgut Strings:
  These strings exhibit B-values very close to zero across most harmonic numbers, reflecting their soft construction and lower stiffness. The minimal inharmonicity correlates with their warm, mellow sound and smooth harmonic content.
- Nylon Strings:
  Pure Nylon strings display a slight negative B-value at the fundamental frequency but stabilize quickly as the harmonic order increases.

3.4 Waveform Envelopes

3.4.1 *Unison Strings*

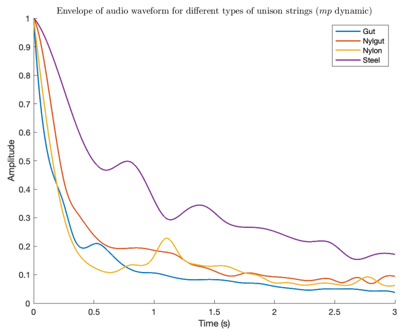

Figure 23: Waveform envelopes of unison strings plucked with soft dynamic.

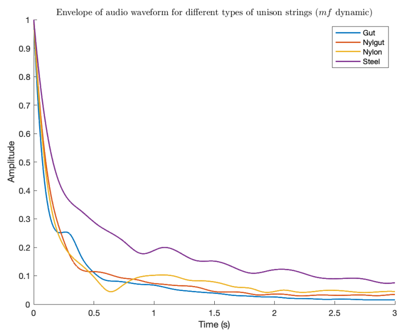

Figure 24: Waveform envelopes of unison strings plucked with medium dynamic.

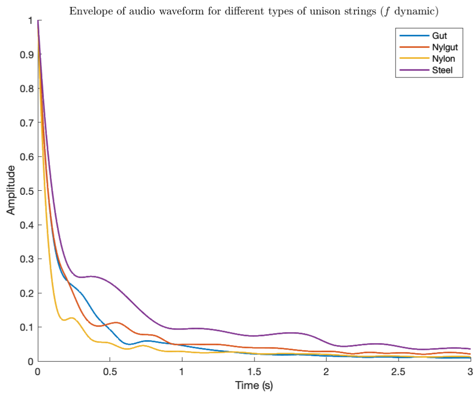

Figure 25: Waveform envelopes of unison strings plucked with strong dynamic.

3.4.2 Wound Strings

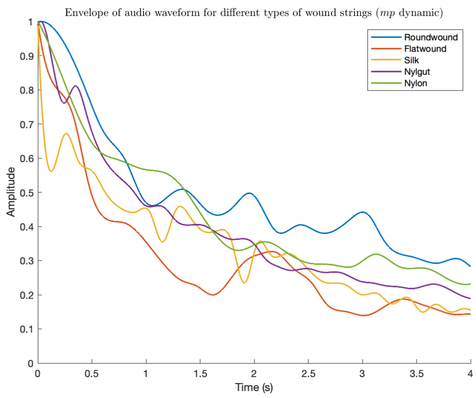

Figure 26: Waveform envelopes of wound strings plucked with soft dynamic.

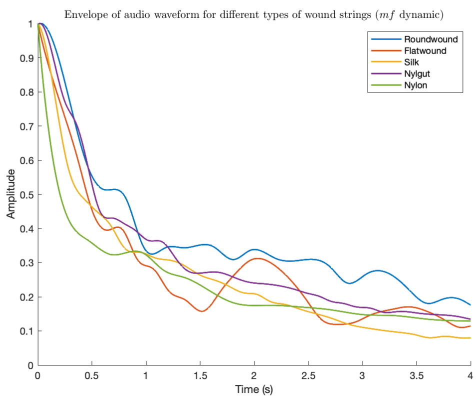

Figure 27: Waveform envelopes of wound strings plucked with medium dynamic.

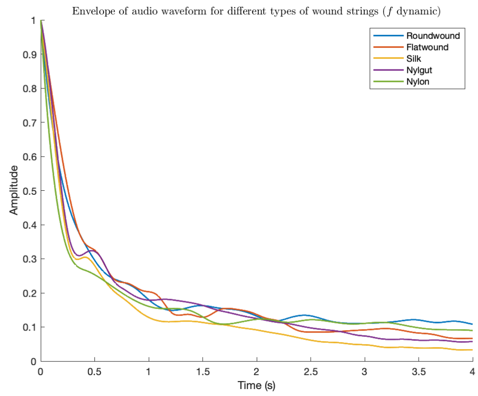

Figure 28: Waveform envelopes of wound strings plucked with medium dynamic.

3.4.3 Conclusions

For unison strings, the steel strings are the big outlier, their amplitude decaying consistently slower than the rest. The rest of the strings types are quite similar but gut strings consistently decay the fastest.

When it comes to the wound strings, the roundwound strings decay the slowest while the flatwound, nylon and silk strings decay faster. For all waveforms, the differences in decay become less distinguishable the higher the plucking dynamic is.

3.5 Frequency Magnitude Envelopes

3.5.1 Unison Strings

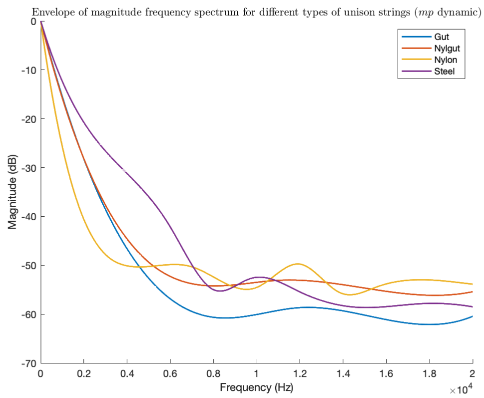

Figure 29: Magnitude envelopes of unison strings plucked with a soft dynamic.

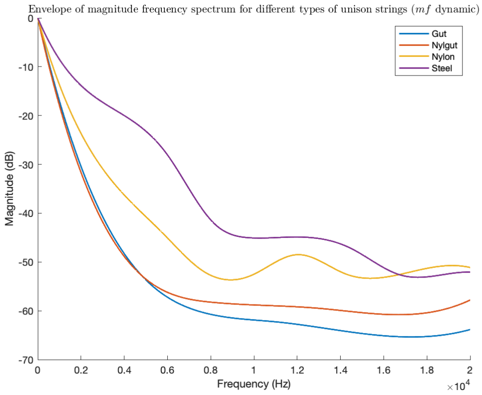

Figure 30: Magnitude envelopes of unison strings plucked with a medium dynamic.

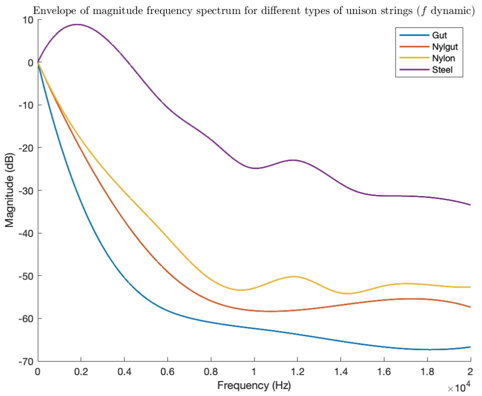

Figure 31: Magnitude envelopes of unison strings plucked with a strong dynamic.

3.5.2 Wound Strings

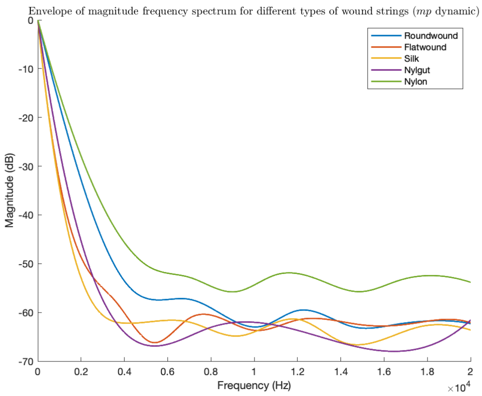

Figure 32: Magnitude envelopes of wound strings plucked with a soft dynamic.

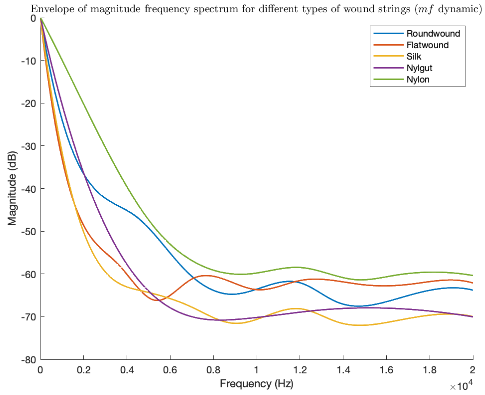

Figure 33: Magnitude envelopes of wound strings plucked with a medium dynamic.

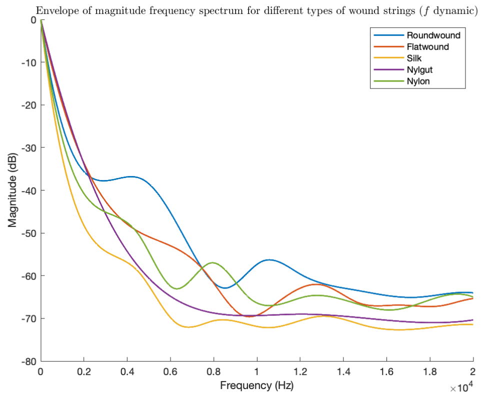

Figure 34: Magnitude envelopes of wound strings plucked with a strong dynamic.

3.5.3 Conclusions

Looking at the frequency magnitude envelopes for the unison strings, the steel strings can again be seen to be the big outlier, especially in the strong dynamic, having much more high frequency content than the rest. For the medium and strong dynamic, a clear trend can be seen in that the strings can be ordered from most to least high frequency content as: steel, nylon, nylgut, gut. This also points to how nylgut imposes the characteristics of gut more successfully than nylon.

For the wound strings, the trend seems to be that nylons and roundwounds have the most energy in the high frequencies, while flatwounds are an intermediate (at least in the medium and strong dynamic) and silk and nylgut have the least high frequency content. This again confirms the purpose of the nylgut strings and shows the high amount of high frequencies in modern strings. In general for all magnitude envelopes, the differences between string types become more distinguishable the higher the plucking dynamic.

3.6 Answers to Imposed Questions

1. Flatwounds exhibit more similar decay, high frequency content and inharmonicity to gut/silk strings than roundwounds do.

2. Different string materials are able to achieve different frequencies when suspended. They also experience different frequency content at these frequencies, emit this content varyingly over time and behave differently at different dynamics.

4. DISCUSSION

This project was able to reach some conclusion about its questions of issue. However, several limitations and potential areas for improvement should be considered.

4.1 Limitations and Potential Issues

- Plucking Method: All strings were plucked with a finger. Different plucking techniques can significantly affect the sound but were not investigated. There is also human error in trying to match the desired dynamics for each string and trying to pluck at the same distance from the bridge. This might have affected the amplitudes and partials recorded.

- Environmental Factors: The recordings were conducted under controlled lab conditions; however, subtle variations in room acoustics or background noise may have influenced the results.

- Simplified Dynamic Range Analysis: While three dynamics (mp, mf, f) were tested, the analysis did not fully explore how intermediate or extreme dynamics affect harmonic content and decay characteristics. Really soft dynamics were excluded for practical reasons but might be beneficial to explore in further research.

- Microphone Positioning: The microphone was quite consistently placed 1.5 cm above the string, but there were variations in positioning because of movements when changing strings. These could introduce minor inconsistencies in recorded amplitude and frequency response.

- Tuning: The tuning was performed with a mobile application that has a limited accuracy. There was not enough time to let the strings stabilize with the tuning so it could also have varied over time during recording.

4.2 Future Research Directions

- Add Polished Strings: Polish the strings (simulating half-wound strings) in the future research and see how the smoothness of string surface affects the sound quality and other properties.

- Plucking Techniques and Playing Styles: Investigating the impact of various plucking methods such as using a plectrum, could yield insights relevant to different playing contexts.

- Wear and Material Effects: Strings change over time due to corrosion, dirt accumulation, and mechanical wear. Studying how these factors affect sound quality would be valuable for practical applications. Different materials have different properties which affect how they wear out over time and their tuning stability through factors like slippage around the tuning peg.

- The Instrument Factor: The properties of string materials were tested on a non-resonating suspension mechanism. These properties might very well be affected by the acoustical response of instrument bodies. Therefore, a very practical further research field would be to test the string materials on actual instruments.

While the study achieved its objectives by highlighting differences in amplitude decay, harmonic content, and inharmonicity among various string materials, addressing the outlined limitations could refine the conclusions and broaden the study's applicability. Future research should consider expanding both the experimental scope and the analytical methods to further explore the complex interplay between string construction, material properties, and perceived sound.

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