



Study on Effects of String Tension on Inharmonicity and Acoustic Characteristics in Classical Guitars

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Abstract- It is generally perceived that higher string tension tends to result in a sound that is perceived as clearer. Therefore, the purpose of this paper is to examine the characteristics of the sound produced when the tension of classical guitar strings is varied, based on 3 indicators: inharmonicity, overtone composition, and volume. Spectral analysis using a Fast Fourier Transform (FFT) analyzer and a comparison of sound volume using an oscilloscope were conducted. The results confirmed that increasing string tension reduces inharmonicity, thereby quantitatively demonstrating the phenomenon given by the theoretical equation. Furthermore, as string tension increased, dissonant interval content rate decreased, while the volume increased. Based on the above results, it is considered that the perceived clarity of tone when string tension is increased is attributable not only to a reduction in inharmonicity but also to a decrease overtone in the dissonant interval domain. Furthermore, an increase in volume was observed, it is suggesting that increasing string tension brings about desirable acoustic characteristics from the perspective of many factors, including clarity and volume. By applying these findings to the selection of strings with higher tension, the development of strings using materials with higher linear density, and the development of guitars with new structures that achieve equivalent higher string tension, it is considered that this paper can contribute to improving the acoustic characteristics of classical guitars.

Keywords: Classical Guitar, Tone, Tension, Inharmonicity, FFT, Overtone.

I. Introduction

Numerous studies have been conducted on the guitar (Cuzzucoli & Lombardo, 1999; Suzuki et al., 2017; Wrzeciono et al., 2018). Authors have also been engaged in work such as proposing evaluation methods for the tone of classical guitars (Tanaka & Itako, 2021, 2022), comparing tones using these methods (Yabuta & Itako, 2024), and developing tone evaluation devices (Yabuta & Itako, 2025). The tone of a classical guitar depends on the instrument's structure and playing conditions, but among these factors, string tension is widely recognized by players as a key influence on tone. Generally, it is understood that when string tension is low, the sound tends to be loose and unfocused, whereas when string tension is high, the sound tends to be clear and well-defined. One of the physical factors contributing to these auditory changes is string inharmonicity. Based on a theoretical formula that quantifies the deviation from an ideal string, it can be theoretically deduced that the inharmonicity decreases as tension increases. However, no previous studies have quantitatively demonstrated the inharmonicity in actual guitar strings. Therefore, this paper proves the relationship between string tension and the inharmonicity quantitatively once again by analyzing the inharmonicity when string tension is varied. Furthermore, the study examines the effects on other factors, such as harmonics and volume.

II. About Sound

2.1. About Overtones

Sound is composed of multiple different frequencies. Among the frequency components that make up a sound, the lowest frequency that is the base is called the Fundamental tone, and those with frequencies that are integer multiples of that are called overtones. In classical guitar, the frequency of an open string is the fundamental frequency of that string. Differences in sound between types of instruments, as well as differences in tone due to the instrument's materials and playing techniques, are determined by the composition of the overtones. Overtone has consonant intervals that are harmonic with the fundamental tone and dissonant intervals that are non-harmonic with fundamental tone. As characteristic features of each interval, consonant intervals are often perceived as clear sound, while dissonant intervals are often perceived as muddy sound. Among the overtones classified as consonant intervals and dissonant intervals, many of the higher overtones beyond the 7th are dissonant intervals (Tanaka & Itako, 2022). Therefore, in this paper, the range up to the 6th overtone is referred to as the consonant interval domain, and the range from the 7th overtone onward is referred to as the dissonant interval domain.

2.2. About inharmonicity

Due to the bending stiffness of guitar strings, the overtone frequencies may deviate from their theoretical integer multiples. This deviation is called “inharmonicity” and causes auditory discomfort. For this reason, inharmonicity is considered one of the factors that influence the tone of a guitar. The overtone frequencies, taking this phenomenon into account, are expressed by Equation (1).

$$f_n = nf_1\sqrt{1 + n^2\zeta} \quad (1)$$

f_n : Natural frequency [Hz], n : Order of the natural frequency, ζ : Differences from an ideal string

Here, ζ is a term representing the deviation from an ideal string, and is given by Equation (2). From Equation (2), it can be theoretically deduced that, for the same string length, increasing the tension causes ζ to decrease, thereby reducing the deviation from the ideal string.

$$\zeta = \frac{\pi^2 EI}{TL^2} = \frac{\pi^3 Er^4}{4TL^2} \quad (2)$$

E : Young's modulus, I : Second moment of area,
 T : Tension [N], L : String length [m], r : Cross-sectional radius of the string [m]

III. Study on the Effects of Changing String Tension on Inharmonicity and Acoustic Characteristics:

3.1. Experimental Conditions

This paper examined the effect of string tension on sound by analyzing inharmonicity, frequency spectra, and the dissonant interval content rate, and comparing volume levels. A Silent Guitar (Yamaha SLG-100N) was used in the experiments to obtain the characteristics of the strings themselves. As shown in Figure 1(a), the silent guitar used lacks a soundboard for amplifying sound, instead converting the vibration of the strings directly into electrical signals via a pickup. To ensure a consistent amount of energy was applied to the strings during plucking, a pendulum as shown in Figure 1(b) was used, and all strings except the one being measured were removed. The plucking position was set at 10 cm from the bridge. The strings used were AUGUSTINE REGAL nylon strings. Measurements were taken for the 1st through 3rd strings. The standard open-string pitches are E for the 1st string, B for the 2nd string, and G for the 3rd string. As shown in Table 1, the string tension was varied by changing the frequency under 4 conditions: the standard open-string pitch, 3 notes lower, 6 notes lower, and 3 notes higher than the standard open-string pitch. For the 1st string, the tension was already high at the standard pitch. Therefore, the condition corresponding to 3 notes higher was excluded from the measurements due to the risk of string breaking caused by further increasing the pitch.



(a) Silent guitar



(b) Plucking by pendulum

Figure 1. The guitar used and the experimental system.

Table 1. Conditions for tension change

String	Frequency [Hz] (Pitch)	Tension [N]
1	330 (E)	76.4
	247 (B)	42.8
	175 (F)	21.5
	330 (E)	98.0

2	247 (B)	54.9
	175 (F)	27.6
	131 (C)	15.4
3	262 (C)	96.3
	196 (G)	53.9
	147 (D)	30.3
	110 (A)	17.0

3.2. Analysis of inharmonicity

Inharmonicity was analyzed by calculating the difference between the overtone frequencies obtained through Fast Fourier Transform (FFT) analysis and the theoretical frequencies. An FFT analyzer (ONOSOKKI CF-3600) was used to measure the frequency spectrum. The measurement frequency range was set to 0–5 kHz. Furthermore, previous research has shown that the spectrum of overtones beyond the 16th overtone is less than 1% of the fundamental tone's spectrum. Because of this low ratio, this paper assumed 16th overtone onwards have little effect on the tone. Therefore, this paper set the overtone measurement range from the 2nd overtone to the 15th overtone. Equation (3) was used to calculate the inharmonicity.

$$\text{Inharmonicity} = \frac{|f_e - f_t|}{f_t} \times 100 [\%] \quad (3)$$

f_e : Frequency obtained by experiment [Hz], f_t : Theoretical frequency [Hz]

Figure 2 shows the analysis results for inharmonicity at the maximum and minimum tensions for each string. For all strings from 1st to 3rd string, increasing the tension resulted in reduced inharmonicity.

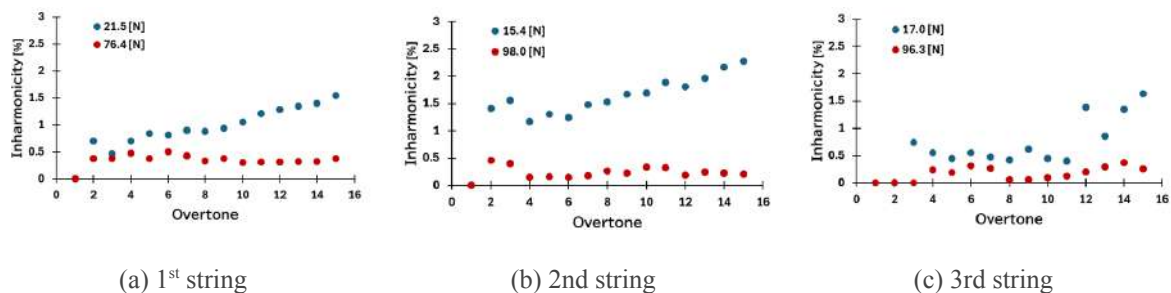
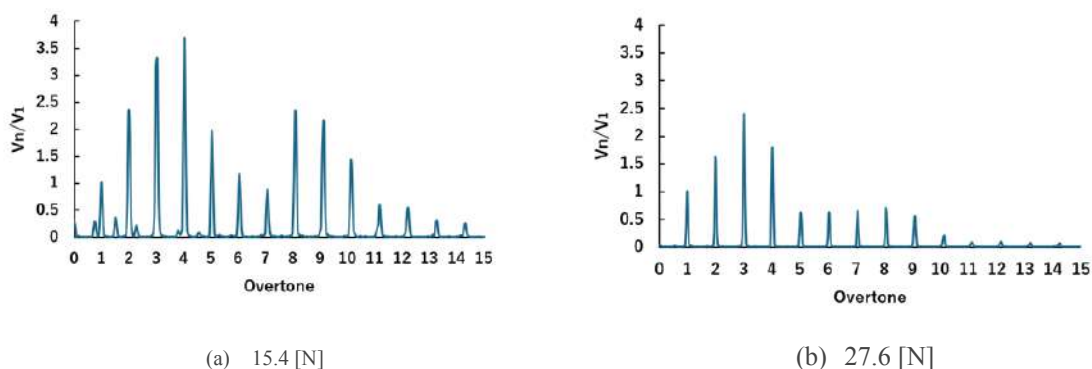


Figure 2. Inharmonicity

3.3. Analysis of the Overtone Spectrum:

For the tone analysis, in order to analyze the overtone composition, the frequency spectra obtained from the FFT analysis in Section 3.2 were converted from the frequency domain to the overtone domain. Figure 3 shows the overtone spectra for the 2nd string under each tension condition. In Figure 3(a), which shows the lowest tension, significant overtones are present in both the consonant interval domain and dissonant interval domain. However, as tension increases, the overtones in the dissonant interval domain decrease, and in Figure 3(d), which shows the highest tension, overtones in the dissonant interval domain are almost entirely absent. It has been confirmed that similar results are obtained for the 1st and 3rd strings.



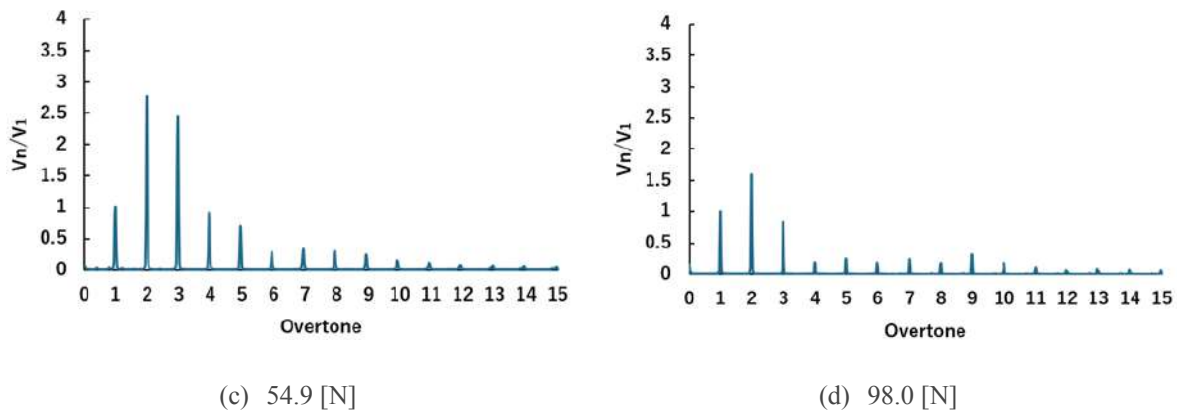


Figure 3. FFT analysis of 2nd string.

When string tension is low, the string becomes more prone to bending and vibrating in multiple directions, resulting in the waveform becomes prone to distortion. As a result, it is considered that the sound contains not only the fundamental tone and consonant interval domain overtones but also a greater number of overtones in dissonant interval domain. On the other hand, when the string tension is high, the direction of vibration is restricted, and it is considered that overtones in dissonant interval domain decreased because vibrations other than the fundamental vibration were suppressed.

3.4. Analysis of dissonant interval content rate:

To quantitatively demonstrate the differences in overtone composition regarding the changes in the overtone spectrum in the range of dissonant interval domain described in Chapter 3.3., this paper analyzed the dissonant interval content rate (D.C.). Equation (4) was used to calculate the dissonant interval content rate.

$$D.C. = \frac{\sqrt{V_7^2 + V_9^2 + V_{11}^2 + V_{13}^2 + V_{14}^2 + V_{15}^2}}{V_1} \times 100 [\%] \quad (4)$$

V_n : Amplitude of the n^{th} overtone [V] ($n=7,9,11,13,14,15$), V_1 : Amplitude of the fundamental tone [V]

Figure 4 shows the dissonant interval content rate under each condition. The results indicate that as string tension increases, the dissonant interval content rate in the sound decreases.

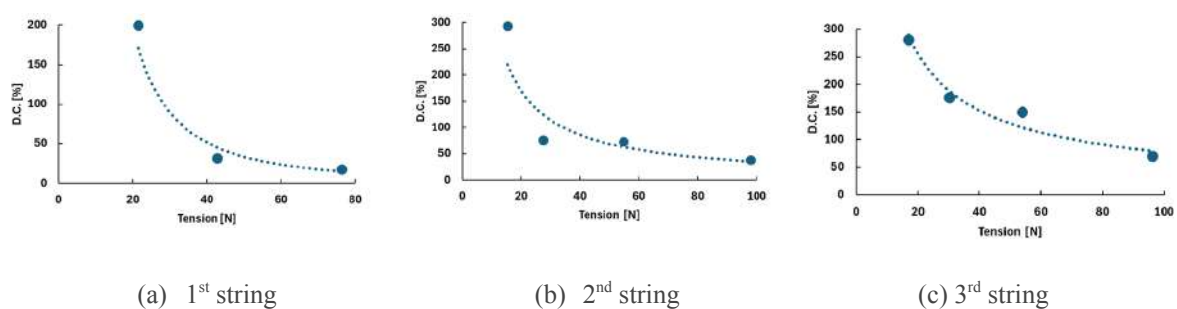


Figure 4: Dissonant interval content rate.

3.5. Volume Comparison

An oscilloscope (YOKOGAWA DL350) was used to measure sound volume. The comparison was based on the amplitude at the attack portion of the measured signal. Figure 5 shows the sound volume measurement results for the 2nd string. The results indicate that as the string tension increases, the sound volume at the attack portion increases. It has been confirmed that similar results are obtained for the 1st and 3rd strings.

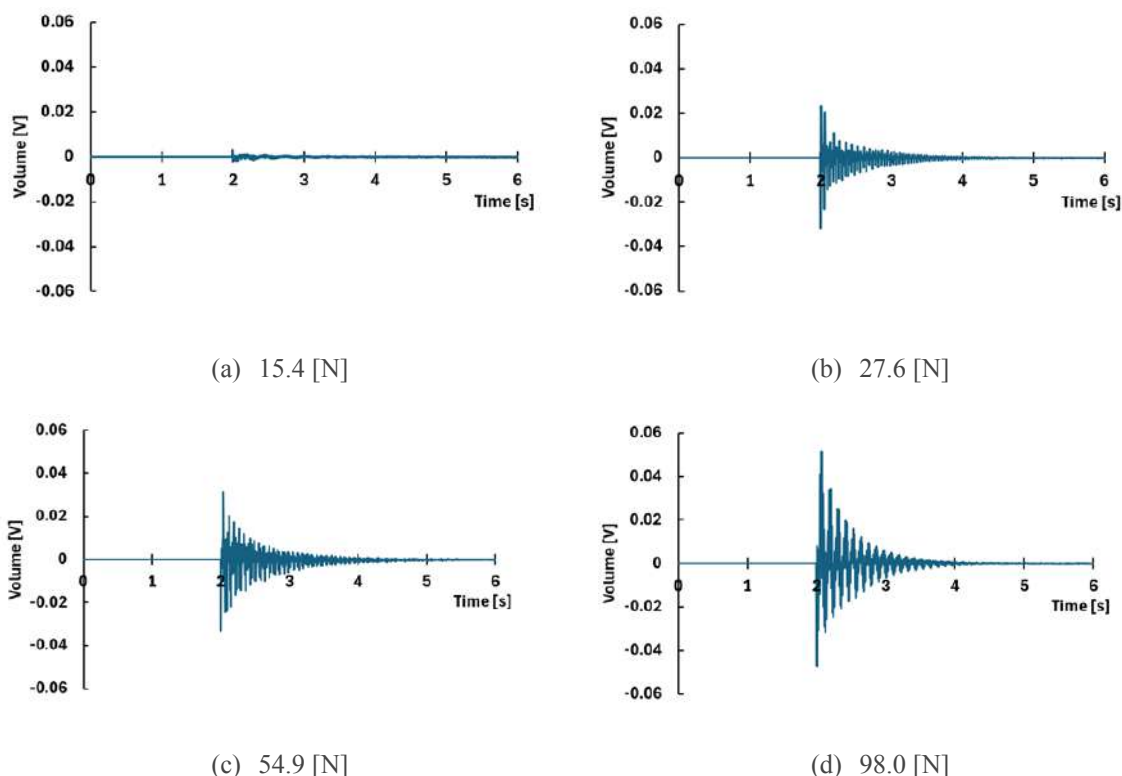


Figure 5: Volume of 2nd string.

The silent guitar used for this paper converts the vibrations produced when the strings are plucked into electrical signals via a pickup under the saddle. As the tension of the strings increases, the force applied to the saddle also increases. As a result, it is considered that the efficiency with which string vibrations are transmitted to the pickup via the saddle was improved, resulting in a louder volume. On the other hand, in a standard classical guitar with a soundboard, the vibrations produced when the strings are plucked are transmitted from the bridge to the soundboard, causing the entire soundboard to vibrate. This causes the air surrounding the guitar and inside the body to vibrate, amplifying the sound. Based on this process, it is considered that even with a standard classical guitar, increasing the string tension improves the efficiency of vibration transmission, resulting in a louder volume.

VI. Conclusion

It is generally perceived that higher string tension tends to result in a sound that is perceived as clearer. Therefore, in this paper, the characteristics of the sound produced when the tension of classical guitar strings is varied were examined based on 3 indicators: inharmonicity, overtone composition, and volume. The results confirmed that increasing string tension reduces inharmonicity, thereby quantitatively demonstrating the phenomenon given by the theoretical equation. Furthermore, as string tension increased, dissonant interval content rate decreased, while the volume increased. Based on the above results, it is considered that the reduction in inharmonicity and the decrease in overtones in the dissonant interval domain contribute to the perceived clarity of tone when string tension is increased. Furthermore, an increase in volume was observed, suggesting that increasing string tension brings about desirable acoustic characteristics from the perspective of many factors, including clarity and volume. By applying these findings to the selection of strings with higher tension, the development of strings using materials with higher linear density, and the development of guitars with new structures that achieve equivalent higher string tension, it is considered that this paper can contribute to improving the acoustic characteristics of classical guitars. The authors plan to conduct similar studies on other stringed instruments in the future.

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