

# VIBRATION MECHANISM AND EXPERIMENTAL VERIFICATION OF VIOLIN STRINGS

ZiChen Xu, EnZe Liu\*

*Student Affairs Office, Shanghai Nanyang Model School, Shanghai 200030, China.*

*Corresponding Author: EnZe Liu, Email: [liu\\_enze@sjtu.edu.cn](mailto:liu_enze@sjtu.edu.cn)*

**Abstract:** This research investigates the vibration mechanism of violin strings and the associated influencing factors by integrating theoretical analysis with experimental measurements.

A mechanical model describing string vibration was developed, indicating the relationship among the natural frequency and key parameters including tension, linear density, and effective string length. Using a smartphone as the recording device, the experimental measurements of string vibration signals were conducted under various conditions, such as differing string materials, excitation positions, forces, excitation methods, and effective lengths. Subsequent spectral analysis was performed utilizing Fourier transform theories. The results demonstrate that: (1) the natural frequencies of the string are determined by its physical properties and remain unaffected by the position or magnitude of excitation. (2) There exists an inverse relationship between effective string length and natural frequency, with the fundamental frequency exhibiting a remarkable decrease as the length increases. (3) While the frequency domain components remain consistent across different excitation methods (plucking versus bowing), the distribution of harmonic energy varies. This research offers an experimental validation approach for the acoustic properties of stringed instruments and elucidates the underlying physical mechanisms by which string vibration affects timbre. The results provide a scientific foundation for instrument manufacturing, performance enhancement, and pedagogical practices in music education.

**Keywords:** Violin string; Vibration mechanism; Natural frequency; Fourier analysis; Acoustic properties; Experimental validation

## 1 INTRODUCTION

Violin is a string instrument renowned for its expressive capabilities in classical music, is often referred to as the "Queen of Instruments". As the most crucial instrument in the string section of modern orchestras, it possesses a pure and beautiful tone with rich emotional resonance. Over centuries of development, it has become a paradigm where art and science converge. Over the past centuries, extensive research has been conducted on the violin. To craft instruments with superior sound quality, scientists have continuously developed scientific methods and conducted experiments to uncover the principles behind exceptional violin manufacturing. Figure 1 illustrates a schematic of violin performance.



**Figure 1** Schematic of Violin Performance

The fundamental mechanism underlying violin sound generation arises from the vibration of the strings induced by friction with the bow hair. Given that the strings exhibit intrinsic resonant frequencies, the bow predominantly stimulates vibrations in proximity to these natural frequencies[1]. Consequently, the vibration of the string fundamentally determines the primary pitch, timbre characteristics, and expressive capabilities of the performance. A comprehensive understanding of this vibration mechanism is essential not only for elucidating the physical basis of the violin's musical appeal but also for its considerable theoretical and practical implications in instrument manufacturing, the refinement of performance techniques, and the design of novel stringed instruments. The violin's four strings (G, D, A, E, from bass to treble, thick to thin) are primarily made of types of materials: gut, steel, and synthetic fibers such as nylon. Each of these materials exerts a distinct impact on the instrument's tonal quality and vibration characteristics. Gut strings generate a brilliant and luminous tone characterized by exceptional responsiveness and strong capabilities for tonal modulation. Nylon strings produce a soft and sweet sound, generally exhibiting slightly lower volume levels compared to metal strings. Steel strings provide a bright and expressive tone and demonstrate greater durability than nylon strings, as illustrated in Figure 2. Violin strings are available in high, medium, and low tension variants,

necessitating selection according to the particular instrument. With the strategic choice or combination of different string types, it is possible to achieve a balanced timbre and volume, thereby enhancing the overall tonal quality.



**Figure 2** Violin Strings

Fundamental theory research on string vibration can be traced back to the 17th and 18th centuries. The partial differential equation describing the transverse vibrations of a uniform string was initially formulated by the mathematician d'Alembert, who demonstrated that the displacement at any point along the string adheres to the wave equation[2]. Subsequently, researchers including Bernoulli and Euler advanced the concept of standing waves, demonstrating that the string vibration is essentially the superposition of the fundamental frequency alongside a series of harmonic frequencies (overtones) that collectively generate standing wave patterns[3]. In the 19th century, through innovative experimental investigations, Helmholtz elucidated that an ideal string subjected to continuous friction from a bow does not undergo sinusoidal vibration. Rather, it exhibits a distinctive motion pattern characterized by an “inflection point” (known as Helmholtz motion), wherein the location of the turning point periodically moves along the contact region between the bow and the string[4]. Contemporary studies have increasingly integrated factors including the Young's modulus of the string material, geometric nonlinearities such as large-amplitude effects, and internal damping mechanisms to develop more sophisticated physical models. Simultaneously, advanced technologies, such as high-speed photography and laser vibrometry, has substantially improved experimental methodologies for capturing transient phenomena and intricate string vibration modes.

Despite increasingly sophisticated theoretical models have been developed, there remains a significant need for comprehensive experimental validation of these vibration characteristics. This research focuses on vibration mechanisms and experimental validation of violin strings, aiming to achieve the following objectives:

(1) To enhance theoretical comprehension by conducting a systematic review of fundamental string vibration theories, including wave equations, the standing waves formation, and frequency formulas, with the focus on analyzing how tension, linear density, and effective string length influence fundamental and harmonic frequencies. (2) The second objective is to formulate practical experimental methodologies. Utilizing commonly accessible devices for high school students, such as smartphones, this research aims to put forward a set of straightforward and quantitative protocols for assessing string vibration frequency, modes, waveforms, and decay properties under diverse conditions, including variations in tension, string material, and excitation position or method. (3) The third objective aims to empirically validate key mechanisms by examining the effects of different excitation methods (including variations in bow speed, pressure, and contact point) on vibration modes (utilizing high-speed photography to capture standing wave patterns), as well as analyzing sound spectra to assess harmonic distribution, thereby elucidating their contributions to timbre. This study seeks to transform abstract physical concepts related to vibrations and waves into tangible, quantifiable scientific phenomena, thereby establishing an empirical connection between musical artistry and physical science. This approach not only strengthens foundational mechanics knowledge but also fosters the development of rigorous scientific reasoning, experimental design skills, and proficiency in data analysis. The results are expected to serve as illustrative case studies for the acoustics of string instruments, providing preliminary physical insights for novices in string selection and tonal modulation. In doing so, the research exemplifies the scientific ethos of “Study Things to Acquire Knowledge,” contributing to a deeper understanding of humanity’s cultural and artistic heritage.

## 2 METHODOLOGY

An integrated methodology encompassing both theoretical analysis and experimental measurement is utilized in this study. Initially, a mechanical model characterizing the vibration behavior of violin strings is formulated. Subsequently, practical experimental methods are investigated, wherein smartphone recordings are employed to capture the acoustic signals produced by the vibrating strings for quantitative assessment. The experimental data are then systematically analyzed to provide insights into the vibration mechanisms of violin strings.

### 2.1 Force Model of Violin Strings

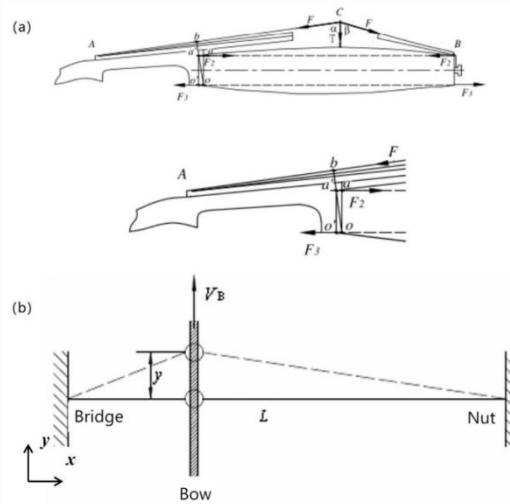
The structural and geometric properties of the violin result in intricate force conditions. Figure 3(a) indicates the primary force points on a stationary violin. The nut end is identified as point A, the saddle end is identified as point B,

and the top of the bridge is identified as point C. Denoted as  $F$ , the tension force exerted by the strings produces a vertically downward component at the angle associated with point C. The resultant of these components constitutes the pressure  $T$  applied by the strings onto the bridge. In the nut section,  $F$  denotes the string tension,  $F_2$  represents the longitudinal pressure exerted on the upper edge of the top plate, and  $F_3$  signifies the longitudinal pressure applied to the end of the back plate.

The mechanical structure of violin constitutes a complex dynamic system, characterized by intricate interactions among all points of force application. Taking point A as an example, its spatial position is determined by the height of the nut and the protrusion of the wooden neck tenon. It is also further refined through the elastic deformation of the neck-fingerboard assembly.

Being a relatively fixed pivot, point B enables luthiers to accurately regulate the compressive force  $T$  applied by the strings on the bridge through adjustments to its vertical position. The spatial coordinates of point C demonstrate a complex dependency on multiple parameters, including bridge geometry, headstock angle, string spacing, tenon protrusion, and top plate curvature. Moreover, these coordinates reflect the combined deformation effects of the instrument body under string tension.

According to system mechanics, enhancing the compressive stress  $T$  exerted by the bridge on the soundboard can be achieved through three primary regulatory mechanisms. First, lowering the position of point A results in a simultaneous reduction of the vector components of forces  $F_2$  and  $F_3$ . Second, modifications to the height of point B have a negligible effect on forces  $F_2$  and  $F_3$ . Third, raising the spatial coordinate of point C leads to a concurrent increase in  $T$ ,  $F_2$ , and  $F_3$ . This quantitative analysis of the force network offers luthiers a scientifically grounded framework for decision-making, allowing for the optimization of specific mechanical parameters in alignment with acoustic performance goals as defined by the acoustic objective function.



**Figure 3** Force Conditions on a Violin. (a) Static Force Analysis of the Violin, (b) Simplified Vibration Model of Bow-String Interaction

In violin performance, the bow (the exciter), strings, bridge, and body (the resonance chamber) collectively constitute a string vibration system. A simplified vibration model is illustrated in Figure 3(b). Upon excitation of the string by the bow, the system vibrates in accordance with its intrinsic properties. When the string undergoes continuous excitation through bowing, the system maintains sustained vibration. The vibration mechanism of stringed instruments during bowing is notably complex. However, this simplified model primarily focuses on the free vibration behavior of the string to analyze its vibration characteristics. Specifically, it examines the initial excitation delivered by the bow followed by its cessation, allowing the string to vibrate freely. Under the assumptions of constant internal tension  $T$  and uniform string thickness with constant linear density  $\rho$ , the free vibration of the string can be mathematically modeled as follows:

$$\frac{\partial^2 y(x,t)}{\partial x^2} = \frac{\rho}{T} \frac{\partial^2 y(x,t)}{\partial t^2} \quad (1)$$

Assuming the displacement  $y$  of the string vibration is separated in time and space, the method of separated variables is employed. We assume:

$$y(x,t) = Y(x)F(t) \quad (2)$$

Substituting into equation (1):

$$\frac{T}{\rho Y(x)} \frac{d^2 Y(x)}{dx^2} = \frac{1}{F(t)} \frac{d^2 F(t)}{dt^2} \quad (3)$$

Both sides of the above equation are functions of variables  $x$  and  $t$ . Consequently, both sides are set equal to a constant. Denoting this constant by  $-\omega^2$ , then equation (3) can be expressed as:

$$\frac{d^2 F(t)}{dt^2} + \omega^2 F(t) = 0 \quad (4)$$

$$-T \frac{d^2 Y(x)}{dx^2} = \omega^2 \rho Y(x), \quad 0 < x < L \quad (5)$$

Solving this equation yields the characteristic frequency (natural frequency) of the string:

$$\omega_i = \beta_i \sqrt{\frac{T}{\rho}}, \quad (i=1, 2, \dots) \quad (6)$$

$$\beta_i L = i\pi, \quad (i=1, 2, \dots) \quad (7)$$

where  $i$  denotes the order of the characteristic frequency. This research primarily focuses on the first-order natural frequency of violin strings, examining the variation patterns of natural frequencies among strings with differing parameters.

## 2.2 String Acoustic Signals Analysis

### 2.2.1 String acoustic signal recording

The entire sound production mechanism of a violin encompasses the initial plucking of the string to induce vibration, which subsequently stimulates air vibrations adjacent to the sound holes via the resonance of the instrument body, thereby producing Helmholtz resonance[5]. Consequently, the act of plucking the string and subsequently recording the emitted sound signal via a mobile phone recording app effectively captures data pertaining to the string's inherent vibration natural frequencies.

The basic information of the four violin strings used in this study is summarized below. All four strings possess an approximate length of 32 cm. The diameters of the strings are listed as follows: the G string ranges from 0.72 to 0.76 mm, the D string ranges from 0.62 to 0.66 mm, the A string ranges from 0.52 to 0.56 mm, and the E string ranges from 0.42 to 0.46 mm. The sound recording were conducted with both the smartphone and violin held stationary throughout the experiments.

Experiment 1 involved selecting the midpoints of all four strings as the plucking positions. Each string was plucked with a consistent force, and the resulting acoustic signals were recorded simultaneously using the smartphone.

In Experiment 2, the E string was designated as the subject. This string was divided into four equal segments, with plucking positions established at 8 cm, 16 cm, and 24 cm from one end. Each segment was plucked with uniform force, and the corresponding acoustic signals were recorded concurrently.

Experiment 3 also utilized the E string as the test subject, where the string was plucked at its midpoint with varying force levels categorized as light, medium, and heavy. Acoustic signals were recorded simultaneously during these plucks.

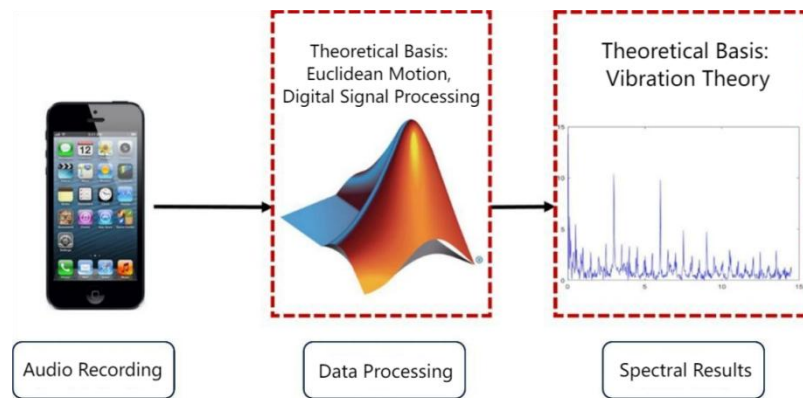
In Experiment 4, the E string's effective vibrating length was altered by firmly pressing the string at positions corresponding to lengths of 17.9 cm, 21.7 cm, and 27 cm, respectively. The string was then plucked, and the resulting acoustic signals were recorded.

Finally, Experiment 5 involved consecutive plucking of the four strings by hand, followed by consecutive bowing of the four strings using a bow, with the corresponding acoustic signals recorded in each case, see Table 1.

**Table 1** Vibration Mechanism and Experimental Verification of Violin Strings

| Number                                                               | String | Length | Material                                | String Tension |
|----------------------------------------------------------------------|--------|--------|-----------------------------------------|----------------|
| 4                                                                    | E      | 31.9cm | steel                                   | 8.0*9.8N       |
| 3                                                                    | A      | 32cm   | nylon core with aluminum-coated surface | 5.5*9.8N       |
| 2                                                                    | D      | 32cm   | nylon core with silver-coated surface   | 4.5*9.8N       |
| 1                                                                    | G      | 32cm   | nylon core with silver-coated surface   | 4.6*9.8N       |
| I Pluck the midpoint of each string                                  |        |        |                                         |                |
| Pluck the E string at three points.                                  |        |        |                                         |                |
| Pluck the midpoint of E string with light, medium, and heavy forces. |        |        |                                         |                |
| II Press the E string                                                |        |        |                                         |                |
| III Consecutively pluck the four strings and bow the four strings    |        |        |                                         |                |

Experiments captured acoustic signals from plucking strings with varying parameters, plucking the same string at different positions, plucking strings with different intensities, strings of different lengths, and plucking or bowing all four strings. A more detailed examination of these acoustic signals was conducted utilizing MATLAB software, which facilitated the extraction of the natural frequencies of the strings. The primary analytical and processing procedure is depicted in Figure 4.



**Figure 4** Acoustic Signal Processing Workflow for Violin String Vibrations

### 2.2.2 Fourier analysis of string acoustic signals

The acoustic signals captured by a mobile phone are digital in nature and are subsequently processed using computational methods. For motion patterns that change over time, these signals fundamentally constitute one-dimensional numerical sequences. Signals may be classified according to the dimensionality of their values into one-dimensional, two-dimensional, or three-dimensional categories, for example, acoustic signals are one-dimensional signals. Given that the independent variable in signal analysis is generally time, extracting the intrinsic frequency characteristics of string vibrations necessitates transforming the signal from the time domain to the frequency domain through the application of the Fourier transform.

According to the principles of Fourier analysis, any periodic signal that meets the Dirichlet conditions—namely, piecewise continuity, a finite number of extrema, and absolute integrability—can be represented as a linear combination of sine and cosine functions at various frequencies. Each sine or cosine term corresponds to a specific frequency component, allowing the Fourier series expansion to facilitate a detailed examination of the signal's frequency content. Consequently, this method enables a comprehensive characterization of the signal's spectral properties[6].

To address the constraint that Fourier series are applicable solely to periodic signals, the Fourier transform is derived by considering the limit in which the period tends toward infinity, as illustrated in the following equation:

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t} dt \quad (8)$$

While the Fourier transform provides a comprehensive mapping of continuous-time signals into the frequency domain for analytical purposes, its formulation as a continuous integral precludes direct implementation within digital systems. To overcome this limitation, the Discrete Fourier Transform (DFT) was introduced. By discretizing the sampled time-domain sequence, the DFT reformulates the Fourier transform into a numerical format amenable to computational processing. Consequently, this transformation enables the conversion of discrete time-series data into their corresponding discrete frequency-domain representations. It preserves the core functionality of spectral analysis while enabling the digital implementation of signal processing algorithms[7]. Let  $x_N(nT_s)$  denote  $N$  sampled values of the continuous function  $x(t)$ , where  $n$  ranges from 0 to  $N-1$ . The discrete Fourier transform is defined as:

$$DFT(x_N(nT_s)) = \sum_{n=0}^{N-1} x_N(nT_s) e^{\frac{i2\pi nk}{N}} \quad (9)$$

From the perspective of signal processing, the sampling operation can be mathematically modeled as the multiplication of the original continuous-time signal by a pulse sampling sequence. According to the convolution property of the Fourier transform, this multiplication in the time domain corresponds to a periodic convolution of the original signal's spectrum with the spectrum of the sampling function in the frequency domain. Consequently, the signal's spectrum is replicated at intervals equal to the sampling frequency, resulting in a periodic extension in the frequency domain. To avoid aliasing distortion within the spectrum, the Nyquist sampling theorem must be observed, which stipulates that the sampling frequency should be at least twice the maximum frequency component present in the signal. This requirement implies that, during spectral analysis, the highest frequency of interest must not exceed half the sampling rate, known as the Nyquist frequency. Adhering to this criterion ensures adequate separation between successive spectral replicas, thereby preventing distortion arising from spectral overlap[8].

Within the MATLAB environment, the robust matrix computation capabilities can be utilized to conduct spectral analysis on the recorded string audio signal. The Fast Fourier Transform (FFT), an efficient algorithmic realization of the Discrete Fourier Transform (DFT), is accessible through MATLAB's built-in 'fft' function[9]. The specific spectral analysis implementation code is shown in Figure 5. In this context,  $Sig$  denotes the acquired discrete time-domain signal sequence, while  $N$  represents the total number of sampled points. The methodological process is as follows: initially, the discrete time-domain signal of the vibrating string is captured via a mobile phone recording, with the sampling interval determined by the sampling frequency  $f_s$ . Subsequently, the Discrete Fourier Transform computed efficiently using the FFT algorithm is applied to transform the time-domain data into the frequency domain, thereby extracting the constituent frequency components of the signal. In summary, once the sampling frequency  $f_s$  is known and the discretized vibration time-history signal is obtained, the spectral properties of the string can be analyzed through

frequency domain transformation, which in turn provides insights into the vibration mechanism of the violin string.

```

Perform an N-point FFT transform on the time-domain signal sig
Sig_f = fft(Sig, N);

Generate the corresponding frequency coordinate axis (0 to Nyquist frequency)
freq = (0:fs/N:fs/2);

Compute the single-sided amplitude spectrum and normalize it
A_Sig_f = abs(Sig_f(1:N/2+1)) / (N/2);

Plot the spectrogram
plot(freq, A_Sig_f, 'b');

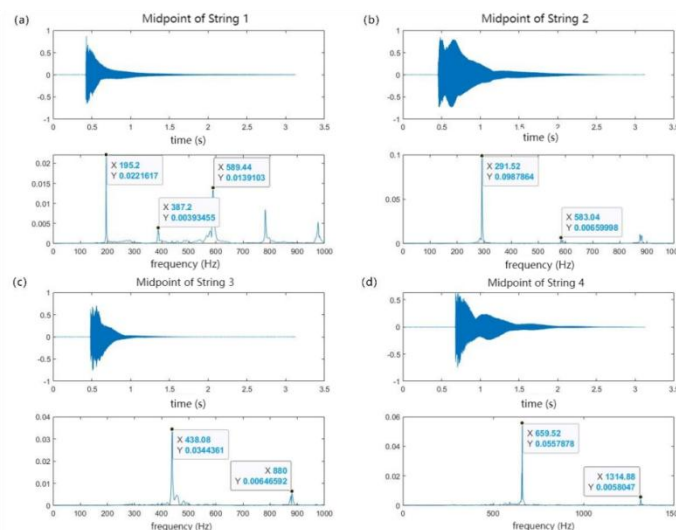
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**Figure 5** Code for Implementing Spectrum Analysis

### 3 RESEARCH RESULTS AND ANALYSIS

#### 3.1 Experiment 1: Results of Acoustic Signal Analysis concerning Strings Plucking with Different Parameters

Figure 6 presents the analytical results of the audio recordings obtained in Experiment 1, in which the midpoints of four individual strings were plucked separately. Although the plucking action is of very short duration, the strings persist in vibrating after being released by the fingers. The frequencies of these vibrations correspond to the inherent characteristic (natural) frequencies of the respective strings. The analysis of the time-domain signal indicates that, following the cessation of plucking, the vibrations of the string undergo a rapid attenuation attributable to damping mechanisms, including material damping and frictional forces. Due to the distinct physical parameters characterizing each of the four strings, their respective time-domain waveforms display unique morphological features. Examination of the frequency-domain data demonstrates that subsequent to plucking, the free vibration frequencies of the strings predominantly oscillate in proximity to their inherent natural frequencies. Specifically, the fundamental natural frequencies for the four strings are approximately as follows: the G string (first string) at 195 Hz, the D string (second string) at 291 Hz, the A string (third string) at 438 Hz, and the E string (fourth string) at 659 Hz. Moreover, spectral analyses for each string reveal that the principal frequency components correspond to the various harmonic orders of the natural frequencies, as delineated by Equation (6). The amplitude distribution further corroborates that the first-order natural frequency constitutes the dominant frequency component for each string.

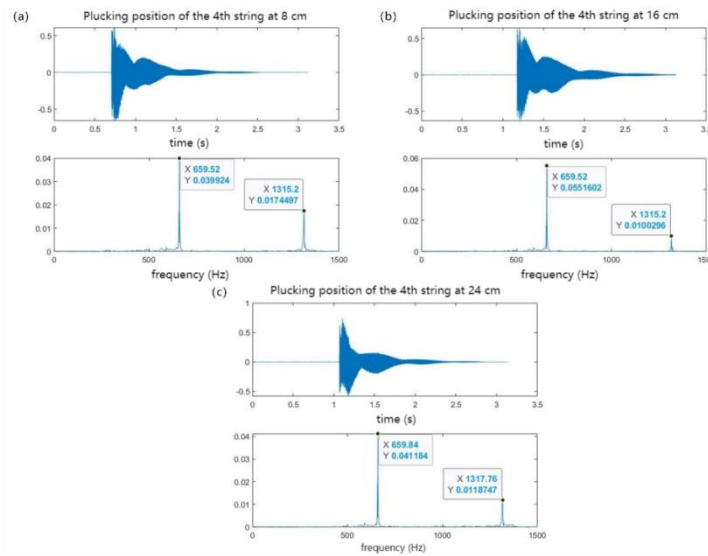


**Figure 6** Audio-Frequency Domain Results for Plucking Four Strings

#### 3.2 Experiment 2: Results of Acoustic Signal Analysis concerning Strings Plucking at Different Positions

The fourth string (E string) was selected as the focus of this study to examine the influence of varying plucking positions on the free vibration response of a violin string. The results are presented in Figure 7. Analysis in the time domain indicates that the waveforms and vibration duration are nearly identical across the different plucking positions. As for the frequency domain, the free vibration frequency components remain largely consistent regardless of the plucking position, predominantly comprising the string's natural frequencies of various orders. It is evident that the

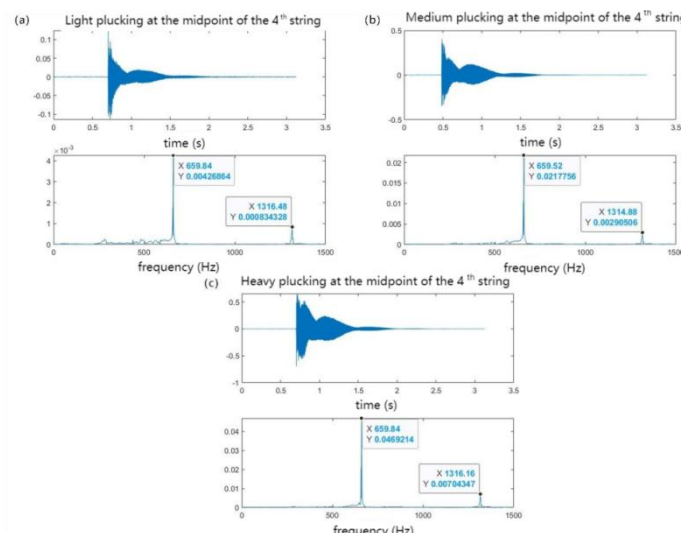
string natural frequencies are unaffected by the point of excitation, in agreement with Equation (6). Nevertheless, variations in the plucking position lead to differences in the energy distribution among the harmonic frequency components. Due to the structural symmetry of the string, the amplitude magnitudes and relative proportions of the harmonic frequencies depicted in Figures 7(a) and 7(c) are almost identical, while they differ to some extent from those shown in Figure 7(b).



**Figure 7** Audio-Frequency Domain Results for Plucking at Different Positions

### 3.3 Experiment 3: Results of Acoustic Signal Analysis concerning Strings Plucking with Different Forces

Experiment 3 also selected the E string (4th string) as the research subject. The violin string was plucked at its midpoint with varying forces to investigate the effect of different input amplitudes on the free vibration response of the violin string. The results are shown in Figure 8. According to Equation (6), the natural frequency of a string depends solely on its linear density, length, and internal tension. Consequently, the results of Experiment 3 closely parallel those observed in Experiment 2: variations in the forces of string plucking yield time-domain waveforms and vibration duration that are almost indistinguishable. Similarly, the frequency-domain analyses reveal frequency components and amplitude ratios among these components that remain largely consistent. Nevertheless, owing to differences in input magnitudes, the output amplitudes exhibit substantial variation. These results indicate that changes in plucking force influence only the output loudness, without affecting the output frequency characteristics.

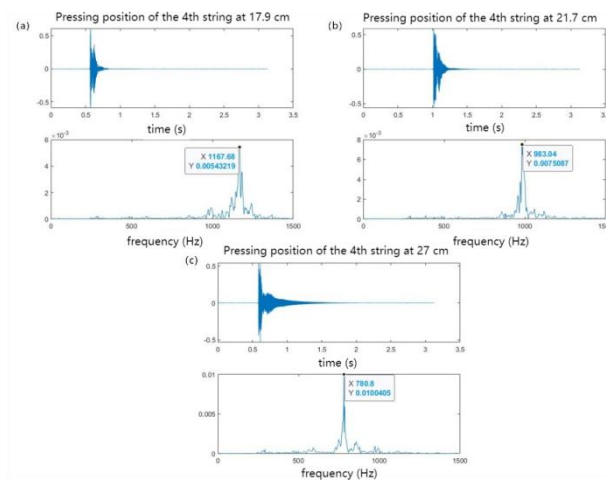


**Figure 8** Audio-Frequency Domain Results for Different Plucking Forces

### 3.4 Experiment 4: Results of Acoustic Signal Analysis concerning Plucking Strings of Different Lengths

Experiment 4 altered the effective vibrating length of the E string (4th string) to investigate the free vibration response of violin strings with varying lengths. The results are shown in Figure 9. The free vibration responses of the three strings, each possessing different effective lengths, demonstrate that an increase in the effective vibrating length corresponds to an elongation of the time-domain output duration. Concurrently, the principal frequency components

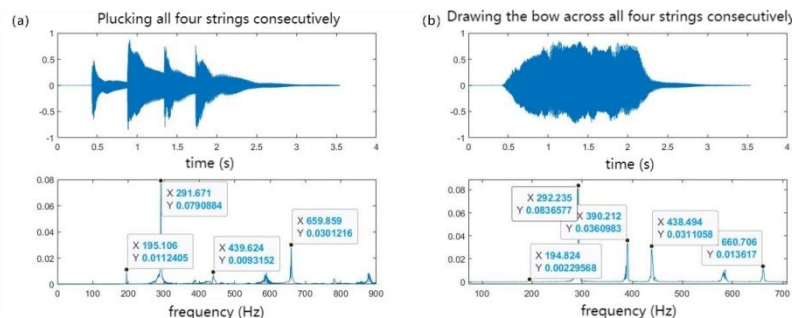
observed in the frequency-domain output exhibit a shift toward lower frequencies. This reduction in dominant frequencies signifies that the natural frequency decreases as the effective vibrating length increases, thereby illustrating an inverse relationship between natural frequency and string length, in accordance with the formulation presented in Equation (6).



**Figure 9** Audio-Frequency Domain Results for Plucked Strings of Different Lengths

### 3.5 Experiment 5: Results of Acoustic Signal Analysis concerning Different Excitation Methods

Experiment 5 involved plucking all four strings consecutively by hand and drawing the bow across all four strings consecutively, investigating the impact of these two excitation methods on the audio frequency of violin string vibrations. The findings are presented in Figure 10. It is evident that the time-domain signals associated with the two excitation methods exhibit significant differences. When the strings are plucked sequentially by hand, the precise time instances at which each string is excited are distinctly identifiable. Conversely, due to the continuous nature of bowing, the time-domain signal generated by this excitation technique does not allow for the clear differentiation of the exact moments at which individual strings are activated. Analysis of the frequency-domain data reveals that the dominant frequency components of the audio output are largely consistent across both excitation methods, corresponding to the inherent natural frequencies of the respective strings. Nonetheless, the amplitude ratios of these frequency components vary between the two excitation approaches, indicating their differential impact on the resultant acoustic output of the violin.



**Figure 10** Audio Time-Frequency Domain Results for Strings Under Different Excitation Methods

## 4 CONCLUSIONS

This research presents a systematic investigation of the vibration mechanisms of violin strings and the factors influencing them, integrating theoretical modeling with experimental validation. A mechanical model of string vibration was developed to theoretically derive quantitative relationships linking the natural frequency to string tension, linear density, and effective string length. Experimentally, an innovative methodology employed smartphones to record vibration signals under varied conditions, including differences in string material, excitation position, force, method, and effective length. Spectral analysis based on Fourier transform techniques substantiated several key findings: (1) the natural frequency of a string is governed by its inherent physical properties and remains unaffected by the position or force of excitation. (2) The effective string length exhibits an inverse proportionality to the natural frequency. (3) Although distinct excitation methods (plucking versus bowing) produce markedly different time-domain responses, their frequency-domain spectra are consistent, differing primarily in the distribution of harmonic energy. This study introduces an accessible experimental framework suitable for secondary education, facilitating an intuitive understanding of the physical principles underlying the sound production of violin. Moreover, it establishes a reproducible model for acoustical research on stringed instruments. By rigorously quantifying the mechanical

foundations of artistic expression, the findings offer empirical support for instrument craftsmanship, performance enhancement, and music education, thereby underscoring the distinctive role of physics in elucidating aspects of the humanities and arts.

## COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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