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Experimental Evaluation of String Tension Determination Using the Ideal String Model on Kacapi Indung

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Abstract. The ideal string vibration model based on Mersenne's law states that the vibration frequency of a string is determined by its length, linear mass density, and tension. In real musical instruments, string tension is commonly determined from physical parameters under static conditions, although the mechanical behavior of vibrating strings may differ from their equilibrium state. This study aims to evaluate a string tension determination method based on the ideal string vibration model applied to the kacapi indung instrument by comparing static tension and effective dynamic tension estimated from frequency responses obtained through Fast Fourier Transform (FFT) analysis. A quantitative experimental approach was conducted on 18 strings with variations in length, diameter, and material. Static tension was determined using the string deflection method, while effective dynamic tension was calculated from the fundamental frequency obtained from acoustic spectrum analysis. The results show that the effective dynamic tension is systematically lower than the static tension for all observed strings, with relative deviations ranging from 74.39% to 98.20% and an average deviation of 86.69%. These discrepancies indicate that the static approach does not fully represent the mechanical behaviour of strings during oscillation due to non-ideal factors such as damping, harmonic energy redistribution, string stiffness, and mechanical coupling between the strings and the instrument resonator. The findings suggest that the ideal string vibration model remains relevant as an initial theoretical framework; however, its application to real musical instruments requires consideration of more complex dynamic system behaviour. From a physics education perspective, these findings provide an empirical context for demonstrating the validity limits of idealized theoretical models when applied to real acoustic systems.

Keywords: Fast Fourier Transform (FFT); Ideal string vibration model; *kacapi indung*; string tension; acoustic measurement;

INTRODUCTION

The Sundanese *kacapi* is a traditional musical instrument that represents the cultural identity of the Sundanese community in West Java (Alfiani et al., 2024). It consists of several types, including *kacapi indung*, *kacapi rincik*, and *kacapi kawih* or *siter*. This study focuses on the kacapi indung, a Sundanese chordophone instrument whose sound is generated by vibrating strings (Andriyanti et al., 2024). The instrument employs multiple strings stretched over a wooden resonator body (Andriani, 2019). The physical diversity of kacapi indung strings, including differences in length, diameter, material composition, and playing technique, influences their mechanical response during oscillation and ultimately affects the acoustic characteristics of the instrument.

In physics, sound is understood as a longitudinal wave that propagates through a medium and originates from a vibrating source (Giancoli, 2014). In stringed instruments, sound is generated by string oscillations that are primarily determined by three physical parameters: string length, linear mass density, and tension (Fletcher & Rossing, 1991). The relationship among these parameters is described by Mersenne's law, which states that the vibration frequency of a string is proportional to the square root of its tension and inversely proportional to its length (Sugiarti et al., 2023). In this context, string tension represents a key mechanical parameter and forms the basis of the ideal string vibration model.

Although the ideal string vibration model provides a clear mathematical relationship between tension and frequency, its application to real instruments often encounters limitations. Real strings exhibit non-ideal characteristics such as elastic stiffness, damping, and mechanical coupling with the instrument body, which can lead to deviations of the dynamic response from ideal model predictions (Fletcher & Rossing, 1991). These deviations may be reflected in the harmonic spectrum structure and energy distribution among vibration modes, ultimately influencing the tonal characteristics of the instrument (Sethares, 2005). Therefore, experimental evaluation is required to determine the extent to which string tension determined using the ideal model represents the actual dynamic condition of vibrating strings. Importantly, previous studies have largely focused on frequency analysis and acoustic characteristics, while none of these studies explicitly examined whether static tension measurements based on the ideal string model can accurately represent the effective dynamic tension of vibrating strings in real musical instruments.

Previous studies on stringed instruments have generally focused on frequency measurements as a representation of wave phenomena. For example, Afifah et al. (2020) analyzed the frequency of acoustic guitar strings using smartphone-based devices to examine the relationship between string parameters and the resulting frequency. While such approaches effectively demonstrate trends among physical variables, they do not explicitly test the validity of string tension determination methods. Meanwhile, Grimes (2014) reported that variations in tension and dynamic conditions in guitar strings can produce frequency responses that do not always follow simple predictions of the ideal string model. These findings indicate that evaluating string tension under dynamic conditions is an important aspect that requires further investigation.

Acoustic studies on Indonesian traditional musical instruments have largely concentrated on frequency measurements in instruments such as gamelan, angklung, and bamboo flute to illustrate the relationship between theoretical concepts and experimental observations (Widayanti & Pramudya, 2017; Nurhidayati et al., 2022; Nursulistiyo, 2015). However, research comparing string tension parameters obtained from static approaches with dynamic tension estimated from frequency responses remains limited, particularly for traditional string instruments such as the *kacapi indung.*

In the context of physics education, the kacapi indung provides a relevant experimental context for demonstrating the relationship between theoretical string vibration models and real acoustic phenomena. The instrument allows students to explore how physical parameters such as string length, linear mass density, and tension influence vibration frequency, while also illustrating the limitations of idealized models when applied to real systems.

Accordingly, this study aims to evaluate a string tension determination method based on the ideal string vibration model by integrating measurements of physical string parameters with experimental frequency analysis using the Fast Fourier Transform (FFT). This approach is intended to assess the extent to which tension determined from the ideal model can represent the mechanical condition of strings during oscillation.

The findings of this study are expected to provide an empirical basis for evaluating the applicability of the ideal string vibration model in real musical instrument systems, particularly in representing the relationship between static string tension and dynamic vibration responses. In addition, this study is expected to contribute to a deeper understanding of the mechanical behaviour of vibrating strings in traditional musical instruments and to demonstrate the validity limits of idealized physical models in real acoustic systems.

METHOD

This study employed a quantitative experimental design with a comparative approach to examine a string tension determination method applied to the kacapi indung instrument. From a pedagogical perspective, this experimental approach provides a contextual example for connecting theoretical concepts of wave mechanics with experimental observations in real acoustic systems. Hands-on experiments and demonstrations are considered important in physics learning because they can improve students' conceptual understanding and engagement with scientific phenomena (Rashid et al., 2024). The evaluation was conducted by comparing the static string tension ($\boldsymbol{T}_{\text{static}}$), obtained from physical measurements, with the effective dynamic tension ($\boldsymbol{T}_{\text{FFT}}$) estimated from frequency responses analyzed using the Fast Fourier Transform (FFT). The instrument investigated was a set of kacapi indung consisting of 18 strings with varying lengths and diameters.

1. Determination of Theoretical Frequency

The theoretical vibration frequency of the strings was calculated using the ideal string vibration model based on Mersenne's law (Fletcher & Rossing, 1991; Sugiarti et al., 2023). This model states that the vibration frequency of a string is determined by the vibrating string length (L), linear mass density (μ), and string tension, assuming that the string is homogeneous, perfectly flexible, and free from damping and resonant interaction effects. The general expression for the harmonic frequency is given by:

$$f_n = \frac{n}{2L}\sqrt{\frac{T_{statis}}{\mu}} \qquad [1]$$

In equation 1, n represents the harmonic order, L denotes the string length (m), T_{static} is the static string tension (N), and μ is the linear mass density (kg/m).

The vibrating string length (L) was measured using a ruler with a precision of 0.05 cm (±0.0005 m). The string diameter was measured using a vernier caliper with a precision of 0.05 mm to ensure consistency between the kacapi strings and the reference strings used for mass measurements. The linear mass density (μ) was determined by measuring the mass and length of strings made of the same material and having the same diameter as those mounted on the instrument. These reference strings were used to preserve the original configuration and playability of the kacapi during the experiment.

String mass was measured using a digital balance with a precision of ±0.001 g and repeated ten times to obtain a more representative average value. String length was measured using a steel ruler with a precision of ±0.0005 m. The linear mass density was then calculated using Equation (2). Differences in string material, namely stainless steel and brass, as well as variations in string diameter resulted in different values of μ, which contributed to variations in the calculated theoretical frequencies.

$$\mu = \frac{m}{l} \qquad [2]$$

where m represents the string mass (kg) and l denotes the length of the identical string (m). The use of identical strings was intended to preserve the original playing condition of the *kacapi* without altering the acoustic characteristics of the instrument.

2. Determination of Static String Tension

Static string tension was determined using the string deflection method. In this method, a horizontally mounted string on the instrument was vertically displaced at its midpoint by applying an external force F. As a result of this force, the string experienced a transverse displacement, forming a geometric configuration resembling an isosceles triangle. The string tension acted along the two inclined segments of the string. By resolving the tension forces along the vertical axis, two downward force components T_{y1} and T_{y2}, were obtained.

By applying force equilibrium analysis along the vertical axis, the relationship between the applied force and the string tension can be expressed as follows:

$$F - T_{y1} - T_{y2} = 0 \qquad [3]$$

Based on the geometry of the deflected string and the angle formed by the tension components T_x and T_1, denoted as α, the following relationship can be obtained:

$$F = 2T \sin \propto \qquad [4]$$

where Tdenotes the string tension and αrepresents the angle between the deflected string segment and the horizontal direction. For deflections that are relatively small compared to the string length, a small-angle approximation was applied, so that:

$$\sin \alpha \approx \tan \alpha = \frac{d}{L/2} \qquad [5]$$

Where d is the maximum transverse displacement at the midpoint of the string and L is the vibrating string length. Accordingly, the static string tension can be expressed as (Gomez, 2018):

$$T \approx \frac{FL}{4d} \qquad [6]$$

This expression is valid under the condition $d \ll L$, indicating that the applicability of the small-angle approximation is limited to small transverse displacements in vibrating string systems (Roy, 2024). In this experiment, the ratio d/L was on the order of 10^{-3} to 10^{-2}, indicating that the linear geometric approximation remained appropriate as an initial estimation of static string tension. The applied force was measured using a spring balance with a measurement resolution of ±1 N. String displacement was determined from the change in the vertical position of the midpoint before and after the force was applied, using a ruler with a precision of ±0.0005 m. The vibrating string length was measured using a steel ruler with the same precision. All measurements were conducted while the strings remained mounted on the instrument under normal tuning tension. The experimental setup for measuring string tension is illustrated in Figure 1.

Figure 1. Experimental setup for measuring the applied force and string displacement

The deflection method employed in this study is highly sensitive to the magnitude of string displacement. Since the estimated tension is inversely proportional to the displacement, measurement uncertainties on the millimeter scale may lead to significant variations in the calculated tension values. In addition, relatively large applied forces may cause deviations from the ideal geometric assumptions due to the influence of string bending stiffness and non-ideal boundary conditions in real instrument systems. Therefore, the obtained static tension values are considered as initial estimations representing the mechanical condition of the strings under equilibrium.

3. Recording Procedure and Frequency Analysis Using FFT

The dynamic response of the *kacapi indung* strings was analyzed by measuring the sound frequency using the Fast Fourier Transform (FFT) method. Sound recording was conducted in a music studio to minimize environmental noise. Background noise levels were monitored using a sound level meter application and were found to be relatively low (±18 dB), indicating that the recording environment was sufficiently quiet for data acquisition.

The recording setup is illustrated in Figure 2. A microphone was positioned above the instrument near the bridge area and aligned with the soundboard plane, following standard acoustic string instrument recording principles (Shure, 2014). The microphone distance was determined through preliminary tests involving several distance variations evaluated using FFT analysis based on the clarity of frequency peaks and the stability of the spectral distribution (Basir et al., 2020). A distance of 14 cm was selected as the optimal configuration, as it produced the clearest and most consistent frequency spectrum.

Figure 2. Experimental setup for recording the sound of *kacapi* strings

Plucking was performed using basic kacapi playing techniques to maintain excitation consistency, since variations in plucking force and angle can influence the vibration response of string systems (Tahvanainen & Hochmuth, 2024). Each string was plucked ten times with an interval of approximately ±1 s between plucks to minimize the influence of variations in plucking force and residual vibrations from previous excitations. Repeated measurements were also intended to ensure the consistency of the identified fundamental frequency obtained from the FFT spectrum, thereby improving the reliability of the spectral analysis. The recorded signals for each string were stored as separate audio files to allow individual analysis.

Frequency spectrum analysis was carried out using Audacity software through the Plot Spectrum feature based on FFT processing, a method commonly applied in time–frequency analysis of musical instrument vibrations (Jannereth & Esch, 2021). A Hann window was applied to minimize spectral leakage and reduce side lobes in the frequency spectrum (Cadum et al., 2007). The FFT size was set to 4096 with a sampling rate of 48 kHz, resulting in a frequency resolution of approximately $\Delta f \approx 11.7$ Hz (Uriostegui-Hernandez et al., 2025). This resolution was considered sufficient to identify the main harmonic components of the *kacapi* sound.

The fundamental frequency was identified as the lowest frequency peak that appeared consistently in the FFT spectrum. To ensure that the selected peak corresponded to the first harmonic component rather than noise, verification was performed across ten plucking trials for each string. Validation was conducted by examining the regularity of the harmonic structure, specifically by confirming that subsequent peaks were located near integer multiples of the fundamental frequency ($\approx 2f$, $3f$, and so forth). The fundamental frequency values were then averaged, and their standard deviations were calculated to represent measurement consistency.

4. Data Analysis

Data analysis in this study focused on evaluating string tension obtained from two different approaches: static tension calculated from the physical parameters of the strings and effective dynamic tension estimated from frequency responses derived from spectral analysis. Static tension (T_s) was determined using the vibrating string length, linear mass density, and the mathematical relationship derived from the ideal string vibration model. This value represents the mechanical condition of the string at equilibrium prior to excitation.

For comparison, the effective dynamic tension (T_{FFT}) was estimated from the fundamental frequency obtained through Fast Fourier Transform (FFT) analysis by applying the inverse form of Mersenne's law.

$$T = 4L^2 \mu f^2 \qquad [7]$$

In equation 7, L denotes the vibrating string length, μ represents the linear mass density of the string, and f_{FFT} is the fundamental frequency obtained from spectral analysis. The estimated tension T_{FFT} represents the effective tension of the system when the string is in a dynamic condition during oscillation.

The comparison between static tension (T_s) and effective dynamic tension (T_{FFT}) was used as the main parameter to evaluate the extent to which the tension determination method based on physical string parameters can represent the mechanical condition of the string system during oscillation. The difference between the two values was calculated using:

$$\Delta T = T_s - T_{FFT} \qquad [8]$$

where ΔT represents the absolute difference between the static tension and the effective dynamic tension for each string. In addition to the absolute tension difference, the relative deviation between the two approaches was calculated to quantify the discrepancy between static and effective dynamic tension using:

$$\text{Relative Deviation} = \frac{|T_s - T_{FFT}|}{T_s} x100\% \qquad [9]$$

Relative deviation analysis is commonly used as a quantitative metric to evaluate the discrepancy between predicted and measured values in experimental studies (Li et al., 2024).

Overall, the data analysis in this study considers string tension as the primary evaluation parameter, while frequency analysis is employed as an indirect approach to estimate dynamic tension and to assess the consistency of the ideal string model with the vibration response of a real system.

RESULT AND DISCUSSION

1. Static String Tension and Theoretical Frequency Prediction Based on the Ideal String Model

In this study, the static tension of each *kacapi indung* string was determined from physical measurements and used as the primary parameter in the ideal string vibration model. Static tension represents the mechanical condition of the string at equilibrium before dynamic excitation is applied. This parameter serves as the basis for evaluating the applicability of the tension determination method when applied to an oscillating string system.

The physical parameters of the strings, the calculated static tension, and the corresponding theoretical frequencies for the 18 *kacapi indung* strings are presented in Table 1.

Table 1. Static string tension and theoretical frequency calculated using the ideal string vibration model

String Material	String Diameter (mm)	Sting No.	L (m)	T_s (N)	μ (kg/m)	$f_{teoritical}$ (Hz)
Stainless steel	0.4	1	0.165	275	0.001017	1575.76
Stainless steel	0.4	2	0.216	360	0.001017	1377.23
Stainless steel	0.4	3	0.243	405	0.001017	1298.46
Stainless steel	0.4	4	0.272	680	0.001017	1503.12
Stainless steel	0.5	5	0.312	585	0.001592	971.40
Stainless steel	0.5	6	0.352	440	0.001592	746.72
Stainless steel	0.5	7	0.393	655	0.001592	816.02
Stainless steel	0.5	8	0.432	540	0.001592	674.04
Stainless steel	0.5	9	0.470	783	0.001592	746.19

String Material	String Diameter (mm)	Sting No.	L (m)	T_s (N)	μ (kg/m)	$f_{teoritical}$ (Hz)
Stainless steel	0.5	10	0.516	1935	0.001592	1068.23
Brass	0.8	11	0.550	1375	0.003073	608.14
Brass	0.8	12	0.598	1495	0.003073	583.23
Brass	0.8	13	0.633	1055	0.003073	462.85
Brass	0.8	14	0.685	856	0.003073	385.33
Brass	0.8	15	0.728	910	0.003073	373.77
Brass	1.0	16	0.765	1434	0.003893	396.71
Brass	1.0	17	0.815	1019	0.003893	313.82
Brass	1.0	18	0.865	2883	0.003893	497.43

Based on Table 1, the theoretical frequencies exhibit clear variation patterns according to string material, diameter, vibrating length, and linear mass density. Stainless-steel strings with smaller diameters (0.4–0.5 mm) generally produce higher theoretical frequencies than brass strings with larger diameters (0.8–1.0 mm). This tendency is associated with the lower linear mass density (μ) of thinner stainless-steel strings, which increases the vibration frequency according to the ideal string vibration model.

Within the stainless-steel group, strings with a diameter of 0.4 mm exhibit the highest theoretical frequencies, ranging from approximately 1298 Hz to 1576 Hz. Although the static tension varies among these strings, the relatively small linear mass density ($\mu = 0.001017$ kg/m) and shorter vibrating lengths contribute to maintaining high vibration frequencies. In contrast, the 0.5 mm stainless-steel strings generally exhibit lower theoretical frequencies because the increase in diameter results in a higher linear mass density ($\mu = 0.001592$ kg/m).

A similar tendency is observed in the brass-string group. Brass strings with diameters of 0.8 mm and 1.0 mm exhibit substantially lower theoretical frequencies despite relatively high static tension values. The larger diameters and higher linear mass densities of brass strings reduce the vibration frequency, indicating that linear mass density has a dominant influence on the resulting frequency when differences in material and diameter become significant.

In addition to material and diameter effects, the results also demonstrate the combined influence of vibrating string length and tension. Theoretically, vibration frequency is proportional to the square root of tension and inversely proportional to string length according to classical string vibration theory (Fletcher & Rossing, 1991; Roy, 2024). Consequently, an increase in tension does not always produce a proportional increase in frequency when accompanied by longer vibrating lengths and larger linear mass densities. This tendency can be observed in several strings with relatively high static tension values but comparatively lower theoretical frequencies. For example, string number 10 exhibits the highest static tension among the stainless-steel strings ($T_s = 1935$ N), yet its theoretical frequency (1068.23 Hz) is lower than several thinner strings with smaller diameters and shorter vibrating lengths. This condition demonstrates that the relationship between tension and frequency in real string systems must be interpreted by considering all governing physical parameters simultaneously rather than individually.

The relationship between physical string parameters and vibration frequency has also been reported in studies on guitar instruments, which indicate that string diameter affects linear mass density and consequently influences the resulting frequency. Strings with larger diameters tend to produce lower frequencies because of their higher linear mass densities (Afifah et al., 2020).

Although the ideal string vibration model provides a clear mathematical relationship between tension and frequency, the static tension obtained from physical measurements represents only the mechanical condition of the string in a stationary state and does not fully describe the dynamic mechanical behaviour of vibrating strings in real musical instruments (Roy, 2024; Kaselouris et al., 2022). In real musical instruments, strings operate under dynamic conditions when plucked and interact with the instrument resonator, leading to more complex vibration responses (Kaselouris et al., 2022). Therefore, the consistency between static tension parameters and the dynamic response of the system needs to be examined through frequency measurements obtained during oscillation. Accordingly, the results presented in this subsection are not intended to evaluate the accuracy of frequency prediction directly, but rather to establish static tension as an initial parameter in the ideal string vibration model. This parameter is subsequently examined through comparison with the effective dynamic tension estimated from the frequency response obtained using FFT analysis in the following subsection.

2. Effective Dynamic String Tension Based on Frequency Analysis Using FFT

The dynamic response of the kacapi indung string system was experimentally examined through sound frequency measurements using the Fast Fourier Transform (FFT) method implemented in Audacity software. In this study, FFT analysis was not intended to investigate the spectral characteristics independently; rather, it was employed as an indirect approach to estimate the effective dynamic string tension when the system was in an oscillatory condition. An example of the frequency spectrum obtained from FFT analysis is presented in Figure 3 to illustrate the process of identifying the fundamental frequency.

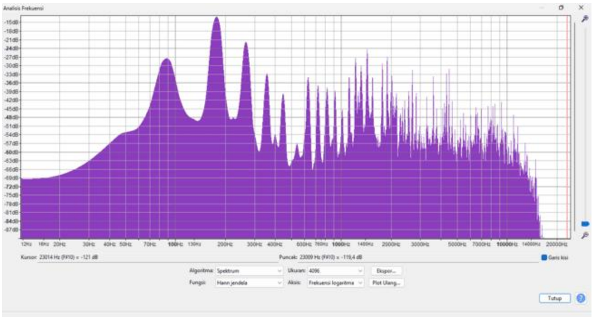

Figure 3. Example of a frequency spectrum obtained from FFT analysis using Audacity

The fundamental frequencies obtained from FFT analysis were subsequently used to estimate the effective dynamic string tension by applying the inverse form of Mersenne's law, as described in the Method section. The effective dynamic tension (T_{FFT}) was calculated using Equation (7). This value represents the effective tension of the string system during oscillation and reflects the actual response of the string when interacting with the instrument resonator. The average fundamental frequencies and the corresponding effective dynamic tension values for each *kacapi indung* string are presented in Table 2.

Table 2. Fundamental frequencies obtained from FFT analysis and effective dynamic string tension of the *kacapi indung*

String No.	Average Fundamental Frequency (Hz)	T_{FFT} (N)
1	753.7 ± 7.3	62.91
2	696.9 ± 2.9	92.18
3	556.7 ± 0.5	74.45
4	501.9 ± 0.9	75.82
5	465.3 ± 0.9	134.22
6	368.9 ± 0.6	107.39
7	349.5 ± 0.5	120.15
8	279.9 ± 0.6	93.12
9	249.9 ± 0.3	87.86
10	231.1 ± 0.7	90.56
11	182.0 ± 0.0	123.15
12	173.7 ± 0.5	132.61
13	137.3 ± 0.5	94.36
14	121.9 ± 0.3	87.10
15	113.9 ± 0.3	107.08
16	88.0 ± 0.0	70.58
17	84.5 ± 0.5	73.86
18	66.8 ± 0.4	52.00

Based on Table 2, the effective dynamic string tension exhibits noticeable fluctuations among the strings. This variation is associated with the decreasing trend of fundamental frequency as the string number increases, while the linear mass density of the strings increases due to differences in material and diameter. These findings indicate that the frequency response of the string system is influenced by various mechanical factors that arise during oscillation.

A similar phenomenon has been reported in studies on guitar instruments, where the vibration frequency of strings is affected not only by physical parameters such as diameter and length but also by excitation conditions during plucking and the mechanical configuration of the instrument (Afifah et al., 2020).

For several strings, the calculated standard deviations were very small or numerically negligible. This condition is likely related to the limited frequency resolution of the FFT analysis rather than indicating the absence of physical fluctuations in the string vibration system.

Overall, the results presented in this subsection suggest that the effective dynamic tension estimated from the fundamental frequency obtained through FFT represents a mechanical condition that differs from the static state of the string. Therefore, the values of T_{FFT} are used as the main comparative parameter in evaluating the string tension determination method based on the ideal string vibration model. A direct comparison between static tension and effective dynamic tension is presented in the following subsection.

3. Comparison Between Static and Effective Dynamic String Tension

The comparison between static string tension (T_s), obtained from physical parameter measurements, and effective dynamic tension (T_{FFT}), estimated from frequency responses derived from Fast Fourier Transform (FFT) analysis, was used as the basis for evaluating the applicability of the string tension determination method based on the ideal string vibration model. This analysis aims to assess the extent to which the static tension approach represents the mechanical condition of the string system when it operates under dynamic oscillatory conditions.

A summary of the calculated parameters based on the ideal string vibration model and the experimental results for the 18 *kacapi indung* strings is presented in Table 3.

Table 3. Comparison of parameters from the ideal string model and dynamic response obtained from FFT analysis for 18 *kacapi indung* strings

String No.	Static Tention T_s (N)	Effective Dynamic Tension T_{FFT} (N)	Relative Deviation (%)
1	275.00	62.91	77.12
2	360.00	92.18	74.39
3	405.00	74.45	81.62
4	680.00	75.82	88.85
5	585.00	134.22	77.06
6	440.00	107.39	75.59
7	655.00	120.15	81.66
8	540.00	93.12	82.76
9	783.33	87.86	88.78
10	1935.00	90.56	95.32
11	1375.00	123.15	91.04
12	1495.00	132.61	91.13
13	1055.00	94.36	91.06
14	856.25	87.10	89.83
15	910.00	107.08	88.23
16	1434.38	70.58	95.08

String No.	Static Tention T_s (N)	Effective Dynamic Tension T_{FFT} (N)	Relative Deviation (%)
17	1018.75	73.86	92.75
18	2883.33	52.00	98.20

Based on Table 3, the effective dynamic tension (T_{FFT}) does not follow the variation pattern of static tension among the strings and exhibits noticeable fluctuations. This phenomenon suggests that the dynamic tension estimated from the fundamental frequency is not solely determined by the initial string tension but is also influenced by various mechanical factors that arise during oscillation. One contributing factor is the change in the geometric configuration of the string during plucking. Deflection from the equilibrium position results in a slight increase in the effective string length, which can lead to variations in tension throughout the vibration process. From a mechanical perspective, similar behavior has been reported in studies on guitar string bending techniques, where string deformation modifies both the effective tension and the vibration frequency of the system (Grimes, 2014).

In addition to geometric effects, the distribution of vibrational energy among different harmonic modes also influences the frequency response of the system. Vibrational energy is not always concentrated in the fundamental mode but may be distributed across several harmonics depending on the plucking position and excitation characteristics (Sethares, 2005). Mechanical interaction between the strings and the instrument body further contributes to the system dynamics. In the *kacapi indung*, the strings do not vibrate in isolation but are coupled with the wooden body that functions as an acoustic resonator, thereby modifying the observed frequency spectrum (Fletcher & Rossing, 1991).

The difference between static and dynamic conditions of the string system can also be examined quantitatively through the difference in tension values. To evaluate this discrepancy, the difference between static tension and effective dynamic tension was calculated using Equation (7). The distribution of tension differences for all *kacapi indung* strings is presented in Figure 4.

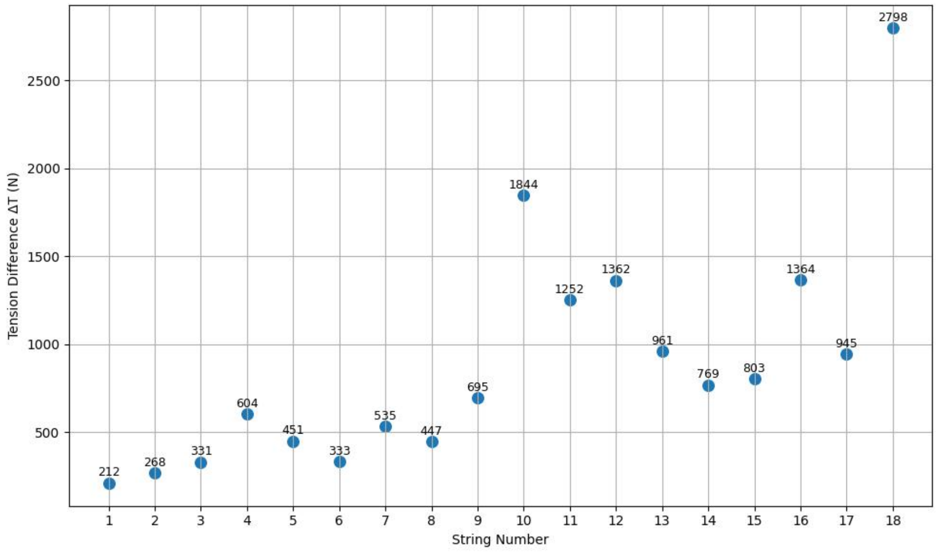

Figure 4. Difference between static tension and effective dynamic tension for each *kacapi indung* string

Based on Figure 4, all values of ΔT are positive, indicating that static tension is systematically higher than effective dynamic tension for all observed strings. In general, the static tension values exceed the effective dynamic tension, suggesting that the mechanical condition of the string in a static equilibrium state does not fully represent the tension characteristics of the system during oscillation.

The relative deviation analysis further demonstrates substantial discrepancies between static tension and effective dynamic tension. The calculated relative deviations range from approximately 74% to 98%, with an average deviation of 86.69%, indicating that the static tension determined from equilibrium-based physical measurements cannot directly represent the effective mechanical behaviour of vibrating strings in real acoustic systems. These large deviations suggest that the dynamic response of the string system is strongly influenced by non-ideal effects such as damping, stiffness, harmonic energy redistribution, and mechanical coupling between the strings and the resonator body. Consequently, although the ideal string vibration model remains useful as an initial theoretical approximation, its application to real musical instruments requires careful consideration of dynamic system behaviour.

This discrepancy can also be interpreted from the perspective of string geometric mechanics. When a string is displaced at its midpoint, its effective length increases, resulting in elastic stretching. For small deflections, the increase in string length is proportional to the square of the displacement relative to the string length, leading to an additional elastic tension component that is not fully accounted for in the ideal string model. Consequently, the deflection method tends to produce higher tension estimates compared to the effective tension of the system under dynamic conditions.

The relationship between the ideal string model and the actual system response can also be observed through a comparison between theoretical frequencies and experimentally measured frequencies, as presented in Figure 5.

The theoretical frequency was calculated using Equation (1), while the experimental frequency was obtained from FFT analysis as described in Section 2.

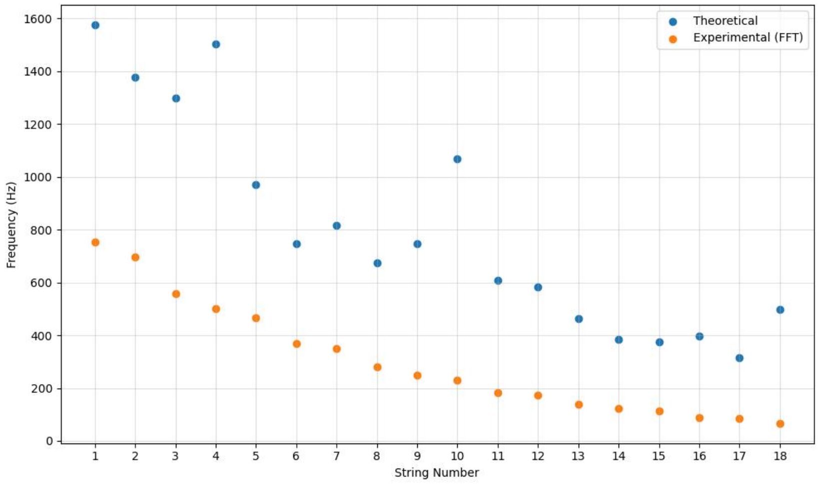

Figure 5. Comparison between theoretical frequencies and experimentally measured frequencies for each string

Based on Figure 5, the theoretical frequencies are consistently higher than the experimentally observed fundamental frequencies. This tendency indicates that the ideal string vibration model tends to overestimate the effective dynamic response of the real string system. However, for several strings, the theoretical frequencies show numerical proximity to one of the harmonic components in the experimental spectrum. This observation reinforces the interpretation that the ideal string vibration model represents idealized mathematical vibration modes, whereas in real systems these modes may appear as harmonic components due to the influence of non-ideal factors.

Overall, the analysis indicates that the ideal string vibration model remains a useful theoretical framework for understanding the relationship between string mechanical parameters and vibration frequency. Nevertheless, its application to real musical instruments such as the kacapi indung requires consideration of various non-ideal factors, including string material elasticity, harmonic energy distribution, and mechanical interaction between the strings and the instrument resonator. To the best of the authors' knowledge, this study represents one of the first systematic experimental comparisons between static string tension determined from physical measurements and effective dynamic tension estimated from frequency responses in a traditional string instrument system. From a physics education perspective, these findings provide an empirical illustration of the validity limits of theoretical models and can be utilized as a learning context to demonstrate the relationship between idealized models and experimental phenomena.

CONCLUSION

The results of this study indicate that the string tension determination method based on the ideal string vibration model produces static tension values that are systematically higher than the effective dynamic tension estimated from frequency analysis using the Fast Fourier Transform (FFT). The relative deviations between static tension and effective dynamic tension ranged from 74.39% to 98.20%, with an average deviation of 86.69%, suggesting that the equilibrium-based tension estimation and the dynamic vibration behaviour of the real string system represent distinct physical conditions. The theoretical frequencies derived from static tension show stronger correspondence with number of harmonic components identified in the acoustic spectrum than with the experimentally observed fundamental frequencies. This behaviour suggests that the vibrational response of the strings is governed by both the ideal string tension model and additional physical characteristic of real things, including elastic and structural effects that contribute to the formation of harmonic resonance patterns.

The discrepancy between static and dynamic conditions of the string system is likely associated with non-ideal factors such as changes in the geometric configuration of the string during deflection and oscillation, harmonic energy redistribution, string stiffness, damping, and mechanical interaction between the strings and the instrument resonator. These findings suggest that the ideal string vibration model remains relevant as an initial theoretical framework; nevertheless, its application to real musical instruments requires consideration of non-ideal system behaviour in order to provide a more representative interpretation of the mechanical response of vibrating strings.

To the best of the authors' knowledge, this study represents one of the first systematic experimental comparisons between static string tension determined from physical measurements and effective dynamic tension estimated from frequency responses in a traditional string instrument system. From a physics education perspective, the findings provide an empirical context for demonstrating the validity limits of idealized theoretical models when applied to real acoustic systems and may serve as a contextual learning resource for wave mechanics and acoustic vibration topics.

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