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A Home-Lab Experiment on the Resonance and Beats of Guitar Strings Using Phyphox

Kittiwat Tangmongkollert*

Department of Physics, Faculty of Science, Ramkhamhaeng University, Bangkok, Thailand
***Corresponding author e-mail: Kittiwat.t@rumail.ru.ac.th**

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Abstract
This work presents an attractive way to teach high school students the concepts of resonance, standing waves, and beats of sound. The guitar and the application "Phyphox" are employed for demonstration. This work consists of three sections. Firstly, the first harmonic is discussed. The same note played from a guitar can be generated by different guitar strings. By plucking a single string, one can observe the resonant vibration of other strings with the naked eye. Secondly, higher-order harmonics are discussed. When plucking a string, many frequencies are generated. The author shows how to mute some harmonic frequencies by gently touching the string. The touching position becomes a node and the muted frequencies can be captured by Phyphox. Harmonics that do not have a node at this point attenuate immediately. This opens an opportunity to explain standing waves to students. Lastly, when two strings play very close frequencies simultaneously, the beat of sound can be captured by Phyphox or even perceived by the ears.

Keywords: Resonance, Standing waves, Beats, Harmonics, Guitar, Phyphox, Physics education

1. Introduction
Nowadays, teaching physics with common, everyday items has become a topic of great interest, especially after the COVID period. It not only makes students' self-experimentation possible but also draws their attention. Some works use things around us to conduct physics experiments (Aji et al., 2022; Helseth, 2023; Monteiro et al., 2022). Smartphones are also very popular tools for physics experiments through their applications and integrated sensors. Many smartphone-related experiments have been conducted (Ait Ben Ahmed et al., 2022; Bonato et al., 2017; Chatchawaltheerat et al., 2021; Coramik & Ürek, 2021; Dumrongkitpakorn et al., 2022; Gabunilas et al., 2022; Goev & Velinov, 2022; Koblischka & Koblischka-Veneva, 2022; Puttharugsa et al., 2021; Puttharugsa et al., 2022; Soares et al., 2022). Numerous mini-lab physics experiments using smartphones have been compiled (Kuhn & Vogt, 2022). The use of musical instruments in physics experiments is a great way to attract students and help strengthen students' understanding of physics concepts, as discussed in Hechter and Bergman (2016), and Andreotti and Frans (2019). Most musical instrument-related experiments focus on acoustic waves and have been discussed in educational contexts (Aguilar et al., 2019; LoPresto, 2012; Matsutani, 2021; Pereyra et al., 2018; Pols, 2021; Torcal-Milla, 2023; Torres & Rendón, 2013). In this paper, the author discusses one of the ways to teach resonance and the beats of sound via guitar strings, with the help of the Phyphox application on a smartphone. Both the guitar and the smartphone are evidently great for drawing students' attention.

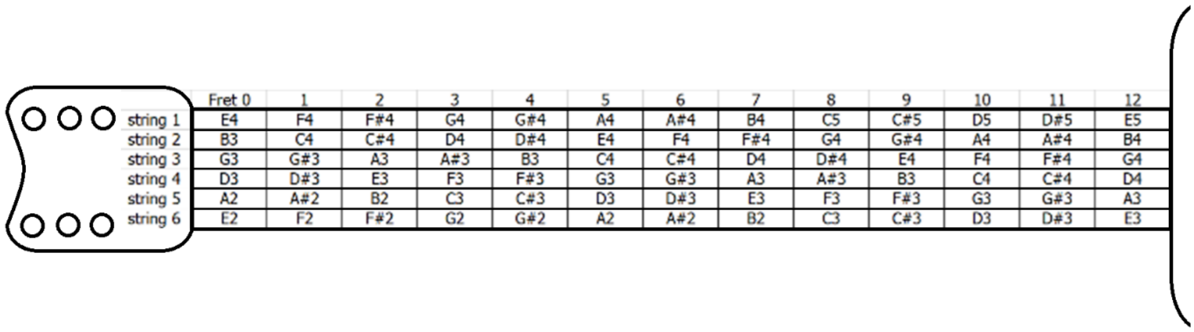
2. Materials, Methods, and Results
2.1 The 1st harmonic resonance on guitar strings
A conventional guitar consists of 6 strings that have different string tensions and masses, which result in different natural frequencies. However, the frequency can be changed by changing the length of the vibrating string. This can be done by putting a finger on a fret. For example, as shown in Figure 1, if we put the index finger on the 5th fret of the 6th string, this plays the note "A2", with its specific natural string frequency of 110Hz (if perfectly tuned). A similar note "A" can also be played by plucking the 5th string without touching any fret. When

two strings have the same natural frequency, this allows us to observe their resonance. By plucking one string, the other strings is induced to vibrate, as shown in Figure 2. This can be demonstrated to students and opens an opportunity to discuss the topic of resonance. The following questions may be asked for students to investigate.

(1) Resonance can occur on any guitar strings if both strings play the same note. Figure 3 shows the notes on the guitar neck. As can be seen, the 5th fret on the 6th string and the open 5th string (0th fret) play the same note, "A2". Another example is that the 5th fret on the 5th string and the open 4th string play the same note, "D3". Hence, resonance can occur between them.

Figure 1. The position of the fret and n-th string of a guitar.

Figure 2. Resonance occurs on guitar strings. The two lowest strings produce the same note, and when plucking one, the other naturally vibrates and can be easily observed.



	Fret 0	1	2	3	4	5	6	7	8	9	10	11	12
string 1	E4	F4	F#4	G4	G#4	A4	A#4	B4	C5	C#5	D5	D#5	E5
string 2	B3	C4	C#4	D4	D#4	E4	F4	F#4	G4	G#4	A4	A#4	B4
string 3	G3	G#3	A3	A#3	B3	C4	C#4	D4	D#4	E4	F4	F#4	G4
string 4	D3	D#3	E3	F3	F#3	G3	G#3	A3	A#3	B3	C4	C#4	D4
string 5	A2	A#2	B2	C3	C#3	D3	D#3	E3	F3	F#3	G3	G#3	A3
string 6	E2	F2	F#2	G2	G#2	A2	A#2	B2	C3	C#3	D3	D#3	E3

Figure 3. The positions of the notes on the guitar fretboard.

(2) While resonance occurs between any two strings, let the students observe the other strings. What happens to them? The students would observe that most strings stay still but may sometimes vibrate (This will be discussed in the next section). After a while, pluck each string individually and let the students listen to them. The students would find that the sound from two resonating strings is very similar because they play the same note, and totally different from the others. Although two resonating strings produce a very similar sound, the quality of sound produced by each string has a slight difference. This helps students distinguish between frequency and quality of sound, as resonance is caused by frequency, not by the quality of sound.

(3) In order to create resonance, do the frequencies of the two strings have to be exactly the same? This can be investigated by using the tuning knob of a guitar. The tuning knob allows changing the string's tension, thereby changing its natural frequency. Let the students slightly tune the knob, pluck one string, and observe how the amplitude of the resonance changes. The students would find that the amplitude of the resonance is maximum at a specific tuning point, and starts to decrease as the frequency slightly changes. This allows the teacher to explain the definition of the natural frequency. While the resonance amplitude is maximum, two strings have exactly the same natural frequency. When slightly adjusting the knob, both strings now have slightly different natural frequencies, and resonance still occurs but at a reduced amplitude. The application Phyphox can be used to measure the frequency of a single-tone sound from a vibrating string. Open the app, swipe down to the "Acoustic" section, select "Audio Autocorrelation," and one possible result is shown in Figure 4.

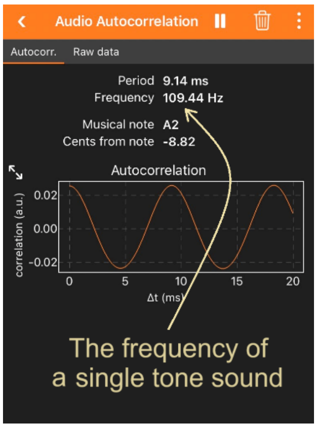


Figure 4. The frequency of a single-tone sound as measured using the Phyphox application.

2.2 Higher-order harmonics and Nodes on guitar strings

The first harmonic of guitar strings is clearly the easiest to observe, as discussed in the first section. After introducing the first harmonic to students, more information will be provided. The sound frequency generated by a single string contains more than one frequency. When a string is plucked, a range of frequencies is initially generated, but those that do not correspond to the natural resonant modes of the string are rapidly attenuated. The frequencies that match the string length will last longer, and that is called harmonics. If the frequency of the first harmonic (the fundamental) is f_0, the other harmonics will have frequencies that are integer multiples of f_0, such as nf_0, where n is a positive integer. We can capture this using Phyphox. For example, plucking the second string generates the first harmonic frequency of about 247 Hz, and the other harmonic frequencies, such as 494 Hz, 741 Hz, etc., are retained, while the others attenuate to zero quickly. The result is shown in Figure 5. The rapid drop of the other unmatched frequencies is caused by the position of the nodes. When plucking a string, waves travel in both directions and are reflected at the fixed end of the guitar. The standing wave is the result of the interference of those waves. The fixed end of the guitar forces the wave at this position to become a node. If a wave of its specific frequency does not have a node at this position, its amplitude is forced to zero.

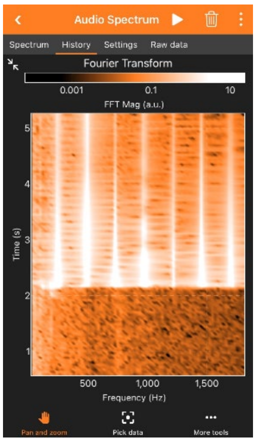


Figure 5. Measuring the sound frequencies created by plucking the second string without pressing any fret. Any frequencies that are multiples of 247 Hz (the first harmonic) appear, while others are quickly attenuated to zero.

Moreover, we can manually add a node at any point on the string by gently touching the string with the index finger, which would temporarily make that point become a node. Figure 6 shows the positions of the nodes for many harmonics. As can be seen, only the even-numbered harmonics (2^{nd}, 4^{th}, 6^{th}, etc.) have a node at the center. If we gently touch the vibrating string at the center, only the even-numbered harmonics would remain, while odd-numbered harmonics are rapidly attenuated. The results are shown in Figure 7 (left). Two more examples- if we touch the string at L/3, only the integer multiples of three harmonics (3^{rd}, 6^{th}, 9^{th}, etc.) will remain. If we touch the string at L/4, only the integer multiples of four harmonics will remain, as shown in Figure 7 (center and right). The fret spacing of a guitar is shown in Figure 8. This means that in order to mute at L/2, L/3, and L/4, one needs to touch the string directly above frets 12, 7, and 5, respectively. Note that during this experiment, the other strings should be muted—either by palm muting or any other method that effectively suppresses their vibrations. Otherwise, unintended results may occur. For example, Figure 9 illustrates the outcome when the second string is plucked and muted at half of its length (L/2). The first harmonic does not disappear as expected. This is because it resonates with the sixth string. The first harmonic of the second string is 247 Hz, while the third harmonic of the sixth string is 246 Hz. This is a very close number, and the resonance between both strings could appear practically. When plucking the second string, the sixth string resonates and vibrates at its third harmonic. When muting the second string at L/2, the sixth string still vibrates and misleadingly shows as the first harmonic of the second string in the measurement.

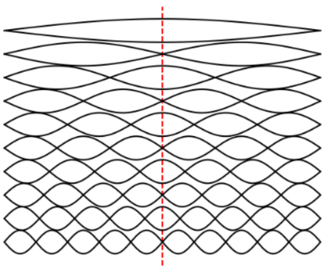


Figure 6. The Positions of the nodes of the first ten harmonics of a standing wave. Only even-numbered harmonics have a node at the center, as shown by the red vertical line.

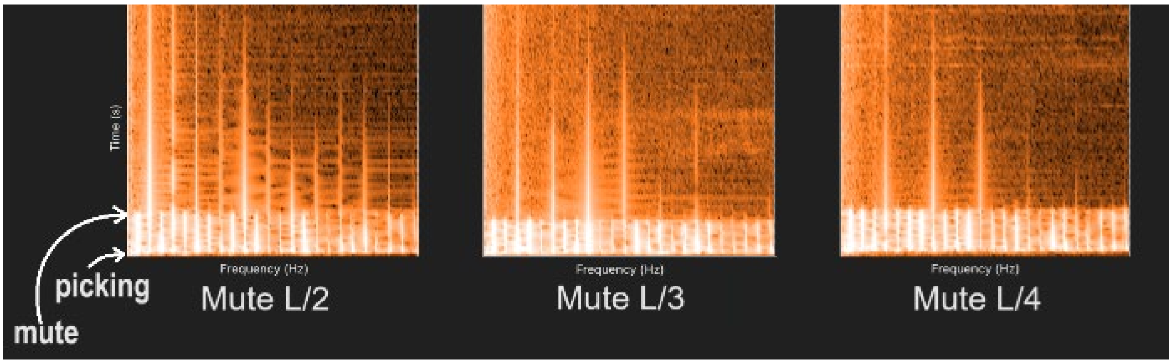


Figure 7. When gently touching the string at any point, it creates a node at that point; hence all frequencies that do not have a node at that point are quickly attenuated to zero. Three examples are provided: (left) Touching the string at L/2 (12th fret), (center) Touching the string at L/3 (7th fret), (right) Touching the string at L/4 (5th fret).

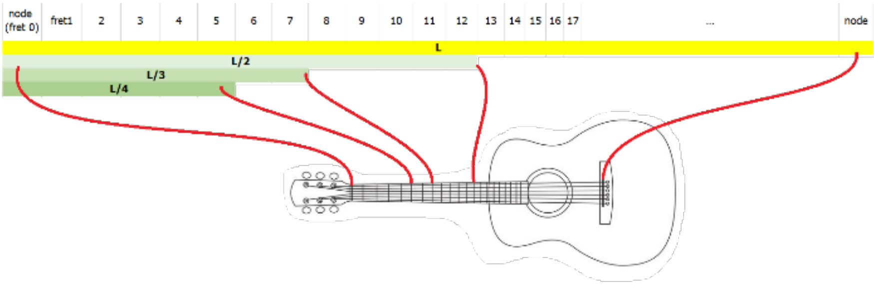


Figure 8. The fret spacing on a guitar.

2.3 Beat of two guitar strings

A beat is the phenomenon resulting from the superposition of two sounds, creating a new sound with periodic variation in volume. We can demonstrate this by using two guitar strings. When plucking two strings simultaneously, if both strings play exactly the same frequency, a beat will not occur. In reality, it is not easy to perfectly tune guitar strings; hence, we can usually observe the beat between two strings. The following activity may help students understand the concept of beats.

(1) Observe beats by listening. When two guitar strings play very close frequencies, e.g., not differing by more than 20 Hz (Serway & Jewett, 2004), it is easy for anyone to hear the beats. For example, place your finger on the 5th fret of the 6th string, then pluck the 5th and 6th strings simultaneously. This would play the same note "A", but if the strings are not perfectly tuned, their frequencies may be slightly different. As a result, you can hear the sound volume periodically changing over time. The teacher can slightly adjust the tuning knob and ask students to observe the change in beat frequency.

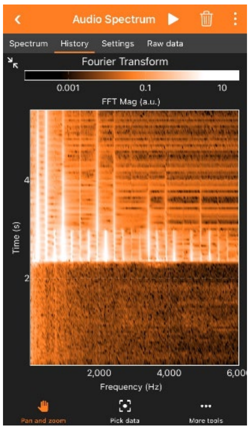


Figure 9. Some misleading frequencies may appear in the experiment. Plucking the second string and muting it at L/2 should eliminate all odd harmonics. However, the measurement still shows the first harmonic. This does not come from the muted second string, but rather from the unmuted sixth string. The third harmonic of the sixth string is in resonance with the first harmonic of the second string.

(2) Observe beats using "Phyphox". When the beat frequency is too high to be perceived by your ears, the variation in sound volume can still be detected using "Phyphox," a well-known smartphone application for physics experiments. In the application, swipe down to the "Acoustics" tab, then select "Audio Amplitude". This will measure the sound amplitude and display it as a graph. One possible result is shown in Figure 10.

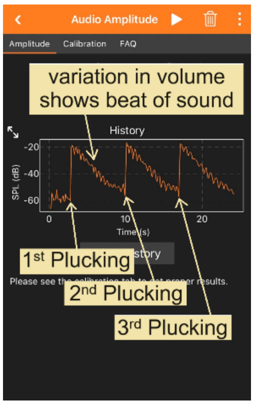


Figure 10. The beat phenomenon of sound displayed using the Phyphox application.

3. Conclusions

This work suggests an alternative way to set up a low-cost standing wave laboratory, which can be practically adapted in any classroom. Using a guitar and a smartphone can attract students and may increase their learning efficiency. By using the Phyphox application on a smartphone, one can measure the frequency spectrum and sound amplitude. The spectrum shows harmonics with frequencies that are integer multiples of the first harmonic. Understanding node positions can be tested by gently touching the string at certain points. For example, touching the string at its midpoint mutes all odd harmonics while even harmonics remain. Resonance between two strings can also be visualized, and the beat between them can be captured using Phyphox. This work provides an idea for integrating art and learning into the physics classroom. Further analysis can be conducted depending on the students' level.

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