Guitar Sounds: From Wood Vibrations to a Mini Power Plant

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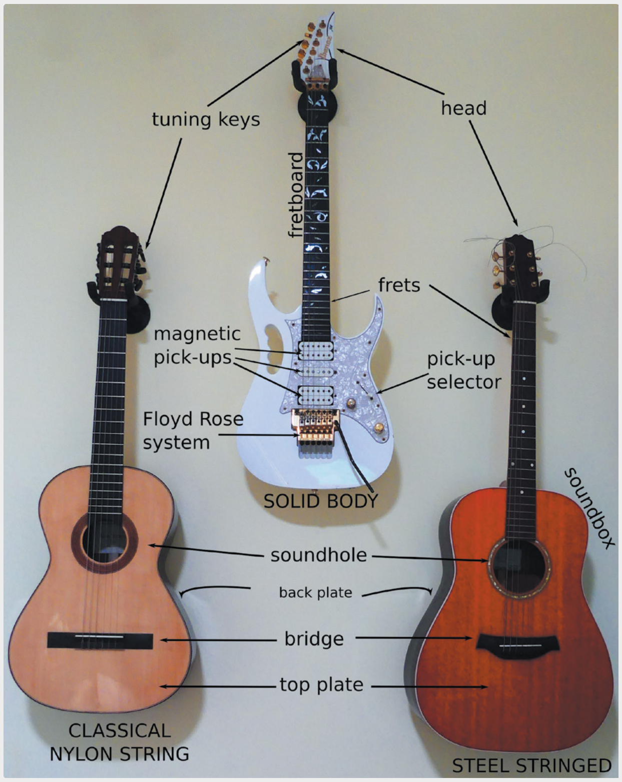
Introduction

When a guitar player attends a party, they are often asked to play. A problem, however, is that this is often on a borrowed guitar. If the guitar player normally plays an electric guitar and the borrowed guitar is acoustic (or vice versa), there are real problems because although electric and acoustic guitars appear to be the same instrument to most people, they are really very different instruments. Indeed, there are even differences in how a musician usually plays the guitar. Have you ever seen a musician playing an electric guitar seated in a chair? On the other hand, do you remember any guitarist stand while playing an acoustic guitar to perform a classical song? (See **Multimedia File 1** and **Multimedia File 2** at acousticstoday.org/torresmedia).

Figure 1. *Anatomy of three different types of guitars.* ***Left:*** *acoustic nylon-string guitar.* ***Center:*** *electric guitar.* ***Right:*** *acoustic steel-stringed guitar.*



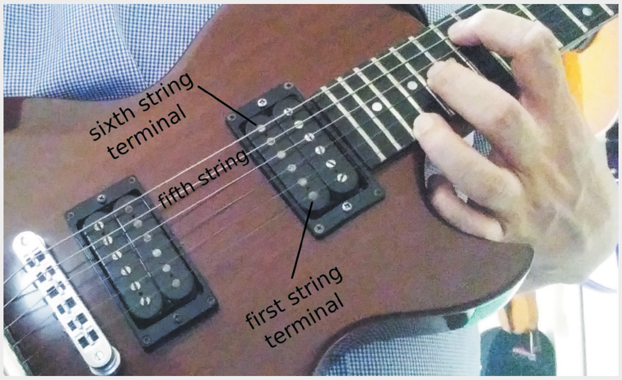


Figure 2. *Vibrating string length in guitars is adjusted by pressing the strings against the metallic frets. Labels show how a vibrating string interacts with a different number of terminals depending on the side of its deflection.*

All guitars have some interesting details in common as well as many differences. For example, the vibrating string length (measured from the bridge to each fret; see parts of the guitar in **Figure 1**) is fixed because the frets cannot be moved. **Figure 2** shows details of the string length limited by the frets. In contrast, bowed instruments, such as the violin, do not have frets. As a result, violinists can impose any vibrating string length without the distances imposed by the frets positions. Thus, fretless instruments allow more expressiveness in the music because the player has more freedom to jump from one note to another. Still, using frets enables beginners to play the guitar because there is no need to guess the exact position of the finger to obtain a well-tuned note.

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Historical Development of the Guitar

French (2008) points out that anthropologists believe that the oldest forerunners of stringed musical instruments evolved from the stretched strings of bows used by hunters early in the history of civilization. Moreover, it is reasonable to infer that three types of musical instruments evolved from this first instrument: the struck string (e.g., piano), bowed string (e.g., violin), and plucked string, with the guitar arising from the plucked string branch. In fact, instruments with clear similarities to the modern guitar can be seen in a 3,300-year-old stone carving at Alaca Huyuk in Turkey (see tinyurl.com/mvybc2rs). Thus, in a certain sense, the evolution of the design of an instrument like the guitar is probably not very different from the evolution of living things, with slow and somewhat random changes over time and across many cultures.

However, different hypotheses have been proposed to explain the evolution of the guitar. Some people say that it comes from the ancient Greeks, whereas other people think that the guitar comes from early Egyptian instruments. Currently, there is no consensus as to the direct origin of the guitar from any particular ancient instrument. It is clear, however, that the oldest musical scores that can be played on a guitar were written in the sixteenth century, according to Chapman (1993), who also illustrates some ancient instruments like the guitar (also see Bucur, 2016).

During the eighteenth century, stringed instruments such as the Spanish vihuela, a close relative of the guitar, lost popularity because it lacked sound power in comparison with other stringed instruments such as the violin (bowed string) or the piano (struck string). However, the manufacture of plucked instruments was significantly easier than the others, and this helped to increase its popularity.

For the first half of the nineteenth century, in pursuit of a more powerful sound from the acoustic guitar, Antonio de Torres proposed the classical design. We know it now with 65-cm-long strings and a soundbox that included internal bracing. These adaptations provided increased loudness by having a stronger but thinner top and back plates (see **Figure 1**). **Figure 3** shows a remarkable replica of the most iconic guitar made by de Torres, named "La Cumbre." The process of making this replica, including all its artistic details, took the guitar maker Abel García López nine years. **Multimedia File 1** (at acousticstoday.org/torresmedia) shows a performance of this guitar played by Abel García Ayala (see more at youtu.be/1UkoiSm32Rs).

Figure 3. ***Left:*** *replica of "La Cumbre" an iconic guitar made by Antonio de Torres dated 1884. Replica made by Abel García López. Artistic details on the soundhole are hown.* ***Right:*** *the entire guitar. Photograph by José Pita, used with permission.*

But later, the sound produced by acoustic guitars was again put at a disadvantage when amplifiers using vacuum tubes (or simply "tubes") were developed. By 1931, Rickenbacker and Beauchamp attached a sensor under the strings to capture their vibrations and send the signal to the amplifier, thus producing the first electric guitar sounds. This is discussed in detail by Wilmering et al. (2020), who also share notes about the development of many other audio effects.

The earliest electric guitars were equipped with single coil pickups (see middle pickup on the electric guitar in **Figure 1**). These pickups were sensitive not only to the vibrations of the strings but also to other external magnetic fields, thus producing some noise in the guitar sound. To cut the noise, a second coil was attached to the first one to improve the signal-to-noise ratio. However, the problem with these dual coil pickups (called a "humbucker") was a lack of high-frequency response. Still, humbuckers were widely used in the Gibson Les Paul guitars (see tinyurl.com/2ptuzc5d), and they are still used by guitarists. One of these guitars was used in **Figure 2**. **Multimedia File 2** (at acousticstoday.org/torresmedia) contains a small exercise demonstrating some typical features of playing an electric guitar.

Tuning the Strings

The theory about vibrational behavior of the plucked string can be found in books about fundamentals of mechanical vibrations and acoustics or even in some about general physics. There are also research papers especially focused on guitar strings. Therefore, instead discussing these topics in detail here, I explain some practical considerations employed by guitar players to obtain different nuances in the notes delivered by the strings to the guitar.

Nominally, guitars have six vibrating strings tuned to E2 (82.4 Hz), A2 (110 Hz), D2 (146 Hz), G2 (196 Hz), B3 (247 Hz), and E4 (330 Hz) to generate the musical notes. Acoustic guitars can be used with nylon strings or steel strings (depending on the music style), but the electric guitars invariably use steel strings for reasons that is discussed in **The Electric Guitar** (see **Figure 1**). Moreover, although most guitars have six strings, a few models add a seventh string, typically tuned to B1 (61.7 Hz), to play notes lower than E2. In addition, players of different musical styles ranging from classical to blues intentionally modify the standard tuning for some pieces by adjusting the tension of the strings using the tuning keys.

According to the pioneering laws published by Mersenne (1636) about the musical sounds of a vibrating string, we know that tuning a string depends on its diameter, material, length, and tension. As mentioned, frets are responsible for limiting the vibrating string length in guitars (**Figure 2**). Therefore, to change a note, one presses the string on a different fret. In addition, gradual variations of the guitar notes can be done without involving changing the fret that is pressed. The most common technique to produce a subtle change in the tuning of a note in the guitar consists of just sliding the finger that is pressing the string over the fret, a technique known as bending. By bending, the tension is greatly increased in comparison with the small increase in the string length, therefore producing an increase in frequency. See Paté et al. (2012) for a brief glossary of techniques for the electric guitarist and the label in **Multimedia File 2** (at acousticstoday.org/torresmedia).

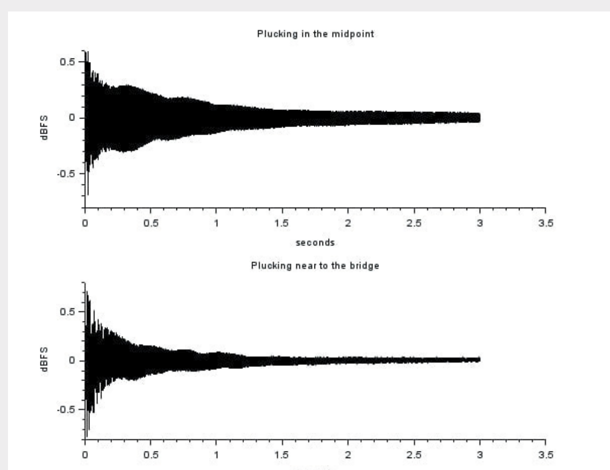
Bending in steel strings can achieve variations up to one tone (see label for bending from D to E in **Multimedia File 2** at acousticstoday.org/torresmedia) or even a little more, whereas the change is less noticeable in nylon strings, although entirely feasible. See Lewis et al. (2014) for a more thorough analysis of the effects of the variations of the tension on a nylon string. In a more sophisticated technique employed in electric guitars, the bridge can be moved, enabling dramatic changes in the tension of the strings (see the end of **Multimedia File 2** at acousticstoday.org/torresmedia).

Controlling Harmonics in Plucked Strings

If the string is plucked close to the bridge, then its vibrations are rich in harmonics. However, because the high-frequency harmonics use a lot of the vibrating energy of the string, the note fades out quickly. As the string is plucked closer to its midpoint, the harmonic content decreases, but the length of the note increases (see **Figure 4**). It is necessary to consider these characteristics to obtain a realistic simulation of the guitar tone, as demonstrated in Torres and Rendón (2013). Because musicians empirically learn that plucking different parts of the strings creates different sounds, they intentionally vary the position of the plucking hand to control both the harmonic content and the length of the notes.

In addition to the plucking location, the plucking technique and the plucking (attack) angle are both important (Fletcher and Rossing, 2012). Predominantly, the nails (tirando) and the fingertips (apoyando) are used with nylon-string guitars (see **Multimedia File 1** at

Figure 4. *First three seconds of the sound made by plucking the first open string of a steel-stringed guitar. The amplitudes are expressed as decibels relative to full scale. The envelope for the graph of the string plucked near to the bridge (**bottom**) fades out more quickly than when the string is plucked at its midpoint (**top**), but the harmonic content of the **bottom** image is richer.*



acousticstoday.org/torresmedia). Steel strings are plucked by means of a plectrum, a thin flat piece of plastic or metal held by the fingers (a metal one is shown in the first seconds of **Multimedia File 2** at acousticstoday.org/torresmedia). There are some techniques in which both styles are combined. For example, if the string is plucked with a plectrum and immediately after this the vibrations are damped with the thumb of the same hand, a vibration is produced that only contains high-frequency harmonics. Indeed, in electric guitars amplified with distortion, this technique causes a particularly spectacular effect that is often referred to as artificial harmonics (see labels in **Multimedia File 2** at acousticstoday.org/torresmedia).

Once the string is installed on the guitar and tightened (tensed), neither the diameter nor the material properties seem to remain constant. In fact, it takes a several days for the newly installed strings to reach stable tuning. Thus, experienced guitarists never change strings on the day of an important performance. Also, as time goes by, the strings keep changing because the harmonic content is affected, whereas the damping in the material increases. Thus, over time, the strings gradually wear out because they are used until they break or until their behavior ceases to be the pleasant sound that they should be for the musician. Then, the strings need to be replaced.

The ability of a vibrating string to generate sound waves by itself is poor because its surface in contact with the air, the propagation medium, is too limited. For this reason, once the guitar strings have been plucked, their vibrations must be collected in some way by other systems responsible for amplification of the sound. In acoustic guitars, a small fraction of the vibrating energy of the string is extracted by the bridge to drive the whole soundbox. In electric guitars, string vibrations are collected through magnetic pickups that generate an electrical signal to be sent to an external amplifier.

The Soundbox

There are many design differences, even among acoustic guitars. **Figure 1** compares the different orientation of the tuning keys in the two types of acoustic guitars shown. The soundbox of a steel-stringed guitar is a little bigger and is subject to more tension than that in a nylon-stringed guitar (seen in **Figures 1** and **5**). To prepare the soundbox of a steel-stringed guitar to support more tension, the internal design of the top plate includes an X-bracing instead of the typical fan bracing employed in the classical nylon-stringed guitars.

Figure 5. *Internal structures of the acoustic guitars of* ***Figure 1****. The nylon-string guitar shows the classical Antonio de Torres fan bracing design (****left****). The steel-stringed guitar shows X-bracing (****right****). Infrared light from inside was employed to reveal the structure.*

Figure 5 shows an internal visualization of the two types of acoustic guitars using infrared light (Torres et al., 2010). Although the reinforcements of the top plate provide structural functions, they also radically affect the sound of the instrument because they alter the vibrational behavior of the top plate. The top plate is largely responsible for the sound amplification in the acoustic guitar, as shown in the simulations made by Torres and Torres-Torres (2015). **Multimedia File 4** (at acousticstoday.org/torresmedia) shows a mode shape of a top plate for middle frequencies, with deflections clearly constrained by the fan bracing of the acoustic guitar.

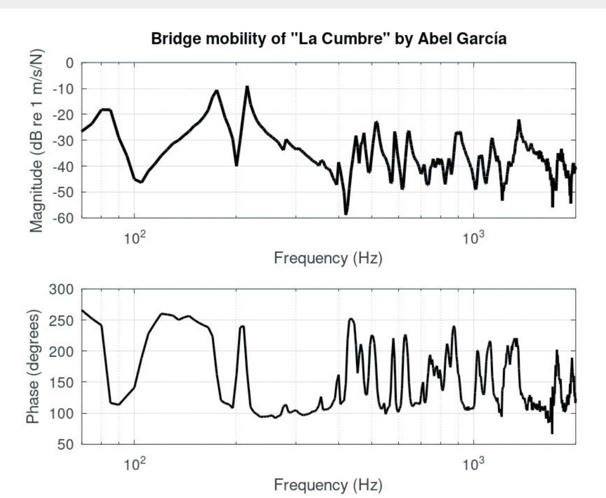
A musical excerpt played on an acoustic guitar made of wood will never sound exactly like the same excerpt played on any other acoustic guitar, even if both instruments have the same design and the same type of strings. But why is the sound of each acoustic guitar unique? It is because the soundbox is responsible for the sound amplification in the acoustic guitars, and the response of each soundbox to the vibrations coming from the strings is unique. To explain more about that, it is necessary to analyze how acoustic guitars work in a little more detail.

To analyze a guitar's performance, it is very useful to study its vibrational behavior in the frequency domain.

For this purpose, the vibrations are measured in terms of motion per unit of input force to the instrument. The typical procedure consists of hitting the bridge with an impact hammer, sensing the velocity caused as a response, and relating both signals (velocity/force) to one another, thus obtaining a transfer function called bridge mobility. A graphic obtained in this way from the "La Cumbre" replica is shown in **Figure 6**, where, with a bit of experience, the contribution of the two main vibratory systems can be easily identified. The first three well-separated peaks are caused by a strong coupling of a Helmholtz-like resonance with the soundbox, and peaks beyond those are mainly due to resonances of the soundbox itself.

The enclosed air of the soundbox supports the amplification of the lowest frequencies of the instrument, mainly by a resonance that resembles that produced when one blows across the hole of an open bottle. Indeed, if the adequate flow of air is directed to the sound hole of an acoustic guitar, one hears the sound of the frequency amplified by this resonance (**Multimedia File 3** at acousticstoday.org/torresmedia). Such behavior is the first one that emerges in the response of acoustic guitars and usually appears at around 100 Hz. The mobility of the "La Cumbre" replica (**Figure 6**) revealed a particularly low frequency for this resonance, matching the fundamental frequency of the E2 note (82.4 Hz). **Multimedia File 1** (at acousticstoday.org/torresmedia) contains a piece played in E tonality using the "La Cumbre" replica.

Figure 6. *Bridge mobility of the "La Cumbre" replica. This is a typical measurement used by scientists to study the vibrational behavior of the instrument.*



The rest of the frequencies of the sound of an acoustic guitar, in the mid and high range, are radiated by the wood itself. Therefore, almost all the sound of the guitar depends on the modal behavior of the soundbox. This, in turn, depends on both the design of the soundbox and the physical properties of the wood. Thus, the same design employing different materials will result in guitars with different responses, such as different samples of wood, even when they are from the same tree (see Torres and Torres-Martinez, 2015). Moreover, most of the processes involved to produce acoustic guitars of wood are handmade, and there are several designs. As a result, each soundbox for the body of a guitar is unique (Skrodzka et al., 2011).

To explain the relationship between the vibrations of the soundbox and the sound generated, we need to learn more about the modal behavior of the structure. The soundbox of a guitar has numerous resonances whose frequencies have no relationship with one another, which is different from the vibrations in strings that show a harmonic series. In the soundbox, resonances depend on the geometry of the structure, mass, elastic properties, and even variations in humidity (Torres et al., 2014). Nevertheless, the first lowest modes of the acoustic guitars tend to be similar despite the variations of the internal bracing.

Figure 7 is a schematic of responses of a 1965 Ramirez guitar, printed by Graham Caldersmith in 1980 where he labeled some peaks with the corresponding mode shapes. In turn, **Multimedia File 5** (at acousticstoday.org/torresmedia) shows the visualization of the first two modes in an experimental guitar (with strong ribs to isolate the vibrations of its top plate) corresponding to modes (0,0) and (1,0). Both modes are hand drawn over the two biggest peaks of the response plotted in **Figure 7**. The harmonics of notes plucked in the strings, matching the resonant frequencies of the soundbox of each guitar, will be selectively amplified by modes with a high radiation efficiency (Torres and Boullosa, 2011), but harmonics with frequencies far from resonances will be scarcely amplified. More details about this experiment in efficiency are available in Torres and Boullosa (2009).

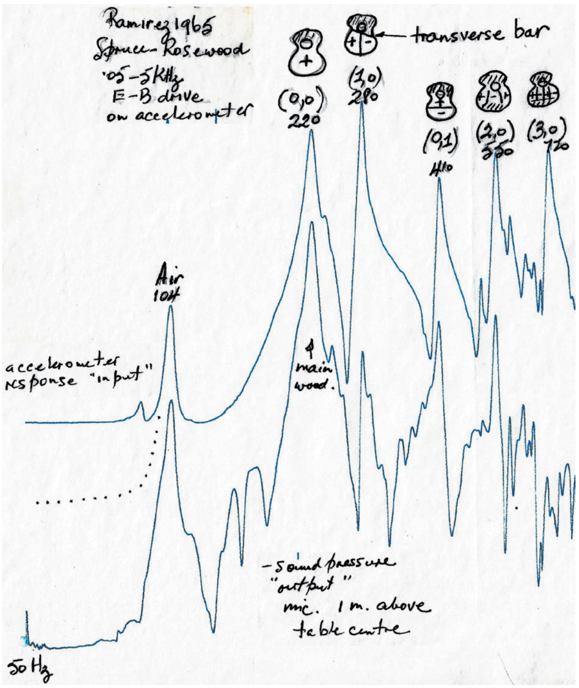


Figure 7. *Mechanical (**top**) and acoustic (**bottom**) frequency responses of a 1965 Ramirez guitar. Image was scanned from the original graph that was mechanically printed by Graham Caldersmith in 1980. He included hand-made sketches of the first-mode shapes and frequencies (in Hz) together with some specifications of the experimental setup.*

The Electric Guitar

A general review of the functionality of the electric guitar is available in books about musical instruments (e.g., Fletcher and Rossing, 2012; Bucur, 2016). In most electric guitars, only the vibrations of the strings are sensed by a magnetic pickup. Because there is no need for vibrations of the guitar body, a solid body substitutes for the soundbox. Moreover, because the energy of the strings' vibrations remains in the strings, the decay of the notes in electric guitars is slower than in acoustic guitars (Paté et al., 2014). Thus, electric guitar players usually damp the vibrations of the strings by gently pressing them on the bridge while they are being plucked using the palm-muting technique (hear the sound obtained using this technique in **Multimedia File 2** at acousticstoday.org/torresmedia). On the other hand, the remarkable sensitivity to small vibrations in the strings, together with the external acoustic energy provided by its amplified loudspeaker, can achieve an infinite sustaining of the notes because of feedback.

Understanding the operating principles of electric guitars require a good deal of physics and mathematics that are discussed in Horton and Moore (2009) and are not considered here. It is important to understand that the basic mechanism of these guitars involved an electromagnetic pickup consisting of a very thin conductive wire coiled to form a spiral around a permanent magnet. The wire is glued to the magnet so that there is no relative motion between them. Because the steel guitar strings are very close to the pickup, they are inside its magnetic field, resulting in a contactless interaction between the vibrating strings and the magnetic field of the pickup system. Therefore, if nylon strings are plucked in an electric guitar, the instrument simply does not work.

Strings disturbing a magnetic pick-up generate signals completely unrelated to the waveform amplified by the body of an acoustic guitar. Indeed, the notes generated by an electric guitar are not like those of any other musical instrument. Moreover, the waveform that is generated by each terminal of the same guitar pickup tends to be different for each string.

To illustrate why, let us analyze the vibrations of the fifth string of a standard electric guitar and the interaction with the terminals of the pickup (see labels in **Figure 2**). Imagine that the oscillations occur in a plane that is parallel to the top of the pickup. In addition to the interaction of the string with its corresponding terminal of the pickup, during the deflections toward one side, the string will be closer to the terminal of the sixth string. When the string moves in the opposite direction, it will have interactions with the terminal of the fourth, third, second, and first strings. Consequently, the signal is markedly asymmetrical, with a high harmonic content for each waveform. Also, such asymmetry will be different for each string depending on its position over the pickup. These interactions have been elegantly described by Horton and Moore (2009).

The peculiar signal generated by the pickup is only a part of the typical sound of the electric guitar. Additionally, the performance of the amplifier used to produce the sound waves is extremely important. It is interesting to consider that when the electric guitar was developed, the only way to amplify sound with a loudspeaker was using tubes. This type of amplifier (named a valve-state amplifier) has no linear behavior, so its output signal is not a larger version of the input signal. Therefore, the waveform is distorted. However, because there was no other option to hear the sounds of an electric guitar, valve-state amplifiers were important during the definition of the original sound of this new instrument.

With the development of solid-state amplification some years later, the signal could be amplified, avoiding distortion and the distinctive sound obtained through the tubes. It is interesting, however, that guitar players never really accepted the distortion-free sound of solid-state amplifiers, and so they have kept alive the manufacture of valve-state amplifiers to the present day in pursuit of the original sound (with the inherent distortion through the tubes). Valve-state amplifiers for electric guitars, it is estimated, consume as many as three out of four of the world's production of audio tubes (Barbour, 1998).

Tube amplification causes distortion under two conditions: turning up the volume of the amplifier or sending a powerful signal from the guitar (see **Multimedia File 2** at acousticstoday.org/torresmedia). Usually, electric guitar players try to find the exact volume on the amplifier where, if they subtly play the strings, a clear sound without distortion is obtained, whereas an aggressive attack causes overdrive. A very enlightening discussion about this was published by Keeports (2017).

One of the most remarkable additions to the electric guitar was a mechanical system to change the position of the bridge during a performance. It is installed in several models, and every electric guitar player knows it by the name of the inventor: the Floyd Rose system (Rose 1979) (**Figure 1**). This ingenious mechanism allows dramatic changes in the tension of the strings by moving the bridge and returning it to the original position. The performance of the Floyd Rose system of the electric guitar of **Figure 1** is seen at the end of **Multimedia File 2** (at acousticstoday.org/torresmedia).

Conclusions

If it is assumed that the key role of guitars is producing musical sounds, from what has been established in this article, the conclusion could be that the acoustic guitar and the electric guitar are two almost unrelated instruments. Indeed, the sound of the two instruments is unmistakably different. **Multimedia File 6** (at acousticstoday.org/torresmedia) shows a brief demonstration comparing the same notes played on the steel-stringed guitar and a single-coil electric guitar.

The quick fade out of the high-frequency harmonics in the sound of the acoustic guitar means that when several notes are played concurrently, there is a clean and well-defined mix of sounds. Because of this characteristic, the acoustic guitar can be considered a polyphonic instrument, meaning that several notes can be played at the same time. Acoustic guitar players can pluck complete chords to provide musical accompaniment, and with more skill, a melody can be played on the same guitar at the same time. Therefore, the support of additional musical instruments (as a piano or a bass) is not required. Most pieces written for the classical guitar are conceived without involving additional instruments.

In contrast, the high-frequency harmonics are present for a longer time in the notes delivered by the electric guitar due to the setup of the magnetic pickup and the nonlinearity of the valve-state amplifier. Although it is possible to obtain clean chords with the adequate setup in electric guitars, the characteristics that became popular are identified when its sound is distorted. Under these conditions, the electric guitar is employed as a monophonic musical instrument, which means that mixing the sound of several notes at the same time tends to be unpleasant or even perceived as noise. However, beautiful melodic lines can be created with the musical accompanying of at least a guitar bass. Occasionally, some nuances or rhythms can also be played using two or a maximum of three notes plucked at the same time, but it is very unusual to simultaneously play the six strings, unlike the case for the acoustic guitar.

Often young guitar students try learning to play both the acoustic guitar and the electric version. But studying each one requires different techniques and a lot of effort. Then, after a certain point, one of the guitar types seduces the musician more than the other type. How does this choice happen? Well, it is hard to explain, but undoubtedly some of the personality of the guitar player will be reflected in the type of guitar selected: acoustic or electric.

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Jesús Alejandro Torres is a researcher of stringed instruments. All the work for his bachelor's degree in mechanical engineering (2003), master's degree (2006), PhD (2010), and postdoctoral position was focused on experimental testing and computer simulations about the vibroacoustic behavior of the acoustic guitar. Since 2011, Dr. Torres has led the acoustics lab at the Violin Making School of Mexico, where he expanded his interest to study the violin. He currently teaches a two-semester course on acoustics of the violin. He is also an enthusiastic electric guitar player.