Analysis of Electric Guitar Pickups

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Nomenclature

$\varepsilon =$ Electromagnetic Force
$\Phi =$ Magnetic Flux
$B =$ Magnetic Induction
$A =$ Area
$c =$ Transverse Wave Speed
$x =$ Displacement, $x -$ Direction
$y =$ Displacement, $y -$ Direction
$t =$ Time
$T =$ Tension
$\rho_L =$ Linear Mass Density
$j =$ Square Root of -1
$\omega =$ Angular Frequency
$k =$ Wave Number
$\lambda =$ Wavelength
$f =$ Frequency
$L =$ Length
$f_1 =$ Fundamental Frequency
$f_n =$ nth Harmonic
$A_n =$ Complex Amplitude of nth Solution
$L/d =$ Pluck Location
$h =$ Height
$n =$ Mode Number
$L =$ Lumped Capacitance
$Z_c =$ Complex Impedance
$L_{coil} =$ Coil Lumped Inductance
$C_{coil} =$ Coil Capacitance
$C_{load} =$ Load Capacitance

Abstract

Many guitarists do not understand how tones are generated by electromagnetic pickups on electric guitars. With further engineering insight, they may become more effective at achieving their desired tone. The creation of a tone - from a plucked string to the sound that emerges from the amplifier - requires the understanding of several strongly-interacting acoustical, mechanical, and electronic systems. These include the theory of electromagnetic induction, the design and fabrication of the pickup, and the location of the pickup relative to the bridge, the structural characteristics of the guitar, and the relationship of the pickup's output impedance to that of the instrument cable and guitar preamplifier. A complete analysis of the three most common electromagnetic pickups, the Single Coil, the Humbucker, and the P-90, used on the Fender Telecaster(TM) and Stratocaster(TM) and Gibson Les Paul(TM), provide examples for the approach developed in this paper.

INTRODUCTION

The electric guitar is one of the most preeminent cultural icons in America. The electric guitar is heavily responsible for the changes in direction of American society from the 1930’s around the time of its invention, up until present day. Guitar players young and old look to the electric guitar as a means to greatness, passion and diversion. Great electric guitar tones are one of the most coveted and sought after characteristics of this influential instrument. History has bestowed many examples of guitar tones upon the listening community, including the good, the bad and the truly bad.

For example, Eric Clapton's tone while he was with John Mayall and the Bluesbreakers is not only epic, but considered to be by many as the ultimate tone. Indeed, many other examples of excellent electric guitar tone exist. As do some very bad ones. Particularly, in the form of the learning player, were coupled with poor tone is poor playing, which often makes for tympanic torture. Visit your local music store to experience this nonsense. The amazing thing is that there are experienced and very talented players that have particularly undesirable tone. It is a general consensus throughout the guitar community that Steve Vai, an exceptional player, has some of the worse tone ever amplified. Frank Zappa, for whom Steve Vai backed up as second guitarist, said to Steve "Your tone sounds like an electric ham sandwich". Presumably this was not a compliment.

The field which we seek to study, sound quality of electric guitar pickups, is a highly subjective area, and presents a number of hurdles for most electric guitar players. Though a great deal of work has been done by people like Zwicker and Fastl [1] and others to help us quantify and qualify sound objectively, the field of sound quality has still remained a mystery to most. Another problem that many guitarists are faced with is that they just don't really listen to the sound of their guitars. A common statement heard at live performances is, 'why does he change guitars after each song, they all sound the same". Nothing could be further from the truth, as each guitar, each pickup, contains its own unique characteristics and spectral content, which distinguish it from the others. Many musicians including guitarists, do not understand the tones generated by pickups on an electric guitar; with further insight they will be more effective at achieving their desired tone.

HISTORY OF ELECTRIC GUITAR & PICKUPS

Understanding the electric guitar pickup begins by knowing its origins. In this chapter we will discuss the history of the electric guitar and pickup development.

2.1. Guitar Seeking Amplification

The guitar's existence may be traced back to ancient times. Though in forms slightly different than today's examples, stringed instruments that were strummed or plucked with the right hand and fretted with the left have been documented before the 15th century. It was in the Baroque and Classical periods that the guitar underwent most of its final mutations and was established as a well recognized classical construction. The classical style acoustic guitar of this period, an instrument generating musical tones by transferring the energy from the vibrations of six gut strings to a radiating sound board, went on mostly unchanged until the mid-1800's. Around 1850, steel strings began appearing on Spanish style guitars which were vertically held. This added volume and a brighter sound. But it also added tension on the neck and sound board, causing warping and shattering of either or both. Developments in the internal bracing for the sound board, called X-bracing, alleviated this problem within the acoustic guitar. It strengthened the guitar by arranging the bracing for the sound board in this new design, in the shape of an X. In addition, the truss rod was introduced to help strengthen the neck. The truss rod was a steel rod inside the neck which counteracted the tension of the strings pulling against it. These design improvements set the new standard for guitars but they still couldn't compete in volume with other instruments typically seen in big bands of the early 1900's.

During the industrial age, the style of popular music and the social events that revolved around it, big band and dancing became popular. The acoustic guitar was unintelligible over the large brass sections of these swing bands, and thus remained unheard. Consequently, the acoustic guitar was demoted to the rhythm section, where it was all but a formality. Luthiers like Orville Gibson, then began to experiment with carved, arched sound boards instead of traditional flat ones to add to the acoustic projection of the guitars. This helped, but not enough to be heard over the rest of band's instruments.

Different measures were then taken to achieve more volume from the guitar. New materials were used and the design of the acoustic guitar was changed. Around 1927 the resonator guitar was born of the National String Instrument Company created by George Beauchamp and John Dopyera. Their creation was made mostly of hollow metal body with large aluminum cone resonators within the body, under the strings. This resonator guitar amplified the sound about 3 -5 times louder than the traditional acoustic guitar. Some of the drawbacks were the weight of the instrument and the sound quality was different then its predecessor.

2.2. Early Attempts In Electrical Amplification

In the beginning of the 20th century, the telephone and the radio were starting to become everyday household technology. Many tinkerers had started amplifying guitar sounds with parts from telephones, like the microphone in the mouth piece. But when did the guitar pickup come along? Who actually invented the electric guitar? People began to experiment with amplified instruments other than guitars as early as 1890. “George Breed was a naval officer who filed a patent for ‘a method of and apparatus for producing musical sounds by electricity’ in 1890” [2]. Another one of the earliest developers was Lloyd Loar of the Gibson Guitar Company, who in 1924, developed a pickup to use for the viola and string bass. Loar’s design was slightly different and less effective than current designs. In his design, the strings passed vibrations through the bridge to the electrostatic pickup which registered those vibrations and passed the signal to an amplifier. Yet, the first marketed electric guitar was from the Stromberg-Voisinet company in 1928 utilizing a similar pickup. The problem with this pickup design was the signal was very weak, even with the help of amplifiers of the time and was extremely prone to feedback.

The need for a more direct pickup design led engineers to the pickup designs we have today, where the electromagnet picks up the vibrations from the strings themselves. This design is based on the principle of electromagnetic induction. “The same principle is used in phonographs, electric motors and generators” [3]. George Beauchamp adapted this principle to a single stringed instrument in 1925, but struggled to adapt it to six strings so that each string would have an evenly powerful signal. About five years later, in 1930 the design was completed. Beauchamp and his friend Paul Barth created a pickup based on two horseshoe magnets with steel poles added onto one side of each internal gap, wound with wire. This allowed the pole placement to amplify each string individually. Once the pickup was working as designed, the two inventors contacted a guitar builder by the name of Harry Watson. Watson built a neck and body for the first viable electric guitar. This guitar was a Hawaiian style lap guitar nicknamed the ‘Frying Pan’.

Beauchamp took the Frying Pan to Adolph Rickenbacker, an owner of a tool and die company that made steel bodies for National’s resonator guitars. Using the influence of Rickenbacker, the two created a company under Rickenbacker’s name, selling the Frying Pan to countless lap steel players. However, it was Adolph Rickenbacker that claimed to be the inventor of the electric guitar.

2.3. Continued Improvements In Pickup Design

Developments continued from the Frying Pan to the Spanish Electric guitar made by Gibson luthiers. Gibson worked with Alvino Rey, a prominent slide guitarist of the time, to improve the pickup making it more suitable for Spanish style guitars. They developed a pickup in which a solid bar magnet was wound with a pickup coil, instead of individual pole pieces for each string. The design was initially incorporated in a Hawaiian style guitar, but was quickly adapted to a Spanish style as intended. This guitar was called the ES-150, standing for Electric Spanish and would be the first ‘normal’ electric guitar.

There were still many issues; the most annoying was that of feedback. At this point, the guitar makers were still looking to the pickup as the culprit. It was only when Les Paul began solving the problems that the design improved again. He believed that the solution was to create a solid body guitar. He turned out to be right. His theory was that the solid guitar would stop feedback caused by the highly acoustic soundboard hearing itself. Paul’s first successful solid body guitar was call the ‘Log’. It was a 4” x 4” piece of pine mounted with simple magnetic pickups that Paul made himself. However, when Paul approached Gibson with concept of a solidbody, they were skeptical and thought it too outlandish for most musicians to accept.

It was in 1943 that Leo Fender, a radio repair man, had a working prototype of a solid body electric that he would rent to players to gather suggestions for improvement. By 1949, Fender released the Esquire, which would be renamed the Broadcaster, and then again renamed as the Telecaster. The guitar had all the benefits of Les Paul’s design but sounded much different than the Spanish Electrics, which were preferred in jazz for their warm sound. The Telecaster however was a hit with the Country and Blues players, for the high pitched tones it produced with its single coil pickups.

Gibson realized they needed to get into the solid body electric guitar market and in 1952 they released their own electric called the Les Paul. The pickups Gibson employed for the Les Paul varied. Originally, the Les

Paul was fit with P-90 pickups (described in Chapter 5), which were originally developed in 1946. Then in 1957, Gibson fit the Les Paul with Humbucking pickups. Since then, the electric guitar has retained basically the same in design.

THEORY OF ELECTRIC GUITAR PICKUP

There are a number of different guitar pickup designs available on the market today. The most traditional is the passive magnetic pickup design employing the physics of electromagnetic induction. This design represents the majority of the pickups used on electric guitars. Other designs include piezoelectric pickups, typically found on acoustic guitars, and optical pickups, currently found on some specialized bass guitars. The scope of our study will be limited to the passive magnetic variety.

All pickups are transducers that convert a portion of the vibratory energy of the string's motion into oscillatory electrical signals. They collect, gather or 'pickup' the oscillation of the guitar strings. To understand the magnetic pickup transducer, one must have an understanding of the principles of electromagnetic induction.

3.1. Introduction To Electromagnetic Induction

There is a distinction between permanent magnets and electromagnets. The former have two ends, North and South and they attract ferromagnetic objects typically made of steel or iron. An electromagnet has the same effect, except it is temporary; the magnetism only exists when electric current is flowing. This is based on the principle of Ampere [4]; whenever you have a current traveling through a wire, a magnetic field is induced. By coiling the wire a few times you increase the strength of the magnetic field induced, so it behaves like an ordinary permanent bar magnet. This phenomenon implies there is a relation between electricity and magnetism. If we can use electricity to create magnetism, can we do the opposite: use magnetism to create electricity?

It was this question that drove Joseph Henry [5] and later Michael Faraday [6], to their independent discoveries of electromagnetic induction in 1830 and 1831 respectively. They did so through the following experiment. A bar was placed across the poles of an electromagnet. Wrapped around the bar was an insulated coil of wire. Connecting the leads of the coil to a galvanometer, Henry was able to see a momentary deflection in the galvanometer when the current in the electromagnet was turned on, even though there was no electrical connect between the coil and the wires of the electromagnet. He had discovered that current is induced or generated in the coil when the magnetic field through it changes. It doesn't matter if the wire is moving or the field or any other moveable conductor crossing through the magnetic field lines. This is the definition of electromagnetic induction.

The generation of an electric current in a circuit implies the existence of an electromotive force (emf). An emf is the work per unit charge done by the source of emf in moving the charge around a closed loop. Faraday stated that the induced emf in a circuit is proportional to the rate at which the magnetic field lines cross the boundary of the circuit. Faraday's Law is expressed in terms of magnetic flux, shown in equation 1.

$$\varepsilon = -\frac{d\Phi}{dt} \qquad (1)$$

Where, Φ is equal to the magnetic flux, shown in equation 2.

$$\Phi_B = BA \qquad (2)$$

"Magnetic flux is the product of the average magnetic induction *B*, times the perpendicular area *A* that it penetrates" [7].

3.2. Electromagnetic Induction Applied to Guitar Pickups

The guitar pickup is made of an assembly of permanent magnets wrapped with a coil of insulated wire, typically copper. The strings of an electric guitar are made of magnetically permeable material, such as an iron or nickel alloy. The strings being in close proximity to the permanent magnets of the pickup become magnetized. This induces two magnetic poles in the string directly above the magnet. As the string vibrates, it causes changes in magnetic flux which induces an emf in the pickup coil according to Faraday's Law. Because magnetic flux changes as a function of time as stated in equation 1, the emf generated is simply a function of string velocity. This emf is physically the open circuit voltage that is output from the guitar to the tone controls and then out to the amplifier. The current produced by the emf is related to the input impedance of the guitar amplifier.

DESIGN & IMPLEMENTATION OF ELECTRIC GUITAR PICKUP

There are many physical design aspects that affect the performance of pickups such as pickup location, pluck location, string height, guitar body type and construction, string type, hardware as well as pickup parameters such as number of windings, inductance, impedance, capacitance, tone controls, and cable and amplifier considerations. A thorough examination of these follows:

4.1. Pickup Location

The physical location of the electric guitar pickup has tremendous impact on the tonal properties of the pickup output, i.e. the timbre of sound created. The timbre of an instrument is defined as the combination of qualities of a sound (harmonic or spectral content) that distinguishes it from other sounds of the same fundamental pitch and amplitude. The unique harmonic content of instruments is part of the reason a guitar sounds different from a piano or any other instrument. The other determinant is the attack and decay envelope that characterizes the transient behavior of the sound.

It is commonly mistaken that tone and timbre are synonymous. Tone can be thought of as the equalization (EQ) that can be adjusted from the guitar's tone controls, a separate EQ device or the tone controls on an amplifier. Timbre is the character of the different sounds that pickups generate prior to modification by the tone control circuit. The timbre is related to the pickup's location with respect to the string's harmonic content. Most guitars are typically designed with 2 or 3 pickup locations depending on the model. See Figure 1 below.

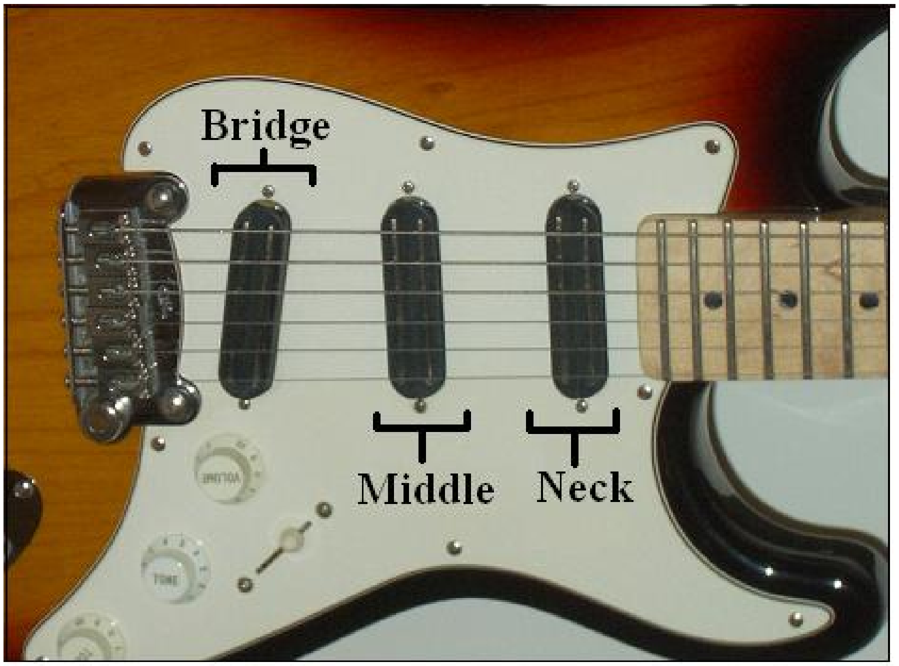

Figure 1. Pickup locations on a guitar affect tonal characteristics of pickup output.

Figure 1 shows a Stratocaster style guitar with the 3-pickup configuration and associated pickup locations. The ‘bridge’ pickup is the pickup located on the body closest to the bridge. The ‘neck’ pickup is the pickup located on the body just before the neck. And the ‘middle’ position is located in between the neck and the bridge pickups. Boosting the treble on the output of a neck pickup with a tone control will not make it sound like the bridge pickup. Similarly, boosting the mids on a strat will not make it sound like a Les Paul! We will explore timbre in more detail, later in this section.

Regardless of type, it may be generalized that the closer the pickup is placed to the bridge the more high frequency content is present, i.e. it sounds brighter or cuts more. Conversely, as the pickup location is moved closer to the neck, the timbre is characterized as being deep and rich. The reason for this is based on the harmonic content that is inherently present in the vibrating strings that the pickup “picks up” at its various locations. It is interesting to note that none of these sound like an acoustic guitar, where every component of the string vibration is coupled to the guitar body through mechanical forces applied by the ends of the strings through the bridge and the nut. This includes longitudinal as well as transverse waves of the fundamental and every harmonic. On the electric guitar only the displacement of transverse waves along the axis of the pickup sensitivity at the pickup location are sensed. In essence, only one specific aspect of a complex mechanical interaction is captured as an electrical voltage and sent to the input stage of the amplifier.

When the strings of the guitar are plucked, triangle–shaped standing waves on the string are set up, consisting of a harmonic superposition of the fundamental and higher harmonics. Let us then develop the equation describing this behavior by looking at the 1D linear wave equation for transverse waves on a string. The linear one dimensional wave equation assuming small transverse displacement as found in any reputable acoustics text is as follows.

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 y}{\partial t^2} \qquad (3)$$

Where the constant c^2 (transverse wave speed) is defined by T, tension and ρ_L, linear mass density.

$$c^2 = \frac{T}{\rho_L} \qquad (4)$$

It is reasonable to assume the boundary conditions of the string to be fixed at the bridge and the nut. The attachment of the string to the guitar body is approximately rigid, and thus the strings transfer relatively little energy to the body. The reality of this phenomenon is responsible for the immortal words of Nigel Tufnel, "listen to that sustain” [8]. To find the normal mode frequencies of a fixed-fixed sting, we assume the general solution of the following form:

$$y(x,t) = Ae^{j(\omega t - kx)} + Be^{j(\omega t + kx)} \qquad (5)$$

In Equation 5, j equals the square root of -1, ω, the angular frequency, k, wave number, and λ, wavelength, have been introduced and are defined in Equations 6-8 below.

$$\omega = 2\pi f \qquad (6)$$

$$k = \frac{2\pi}{\lambda} \qquad (7)$$

$$\lambda = \frac{c}{f} \qquad (8)$$

We know that the string's displacement at x=0 and x=L will be zero as seen in the Figure 2 below.

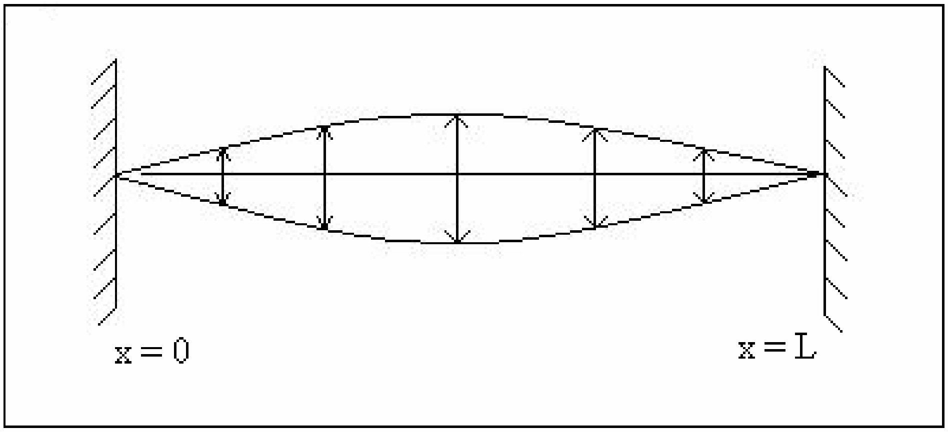

Figure 2. Fixed-fixed string displacement based on distance.

So applying boundary conditions gives the following:

$$y(0,t) = 0 \quad \rightarrow \quad A + B = 0 \quad \rightarrow \quad B = -A \qquad (9)$$

$$y(L,t) = 0 \quad \rightarrow \quad Ae^{-jkL} + Be^{jkL} = 0 \qquad (10)$$

$$A\left[e^{-jkL} - e^{jkL}\right] = 0 \qquad (11)$$

$$e^{-jkL} - e^{jkL} = 0 \qquad (12)$$

$$-2j\sin(kL) = 0 \qquad (13)$$

The frequencies that satisfy the boundary conditions are:

$$kL = n\pi \quad n = 1,2,3... \qquad (14)$$

$$\lambda_n = \frac{2\pi}{k_n} = \frac{2L}{n} \qquad (15)$$

$$f_n = \frac{\omega_n}{2\pi} = \frac{k_n c}{2\pi} = \frac{nc}{2L} \qquad (16)$$

These solutions correspond to an integer number of half-wavelengths fitting between the bridge and nut, as shown in Figures 2 and 5. Where f_1 is the fundamental frequency, f_n is the nth harmonic, c is the transverse string velocity, n is the mode number and L is the length of the string. Recalling from above that $B = -A$, the Eigen functions (or mode shapes) are:

$$y(x,t) = A_n e^{j(\omega_n t - k_n x)} + B_n e^{j(\omega_n t + k_n x)} \qquad (17)$$

$$= A_n \left[e^{jk_n x} - e^{jk_n x} \right] e^{j\omega_n t} \qquad (18)$$

$$= A_n \left[-2j \sin(k_n x) \right] e^{j\omega_n t} \qquad (19)$$

Incorporating the -2j into the A_n, this leaves us with the well known expression for a standing wave.

$$y(x,t) = A_n \sin(k_n x) e^{j\omega_n t} \qquad (20)$$

Where A_n is the complex amplitude of the nth solution. As discussed earlier, electromagnetic induction produces an emf that is directly proportional to the velocity of the string at the pickup location. By taking the time derivative of Equation 20, we produce the expression for velocity of a standing wave in Equation 21.

$$v(x,t) = \frac{dy}{dt} = j\omega_n A_n \sin(k_n x) e^{j\omega_n t} = j\omega_n y(x,t) \qquad (21)$$

where:

$$k_n = \frac{n\pi}{L} \qquad (22)$$

$$\omega_n = k_n c \qquad (23)$$

For n = 1 to infinity, the complete solution transverse displacement is:

$$y(x,t) = \sum_{n=1}^{\infty} y_n(x,t) = \sum_{n=1}^{\infty} \left[A_n \cos(\omega_n t) + B_n \sin(\omega_n t) \right] \sin(k_n x) \qquad (24)$$

This result says that an arbitrary initial displacement, y(x,0) can be represented as a superposition of the normal modes of the system. This equation describes the physical behavior of the entire string. However, the guitar pickup reads vibrations off a narrow portion of the string. This has a critical effect on the timbre of the pickups.

Figure 3 is a drawing of the string as found on an electric guitar. The string is attached as fixed-fixed, with the bridge being the left attachment point and the nut being the right attachment point. Three pickups are shown in the "neck", "middle" and "bridge" positions, as found on a Stratocaster style electric guitar. The string is shown to be vibrating at the fundamental frequency.

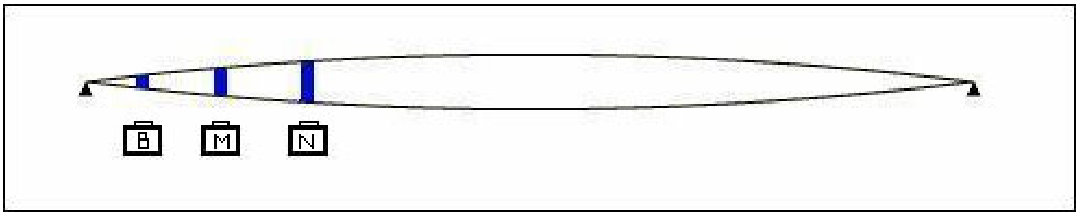

Figure 3. Fixed-fixed vibrating string in fundamental frequency and associated output over bridge, middle and neck pickup locations.

Since all parts of the string oscillate at the same frequency, the blue stripes represent the output level of the vibrating string sensed by the individual pickups at each location. The output increases as the location is moved closer to the neck from the bridge for the fundamental (n = 1) mode. It is important to remember that the electromagnetic pickup output is proportional to velocity not displacement. Therefore, if the string in Figure 3 is vibrating at a particular frequency, the center of the string has the highest velocity and the ends of the string have zero velocity. As you move away from the bridge end towards the center, the pickup output increases due to the higher velocity of the string. For a given displacement, as frequency increases, the output increases, meaning the pickups have a greater sensitivity to higher frequencies. This is simply because at higher frequencies the string vibrates faster for a given displacement amplitude.

The plucking position affects the amplitudes of the modes. This can be heard when the closer to the bridge the string is plucked, the sharper the note sounds. This is because the higher modes are being excited more than the lower modes. In Figure 4 below, a string with plucking location L/d is pictured.

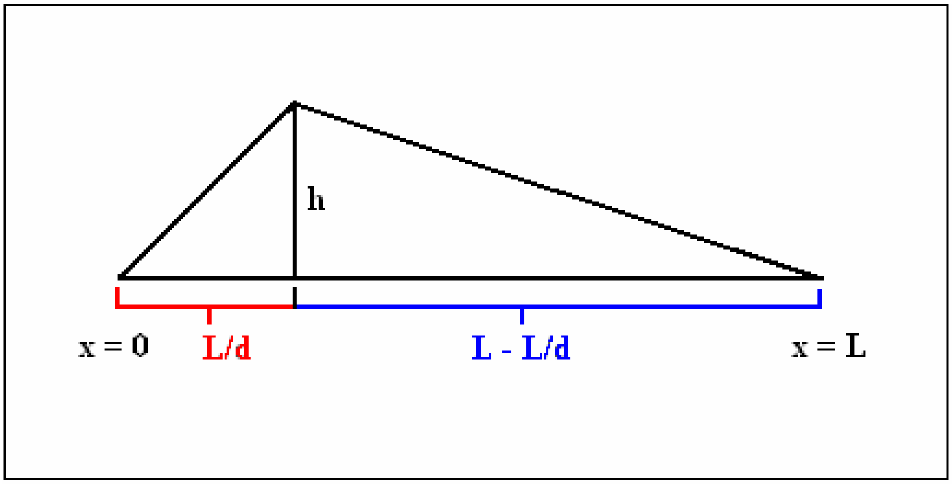

Figure 4. Plucked fixed-fixed string with length L, height h, and arbitrary pluck distance L/d.

Figure 4 is a general representation of a plucked fixed-fixed string. The associated boundary conditions for initial displacement (t = 0), are the following:

$$y(x,0)=\begin{cases} \dfrac{dh}{L}x & 0\le x\le \dfrac{L}{d} \\ \dfrac{d}{(d-1)}\dfrac{h}{L}(L-x) & \dfrac{L}{d}\le x\le L \end{cases} \qquad (25)$$

The Fourier coefficients for the fixed-fixed string based on initial displacement is shown below in Equation 26.

$$A_n=\frac{2}{L}\int_0^L y(x,0)\sin k_n x dx \qquad (26)$$

Knowing the boundary conditions of initial displacement from Equation 25, the general equation for the amplitudes (A_n) of a string length L, plucked at location L/d, at height h is shown below in Equation 27.

$$A_n = \frac{2}{L}\left[\int_0^{L/d} \frac{dh}{L} x \sin k_n x dx + \int_{L/d}^{L} \frac{d}{(d-1)} \frac{h}{L}(L-x)\sin k_n x dx\right] \quad (27)$$

The solution to the general equation is shown in equation 28.

$$A_n = \left(\frac{2hd^2}{d-1}\right)\frac{1}{(n\pi)^2}\sin\left(\frac{n\pi}{d}\right) \qquad (28)$$

Harmonics that represent the plucked string decrease in amplitude proportional to the frequency squared…we can apply this to a specific case such as at L/3. So for plucking at L/3.

$$y(x,0) = \begin{cases} \frac{3h}{L}x & 0 \le x \le \frac{L}{3} \\ \frac{3}{2}\frac{h}{L}(L-x) & \frac{L}{3} \le x \le L \end{cases} \qquad (29)$$

$$A_n = \frac{2}{L}\left[\int_0^{L/3} \frac{3h}{L} x \sin k_n x dx + \int_{L/3}^{L} \frac{3}{2} \frac{h}{L}(L-x)\sin k_n x dx\right] \quad (30)$$

Equation 30 simplifies to:

$$A_n = \frac{9h}{(n\pi)^2}\sin\left(\frac{n\pi}{3}\right) \qquad (31)$$

For the case of L/3, the coefficients are calculated below in Table 1.

Coefficient	Amplitude	Ratio (An/A1)
A_1	0.7897h	-
A_2	0.1974h	1/4
A_3	0h	-
A_4	-0.0494h	1/16
A_5	-0.0316h	1/25
A_6	0h	-
A_7	0.0161h	1/49
A_8	0.0123h	1/64
A_9	0h	-

Table 1. Harmonic coefficient amplitudes and ratios with respect to A_1.

Recall that the pickup output is proportional to the velocity of the string.

$$emf(x) = j\omega_n A_n \sin(k_n x) \qquad (32)$$

Based on Equation 28, the coefficients A_n are proportional to the reciprocal of the mode number (n) squared.

$$A_n \propto \frac{1}{n^2} \qquad (33)$$

For $k_n x < 1$, the sine function can be approximated by the first term in a Taylor series.

$$\sin(k_n x) \cong k_n x \quad for \quad k_n x < 1 \qquad (34)$$

From Equation 16, we see that the wave number, frequency and mode number are proportional.

$$k_n \propto \omega_n \propto n \qquad (35)$$

As shown in Equation 32, both ω_n and k_n, are proportional to n for $k_n x < 1$, the velocity is proportional to n^2. This n^2 dependence of the velocity of the n^{th} harmonic is cancelled by the n^2 dependence of the harmonic amplitude, A_n. Therefore, for a pickup located a distance x from the bridge such that $k_n x < 1$, the pickup's open-circuit output voltages will be equal for all of the harmonics of a plucked string up to the n^{th} mode satisfying $k_n x < 1$.

Figure 5 depicts the simplest case of string vibration, the fundamental. In reality the string vibration is characterized by the fundamental as well as sustained harmonic frequencies and some transient vibrations. The sustained harmonic frequencies are of interest because they define the timbre of the guitar. In the figure below the same string is shown vibrating at the fundamental (n = 1), second (n = 2), third (n = 3), fourth (n = 4) and fifth (n = 5) harmonics.

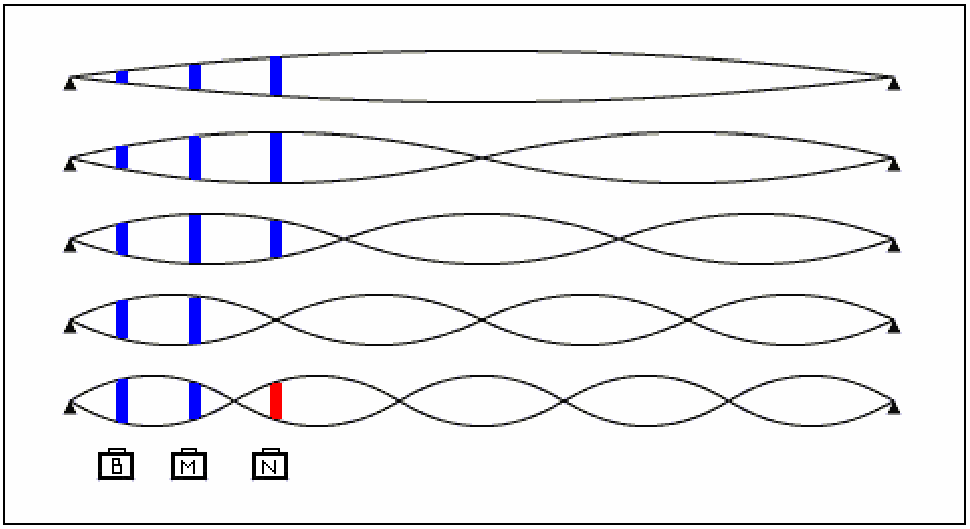

Figure 5. String vibration shown with the neck pickup (N) located at x = L/4 as measured from the bridge. The maximum amplitudes of each mode are equal for illustrative purposes.

The harmonics exist as components of a played note or individually forced by muting the string lightly with the finger over a node point on the string. The node points are those where string vibration is at a minimum and the anti-node is where vibration is at a maximum. Together the harmonics add by harmonic superposition as described in Equation 24.

By looking at the individual harmonics we gain further insight to the nature of the emf produced by an electric guitar pickup. The fundamental has an anti-node directly at the center of the string representing maximum amplitude and nodes at the ends of the fixed-fixed string. The second harmonic has a node at the center of the string and anti-nodes at 1/4 and 3/4 of the string length (L). In this figure, one of the anti-nodes is directly above the neck pickup, resulting in a higher output than the other pickup locations. The third harmonic has two nodes at 1/3 and 2/3 the string length and three anti-nodes at 1/6, 3/6, and 5/6 the string length. The middle pickup location is directly underneath an anti-node for the 3rd harmonic ($n = 3$) and has the highest output, while the neck and the bridge have lesser outputs. The fourth harmonic has nodes at 1/4, 2/4 and 3/4 of the string length. This represents an interesting effect since the neck pickup is directly underneath a node at 1/4 the string length. This means there will be no output at the neck pickup for that frequency. Many electrics are designed with the neck pickup at one-quarter of string length. The fifth harmonic has nodes at 1/5, 2/5, 3/5 and 4/5 the string length. Here the red stripe indicates that the displacement is out-of-phase above the neck pickup. If the neck pickup is combined with other pickups, phase cancellation of this frequency will occur, although the cancellation will only be complete if the amplitudes of the string's motion is equal at both locations, as shown. In this case, M and N cancel and the total output is due to B.

Timbre is determined by the relative levels of each of the different harmonics, which physically include the highest harmonic that an amplifier can reproduce or the highest harmonic a person can hear (which ever comes first)! A higher level of upper harmonics compared to the lower harmonics and fundamental, produces that brighter, sharper tone as found at the bridge pickup. This can be seen in Figure 5, when looking at each of the harmonics just over the bridge pickup. Physically, there is more upper harmonic content, and less fundamental at the bridge than at the neck or middle position for the rather uncommon case where all five harmonics have the same amplitude.

As a player frets notes on the fret board, this changes the effective length of the string and alters the frequency of vibration to produce different notes. This also progressively changes the locations of the nodes, which changes the harmonic content of the notes. Seen below in Figure 6 are the effects of the fundamental, second, third and fourth harmonic, subject to fretting at the 12th fret (one half the distance from bridge to nut).

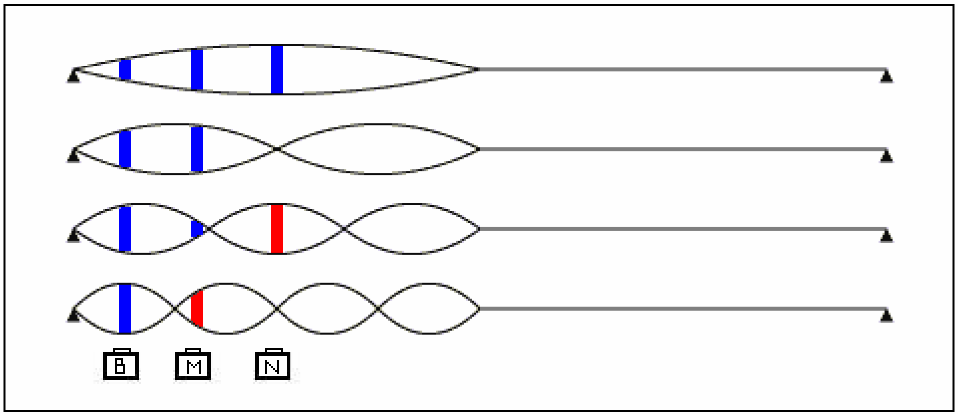

Figure 6. Strings vibrating while fretted at octave.

The exercise of cataloging each of the node locations for each string at each fret is better left to a research student with spare time and a computer. The principles remain the same, though the values of frequency and node location change.

4.2. Pickup vs. String Height

The height of the strings with respect to the fret board is referred to as the "action". It is a parameter that players change to suit their playing style and to achieve a particular sound. On an acoustic guitar with a higher action the output grows acoustically. A high action is well suited for rhythm playing, typically characterized by strumming. It is more difficult to play arpeggios with a higher action. On an electric guitar the opposite is true for output. As the distance from the strings to the pickups increases the output decreases. Recall, that the strings become magnetized in the presence of the pickups and the alignment of the dipoles in the string generates the emf's. This means that if the strings are further away, the pickups magnetize the strings less. Also with a greater distance, the pickups sense less of the emf's given off by the strings during vibration.

4.3. Guitar Body and Construction Considerations

In the Pickup Location section, it was stated that the boundary condition imposed on the motion of the strings of a guitar may be treated as fixed-fixed due to the relatively rigid mounting to the guitar body at the bridge and nut. Thus, very little energy is transferred to the body, and this means the harmonic content of the strings during vibration is not appreciably changed by the body of the guitar. This was a fair assumption for the derivation of the modes of the string in Equation 24. In reality, the guitar body and neck made of wood, and usually solid, are not infinitely stiff. Due to the guitar itself having its own vibration characteristics and possibly affecting the response of the string vibration, the sound that is output may vary depending on the shape, construction, type of materials used, and whether the body is solid, semi-hollow or hollow.

At this point it is helpful to define the different characteristics of electric guitar tone. Tone can be broken down into time and frequency domain components called the envelope and harmonic content. The envelope of tone refers to the attack, sustain and decay of the note played. The harmonic content is the superposition of the fundamental frequency along with any harmonics sensed by a particular pickup. Guitarists often refer to "attack" to express angle, pressure and method of the hand, fingers, plectrum, etc, during the act of plucking the string. This discussion refers to the attack as the change in the shape of the plucked string and the resulting sound, just after the string has been released. Essentially, how quickly the sound reaches maximum amplitude. The attack portion of the signal or note is determined by the higher harmonics which decay much more quickly than the lower harmonics and fundamental. This transient portion of the signal is generally referred to as the 'twang' of the guitar. Its duration is measured in milliseconds but is a distinctive and important characteristic of the guitar's sound. The attack portion of the signal is represented in the figure below label as section "A".

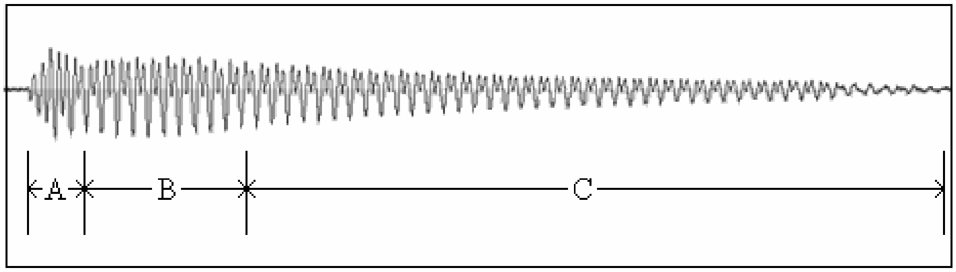

Figure 7. Time history of a plucked note showing the attack (A), Sustain (B) and Decay (C).

Sustain is defined as the constant volume portion of the signal until it begins to decay. In reality, a plucked guitar signal has zero sustain because it begins to decay immediately after it is generated. However, there is a portion of the signal after the attack represented in Figure 7 as section "B", where the signal is nearly constant called the sustain. In other words, the decay is very gradual, before reaching section "C" which represents a greater decay rate.

Many guitarist mistakenly refer to the "sustain" of the instrument to mean the decay rate. Amongst the guitar community, a Les Paul is known for having long "sustain", when technically it has none. It has a slower decay rate compared to other guitars. The decay rate quantifies how quickly the amplitude of string vibration (output of the guitar) returns to zero. From inception, the signal is decaying due to loss of energy. The decay itself is caused by a number of mechanisms that together drain the vibrating string of its energy. The mechanisms that cause decay are the strings resistance to bending (damping), air resistance slowing the movement of the string, and the transfer of energy from the string to the body of the guitar.

In high amplitude or 'stage volume' cases, feedback sustain may be present. Feedback sustain occurs when energy is returned to the strings from the amplified pickup output. This feedback loop has an interesting effect by creating tones that last indefinitely, something that is not possible with a traditionally plucked string. This feedback mechanism depends upon the mechanical response of the guitar body which is coupled to the strings. Depending on the style of music the artist is playing, feedback may be desirable. Carlos Santana uses feedback sustain during live performances regularly. During sound check (before the show) he determines the locations on the stage where feedback occurs for different frequencies. He then marks those points with tape on the floor to be able to use feedback as needed during the performance.

The method by which the string is attached to the guitar and the tension are the first two physical parameters affecting tone. The more rigidly the string is attached to the guitar, the more coupled it is with the guitar's structural response. The structural response of a particular guitar can be found from a number of analysis techniques such as modal analysis or laser vibrometry. Results of such studies have shown that there are many different natural frequencies and associated mode shapes for guitars of various shapes. It is not the intent of this chapter to examine these techniques in detail, but rather to analyze how the results may affect pickup response.

The concept of tone may be intuitively described in the following manner: As the note is initiated (attacks) and decays, the harmonic character changes with time. The resonance or structural response of the guitar determines what progress the harmonic changes make within the note's envelope.

The fundamental frequencies of the six strings on guitar tuned to concert pitch (A= 440 Hz) are listed in Table 2 below.

String	Frequency (Hz)
6th String (Low E)	82.4
5th String (A)	110.0
4th String (D)	146.8
3rd String (G)	196.0
2nd String (B)	246.9
1st String (E)	329.6

Table 2. Guitar string natural frequencies.

Published research by Dan Russell of Kettering University [9] shows that the structural characteristics of guitars can be found through experimental modal analysis techniques. Below in Figure 8, is the plot of the first bending mode of a solid body guitar. The natural frequency is 55Hz.

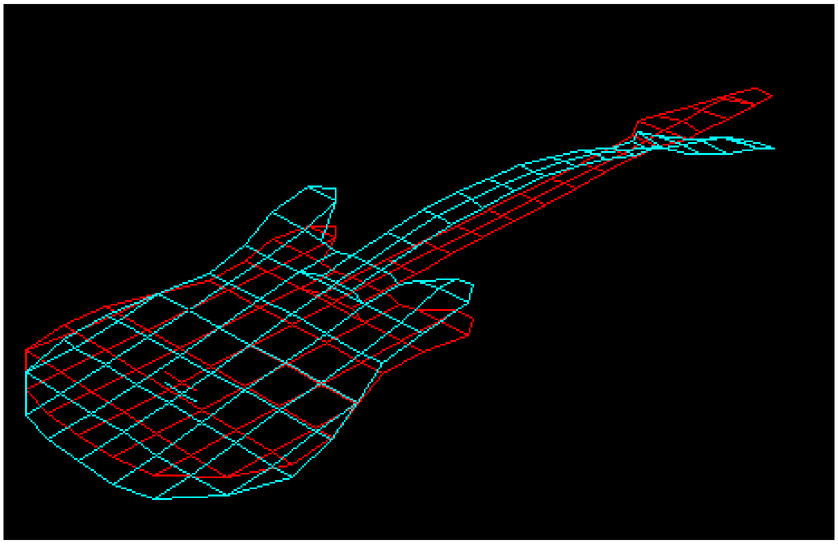

Figure 8. Fundamental bending mode of solid body guitar at 55Hz (Courtesy of D.Russell).

Similarly, in Figure 9 the second mode of vibration occurs at 160 Hz for this same guitar and is the second free-free bending mode.

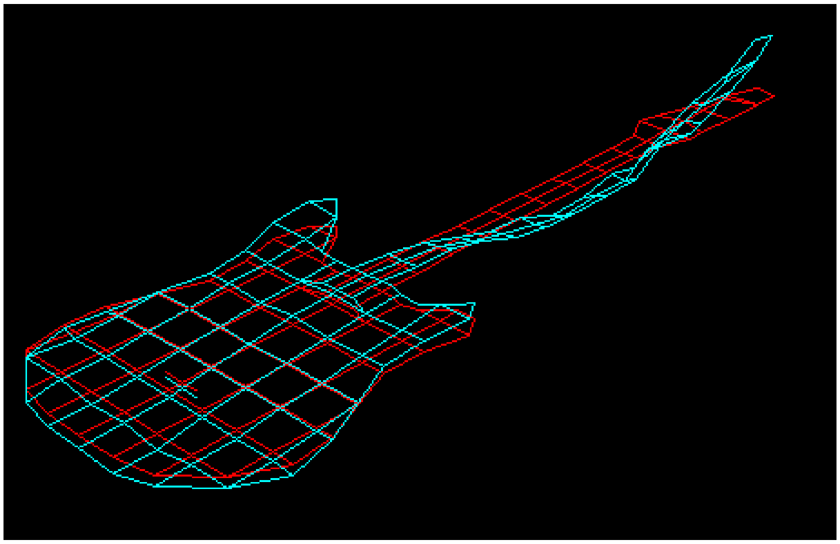

Figure 9. Second bending mode of solid body guitar at 160Hz (Courtesy of D.Russell).

The third mode of vibration is a torsional mode occurring at 372Hz. It is most clearly seen in the vibration of the body at opposite corners. See Figure 10 below.

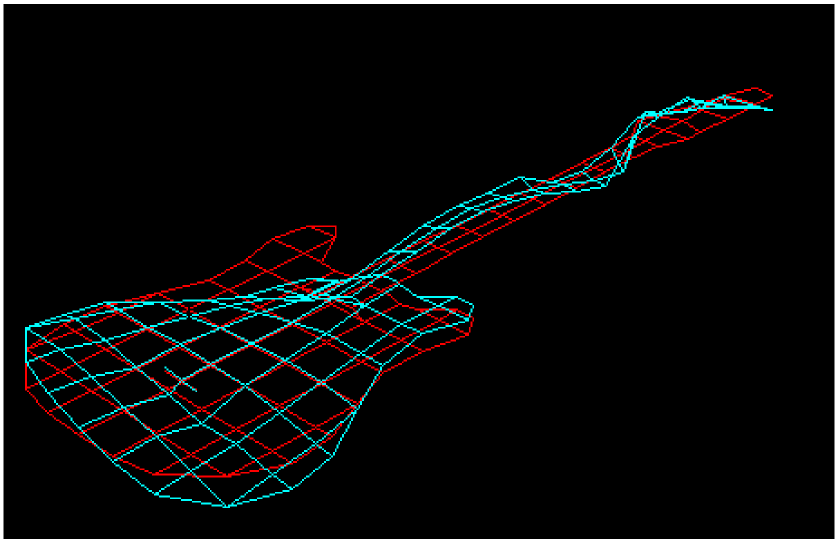

Figure 10. First torsional mode of solid body guitar at 372Hz (Courtesy of D.Russell).

Figure 11 represents the fourth mode of vibration at 472Hz. This is a bending mode along the width of the guitar.

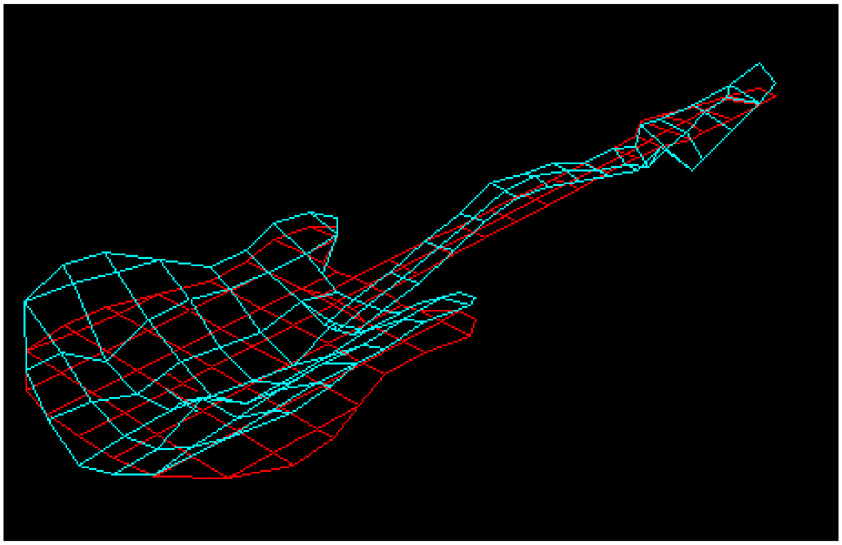

Figure 11. Third bending mode of solid body guitar at 472Hz (Courtesy of D.Russell).

In this example the resonant frequencies of the 2nd, 3rd, and 4th modes are well within the range of frequencies generated by the guitar. It should be clear that due to the physical characteristics of the guitar within the frequency range of the notes played that the harmonic response of the vibrating strings will be affected.

The wood that is utilized in the guitar receives the vibrations from the string by means of coupling through the bridge and nut. It vibrates in response and transmits vibrations back to the strings. When playing a guitar, one can physically feel the guitar body vibrations as different notes are played. It's important to note that the guitar will vibrate more at certain frequencies, which means that the natural resonances of the body are being excited and therefore feedback into the string vibration at various levels depending on the frequency being played. How the vibrations feed back and forth between the strings and the guitar body determines how the harmonic content changes during the envelope. Typically, thicker and denser wood resonate at higher frequencies. This can be heard by suspending a Les Paul and a Strat by the neck and tapping on the back of each. The Les Paul has a higher resonance frequency than the Strat, aside from the vibrating springs that connect the tremolo bridge.

The guitar is made of 4 main parts with different densities. In order of importance to the modal response, these are the neck, fingerboard, body, and top. These combined parts of the guitar affect the envelope and harmonic response of the guitar. In order of density from highest to lowest, typical woods used by luthiers are Ebony, Wenge, Cocobolo, Rosewoods, Purpleheart, Bocote, Paduak, Hard Maple (flamey or birdseye), Soft Maple (Quilted), Ash, Alder, Mohagany, Korina, Swamp Ash, Cedar, Redwood and Basswood.

Metal components such as truss rods and neck joints also contribute to the structural response of the guitar and are integral to is construction. A screwed-in neck referred to as 'bolt on' creates a break in the middle of the guitar, which though firmly attached, lowers the stiffness of the guitar as a whole. Fender guitars are known for this type of neck. This lowers the resonance of the guitar. On the other extreme, the neck through design most often found on high end bass guitars, is such that the neck runs though the entire length of the body. Then two additional pieces are attached to make up the rest of the body. This is the most solid and most stiff construction. The middle of the road solution is a set neck as found on most Gibson guitars. The set-neck is firmly set into the body of the guitar and secured by adhesive, providing a more rigid connection than the screw-in neck. The sounds associated with the different neck joints are a subjective matter, though from a practical standpoint, the bolt on necks are much easier to adjust, repair or replace.

Semi-hollow and hollow body electric guitars have unique characteristics that affect the envelope and harmonic content of the signal. The hollow body electrics are prone to feedback because of the pickup being mounted directly to the sound board. This means that when the sting vibrates the sound board it is vibrating the pickup also. In addition, when the guitar is near the amplifier the interaction is strong and feedback can occur. The decay of the signal is much faster with a hollow body guitar because there is little stiffness and mass to prevent the energy from dissipating through the acoustic radiation and mechanical damping. Semi-hollow guitars are chambered and typically have a piece of solid wood that runs down the center of the body from the neck to beyond the bridge. This adds stiffness to the pickup mount and the bridge and is therefore less prone to feedback and has a long decay time.

4.4. String Type

Strings themselves affect the type of response the pickup outputs. Heavier gauge strings are stretched at higher tension and have longer decay times since more energy is stored in the string for the same vibration amplitude. Lighter strings have shorter decay times but have sharper perceived attack. Many strings are wound in nickel and some in steel. Steel wound strings have a sharper attack and therefore sound brighter. Coated guitar strings have a very thin layer of proprietary material to extend string life. This adds damping to the string which makes the string sound slightly less bright than strings that aren't coated.

4.5. Hardware

The bridge, nut, tuners, and tailpiece all determine structural coupling between the string and the neck and body of the guitar. The more mass and contact area the more coupling there will be present. The bridge and anchoring points of the strings interact together to transmit vibrations between the guitar and the string. As this transfer occurs, certain frequencies are reinforced. Coupling dictates the amount of transfer that occurs. For example, a tremolo bridge, as found on a Strat, transmits higher harmonics better than lower ones. A hardtail brass or steel tune-o-matic as found on a Les Paul, transfers more lower harmonics.

4.6. Performance of Pickups

The discussion of pickups until now addressed implementation of the pickup within the guitar as a mechanical system. Let us now consider the pickup itself and its parameters in determining the tone of a guitar. Tone and output mainly depend on the relationship between inductance, capacitance, magnetic strength and the efficiency of the pickup, as well as the relationship between the pickup parameters and the load seen by the pickup due to tone controls, cables, effects and the preamplifier stage of the amp.

The pickup may be thought of a transducer functioning primarily as an inductor. As with any transducer, the pickup has a frequency response that is not equal for all frequencies. As with other transducers such as microphones and accelerometers, the pickup has a resonance peak at a certain frequency. This is due to the combination of the inductance and resistance inherent to the pickup and the interwinding capacitance of the coil and the capacitance found mainly within the cable connecting the guitar to the amplifier, as well as the pickup tone controls.

As a simplified electrical circuit, the pickup has a lumped inductance *L*, dc resistance *R*, and winding capacitance *C* as shown below in Figure 12.

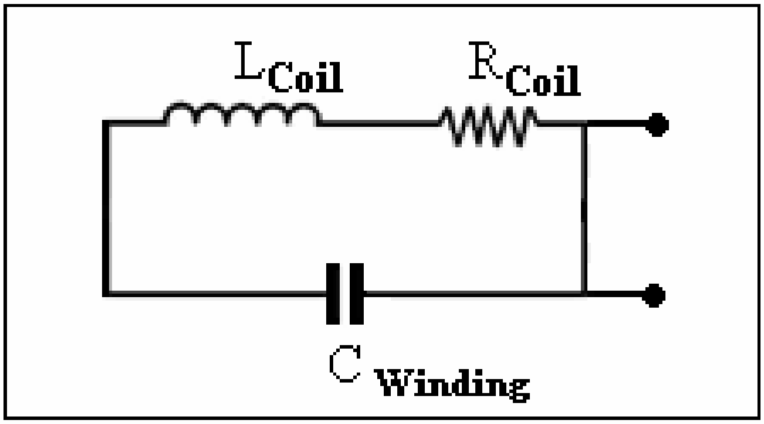

Figure 12. Electromagnetic guitar pickup equivalent circuit diagram.

A pickup coil has a dc resistance based on the type of wire used and the number of turns. 42 AWG has a resistance of about 1.6 Ohms/ft and 43 AWG has a resistance of 2.1 Ohms/ft. Pickups have between several thousand turns of wire up to 10,000 turns. The dc resistance and the lumped inductance are in series with each other. Due to the resistances associated with pickup coils and the large number of turns, the turn-to-turn capacitances build up to a non negligible lumped winding capacitance. The inter-winding capacitance is typically between few 10's -100 pF. The complex impedance of a capacitor is shown below in Equation 36:

$$Z_C = \frac{1}{j\omega C} = \frac{1}{j2\pi f C} \qquad (36)$$

Thus, the magnitude of the capacitor's impedance is shown below in Equation 37:

$$\left|Z_C\right| = \frac{1}{\omega C} = \frac{1}{2\pi f C} \sim \frac{1}{f} \qquad (37)$$

When the frequency is zero, Z_C goes to infinity, where as when the frequency goes to infinity, Z_C goes to zero. Thus, at low frequencies, the lumped inter-winding capacitance of a guitar pickup has little impact. At higher frequencies, the lumped inter-winding capacitance has an increasingly significant effect. As the frequency induced by the strings motion increases, the pickup capacitance increasingly shunts or shorts-out the signal to ground.

An external load acting on the pickup consists of resistance from the volume and tone potentiometer in the guitar, and any resistance to ground at the amplifier input. It is industry standard to match the high output impedance of the guitar pickup to a high input impedance of the preamp stage at around 1MOhm. Also part of the external load is the capacitance due to the lead and shield of the cable which has a significant impact on the tone of the pickup. Figure 13 shows circuit diagram with these parameters.

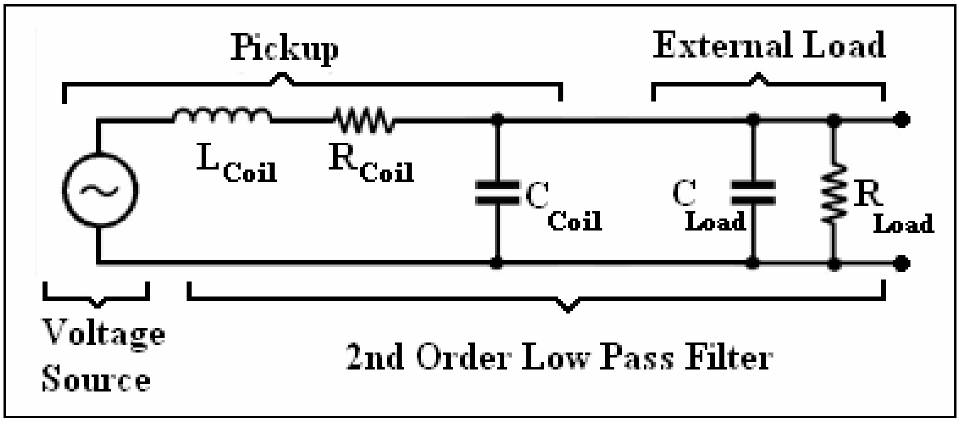

Figure 13. Electromagnetic pickup and external load circuit diagram.

These components form a second order low pass filter which has the frequency response as shown below in Figure 14.

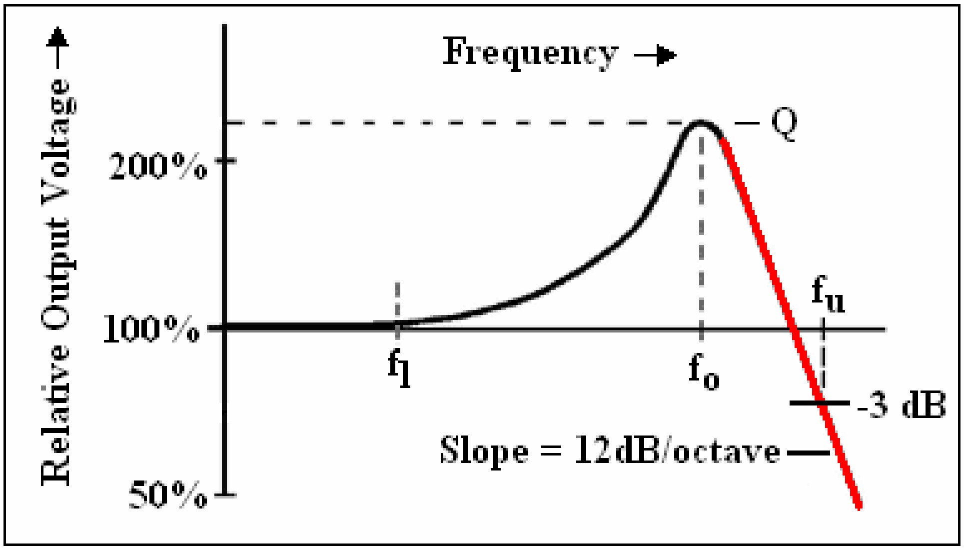

Figure 14. Second order low pass filter created by loading of pickup.

The response at low frequencies is linear until about f_l. Then the response increases until f_o. The frequency f_o is the frequency of the resonance peak. Equation 38 describes the relationship of f_o to inductance and capacitance.

$$f_0 = \frac{1}{2\pi} \frac{1}{\sqrt{L_{coil}\left(C_{coil} + C_{load}\right)}} \qquad (38)$$

The response from f_o to f_u rolls off at -12 dB per octave as shown by the red colored line. The cutoff frequency of this second order low pass filter is designated by f_u. This represents the half power point where the response is 3dB down. This means that any tones or harmonics in the range of the resonant frequency are amplified. Far below the resonance frequency the fundamentals and harmonics are reproduced without being significantly altered. Above the resonance frequency, the harmonics are attenuated by -12dB/octave. As can be seen, knowing the frequency f_o, as well as the relative amplitude of the resonance peak provides insight into the pickups transfer characteristics. The frequency response of just the pickup without cable would be relatively flat until a certain frequency and then roll off. But, amplifying the guitar without connecting it to either a cable directly to the amplifier, effects units, or a cable to a wireless transmitter, then to the amplifier, is unlikely.

But how does this resonance affect the way the guitar sounds? The resonance peak of most pickups in combination with normal instrument or guitar cables lies between 2000Hz and 5000Hz. This is the frequency range where the human ear has its highest sensitivity due to the ear canal. At 2000Hz the sound is characterized as warm and mellow, at 3000Hz brilliant or present, at 4000Hz piercing, and at 5000Hz more brittle and thin. The height of the resonant peak also affects the sound; a high peak amplitude produces a powerful and characteristic sound and a low peak amplitude produces a weaker, more even sound. The height of the resonance peak can range between 0 and 12 dB on most guitars and is governed by the magnetic material in the coil, the external resistive load, and metal pickup cover sometimes found covering the pickups. The higher the magnetic strength, the higher the amplitude, the lower the resistive load the lower the amplitude and without the metal cover the amplitude is higher. Some guitarists prefer this and remove the metal cover most notably from their Les Paul humbucking pickups to achieve tone with more high frequency harmonics.

The resonance frequency depends on the combination of the inductance, the winding capacitance and the cable capacitance (typically 300 – 1000 pF). By increasing capacitance the resonance peak is lowered in frequency and the amplitude of the peak is increased. This has two effects; it lowers the high frequency content by lowering f_u and boosts the mid range by lowering f_0. Typically the treble tone control of a guitar is a capacitor connected to a voltage regulator to roll off the highs as desired. Inductance has the opposite effect of capacitors, they affect the low frequency. So the frequency resonance can also be affected by altering the inductance. By lowering the inductance the frequency of resonance is raised as shown in Equation 38, for f_0. This can be controlled by the number of windings, the strength of the core or the pickup coil configuration.

Pickups are high impedance devices. The higher the number of windings there are, the greater the output of the pickup will be. However, increasing the number of windings also increases the lumped pickup inter-winding capacitance which attenuates pickup output and lowers the pickup's resonance frequency. A pickup with a higher inter-winding capacitance will sound 'dead' (less lively) and dull (less detail/less shimmer or sparkle), compared to the same pickup with less overall inter-winding capacitance, assuming the same inductance.

The lumped inductance is due to the self inductance of the coil and is enhanced by the magnetic permeability of all of the magnetic materials used in the pickup. These include the permanent magnets and any magnetically permeable pole pieces or booster plates. The stronger the magnet the stronger the output will be which means fewer turns of wire are required for a certain voltage output. There are a few drawbacks to higher magnet strength. First, they are more expensive. Secondly, since strings are ferromagnetic and are attracted to magnets, a stronger magnet may affect the strings vibration. This is very bad because it compromises the harmonic integrity. It physically produces a discordant beat note when the string is plucked. This is to be avoided.

SPECIFIC ELECTRIC GUITAR PICKUP ANALYSIS

There are many electric guitar pickups available on the market today. Our analysis will focus on the three most common including the single coil, P-90, and humbucker as found in the most common electric guitars, the Telecaster, Stratocaster and Les Paul.

5.1. Single Coil

Single coil pickups are usually found on Stratocaster and Telecaster style electric guitar. They represent the general purpose pickup, used in many styles of music including country, rock, blues, funk, jazz, R&B and everything in between. The single coil pickup grew in popularity with the Fender Telecaster. Incorporating two single coil pickups, one at the bridge location, one at the neck location, the Telecaster had a strong presence in the country music scene. This trend still continues today. The tone of a bridge position telecaster with a single coil is most notably characterized to have that 'twangy', 'sharp' sound. This tone benefits from the higher frequency harmonics found near the bridge, but also because the bridge pickup is mounted on a steel plate. This steel plate is part of the bridge assembly and can be seen below in Figure 15.

Figure 15. Telecaster bridge pickup.

In most Telecaster designs, the strings pass through the body and up through the bridge and over the saddles as seen in Figure 15. This increases decay time of the signal. Brad Paisley provides us an excellent example of modern country Telecaster bridge tone.

The single coil used in the neck pickup of the Telecaster is a slightly different design. It is smaller in size than the bridge pickup. It has a mellower, fuller tone that contrasts extremely well with the bridge pickup tone. It is commonly used for lead and rhythm duties. With distortion, the neck produces a smooth, creamy sustaining tone and played clean has a full bodied character. This pickup can be seen below in Figure 16.

Figure 16. Telecaster neck pickup.

The Telecaster neck pickup sounds very similar to a single coil on a Stratocaster in the neck position show in Figure 17.
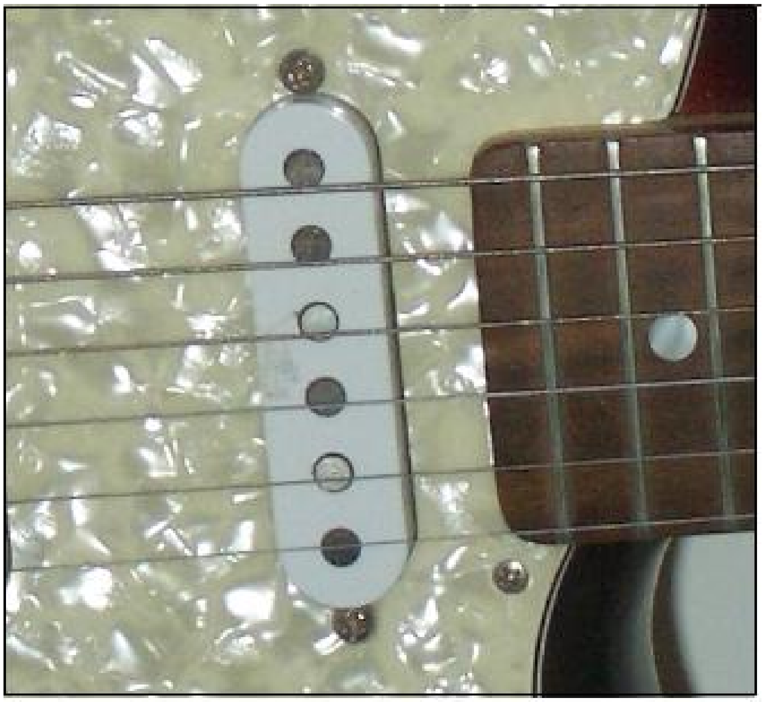
Figure 17. Stratocaster neck pickup.

The Stratocaster pickup in the neck position has a bit more sparkle and high frequency content. It is characterized as crisp, bright and clear with an explosive quality. To listen to Stevie Ray Vaughn is to listen to a neck position strat pickup tone done properly.

Sticking with the Stratocaster model, the guitar offers two other single coil pickups as previously discussed; the middle and bridge pick up. This makes for a very versatile guitar as shown in Figure 18.

Figure 18. Bridge, middle and neck Stratocaster pickup locations.

The middle pickup has a similar tone to the neck but less low frequencies and more high frequencies. The bridge pickup has a sharp and shrill like quality to it, though sounding distinctly different than the Telecaster bridge pickup. The unique aspect of the circuit design within the Stratocaster is the ability to combine the tone of multiple pickups through the use of a selector switch. The Telecaster has this feature but doesn't produce a sound quite as sweet as the Stratocaster. The 5-position selector switch is circled in red in Figure 19.

Figure 19. Stratocaster pickup selector switch.

It is in positions 2 and 4 that the famous glassy sound is generated by combining either the bridge and the middle pickup or the neck and the middle pickups respectively. Mark Knopfler of Dire Straits used position 2 and 4 extensively. These are the features that make the Stratocaster the world's best selling, most popular electric guitar.

5.2. P-90

In response the growing popularity of Fender's single coil guitars, Gibson designed their own version of the single coil pickup long before it made its well known humbucker. The P-90 was very popular but quite different than the single coil pickups designed by Fender. P-90's have a large flat coil with adjustable steel screws as pole pieces and a pair of flat Alnico bar magnets lying under the coil bobbin. This sound can be classified as a cross between a Gibson humbucker and a Fender single coil. It has extremely high winding count, around 10K turns. It has a higher inductance than other single coils, which means it has high output and biting treble response. The draw back is that of electromagnetic background noise, which this pickup is very prone to picking up. P-90 may be found on Les Pauls, Specials and Juniors as well as a number of semi-hollow and hollow-body Gibson guitars.

5.3. Humbucker

A serious problem with the single coil guitar pickups is that they induce a great deal of electromagnetic background noise along with the emf from the strings. When played at normal volume, the pickup output usually has a high enough signal-to-noise ratio that the noise is barely heard. The problems arise when the player is using lower dynamics or stops playing. The 60Hz noise generated by all sorts of electronic systems from power lines to fluorescent lights don't stop when the player stops playing and consequently get induced by the pickup and are then amplified. This can be very obnoxious. The humbucker as the name implies deals with this issue of electromagnetic background noise by wiring two single coil pickups next to each other, wound with opposite polarity. This cancels or 'bucks' the hum but has a number of other impacts on the tone produced. First of all, because there are now two single coil pickups side-by-side responding to magnetic flux changes (see Figure 20), a greater length of the vibrating string is read.

Figure 20. Humbucker pickup.

This results in a sound that is fuller, thicker and more robust. In effect, the pickup is able to read more of the longer wavelength vibrations that correspond to lower frequencies including the fundamental. Another effect is that the high frequency is attenuated when compared to a single coil or P-90 pickup. Part of the reason for this is due to the pickup covers usually made of brass with a coating of chrome, as seen in Figure 21.

Figure 21. Humbucking pickups with chrome pickup covers.

This makes for a very smooth and rich tone, excellent for lead playing with distortion. It also doesn't suffer from the shrill or cut of single coils which may be offensive to the listener if not controlled. The drawback is it doesn't cut through the mix as effectively, which requires more volume to be heard. Thus, it is typical to find a guitar fitted with humbuckers like the Gibson Les Paul mated to a high power, air moving amplifier like a Marshall stack. Another drawback, particularly at the neck position is that the humbucker may sound 'muddy'. This muddiness occurs when there are higher levels of low and mid frequencies which prevent clarity of the individual notes and harmonics, i.e. lower resolution. This effect may be overcome by proper equalization. Typically the bridge pickup is favored amongst the Les Paul and humbucking crowd, especially for lead tones. It has higher frequency harmonics due to its proximity to the bridge yet it maintains a full rich tone, lush with mid frequencies. The neck pickup has much more low frequency content, and can produce a great jazz tone. Although, the neck pickup is also a good lead tone as well, just ask Slash.

CONCLUSIONS

The process of listening to and identifying the tones generated by the guitar coupled with an engineering understanding of the production of those tones will undoubtedly lead a guitarist closer to the tone of their desire as well as help them use those sounds in different musical contexts more effectively. The principles of acoustics, mechanics and electronics, that go into making an electric guitar work are not trivial, but are certainly understandable with proper investigation. These principles are directly applicable to any guitarist and can be implemented immediately. At the very least, applying the understanding of electric guitar pickups should eliminate one component of the torturous music store experience. The other component (that of technique), will be left to each player to address.

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