The Acoustic System of the Electric Guitar

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The Acoustic System of the Electric Guitar

1. Introduction

The electric guitar is a complex system of mechanics and electronics working together to create a rich spectrum of sound, which can then be further manipulated using various analog and digital filters in a live setting or on a recorded track. The energy chain of the electric guitar is as follows: Performance gestures, strings, pickups, on-board controls, cable, pre-amplifier, power amplifier, and speaker. This paper discusses how each of these steps can affect the final sound of the electric guitar.

2. Performance Gestures

2.1 Standard Techniques

There are many ways of producing sound with an electric guitar. The most common ways to instigate string vibration are to pluck or strum the strings with the fingers or a plectrum. However, a guitarist may also execute a technique such as a “hammer-on” or “pull-off” with only the fretting hand to vibrate the string. The plucking hand may be used to hammer-on or “tap” on the fretboard and when combined with the fretting hand’s hammer-ons and pull-offs can create an interesting timbre for melody and harmony.

2.2 Overtones

Guitarists have a few techniques for producing overtones. Most commonly, a guitarist may lightly touch a node on one or more strings with the fretting hand while plucking or strumming. Another way is to touch a node after plucking while the other hand is fretting a note. The third way is to hold the plectrum close to the tip so that the string can be lightly brushed at a string node by the thumb immediately after plucking a note. This technique is performed mainly on electric guitars because the intensity is very low and requires the pickups to be on the brightest tone setting to be heard.

2.3 The EBow

The "EBow" is a device that focuses a sympathetic oscillating magnetic field to vibrate a single guitar string.[1] A focused feedback loop can sustain string vibration indefinitely. Moving it along the length of the string can shape the timbre and moving it closer to the pickup will increase the intensity. The EBow can be used on any ferromagnetic string including acoustic guitar strings, piano strings, or as John Cage did in his piece "Postcard from Heaven", on harp strings.

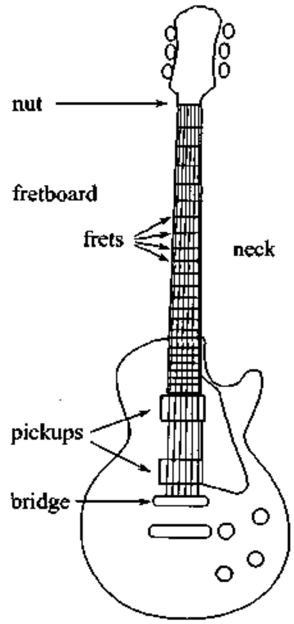
Whatever methods of playing are used, an electric guitar needs to be quite durable to withstand some of the aggressive playing styles that guitarists will use. There are many parts that have become commonly used to accommodate the often demanding imagination of guitarists.

3. Construction

3.1 Guitar Basics

The guitar may be thought of as a collection of strings fixed at both ends. When a string is plucked, the standing wave is produced. The efficiency of an acoustic guitar depends on its ability to transmit the vibration of the strings to the other parts of the guitar. In an electric guitar, the sound propagation depends more the electronic chain representing the strings' vibrations, but an electric guitar's sustain depends on its ability to transmit vibration from the strings through the bridge and to the body. Here is an example of an electric guitar:

[1] http://www.ebow.com/lessons.php?cat=1



From “Electric guitar - a blank canvas for timbre and tone”

3.2 Bridges

Each of the parts labeled in this diagram plays an important role in sustaining the vibration of the strings. The bridge, for example, can be fixed or floating. A fixed bridge is secured to the body of the guitar without the ability to move. A floating bridge has the ability to shift one end closer to the nut, decreasing the stiffness of the strings to lower the pitch, and on some bridges, shift away from the nut, increasing the stiffness of the strings and raising the pitch. This is done by using a lever called a “whammy bar,” “vibrato bar,” or incorrectly, a “tremolo bar.” Floating bridges also require springs to be installed to counter the tension of the strings on the bridge. Guitars equipped with floating bridges suffer a loss of sustain because the string vibrations dissipate quicker due to motion of the springs, even when the vibrato system is not in use.

3.3 Guitar Nuts

When the vibrato bar is used, it changes the tension of the strings, which means that the strings will need to move to stay in tune. Two types of nuts are used to accommodate this: roller nuts and locking nuts. Roller nuts have roller bearings that reduce the friction of the strings.

Locking nuts use a screw adjustable by hex key (aka. Allen wrench) that depresses a clamp on the strings, locking them in place, allowing the strings to return to their original tension.

3.4 Scale and Intonation

The guitar fingerboard is divided into half-steps by the fret wire. Both the bars and the fretting position are referred to as the “frets.” By placing the finger behind a fret bar, a high impedance barrier is created, virtually shortening the string to raise the pitch. The frets bind most guitars to a 12-tone, theoretically equal-tempered octave, though without them intonation would depend more on the skill of the guitarist and sustain would suffer because the hand is not capable of producing as high an impedance barrier alone as with a fret. The bridge can also affect intonation. Acoustic and electric guitars have saddles attached to or close to the bridge to compensate for inharmonicity. On electric guitars, saddles are often adjustable.

3.5 Body, Fingerboard, and Shape

Regarding body shape and material, these properties primarily affect sustain, though some guitarists will claim that body material can affect the timbre as well. Generally, the denser the material, the greater the sustain, but there must a compromise between sustain and comfort. Some guitars are made from one type of wood, such as alder, ash, or mahogany. Others will have a lighter body wood and a denser top wood like maple. Less common are guitars made with composite materials. An asymmetrical shape will negatively impact the guitar’s sustain, while more traditional shapes (closer to the classical guitar) will improve sustain, including the archetypal shapes of the Fender Stratocaster or Gibson Les Paul. As for fingerboard material, some guitar companies claim that maple produces more overtones while rosewood and ebony produce a stronger fundamental.[2]

[2] Schecterguitars.com

3.6 Strings

Guitar strings are made from ferromagnetic material and are parallel to the pickups. Some common materials used for string cores or wrappings include steel, nickel, cobalt, and titanium. Since guitar strings are made for approximately the same scale length, lower pitch is achieved by increasing the mass of the string, which increases the tension. The guitar tuning pegs, headstock, neck, bridge, and body are a system that work to balance the tension of the tightened strings. Strings come in three varieties of windings: round-wound, half-wound, and flat-wound, which changes the way the strings feel. String manufactures claim that the tone of the guitar is affected by both the type of winding and the materials of the string.[3] While a well-constructed guitar is important for sustain and intonation, the electronic chain is the primary factor in shaping the electric guitar's tone.

4. Pickups

4.1 Pickup Basics

Whether an electric guitar is solid-body or semi-hollow, its body is not capable of propagating sound well without at least one pickup. A pickup is an electromechanical transducer. It converts the physical vibration of the guitar strings to an electrical signal. Guitar pickups come in several varieties: magnetic, piezoelectric, seismic, and more. Magnetic pickups may be passive or active, and have one or two coils. Some guitars may have built-in preamps, and various controls to combine pickups in series or parallel, split a double-coil pickup, and more. All pickups have the same basic function: to translate string vibrations to a voltage signal.

[3] http://daddario.com/DADProductsElectric.Page?ActiveID=1903

4.2 Passive Magnetic Pickups

The electric guitar's pickups are responsible for creating an electrical representation of the strings' vibrations. The most common type of pickup is the magnetic pickup. A magnetic pickup consists of two main components, a permanent magnet and a coil of wire wrapped thousands of times around the magnet. The magnet creates a field around the pickup, and the wire winding captures the vibrations of the ferromagnetic strings by measuring the change in the magnetic flux caused by the movement of the strings. The wire then converts the change to a variable current which is eventually amplified and played through a speaker.

Magnets used for pickups can be made from alnico or a ceramic material. Alnico is a blend of Iron, Aluminium, Nickel, and Cobalt. Ceramic material is clay with ferrous particles. Ceramic magnets are twice as strong as alnico, last longer, and are less expensive, but they are electrically non-conductive, which results in a less than pure signal.

Pickups will often use separate pole pieces for each string, which are charged by a single magnetic bar, and a single wire wrapped around each of the pole pieces. The individual pole pieces can also have screws as magnetic extensions that can adjust the proximity of the pole pieces to the string individually or as a whole, raising the amplitude of the strings. Other pickups use just a single magnetic bar for all of the strings; this provides constant sustain even when a string is bent, which would place the string farther away from a pickup pole piece.

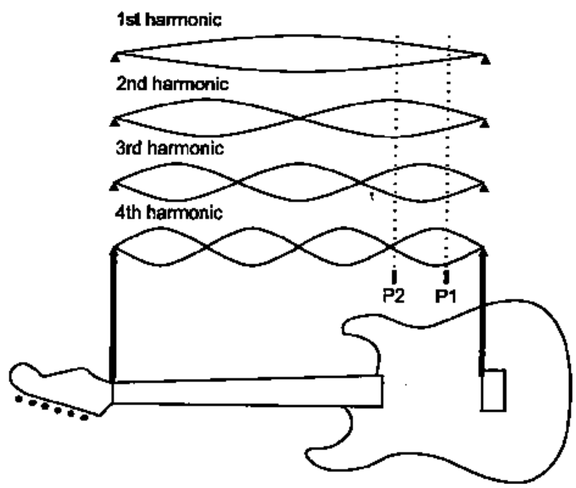
If the number of times the wire is wrapped is increased, the amplitude and sustain are increased. With more wire wraps also comes higher inductance, and therefore a higher impedance of high frequencies. Too many turns can turn the pickup into a low-pass filter.

4.3 Single-Coil and Humbucker Pickups

A pickup may use a single coil or two connected windings. A double-coil pickup is called a “hum-bucker” because it suppresses electrostatic and electromagnetic noise (or “hum”) captured by the strings and pickups. It can do this because the induced current flows of each coil move in opposite directions, cancelling out the noise and combining their amplitudes. Humbuckers generally have a darker timbre than single-coil pickups because their pickup sensitivity width is greater due to having two single-coils in such proximity. This causes the shorter wavelengths to be cancelled out, leaving only the longer wavelengths to contribute to tone. This, combined with their increased intensity, causes guitarists to describe their tone as “full” or “punchy,” compared to the “thin” or “twangy” sound of single-coils. Both tones are desirable and can be blended on guitars with the appropriate controls. Some humbuckers have the ability to be used in “coil-split” mode, in which only one of its coils is used, which in turn negates the hum-cancelling effect.

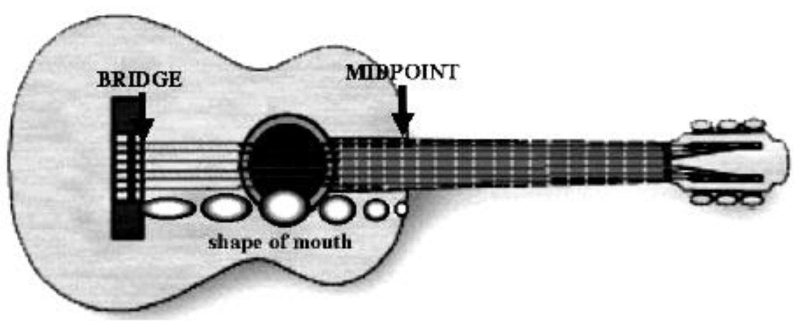
4.4 Pickup Tone

The placement of the pickup along the vibrating string is the primary influence on the pickup’s tone. When a pickup is placed near an antinode of a partial, the intensity of that partial is increased. If placed near the node of another partial, that partial will be attenuated. A pickup works like a comb filter, boosting certain frequencies or bands while decreasing others. When combined, pickups can create complex comb-filtering effects. The following diagram illustrates this effect:



From “Acoustics and modeling of pickups”

A pickup closer to the bridge will capture more overtones and less of the fundamental, giving it a brighter timbre, while a pickup near the neck will amplify the fundamental and second harmonic, giving it a darker timbre. This is an effect well-noted by classical guitarists, who change their plucking position in order to change their tone, which is often compared to vowel shapes of the voice. Darker tones are described as “round” while brighter tones are described as “nasal.”[4]



From “Timbral analogies between vowels and plucked string tones"

There are more attributes that contribute to pickup tone in addition to the comb filter effect. First, pickup sensitivity width affects tone. Pickups are sensitive to an area, not just a specific point. The width effect is noted to cause a low-pass filtering effect. Second, a pickup

[4] Traube, C. & Depalle, P. (2004). Timbral analogies between vowels and plucked string tones.

may be thought of as a RLC (resistance, inductance, capacitance) circuit,[5] in which the magnetic properties of the core and the number of turns of the wire determine the inductance, the distance between each turn of the wire creates a capacitance, and the length of the wire creates the resistance. These properties working in tandem create a resonant peak – a narrow band to which the pickup responds most – which contributes greatly to the pickup's tone.

The way two pickups are combined can affect tone. Pickups may be connected in series or in parallel:

> ...[T]he pickups may be connected in series or in parallel. This additional connection option not only varies the signal magnitude at the output jack but also affects the tone coloration. Traditionally, the two coils on a humbucker pickup are connected in series to produce a loud "punchy" tone. The combination of two single-coil pickups have traditionally been connected in parallel, resulting in a brighter tone while retaining the hum-cancelling effect.[6]

Pickups in series have the same two resonant peaks of each pickup and increased intensities in low frequencies. They gain an additional six decibels, lower output capacitance, and higher sensitivity to cable impedance. Pickups in parallel have a single resonant peak between the resonances of pickups one and two, and the intensity of the low frequencies is not affected much; the combined pickups resemble a single pickup with an intermediate resonant frequency. They have no change in intensity, a lower capacitance, and a more robust sound.

4.5 Other Pickup Types

A majority of magnetic pickups are "passive." The pickups described above are passive. "Active" pickups are built with a preamp, and they require additional battery power to be built into the guitar. Their advantages include a more powerful signal with less noise.

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[5] de Paiva, R. (2013) Circuit modeling studies related to guitars and audio processing.

[6] de Paiva, R. et al. (2012). Acoustics and modeling of pickups.

Common on semi-hollow and acoustic guitars, but available on some solid-body electric guitars, are piezoelectric pickups. These use the natural electric properties of quartz, topaz, or other compounds to measure the mechanical pressure from in between the saddle and the bridge to create a signal. When the compound becomes electrically excited, it oscillates at a resonant frequency. “Piezo” pickups may be passive or active with an on-board preamp. They are desired for the “acoustic” tone they produce.

Seismic pickups are yet another type of pickup that uses an accelerometer to measure the vibration from the body of the guitar. Guitars may also be equipped with analog-to-digital converters to send data to a 5-pin MIDI or a 13-pin guitar-synthesizer, to synthesize the guitar’s sound with either software or a dedicated synthesis device.

While pickup tone is most greatly influenced by the pickup itself and its placement, a guitarist can use tone and volume controls to adjust the overall tone of the signal. A tone control is a capacitor that drains or diverts the high frequencies. In other words, it is a low-pass filter. The volume control is a potentiometer; it is a variable resistor that increases the series resistance between input and output and decreases the series resistance between output and ground. The tone circuit interacts with the resistance of the volume control and the pickups selected so that adjusting the volume control further alters tone.

5. Amplifiers and Speakers

5.1 Amplifier Basics

Electric guitars require a loudspeaker to be heard, but a speaker alone would not be enough to hear the guitar. The output from a pickup only produces milli-Watts. An amplifier is used to increase the amplitude of the pickup output and drive it through the speaker. There are several components that comprise the amplifier-speaker system. From the pickup, the signal travels through a cable to a pre-amplifier, then a power-amplifier, and finally a speaker. The pre-amplifier, power-amplifier, and speaker can exist as separate devices or together as one "combo" amplifier. An amplifier can fall under one of several classes, including A, B, AB, C, D, E, F, G, or H. Only certain amplifier classes are used for guitar amplification. Guitar amplifiers are divided into three major categories: those that use vacuum tubes, those that are "solid-state" and use transistors, and "hybrid" amplifiers.

Class A amplifiers amplify an entire cycle of a signal. They generally have low noise, but are inefficient because their transistors or tubes are always on, even without a signal. They have a theoretical efficiency of 50%, dissipating one watt as heat for every watt delivered to the speaker. Class B amplifiers use two transistors or tubes to amplify only half of the signal. This is what is called a "push-pull" amplifier. The transistor only turns on when a signal is present, making them more efficient than Class A amplifiers. Their theoretical efficiency is 78.54%. However, there is "crossover distortion" when the signals are recombined because the signals may not be joined in phase. Class D amplifiers convert the analog signal to a digital signal and send it through a low-pass filter to reduce the noise before being sent to the speaker. There are no large resistors and so they dissipate no heat and have a theoretical efficiency of 100%, sending all energy to the speaker. Class D, E, and F amplifiers are primarily used in hi-fidelity audio situations and public address systems and are not widely used as guitar amplifiers. Class G and H amplifiers are very efficient because they use only as much voltage as is required for the level of output and switches the power supply voltage rails as necessary. These are also not used in guitar amplifiers.

5.2 Solid-State Amplifiers

A solid-state amplifier is comprised of transistors, resistors, diodes, and capacitors. They can be made using discrete components soldered to a circuit board or simpler integrated circuits on a thin substrate of semiconductor material. Whether using discrete components or integrated circuits, the transistor is the most important part of the design. Transistors use a small signal to control a larger signal. There are two main types of transistors: bipolar junction transistors (BJT) and field effect transistors (FET). A BJT acts as a current-controlled current source, making a current proportional to the input current, while a FET acts as a voltage-controlled current source, making a current proportional to the input voltage. FETs are usually used in the input stage of linear integrated circuits, while BJTs are mainly used in the stages that follow. Solid-state amplifiers typically use several transistors to set gain value, maintain high input impedance to preserve input signal, and maintain low output impedance to preserve output signal.

5.3 Tube Amplifiers

Guitar amplifiers originally used vacuum tubes, which are sometimes called valves. Tubes are much larger than discrete components or integrated circuits and require much more power as well as large audio transformers and other components. The transformer couples the amplifier to the speaker and saturates along with the output tubes. It is due to the transformer that a tube amplifier produces its characteristically “warm” tone that is desired by guitarists. A solid-state amplifier would be smaller, more efficient, and more affordable than an equivalent-powered tube amplifier, but despite their inefficiency and size, many guitarists prefer tube amplifiers because of their tone.

This warm tone is created by distortion of even harmonics.[7] Tube amplifiers produce distortion of even and odd harmonics, while solid-state amplifiers primarily distort odd harmonics. Early tube amps were low in power and could easily be driven into clipping, producing a timbre compared to brass instruments. This became the standard tonal effect for rock music of the 1950's and '60s on through today. Raising the distortion primarily increases the high frequencies.[8] This effect is so desired that there are several products including pre-amplifiers, foot-pedals, and software made to be used with solid-state amplifiers in order to model the distinctive tone of tube amplifiers.

5.4 Preamps

A pre-amplifier (or preamp) is a low-power amplifier placed between the guitar and the power amplifier and is used to amplify the signal from the pickups and to match the impedance to the power amp. Preamps can be incorporated into the chassis of the power amplifier, in separate housing, or built onto the guitar. If built onto a guitar, an on-board battery will also be required, but it will allow the pickup to be less sensitive, require fewer turns of wire, and thus produce less electromagnetic noise. Preamps will have controls for equalization in some form, gain (before the master volume of the power amp), and many more possibilities.

5.5 Speakers

An electrical signal is sent from the guitar's pickups, through a cable, to a preamp, to the power amp, and finally to the speakers. A speaker is a transducer that converts an electrical signal to acoustic energy in the form of a vibrating speaker cone. Efficiency is a ratio of the electrical input to auditory output; a more efficient speaker is usually louder. The larger the

[7] Barbour, E. (1998) The cool sound of tubes

[8] Hanssen, A. et al. (2005) Spectral, bispectral, and dual-frequency analysis of tube amplified electric guitar sound.

speaker, the more low frequencies it can handle. Different materials may also affect a speaker's durability and tone.

The speaker for a guitar amplifier is housed in a cabinet. Cabinets fall under categories such as open back, infinite baffle, bass reflex, horn enclosure, rear-loaded horn, and front-loaded horn. These different varieties affect frequency range and volume. The output from a tube amp must be transformed from high impedance to low impedance to match the speaker, while a transistor amp has low impedance and so can be directly coupled to the speaker without a transformer.

5.6 Guitar Cables

The guitar sends the signal from the pickups to the preamp via a cable. Ideally, the cable sends the signal unaffected to the preamp, but the cable has an important affect on the pickup's tone. The cable's impedance is combined with the pickup's impedance and the cable's capacitance affects the resonance of the pickups, which, as discussed earlier, is in an important factor on the electric guitar's tone.

5.7 Nonlinearity

Nonlinearity of the signal caused by magnetic pickups as well as tube amplifiers also affects the tone of the electric guitar. Nonlinearity begins when a magnetic pickup distorts the strings' vibrations due to such factors as the geometry, location of the pickup, and the nonuniformity of the magnetic field. These distortions enhance the harmonics of the strings. Secondly, a tube amp's transformer is a nonlinear element that contributes to the desirable tube amp tone. Considering that magnetic pickups are the most common type of pickup and that tube amplifiers are considered by many guitarists to be the preferred type of guitar amplifier, it can be deduced that guitarists and lovers of music enjoy the electric guitar tone due to its nonlinearities.

6. Discussion

This paper addressed many of the properties of the electric guitar that contribute to tone, however there are topics that I would like to delve deeper into that were not covered extensively or at all in the sources I have found to date. Such topics include the timbral properties of various pickup types including active, piezoelectric, and seismic; timbral properties of different guitar string and pickup magnet materials; resonances of different guitar body shapes; the effects of various signal filters; and the effect of different guitar cable lengths and materials. As a guitarist, this search for knowledge will be an ongoing project.

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