ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Architectural Acoustics
Session 2aAAa: Adapting, Enhancing, and Fictionalizing Room Acoustics I

2aAAa9. Electric guitar - A blank canvas for timbre and tone
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The electric guitar is a complex mechanical, electrical, and acoustic system, invented less than a century ago. While more traditional instruments such as voices and violins, trumpets and tympani, piano and piccolo might possess innate traits that most listeners easily identify, the electric guitar is a sound synthesizer capable of a vast range of sounds. The guitar, the amp, and the recording techniques used enable the performer and the engineer to define and refine elements of tone, almost without limit. Electric guitar has no single reference tone quality, but instead invites, and even inspires performers and recordists to create new sounds and explore alternative timbres as desired.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

The ideal string is on a short list of fully knowable acoustic vibrating systems, along with the column of air and an infinitely rigid, perfectly rectilinear room. It represents a rare opportunity for acousticians in that the boundary conditions are simple enough that the wave equation can be solved [1]. Where guitar is concerned, such mastery is unavailable; it is not an ideal string in vibration. The electric guitar adds to the challenge by relying on a loudspeaker-equipped amplifier to realize the sound. Further, if it is to become part of a sound recording, microphones and room acoustics have their influence.

The sound of the electric guitar as realized in sound recordings might be born of simple harmonic motion, but it is rich with the noise and non-linearities. The electric guitar might be thought of as a system that is part mechanical, part electrical, part acoustic, driven into action by a musician eager to express.

ELECTRIC GUITAR AS COMPLEX, NON-LINEAR SYSTEM

Key components driving the tone of the electric guitar – instrument and amplifier – and contributing to non-linearities and other complexities, are shown in Figure 1. The system includes Performance Techniques and Gestures; Pickups; Preamp and Power Amp; Driver Breakup and Radiation; and Microphone Selection and Placement.

![System elements contributing to the spectral content of the electric guitar.](FIGURE 1)

Performance Techniques and Gestures

When no notes are fingered by the performer, and open strings are played, the guitar might be thought of as a collection of strings fixed at both ends [2]. As frequent tuning and re-tuning of the instrument is required after even a brief period of performance, it is clear that the string stretches and the fixed ends aren’t fixed enough to endure even typical playing dynamics. Tension changes, and energy is dissipated. Calling the ends of the strings fixed is a crude approximation at best.

When a note other than an open string is desired, the performer presses the string against a fret to shorten its length and change its pitch. This introduces another form of less-than-perfect fixing of the end of the string, depending on the strength and positional accuracy of the performer’s hands, as well as any deliberate gestures toward less-than-fixed termination. Bending the string, softening the performer’s touch and moving the fretted end of the string during its vibration (sliding up or down the fretboard for legato-type expression) are common performance gestures [3] which remove energy from the system in ways that are difficult to quantify. Clearly, the boundary conditions at both ends of the strings of an electric guitar offer varied and complex modifications to a fixed end assumption.

The vibration of the string can be initiated in many ways, at almost any location along the length of the string. The string is strummed up or down in parallel with the plane of the fingerboard, or plucked perpendicular to the fingerboard, or picked any angle in between. The driving impulse is shaped by the performer through their use of thumb, fingers, fingernails, and/or a pick/plectrum that itself offers a range of stiffness and string-contact-width. Hammer-on techniques initiate vibration with the hand that fingers the note, pressing the string down against the fingerboard with enough velocity to set the string in motion. Hammer-off techniques are a lifting of the finger off of a fretted note with the deliberate goal of giving voice to the note of the string after the finger is removed, through a combination of finger velocity while lifting with slight lateral motion during release, to make the string vibrate. Tapping is a similar technique, performed with the other hand. Other fingers or the palm of the hand might also be placed in partial contact with any of the strings to dampen their motion and tailor the envelope of the attack and
release of a note or chord, altering the spectral content of the string vibration, particularly during attack, decay and release.

The actions of the performer, at the left and the right hand, offer a range of initial conditions and boundary conditions that shape the complex sound that results.

**Pickups**

The electrical representation of the vibration of the string is created by the guitar’s pickups. The motion of the metal string through a magnetic field pushes and pulls the lines of magnetic flux through a nearby coil, generating a changing voltage with a waveshape of voltage over time similar to the string displacement over time.

The type and placement of the pickups is a key driver of tone. Makes and models vary in design, with essential classes of pickups including single coil and dual coil, humbucking designs. The placement along the length of the string gives the pickup additional frequency-based performance features, as placement near a vibrational node leads to little output at that frequency, while anti-node placement leads to maximal output from the pickup at the associated frequency.

In addition to these amplitude differences as a function of frequency between pickup locations, there is also a time difference, as the distance from the reflecting string termination points leads to a propagation delay for capturing the traveling waves past any pickup location. Pickups in different locations capture the vibrations at slightly different times.

While the type and placement of the pickup is not a performance variable – the performer essentially sets these features when they choose a specific guitar to play – performance decisions do include selecting which of the guitar’s installed pickups to use by means of a switch on the instrument. Most guitars allow for multiple pickups to be combined, mixing the electrical outputs of the pickups together into a single new signal. There are amplitude (node vs. antinode placement) and time (lateral waveform propagation time) differences that make the combined signal richly complex in frequency content.

The materials and geometry of the magnet and coil assembly of the pickup further reshape the spectral content of the transduced signal [4]. The intended generation of electricity in which a changing magnetism induces a current on the coil, is necessarily accompanied by electrical resistance, inductance and capacitance in the assembly that gives the system its own electrical resonances, very much analogous to the challenges faced by designers of audio transformers.

Tone controls, typically in the form of a simple low pass filter, are often provided on the guitar, and guitarists may modify this setting between songs to give each tune the desired character. Many performers also interact with the tone and pickup settings during the performance, allowing the tone of the guitar to change during the course of the song, separating solos of rhythm parts, verses from choruses, and even modifying tone phrase by phrase for special effects. The simple tone circuit interacts with the resistance of the volume control and with the electrical properties of any other pick-ups that are selected, and thereby electrically connected. The net result is that adjusting volume or combining pickup outputs further alters tone.

**Preamp and Power Amp**

The electric guitar, as a system, does not stop at the guitar. It includes the electric guitar amplifier. The earliest amps were tube-based with so little power that it was not unusual to drive them well into non-linearity. As more power became feasible, and as solid state was developed, the expressive and musical significance of distorted guitar was not forgotten. Guitar amps today provide multiple opportunities for deliberately introducing distortion artifacts, making use of solid state, tube, and hybrid (solid state plus tube) designs.

The guitar sound is often further modified by external signal processors, called pedals and stomp boxes because of the foot-actuated on/off switch that enables the guitarist to interact with it while playing their guitar. These effects include distortion, equalization, compression, delay, phasing, flanging, chorus, reverb, and more [5].

A variety of amplifier topologies are in use, many built on the use of multiple, serial gain stages, with intermediate controls between gain stages, used by the guitarist for development and refinement of tone (see Figure 2).

The level from the guitar and any effects pedals may be pushed as to overdrive the input of the preamp stage of the guitar amplifier. On the amp, a Volume control (sometimes called Drive) is added to make overdriving of a second gain stage a creative possibility. Tone controls on the amp necessitate make-up gain, so an additional gain stage is required and it, too, is strategically overloaded when the tonal result is found flattering. A final volume
control, shown as Master Volume, sets the level going into the power amp stage of the guitar amp. Single-ended up to this point, a Phase Inverter divvies up the signal between two power amp stages, operating in push/pull mode to provide the power necessary to drive the loudspeaker to sufficient sound pressure levels. The Phase Inverter and Power Amp present added opportunities for distortion-based tone modification which are regularly exploited by guitarists.

**FIGURE 2.** Key gain stages of a representative electric guitar amp topology. Any and all may be driven into non-linearity as desired to contribute to the overall tone of the instrument.

**Driver Breakup and Radiation**

Just as the gain stages of an electric guitar amplifier are designed – not for faithful, accurate, linear behavior – but for sonically interesting non-linear performance, so too is the driver. Unlike high fidelity loudspeakers for audio monitoring, the loudspeakers in a guitar amp are purpose-built to have modal breakup that contributes additional harmonic (and inharmonic) distortion components [6]. The ideal, infinitely rigid piston is abandoned in favor of a material just flexible enough have modal resonances that shape the tone in ways that satisfy a guitarist. Surrounds and voice coil designs can also limit excursion in non-linear ways.

The loudspeaker(s) might be placed in an open-backed, finite baffle, or in a fully closed box, or, though less common, in a ported, bass reflex cabinet. The design of the box isn’t driven solely by sound quality. Portability, manufacturing cost, and durability also influence the cabinet design, with the result that the frequency response takes yet another turn away from flat, and the radiation is far from well-behaved [7] [8].

A single driver, open-backed guitar amp (Fender 1 x 12” Hot Rod Deluxe) has spectral radiation variabilities shown in Figures 3 and 4 (from [7] and [8]). Figure 3 presents a bird’s eye view of the horizontal radiation pattern in the plane passing through the center of the driver, in 1/3rd octave bands centered at 250, 500, 1000, 2000, 4000, and 8000 Hz, for the right half the guitar amp. The x-axis represents the dimension across the width of the guitar amplifier and the y-axis is the distance away. The amp faces upward.

Figure 4 presents the radiation pattern with a view looking at the vertical face of the front, grille cloth plane of the guitar amplifier for the same 1/3rd octave bands. For this analysis, x-axis represents the width across the whole guitar amplifier and the y-axis represents the height up from the floor.

As expected, in both sets of analysis, the radiation pattern is more omni-directional in the lower frequencies, becomes directional in the mid to higher frequencies, and produces significant energy in the back of the amplifier.
FIGURE 3. Acoustically measured energy of the radiation from the amplifier in 1/3rd octave bands centered at (a) 250Hz, (b) 500Hz, (c) 1000Hz, (d) 2000Hz, (e) 4000Hz, and (f) 8000Hz. The measurement plane passes horizontally through the center of the driver [7].
**Microphone Selection and Placement**

The tone of the electric guitar, as presented in a sound recording, requires the audio engineer to capture the sound in a recording studio. Opportunities for further changes to tone are seized. The high-end microphones of the recording studio include accurate, small diaphragm, omnidirectional, pressure transducers, to be sure. Recording engineers also make frequent use of less accurate, large diaphragm condensers as well as ribbon and moving coil transducers. Velocity, pressure, and combination velocity/pressure transducers exhibiting directional pickup patterns are also employed [9]. Audio engineers strategically unite the known performance features and anomalies of a microphone with the electric guitar amp to capture a net tone that they predict will serve the music. Additional effects, such as compression, reverb, and equalization are frequently applied.

Electric guitar-oriented music, particularly styles within the pop and rock genres, rely primarily on close microphone techniques for the recording of most instruments, particularly guitar [10]. Close microphone strategies regularly place the transducer just inches away from the instrument, often less than one inch away from the loudspeaker driver within the guitar amplifier. The motivations for such close placement include the need for increased isolation among multiple instruments recorded simultaneously, deferral of decisions regarding ambience and reverberation until mixdown, minimizing the audibility of small or unpleasant room acoustics, and capturing unique recorded timbres through proximity to localized resonant elements and spectral pockets in the very near field of the musical instrument [11]. The craft of recording includes a tradition of making fine adjustments to the placement of the microphone in search of modifications to the recorded timbre [12]. The spectral content of the recorded signal clearly depends on placement, where moving the microphone just a couple of inches can cause a swing of 6dB or more in a mid- or high-frequency 1/3 octave band (Figures 3 and 4). Recording engineers regularly exploit this for technical and creative advantage.

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**FIGURE 4.** Acoustically measured energy of the radiation from the amplifier in 1/3rd octave bands centered at (a) 250Hz, (b) 500Hz, (c) 1000Hz, (d) 2000Hz, (e) 4000Hz, and (f) 8000Hz. The measurement plane passes vertically across the face of the amp [8].
CONCLUSIONS

With so many drivers of spectral content, from the string to the microphone, mediated by electro-acoustics, modulated by performer, and manipulated by recordist, it is not surprising that the electric guitar has such a wide palette of sounds. What might be surprising is that appealing sounds are ever created at all. In the creation of tone, guitarist and recordists are presented with an infinite range of possibilities as they coax a long list of spectral-driving variables into order guided largely by ear, passion and experience. As the rich body of artistically successful recordings to date would seem to indicate, the electric guitar system is a powerful way to create timbres that resonate with what so many musicians wish to communicate.

REFERENCES