

ACOUSTIC SOUND FROM THE ELECTRIC GUITAR USING DSP TECHNIQUES

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ABSTRACT

The electric guitar has been developed to withstand electric amplification and utilize (mostly analog) signal processing in order to create a multitude of timbres and sound types. Sometimes it would be desirable to play the same electric guitar, yet with a sound that resembles a good acoustic guitar or some other member of the plucked string instrument family. In this study we have investigated DSP techniques that can be used to shape the magnetic pickup output of the electric guitar to simulate acoustic instruments. This includes linear filtering for body simulation, time-varying modulation to generate beating of the harmonic components, and techniques to simulate the general temporal envelope of the plucked notes. (See also <http://www.acoustics.hut.fi/~mak/elguitar/>)

1. INTRODUCTION: HISTORY AND MOTIVATION

The electric guitar was originally developed to use electronic amplification in order to make the sound loud enough for playing along with an orchestra. The solid-body electric guitar with a magnetic pickup can withstand without acoustic feedback much more amplification than the acoustic one or even the semiacoustic guitar. Since amplified guitars sounded ‘dry’ and ‘electric’, a multitude of signal processing techniques were developed, first in analog and later in digital form, to add color to the sound. Some of these methods resemble the functioning of the acoustic guitar, such as reverb and echo. There are guitar processors that enable a electric guitar with a magnetic pickup to emulate another ‘vintage’ guitar, for example.

The present study started from our experiments in physical modeling and model-based sound synthesis [1, 2, 3]. Earlier experiments in [4, 5] were extensions of the extremely simple Karplus-Strong model [6]. Later Smith formulated more general digital waveguide modeling [7] which has been found very successful in generating convincing acoustic guitar sounds and music [2, 3]. Electric guitar simulation has been demonstrated as well [8].

The modeling of an autonomously vibrating string is relatively simple. In [9] it was derived in detail how the physical model of a string in a digital waveguide formulation can be transformed into a single-delay-loop (SDL) model. In [10] and [2] it was shown how to deal with the *excitation-string-body* chain in order to implement very efficient synthesis and in [11] how the body of the acoustic guitar can be modeled using digital filtering techniques.

The next step leading to the present study was to investigate the acoustic guitar with a bridge pickup. Since the transfer function from the bridge vibration to the radiated sound field can be assumed to be relatively linear and time-invariant (LTI), it is possible to equalize the bridge pickup output to sound more like the

original acoustic signal [12]. What is needed is a relatively high-order digital filter that creates the body modes and reverberance, i.e., proper time-frequency properties of a plucked sound.

Based on these earlier studies we encountered the question whether it would be possible to use DSP techniques to transform the signal from a magnetic pickup to sound like an acoustic guitar. Although a player of the solid-body electric guitar can always change to an amplified or unamplified acoustic guitar, it would be useful to have the possibility to play the same electric guitar, yet with acoustic-like timbre. Our first experiments were targeted to simulate acoustic body function by digital filtering. The results were partly successful: the attack part of the sound had more acoustic timbre. However, the sound in general was still quite electric. The two main reasons were assumed to be that (a) the string vibration is too ‘steady’ with only minor beats, i.e., amplitude envelope modulation, and (b) that the long sustain, i.e., slow decay of vibration due to minor damping of the string, is not characteristic to the acoustic guitar. The role of the magnetic pickup [13] may also not be fully understood.

In this study we approach the goal to obtain acoustic sound from the electric guitar, from a more systematic point of view. First we formulate signal processing models of both the acoustic and the electric guitar. These models are used for investigating how to transform the electric guitar sound to an acoustic one. Experiments are discussed which show that the direction taken is useful and practical, and while the result is not an ideal timbre of the acoustic guitar or any other plucked string instrument, further work can certainly improve the result. An equally important fact is that this methodology can lead to entirely new sounds and timbres, not similar to any existing musical instrument.

2. MODEL-BASED ANALYSIS OF THE ELECTRIC VS. ACOUSTIC GUITAR

Making the electric guitar sound acoustic means emulation of the acoustic guitar. To accomplish this, we should have a look at their models in order to derive algorithms to transform the former timbre to the latter. Figure 1 depicts a block diagram that includes the important functional elements of a generic guitar, both acoustic and electric. The models and blocks are assumed linear and time-invariant (LTI) which is found a useful simplification.

The acoustic guitar consists of the following chain:

$$excitation \rightarrow string \rightarrow bridge \rightarrow body \rightarrow radiation,$$

where *excitation* is the signal that is fed to the string model to simulate the pluck (or pick) event. In the electric guitar the signal path is

$$excitation \rightarrow string \rightarrow pickup.$$

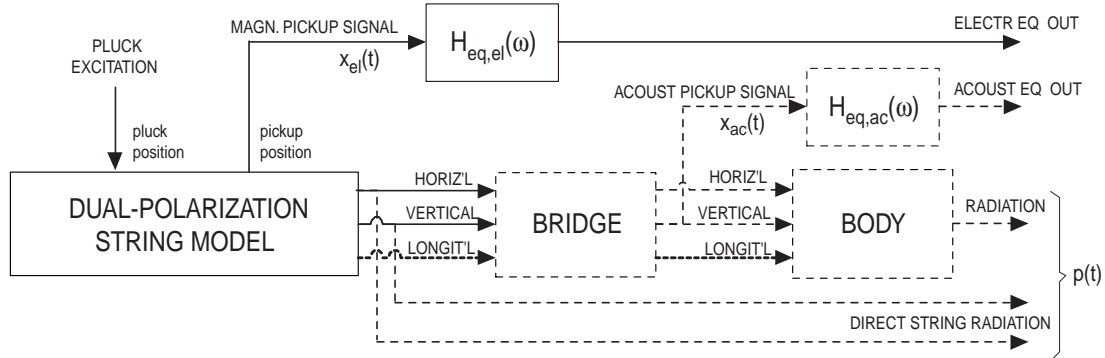


Figure 1: *Generic guitar model. Both the acoustic and electric guitar elements and signal paths are shown. The acoustic guitar body and bridge pickup signal paths are drawn in dashed line. Details of the string model block are shown in Fig. 2.*

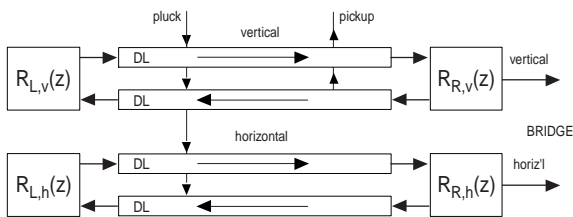


Figure 2: *Dual-polarization string model with vertical (v) and horizontal (h) submodels, termination reflection filters (L = left, R = right), pluck point and pickup point. DL = delay line.*

Details of the string model are described in Fig. 2. The model consists of two submodels, corresponding to the horizontal vibration in the body top plane and the vertical polarization perpendicular to the first one. The excitation from a pluck event propagates as a waveform in both directions, reflecting back from string terminations and forming a decaying standing wave. The frequency-dependent decay is due to energy dissipation in the string, radiation from the string, but in the acoustic case mainly through the bridge to the body. In the solid-body electric guitar the damping effect through the bridge is less substantial, resulting in a sound with long sustain.

In the acoustic guitar the bridge vibration excites the body to vibrate and radiate sound to the environment, see the path *bridge* \rightarrow *body* \rightarrow *radiation* in Fig. 1. The essential functions of the body are (a) amplification of sound by higher efficiency of string energy transfer than the string itself has, (b) adding resonance modes to the low frequency portion of the spectrum, and (c) adding dense distribution of mid-to-high frequency modes with audible body reverberation. This resembles modes and reverberation in a room although the body has a lower mode density. It is the time-frequency response of the body, not just the magnitude response, that makes the characteristics of the acoustic guitar (see Fig. 3).

3. EQUALIZATION STRATEGIES

The conversion of the electric guitar sound to a more acoustic one may be called equalization since its goal is a specific time-frequency behavior for the resulting sound. In this context the term equalization refers primarily to simulation of the acoustic body response, optionally including effects of timbre shaping due to differences in pluck excitation.

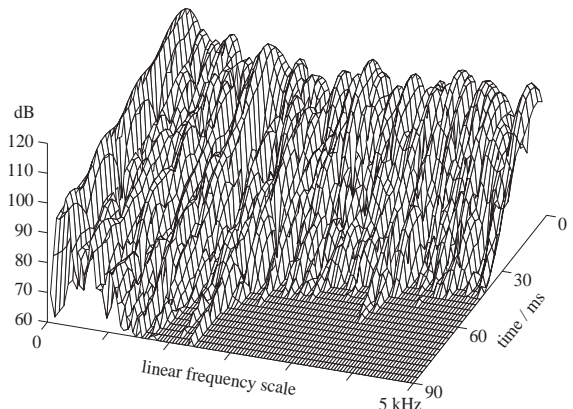


Figure 3: *Time-frequency plot of a guitar body response.*

As a background for the equalization task of this study we first review how a similar problem was solved for the equalization of the acoustic guitar bridge pickup. In [12] we introduced methods to estimate and realize a digital filter equalizer, i.e., the block $H_{eq,ac}(\omega)$ in Fig. 1. A simple way to do this is to measure the response from bridge impact hammer excitation to radiated sound $p(t)$, while the strings are damped, and use it as an estimate for the equalizer filter $H_{eq,ac}(\omega)$. Better results were achieved, however, using a sequence of played notes as an excitation to the strings and estimating the bridge-to-radiation transfer function by dividing the FFTs of signals $p(t)$ and $x_{ac}(t)$, that is

$$H_{eq,ac}(\omega) = P(\omega)/X_{ac}(\omega) \quad (1)$$

The resulting equalized sound was very similar to the acoustic signal. An exception is the lack of signal components that do not pass through vertical vibration of the bridge [12], such as friction hiss of a left hand finger moving on a string. High-quality equalization requires a high-order filter such as an FIR filter of order 1000 or above. Isolating the lowest body resonances and realizing them by IIR sections, possibly with a multirate implementation, helps reducing computational expense.

This body equalizer design technique cannot be applied directly to the case of the solid-body electric guitar since no acoustic body radiation is available simultaneously to the magnetic pickup recording. However, a variation of the method was found where

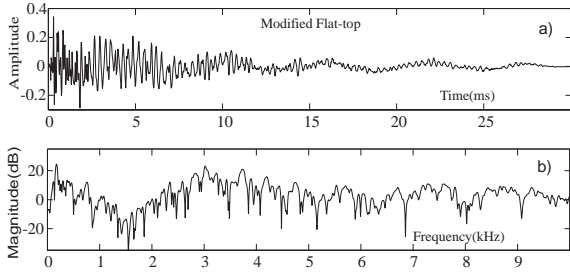


Figure 4: *Electric guitar equalizer for flat-top acoustic guitar body sound: (a) impulse response and (b) magnitude response.*

a flat-top guitar with metal strings was equipped with a magnetic pickup in the sound hole. This setup corresponds to the entire model of Fig. 1, except $H_{eq,ac}(\omega)$, and the estimation of body equalizer transfer function, based on recording $p(t)$ and $x_{el}(t)$, is

$$H_{eq,ac}(\omega) = P(\omega)/X_{el}(\omega) \quad (2)$$

The resulting body equalizer filter was used with a solid-body electric guitar (Fender Stratocaster). It sounded definitely more acoustic-like although not as good as expected. Reasons to this are that the guitar is different, pickups and their positioning were different, and the deconvolution through Eq. (2) was noisy. This method could probably be improved using very careful experimentation.

As another technique we applied impact hammer excitation to the bridge of both a flat-top and a classical guitar (strings removed) and recorded the radiated responses. These were used as body equalization filters so that the envelope spectra of the acoustic guitar and the equalized electric guitar were shaped similar, while plucking equivalently. This means that high frequencies above the cutoff frequency of the magnetic pickup were strongly emphasized (from 0 dB at 2 kHz to 45 dB at 4 kHz). Although this is a more ad hoc method than the deconvolution technique, the resulting sound was subjectively about as much acoustic-like and the method worked both for the classical and the flat-top guitar. The impulse and the magnitude response of the equalizer for flat-top sound equalization are shown in Fig. 4.

4. SIMULATION OF BEATS IN HARMONICS

After the body equalization has been done, the attack part of plucked sound from the electric guitar sounds relatively acoustic-like. However, in long notes the sound is too steady, i.e., very little variation due to beating harmonics is heard, which should be there to characterize the acoustic guitar. Thus we should find a method of time-varying processing to simulate it in the electric guitar.

The theory of the beating harmonics is based on the dual-polarization string model of Fig. 2. If the effective length of the string is different in the two polarizations of vibration, the sum signal at the bridge exhibits amplitude modulation corresponding to the modal frequency difference. This effect is very strong in some instruments, e.g., the Finnish kantele [14] that has a knotted termination around a bar. Nonlinear mode coupling may also contribute to the envelope fluctuations of harmonic components [15].

In the acoustic guitar the beating of harmonics is subtle but noticeable. The difference in effective lengths of the string comes from the fact that the mobility of the bridge is different in the horizontal and vertical directions. Especially at frequencies where the

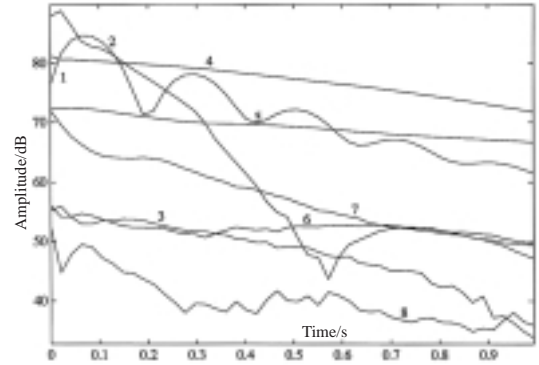


Figure 5: *Amplitude decay envelopes for a guitar note harmonics with prominent beat and fluctuation in some harmonics.*

bridge admittance is reactive it acts as a lengthening or shortening of the string. Fig. 5 illustrates amplitude decay envelopes of guitar tone harmonics after a pluck. Beating and fluctuation of some harmonics is relatively strong here.

The principle that we have used to add fluctuation to the harmonic envelopes of the electric guitar sound is to modulate each harmonic or group of harmonics independently. A modulated filterbank can be used as shown in Fig. 6 where each channel is amplitude modulated with a proper signal. There is no general simple rule how to design the filterbank and the modulating signals. (In the case of the kantele the modulation frequency should be proportional to the order of the harmonic.) What is important is that the separate channels should not be synchronized. Note that in the case of common modulation of all channels this method is reduced to a simple tremolo effect. From an auditory point of view, the filterbank does not need more channels than one for each critical band. Even a relatively small number of channels works as an interesting audio effect. Random signals with a proper spectrum may also be used as modulation signals. In principle the pluck should trigger modulations in a synchronized way but this is not possible for polyphonic playing unless each string has a separate pickup channel.

5. CONTROL OF DECAY AND SUSTAIN

The next property where the solid-body electric guitar is definitely different from the acoustic one is the slow decay and long sustain of string coupling. To simulate acoustic sound, the electric guitar strings may be damped mechanically or the signal from pickup may be processed to decay faster. The first principle can be realized for example by a soft damper under the string close to the bridge. A skillful player may also do it by the palm of the right hand.

The DSP way to make the decay faster is to use dynamic expanding of the pickup output signal. Any feedforward or feedback expander technique may be used as far as it yields an appropriate envelope and does not distort the signal in an undesirable way.

The dynamics expansion helps with non-polyphonic sounds but is problematic when a new sound is plucked while another is playing. In such a case the new sound will scale the level of the previous sound down, thus producing a kind of 'envelope intermodulation'. This can be avoided if a multichannel pickup is used where each string has a separate output. In principle it is also

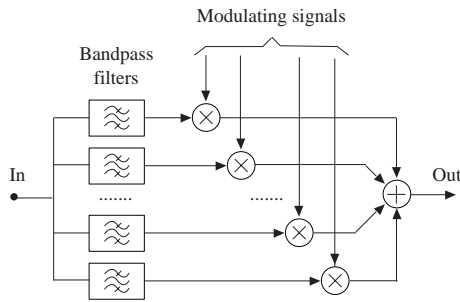


Figure 6: Filterbank modulator for generating beating harmonics in the electric guitar sound.

possible to use advanced sound segregation techniques to separate strings from a composite signal, but this cannot presently be done reliably in real time.

6. SYMPATHETIC VIBRATIONS

One more important phenomenon of the acoustic guitar that differentiates it from the electric one is the sympathetic vibrations. In the acoustic guitar all undamped (especially open) strings start to vibrate along with the actively vibrating ones at harmonic frequencies that are common to them. Due to rigidly supported terminations of strings the couplings between strings are weaker in the electric guitar, thus eliminating sympathetic vibrations.

There is no simple way to simulate this phenomenon by DSP for pickup output signals. It could be possible to construct electromechanical couplings between strings but it is not a true DSP solution. A technique following the spirit of this study is to use separate synthetic sympathetic string models of type shown in Figures 1 and 2. However, the problem remains that these synthetic strings are more like resonance strings that cannot easily and automatically be damped or undamped according to the fingering of the electric guitar.

7. DISCUSSION AND CONCLUSIONS

The techniques proposed above have been found useful in emulating acoustic guitar sound while playing a solid-body electric guitar equipped with a magnetic pickup. On a general level the resulting sound resembles well the acoustic sound but it is not possible to achieve a very detailed sound of a particular guitar since there are many differences in the construction and functioning of the two instrument types. In addition to the difficulties in estimating the parameters of the models and algorithms, strings are typically different in the two cases, a comb filtering effect due to the magnetic pickup changes according to the fret and pickup position, a detailed model of the pickup behavior is not available, etc. In spite of these, the acoustic-like sound achieved here is a useful extension to the set of electric guitar effects and the study has taught an interesting lesson in audio signal processing.

Sound examples related to this study can be found at URL: <http://www.acoustics.hut.fi/~mak/elguitar/>.

8. ACKNOWLEDGEMENTS

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