A DIGITAL FILTERING APPROACH TO OBTAIN A MORE ACOUSTIC TIMBRE FOR AN ELECTRIC GUITAR

Henri Penttinen, Vesa Välimäki, Matti Karjalainen
Helsinki University of Technology, Laboratory of Acoustics and Audio Signal Processing
P.O. Box 3000, FIN-02015 HUT, Finland
henri.penttinen@hut.fi, vesa.valimaki@hut.fi, matti.karjalainen@hut.fi
http://www.acoustics.hut.fi/

ABSTRACT

In this paper we propose signal processing methods to transform electric guitar tones to sound more acoustic. This is achieved by applying digital filtering to the signal obtained from a pickup of an electric guitar. The electric guitar differs from the acoustic one structurally and in the way the final acoustic radiation is produced. Hence, the timbres of the two guitars are distinguishably different. We use two digital filter designs to transform the electric guitar tones to resemble an acoustic guitar. The first one relies on impulse response measurements of the body of an acoustic guitar and the second method builds on deconvolving two spectrally rich signals. We also accomplish an improved controllability over the final timbre by extracting and replacing the lowest resonances with IIR resonators. The presented methods achieve to give the magnetic pickup tone an acoustic guitar-like timbre. The perceived responses have a distinct soundbox effect and simulate the important lowest resonances between 80 and 200 Hz of the acoustic guitar and the reverberant response of the body.

1 INTRODUCTION

The idea of being able to play an electric guitar with a timbre of an acoustic guitar is extremely fascinating and appealing. This would be a considerable advantage in a live performance situation and would widen the range of possible tones created by the player without having to switch between guitars.

Prior to this study the modification of guitar pickup signals by equalizing has been investigated by successfully improving the response of a bridge pickup, mounted to an acoustic guitar, to resemble the acoustic radiation[1]. This is possible since the signal path from the string to sound radiation in the acoustic guitar is relatively linear and time-invariant and since the signal path's transfer function can be simulated with digital filtering [2, 3, 4]. In [5, 6] it was shown that equalization methods can also be used to obtain an acoustic response from the electric guitar.

In this study the discussion and development of obtaining a more acoustic timbre for an electric guitar is continued further and the controllability of the filters is investigated. The filters discussed in this study are implemented as FIR filters with optionally two IIR resonators in cascade. When the order of the FIR filters is equal to 1300 or below and the sampling frequency is 44.1 kHz they can be realized on a modern architecturally efficient DSP processor and run in real time.

2 THE ACOUSTIC VS. THE ELECTRIC GUITAR

The electric guitar differs indisputably from the acoustic guitar, both in appearance and in tone. The two main ingredients that set the acoustic guitar apart from the electric one are the structural differences (soundbox vs. solid body) and the means by which the airborne sound is produced (soundbox vs. pickup, amplifier, and loudspeaker). These factors are intertwined and include many sub-elements. Moreover, these differences cause the audible timbres to differ distinguishably.

2.1 Structural Differences

Structurally the most prominent difference is the lack or presence of a soundbox. The strings themselves radiate sound very inefficiently. To get a useful sound level of the acoustic guitar the bridge transfers the vibrations of the strings to the hollow body. Therefore the body and the air enclosed within vibrate and amplify the signal. The vibrating soundbox and air give the audible response its most significant characteristics. The audible effect is a slightly reverberant response. The soundbox can be considered a small room where the strongest resonance is typically 170 to 190 Hz and the rest of the higher modes are weaker. Moreover, the soundbox forms a Helmholtz resonator whose center frequency is about 80 to 100 Hz. The lowest resonances affect the audible response to have a strong low-frequency representation whereas the higher-frequency resonances bring about a diffuse reverberation. [7]

In the electric guitar the influence of the body vibrations to the final tone are less significant than in the acoustic one. The string termination in the neck-end provides a minor energy sink at resonance frequencies which affects some notes to decay faster [8]. The total effect of this is more in the vein of a delicate deviation in the behavior than a drastic coloring effect of the overall timbre.

2.2 Sound Production Differences

The means to produce the acoustic radiation also differs between the two types of guitars. For the acoustic guitar the soundbox acts as an amplifier. In the electric one the vibration of the strings is detected by pickups and amplified electrically before providing the signal to a loudspeaker. Con-

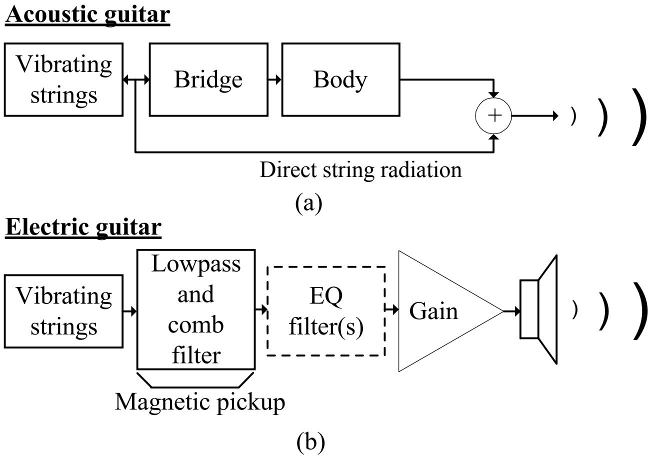

Figure 1: Flow charts representing signal paths in the (a) acoustic and the (b) electric guitar.

ventional magnetic pickups in electric guitars have a lowpass filtering characteristic [9] and therefore attenuate the level of higher frequencies present in the response. This renders the final tone to be softer.

Figure 1 depicts the signal paths from the vibrating string to the acoustic radiation in the two guitar types. The behavior in the acoustic guitar is presented in Fig. 1a where the final acoustic radiation consists of the vibrations filtered and amplified by the body, and the direct string radiation. Fig. 1b illustrates how the vibrations of the strings in the electric guitar are detected by a magnetic pickup and are amplified before supplying the electrical signal to a loudspeaker that creates the final acoustic radiation. The impedance of the magnetic pickup causes a lowpass filtering effect [9] and its position results in a comb filtering behavior in the same manner as the plucking position [7]. The EQ filter box refers to the body simulation filters discussed in this study. In addition, the magnetic pickup senses mainly the vertical string vibrations, perpendicular to the top plate, and only weakly the horizontal vibrations, whereas the acoustic guitar is more responsive to string motion in all directions.

2.3 Other Differences

Other important elements that distinguish these two instrument variations from each other naturally exist, but are less significant or could be thought as being included in the two factors mentioned previously.

As a consequence of the energy transfer from the string to the mobile bridge, the string vibrations in the acoustic guitar decay relatively fast, whereas the more rigid termination and the solid body of the electric guitar enables the strings to vibrate longer. The mechanical impedance of the bridge, in the acoustic guitar, is different in the horizontal and vertical directions and causes modest beating of harmonics in the acoustic guitar**.** This can be simulated with amplitude modulated filter banks [6]. The placement of the pickup also affects the final result. As for the excitation point of the string, the location of the pickup results in a comb-filtering effect that suppresses certain modes, depending on the position of the transducer.

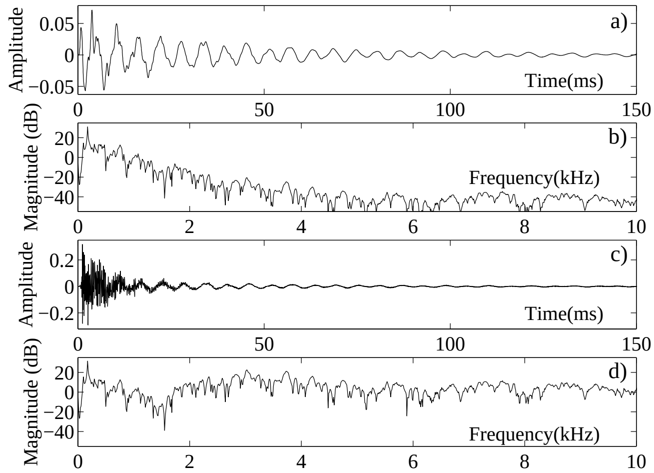

Figure 2: Equalizer target responses obtained from impulse response measurements with the acoustic flat-top guitar without strings: (a) impulse response, (b) magnitude response, (c) and (d) impulse and magnitude responses after highpass filtering, respectively.

3 DIGITAL FILTERS FOR BODY SIMULATION

To render a more acoustic sound for the electric guitar, two fundamentally different filter estimation techniques were used. In the first method, filters were derived from body impulse response measurements conducted in an anechoic chamber. The second method for estimation of the filter is based on a deconvolution technique introduced in [1]. The filters used in this study may be called equalization filters since the target is to reach a modified time-frequency behavior of the response.

3.1 Filters Obtained from Body Impulse Response Measurements

The impulse responses were obtained by hitting the bridge of the acoustic guitar with an impulse hammer. To account for the influence of the player's body, the measurements were executed in an in-situ fashion where the guitar is held in the same manner as while playing. Both the classical guitar and the flat-top guitar were measured.

First the strings were damped with absorbent cotton and the left hand. Since the hit of the impulse hammer to the bridge acts as a good excitation for the strings, the cotton and the hand cannot damp the vibrations of the strings perfectly and therefore some vibrations of the strings will remain and a short and silent ringing can be perceived. As a second alternative the strings were removed. This prevents any ringing sounds to emerge. This changes the tension in the neck and in the soundbox, but on the whole does not introduce any significant errors.

To extract a preferred target EQ filter from the measurement data the impulse response was windowed by using a rectangular window for the buildup and the right-hand half of a 200 samples long Hanning window for the end. Figures 2a and 2b illustrate the impulse and magnitude responses, respectively, obtained from the flat-top guitar without strings. The length of the FIR filter is 6615 taps which corresponds to a response of 150 ms at the sampling rate of 44.1

kHz. Because the magnetic pickup can be modeled as a low-pass filter [9] the filters were modified to compensate the undesirable effect by emphasizing high frequencies. The modified response of the target EQ filter obtained from the flat-top guitar are shown in Fig. 2c and 2d.

3.2 Filters Obtained Through Deconvolution

In the second method the measurement setup consists of a single-coil bridge pickup mounted to the sound hole of the acoustic guitar and a condenser microphone that is placed half a meter from the sound hole. The acoustic response $p(t)$ is obtained from the microphone signal and the string vibrations $x(t)$ are captured by the magnetic pickup. By using spectrally rich playing of the guitar as an excitation signal a target response $H_{eq}(\omega)$ of the EQ filter is computed by deconvolving $p(n)$ and $x(n)$ in the frequency domain. The impulse response of the target EQ filter $h_{eq}(n)$ is obtained by calculating the inverse DFT of $H_{eq}(\omega)$:

$$h_{eq}(n) = \mathrm{DFT}^{-1}\left(\frac{\mathrm{DFT}\{p(n)\}}{\mathrm{DFT}\{x(n)\}}\right) \quad (1)$$

where $p(n)$ and $x(n)$ are discrete-time signals of the air radiation and the string vibrations, respectively, n is the discrete time variable and DFT is the Discrete Fourier Transform.

The pickup placed in the sound hole reduces the area of the hole. Therefore the Helmholtz resonance of the guitar body will be lowered but can be considered an insignificant factor on the whole. The impulse response obtained by deconvolving is an approximation of the transfer function from the magnetic pickup to the sound radiation. This impulse response of an FIR filter of length 1000 (22.8 ms, f_s = 44.1 kHz) is depicted in Figure 3 with its magnitude response. The lower pane illustrates how the lowpass filtering characteristic of the magnetic pickup is canceled by the filter: the envelope of the magnitude response level increases between 500 Hz and 4 kHz from –10 dB to a +10 dB level that is maintained at higher frequencies.

The nylon strings in the classical guitar do not effect the magnetic field of the magnetic pickup and consequently do not induce a current to the coil of the magnetic pickup. Therefore only a steel-stringed flat-top acoustic guitar was used in this method.

3.2.1 Modifications During the Deconvolution Procedure

For a proper implementation of the deconvolution technique the processed signals have to be modified during the procedure to reach a satisfactory result.

Before the signals $p(n)$ and $x(n)$ are treated with the DFT they have to be aligned. This arises from the delay caused by the time the air radiation signal has to travel before reaching the measurement microphone.

Due to circularity of the inverse DFT, the impulse response h_{eq} obtained by using Eq. (1) has to be altered. The buildup of the wanted impulse response is located at the very end of the deconvolution result and the tail respectively at the beginning. Hence, the deconvolution result is split into two equal length sequences and the sections are swapped.

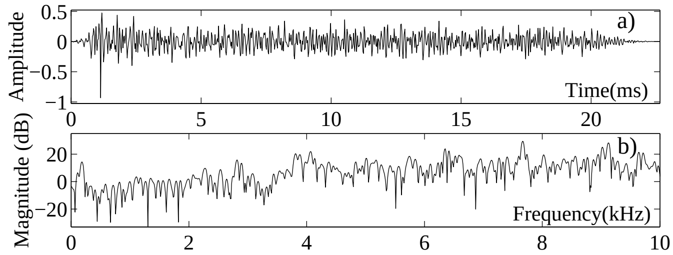

Figure 3: The impulse response (a) and the magnitude response (b) of the deconvolution filter.

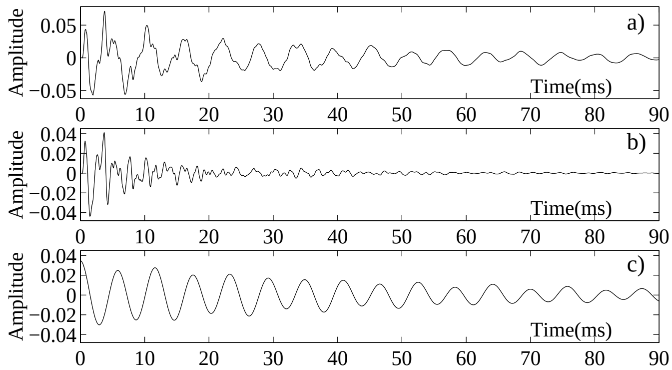

Figure 4: The impulse responses of the original filter (a), the filter after removing the two lowest resonances (b), and the filters that simulate the extracted modes

After these steps have been concluded the target impulse response of the body simulation filter is windowed from the modified deconvolution result. To obtain a desired behavior for the buildup the left-hand half of a 100 samples long Hanning window was used for the onset. To attain a more natural and smooth tail the latter half of a 200 samples long Hanning window was used for the end.

3.3 Modifications of the Body Simulation Filters

To achieve an adjustable solution the lowest resonances can be removed by notch-filtering and be replaced with IIR resonators [1, 4]. The filters used to remove and synthesize the lowest modes are discussed in [10] and are used in cascade with the FIR filter. The center frequency and –3 dB bandwidth of the removed modes determine the parameter values of the notch and resonator filters. By removing the lowest resonances the length of the FIR filters can be significantly shortened. When synthesizing the removed modes with cascaded resonators the long decaying tails of the important modes are preserved. This way an improved real-time implementation can be achieved. This also gives the possibility to change the characteristics of the simulated soundbox, and to effect the overall tone more specifically.

Figure 4a shows the impulse response obtained from the flat-top guitar's body impulse response measurements without strings when the response is viewed from the beginning to 90 ms. This illustrates the behavior of the impulse response before the two lowest resonances have been removed. Figure 4b depicts the impulse response after the two lowest body modes have been extracted. The amplitude of the tail has distinctly decreased. The impulse response of the resonators that synthesize the removed modes is presented in Fig. 4c.

4 RESULTS

All of the implemented filters produce a response that gives the signal from the magnetic pickup an acoustic- guitar-like tone. The filters simulate the important lowest resonances between 80 and 200 Hz of the acoustic guitar and the reverberant response of the body at higher frequencies. Hence the perceived response has a distinct soundbox present. Furthermore, as a consequence of strong amplification of high frequencies the filtered result distinguishes itself from the typical lowpass-filtered electric guitar sound. A disadvantage is that this causes the perceived response to be sensitive to noise in the input signal.

4.1 Classical and Flat-top Guitars

The high-frequency response of the filters obtained from the impulse response measurements has to be strongly emphasized before a satisfactory result can be achieved. The body impulse response measurements, with the strings attached, leads to filters that reproduced the silent ringing that could be perceived during the measurements. More suitable results were achieved with the body impulse response filters obtained when the strings were removed.

The equalizing filter obtained from the classical guitar results in a response that sounds slightly nasal. Moreover, the classical guitar is designed to amplify the vibration of nylon strings, whereas the electric guitar uses steel strings.

The flat-top target EQ filter accommodates the filtering of the magnetic pickup signal even better than the filter obtained with the classical guitar. This is natural since both flat-top and electric guitars use steel strings. In addition even the mere physical size of the flat-top guitar's soundbox can be perceived to be larger than the classical ones.

4.2 Deconvolution

Overall the best results are accomplished with the deconvolution-based filter and its modified versions. They give a rich and natural response where the important characteristics of the acoustic guitar are present.

The best results were attained with a 1000 tap FIR filter with two IIR filters in cascade. If the length of the filter is 1500 or more, an undesired diffuse room-like reverberation can be perceived. The synthesizing of the lowest modes enables the response created with the deconvolution-based filter and cascaded IIR filters to have a longer decay of the lowest modes without introducing the undesired diffuse reverberation. However, the deconvolution-based filter requires careful windowing to obtain a suitable response.

5 DISCUSSION AND CONCLUSIONS

Even if it would be possible tonewise to achieve realistic results, the feel of the two guitar types are different. The vibration of the back plate of the soundbox can be felt by the player. In addition the sound sources are located differently. The electric guitar tones reach the player from a loudspeaker and the sound field caused by the acoustic guitar has its center just in front and below the player's head. These features cause the feel of the instruments to differ and consequently affect the playing.

The synthesis of the removed body modes using IIR resonators enables the adjustment of the characteristics of the low-frequency response of the soundbox model. This controllability was found to be beneficial, since it can be used to vary the perceived final tone.

Even though the filtering methods presented in this study can achieve convincing results they cannot match in detail the rich and lively timbre of the acoustic guitar. This arises from the several differences that the discussed guitar types possess. Regardless of the dissimilarities the proposed techniques expand the tonal arsenal of the electric guitar by bringing its timbre closer to an acoustic guitar.

6 ACKNOWLEDGMENTS

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REFERENCES

[1] M. Karjalainen, V. Välimäki, H. Räisänen and H. Saastamoinen, "DSP Equalization of Electret Film Pickup for the Acoustic Guitar," 106th AES Convention. Munich, Germany, preprint no. 4907, 1999.

[2] M. Mathews and J. Kohut, "Electronic Simulation of Violin Resonances," J. Acoust. Soc. Am., vol. 53, no. 6, pp. 1620-1626, 1973.

[3] J. O. Smith, Techniques for Digital Filter Design and System Identification with Application to the Violin. PhD thesis, CCRMA, Dept. of Music, Stanford University, Stanford, CA, 1983. Report STAN-M-14.

[4] M. Karjalainen and J. O. Smith, "Body Modeling Techniques for String Instrument Synthesis," Proc. Int. Computer Music Conf., Hong Kong, 1996, pp. 232-239.

[5] M. Karjalainen, H. Penttinen and V. Välimäki, "More Acoustic Sounding Timbre from Guitar Pickups," Proc. 2nd COST G-6 Workshop on Digital Audio Effects, Trondheim, Norway, 1999, pp. 41-44.

[6] M. Karjalainen, H. Penttinen and V. Välimäki, "Acoustic Sound from the Electric Guitar Using DSP Techniques," Proc. IEEE ICASSP'2000, Istanbul, Turkey, June 2000.

[7] N. H. Fletcher and T. D. Rossing, The Physics of Musical Instruments, Second Edition. Springer-Verlag, New York, 1998.

[8] H. Fleischer, "Mechanical Vibrations of Electric Guitars," Acustica united with Acta Acustica, vol. 84, no. 4, pp. 758-765, 1998

[9] T. Jungmann, Theoretical and Practical Studies on the Behaviour of Electric Guitar Pickups. MSc thesis, Lab. of Acoustics and Audio Signal Processing, Helsinki Univ. of Tech., Espoo, Finland, 1994.

[10] S. J. Orfanidis, Introduction to Signal Processing, Prentice Hall, Englewood Cliffs, New Jersey, 1996.