A DIGITAL WAVEGUIDE MODEL OF THE ELECTRIC BASS GUITAR INCLUDING DIFFERENT PLAYING TECHNIQUES

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ABSTRACT

In this paper, we present a novel audio synthesis model that allows us to simulate bass guitar tones with 11 different playing techniques to choose from. In contrast, previous approaches focussing on bass guitar synthesis only implemented the two slap techniques. We apply a digital waveguide model extended by different modular parts to imitate the sound production process on this instrument. The results of a MUSHRA listening test reveal that an audio coding scheme based on the presented algorithm offers a high perceived sound quality in comparison to conventional low bit-rate coding schemes while requiring a much lower bit-rate.

Index Terms— electric bass guitar, waveguide synthesis, playing techniques, plucking style, expression style

1. INTRODUCTION

Within the last decades, many sound synthesis algorithms were presented that try to model the sound production process of musical instruments. These synthesis algorithms generate a synthesized waveform based on given input parameters.

Many existing algorithms based on physical modeling offer various input parameters that affect different perceptual aspects such as timbre or loudness. However, these parameters fail to represent important sound characteristics that are typical for each instrument. In order to improve the perceived quality of the synthesized instrument track, possible playing techniques and performance gestures must be included in the synthesis model. A synthesis algorithm offering those features can be applied in live music performances, in recording studios, but also in an *instrument coding* application. Here, an instrument recording (e.g. a bass track) is analyzed with a music transcription algorithm. The output of this algorithm is a detailed parametrization of the note that was played. These parameters then can be transmitted to the synthesis algorithm at a significantly lower bit rate compared to transmitting the raw wave data.

This paper is structured as follows. We outline the goals of this publication in Sect. 2 and give a brief overview over related work in Sect. 3. In Sect. 4, we provide a detailed overview over the digital waveguide model of the bass guitar that incorporates 11 different playing techniques. We present the results of a user study to evaluate the perceived sound quality of the synthesis algorithm in Sec. 5. Finally, we give a conclusion in Sect. 6.

2. GOALS & CHALLENGES

The goals of this publication are to design and to evaluate a sound synthesis algorithm that mimics the sound production process of the electric bass guitar. We aim to simulate 11 different playing techniques that are typical for this instrument. The spectral properties of the notes played on the instrument are directly affected by these playing techniques. Thus, the biggest challenge is to identify all relevant parts of the sound production process and include them in the synthesis model. The proportions of the electric bass and its strings need to be simulated properly in order to achieve an perceptually convincing synthesis model of the bass guitar.

3. PREVIOUS APPROACHES

The physical modeling of string instruments relies on the decomposition of the one-dimensional vibration into two waves traveling in opposite directions. The digital waveguide synthesis [1] is a proven and computationally efficient method to simulate this behavior. Various string, brass and wood wind instruments have been modelled according to this approach, e.g. [2, 3]. Previous publications that focussed on the electric bass guitar dealt with the slap bass techniques and the fretboard collision [4, 5] in digital waveguides. Expression techniques on the guitar that were considered in the literature so far are frequency modulation effects [2], harmonics [6], and dead-notes [5]. To the best knowledge of the authors, no publication so far presented a waveguide model for the bass guitar that incorporates multiple playing techniques.

4. NEW APPROACH

First, we analyze the typical way of playing a bass guitar. All simulated playing techniques are provided in Sec. 4.1. We present a waveguide model for the bass guitar and discuss the different components that mimic different aspects of the sound production process in Sec 4.2. Finally, we show how different configurations of the waveguide model allow to simulate different playing techniques in Sec. 4.3.

4.1. Bass guitar playing techniques

A performance gesture on string instruments such as the bass guitar involves plucking the string with the plucking hand (plucking style) and using the gripping hand to define the note pitch (expression style). In this paper, we focus on the 5 plucking styles *finger-style* (FS), *picked* (PK), *muted* (MU), *slap-thumb* (ST), and *slap-pluck* (SP) and the 5 expression styles *normal* (NO), *vibrato* (VI), *bending* (BE), *harmonics* (HA), and *dead-note* (DN) as previously described in detail in [7]. In addition, we add the expression style *slide* (SL) [8].

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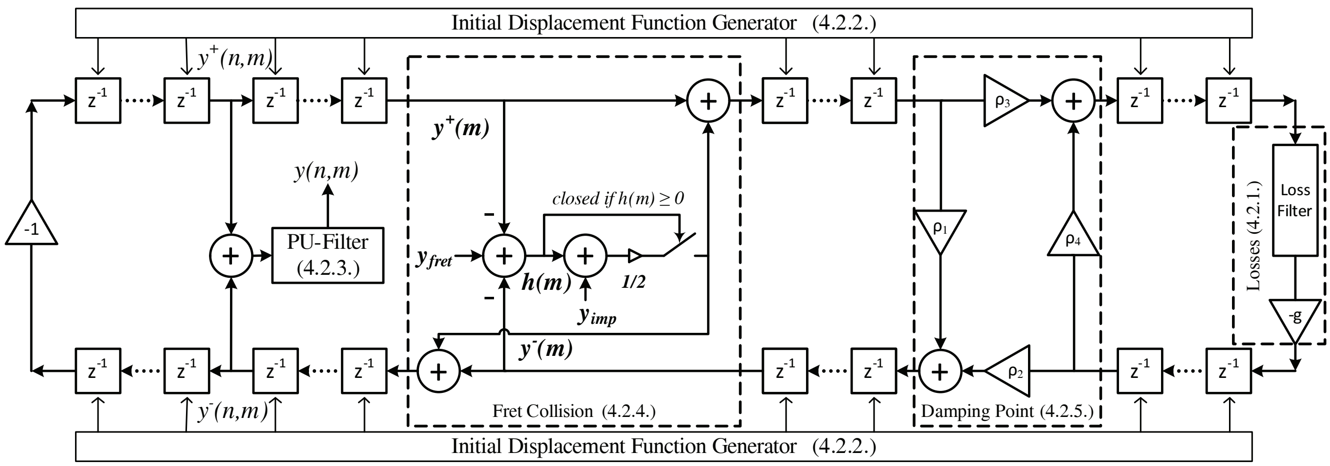

Fig. 1. The waveguide model including a collision and damping point. The number of the corresponding sections, where the model components are explained, are given in brackets.

4.2. A waveguide model of the bass guitar

4.2.1. The basic waveguide model

The basic waveguide model presented in this paper consists of two delay lines representing both waves travelling in opposite directions on the string. The delay lines are connected on both ends, where the elements of one delay line are reflected inverted into the other delay line, representing the rigid termination of the string on the bridge and the nut of the electric bass. The overall decay of the simulated string is handled by a damping factor $g < 1$ which is controlled by the decay rate of the note to be synthesized given as an input parameter. In addition a parametric zero phase FIR filter design presented in [9] is used to simulate the frequency losses of each of the four bass strings separately.

A simple linear interpolation of fractional delay values is used for fine tuning the waveguide model to frequencies that are not a partial of the sampling frequency f_s. The linear interpolation offers two advantages. First, it is computational very efficient. Second, the listening tests (see Sec. 5) reveal that it is sufficient for modeling the time varying fundamental frequency for the techniques BE, SL, and VI. This is because the delay line element number $N = f_s/f_0$ is fairly high for the low fundamental frequencies that correspond to the pitch range of an electric bass guitar. Considering 20 frets and four strings, the fundamental frequency values range from $41.2Hz$ to $311.1Hz$ with a standard tuning (E1-A1-D2-G2).

4.2.2. The excitation signal

As shown in fig. 1, both delay lines of the waveguide model are initialized with an excitation signal which can either be representing the displacement of the string or a time derivative like the velocity of the string. In our model, displacement is used as the state variable.

Thus, the displacement function is responsible for the harmonic content of the resulting tone, which depends for instance on the plucking position and strength. The shape of the initial function mainly affects the attack period of a note. This is due to the high losses of a vibrating string simulated by the frequency loss filter described in section 4.2.1. Therefore, it is possible to simulate different plucking styles through the choice of the excitation signal.

The plucking position stays approximately constant on the bass guitar throughout all strings and fret positions. The waveguide model only simulates the vibrating part of the string whose physical length depends on the fundamental frequency. Therefore, the plucking position within the displacement function changes relatively with different fundamental frequency values and thus needs to be calculated in reference to the string length.

4.2.3. Simulation of the electromagnetic pickups

In order to generate an output signal, the string deflection is captured at each sampling step at the delay line element, which corresponds to the geometric position of the pickup on the real instrument. Thus, the correct pickup position is chosen for all possible strings and fret positions.

On bass guitars, the vibrating string is captured by the electromagnetic pickups. The output signal of the instrument is formed by the response of the inner tone circuitry including the pickup itself [10]. To consider this behaviour in the model, a SPICE simulation of the circuitry was performed including the pickups internal properties (resistance, capacitance and inductance), a fixed tone circuit and a connected load (also considering a specific cable capacitance). Based on the simulation results, an approximated FIR filter was implemented that is applied to filter the output signal of the waveguide model.

4.2.4. Fret collision

The characteristic sound of the slap-bass plucking techniques is mainly caused by the collision of the string with the fretboard. To simulate this collision behavior in the waveguide model, the method presented in [5] was used. A scattering junction is placed between the delay lines at each fret position. In every sampling step, the sum of both delay lines $y_{in}(m)$ is compared with the distance y_{fret} at this point with $h(m) = y_{fret} - y_{in}(m)$. A collision between the string and a fret is indicated by $h(m) \geq 0$. In this case, a partial of the delay line elements travelling into the junction get reflected in the opposite direction. At the same time the overall displacement is held fixed on the obstacle until the simulated string is leaving the fret again. Considering that the collision is not completely inelastic, a constant impulse y_{imp} is added to the signal for a short period Δt of the collision time to simulate the string bouncing of the fret a few times before it rests on it. The output values of the scattering junction $y^-_{out}(m)$ and $y^+_{out}(m)$ in the moment of a collision are given by

$$\begin{bmatrix} y^-_{out}(m) \\ y^+_{out}(m) \end{bmatrix} = S_c \begin{bmatrix} y^-_{in}(m) \\ y^+_{in}(m) \end{bmatrix} + \frac{y_{fret} + y_{imp}}{2} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{1}$$

with the scattering matrix

$$S_c = \frac{1}{2} \begin{bmatrix} +1 & -1 \\ -1 & +1 \end{bmatrix}. \tag{2}$$

With this method, 20 frets are simulated at maximum for an open string. Here the number of simulated frets is computed from the fundamental frequency in reference to the used string and resulting fret position. The distances between the frets are calculated with respect to the real fretboard geometry of a bass guitar. In relation to the simulated string, the frets are positioned in a slight curve which imitates the slightly bowed neck of the instrument.

4.2.5. Finger damping

A wave digital resistor was used as proposed in [6] in order to simulate the damping interaction between a players finger and the string needed for some of the expression techniques. This wave digital filter can be easily connected to the waveguide model with a 3-port junction, because both physical modeling methods are based on the traveling wave decomposition. While the wave digital resistor is connected to the delay lines, it keeps damping all the displacement at this point in the digital waveguide. After some cycles of the initial displacement through the delay lines only those standing waves keep on existing in the digital waveguide that have a node $y_{in}(m) = 0$ at this damping position.

Considering the wave resistors damping factors ρ_1 to ρ_4 the output values $y^-_{out}(m)$ and $y^+_{out}(m)$ of the wave digital filter junction are given by

$$\begin{bmatrix} y^-_{out}(m) \\ y^+_{out}(m) \end{bmatrix} = \begin{bmatrix} \rho_1 & \rho_2 \\ \rho_3 & \rho_4 \end{bmatrix} \begin{bmatrix} y^+_{in}(m) \\ y^-_{in}(m) \end{bmatrix} \tag{3}$$

where the damping factors depend on the three ports impedances.

4.3. Realisation of playing techniques

4.3.1. Plucking styles

Plucking Styles	FS	PK	MU	ST	SP
Displacement Function	x	x	x	x	x
Modification of Losses			x		
Fret Collision				x	x

Table 1. Model configurations for the plucking styles *finger-style* (FS), *picked* (PK), *muted* (MU), *slap-thumb* (ST), and *slap-pluck* (SP)

Figure 1 shows the complete waveguide model with one of each junction type. For realizing 11 playing techniques different combinations of model modifications where used (see Tab. 1).

For each plucking technique the model is initialized with a special displacement function inducing a different amount of harmonics into the digital waveguide. Every function contains a nearly triangular shape with its maximum at a typical plucking position of its corresponding style. A sharper function leads to a greater amount of higher harmonics in comparison to a smoother, pre-filtered displacement function. With this in mind a finger plucked string sound (FS, MU, SP) and a pick plucked sound (PK) can be differentiated in the model. In the special case of the ST technique, an initial velocity is used with zero displacement as proposed in [4]. Since the velocity equals the first time derivative of the displacement, we integrate over the initial velocity function by computing its cumulative sum. The upper delay line is initialized with this displacement function and the lower delay line is initialized with the inverted displacement function. This ensures that the total sum of both delay lines is zero. In addition, the fret collision is activated on the slap-bass techniques (ST, SP). To simulate the higher frequency losses of the MU style resulting of the damping palm on the string, the overall losses of the model are raised by cascading the loss filter.

4.3.2. Expression styles

Expression Styles	NO	SL	VI	BE	HA	DN
Displacement Function					x	x
Delay Line Modulation		x	x	x		
Fixed Delay Line	x				x	x
Damping Points					x	x

Table 2. Modifications for the expression styles *normal* (NO), *slide* (SL), *vibrato* (VI), *bending* (BE), *harmonics* (HA), and *dead-note* (DN)

The model configurations used to simulate different expression styles are illustrated in Tab. 2. For the expression styles BE, SL, and VI, the delay line length is smoothly varied by a certain amount of frequency difference in contrast to NO, HA, and DN where the delay line length is fixed to the fundamental frequency. The varying length can be given by any type of function. In the presented model the modulation function can either be a simple sine-function resulting of a given frequency difference (BE, SL, VI) and vibrato frequency (VI) or an arbitrary segmented function resulting out of parts of a sine-function recreated out of the given turning points [8]. For HA and DN, the damping points are used to realize the selective damping of the digital waveguide. In the case of HA, one damping point is placed on a certain fraction of the delay line where the wanted harmonic has a node. For a DN, two damping points are used randomly placed over the ”neck part” of the digital waveguide. Both techniques also use a specific displacement function where only the part between the damping point and the bridge reflecting point are displaced, the plucking position with HA is placed on the wanted harmonics wave crest so that this harmonic is induced with the most energy. The waveguide model is designed to be able to use all plucking styles in combination with any expression style.

5. EXPERIMENTS & RESULTS

Based on the lack of bass guitar synthesizer algorithms offering the same quantity of playing techniques to compare to, we chose to consider the algorithm as a part of an instrument coder (as decribed in Sect. 1) for the evaluation process. Therefore a MUSHRA hearing test was performed to evaluate the perceived sound quality of the synthesis algorithm. Common low bit rate audio coders (HE-AAC at 14.1kbit/s, Ogg Vorbis at 17.2kbit/s, and AMR-WB+ at 6kbit/s) were chosen to compete against the resynthesizing decoder. All coders were used with maximum compression settings to get as close as possible to the instrument coders low bit rate. The goal was

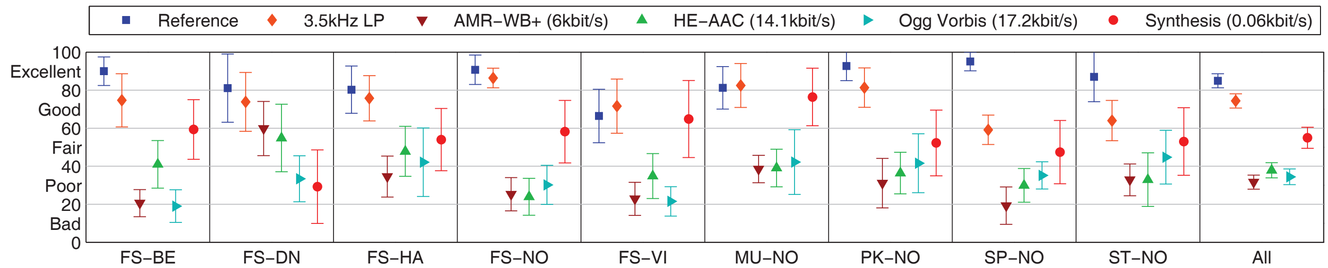

Fig. 2. The results of the MUSHRA test of different audio coders and our synthesis algorithm. The bit-rates are given. Mean ratings with 95%-confidence intervals are given. For each experiment, the abbreviations for the plucking style and the expression styles are given as explained in Sec. 4.1.

to test the acceptance of the transform coders low bit rate artefacts against the resynthesised bass guitar signal. The test was performed throughout all playing techniques separately. The 12 participants ranged from average music listeners to professional bass-guitar players.

Figure 2 shows the averaged results of the test including a 95%-confidence interval. The transform coders artefacts were all rated in the upper "poor" region on average over all playing techniques. The best transform coder reached 37.86%. The resynthesised signals in comparison reached 54.96% in the "fair" region.

6. CONCLUSIONS

We presented a new sound synthesis model mimicking the physical properties of the electric bass guitar. We successfully included physical models of specific playing styles of this instrument. The parts of the model were designed to simulate 11 different playing techniques that can be adjusted with various parameters. The results of a MUSHRA listening tests revealed that the perceived audio quality of a coding scheme based on the presented model surpasses three low bit-rate audio coding schemes. At the same time, the novel method allows for a significantly lower bitrate of 1.88kBit/s. This corresponds to a bitrate of 94bit/note at a theoretical note density of 20notes/s. Sound examples of the presented algorithm will be made available on a designated web-site[1].

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8. REFERENCES

[1] J. O. Smith, "Physical modeling using digital waveguides," *Computer Music Journal*, vol. 16, pp. 74 – 91, 1992.

[2] M. Laurson, J. Hiipakka, C. Erkut, M. Karjalainen, V. Välimäki, and M. Kuuskankare, "From Expressive Notation to Model-Based Sound Synthesis: a Case Study of the Acoustic Guitar," in *Proceedings of the 1999 International Computer Music Conference*, 1999, pp. 1–4.

[3] V. Välimäki, M. Karjalainen, Z. Jànosy, and U.K. Laine, "A real-time DSP implementation of a flute model," in *International Conference on Acoustics, Speech and Signal Processing*, 1992, pp. 249–252.

[4] E. Rank and G. Kubin, "A waveguide model for slapbass synthesis," in *IEEE International Conference on Acoustics, Speech, and Signal Processing*, 1997, pp. 443–446.

[5] G. Evangelista and F. Eckerholm, "Player-instrument interaction models for digital waveguide synthesis of guitar: Touch and collisions," *IEEE Transactions on Audio, Speech & Language Processing*, vol. 18, no. 4, pp. 822–832, 2010.

[6] J. Pakarinen, "Physical modeling of flageolet tones in string instruments," in *Proceedings of the 13th European Signal Processing Conference*, 2005, pp. 4–8.

[7] J. Abeßer, H. Lukashevich, and G. Schuller, "Feature-based extraction of plucking and expression styles of the electric bass guitar," in *IEEE International Conference on Acoustics, Speech, and Signal Processing*, 2010, pp. 2290–2293.

[8] J. Abeßer, C. Dittmar, and G. Schuller, "Automatic recognition and parametrization of frequency modulation techniques in bass guitar recordings," in *Audio Engineering Society Conference: 42nd International Conference: Semantic Audio*, 2011, pp. 121–128.

[9] M. van Walstijn, "Parametric fir design of propagation loss filters in digital waveguide string models," *IEEE Signal Processing Letters*, vol. 17, no. 9, pp. 795 – 798, 2010.

[10] M. Karjalainen, V. Välimäki, and T. Tolonen, "Plucked-String Models: From the Karplus-Strong Algorithm to Digital Waveguides and Beyond," *Computer Music Journal*, vol. 22, no. 3, pp. 17–32, 1998.

[1] http://www.idmt.fraunhofer.de/en/Departments_and_Groups/smt/bass_synthesis.html
[2] see www.songs2see.net