Proceedings of the 2000 International Computer Music Conference, Berlin, Germany, 27 Aug.-1 Sept. 2000, pp. 50–53

Model-Based Synthesis of the Clavichord

Vesa Välimäki[1], Mikael Laurson[2], Cumhur Erkut[1], and Tero Tolonen[1]

[1]Helsinki University of Technology, Lab. of Acoustics and Audio Signal Processing
P.O. Box 3000, FIN-02015 HUT, Espoo, Finland
Vesa.Valimaki@hut.fi, Cumhur.Erkut@hut.fi, Tero.Tolonen@hut.fi
http://www.acoustics.hut.fi/

[2]Sibelius Academy, Center for Music and Technology, Helsinki, Finland
Laurson@siba.fi, http://www.siba.fi/

ABSTRACT

A synthesis model for the clavichord is developed applying the principles of digital waveguide modeling. A commuted waveguide synthesis model is used, where each tone is generated with two coupled string models that are excited with a common excitation signal that is obtained from analysis of recorded clavichord tones. The characteristic knock terminating tones played by the clavichord is reproduced by triggering a sample that is separated from a recorded tone. A simple technique enables the realistic variation of the fundamental frequency by using a control function that can be a constant value plus the impulse response of a low-order digital filter. Sound examples will be available at http://www.acoustics.hut.fi/~vpv/publications/icmc00.htm.

1. INTRODUCTION

We describe a technique for sound synthesis of the clavichord using the physical modeling approach. The clavichord is one of the oldest keyboard instruments, which is still used in performances and recordings of renaissance and baroque music [1–5]. The sound of the instrument is pleasant but quiet. The maximum SPL at 1 meter is only about 50 dB or 60 dB—depending on the individual construction of the instrument. The reasons are that the strings are thin and their tension is low, the tangent hits the string at its end, which is a nodal point for all its modes, and the soundboard is small and thus does not much amplify the sound [2]. Consequently, the instrument can only be used in intimate performances for small audiences. This is the main reason why the clavichord was replaced by the harpsichord and finally by the modern piano. One of our motivations in this research is to give the clavichord a new life in the digital world, where the faint sound level of the instrument can be amplified by simply turning a volume knob.

The suggested synthesis model is based on digital waveguide modeling [6], [7]. In Section 2 of this paper, we discuss the acoustical properties of the clavichord. Section 3 describes the synthesis model, and Section 4 presents some synthesis examples. Section 5 concludes the paper.

2. ACOUSTICS OF THE CLAVICHORD

For each key of the clavichord, a pair of strings has been tuned in unison [1–5]. The keys are at one end of a lever while a *tangent* has been attached to its other end. When a key is depressed, the tangent hits the string pair and initiates vibration. One end of the strings has been damped with felt, and the other end goes over a bridge to the tuning machine. Thus, the strings are freely vibrating between the bridge and the tangent, which works as both a hammer and a termination. The tangent mechanism is pretty noisy as it excites modes of the soundboard but also itself causes sound from its moving parts.

The string pairs are always slightly detuned, and since they are coupled via a non-rigid bridge, both beats and a two-stage decay result. Figure 1 shows the envelope of a recorded clavichord tone. The irregular (non-exponential) decay of the tone can be observed.

When a key is released, the vibration again propagates to the felt, which efficiently attenuates the tone. The key mechanism also generates a loud knock, which is characteristic to the sound of the instrument. In Fig. 1, a burst located at 1.1 s corresponds to the knock; at the same time the tone starts to decay fast.

The envelope curves of the first 5 harmonics are presented in Fig. 2. It is seen that regular exponential decay (i.e., linear decay on a dB scale) is rare: there is some beating and other irregularities in many harmonics.

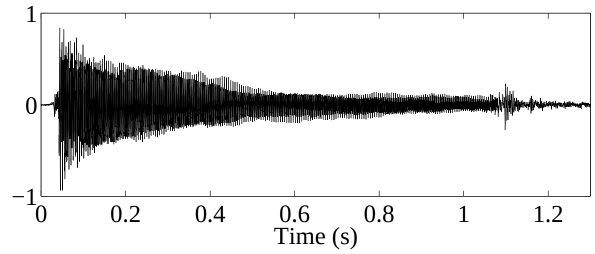

Fig. 1. Waveform of a clavichord tone (A3, 197.5 Hz) that shows the irregular overall decay pattern and the knock at the end of the tone.

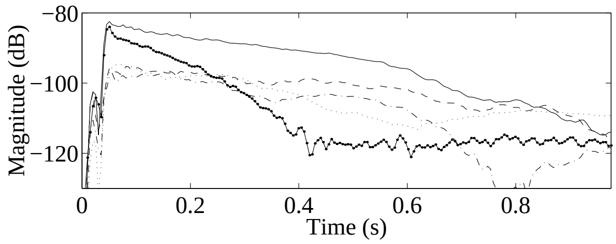

Fig. 2. Envelopes of the lowest partials of the tone shown in Fig. 1: 1st (•), 2nd (solid line), 3rd (dashed line), 4th (dash-dot line), and 5th (dotted line).

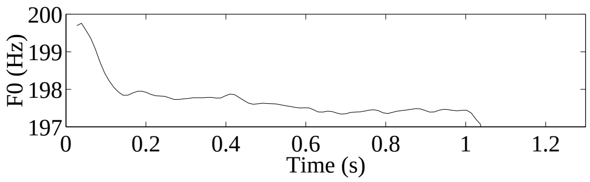

Fig. 3. Time history of the fundamental frequency of the clavichord tone in Fig. 1.

A particularly interesting feature in the clavichord is the *mechanic aftertouch*: when the player increases pressure to the key, the tangent is replaced more, which in turn increases the tension of the string pair resulting in a raise of pitch. This enables continuous control of *vibrato*. Aftertouch has been part of keyboard controllers since 1980's, and it is thus easy to include this control in the clavichord synthesizer. However, a fully polyphonic aftertouch, which would really be needed, is only available in most exclusive mother keyboards.

The fundamental frequency of clavichord tones in the two lowest octaves varies over time, as shown by an example given in Fig. 3[†]. This may be partly caused by tension modulation [8] but also by the pressure of the player's finger, which directly controls the string tension during playing. In order to find out the possible contribution of tension modulation, we conducted a simulation.

Figure 4 shows the ratio of the string elongation to the length of the string as a function of frequency in a 4-octave range (55–880 Hz). The elongation is estimated using a time-domain finite-difference simulation. The initial tangent velocity is assumed to have an ideal exponential decay, and the initial displacement of the string is calculated by integration. As stated in [1], this idealization gives a reasonable approximation to the real excitation mechanism. The elongation ratio is obtained by estimating the deflection of the string at its maximum and dividing this value by the nominal string length. Figure 4 shows that the elongation ratio has a rapid exponential decay as the frequency is increasing. Even for the lowest frequencies, the elongation (and the resulting tension modulation) is negligible compared to that caused by the mechanic aftertouch.

† The instrument used in our measurements was tuned almost a wholetone lower than the standard modern tuning where A4 is 440 Hz and thus A3 is 220 Hz.

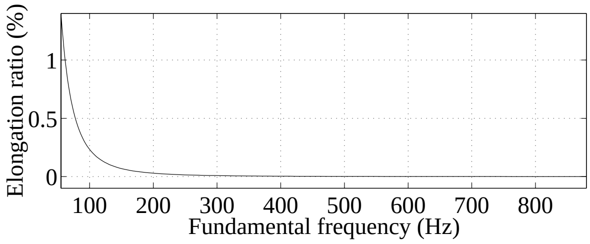

Fig. 4. Elongation ratio of a simulated clavichord string as a function of fundamental frequency.

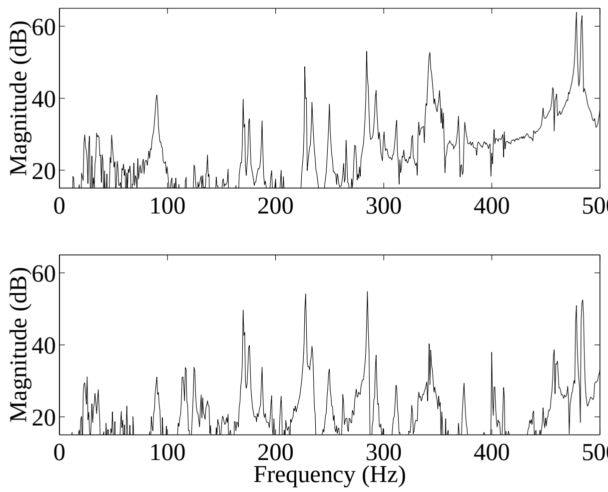

Fig. 5. Magnitude spectrum of the soundboard excited with an impulse hammer at the high (top) and at the low end of the bridge (bottom).

We have also conducted a series of acoustic measurements on the soundbox of the instrument to identify the most prominent modes. Figure 5 shows the magnitude spectrum of the soundboard that was hit with an impulse hammer when the strings were carefully damped with soft material. Many narrow peaks are seen, which correspond to long ringing resonance modes. It can also be seen that the excitation of modes depends on the location of excitation: for example, the 90-Hz mode is much stronger in the top part of the figure than in the lower

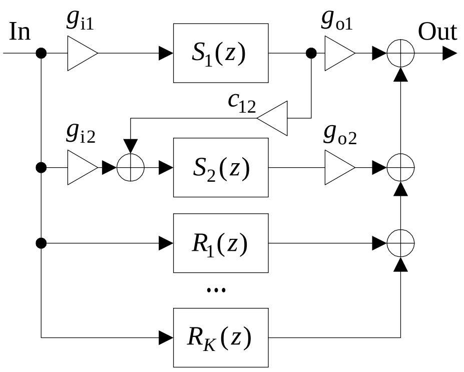

Fig. 6. Block diagram of the clavichord synthesis model showing the coupled dual-string model and K resonators.

part. A similar phenomenon occurs in the case of the mode at about 340 Hz.

3. SYNTHESIS MODEL FOR THE CLAVICHORD

This section describes the proposed synthesis model for clavichord tones. The strings of the clavichord are simulated using digital waveguide string models. In principle, two digital waveguide models should be used for each string since they have two polarizations of vibration (horizontal and vertical), but at present we only use one digital waveguide per string. This choice results in an efficient algorithm and still generates some beating in the synthetic tones, since two strings are sounding together for each tone. The commuted waveguide synthesis method [9], [10] is applied by using inverse filtered clavichord signals as excitation for the synthesis model.

The loop filter used in each of the digital waveguide models has the following transfer function [11], [12]

$$S(z) = \frac{1}{1 - F(z)H_l(z)z^{-L}} \qquad (1)$$

where $F(z) = h_0 + h_1z^{-1} + h_2z^{-2} + h_3z^{-3}$ is a fourth-order Lagrange interpolation filter [13], L is the (integer) length of the delay line, and $H_l(z)$ is a loop filter with the following transfer function [12]:

$$H_l(z) = g_l \frac{1 + a_l}{1 + a_l z^{-1}} \qquad (2)$$

with $0 < g_l < 1$ and $-1 < a_l < 0$. The values of these parameters can be estimated for each string using previously proposed methods [10], [12].

Figure 6 shows the structure of the synthesis model. The coupling of the two strings implemented with transfer functions $S_1(z)$ and $S_2(z)$ is realized with an unconditionally stable technique suggested in [14]: the output of only one of the string models is fed to the input of the other and hence there is no feedback. The coupling coefficient c_{12} is selected to have a small value. The input and output signals of the string models are scaled by constant multiplying coefficients g_i and g_o, respectively. The most prominent modes of the soundbox are simulated using digital resonators, which are parallel with the string models, as indicated in Fig. 6 [12]. About five resonance modes in the frequency range below 400 Hz can be selected as indicated by Fig. 5. Note that one resonator bank can be shared by all strings of the instrument, since only the input gain of each resonator needs to be varied for different notes.

The damping of the string vibrations as a result of releasing a key is simulated by injecting another excitation signal and changing the loop filter characteristics at the same time. A similar method has been used successfully to simulate damping of a guitar string [15].

The variation of the fundamental frequency is simulated in the following way: a decaying control function, e.g., a scaled impulse response of a leaky integrator, is subtracted from the delay-line length of both string models. This imitates the change of pressure on the key by the player's finger right after depressing the key, and brings about the progression of the fundamental frequency similar to that shown in Fig. 3. Note that this is a simpler way of producing a time-varying pitch than the tension-modulation technique [8] needed, e.g., for the synthesis of the kantele [16] or the tanbur [17].

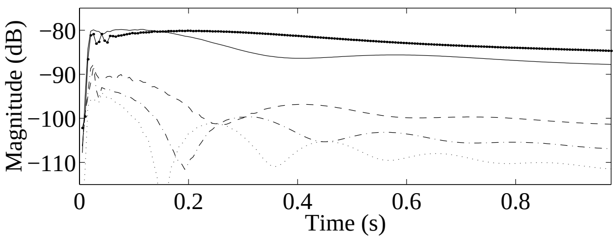

Fig. 7. Envelopes of partials of a synthesized tone: 1st (•), 2nd (solid line), 3rd (dashed line), 4th (dash-dot line), and 5th (dotted line).

4. SYNTHESIS EXAMPLE

Figure 7 presents the analysis of a synthetic clavichord tone. The loop filter coefficients for $S_1(z)$ were g_l = 0.9976 and a_l = –0.1490 and for $S_2(z)$ they were g_l = 0.9737 and a_l = –0.0878. The coupling coefficient between the string models was c_{12} = 0.25. The input and output gains (see Fig. 6) for $S_1(z)$ were g_{i1} = 0.2 and g_{o1} = 0.65, respectively, and for $S_2(z)$ they were $g_{i2} = 1 - g_{i1}$ and $g_{o2} = 1 - g_{o1}$. The fundamental frequency of string #1 was 1.000125 times that of string #2.

It is seen that the initial amplitudes of the partials, are which determined by the excitation signal of the model, match well with the original ones (see Fig. 2). The decay of partials of the synthetic signal is irregular, as desired, but not identical when compared with Fig. 2, because there are no degrees of freedom in the simple model of Fig. 6 to match decay rates and beating of all partials. The similarity is considered to be good enough for high-quality synthesis. However, copy synthesis is impossible with the current model.

5. CONCLUSIONS AND FUTURE PLANS

A simplified physical model was proposed for the synthesis of the clavichord. Two coupled digital waveguide string models are used for each tone. The excitation signal must be obtained from analysis of recorded clavichord tones. The ending of a tone also requires an input signal to the synthesis model, since there must be a knocking sound which is characteristic to the clavichord.

We are working on a real-time implementation of the proposed clavichord synthesizer with a C-based software. The system will be played either from a MIDI keyboard or from ENP [18]. Sound examples will be available at http://www.acoustics.hut.fi/~vpv/publications/icmc00.htm.

There is a need for some further measurements on the instrument to improve the synthesis model. Particularly, the acceleration of the tangent needs to be measured during the attack of the tone, because this information is needed for modeling tension modulation and the tangent action. A tangent model—which must be somewhat different from piano hammer models, as explained in [19]—should be developed to be able to control the excitation using physical parameters.

ACKNOWLEDGMENTS

V. Välimäki is supported by a postdoctoral research grant of the Academy of Finland. The work of M. Laurson is part of the project “Sounding Score—Modeling of Musical Instruments, Virtual Musical Instruments and their Control”, and the work of C. Erkut is part of the project “Sound Source Models—Analysis, Synthesis, and Coding”. Both projects are funded by the Academy of Finland. T. Tolonen is supported by the GETA Graduate School, Nokia Research Center, Tekniikan edistämissäätiö, and the Jenny and Antti Wihuri Foundation.

REFERENCES

[1] S. Thwaites and N. H. Fletcher, “Some notes on the clavichord,” *J. Acoust. Soc. Am.*, vol. 69, no. 5, pp. 1476–1483, May 1981.

[2] M. Campbell and C. Greated, *The Musician’s Guide to Acoustics*, Schirmer Books, 1987, pp. 234–236.

[3] N. H. Fletcher and T. D. Rossing, *The Physics of Musical Instruments*. Springer Verlag, 1991, pp. 300–303.

[4] T. D. Rossing, *The Science of Sound. Second Edition.* Addison–Wesley, 1990, pp. 297–298.

[5] A. Benade, *Fundamentals of Musical Acoustics*. Oxford, 1976, pp. 353–354.

[6] J. O. Smith, “Physical modeling using digital waveguides,” *Computer Music J.*, vol. 16, no. 4, pp. 74–91, 1992.

[7] J. O. Smith, “Principles of digital waveguide models of musical instruments,” in M. Kahrs and K. Brandenburg, Eds., *Applications of Digital Signal Processing to Audio and Acoustics*. Kluwer, 1998, chapter 10, pp. 417–466.

[8] T. Tolonen, V. Välimäki, and M. Karjalainen, “Modeling of tension modulation nonlinearity in plucked strings,” *IEEE Trans. Speech and Audio Process.*, vol. 8, no. 3, pp. 300–310, May 2000.

[9] J. O. Smith, “Efficient synthesis of stringed musical instruments,” in *Proc. Int. Computer Music Conf.*, pp. 64–71, Tokyo, Japan, Sept. 1993.

[10] M. Karjalainen and V. Välimäki, “Model-based analysis/synthesis of the acoustic guitar,” in *Proc. Stockholm Music Acoustics Conf.*, pp. 443–447, Stockholm, Sweden, July–Aug. 1993.

[11] D. A. Jaffe and J. O. Smith, “Extensions of the Karplus–Strong plucked-string algorithm.” *Computer Music J.*, vol. 7, no. 2, pp. 76–87, 1983.

[12] V. Välimäki, J. Huopaniemi, M. Karjalainen, and Z. Jánosy, “Physical modeling of plucked string instruments with application to real-time sound synthesis,” *J. Audio Eng. Soc.*, vol. 44, no. 5, pp. 331–353, May 1996.

[13] T. I. Laakso, V. Välimäki, M. Karjalainen, and U. K. Laine, “Splitting the unit delay—tools for fractional delay filter design,” *IEEE Signal Processing Mag.*, vol. 13, no. 1, pp. 30–60, Jan. 1996.

[14] M. Karjalainen, V. Välimäki, and T. Tolonen, “Plucked-string models: from the Karplus–Strong algorithm to digital waveguides and beyond,” *Computer Music J.*, vol. 22, no. 3, pp. 17–32, 1998. Reprint is available online at http://www.acoustics.hut.fi/~vpv/publications/cmj98.htm.

[15] C. Erkut, V. Välimäki, M. Karjalainen, and M. Laurson, “Extraction of physical and expressive parameters for model-based sound synthesis of the classical guitar,” *AES 108th Conv.*, preprint no. 5114, Paris, France, Feb. 2000. Sound examples available at http://www.acoustics.hut.fi/~cerkut/calib/.

[16] V. Välimäki, M. Karjalainen, T. Tolonen, and C. Erkut, “Nonlinear modeling and synthesis of the kantele—a traditional Finnish string instrument,” in *Proc. Int. Computer Music Conf.*, pp. 220–223, Beijing, China, Oct. 22–28, 1999. Full paper and sound examples are available at http://www.acoustics.hut.fi/~vpv/publications/icmc99.htm.

[17] C. Erkut and V. Välimäki, “Model-based sound synthesis of tanbur, a Turkish long-necked lute,” in *Proc. IEEE Int. Conf. Acoust. Speech, and Signal Process.*, vol. 2, pp. 769–772, Istanbul, Turkey, June 2000.

[18] 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 *Proc. Int. Computer Music Conf.*, pp. 1–4, Beijing, China, Oct. 22–28, 1999.

[19] D. E. Hall, “String excitation: piano, harpsichord and clavichord,” in *Proc. Stockholm Music Acoustics Conf.*, pp. 309–314, Stockholm, Sweden, Jul.–Aug. 1993.