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Commuted Waveguide Synthesis of the Clavichord

The clavichord is one of the oldest keyboard instruments, and it is still often used in performances and recordings of Renaissance and Baroque music. The sound of the instrument is pleasant and expressive but quiet. 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, both of which produce a considerably louder output. Attempts have been made to amplify the sound of the clavichord using a piezoelectric pickup (Burhans 1973).

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 of string instruments (Smith 1992, 1998; Välimäki et al. 1996; Karjalainen, Välimäki, and Tolonen 1998) and uses the principle of commuted waveguide synthesis where the soundbox's response is incorporated in the excitation signal (Smith 1993; Karjalainen and Välimäki 1993; Karjalainen, Välimäki, and Jánosy 1993). Special sampling techniques are also employed. Musical examples produced using the proposed synthesizer will be included on a forthcoming *Computer Music Journal* CD.

Acoustics of the Clavichord

A photograph of the clavichord used for the measurements in this study is shown in Figure 1. The instrument is an Anthony Sidey clavichord manufactured by Heugel in Paris, France, in 1988. This clavichord is an unfretted one, so any combination of notes can be played. The range of a clavichord is anywhere from three octaves to over five octaves. Our clavichord has 51 keys ranging from C2 to D6. The instrument was tuned about a whole tone lower than the standard modern tuning (A4 = 440 Hz): the nominal frequency of A4 is 395 Hz. The Werkmeister tuning system was used.

For each key of the clavichord, a pair of strings is tuned in unison, as sketched in Figure 2 (see, for example, Thwaites and Fletcher 1981; Campbell and Greated 1987). However, the two strings are always slightly detuned around the same note, because exact tuning is impossible manually. Every key forms one end of a lever that has a tangent 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 mechanism. 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 rather noisy, as it excites modes of the soundboard but also itself causes sound from its moving parts owing to friction.

When the key is released, the tangent falls back with the aid of gravity, and the string vibration is allowed to propagate to the felt-covered end of the string, which efficiently damps the vibration. At the end of each note, another knock is heard as the tangent returns to its resting position. The somewhat mistuned strings of each pair are coupled via a non-rigid bridge, and thus both beats and a two-stage decay result (Weinreich 1977).

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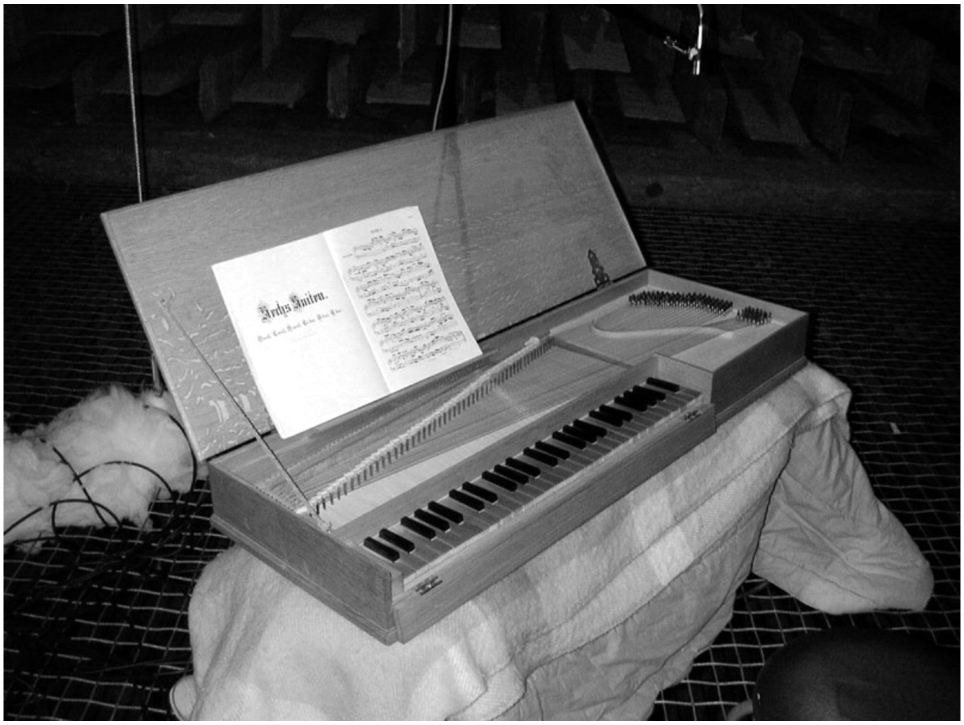
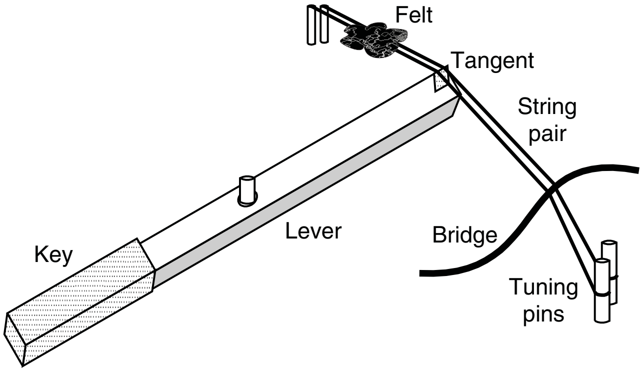
Figure 1. Clavichord used in this study.



The first thing that people usually notice about the clavichord is that the sound level is very low. The maximum sound pressure level at 1 meter is only about 50 dB or 60 dB, depending on the individual construction of the instrument. This makes this ancient instrument a sound source less efficient than a human speaker. There are many reasons for the weak output (see Campbell and Greated 1987; Fletcher and Rossing 1991). The strings are thin and their tension is low, and they radiate sound inefficiently. The soundboard is small and light, and it cannot amplify the sound much.

A particularly interesting feature in the clavichord is the mechanical aftertouch known as *Bebung*. When the player increases pressure on a key, the tangent is raised more, which in turn increases the tension of the string pair, resulting in a raise of pitch. This enables continuous control of vibrato, which is a used performance style. Aftertouch has been part of keyboard controllers since the 1980s, 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 high-end keyboard controllers.

Figure 2. Tangent mechanism of one key of the clavichord and a string pair associated with it.



As the key pressure is changed, the tangent causes a slightly different change in the tension of the two strings of a pair. This feature affects the timbre of clavichord tones by introducing a flanging effect. It is heard during and after the attack, particularly in the bass register.

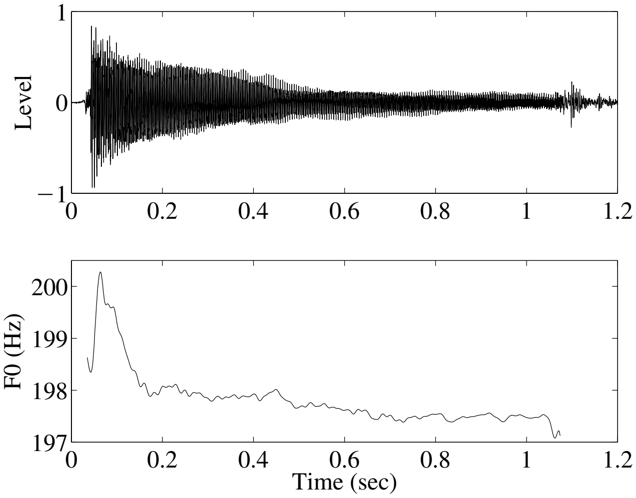


Figure 3. (Top) Waveform of a clavichord tone (A3) showing the irregular overall decay pattern and the thump at the end of the tone at 1.1 sec, and (bottom) the time history of its fundamental frequency (nominal fundamental frequency is 197.5 Hz).

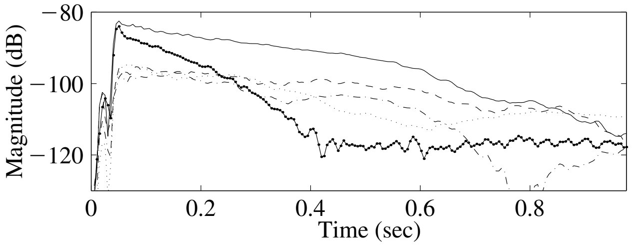


Figure 4. Envelopes of the lowest partials of the tone shown in Figure 1: 1st (solid line with circles), 2nd (solid line), 3rd (dashed line), 4th (dash-dot line), and 5th (dotted line).

Properties of Single Clavichord Tones

Figure 3 shows the envelope of a recorded clavichord tone. The irregular, non-exponential decay of the tone can be observed. The key mechanism of the clavichord generates a loud knock at the beginning and end of a tone, which is characteristic to the sound of the instrument. In Figure 3, a burst located at 1.1 sec corresponds to the thump caused by release of the key, at the same time the signal starts to decay quickly. The envelope curves of the first five harmonics are presented in Figure 4. Note that regular exponential decay (i.e., linear decay on a dB scale) is rare: pronounced beating and other irregularities are observed in many harmonics (e.g., the beating of the fourth partial).

The fundamental frequency of clavichord tones varies over time, as illustrated by an example in the lower part of Figure 3. This may be partly caused by tension modulation (Tolonen, Välimäki, and Karjalainen 2000), which is a purely physical phenomenon in vibrating strings, but also by the pressure of the player's finger (i.e., the mechanical aftertouch), which directly controls string tension during playing. A time-domain finite-difference simulation suggests that the tension modulation effect is negligible compared to that caused by the mechanical aftertouch (Välimäki et al. 2000). In Figure 3, the pitch glide is about 2 Hz, which is lower than the threshold of audibility for this effect. According to Järveläinen and Välimäki (2001), the threshold at 196 Hz (the nearest frequency tested) is 4.4 Hz. In the case of the clavichord used in our measurements, during normal playing the pitch glide can be inaudible for most listeners. Audible pitch glides can be generated easily, however. Figure 5 gives an example of a tone that contains an exaggerated pitch vibrato, which should be obvious for all listeners. Note that the vibrato width is typically about 2 Hz or less, but can occasionally peak higher. The vibrato rate is about 7 Hz in this case, which is slightly faster than what would be usual in a musical context. The above fundamental frequency measurements reflect the effective pitch, where the contributions of both strings are present.

Impulsively driven string instrument sounds are always at least weakly inharmonic (Fletcher and Rossing 1991). This is caused by the stiffness of the string material. It is well known that piano tones, particularly in the bass range, are highly inharmonic, which affects both the timbre and the tuning. Measurements of inharmonicity have not been published previously for the clavichord, so we conducted them ourselves. This was needed to decide whether we had to implement the inharmonicity using an allpass filter, as is customary to do in waveguide synthesis (Jaffe and Smith 1983; Bank 2000). We used our parameter estimation software to extract partial frequencies of clavichord tones as a function of time. Using a least-squares fit, we estimated from the data the inharmonicity coefficient. We found that the clavichord used in our measurements produces almost perfectly harmonic tones. (The inharmonicity coefficient does not exceed 10^{-6}.) Thus, the effect of inharmonicity can be considered inaudible (Järveläinen, Välimäki, and

Figure 5. (Top) Waveform of clavichord tone A3 with strong vibrato (mechanical aftertouch) and (bottom) its fundamental frequency as a function of time.

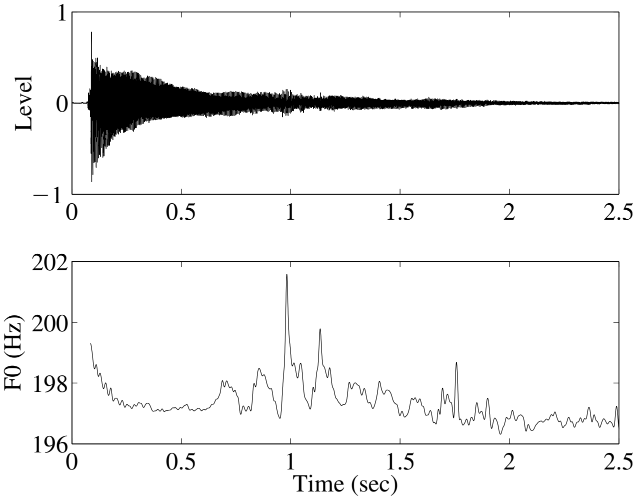
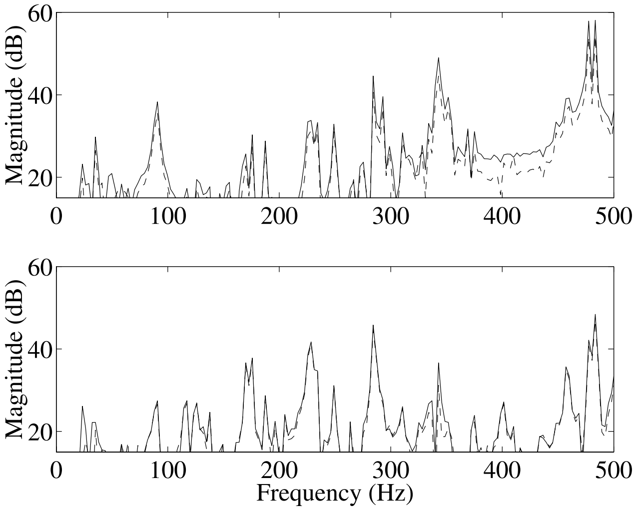


Figure 6. Magnitude spectrum of the soundboard excited with an impulse hammer at the high-frequency (top) and at the low-frequency end of the bridge (bottom). Results of two measurements (solid and dashed line) are plotted one on the other for both cases.



Karjalainen 2001), and perfectly harmonic synthesis is adequate.

Soundbox

An essential part of clavichord tones is the response of the soundbox. The box is strongly excited every time a key is pressed. This reverberant response will ring for about five seconds, and it stands out particularly in staccato notes, where the string vibration itself is damped quickly after the attack.

We have conducted a series of acoustic measurements on the soundbox of the instrument to identify the most prominent modes. Figure 6 shows the magnitude spectrum of the soundboard that was hit with an impulse hammer when the strings were carefully damped with soft material. Results of two separate measurements are plotted on top of each other. The differences between these curves are quite small, verifying the repeatability of the measurement. Many narrow peaks are visible in Figure 6. They 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 part. A similar phenomenon occurs in the case of the mode at about 340 Hz.

Synthesis Model for the Clavichord

Next, we describe the synthesis model for clavichord tones. The commuted waveguide synthesis method invented by Smith (1993) and Karjalainen and colleagues (Karjalainen and Välimäki 1993; Karjalainen, Välimäki, and Jánosy 1993) is applied by using inverse-filtered clavichord signals as excitation for the synthesis model. Inverse filtering here refers to the processing of a signal with the inverted transfer function of a waveguide string model. In this case, the inverse filtering essentially cancels the partials of a recorded tone. The commuted waveguide synthesis method has been formerly used successfully for the synthesis of the acoustic guitar (Karjalainen, Välimäki, and Jánosy 1993; Välimäki et al. 1996; Laurson et al. 2001) and the piano (Smith and Van Duyne 1995).

Figure 7 shows the structure of the synthesis model developed in this work. The coupling of the two basic strings models $S_1(z)$ and $S_2(z)$ is realized with an unconditionally stable technique suggested by Karjalainen et al. (1998): the output of only one of the string models is fed to the input of the other, and hence there is no feedback. In practice, the coupling coefficient g_c is selected to have a small value, but this is not required, because there can be no stability problems. The input and output signals of the string models are scaled by constant multi-

Figure 7. Clavichord synthesis algorithm for one key consists of three databases of samples and two basic string models that are coupled.

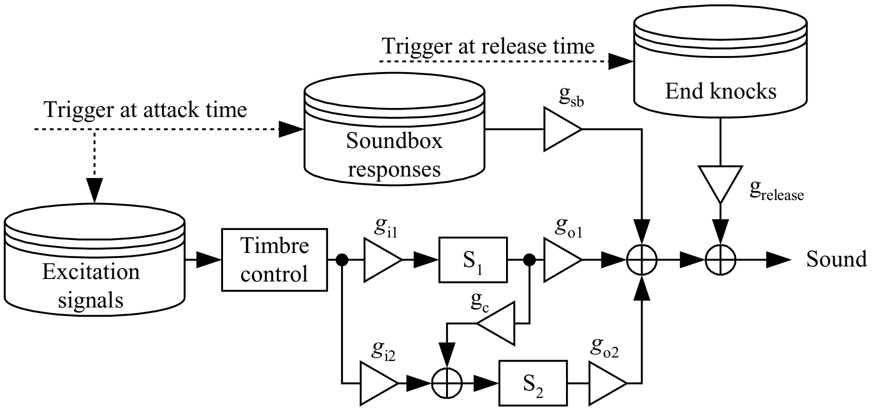
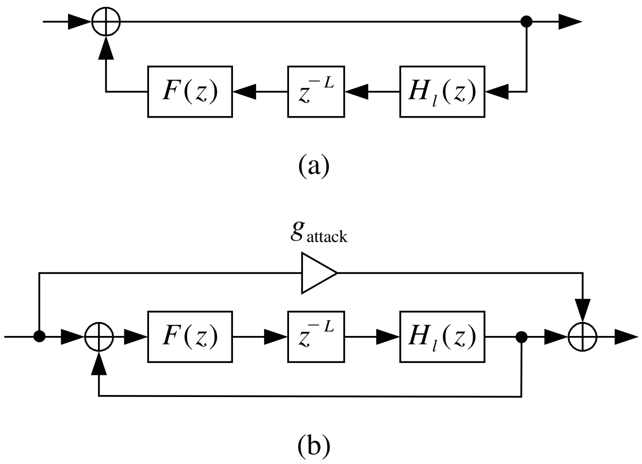


Figure 8. Block diagram of (a) the standard and (b) modified string algorithm. The latter allows controlling the sharpness of attack using parameter g_{attack}.



(a)

(b)

plying coefficients g_i and g_o, respectively. In addition, two sample databases are needed for realistic simulation of the soundbox response and the percussive noise caused by key release. In the following, we discuss the string algorithm, model parameters and their control, and the sample databases.

Modified String Algorithm

The strings of the clavichord can be 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 (i.e., horizontal and vertical with respect to the soundboard), but at present we only use one digital waveguide per string. For a pair of clavichord strings, we thus have two digital waveguide string models, not four. This choice results in an efficient algorithm and still generates some beating in the synthetic tones.

Usually, a digital waveguide string model has the following transfer function (Jaffe and Smith 1983; Välimäki et al. 1996), as also illustrated in Figure 8(a),

$$S(z) = \frac{1}{1 - F(z)H_1(z)z^{-L}} \tag{1}$$

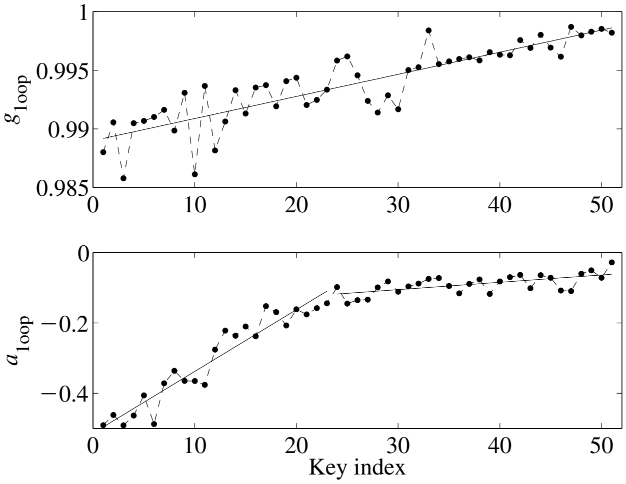
where $F(z) = h_0 + h_1z^{-1} + h_2z^{-2} + h_3z^{-3}$ is a third-order Lagrange interpolation filter (Laakso et al. 1996), L is the (integer) length of the delay line, and $H_1(z)$ is a loop filter with the following transfer function (Välimäki et al. 1996):

$$H_1(z) = g_{\mathrm{loop}} \frac{1 + a_{\mathrm{loop}}}{1 + a_{\mathrm{loop}}z^{-1}} \tag{2}$$

with $0 < g_{\mathrm{loop}} < 1$ and $-1 < a_{\mathrm{loop}} < 0$. The values of these parameters can be estimated for each string using previously developed methods (Välimäki et al. 1996; Erkut et al. 2000).

While testing an early version of the clavichord synthesizer, we noticed that the contribution of the tangent knock was not sufficiently prominent. In particular, the attack of high notes sounded too soft. To fix this deficiency, we modified the above string algorithm to allow the attack sharpness to be controlled with one parameter. The block diagram

Figure 9. Estimated values of string model parameters g_{loop} (top) and a_{loop} (bottom) (dots connected with dashed line) together with their straight-line approximations (solid lines).



of the new algorithm is shown in Figure 8b. Its transfer function can be written as

$$S(z) = g_{\mathrm{attack}} + \frac{F(z)\,H_l(z)\,z^{-L}}{1-F(z)\,H_l(z)\,z^{-L}} = \frac{g_{\mathrm{attack}}+(1-g_{\mathrm{attack}})\,F(z)\,H_l(z)\,z^{-L}}{1-F(z)\,H_l(z)\,z^{-L}} \quad (3)$$

Note that with $g_{\mathrm{attack}} = 1$, this algorithm is identical to the standard plucked-string algorithm of Equation 1. A value larger than unity, such as $g_{\mathrm{attack}} = 4$, may be used to imitate the aggressive attack of acoustic tones. In the current version, the value of the attack sharpness parameter increases linearly with key number, so that for C2 it is 2.0 and for D6 it is 4.0. The linear trend and the actual values were adjusted by informal listening. There is no physical motivation for this new model structure, other than that it enables separate control of two different components of the tone: the tangent knock and the vibrating string sound.

String Model Parameters

Parameter values for the synthesizer are obtained from analysis of recorded signals. We use a method based on the short-time Fourier transform and sinusoidal modeling of the clavichord tones. These methods have proven successful earlier in the case of the acoustic guitar. Details can be found elsewhere (Välimäki et al. 1996; Erkut et al. 2000).

Figure 9 shows the g_{loop} and a_{loop} parameters for all 51 keys of the clavichord. These values were estimated from recorded clavichord tones. The second string model uses the same parameters but slightly different delay lines lengths for mistuning. The fundamental frequencies of the lowest (#1) and highest (#51) key are 58.7 Hz and 1056 Hz, respectively. Note that the loop gain parameters g_{loop} have a nearly linear trend as a function of key index (i.e., logarithm of frequency) with some variations and a few outliers. Järveläinen and Tolonen (2001) have investigated the tolerance of parameters value variation. Their results show that –30% to +40% changes in the time constant (which depends on g_{loop}) are inaudible. Also, in the a_{loop} parameter, variations between –17% and +16% cannot be perceived. It appears that the g_{loop} parameters presented in Figure 9 can be replaced with values obtained by linear regression:

$$g_{\mathrm{loop}} \approx 0.989 + 0.000189k \quad (4)$$

where $k = 1\ldots51$ is the key number starting from C2 ($k = 1$), and continuing up to D6 ($k = 51$). This straight-line fit is illustrated in Figure 9 (top) with a solid line.

The values of parameter a_{loop} may be approximated by a low-order polynomial as well. However, a linear regression to the data shown in the lower part of Figure 9 yields intolerably large errors. To reduce the error, we attempt a piecewise linear regression with a knee point between key indices 23 and 24:

$$a_{\mathrm{loop}} \approx \begin{cases} -0.514 + 0.0176k, & \text{for } k \leq 23 \\ -0.175 + 0.00225k, & \text{for } k \geq 24 \end{cases} \quad (5)$$

This two-part straight-line fit is shown in Figure 9 (bottom) with solid lines, one for the low end of the keyboard and another for the high end. This approximation for the a_{loop} values introduces minor changes in timbre that can be perceived, but it does not necessarily render the sound quality worse. In fact, the overall tone color behaves more uniformly with the linear approximations than with the unprocessed parameter data.

The damping of the string vibrations as a result of releasing a key is simulated by changing the loop filter characteristics (e.g., by setting loop gain g_{loop} equal to 0.1 momentarily). A similar method has been used successfully to simulate damping of a guitar string by finger (Erkut et al. 2000; Laurson et al. 2001).

Sample Databases

Excitation signals for the synthesis have been obtained by processing anechoic recordings of clavichord tones using the methods described by Erkut et al. (2000). The procedure consists of sinusoidal analysis, subtracting partials, equalizing the residual, and truncating the resulting signals with the right half of a Hanning window. One such excitation signal is used for each of the 51 keys. Currently, all excitation signals are 20,000 samples long (about 0.45 sec at a 44.1 kHz sampling rate). It would be possible to reduce their length further, but we have found it unnecessary in our current implementation, since there is no lack of memory.

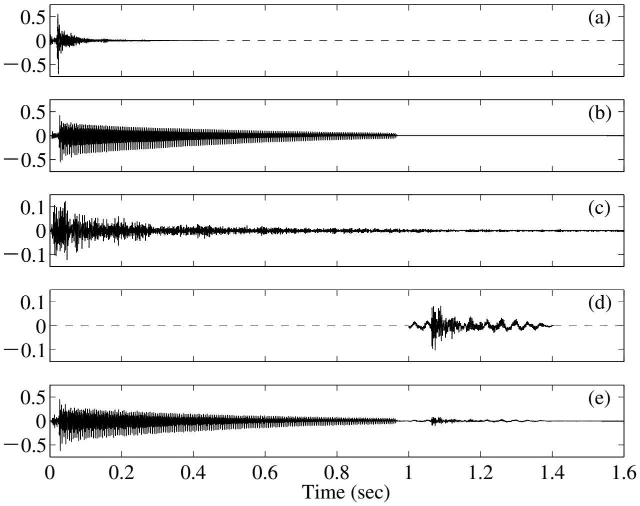
The reverberation caused by the soundbox is incorporated by triggering a soundbox response sample at a low level each time any note is played (see Figure 7). This sample must be long enough (about five seconds) so that it provides the reverberant character of the instrument. This is particularly important for short notes, such as staccato playing, for which the output signal would otherwise stop suddenly in an unnatural manner. Note that in principle we could instead use very long excitation signals for each note, in which case the full soundbox response would automatically sound with each note. However, we prefer using short excitation signals, because we can avoid certain problems related to the inverse filtering (e.g., ringing and beating due to imperfectly cancelled partials). This also saves memory, because we use fewer soundbox samples than excitation signals. Using a separate soundbox sample also allows adjusting the relative levels of soundbox reverberation and string sound, which is an advantage.

The soundbox samples can be obtained by hitting the bridge of the clavichord with an impulse hammer at various points. The response must be edited to remove the sharp attack caused by contact of metals, that is, the tip of the hammer and a tuning pin. This is easily done with a fast fade-in. Note that this editing is not extremely critical, because the impact noise from the tangent mechanism, which is included in the excitation signal, dominates during the attack and masks the beginning of the soundbox response. For each key, a soundbox sample should be chosen, which is obtained close to the point where the strings are attached. However, it is practically impossible to excite the bridge of the clavichord between the tuning pins, and the only clean samples that we could obtain are from both ends of the bridge (see Figure 6). This leaves us with possibilities to use one of the samples for the left half of the keyboard and the other for the right one, or to interpolate between the high- and low-end samples along the keyboard. Although the sampling-based reverberation modeling is clearly simplified, it yields a natural-sounding ambience in the synthetic output and is very cheap to implement because it requires no filtering.

The knock database for note endings consists of a few short samples (duration less than 0.5 sec). These samples may be obtained from recorded long tones, where the sound of string vibration is allowed to decay below the threshold of audibility before the key is released. Now the isolated thump can be simply edited from the recording. One practical problem was caused by the poor signal-to-noise ratio of the release samples. It was possible to hear when a key release occurred from the increased hiss during synthesis. This led us to apply a de-noising algorithm to suppress the background noise from the key release recordings, which solved the problem.

It is unnecessary to record a release sample for each key. Because the tangent mechanism for every key is identical and the resulting sound is similar, it is plausible to use a single sample for all synthetic notes. To avoid a boring similarity, as a compromise a small collection of release samples may be used. We have observed that the largest variation among different tangent releases is caused by the velocity of release, which slightly changes the rhythm of different noises within the knock. Thus, one choice is to gather a collection of tangent releases for different release velocities, and select one

Figure 10. Signals involved in the synthesis of a single clavichord tone: (a) excitation signal, (b) string algorithm output, (c) soundbox sample, (d) end noise sample (triggered at about 1 sec), and (e) synthetic tone, which is sum of signals (b) to (d).



randomly or based on some rule, such as the playing tempo. We are currently using two release samples, and we slightly randomize the release times of different keys. More sophisticated but still fairly simple synthesis models employing physically informed randomization have been proposed by Cook (1997).

Delay Line Variations and the Flanging Effect

Although the variation of the fundamental frequency in clavichord sounds can be inaudible as discussed earlier, it is also easy to cause pitch changes with mechanical aftertouch. Because any change in the string tension will be different for the two strings of a pair, a flanging-like effect can appear also in tones where the pitch change is negligible. Variation of the fundamental frequency can be simulated in the following way: a decaying control function, for example, a scaled impulse response of a leaky integrator (a one-pole filter), 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 (or the decrease of tension modulation depth while the string vibration begins to decay), and brings about the progression of the fundamental frequency similar to that shown in Figure 3. Note that this is a simpler way of producing a time-varying pitch than the tension-modulation technique Tolonen et al. (2000) used previously for the synthesis of the kantele (Välimäki et al. 1999; Erkut et al. 2002) and the tanbur (Erkut and Välimäki 2000). The tension-modulation algorithm would require computing the elongation of the string in real time and controlling the delay-line length of the string model according to it.

For the mechanical aftertouch, a more sophisticated control signal is required. The pitch contour of a note is generated with a help of a pitch scaler in the same fashion as in Laurson et al. (2001). If there is neither an initial pitch glide nor vibrato, the scaler value is 1. The initial pitch glide is implemented as a ramp starting from a value larger than 1 and ending at 1 after around 0.1 sec. (The initial value depends on the dynamic level of the current note so that *forte* playing yields a higher value than *piano* playing.) The vibrato control, in turn, is realized with separate parameters for rate and maximum depth, and a temporal envelope for depth (for more details, see Laurson et al. 2001).

A specific feature of the clavichord synthesizer is that the pitch scaler affects a detuning parameter of the two string models dynamically. Thus, a more drastic pitch drift results in a tone that is more out of tune. This mimics the imperfect mechanism of the tangent that pulls the two strings unequally. A database of detuning parameters was generated by trial and error. An alternative way would be to measure detuning parameters from the original recordings, which turns out to be difficult. High-pitched tones tend to be more detuned than low ones. The sound resulting from the time-varying detuning is suggestive of the flanging effect, which brings warmth and variation to the synthesis.

Synthesis Example

Figure 10 presents the components for the synthesis of a single clavichord tone. The excitation signal shown in Figure 10a is inserted into the two string algorithms. The name "commuted synthesis" comes from the principle that this excitation signal includes both the contribution of the excitation mechanism (the tangent) and the soundbox response. However, as can be seen, in our implementation the input signal contains only the very beginning of the soundbox response. The tail of the soundbox response is produced separately using the sampling-based method.

The summed output signals of the string models constitute the basic vibrating string component of the synthetic tone, which is displayed in Figure 10b. The key release occurs at 0.97 sec; note how the string tone in Figure 10b decays quickly after that. Figure 10c shows the beginning of a five-second-long soundbox sample, which has been edited from the impulse response of the low-frequency end of the bridge. A tangent release sample, which is started at the release time, is given in Figure 10d. Finally, Figure 10e presents the sum of the signals shown in Figures 10b, 10c, and 10d, and it is the output of the clavichord synthesizer.

Although remaining almost invisible in Figure 10e, the soundbox sample rings several seconds after the string tone and the key release sample have died out. The soundbox sample will also be clearly audible only after the string tone has been ringing and decaying for some time, and particularly after the key has been released. We may note that identity resynthesis is impossible using the proposed synthesis model and parameter estimation methods. Nevertheless, the obtained similarity is considered to be sufficient for high-quality synthesis. This is confirmed by musical examples produced with the synthesizer.

Musically Interesting Modifications

The proposed synthesizer structure allows the user to modify the timbre in numerous ways. Many of the possible variations have a clear intuitive interpretation. For example, varying the gain g_{loop} of the loop filter affects the decay time, but otherwise the timbre remains unchanged. However, varying the loop filter coefficient a_{loop} changes the decay time at different frequencies, resulting in a curious evolution of the spectrum over time. The attack sharpness parameter and the gain of the note-off noise also enable meaningful and useful controls. Exaggerated detuning of the two string models for each voice leads to a low-quality—or possibly a very old—clavichord. As a consequence of the above parametric modifications, the synthetic tones will still be reminiscent of the clavichord.

Extending the range of an instrument is fascinating and useful in the case of the acoustic guitar. Design of a synthetic ‘‘super guitar’’ that has a wide range, almost like that of a grand piano, has been documented recently (Laurson, Välimäki, and Erkut 2002). While an arbitrary change of pitch is easy in a waveguide synthesizer (simply vary the length of a delay line), the loop filter parameters and excitation signals should be extracted from recordings, but for non-existing fundamental frequencies, they are unavailable. The extension of the pitch range thus involves extrapolation problems that must be solved somehow. We are planning tests on extending the range of the proposed clavichord synthesizer.

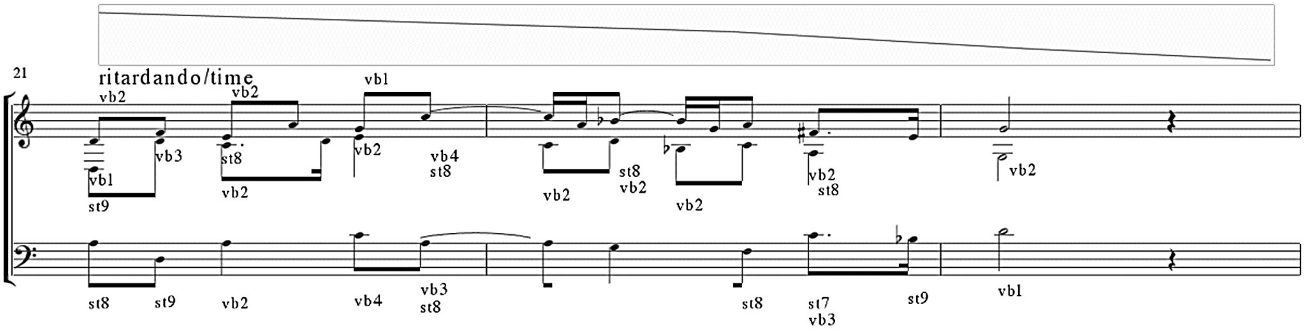
Naturally, it is also possible to turn the clavichord synthesizer into a previously unheard virtual instrument. For instance, modifying or replacing the signals in the sample databases allows dramatic variations. Exploring all such transformations was not included in the goals of this study, and the potential of these modifications thus remains mostly unknown.

Software Implementation of the Synthesizer

The real-time implementation of the proposed clavichord synthesizer has been realized using a PatchWork (Laurson 1996) user-library called PWSynth (Laurson and Kuuskankare 2001). The high-level part of PWSynth is based on Lisp and CLOS, but the low-level and time-critical DSP-routines have been implemented in C. The system can be played either from musical notation and control software called Expressive Notation Package (ENP, described in Kuuskankare and Laurson 2001; Laurson et al. 2001), or from a MIDI keyboard.

The starting point for the clavichord implementation was to use a guitar synthesizer implemented earlier (Laurson et al. 2001). These systems have

Figure 11. ENP screenshot from the final cadence of Par le regard de vos beaux yeux *by Guillaume Dufay.*



several features in common. Both use basically the same dual-polarization string model, although in the case of the clavichord, it models a pair of strings and not the orthogonal polarizations of a single string. The database of samples—needed for the excitation signals and the noise effects in the clavichord simulation—could be used in both cases in a similar way.

The main difference between the implementations is the fact that the clavichord consists of 51 strings, while the classical guitar has only six. To create a synthesizer that could be used in real time, we designed a voice-allocation algorithm that allows us to effectively play typical pieces of the clavichord repertoire. We found that a synthesizer for six simultaneous strings could be played in real time on a Macintosh G3 400 MHz portable computer. This is sufficient for a large percentage of old keyboard music. New, faster computers will allow playing more voices simultaneously.

The control information for the clavichord synthesizer is calculated from an ENP input score. The user enters first the basic musical information (i.e., pitches and rhythms) of the piece using the graphical front-end of ENP. After this, the user typically adds expressions and tempo functions that allow fine tuning of the timing information in the score. Also, one can include expressions specific to the clavichord, such as the amount of vibrato to be applied to a given note. Furthermore, a special rule modifies the end time of notes (i.e., the time when the player lifts the fingers from the keyboard). This was done to make the performance more lively. The characteristic noise burst of the instrument when the fingers are released was found to be essential for the realism of the synthesis.

Figure 11 shows the three last measures of a piece by Guillaume Dufay (1400–1474). Besides pitch and rhythm information, the piece includes several expression markings that control both vibrato (see the labels starting with "vb") and articulation (see labels starting with "st," which stands for staccato). The numbers after the expression markings denote how much vibrato or staccato should be applied to a given note. This example has also a special expression containing a tempo function (see the function above the staff marked with "ritardando" in Figure 11), which controls the tempo of the piece.

Our current MIDI keyboard implementation is fairly rudimentary and serves only as a basic tool for testing. The control parameters of the MIDI keyboard include key number, key velocity, attack time, and end time of notes. Furthermore, we use the MIDI aftertouch parameter to simulate the finger vibrato effect of the clavichord. A more usable MIDI implementation would require a keyboard with polyphonic aftertouch. Also, we found that the MIDI keyboard at our disposal was not responsive enough when simulating the finger vibrato. A playable keyboard simulation of the clavichord model requires more sensitive hardware than what is commonly available today.

Conclusions and Future Plans

A simplified physical model was proposed for the synthesis of the clavichord. It follows the principle of commuted waveguide synthesis, but also uses many samples obtained by editing and processing recordings. The excitation signal can be obtained by inverse filtering and truncating a recorded clavichord tone. Two coupled digital waveguide string models are used for synthesizing each voice. A minor modification to the plucked string model was introduced to enable control over attack sharpness, which was found necessary during testing of the synthesis algorithm. The reverberation caused by the soundbox that has many resonant modes was implemented in a computationally economic way by triggering a soundbox response sample with each note. The ending of a note requires another sample to be played, because there must be a ''knocking'' sound, which is characteristic to the clavichord. The mechanical aftertouch of the clavichord can be implemented by varying the delay line lengths of the waveguide string models over time. When these changes are different for the two string algorithms modeling a pair of strings, a flanging effect is generated, which is also heard in the real clavichord.

In the future, we plan to develop another version of the clavichord synthesizer using the direct physical modeling approach, where the excitation, strings, and the soundbox have a counterpart in the model. To accomplish this, the sampling-based implementation of the reverberant response of the soundboard must be replaced with a soundbox model that filters the output of the string models. The soundbox can be considered a small reverberant room and be simulated with an artificial reverberation algorithm (e.g., Gardner 1998; Bank 2000).

In addition, further measurements of the real instrument should be taken. Particularly, the acceleration of the tangent needs to be registered during the attack of the tone, because this information is needed for an algorithm simulating the tangent action, similar to piano hammer simulations (Bank 2000). This might also reveal the importance of the tension modulation effect in the sound production of the clavichord. The tangent modeling algorithm—which will be different from physical models available for the piano hammer, as Hall (1993) has pointed out—should be developed to be able to control the excitation using physical parameters.

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