Note transitions in Physical Models of a Wind Instrument.[1]

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Abstract

In simulating the playing of a musical note sequence with a physical model, not only the steady state tones but also the transition between the tones have to be modeled. This paper gives an overview of six different techniques for implementing note transitions, applied to a physical model of a wind instrument. Two specific solutions are further analyzed and compared. It is found that the parallel crossfading technique has a better cost/performance than serial crossfading.

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Key–Words: Music, Sound synthesis, Physical modeling, Multinote, Waveguide

1 Introduction

Physical modeling sound synthesis is based on a mathematical description of the acoustical behavior of a real instrument [1],[2]. Unfortunately, most models have to be simplified to be usable for real–time synthesis. This simplification often leads to models that are only capable of generating a single note. When several notes are played in a sequence, one has to create a new model for each note played. Several techniques have been developed to make this model swap as smooth and natural as possible.

After an overview of six possible methods, this paper compares the serial crossfading and the parallel crossfading solutions.

2 Multinote Models

When playing several notes in a sequence on a real wind instrument, one effectively changes the acoustic configuration of the instrument. The start and the end note can be modeled by separate systems. During the transition of one note to another, the real instrument goes through a whole range of intermediate states. The output of the physical model of the instrument should match the output of the real instrument during these states as closely as possible. In this paper, we use the digital waveguide physical modeling technique [2]. When used for modeling wind instruments, these waveguide models basically consist of a linear resonating structure, coupled to a non–linear function. The toneholes are a part of the resonating structure. Changing the configuration of the toneholes results in a change in the resonator. The next sections describe several solutions to the note transition problems when using waveguide models.

2.1 Full Acoustic Model

The most complete solution is to make a full acoustic model of the instrument including all toneholes and to model the effect of opening and closing a tonehole (see fig. 1(a)) [3]. This requires an accurate tonehole model and specific control information when simulating the model (like the intermediate key or finger position above the tonehole) [4]. The resulting model is quite complex and difficult to calibrate but yields the best result. This model is used as the ultimate benchmark for the other solutions.

2.2 Serial Crossfading

A simpler solution is obtained by approximating the full acoustic model with a one–tonehole model (fig. 1(b)), effectively "plugging in" a tonehole when needed. Further, we could model the tonehole itself as a two–port, with simple scalars as reflection and transmission coefficients. This technique keeps a large part of the quality of the full acoustic model,

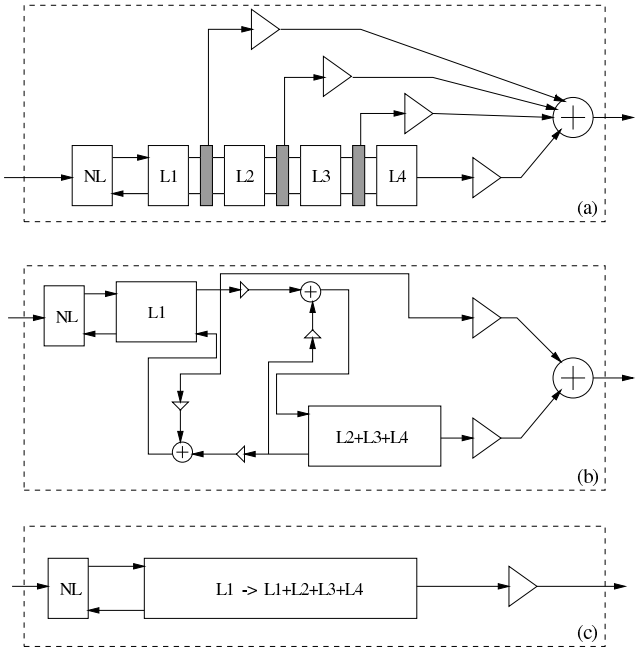

Fig. 1 (a) The full acoustic model. The different resonators (lengths L1 to L4) are linked through tonehole scattering junctions (gray boxes). (b) Serial crossfading: the two resonators are linked through a simple scattering junction. (c) Model morphing: the model parameters gradually change. (NL=non–linear function)

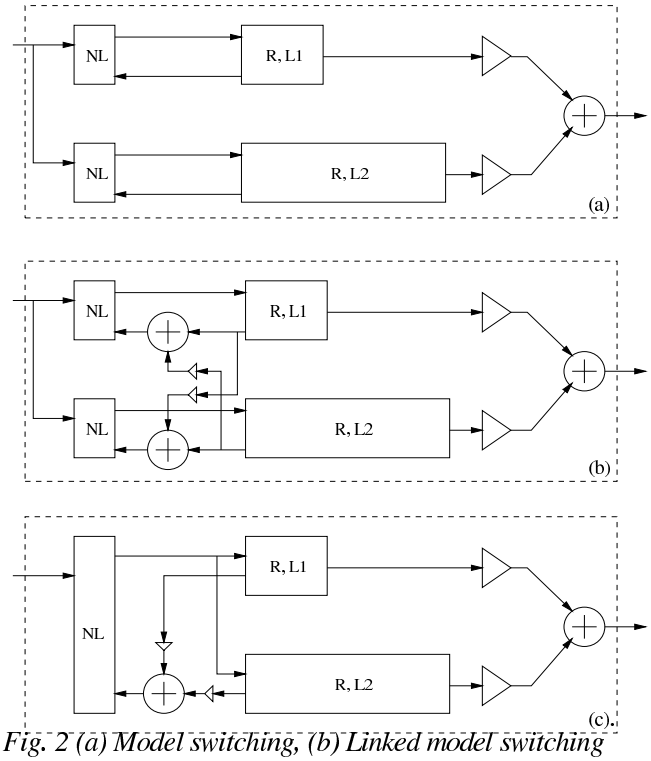

Fig. 2 (a) Model switching, (b) Linked model switching and (c) Parallel crossfading. (NL=non–linear function, R=resonator)

while being a lot simpler.

2.3 Model morphing

The previous system can be approximated once more by gradually changing or morphing the model for the first note to that of the second note (fig. 1(c)) during a note transition [4]. When using a waveguide model, this means a gradual change of the length of the delay line and changes of most or all of the filter coefficients. This, however, can introduce audible artifacts. This solution is usable for small changes in delay length and filters but becomes increasingly difficult and less natural–sounding for larger changes.

2.4 Model switching

At the other end of the spectrum, one could simply use a note–specific model and switch to another model when needed (fig. 2(a)). The outputs of the two separate models existing during the note transition can be crossfaded to obtain a *legato* effect. This very simple solution needs careful tuning of the mixing function used to avoid an audible "gap" between the two notes. It is very easy to implement.

2.5 Linked Model Switching

Instead of using two completely separate models, one could use two models with the output of the first model coupled to the input of the second model and vice versa. During the transition, both models are linked. This creates more intermediate states and makes a smoother sound. As can be seen on figure 2(b), the resulting system is still quite complex and requires two non–linear functions.

2.6 Joined Parallel Crossfading

A further possibility is by using two separate models for the resonator part and only one for the non–linear function (fig. 2(c)). It is a quite simple solution that gives output similar to the serial crossfading solution, while being a lot easier to implement. This solution is related to the banded waveguide models [5], without bandpass filtering. Before and after the transition, we have a one–note model while during the transition, we need an extra resonator.

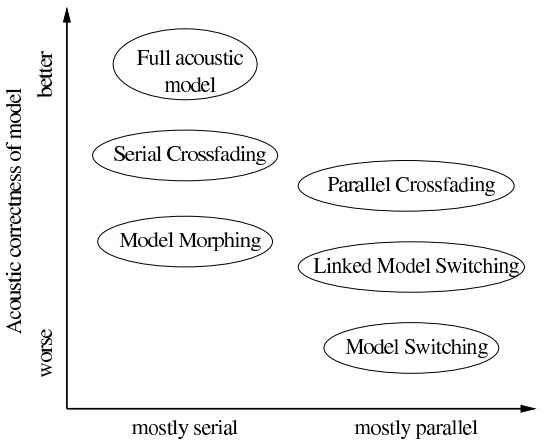

Fig. 3 Comparison of the different methods.

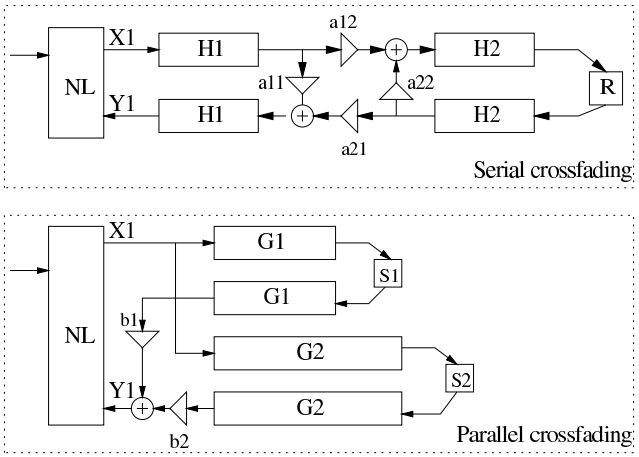

Fig. 4 The two compared techniques. (top) serial crossfading and (bottom) parallel crossfading. H1, H2, G1 and G2 are the transfer functions of single delay lines with fractional delay, dispersion damping filters. R, S1 and S2 are reflection functions.

3 Model comparison

Fig. 3 shows a general comparison of all these models in terms of acoustic correctness and serial or parallel linking of the resonators. What we are looking for is a model that is fairly simple to implement and that is capable of a realistic note transition. Of the models presented in section 2, the serial and the parallel crossfading methods have similar complexity. To determine which one of these two is best regarding computational cost vs. performance, we need an objective comparison.

For a start, assume that we want to play two notes sequentially, and the first note has a higher pitch than the second one. This leads to a waveguide structure with the first note necessitating a delay length L_1 and the second note a delay length L_1+L_2. The two models can be found in figures 4. We choose the output of the non–linear function (*X1*) as the output of the system. The resonator part of the models can be seen as a black box with transfer function *M,* connected to the non–linear function.

As a first test, we calculate *M* for the two cases. The input of the black box is $X1_{ser,\ par}$, the output is $Y1_{ser,\ par}$. If the transfer function is similar in the two cases, this test gives a strong indication that the output of the two cases will also be similar. The transfer function is determined by

$$M_{ser,par}=\frac{Y1_{ser,par}}{X1_{ser,par}} \qquad (1)$$

For the serial case, we find the following input–output relation:

$$Y1_{ser}=[a_{11}H_1^2+\frac{a_{12}a_{21}H_1^2H_2^2R}{1-a_{22}RH_2^2}]\cdot X1_{ser} \qquad (2)$$

and for the parallel case:

$$Y1_{par}=[b_1S_1G_1^2+b_2S_2G_2^2]\cdot X1_{par} \qquad (3)$$

Note that the denominator of eq. (2) only has influence during the transition if we assume that a closed tonehole effectively "disappears" from the system. To make the two cases comparable, we now determine the values for the parameters *b*, *S* and *G* of equation (2) such that M_{par} matches M_{ser}. This translates to: a) the two systems must have the same output for the steady state case (only one note played) and b) the outputs should be as close as possible during the note transition.

3.1 Steady state behavior

When the model is in steady state, we can make a few assumptions about the parameters for both sequentially played notes. During the first note, we assume that the system behaves as if the part of the instrument behind the open tonehole isn't there (full reflection at the junction). During the second note, it is as if there is no tonehole at all (full transmission at the junction). Compared to the full acoustic model, this is a quite rough approximation of reality. On the other hand, when using calibrated models for the two steady–state configurations, the influence of the

closed toneholes is implicitly incorporated into the resonator. We can now translate these conditions to the two cases. For the serial case these assumptions become (cfr. fig. 4, top):

$$\text{First: } \begin{matrix} a_{11}=-1 \\ a_{12}=a_{21}=0 \end{matrix} \qquad \text{Second: } \begin{matrix} a_{11}=a_{22}=0 \\ a_{12}=a_{21}=1 \end{matrix}$$

while for the parallel case (fig. 4, bottom)

$$\text{First: } \begin{matrix} b_1=1 \\ b_2=0 \end{matrix} \qquad \text{Second: } \begin{matrix} b_1=0 \\ b_2=1 \end{matrix} \qquad (4)$$

This gives the following relations between the two models:

$$\begin{matrix} S_1=a_{11} \\ G_1=H_1 \end{matrix} \quad \text{and} \quad \begin{matrix} S_2=R \\ G_2^2=H_1^2 H_2^2 \end{matrix} \qquad (5)$$

3.2 Transition behavior

Using (5) in equations (2) and (3) yields as a possible solution:

$$b_1=1 \qquad (6)$$

$$b_2=\frac{a_{12}a_{21}}{1-a_{22}RH_2^2} \qquad (7)$$

We now approximate this by putting the denominator equal to 1. This corresponds to removing the resonance in the second part of the bore (behind the tonehole). This will have a minor effect as the resonance is damped. The parameter b_2 now becomes frequency–independent.

$$b_2=a_{12}a_{21} \qquad (7)$$

Again, this is not as accurate as the full acoustic model, but we have to take into consideration that during normal playing the transition time between two notes is rather short, making it difficult for us to actually hear the difference. We conclude from this theoretical analysis that serial and parallel crossfading produce very similar output.

Simulation of the two cases confirm this analysis. Both the time domain and frequency domain outputs are very close. For comparison, fig. 5 shows the spectrogram of the transition using model switching, serial crossfading and parallel crossfading. One sees the change of the partials during the transition in the serial and parallel crossfading methods, while model switching only shows a shift of the partials (not visible on fig. 5 due to the frequency scale). Subjectively, there is no audible difference between the two crossfading methods.

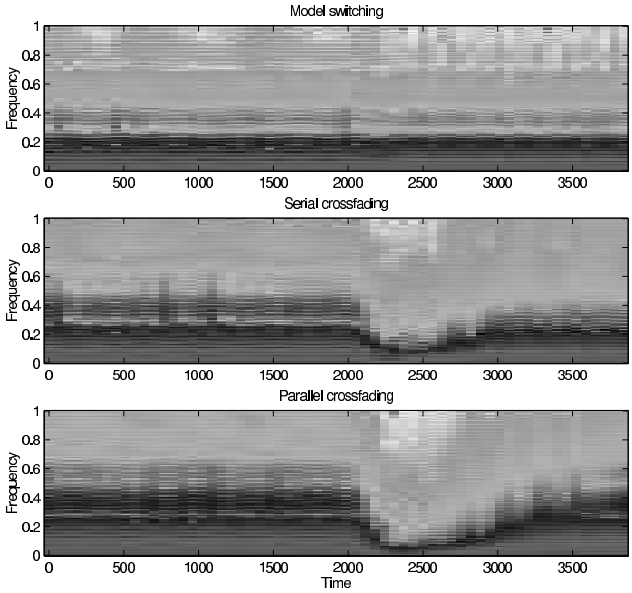

Fig. 5Spectrogram of a transition using (top) model switching, (middle) serial crossfading, (bottom) parallel crossfading.

From the implementation standpoint, the parallel crossfading technique is the superior choice. A drawback of the serial crossfading method is that one must be able to "tap" into the delay line or to attach a new delay line when needed. This is not the case with parallel crossfading. Another factor common to all scattering junction–based methods is that potentially unnecessary calculations are done in the part of the model behind the tonehole. With the parallel crossfading method, after the transition is complete, the unused resonator can be cleared and replaced as needed, making it more flexible. One has to choose between one large model running all the time or two smaller models existing in parallel during the transition.

4 Conclusion

This paper gives an overview of six possible techniques for modeling note transitions with physical models. Two types (serial and parallel crossfading) were further analyzed. It has been found that parallel crossfading offers the best cost/performance of the two.

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