Analysis and synthesis of unusual friction-driven musical instruments

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Abstract

In this paper we propose different models of unusual friction-driven musical instruments, together with a spectral analysis of the instruments. A real-time implementation of the glass harmonica and the musical saw is proposed.

1 Introduction

Friction-induced self-excited vibrations appear in many different structural materials and with different surfaces of contact. All these materials present similar frictional behaviors. Friction is also the excitation source of a well-known family of musical instruments, i.e. the family of bowed string instruments. The player coats his bow with rosin, in order to increase the amount of adherence between the bow and the string.

In this paper we are interested in musical instruments driven by friction which are less common than those belonging to the bowed string instrument family, i.e. the musical saw and the glass harmonica. We studied the sounds generated when exciting a saw or a wine glass with a cello bow and when rubbing a finger along the rim of a wineglass.

Sounds have been recorded and analyzed in these cases in order to construct models simulating these instruments. Both physical and signal models have been used for this purpose, and parameters related to attenuation and dispersion have been extracted from the real sounds and compared with already existing models describing the physics of these instruments. A real-time implementation based on digital waveguides with different models for the excitation mechanism is proposed.

2 The musical saw

The origins of the musical saw go back to the early 20th century. First played with a mallet, it later became standard to play the saw using a violin bow in the lap style of playing, as is shown in figure 1.

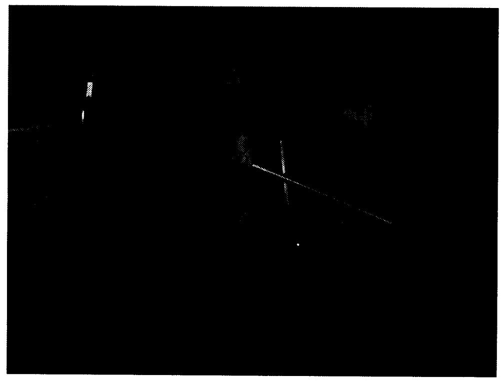

Figure 1: *One of the authors playing a saw.*

2.1 Acoustics of the musical saw

When an ordinary handsaw is bent into an S-shape, an interesting acoustical effect can occur. Beyond a certain critical degree of curvature, a very lightly damped vibrational mode appears which is confined to the middle region of the S. This confined mode can be excited by a bow to produce the pure sound of the "musical saw" (5).

The S-shape forces other modes as well to be trapped in the vicinity of the inflection by a process of reflection from points of critical curvature. Since these modes must have an integral number of wavelengths on a round trip of propagation, the frequencies of higher modes are brought into harmonic relation with the main (fundamental) mode.

The tone produced is almost sinusoidal, and the player controls the pitch by changing the curvature of the blade. Increasing the curvature gives rise to a higher pitch. The vibrato is obtained by slightly moving the extremity of the saw in the hand of the player. Figure 2 shows the spectrogram of a sound obtained from a Stanley 26-inch crosscut handsaw bowed at the curvature. While the saw is bowed many harmonics appear in the spectrum, but when the bow is released mainly the fundamental frequency resonates.

For analysis purposes, the curvature of the saw was kept constant by fixing the handle against the wall and securing the tip with a clamp, as shown in figure 3.

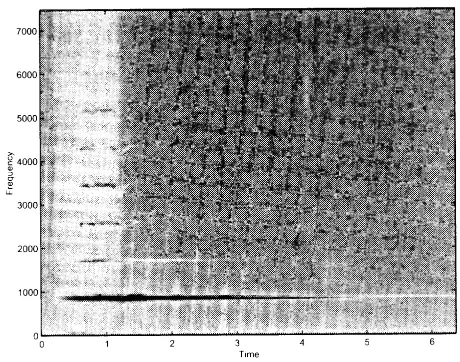

Figure 2: *Sonogram of a bowed saw tone. The saw is bowed for about one second and then left to resonate. While the fundamental has a long decay time, the higher harmonics are quickly damped.*

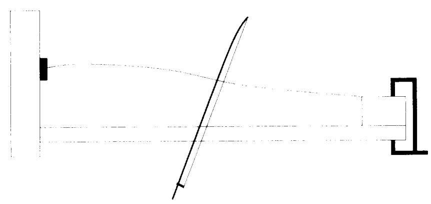

Figure 3: *Configuration of a saw fixed at both ends.*

3 The glass harmonica

Glass harmonicas are musical instruments of two kinds. The first one, invented by Benjamin Franklin, adopts glass bowls turned by a horizontal axle so that one side of the bowl dips into a trough of water. The second one is a combination of wineglasses similar to the ones shown in figure 4. Different melodies can be played on a set of tuned glasses (filled with appropriate amounts of water or carefully selected by size), simply by rubbing the edge of the glass with a moist finger. Rubbing rims of glasses in order to produce music became very popular in Europe during the 18th century. Music on glasses has been successfully composed by Mozart, Beethoven, and many others.

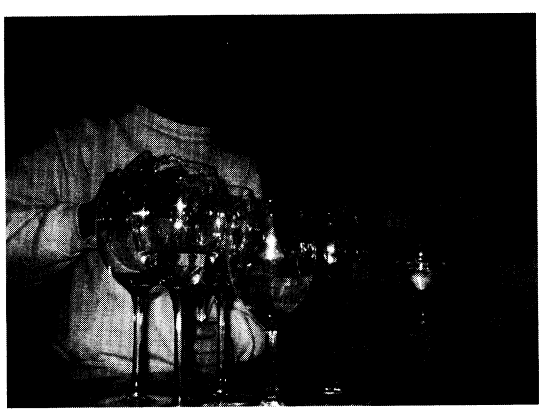

Figure 4: *Young performers playing the glass harmonica.*

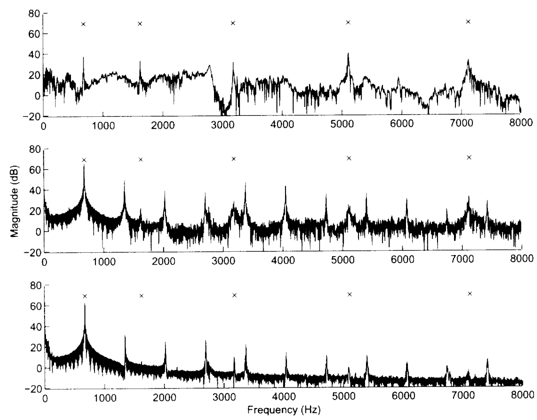

Figure 5: *Spectrum of a large wineglass. Top: impulse response; center: bowing with a cello bow; bottom: rubbing with a wet finger. The circles indicate harmonics of the* $(2,0)$ *mode, and the x's indicate the* $(m,0)$ *modes for* $m = 2$ *to 6.*

Mode	Freq.(Hz)	Amp. (dB)	Decay (dB/sec)
(2,0)	676	-16.669	-19.474
(3,0)	1625	-18.207	-52.477
(4,0)	3185	-10.582	-86.801
(5,0)	5111	0	-153.23
(6,0)	7127	-12.963	-172.42

Table 1: *Frequencies, relative magnitudes (normalized to 0 dB), and decay rates for the first few major modes of a large wineglass.*

3.1 Acoustics of wineglasses

The main vibrational modes of a wineglass resemble those of a large church bell. The modes can be described with the label (m,n), where $2m$ is the number of nodes around the rim and n is the number of nodes around the circumference of the glass. The wineglass modes are generally of the form $(m,0)$, and the resonance frequencies are nearly proportional to m^2 (1).

During the recordings two wineglasses of diameter 6.7 and 6.0 cm, respectively, and of height 10.3 and 9.5 cm were used. A microphone was positioned about 1 meter from the glasses. The wineglasses were tapped with an impulse hammer, rubbed with a wet finger, and bowed with a cello bow. Tapping the glass excites a number of "bell modes", while rubbing or bowing it strongly excites the $(2,0)$ mode and its harmonics, and to a lesser degree the other modes as well. Figure 5 shows spectra of the steady-state portion of bowed and rubbed tones of the larger glass when played at medium volume, as well as its impulse response. Table 1 summarizes the resonance behavior of the same glass; here the mode frequencies are proportional to $m^{2.17}$.

As in the case of the bowed string and the musical saw, rubbing the rim of the glass with a wet finger excites vibrations in the glass through a stick-slip process. Moving the finger around the rim creates a pulsation of about 4 to 8 beats per second, depending on the speed of the player.

4 Analysis of the instruments

Analysis of natural sounds can be used to extract parameters for different kinds of synthesis models. In this paper the resonator model using digital waveguides and the signal model of the source use parameters extracted from the analysis.

By filtering each individual spectral component of the analytic signal of the transient sounds, the frequencies and damping factors of the main resonances can be extracted. The frequencies are obtained from the mean values of the average instantaneous frequencies, while the damping factors are obtained from linearization of the logarithm of the instantaneous amplitude (4).

5 Real-time synthesis models

In order to reproduce the behavior of the glass harmonica and the musical saw while rubbed, tapped, or bowed, we developed a digital waveguide model using the exciter-resonator approach. The resonator was modeled using digital waveguides. To model the excitation we developed both a physical model of the stick-slip mechanism and a spectral model of the source, as described in section 5.2.

5.1 The resonator model

In order to model the resonator, we considered the main resonating modes of the glasses and the saw and developed each inharmonic mode using a digital waveguide.

In the case of the saw, as figure 2 shows, all components are harmonic and only the first and the second harmonics resonate long after the release of the bow. Our implementation consists therefore of a single waveguide model whose damping filters are very sharp around the main resonance.

In the case of the wineglasses, the presence of strong inharmonic modes required the implementation of five waveguides all connected at the excitation point. In order to model waves propagating in both directions, each mode of the wineglass is modeled as a pair of digital waveguides, each one propagating in each side of the glass. For each waveguide pair i we have combined delay lengths $d_{i1} + d_{i2} = s_i$ with $s_i = fs/f_i$, where fs is the sampling rate (44.1 kHz) and f_i is the frequency of that mode in Hertz. The motion of the finger around the rim of the wineglass is obtained by moving the excitation point around the waveguide.

5.2 The source model

The resonator model takes into account damping and dispersion in the glass and in the saw. This means

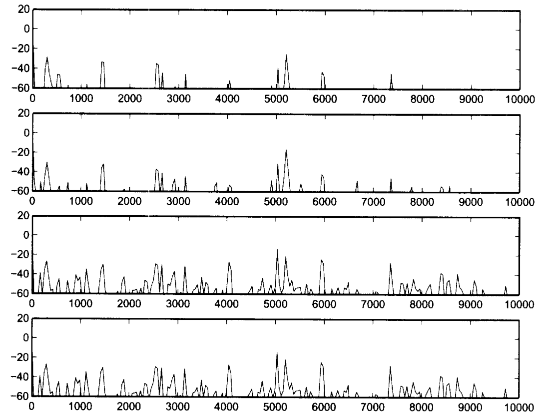

Figure 6: *Spectrum of the source for the fixed saw, exracted from notes played at different dynamics. Horizontal axis: frequency (Hz); vertical axis: magnitude (dB). From top to bottom: piano, mezzo forte, forte, and fortissimo.*

that this model makes it possible to accurately resynthesize transient sounds obtained by striking the saw or wineglass. However, if we want to model sustained sounds, an additional model should be made for the source.

In this section we describe both a physical and a signal model approach to this problem. The physical approach is based on an exponentially decaying friction model in which friction depends on the relative velocity between the exciter and the resonator. The signal model is obtained by extracting the excitation by deconvolution between the recorded signal and the resonator model. The spectral evolution of this signal as a function of the dynamic level is further modeled by a waveshaping model, allowing a resynthesis of the original sound.

5.2.1 A signal model of the source

By observing the spectra of the extracted sources in the glass and in the saw cases we can see that they evolve nonlinearly as the dynamic level increases (see figure 6). To model this nonlinear source behavior, we used a so-called waveshaping synthesis method (2) which consists in distorting a sinusoidal function by a nonlinear function:

$$s(t) = \gamma(I(t)\cos(w_0 t)) \quad (1)$$

It is convenient to decompose the nonlinear function into Chebychev polynomials T_n where n is the number of spectral components, since this gives a simple relationship between the function and the generated signal. For $I(t) = 1$ for all t, we obtain

$$s(t) = \sum_{n=0}^{K} \alpha_n T_n cos(\omega_0 t) = \sum_{n=0}^{K} \alpha_n cos(n\omega_0 t)$$

In this case α_n is given by the values of the components of the spectrum to be generated.

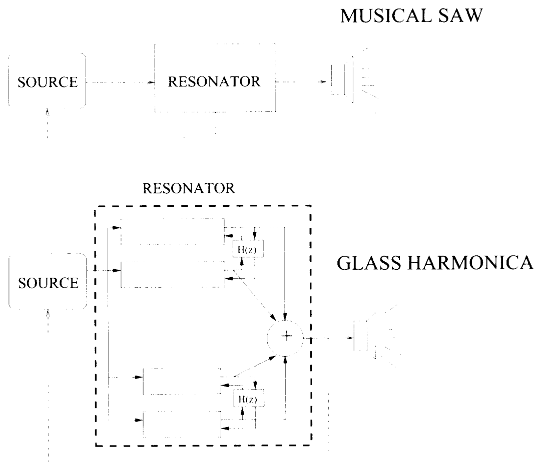

Figure 7: *Waveguide structure of the models. $H(z)$ represents lowpass filters used to model internal losses. The filters' coefficients are estimated using the data obtained from the analysis described in section 4.*

By varying the index of distortion a spectral evolution close to the real one can be simulated (7). Since the waveshaping function does not allow us to exactly simulate the spectral evolution of the real sound, perceptual criteria are used to evaluate the values of I for which the spectrum evolves from pianissimo to fortissimo. In our case the spectral centroid criteria was used for this purpose.

5.2.2 A physical model of the source

Considering the strong analogy between the musical saw, the bowed glasses, and the bowed string, we decided to model the source using a simplified friction curve on a violin:

$$\mu = \mu_d + \frac{(\mu_s - \mu_d)v_0}{v_0 + v - v_b} \tag{2}$$

where v, v_b, and v_0 are the string velocity, bow velocity, and initial bow velocity, μ_d is the dynamic friction coefficient, and μ_s is the static friction coefficient. Friction coefficient tables suggest $\mu_s = 0.9$ and $\mu_d = 0.4$ for glass and $\mu_s = 0.6$ and $\mu_d = 0.4$ for metal-when excited by a lubricated surface. This function is coupled with the equation representing the wave propagation in the resonator (6).

An advantage of this approach is the ability to use physically meaningful parameters. A disadvantage is the lack of real data concerning the real shape of the friction curve specific to the materials in contact.

5.3 Implementation

Figure 7 shows the digital waveguide structure of the musical saw and the glass harmonica. The real-time models have been implemented as Pure Data (3) external objects, in order to explore the performance possibilities.

When the source is modeled by the signal model, the input is a sinusoidal function whose frequency equals the fundamental frequency of the sound. When the source is physically modeled, the control parameters are the velocity and force of the excitation (either the bow or the finger), the position of the excitation, and the fundamental frequency (determined either by the curvature of the saw or the dimensions and amount of water in the glasses). In addition, the resonator output is coupled back into the excitation source in order to take into account the mutual interaction between the two parts (see, for example, (6)).

6 Conclusions

In this paper we proposed exciter-resonator models of unusual friction-driven oscillators. The purely physical model is driven by physically meaningful parameters but lacks precise data on the frictional interaction between the excitation mechanism and the resonator. The hybrid model makes use of spectra data to construct a close perceptual rendering of the frictional characteristics. On the other hand, the input parameters are not the actual physical inputs of the instruments and are not as intuitive to control.

7 Acknowledgements

The work was supported in part by the Norwegian Research council. The authors would like to thank Julien and Richard for sacrifing their wineglasses for research purposes.

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