Computer models and compositional applications of plastic corrugated tubes

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A flexible plastic corrugated tube known as the *Hummer* was a popular sonic toy in the early 1970s. It produces pleasing sonorities when whirled in the air. In this article, we propose a physically informed model of a singing corrugated tube. The model was used in the composition *Garden of the Dragon*, which is also described in this paper.

1. INTRODUCTION

Marketed under the name *Hummer*, singing corrugated tubes were adopted and widely popularised as musical toys in the United States in the early 1970s. The *Hummer* is a plastic corrugated tube about one metre long, similar to the one shown in figure 1. The physicist Mark Silverman, during a visit to Japan, heard by chance the sound produced by a group of children twirling flexible plastic corrugated tubes above their heads. Intrigued by such sonorities, he proceeded to study their behaviour and acoustical principles (Silverman 1989).

Silverman mounted a corrugated tube on a thin slab attached to a wheel. The wheel freely rotated in a vertical plane with a counterweight fixed at the opposite end of the slab. The centre of the system's mass lay on the axis of the wheel, as shown in figure 2. A velocity-varying motor using a rheostat moved the wheel. Using a microphone, a stroboscope and a counter, Silverman recorded the produced tones and measured the spin rates. Then he analysed the sonic data using Fourier analysis.

Another physicist, Frank Crawford, approached the study of the plastic corrugated tubes and their acoustics differently (Crawford 1974). By 'taking a tube for a car ride', Crawford observed that the frequency of produced tones changed according to the car's increasing and decreasing speed. Both researchers observed the following relationship between the whirling speed and produced frequency: whirling the tube at low speed initiates the first overtone. Increased velocity excites the higher partials. Additionally, they noticed that the length of the tube determines the singing pitches.

Whirling a smooth tube produces no sound. However, whirling a corrugated tube opened at both ends results in a noticeable tone. A tone is generated when the 'bump' frequency of the air flowing through the tube equals one of the tube's resonant frequencies. Air velocity, tube length, corrugation, and diameter size therefore influence the pitch and volume of the sound.

2. ACOUSTICS OF CORRUGATED TUBES

The resonant frequencies of an open-ended tube are well known and can be found in any acoustics textbook (e.g. Benade 1976). As suggested in Silverman (1989) and Crawford (1974), the tube resembles a centrifugal pump. When whirled, the air is sucked in through the end close to the player's hand and pushed out through the distant end. When some of the airflow energy is converted to excitation energy, the vibrational modes resonate and, thus, produce pitch.

In the following paragraphs the dynamics of the tube is described. There are two types of airflow at work: vortical flow centred in the stationary end of the tube and normal airflow along the axis of the tube. The rotationally induced pressure difference between the two ends produces an axial flow along the tube.

The essential component of the singing tube is a set of equally spaced corrugations. Moving along the corrugations, the air is perturbed at a frequency proportional to the axial air velocity and inversely proportional to the corrugation spacing. When the frequency of perturbation of the air matches the resonant frequency of the tube, the sound is amplified. Figure 3 displays the sonogram of the rotating tube while performing two arpeggios at varied rotational speed. High partials are amplified with the increased rotational speed.

3. MODELLING CORRUGATED TUBES

To model the corrugated tube, we consider the tube to be an organ pipe open at both ends. Thus, it appeared most effective to use a one-dimensional digital waveguide to model the tube resonator (Smith 1992).

Since the turbulence inside the rotating tube is complex and still not well understood, we modelled the effect of corrugations. In our algorithm, the distance d between corrugations is known, and the axial air velocity vn of mode n is easily calculated. At each

Figure 1. *Hummer*.

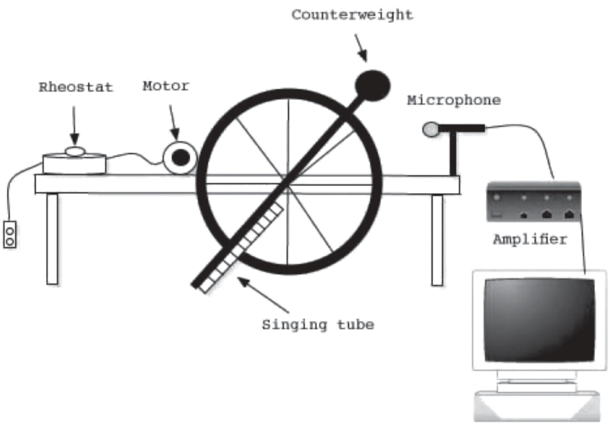

Figure 2. Experimental setup for Silverman's analysis of *Hummer*'s acoustical properties.

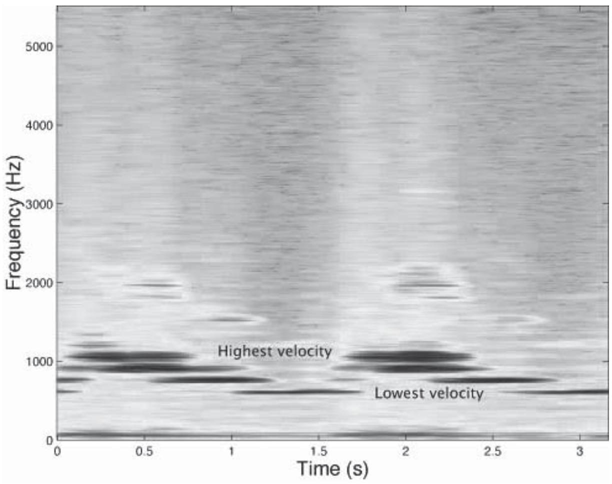

Figure 3. Sonogram of rotating *Hummer*.

sample i, we calculate the frequency fcn for which $fcn = vn/d$. Then we determine the mode fa which is the mode of the tube closest to fcn. This becomes the centre frequency of a bandpass resonant filter whose role is to amplify fa.

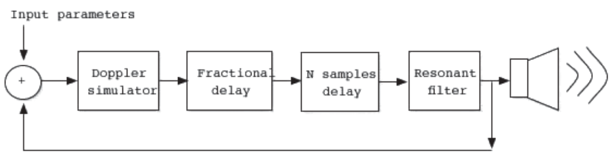

Figure 4. Block diagram of tube physical model.

To complete the model, it is necessary to simulate the rotational behaviour of the tube. The motion of the tube relative to the listener produces the well-known Doppler effect, i.e. an apparent change in frequency content of an acoustic signal. Simulation of the Doppler shift was proposed in Takala and Hahn (1992) and Savioja, Huopaniemi, Lokki and Väänänen (1999). Recently, a detailed simulation of the Doppler shift using time-varying delay lines was proposed (Smith, Serafin, Abel and Berners 2002). In this last example, the Doppler shift was applied to the simulation of the circular rotation of a Leslie horn. A strong resemblance can be observed between the rotation of a Leslie horn and the rotation of a plastic corrugated tube. Therefore, in our simulation the same algorithm as proposed in Smith *et al.* (2002) is adopted. The block diagram of the complete tube physical model is shown in figure 4.

The model is driven by two types of parameters – (i) physical parameters: length of the tube and distance between corrugations; (ii) control parameters: angular velocity and rotational radius. The angular velocity and the rotational radius are used to model the Doppler effect. A fractional delay line (Laakso, Välimäki, Karjalainen and Laine 1996) allows one to continuously vary the discrete length N of the tube, where $N = 2fsL/c$, where fs is the sampling rate, c represents the speed of sound in air, and L is the tube's length in metres. The effect of corrugations and propagation losses is modelled using a sharp second-order resonant filter tuned to the mode of the tube closest to $wm = L/d$, in which d is, as before, the distance between corrugations.

We decided not to include an additional lowpass filter to account for propagation losses along the tube, since it does not improve the quality of the synthesis. Instead, we lumped all frequency-dependent losses into the bandpass filter that accounted for the corrugations.

4. MUSICAL APPLICATIONS

Besides toy makers, the singing tubes also attracted composers' attention due to their simplicity, expressive potential, and unusual ear-pleasing sonic qualities. In the following paragraphs, we describe the composition *Garden of the Dragon* in which real and physically modelled corrugated tubes were utilised.

Bugs, a documentary 3D-movie (2003, Sky Films) in which a small portion of the rain forest is visually amplified, inspired the composition of *Garden of the Dragon* (2003). In the movie, a viewer perceives a magnified ecosystem and its inhabitants (a variety of insects in all stages of their lives). Such ecosystems are typically unavailable to humans' visual reach.

In *Garden of the Dragon*, the musical capacity of two sonically unnoticed daily-life objects, cellophane and plastic corrugated tube, was explored. Engaging these objects in music performance resulted in the creation of a sonic ecosystem. Through an interactive communication between the real instruments and their computer counterparts (i.e. the tube physical model and processed cellophane), this ecosystem was shaped into a sound sculpture.

The composition is scored for amplified cellophane, plastic corrugated tubes, and electronics. Three or more performers (with the extra players doubling the parts) can perform the piece. The electronic music portion consists of the real- and non-real-time processed sounds of the tube physical models, physically present tubes, and cellophane.

Garden of the Dragon is composed in a three-part arch form. In the first part (0 – ca. 3′20″), the percussive and noisy cellophane sound is presented. The cellophane players perform with the instrument on a microphone. Pre-recorded and digitally processed cellophane samples contribute to the musical flux of this section. The climactic moment occurs at 2′56″ with the players releasing the instruments one by one and moving away from them. Figure 5 illustrates the density and amplitude of the amplified cellophane gestures.

In the second part (ca. 3′20″–7′20″), the tube sound is introduced. The sound of the physical model emerges from the cellophane sound. This was achieved by inducing the cellophane samples into the model, where they act as the excitation mechanism. Simultaneously, the cellophane players are transformed into the tube performers. The sound of the instruments whirled in the air is amplified and transmitted to the computer. Its accumulation breaks soon after the highest reachable harmonic of the physical tube is performed (7′10″). Figure 6 exemplifies performed frequencies and their durations. The performers cease

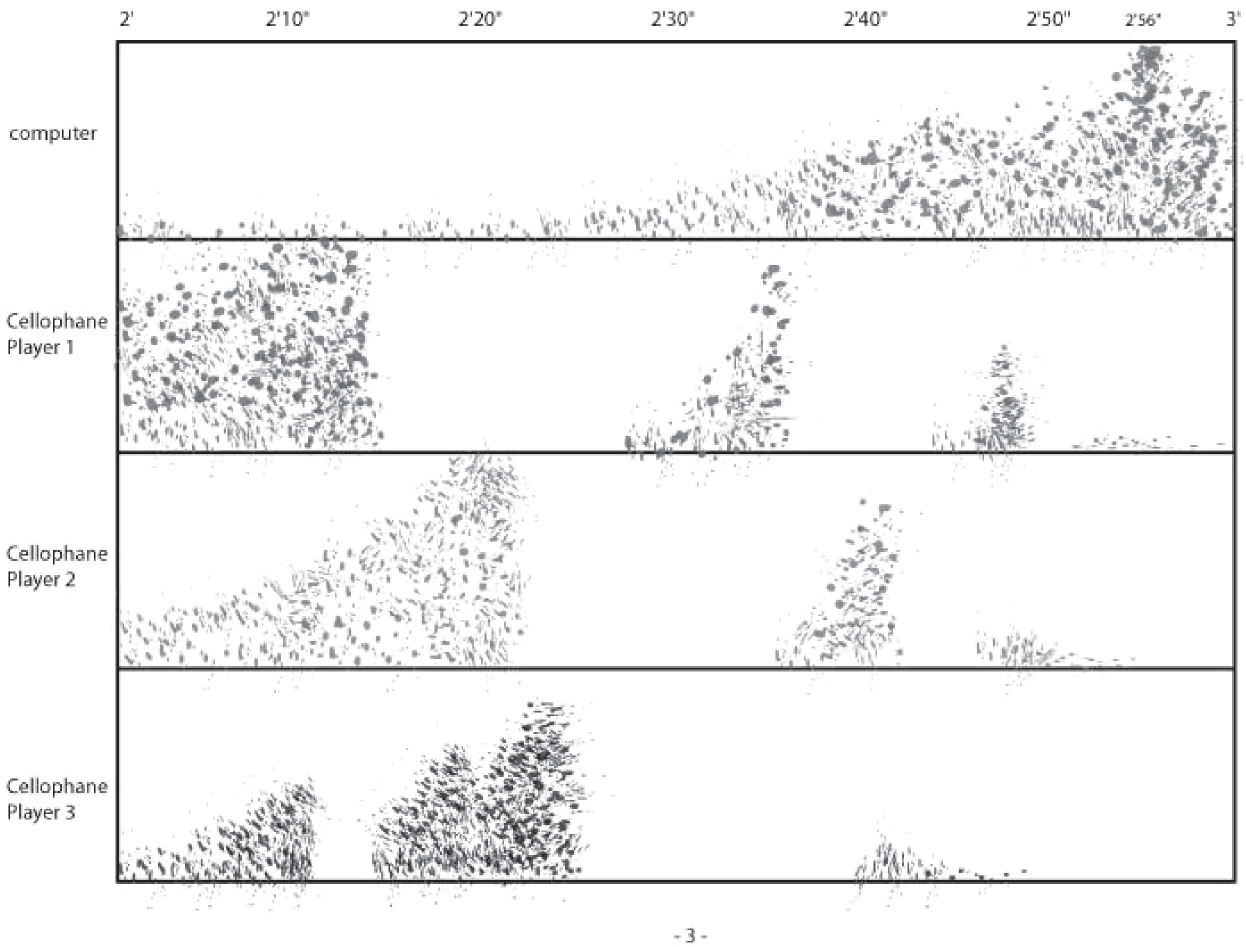

Figure 5. Juraj Kojs: *Garden of the Dragon*, score page 3. The horizontal axis indicates time, the vertical axis displays the density and amplitude of the gestures.

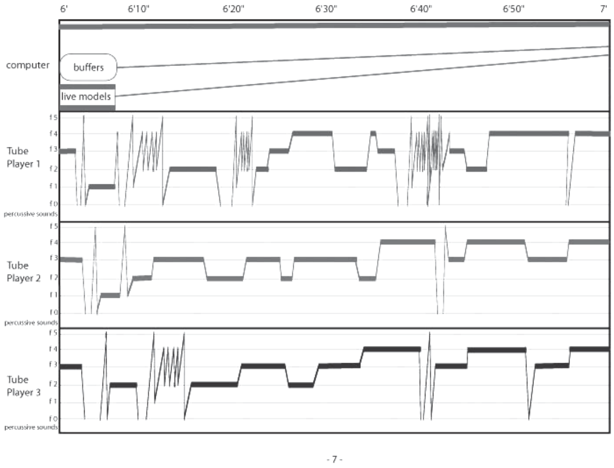

Figure 6. Juraj Kojs: *Garden of the Dragon*, score page 7. Individual frequencies to be performed are marked on the lines f0–f5 with f0 being the fundamental.

whirling the tubes and position themselves to blow inside and scratch the instrument.

Transformed noisy percussive sounds reappear in the final part (7′20″–9′). The sonic transformation is a result of the newly introduced performing techniques such as blowing inside the tube, scratching its surface, and tapping on its ends. Slightly pitched sound produced when the tube is blown dissolves into the non-pitched noise of tapped and scratched instrument at the end of the composition. This ultimate disappearance of the sound through a variety of percussive techniques is portrayed in figure 7.

The players' stage movement reinforces the composition's arch form and contributes to the dramatic aspect of the performance. The performers move from the central front stage to the back stage and again to

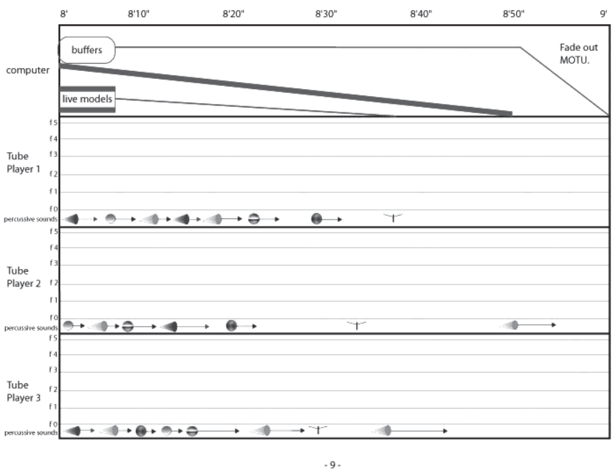

Figure 7. Juraj Kojs: *Garden of the Dragon*, score page 9. The symbols indicate performing techniques such as variety of blowing inside the tube (left oriented cones), tapping on it (the circles), and scratching it with nails (the fork).

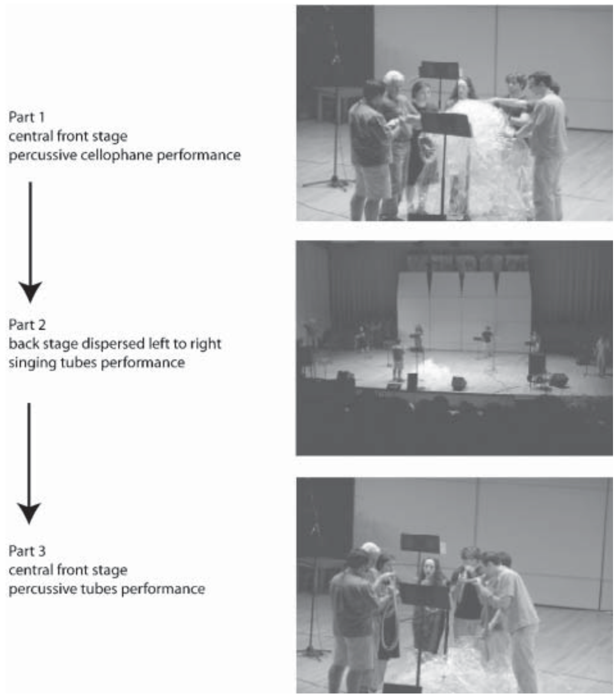

Figure 8. Performance trajectory in *Garden of the Dragon* (pictures by Rolf Nordahl from the performance at ICMC 2004, Miami, FL).

the central front stage. A conductor indicating the time cues is needed for the performance since the composition, as seen in the score examples, is notated in seconds. The movement trajectory is portrayed in figure 8.

The visual aspect of *Garden of the Dragon* undoubtedly contributes to the composition's drama. The piece could indeed be characterised as electroacoustic music theatre (Truax 2000). The stage choreography first resulted from practical solution seeking since the performers require additional space when whirling the tubes after performing with the cellophane. The stage movement was later adopted as an internal part of the performance, which strengthens the formal direction of the composition.

The players' physical contact with the two materials introduced yet another dimension to the performance. It was described as sensual and organic at an interview for the National Cuba Radio at the Primavera in Havana Festival in spring 2004. This is perhaps due to the fact that the physical instruments are created, moulded, performed and abandoned (as in the case of cellophane) during the performance.

In *Garden of the Dragon*, the model of the singing tube implemented as an external object in the MAX/MSP environment was primarily utilised to extend the sonic limitations of the real tubes. Fixed parameters such as vibrato, Doppler effect, frequency and transitions between adjacent frequencies, amplitude,

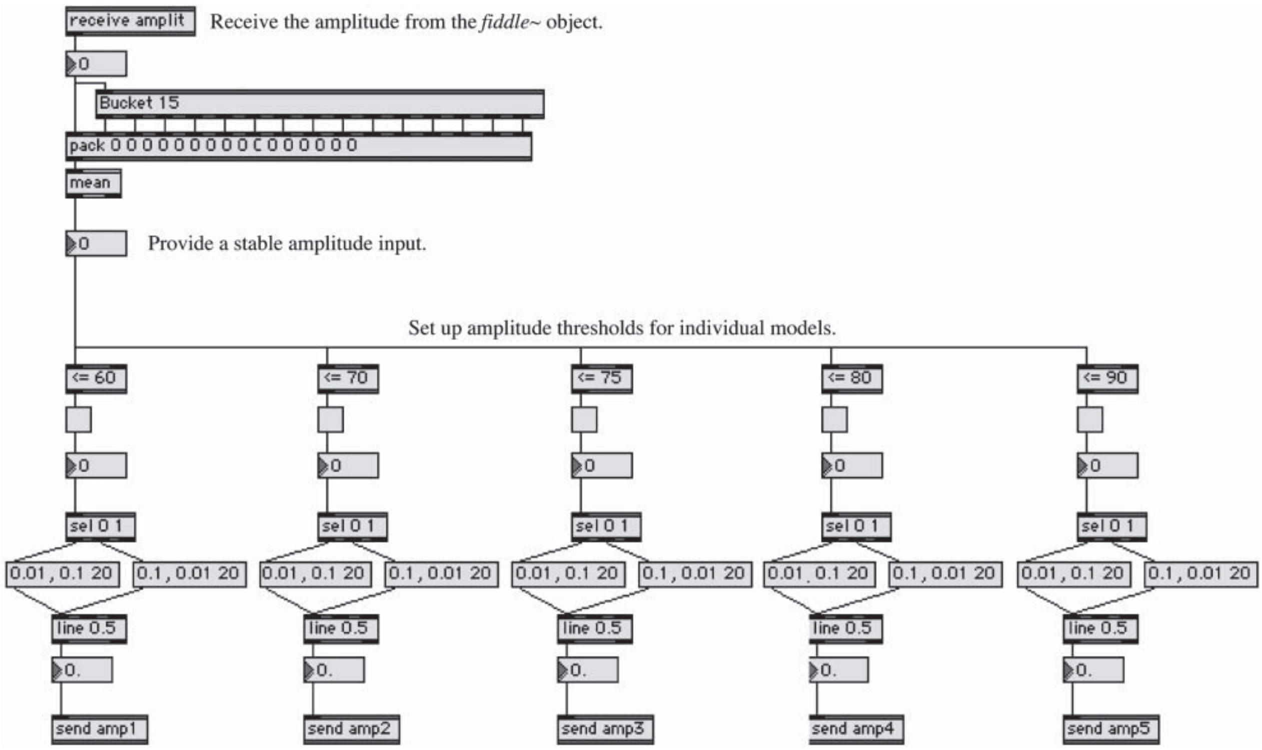

Figure 9. AmpEx: amplitude control over five models.

and noise-to-pitch ratio are characteristic of the real tubes. The model allowed us to create instruments with unrestricted control over all aspects of the tone production. The real tube and model parameters are compared in table 1.

The vibrato of the real tube is very subtle and closely centred around the pitch. With the model, the vibrato variation was intensified and weakened continuously. Vibrato alterations along with Doppler effect may be observed specifically in the pre-recorded model part.

In the composition's MAX/MSP patch, the tube physical models respond to the amplitude and frequency modifications of their physically present counterpart. Both the amplitude and frequency of the real tubes are tracked by the *fiddle~* object, a pitch tracker developed by Miller Puckette (Puckette and Apel 1998). The number of sounding models is proportional to the amplitude of the physically present tubes. A higher amplitude will result in triggering a larger number of models. Figure 9 displays amplitude control over five models. Furthermore, specific amplitudes of the real tube correspond to specific frequencies. The general observation is that higher frequency is produced at higher amplitude and vice versa. Using the physical model allowed us to vary the tone's amplitude independently from its frequency.

Various transpositions of the pitch provided by the real tubes became the fundamental frequencies for five physically modelled tubes. Table 2 displays the available frequencies of the real tube and the models. Those in bold were used in a past performance of *Garden of the Dragon*.

Static leaping from and to neighbouring tones of the real tube was extended by fluid transitions by means of glissando and microtonal stepwise motion. The model allowed us to produce tones with a variety

Table 1. Comparison of flexibility among real and modelled tube parameters.

Parameter	Real tube	Virtual tube
Pitch	Fixed	Variable
Vibrato	Fixed	Variable
Transitions between pitches	None	Variable
Amplitude	Fixed	Variable
Noise-to-pitch ratio	Fixed	Variable

Table 2. Resulting frequencies of the real and modelled tubes from the past performance of *Garden of the Dragon*.

	F1 Fundamental frequency	F2	F3	F4	F5	F6
Real tube	156	**310**	**464**	**625**	**768**	**925**
Model 1	38	**73**	**110**	**147**	**185**	**220**
Model 2	82	165	**247**	**330**	**415**	**494**
Model 3	139	277	415	**554**	**698**	**831**
Model 4	175	349	523	698	**880**	**1,047**
Model 5	311	622	932	1,245	1,568	**1,865**

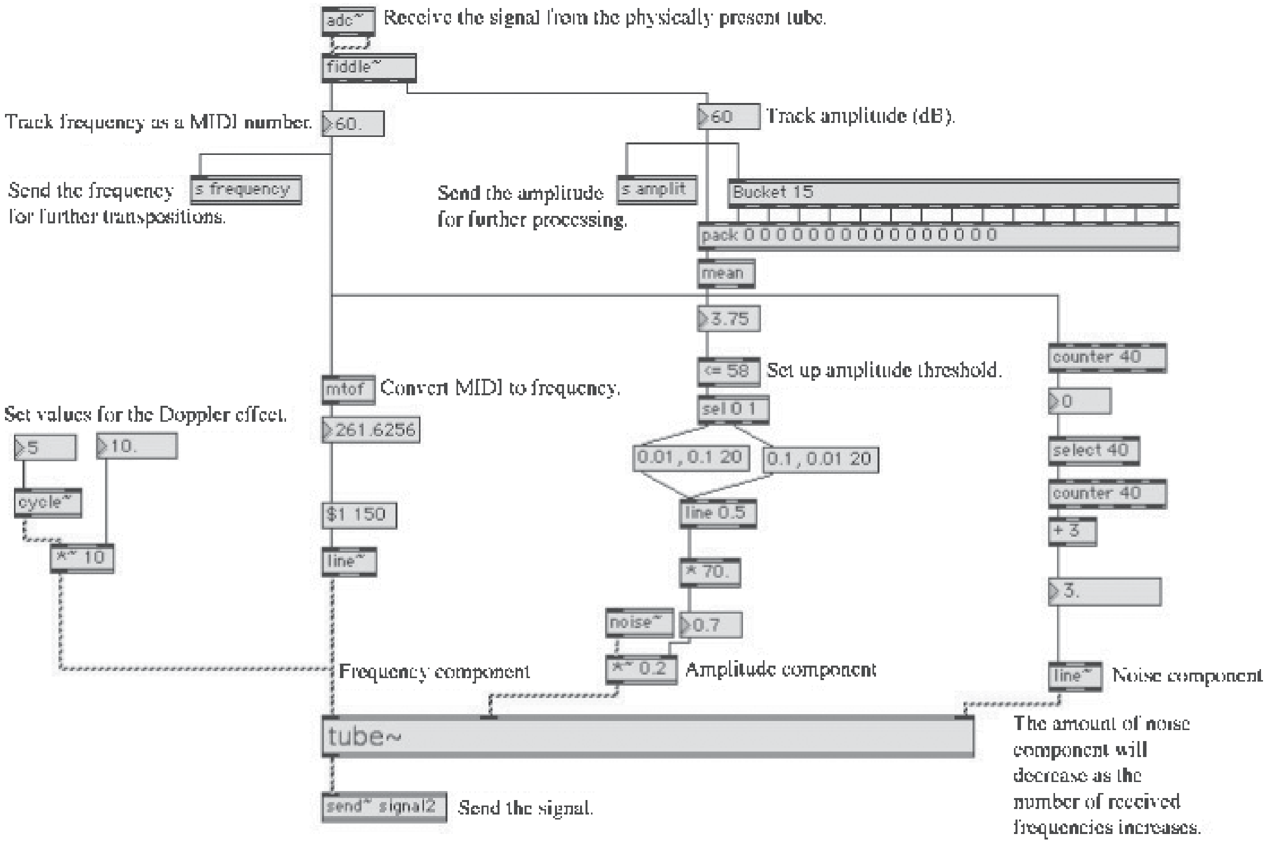

Figure 10. Tube~: a complete tube model as used in *Garden of the Dragon.*

of frequency values not based on the harmonic series. The noise colouration of the tone is restricted in the physically present tube. This may be adjusted in the model as needed. For example, when the real-time physical models first appear in the composition, they emerge from noise (the cellophane percussive sound). Here the noise prevails over the pitch. As the composition progresses, clearer articulation of sound is presented.

The sounds of instruments that have no equivalent in the physical world were generated while varying all these parameters. The complete model as used in *Garden of the Dragon* is shown in figure 10. In addition to the models operating in real time, short excerpts of the physically present tubes sounds are recorded, transposed, delayed and looped by a simple MAX/MSP patch. This increases the density of texture as the climactic moment at 7′10″ approaches.

Figure 11 summarises progressions of individual musical parameters in the course of the composition. Two climactic moments, marked with steep amplitude, represent divisions between adjacent parts. The arch form, as seen through the noise-to-pitch-to-noise trajectory, is most noticeably reflected in the real tube staff.

5. CONCLUSION

In this paper we proposed a physical model and musical application of a plastic corrugated tube. Typically, the best-sounding tubes are made of flexible materials. The corrugations of such tubes must be located inside the tube, otherwise the tube does not sing. Symmetrically positioned corrugations produce the most desirable sonorities. When used for a long period of time, the tubes either break or wear out. However, this poses no serious problem since the plastic corrugated tubes may be found in any hardware or toy store.

The model allowed us to extend the fixed parameters of the real tube. The relationship between virtual and real tubes was explored in the composition *Garden of the Dragon.* Performing the piece became increasingly attractive both for the viewers and performers. The viewers commented on the uniqueness of the amplified cellophane and tubes' sonorities, as well as the visual drama of the staged performance. Due to the uncomplicated control over both cellophane and tubes, a multiplicity of performers were easily trained to participate in the performances.

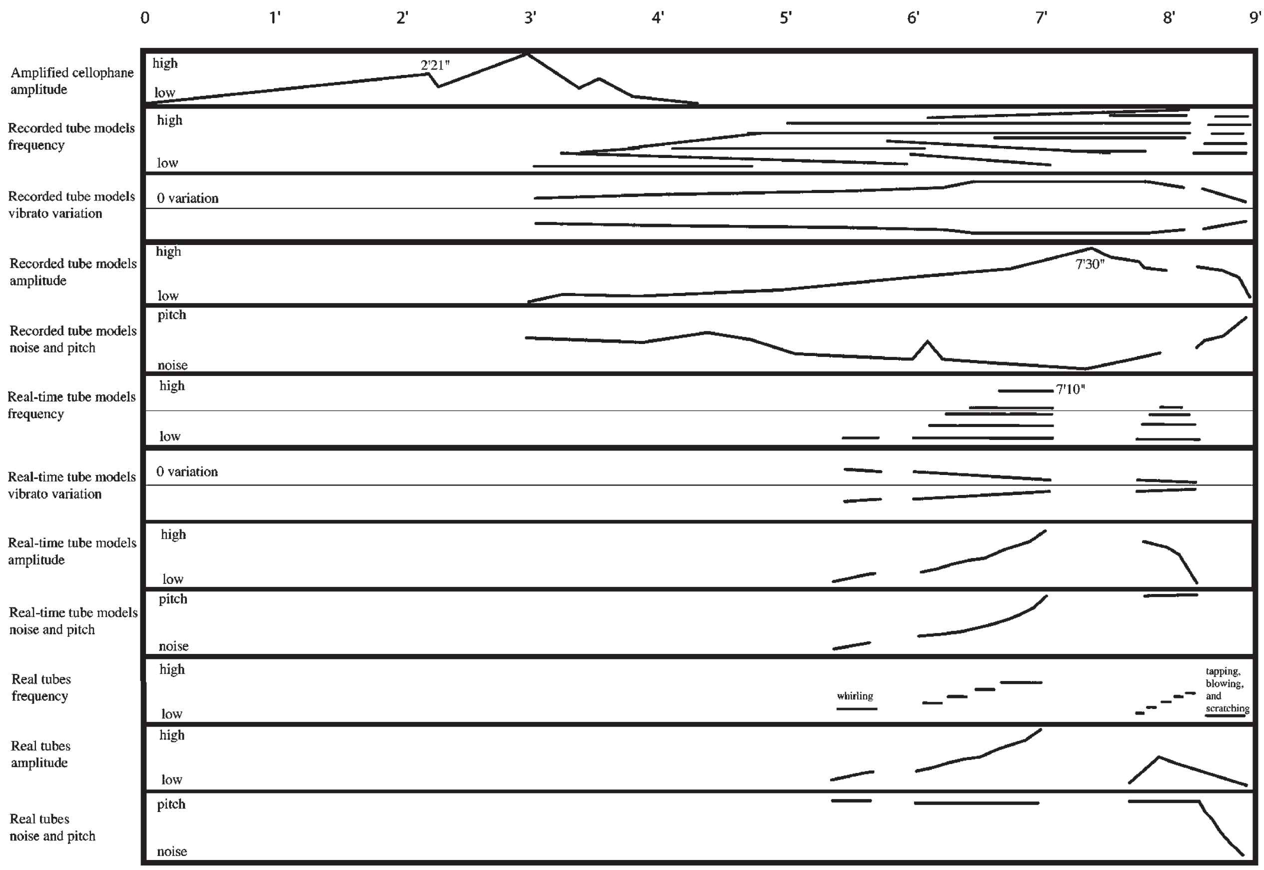

Figure 11. The overall chart for the performance involving cellophane, ten pre-recorded and five real-time tube models, and physically present tubes.

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