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Pulsed Noise and Microtransients in Physical Models of Musical Instruments

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PULSED NOISE AND MICROTRANSIENTS IN PHYSICAL MODELS OF MUSICAL INSTRUMENTS

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Musical tones from bowed strings and winds, though nearly periodic, have a noise component that is a subtle but crucial part of the sound. Attempts to simulate these instruments in digital electronic synthesis are often deficient with regard to the exact quality of the noise component. A new description of the noise generation mechanism accounts for some of the noise present in self-sustained mechanical oscillators. Analyses have verified the existence of the predicted noise and digital simulations have synthesized tones with improved bow and breath noise [1] [2].

Fluctuations are present from period to period both in period length and waveform shape. The fluctuations often appear to have short-lived repeating structures which include a complex mixture of subharmonic features. When simulating string or wind tones with a physical model, the existence of these features is linked in simulations to the presence of pulsed noise. The purpose of this paper is to propose an explanation for the relationship.

The type of noise under study is pulse modulated in a pitch synchronous fashion. Frictional or turbulent noise in the excitation mechanism is gated by its periodic motion. If there were no phase where the string sticks to the bow, or the reed aperture widens, the noise emitted by scraping or air constriction would be continuous. In visualizing a violin string travelling along the bow hair, it is seen that the string spends the major portion of its time at successive sticking points. Each release jerks it along and the string periodically scrapes the bow hair. Similarly, air rushing into a woodwind mouthpiece creates turbulence at the reed aperture and is pulse modulated as open – close phases alternate. The noise is "well-incorporated" in the sound by its period-synchronous timing and perhaps by its influence on short-lived subharmonic features.

Time-domain analysis is required since subharmonic structures are found only in short, sub-period features in the waveform and are highly transient in nature (frequency-domain techniques which average several periods at a time are often blind to these subtleties). The present approach for examining the relationship between noise and subharmonics proceeds in an analysis by synthesis fashion: A drastically simplified simulation of a clarinet with controllable noise components has been paired with a technique devised for visualizing the stability of its oscillation. A distinctive feature of the simulation is the strong dynamical interaction between the excitation mechanism and a high-Q resonant system. Noise at the excitation in this strongly coupled system elicits a variety of subharmonic features.

The simulation generates self-sustained oscillations resembling the square wave of a clarinet. It is a *lumped circuit* approximation of a cylindrical tube with an excitation device on one end and open at the other. The half-period resonator is a recirculating delayline that includes a low-pass filter in its feedback loop. The excitation is derived from a very simple non-linearity of the form,

$$f(x, y, s_{t-d}) = \begin{cases} (y - s_{t-d})^2 & \text{if } (y - s_{t-d}) \geq x \\ (y - s_{t-d}) & \text{otherwise} \end{cases} \tag{1}$$

where each new sample, s_t, is obtained as a function of s_{t-d} = value returning from the delay line, x =pressure control, and y =velocity control.

The delay length, d, is held constant in the simulation, resulting in a fixed period length $2 * d + 1$, after accounting for one sample of delay accrued in the low-pass filter. Figure 1 shows the result of running the simulation with $d = 5$ in which the same time-series is displayed three ways. The third plot, which highlights period-by-period fluctations, is based on a method first discussed in [4]. This new version displays fluctations as a ratio of each period against a reference period (in dB) rather than its difference.

The nonlinearity is bypassed unless the differential velocity $y - s_{t-d}$ exceeds the pressure control term. When this happens, the oscillation is being driven by the nonlinear product $(y - s_{t-d})^2$. Figure 2 illustrates a phase transition at this threshold. The dots are plotted at excitation samples in an overlay of the period-by-period difference plot of the previous signal. Approximately one half of the period is spent in a regime where the threshold is crossed only intermittently. The plot shows a system with constant con-

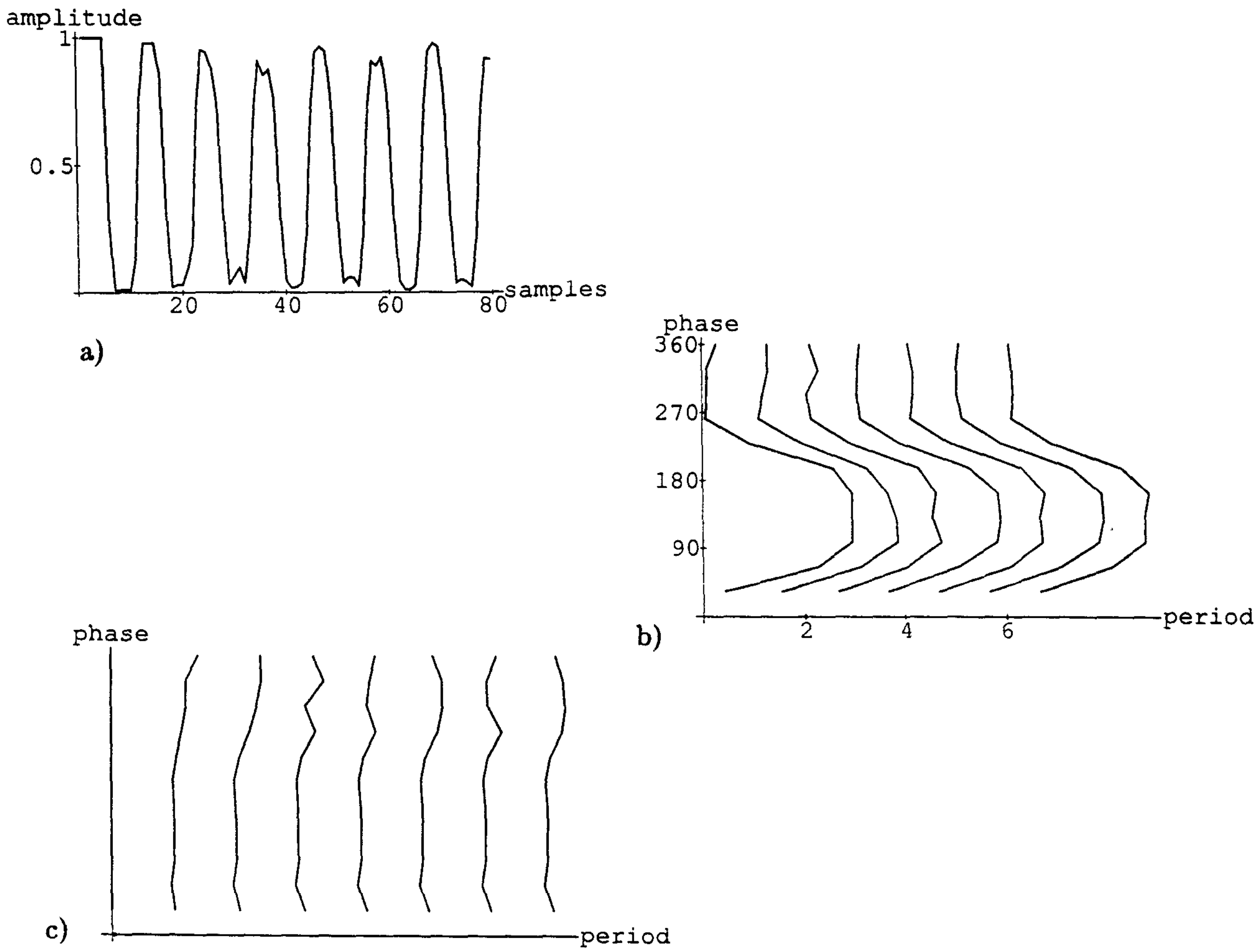

Figure 1: Waveform of a drastically simplified clarinet simulation a) continuous time-series b) period-by-period time-series and c) period-by-period ratio with the first period

trol parameters settling into an equilibrium (its limit cycle oscillation) after an initial transient has died out. So far, no noise or other perturbations are added. If the pulse noise mechanism were enabled, noise values would perturb the oscillation only at the points exceeding the phase transition threshold.

Extending the duration to 48 periods in Figure 3, it is apparent that excitation passive switching during equilibrium is chaotic. Short-lived patterns are evident, skipping 2, 3 or 4 periods before the threshold is passed.

To test the dynamics of the system for transient response to noisy perturbations, a single sample was changed at a point in the signal after the starting transient. The change then reverberated in succeeding periods. Since the simulation is perfectly repeatable, a convenient display is made

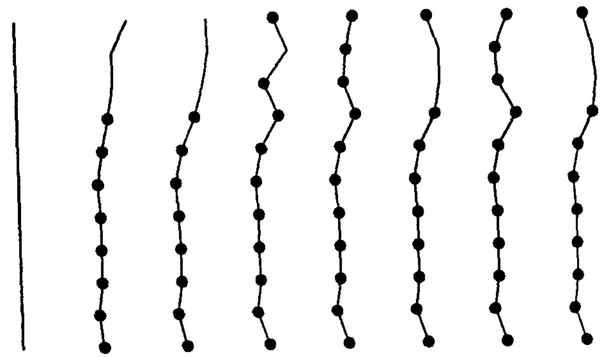

Figure 2: Phase transition threshold.

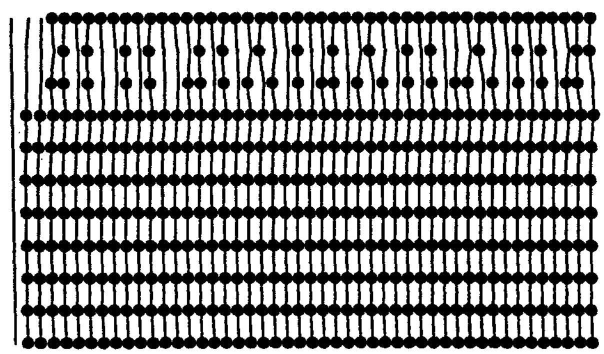

Figure 3: Longer view of phase transition threshold.

by drawing the difference plot of the perturbed signal and then erasing the lines overlayed by a plot of the unperturbed signal. The remaining display graphs the effect of the perturbation, Figure 4. Resulting transients varied depending on where in the period the perturbation occured.

Subharmonics in musical tones can be explained in at least three ways. Schumacher has demonstrated subharmonics in the french horn and clarinet near the pedal tone under an overblown note. He explains that such *resonance subharmonics* arise from some coupling with the roundtrip path of the low tone [4].

Another type of subharmonic is suspect in situations other than those involving passively coupled resonances. The problem is to identify the delay path corresponding to the subharmonic periodicities observed. Where is the

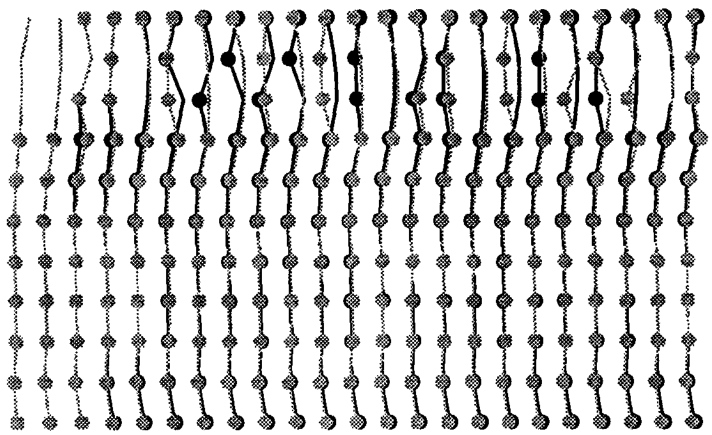

Figure 4: Effect of one perturbed sample on stability. The dark areas show differences from the same, but unperturbed, oscillation.

system memory that can correlate features over a time span greater than one period?

A theory developed in regard to the bowed string accounts for another path that skips numerous periods [3]. An instability is repeatedly reflected off a sticking bow until it meets a slipping event and can pass through to the other half of the string. In terms of timing (only), the effect is like the beating of two frequencies, that are coincident in phase at some longer period. Again, the subharmonic path depends on coupled resonances, though in this case it is comprised of shorter, sub-period resonance paths coupled by an active gating mechanism that opens only at the coincident delay interval.

The present clarinet simulation contains only a single resonance, so a third mechanism must be at work. The present explanation involves the self-regulating behavior of the excitation–feedback system. At the start of a constant (non-noisy) tone, an alternating pattern of waveform periods is set up that decays away until the system converges on its limit cycle (steady state oscillation). Once the limit cycle oscillation has been reached, a single perturbed sample can evoke another transient alternating pattern, as shown in Figure 4. Single transient events can combine to form subharmonic patterns becasue of the self-regulating property. A returning noise pulse inhibits the possiblity of a subsequent pulse, and instead damps it. The opposite condition is also true, a damped value returning to the input can result in a new noise pulse. Such a mechanism would at least account for subharmonics at twice the period.

Subharmonics with a much longer period are frequently found, for exam-

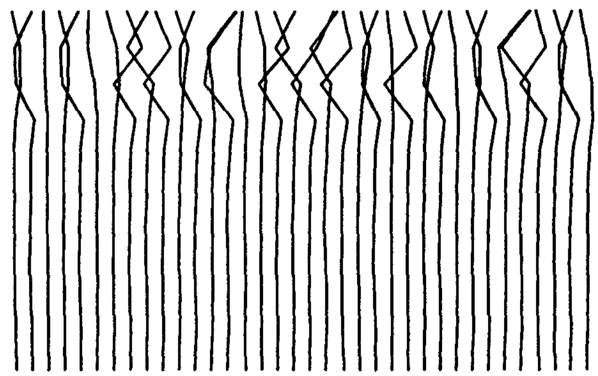

Figure 5: Pulsed noise included in the simulation.

ple subharmonic 10 is prominent in the french horn [4]. Longer periodicities are also present in the present simulation. Figure 5 shows the effect of incorporating pulsed noise, accomplished by adding up to $.5dB$ of gain randomly to the the excitation function output when the threshold in the excitation function is exceeded.

The series of plots in Figure 6 are another view of the data. Horizontal slices plot values for each of the 11 phase points period-by-period. Different subharmonic cycles are found for the various phase points and some insight can be gained about their relationship. Adjacent phase points seem to interact. The probable mechanism to account for influence between neighboring phase points is the one-zero low-pass filter in the feedback loop.

The conclusion is reached that the noise creates *micro-transients* which keep an otherwise stable system in a perpetual transient state. Complexes of subharmonics are spawned intermittently and can contain numerous periodicities. The existence of shorter or longer cycles is due to period synchronous noise pulses directly affecting some phase points and not others. The effect is combinatorial: short-period subharmonics foster growth of longer term subharmonics at neighboring phase points. Imperfect reflection boundaries, such as the low-pass filter in the simulation, are implicated in the process. Averaging of nearby phase points would occur at the clarinet bell, tone holes, the mouthpiece and at string terminations and the bow contact point.

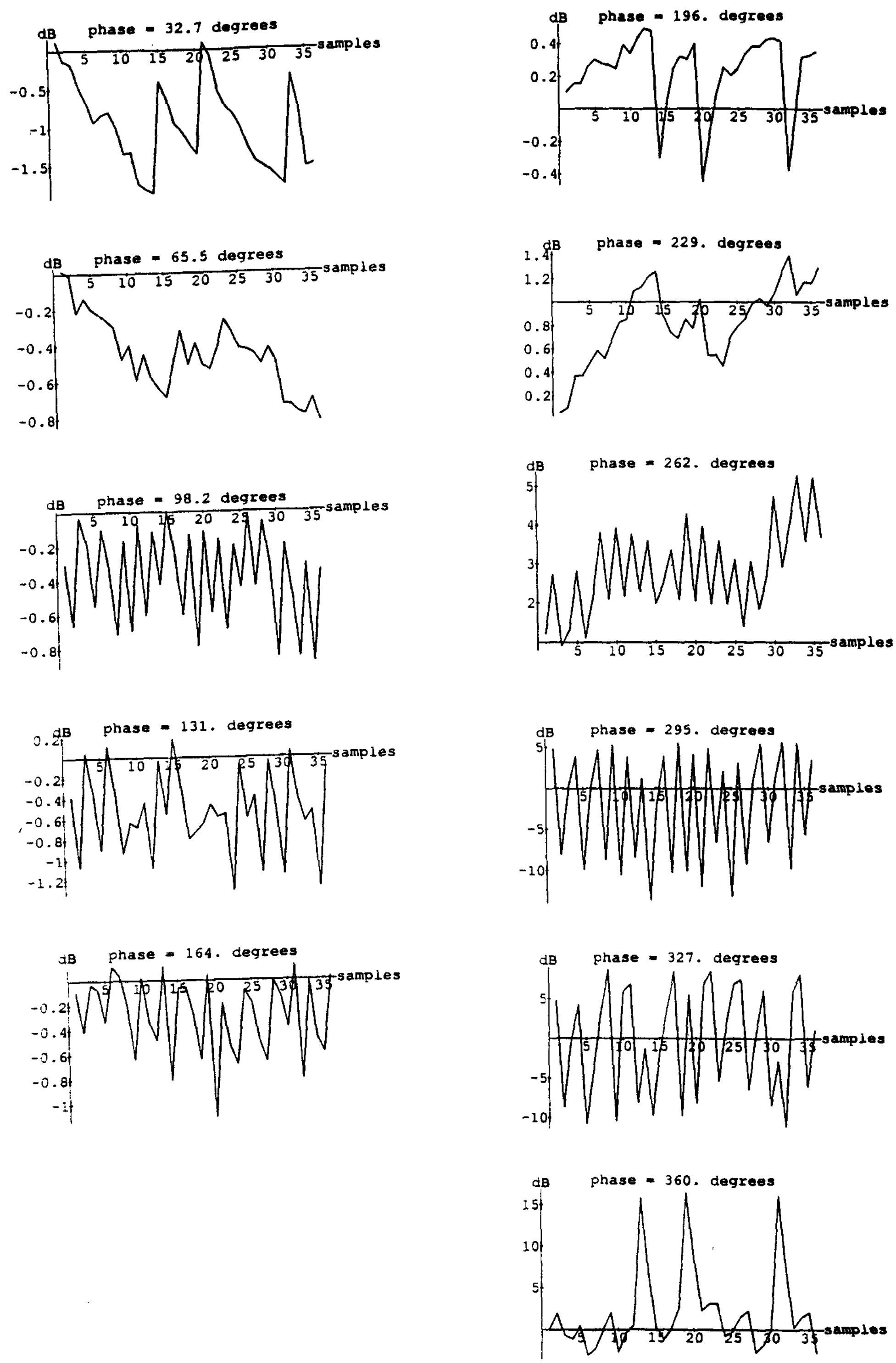

Figure 6: Plots of each of 11 phase points across succesive periods. Samples indicate period number.

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