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PULSED NOISE IN SELF-SUSTAINED OSCILLATIONS OF MUSICAL INSTRUMENTS

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ABSTRACT

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.

I. INTRODUCTION

Adding noise to improve models of bowed strings and wind instruments has become a focus of study. Precise quality of the noise is important in achieving an improved sound synthesis capability, and mixing in spectrally shaped Gaussian noise has not proved sufficient. There is no fusion and the listener hears two sources. A subjective impression from the best attempts is that the noise is "not well-incorporated." Though not a common evaluation in acoustic parlance, the meaning will become evident in the following study.

Self-sustained oscillators, such as strings and winds, are set into vibration when energy is applied through bow motion or breath pressure. Excitation is governed by a non-linear driving function – either the frictional characteristic of the bow hair or a relaxation mechanism like a reed, a switching air jet or the lips. Stability and pitch of the resulting oscillation depends on wave motion in the resonant element of the system (the string or bore) that is fed back into the excitation function. Simulations based on this description of an instrument's mechanics are implemented on digital computers and are broadly classed as *physical models.*Figure 1 and Figure 2 show circuit representations of a violin and a clarinet in these terms.

The components of these circuits fall into two categories: non-linear junctions (which excite the system) and elements of resonant networks (which model characteristics of acoustic wave-guides). Non-linear junctions have been implemented either as algorithms to be computed at each time sample or as table-lookup functions. In either case, a non-linearity is expressed which mimics the behavior of the driving element: the bow or the reed.

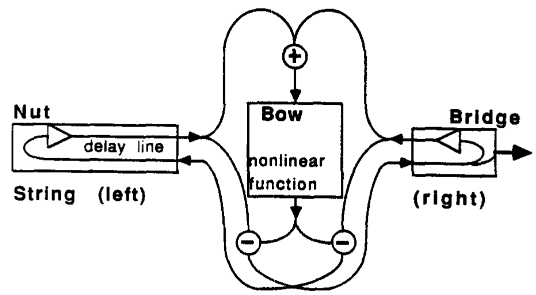

Figure 1: A *lumped circuit* representation of a bowed string, in which the string is broken into 2 resonant sections separated by the bow. The resonant elements are simplified as a single filter and delay-line.

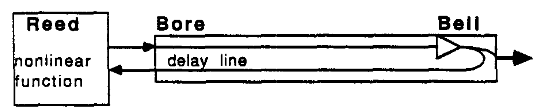

Figure 2: A clarinet.

For example, Equation 1 is an algorithm which determines the stick-slip phenomenon in bow-string interaction.

$$sv_t = \begin{cases} H(bv_t, bp_t, sv_{hist}) & \text{if } (bv_t - sv_{hist}) \geq (bp + 1.) \\ (bv_t - sv_{hist}) & \text{otherwise} \end{cases} \quad (1)$$

At each time sample, the current contribution from the junction into the string, sv_t, is dependent on sv_{hist} which may contain earlier excitations reflecting back to the junction from the string's terminations. Junction control parameters, bv_t and bp_t, specify current bow velocity and bow pressure. The function H is a characterization of slipping friction as described in [1]. During play, energy is imparted to the string when $bv > 0$. The string, at first stuck to the bow, is pulled from its resting position until its restoring force overcomes the sticking friction (governed by *bp*, the downward force on the string). It then releases from the bow, flying back to the point where it is recaptured and another cycle begins. The rapid flyback motion generates an impulse which propagates down the string and will provoke the next release one period later (the time interval of a round-trip on the string).

The clarinet differs in that it has a single resonant section coupled to the nonlinear junction and that the nonlinearity is characteristic of a reed. The basic dynamical interactions between excitation and resonance which govern the oscillation are the same.

II. PRODUCTION OF NOISE

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 narrows, the noise emitted would be unmodulated. However, in terms of the string travelling along the bow hair, the string spends the major portion of its time at successive sticking points. Each release jerks it along an interval of bow generating a sequence of noise pulses as the string periodically scrapes the bow hair. Air rushing into a woodwind mouthpiece creates turbulence at the reed aperture and is pulse modulated as open – close phases alternate. The pulse width corresponds to the duty cycle of the noisier phase, which is a parameter manipulated by the player's bowing or embouchure.

The bow contact position parameter, β, is determined by the ratio of bow-bridge distance to string length, in other words, the right delay length divided by the total delay length of the circuit in Figure 1. Contact position influences waveshape, for it determines the division of the period into equal segments some of which appear as *crumples* (see Figures 5 which has a β of ca. 12%). The abrupt flyback is another segment and roughly corresponds to noise pulse width. It lengthens with larger β (as the waveform is divided into fewer sections).

III. ANALYSIS OF RECORDED TONES

For verification, it was decided to apply a recently devised sound analysis package, based on a deterministic plus residual model, to look for noise pulses in bowed string waveforms. The method has been designed to separate the sinusoidal components of a sound from noise, or *non-deterministic* components, ultimately to be able to resynthesize a tone with modifications to either domain. The method works by tracking observable partials through successive FFT frames, building up a record of their frequency, amplitude and phase fluctuations. The signal is then regenerated from a bank of sinusoid oscillators following the analyzed data. This creates a noiseless facsimile of the original. The deterministic components are represented by

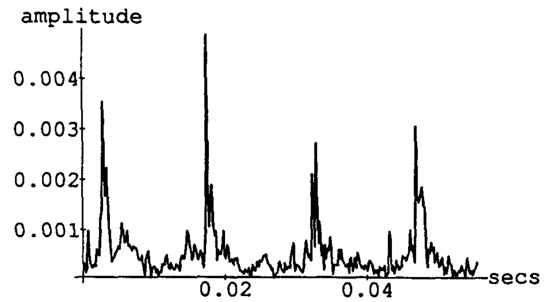

Figure 3: Noise pulses extracted from a signal digitized from the *Celletto*. The pitch of 65Hz corresponds to its open 'C' string. Bow contact position is very near the bridge with β ca. 2%.

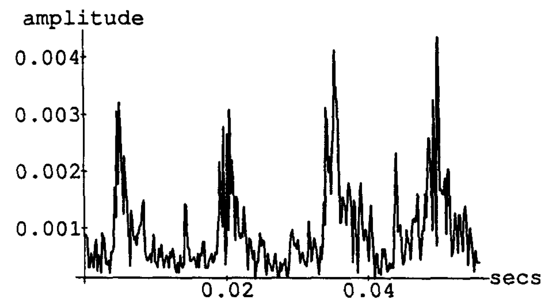

Figure 4: $\beta = 11\%$

$$s(t) = \sum_{r=1}^{R} A_r(t) \cos[\theta_r(t)] \tag{2}$$

where R is the number of sinusoids, $A_r(t)$ is the instantaneous amplitude, and $\theta_r(t)$ the instantaneous phase determined by

$$\theta_r(t) = \int_0^t \omega_r(\tau) d\tau + \theta_r(0) + \phi_r \tag{3}$$

where $\omega_r(\tau)d\tau$ is the instantaneous radian frequency, $\theta_r(0)$ is the initial phase value and ϕ_r is the fixed phase offset. A final transformation extracts bow or breath noise by subtracting the new signal from the original [2].

Figure 3 shows the existence of the predicted noise pulses after processing removed periodic components from a digitized cello tone using the above technique. The amplitude envelope is plotted for 4 periods. Tones were played on the *Celletto*, a body-less, electronic cello with piezo-ceramic transducers inlayed in the wood of the bridge directly beneath each string.

Figure 4 compares a tone played with higher β. The predicted lengthening effect on noise pulse width is apparent.

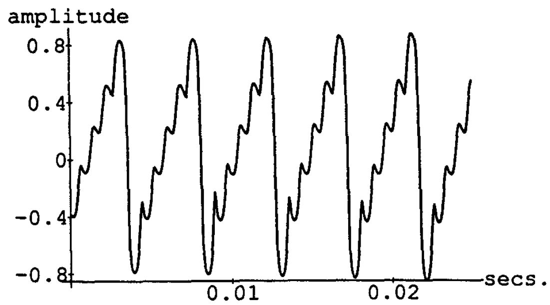

Figure 5: Simulation of a cello tone of 220Hz.

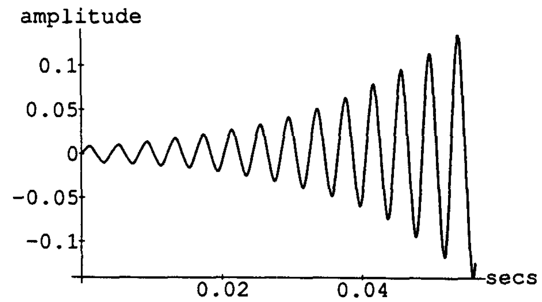

Figure 7: Simulation of a clarinet tone of 220Hz.

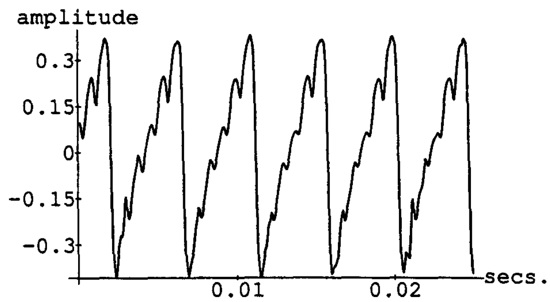

Figure 6: Noise incorporated in the slipping portion of the simulation method is most noticeable as instabilities in waveform *crumples*.

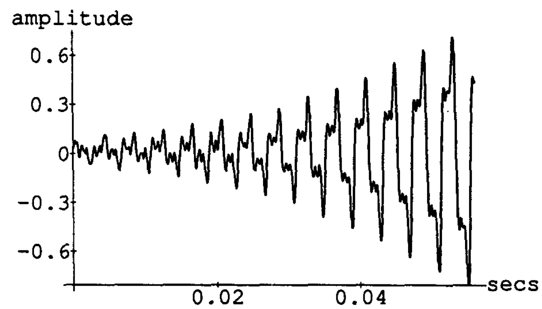

Figure 8: Noise incorporated in the wider aperture portion of the reed duty-cycle.

IV. SIMULATION OF TONES

Adding noise to Equation 1 entails a modification of the slipping portion of the period. In Equation 4, slipping output is perturbed by a noise function, $N(x)$. Its noise term, $u(n)$ in equation 5, is non-negative uniform noise. The slipping force is multiplied by noise that is offset by O and scaled by G. The *coarseness* of $N(x)$ is governed by P, which controls the percentage of samples that will be perturbed by randomly controlling frequency of noise sample inclusion.

$$sv_t = \begin{cases} N(H(bv_t, bp_t, sv_{hist})) & \text{if } (bv_t - sv_{hist}) \geq (bp + 1.) \\ (bv_t - sv_{hist}) & \text{otherwise} \end{cases} \tag{4}$$

$$N(x) = \begin{cases} x \cdot (O + Gu(n)) & \text{if } u(n)) > P \\ x & \text{otherwise} \end{cases} \tag{5}$$

Figures 5, 6 and 7, 8 show the effect of incorporating noise during the sustained portion of a cello simulation and during the starting transient of a clarinet simulation (values were $O = .05, G = 4.0, P = .5$).

V. EVIDENCE FOR A ROLE IN THE PRODUCTION OF SUBHARMONICS

Traces of subharmonics are often present in musical tones, and are detectable using the DFT or the time-domain method introduced in these Proceedings [3]. Subharmonics have been absent from previous simulations of sustained bowed string tones. After starting transients have died out and the system stabilizes, periodicity is quite exact. Applying the $\mathbf{NORM}^{i,j}$ difference technique of [3], simulations with and without pulse noise were compared for subharmonic features. The result is that bow noise generated with the above method also generates sustained subharmonics, and moreover, control of subharmonic number is accomplished by varying β.

Figure 9 is a long (.4 sec.) DFT of a simulated cello note and Figure 10 is a DFT of the same tone with pulsed noise present. Portions of the original waveforms are shown in Figure 5 and Figure 6. The fundamental at 220Hz and its first overtone are displayed, and subharmonic features generated by incorporation of noise can be seen at -40dB in the vicinity of 100Hz.

The 1760Hz violin tone described in Section III. of [3] was simulated with bow noise and with a continuous change of β. The waveform locks into divisions of 6, 5, 4 and 3 parts as β increases. After extraction, the non-deterministic components reveal the characteristic D-minor arpeggio (the subharmonic series of pitch 'A') which is audible in the natural tone. The timbre that is heard sounds like band-passed noise whose center moves between the subharmonic pitches.

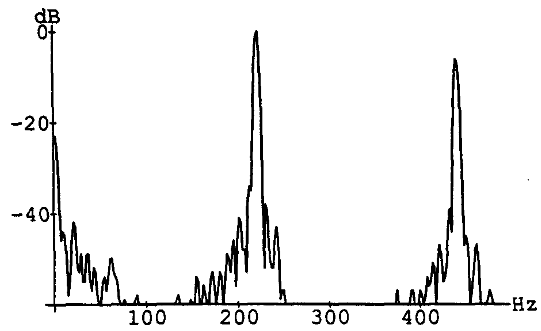

Figure 9: DFT of cello simulation without noise generation method showing the first 2 harmonics of a 220Hz pitch.

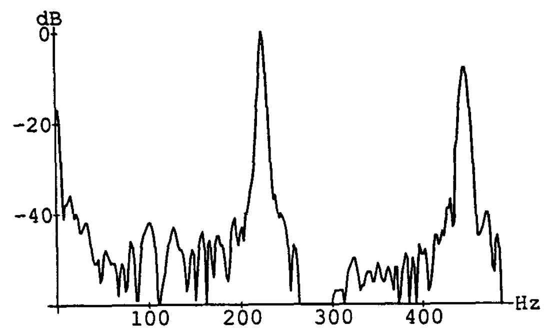

Figure 10: DFT showing subharmonic features when the noise generation method is included in the simulation. The most prominent peaks below the fundamental are possibly harmonics of very low subharmonics (see discussion in [3]).

The supposition can be made that some subharmonic features are very short-lived, enough so that they "sneak by" the deterministic analysis and remain in the residual. If so, it would seem that bow noise is implicated in causing *micro-transients* during sustained bowing and that the *micro-transients* give rise to subharmonic features in the waveform. Further work is needed to describe the mechanism responsible.

VI. THE GLOTTIS

In singing and speech, voiced-fricatives exhibit a pulsed noise component. The unvoiced-fricatives of English, for example /s/, constrict the air passage in a manner that produces audible, continuous, turbulent noise. Their voiced counterparts use an identical vocal tract shape which is driven by glottal impulses rather than a continuous incoming air stream. In the case of /s/, this produces /z/. The two words, "loose" and "lose", demonstrate the unvoiced - voiced distinction.

The digital-formant synthesizer of Rabiner [4] implements pulse modulation of its frication generator for production of /z/. Pulse waveshapes are manufactured from the glottal pulse train (passing the signal through a resonance followed by half-wave rectification) and are used to amplitude modulate a continuous friction source. The resulting period-synchronous noise pulses are added into the voiced signal.

VII. CONCLUSION

A theory of bow and breath noise generation has been tested by analyzing recorded cello tones and by simulation using physical models of the cello and clarinet. For the synthesis to be successful, the percept of noise must fuse into the sound. Evidence has been presented that the noise must be pulse modulated in a period synchronous way, as has been shown for voiced-fricatives.

A distinctive feature of the musical instruments studied is the strong dynamical interaction between the excitation mechanism and a high-Q resonant system. This is not the case in the vocal tract, where feedback to the glottal source from the vocal tract is thought to have less effect on the overall regime of oscillation and where the source of noise is apart from the glottal excitation. Fricative noise is generally caused by constrictions at the other end of the tract. Noise at the excitation in a strongly coupled system apparently has an effect on subharmonic features.

The conclusion is reached that the noise creates *micro-transients* which keep an otherwise stable system in a perpetual transient state. The noise is "well-incorporated" in the sound by its period-synchronous timing and perhaps by its influence on short-lived subharmonic features. That the center pitch of the noise follows the subharmonic series seems a good indication.

A method has been described which is practical for enhancing naturalness of synthesis from physical models. No additional control parameters are required. Changes in the noise sound follow in a predictable way control changes in bowing, breath and embouchure parameters in the simulations.

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