Adding Vortex Noise to Wind Instrument Physical Models

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ABSTRACT: Flutes and other switching air jet instruments do not exhibit period-synchronous pulsed noise. However, period-synchronous spectral changes were detected in a flute tone. A synthetic flute model is described which imitates turbulent qualities of breath noise with a *vortex noise generator*circuit.

1 Introduction

Noise in bowed stringed instruments and many other musical oscillators exhibits distinct pitch-synchronous amplitude pulses (Chafe, C.). Synthesis quality has been improved by coupling a pulsed noise mechanism to the basic physical model of these instruments. Edge-tone instruments such as flutes and organs are an exception. In the present study, their breath noise is shown to have pitch-synchronous spectral features and a more constant amplitude contour.

Turbulent noise caused by the switching air jet of edge-tone type instruments includes vortex formation and shedding in three dimensions (Verge, M.). As the player excites the air column into oscillation by blowing across the edge, the air jet at the mouthpiece begins to rapidly alternate direction in time with the column's vibration. The process elicits both frictional noise at the constriction where air enters the pipe and air puffs that roll away as the returning pressure wave impedes the entering flow. The formation of vortices and modulation of fricative noise is regulated by the oscillation of the air column. When the instrument starts to "speak," these are timed by its pitch. The hypothesis that prompted the present investigation is that though breath noise appears fairly constant in amplitude, periodic vortex shedding suggests a source for spectral modulation.

2 Analysis of Pitch-Synchronous Spectral Change

Recordings were made from a plastic "research" flute with no tone holes. Breath noise was extracted from audibly stable portions of tones and examined for pitch-synchronous features. The extraction method used an adaptive linear pitch predictor which allowed the predicted (periodic) signal to be removed (Cook, P. 1993). Spectral fluctuations in the residual (breath noise) signal were detected via transformation to medium-width frequency bands. These fluctuations were projected against the original waveform to reveal pitch-synchronous and longer-term features.

Pitch-synchronous noise extracted from a bowed cello tone is pulsed in comparison with the flute in Figure 1. The latter was further analyzed for the possibility of fast time-varying spectral changes. The noise residual was transformed with a Hamming window and 64-point Fast Hartley Transform. The analyzed tone had a pitch of 204 Hz. and was recorded at a sampling rate of 44100 kHz., resulting in a frequency resolution of approximately 690 Hz. per bin and a temporal resolution

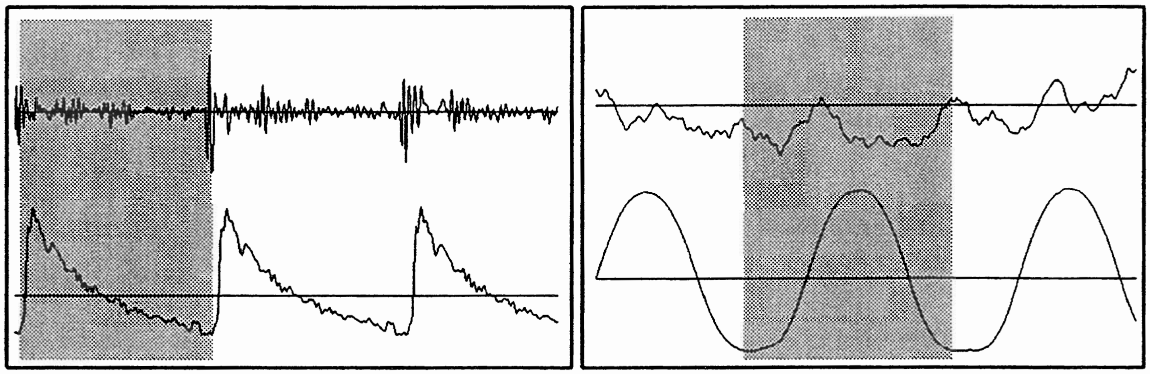

Figure 1: *Pulsed noise is detected in the residual (top traces) of a cello waveform (left) but not in a flute waveform (right).*

of one third of a period per window. Hopping every 8 samples, 27 transforms were measured per period.

A new display method was developed to detect pitch-synchronous features based on a two-dimensional phase portrait of the oscillation. For each time sample in the original flute tone (not the residual), a point is plotted in two dimensions whose axes are instantaneous amplitude vs. instantaneous amplitude at a given time delay (approximately one-quarter of a period). When many periods are plotted, an average cyclic shape emerges. Stable portions of the duty cycle of the oscillation are sharply defined. Variable, or noisier parts of the cycle are visible as blurred regions. Only the extent of variability is observable and the period-to-period structure within these regions is not resolvable.

To better resolve individual period-to-period differences, the phase portrait was projected onto a time spiral, thereby separating each period. In Figure 2, time begins at the perimeter and spirals inward. One orbit around the graph corresponds to a full period of the waveform. The trace can be colored according to spectral qualities of the residual signal at the same instant in time. RGB color balance is directly controlled by (logarithmic) magnitudes of three bins chosen from the spectrum analysis. Here, something similar is rendered in monochrome by displaying an offset from neutral gray. Lighter / darker variation depicts the magnitude difference between bins 4 and 8 (2400 and 5200 Hz.) of the time-varying frequency transform. Color versions can be seen in (Johnstone, B.).

Angular regions (pie slices) with lighter or darker features indicate changes which are pitch-synchronous. Alternation between regions at differing angles is consistent with the notion of of periodic vortex shedding governed by the switching air jet. Longer-term features are evident, where after many periods, the angular position of lighter and darker regions reverses. The presence of multiple quasi-stable regimes suggests modeling the system with chaotic components.

3 Synthesis of Vortex Noise

Detailed three-dimensional modeling of vortex formation is a challenging problem in fluid dynamics. It would be overkill for music synthesis via physical models that are (at the present time) largely one-dimensional. The *Exhaust Pipe* is an example of an efficient, realistic physical model of the flute based on a one-dimensional waveguide (Cook, P. 1995). A reasonably efficient vortex-like noise circuit has been added to enhance its breath noise component.

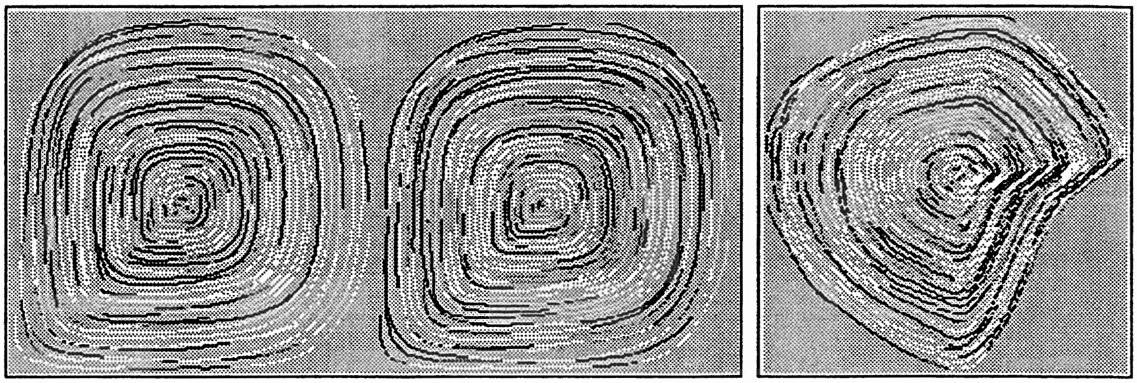

Figure 2: *The left pair shows a phase portrait of a flute tone projected onto a time spiral where time progresses inward. Shading indicates spectral balance in the extracted noise. The tone was simultaneously recorded at two microphones: one outside and one inside the wall of the flute, just off the mouth hole. Note the complementary aspect of spectral balance at many instants – where one is light, the other is dark. A synthetic tone appears at the right. Because it is richer in some harmonics, the overall shape has changed, but the structure of fast time-varying spectral features is similar.*

Vortex-like behavior can be mimicked by a simple one-dimensional chaotic oscillator. By analogy, its behavior represents the effect of vortex shedding on one point in space as successive whorls pass by, Figure 3.

An iterated quadratic map was chosen as the source of chaotic oscillation. The quadratic's coefficients were found with an automated search suggested in (Sprott, J.), run over a range of values suited for the fixed-point implementation of the real-time flute model . The values picked can produce a strange attractor; nearby values are rich in widely varying behaviors. Within the region, the map can produce a variety of spectral mixtures with differing amounts of periodic and random components.

According to the hypothesis, spectral content of the vortex noise generator needs to be modulated pitch-synchronously. Signal-dependent control of one of the map's coefficients creates this effect. For the map: $x(n) = a + bx(n-1) + cx(n-1)^2$, a unit generator was designed with coefficient b as an input. Varying this term causes the unit generator to traverse the region containing the map's variety of behaviors. Pitch-synchronous modulation of spectral content is accomplished by controlling b with the flute's oscillating signal.

Noise injection is somewhat more complicated than before: originally, output of a random number unit generator was directly mixed with incoming breath pressure. In the present form, vortex noise is also allowed to interfere with the operating point of the flute's non-linear excitation function, $ax + bx^2 + cx^3$. The noise very lightly modulates the cubic polynomial's coefficient a. Slight changes affect the regime of oscillation of the system, which in turn affect modulation of the vortex generator in a highly complex way.

4 Evaluation of Results

The resulting breath noise is well-incorporated in the tone, as opposed to noise that seems to arrive from another source and is simply mixed with the original. The spectral analysis on the right in

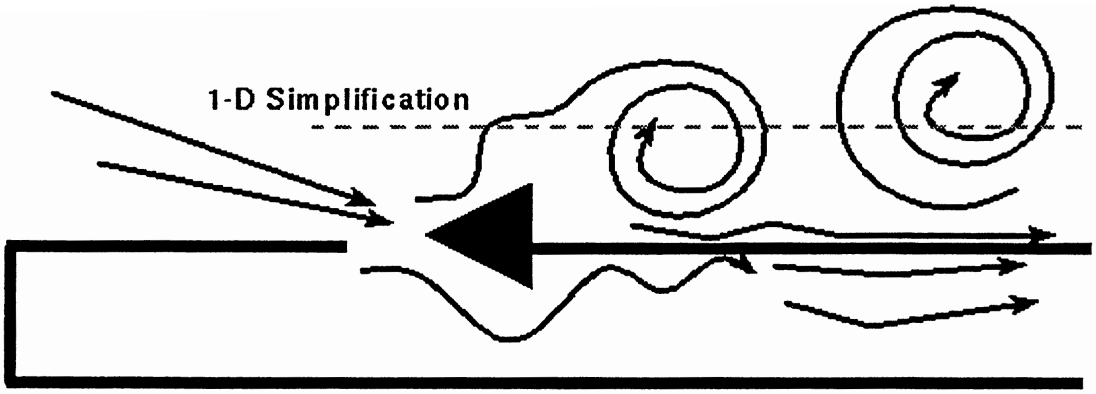

Figure 3: *Edge-tone vortex shedding can be simplified by emulating its effect measured at one point in space.*

Figure 2 shows that the synthetic tone compares well with the natural tone in mimicking pitch-synchronous and longer-term spectral features. Sub-period pitch-synchronous alternation of noise spectra is present, and longer-term shifts are present in the phase position of the regimes. The instrument also seems to speak more easily.

No new performer controls are required. The vortex unit generator is essentially governed by blowing pressure. It is quiet if there is no pressure, it begins hissing at the first onset and then changes to a pitch-synchronous sound after the tone "speaks." Voicing alternatives are possible by varying the amount and quality of vortex noise; these can yield different flute types, levels of breathiness and distance effects.

It is likely the technique may apply beyond air jet instruments, for example to the glottis and other winds such as single, double and lip reeds. Common to the group is the existence of an excitation mechanism that possibly incites some degree of periodic vortex shedding.

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