Musical Signals from Chua's Circuit

Gottfried Mayer-Kress, Insook Choi, Nicholas Weber, Robin Bargar, and Alfred Hübler

Abstract— **Chua's circuit can produce a very rich variety of signals that are both periodic and chaotic. We explore some classes of these attractors with respect to their auditory display and musical properties. We discuss the fast control of the circuit through a specially developed computer-controlled electronic resistor and how chaotic control methods might be applied to optimally switch between different attractors. The Chua circuit has parameter regions where noisy frequency and amplitude modulated sounds are generated, each of which is related to a certain transition to chaos. We discovered a period-adding sequence of bassoon-like sounds that produces interesting almost harmonic pitch changes. Finally, we emphasize the importance of transient dynamics especially in the context of percussion-like sounds.**

I. Introduction

The ENORMOUS variety of attractor classes that can be realized by the Chua circuit makes this circuit an excellent candidate for a universal signal generating standard [1]–[3]. We want to investigate these properties in the context of sound synthesis and musical composition [4].

Sound synthesis as a field of research for composers involves the design of the sound structure at a microscopic level [13]. The concern for design at that level reflects composers' interests in auditory information potential. Composers investigate and develop sound synthesis capabilities as a means for rendering intelligible structures in sound. A related field of research is the design of sounds modeled after existing musical instruments (see, for example, [5]–[11]). The common concern of synthesis and composition is the generation of microscopic events that contribute to macroscopic auditory patterns.

II. Auditory Characteristics of Musical Signals

Informative characteristics of sound are closely associated with the structure and dynamical behavior of the spectrum of the sound, including the number and distribution of peaks, their characteristic contours, and the rate and relative periodicity of their change over time. Musical applications of these signals rely heavily on these properties for encoding complex messages. Many of these signals exhibit nonlinear behavior.

The application of voltage-controlled linear transformations of periodic waveforms provides poor models for the complex behavior of musical signals. The Chua circuit has a remarkable capability to produce sounds that inherently display many sought-after characteristics that are difficult to construct using traditional synthesis methods. These include its capability to perform as a signal generator and as a control device as well. In light of the traditional sound synthesis resources, the Chua circuit provides a radical and innovative approach to sound design based on the understanding and control of chaotic attractors.

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III. Noise Content of the Signal

Noise is present in every musical signal. Composers have long been aware of noise as an important aspect of musical signals, noise which often takes the form of an intentional interference with an established pattern to generate alternatives. In acoustic instrument performance, small amounts of noise may be intentionally introduced to add colors to the inflection; additionally, the attack and decay portions of an acoustic instrument sound carry a substantial amount of noise that characterizes an instrument with its unique auditory signature. Experienced performers are able to finely control the amount of noise that the instrument generates on top of the harmonic spectrum. Some Chua attractors produce sounds reminiscent of the wide range of dynamics of these efforts to achieve well-controlled tones in acoustic instruments.

Some performers display their ability to control the amount of the intentional noise injection to their sounds as well as the ability to produce finely controlled tones. When the performance of these two sides of tone production is well composed, it is musically intriguing since the audience is given an opportunity to observe the tone production that explores the boundary between periodic and chaotic charateristics of sounds.[1]

With the Chua oscillator, we are able to add noise to harmonic sounds that are of different types related to the transitions to chaos that occur close in parameter space to the harmonic signal. We can identify and demonstrate the following classes: chaotic amplitude modulation, chaotic waveform modulation, chaotic mixing of periodic elements, and intermittent glitches. The transitions to chaos that are associated with these types of noise are subharmonic period doubling, torus breakdown, intermittency, and mode-locking resonance overlap. In the following, we discuss the sonic properties at the onset of chaos with the help of the examples provided in the gallery of attractors in [2]. All the parameters have been chosen to reproduce those examples.

[1] This parameter region is often loosely referred to as the "edge of chaos."

A. Period Doubling

In the Table 2 examples 2.3, 2.5, and 2.6 in [2], we observe an increase in band-limited noise that preserves the pitch characteristic of example 2.1, which is a frequency we refer to as the tenor[2] of the period-doubling route to chaos. A further characteristic is that the frequencies of the noise bands lie beneath the frequency of the tenor. In 2.6, the broad noise band still contains an emphasis of the original tenor, although it appears to be several octaves lower, and it is largely obscured by the noise.

B. Intermittency

In [2], the Table 3 examples 3.1, 3.2, 3.3, 3.4, and 3.6 provide a common tenor frequency of 1052.63 Hz. Noise appears first as brief interruptions of a steady pitch (example 3.3); this noise sounds band limited in a frequency range below the tenor. In subsequent examples, noise increases, becoming continuous but remaining weaker in amplitude than the tenor (in contrast with period-doubling noise, which gains much higher amplitudes than the tenor). The noise does not contain spectral energy above the mid-range (approximately 1000 Hz). In example 3.6, the noise is lower in amplitude than example 3.3, showing that increases in the control parameter do not always result in a greater noise level.

C. Torus Breakdown

Comparing, in [2], Table 4 examples 4.1, 4.2, 4.3, 4.5, and 4.6, we observe that torus breakdown does not preserve a consistent tenor as period doubling did. Torus breakdown produces multiphonics from complex amplitude modulation. Each example combines two distinct pitches; these do not offer a simple relationship between themselves nor between one example and the next. Broadband noise first occurs in example 4.6.

We want to emphasize that each of the above cases (period doubling, intermittency, torus breakdown) has an often large harmonic content in the signal. It is different from the noise that we perceive from broadband chaotic attractors, which is more reminiscent of white noise. Without necessarily reproducing models of traditional instruments, sound synthesis techniques can also make effective use of the differentiations that noise provides when combined with a harmonic signal.

IV. Filter Characteristics

Many sounds from Chua exhibit the characteristics of filtered white noise or filtered complex tones, particularly band-pass filtering. The technique of filtering has been adopted in traditional sound synthesis as subtractive synthesis [16].

This filtering effect in sound synthesis so far has been achieved by passing the audio signal through a separate processor, which is a filter. The significance of these filtering characteristics in the Chua circuit is that now we can achieve this effect at the level of sound generator. The Chua circuit provides filter-like effects that do not depend on the use of a separate filter module in the sound processing pipeline. This occurs when a change in a Chua parameter does not affect the pitch of the resulting waveform but redistributes the spectral energy, attenuating some frequency bands while amplifying others.

[2]There is no terminology in music to refer to a counterpart to the fundamental frequency of a complex tone, which a series of higher partial frequencies are built upon. In order to express the frequency that carries subharmonics, we propose the term tenor frequency. The differences between the sounds of examples 2.1, 2.2, and 2.3 are nearly indistinguishable.

V. Complex Transients to Attracting Fixed Points—Envelope Characteristics

Whereas in science the main interest is focused on stationary and asymptotic states, in music, the main focus is on transients and finite time dynamics. We know that invariant manifold structures of vector fields vary smoothly with parameters, whereas attractor sets generically are not structurally stable and might have fractal parameter dependencies. Therefore, we will expect that the transient dynamics will be determined by the stable manifolds of the fixed point that will characteristically depend on the region in parameter space. As a variant of this method, we can represent the structure of the unstable manifold of a fixed point by time reversal of a solution that diverges along the unstable manifold. For fixed points with complex eigenvalues, we always observe a characteristic frequency that corresponds to the imaginary part of the eigenvalues.

A similar inherent property that resembles the output of modular voltage-controlled sound synthesis is the Chua circuit's potential to generate envelope characteristics using attractor behavior. Envelope characteristics can be investigated in regions that have transitions toward fixed points. The attenuation of amplitudes approaching the fixed point resembles the slope of the attenuation of percussion sounds. The duration to reach the fixed point will define the shape of the envelope, and the transient characteristics will define the timbre. We experienced well-tuned percussive sounds when the transient characteristics were close to periodic, and enharmonic percussive sounds were experienced when the fixed point was approached by transients with intermittent noise characteristics. Initial conditions used to create a transient to a fixed point may be selected for the variety of envelope-like contours they can generate. These conditions may also be used to generate differences of timbre. One significance of these filter and envelope properties is that they are inherent to the Chua circuit and are not superimposed onto static waveforms as they are in traditional sound synthesis.

VI. Fast Control of Electronic Resistor

We obtained data from Chua's circuit with an electronic resistor (see the diagram in Appendix B) that allows very fast computer control of one of the parameters in Chua's circuit (significantly faster—10μs switching time—than the typical time scales of audio processes—25μs sampling time—for CD recordings). This control allows us to design sound events with a specific sequence of dynamical variables. For example, we can determine the temporal evolution of the sound spectrum, which is a characteristic that is especially relevant for recognizing acoustic instruments.

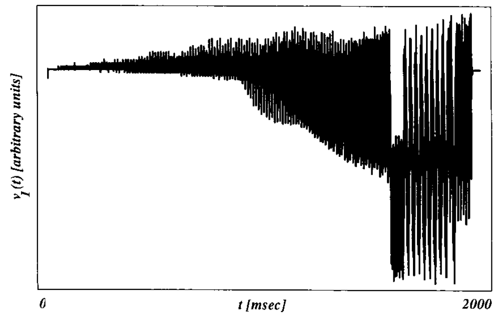

Fig. 1. Example of the response of the Chua circuit to a time-dependent resistor R.

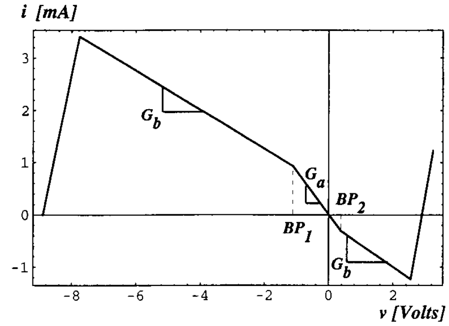

Fig. 2. Characteristic nonlinear resistor of our implementation of Chua's circuit.

If we drive the circuit with a signal that changes fast enough so that the attractor is never reached, then we observe a transient trajectory that can be interpreted as a distortion of the driving system. An example where the driving force is a ramped sine wave is shown in Fig. 1. During the large portion of the ramping, the sound increases in amplitude and spectral brightness while maintaining constant pitch. Toward the end of the ramping, the pitch descends in a leap by an interval of roughly 4:3 (a distance of roughly four semitones), which is a simple harmonic interval common in music.

In this example, the resistance oscillated at a frequency of 300 Hz with linearly increasing amplitude (detailed parameters are not available).

VII. Convex Sums of Vector Fields

One of the fascinating aspects of sound synthesis is the potential for the creation of completely new electronic instruments. We have studied a method of generating new attractors that inherit properties of two parent attractors. It basically consists of taking the convex sums of the vector fields thta generate the attractor. In [14], we could construct attractors that would interpolate between one of the Chua categories (example 5.3 in [2]) and the Lorenz attractor, except for a small gap where no attractors where found. Conditions for their existence and properties of these derived attractors will be presented elsewhere [14].

VIII. Multiple Attractors and Hysteresis

In many cases, multiple attractors exist for nonlinear dynamical systems. Depending on the initial conditions, the solution will tend to the attractor in whose basin of attraction the initial condition was contained. For a given initial condition, we can induce transitions to a desired attractor through change of parameters or external additive perturbations. The precise path along which these parameters are changed as well as the rate at which they are changed will determine which attractor will be reached. The systematic basis of these methods is given by optimal parametric or additive control [15]. In the context of musical instruments, especially wind instruments, this phenomenon is well known: The same air pressure applied to an instrument can result in different tones, depending on small preceding details. This creates an extra threshold of difficulty for learning to perform on a musical instrument; once mastered, it provides musicians additional controls for producing differentiated sounds.

IX. The Actual Electronic Circuit

The equations of motion for a Chua circuit are the following:

$$\begin{aligned} C_1 \frac{dv_1}{dt} &= G(v_2 - v_1) - g(v_1) \\ C_2 \frac{dv_2}{dt} &= G(v_1 - v_2) + i_3 \\ L \frac{di_3}{dt} &= v_2 + R_0 i_3. \end{aligned} \tag{1}$$

For our circuit (see Figs. 2 and 7)

C_1—48 nf	C_2—468 nf
L—100 mH	R_0—66Ω
VB_-—−10.19 V	VB_+—−3.71 V
B_{p1}—−1.1 V	B_{p2}—−0.38 V
$\hat{B}_{p1}$—−7.76 V	$\hat{B}_{p2}$—−2.25 V
C_a—−0.764 mA/V	C_b—−0.4085 mA/V
C^{-1}—R−1.6–2.1 kΩ.	

Here, R is computer controllable with an adjustment rate of 100 Hz, and $g(v_1)$ is the current through the nonlinear resistor as a function of the voltage across it. Ordinarily, the Chua circuit employs a $g(v_1)$, which is a nonlinear (often piecewise linear) function of v_1, which is shown in Fig. 2.

This i-v_1 characteristic can be achieved with op amps. In order that some oscillations not diverge, it is essential that $g(v_1)/v_1$ be positive for $|v_1|$ large. In our circuit, this $g(v_1)$ was made asymmetric by altering the supply voltages V_{B-}, V_{B+} of the op amp used in the antisymmetric $g(v_1)$. The two break points B_p and $\hat{B}_p$ are proportional to the negative op amp supply voltage, and the break points to the right are proportional to the positive supply. The slopes are a function of feedback resistors and do not depend on supply voltages. Therefore, by altering the supply of one voltage polarity, it is possible to bring the break points and hence the outer positively sloped portion closer to the origin while leaving the other side of the curve unchanged. The resultant

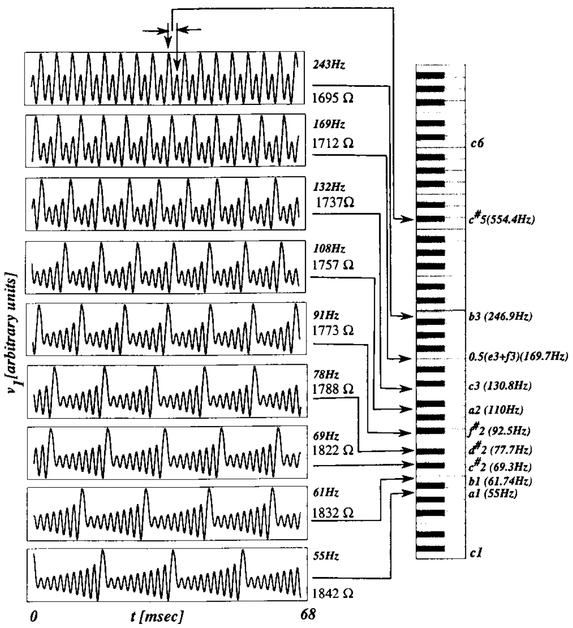

Fig. 3. Examples of bassoon sounds obtained through period-adding bifurcations.

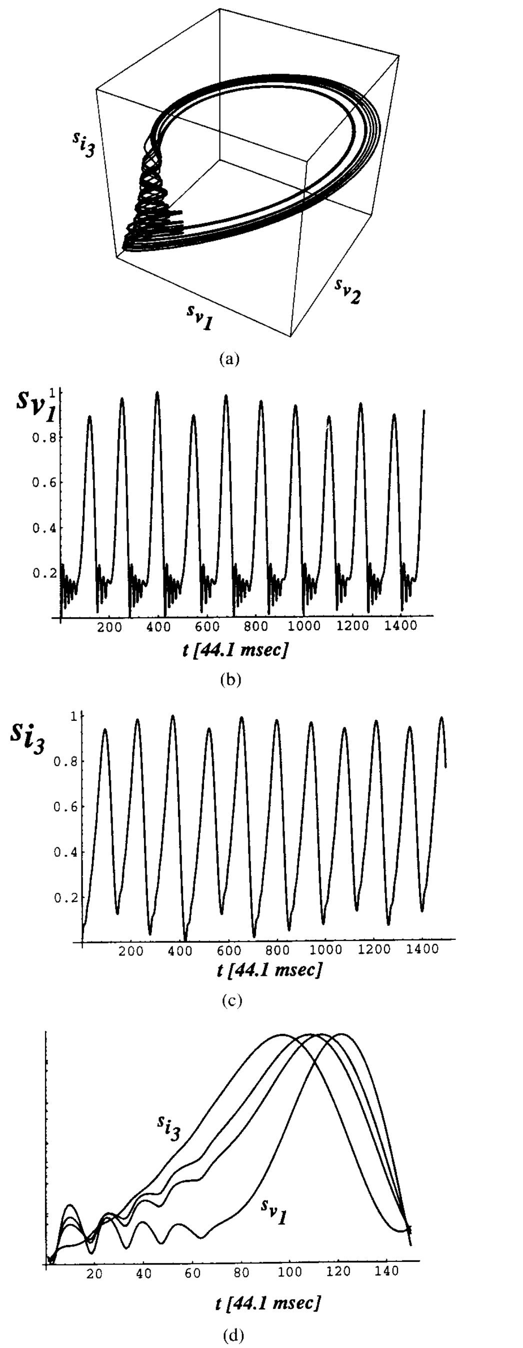

Fig. 4. Effect of different projections on waveform. We have chosen parameters of example (5.13) of [2]. (a) Attractor with normalized, dimensionless variables. (b) Waveform from variable v_1. (c) Waveform from variable i_3. (d) Shape of individual oscillations changing the projection from the v_1 to the i_3 axis.

oscillations extend to a lesser extent into the region whose positively sloped portion has been moved closer to the origin.

In particular, it is in this manner possible to shrink or even suppress one of the lobes in the double scroll oscillation. It was found that this resulted in an abundance of intermittent, stable, closed-loop oscillations in the midst of Rössler type chaotic oscillations.

The type of oscillation is determined by the potentiometer value. The potentiometer can be the ordinary manually turned type. For the purpose of investigating the types of oscillations that occur when the potentiometer setting is varied on a time scale that is short in comparison to the dominant frequencies in the power spectrum, the manual device was replaced by a two-terminal device whose current through its terminals is linearly proportional to the voltage across them, with the constant of proportionality being electronically adjustable. This device is also realized with op amps.

X. Examples of "Musical" Sounds from the Chua Circuit

While investigating the Chua system, we experienced several distinct features that can be described in musical terms. Three predominant classes experienced in the Chua circuit are the strong tendency to produce pitch due to its isochronic behavior, the simultaneous presence of noise along with embedded periodic orbits, and sounds resembling the formant structures of acoustic instruments. The interplay of these factors can create steady-state waveforms that resemble steady-state portions of acoustic instrument sounds.

For example, one parameter range produces a bassoon-like steady-state timbre that lies predominantly within the frequency range of the bassoon. The sound is characterized by "hollow" formant characteristics common to double-reed acoustic instruments (instruments such as the oboe and bassoon having two oscillating membranes that are placed in contact with one another). These formant characteristics are

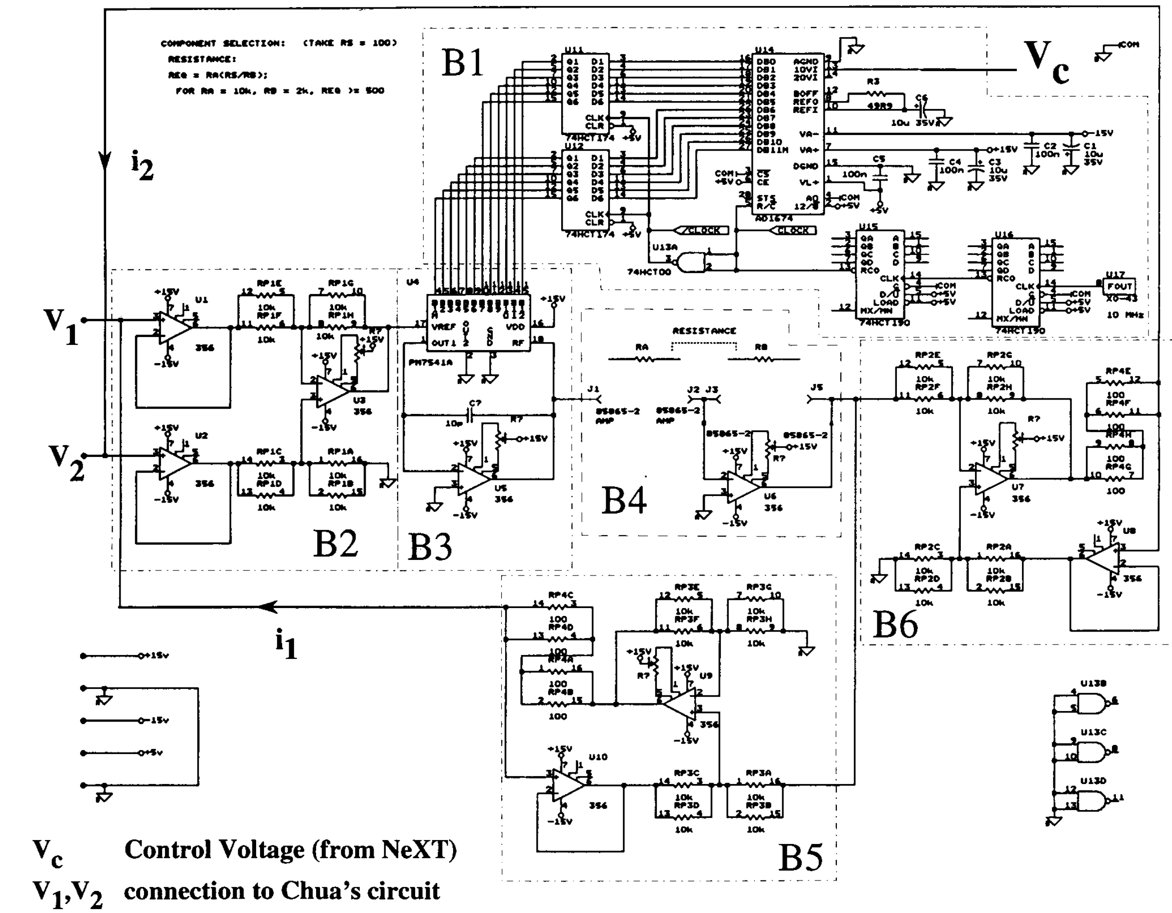

Fig. 5.

created by the presence of strong spectral amplitudes in the fundamental frequency and the upper partials and weaker amplitudes in the lower partials. These are characterized by a waveform that reflects the spiral nature of the attractor having a number of periods of nearly equal amplitude followed by a larger amplitude cycle that represents the reentry of the attractor into the cycle (see Fig. 3). The perceived pitch of the sound is related to the overall period of the periodic attractor that consists, in this case, of several small oscillations and one large oscillation. Through the period-adding bifurcations, we obtain a pitch sequence that descends as the number of small oscillations increases while it preserves the bassoon tone quality. The intervals that make up this descending sequence are not the same as the sequence of integer multiples of frequencies that make up standard musical intervals. For example, the signal in row 3 of Fig. 3 (132 Hz) contains twice as many oscillations as the signal in row 1; however, it is displaced by an interval of an octave plus a whole step rather than an octave, which would be produced by the frequency ratio of 2:1.

It is important to note that these waveforms are essentially steady state and thus do not necessarily resemble the macroscopic (note-level) amplitude and frequency contours that occur when notes are played on acoustic instruments. In traditional sound synthesis, these characteristics are added to a signal using voltage-controlled amplification and filtering or modulation.

Since we want to take a hybrid approach to the Chua circuit (integrating digital simulation and direct measurement), we include a brief discussion of the reproduction of electronic realization by numerical simulation.

The values of the time-independent parameters such as C_1, C_2, L, potentiometer setting, and nonlinear resistor slopes and break-point voltages were given values that corresponded as closely as possible to the values as best as could be determined experimentally or via manufacturer's specifications. The oscillations thta occurred at some measured value of resistance in the lab occurred at a value of simulation resistance that was higher by several percent. This is attributed to the fact that time-independent parameters cannot be precisely determined experimentally.

In order to obtain the bassoon sequence, we checked that the oscilloscope traces resembled a double scroll with one scroll shrunk to an extent where oscillations on its side of

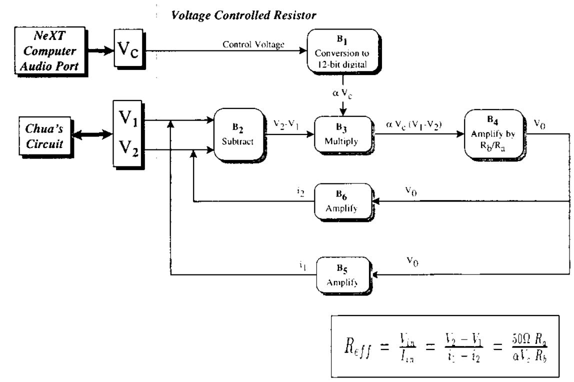

Fig. 6.

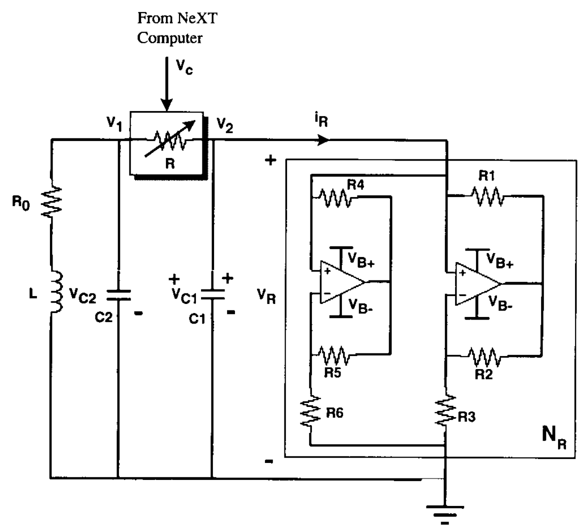

Fig. 7.

the origin were almost extinct. At certain values of resistance, the trace made no more than a slight excursion to the side with the shrunken scroll. Between these certain values of resistance, a scroll of limited size did occur on this side. The shrinking of one of the scrolls was accomplished by decreasing one of the two voltages of opposite polarity, which powered the nonlinear resistor. Decreasing the positive voltage, for example, limited the extent to which the voltage across the nonlinear resistor could swing positive. It was by the variation of these supply voltages that the bassoon-like oscillations were first discovered. The resistor values that were used for the analog bassoon sounds are given in Fig. 3.

As the resistance was decreased, the number of loops were encountered in the following sequence: 10, 9, 8, 8, 7, 6, 6, 5, 4, 5, 3, 4, 2. For resistance values near the above listed ones, there arose oscillations that were identical except that the number of loops was exactly doubled and, in the case of 7, tripled. The nine-looped oscillation, for example, would continuously bifurcate to an 18 loop as the resistance was slowly decreased. This 18 loop consisted of a pair of nines slightly offset from each other in the same fashion that the period-2 oscillation of the ordinary Chua oscillator is slightly offset from the period 1.

XI. Sonic Properties of Projections of 3-D Orbit on Attractor

The specific waveform of a signal will ultimately determine the way it sounds. Spectral peaks are derived properties that often do not represent the signal adequately. One interesting aspect suggested by the Chua circuit consists of deriving signals from the attractor that correspond to different projections from the state space onto a signal domain. For example, in the bassoon sound case, we can precisely influence the ratio between small and large peaks: We know that the complex eigenvalues of the relevant fixed point defines a plane in the 3-D state space. The reinjection trajectory (corresponding to the large peak) will leave this plane and approach/leave the fixed point in a direction that is orthogonal to the previously mentioned plane. Thus, by choosing the projection at a given angle with respect to this plane, we can determine precisely the relative contribution of small and large oscillations. We illustrate this method with the help of example 5.13 of [2] (see also Fig. 4).

Signals corresponding to different variables of the Chua system may differ in details of their waveform. Geometrically, they correspond to projections of points on the 3-D solution curve onto orthogonal axes. Therefore, we expect different timbres for different variables of the system. We can go even further and introduce a geometrical basis for sound mixing (in arbitrary dimensions) that allows global interpretations of the resulting sounds as 1-D projections of n-dimensional curves.

Sounds generated from changing the projections onto the v_1 axis to a projection onto the i_3 axis then undergo three types of change: spectral brightness, spectral formant characteristics, and perceived emphasis of secondary pitches. These secondary pitches (multiphonics) result from the irregular frequency and amplitude modulations of fundamental harmonic periods within the sound. Due to small shifts in these periods, noise is generated that has a pitch-like bandpass filtered quality. These noises and their suggested pitches are more easily perceived when other frequency regions with strong spectral energy are attenuated. In the example of Fig. 4(b), the small set of oscillations indicates the presence of high-frequency components; the example of Fig. 4(c) is a different projection of the same attractor. Fundamental frequency is constant in these examples, as are noise components in the low-frequency range that originate from irregular frequency modulation of the fundamental period, which varies between 150 and 165 Hz. Fig. 4(b) is bright and has some high-frequency noise coloring the fundamental; Fig. 4(c), missing these oscillations, is significantly muted (upper spectrum attenuated).

Appendix A
Circuit Diagram of Voltage-Controlled Resistor

The resistance R is controlled by a voltage taken from the amplified and rectified audio output of a NeXT computer. The waveforms are directly played from its mathematical definition from within a `Mathematica` notebook. The exact `Mathematica` command used for Fig. 1 is

Play [Sin[300 2Pi t] t, t, 0, 2]

(see Fig. 5).

APPENDIX B
SCEMATIC DIAGRAM OF THE MAIN COMPONENTS OF THE VOLTAGE-CONTROLLED RESISTOR

The conection to the control voltage is indicated as V_c. The Chua circuit provides voltages V_1, V_2 (see Fig. 6).

APPENDIX C
CIRCUIT DIAGRAM OF THE UNFOLDED CHUA CIRCUIT

The unfolding occurs with the help of resistor R_0 (see Fig. 7).

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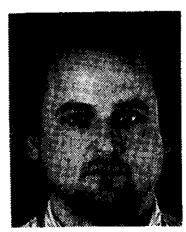

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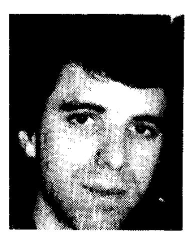

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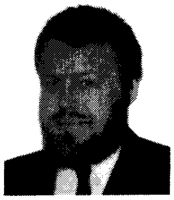

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