dependence of the dead time on the amplitude of the gate drive voltage makes the feedback circuit design very simple.

V. Design Procedure

We perform the design for the specifications: operating frequency $f_o = 1.0$ MHz, deadtime duty-ratio = 0.25, load resistance $R_L = 12.5$ Ω, quality factor $Q = 10$ and input dc voltage $V_{cc} = 20$ V (see, Fig. 7). From [2], the relationship between the input dc voltage and output sinusoidal voltage is

$$|v_o| = \frac{V_{cc}}{\pi}. \tag{27}$$

Therefore, the output voltage v_o is 6.37 V. Using (1)–(4) and (9)–(19), we find the values of the circuit elements of the inverter part as

$$\begin{aligned} C_{s1} &= C_{s2} = \frac{1}{2\pi \cdot (2\pi \cdot 1.0 \cdot 10^6) \cdot 12.5} \\ &= 2.03 \text{ [nF]} \end{aligned} \tag{28}$$

$$\begin{aligned} L_r &= 10 \cdot \frac{12.5}{2\pi \cdot 1.0 \cdot 10^6} \\ &= 19.89 \ [\mu\text{H}] \end{aligned} \tag{29}$$

$$\begin{aligned} C_f &= \frac{1}{(2\pi \cdot 1.0 \cdot 10^6) \cdot \left(10 - \frac{\pi}{2}\right) \cdot 12.5} \\ &= 151 \text{ [pF]}. \end{aligned} \tag{30}$$

IRF510 MOSFET's were used as switches S_1 and S_2. Their characteristics of are shown in Table I. Using (9)–(22) and (28)–(30), we find the values of the circuit elements of the phase-shift part of the oscillator as

$$C_1 = 264 \text{ [pF]} \tag{31}$$

$$C_2 = 50 \text{ [pF]} \tag{32}$$

$$L_1 = 126.65 \ [\mu\text{H}]. \tag{33}$$

VI. Experimental Results

An experimental circuit designed in Section V was tested. For starting, we gave the driving signals D_{s1} and D_{s2} from reference inverter because the circuit needs an external trigger signal to start the oscillation.

Fig. 6 shows the waveforms of the switch voltage v_{s1} and output voltage v_o. They agreed well with theoretical predictions. The measured efficiency was 93.3% at the output of 2.3 W and operating frequency of 1.0 MHz.

VII. Conclusion

In this paper, a high-efficiency class DE tuned power oscillator was introduced. The proposed circuit can be used as a simple high-efficiency tuned power inverter. The analysis, design examples, and experimental results were presented. The measured performance showed good agreement with the theoretical predictions.

References

[1] S. A. Zhukov and V. B. Kozyrev, "Double-ended switching generator without commutating loss" (in Russian), *Poluprovodnikovye Pribory v Tekhnike Elektrosvyazi*, vol. 15, pp. 95–107, 1975.

[2] H. Koizumi, T. Suetsugu, M. Fujii, K. Shinoda, S. Mori, and K. Ikeda, "Class DE high-efficiency tuned power amplifer," *IEEE Trans. Circuits Syst., Part—I*, vol. 43, pp. 51–60, Jan. 1996.

[3] S. A. El-Hamamsy, "Design of high-efficiency RF class-D power amplifier," *IEEE Trans. Power Electron.*, vol. 9, pp. 297–308, May 1994.

[4] D. C. Hamill, "Class DE inverters and rectifiers for DC-DC converter," in *IEEE Proc., Power Electron. Specialist Conf. (PESC '96)*, June 1996, pp. 854–860.

[5] K. Shinoda, M. Fujii, M. Matsuo, T. Suetsugu, and S. Mori, "Idealized operation of Class DE frequency multipliers," *IEEE Proc., Int. Symp. Circuits Syst. (ISCAS '96)*, vol. 1, pp. 581–584, May 1996.

[6] J. Ebert and M. K. Kazimierczuk, "Class E high-efficiency tuned power oscillator," *J. Solid-State Circuits*, vol. SC-16, no. 2, pp. 62–66, Apr. 1981.

[7] P. J. Baxandall, "Transistor sine-wave LC oscillators, some general considerations and new developments," *Proc. IEE*, pt. B, vol. 106, pp. 748–758, May 1959.

[8] W. J. Chudobiak and D. F. Page, "Frequency and power limitations of class-D transistor amplifier," *IEEE J. Solid-State Circuits*, vol. SC-4, pp. 25–37, Feb. 1969.

[9] M. K. Kazimierczuk and J. S. Modzelewski, "Drive-transformerless class-D voltage-switching tuned power amplifier," *Proc. IEEE*, vol. 68, pp. 740–741, June 1980.

[10] D. Czarkowski and M. K. Kazimierczuk, "Simulation and experimental results for class D series resonant inverter," in *IEEE Int. Telecom. Energy Conf. (INTELEC'92)*, Oct. 1992, pp. 153–159.

[11] N. O. Sokal and A. D. Sokal, "Class E-A new class of high-efficiency tuned single-ended switching power amplifiers," *IEEE J. Solid-State Circuits*, vol. SC-10, pp. 168–176, June 1975.

[12] F. H. Raab, "Idealized operation of the class E tuned power amplifier," *IEEE Trans. Circuit Syst.*, vol. CAS-24, pp. 725–735, Dec. 1977.

[13] N. O. Sokal and F. H. Raab, "Harmonic output of class E RF power amplifiers and load coupling network design," *IEEE J. Solid-State Circuits*, vol. SC-13, pp. 239–247, Apr. 1978.

[14] F. H. Raab, "Effects of circuit variations on the class E tuned power amplifier," *IEEE J. Solid-State Circuits*, vol. SC-13, pp. 239–247, Apr. 1978.

Self-Control of Chaotic Dynamics using LTI Filters

Pabitra Mitra

***Abstract*—In this brief, an algorithm for controlling chaotic systems using small, continuous-time perturbations is presented. Stabilization is achieved by self controlling feedback using low order LTI filters. The algorithm alleviates the need of complex calculations or costly delay elements and can be implemented in a wide variety of systems using simple circuit elements only.**

***Index Terms*—Feedback control of chaos, linear time invariant filters, unstable periodic orbits.**

I. Introduction

There has been some increasing interest in recent years in the study of controlling chaotic nonlinear systems [2], [7]. The possibility of obtaining periodic waveforms from a chaotic system by stabilizing any of the numerous embedded unstable periodic orbits (UPO's) has been the guiding control philosophy. The breakthrough in this direction is the

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The author is with the Machine Intelligence Unit, Indian Statistical Institute, Calcutta, India (e-mail: pabitra_r@isical.ac.in).

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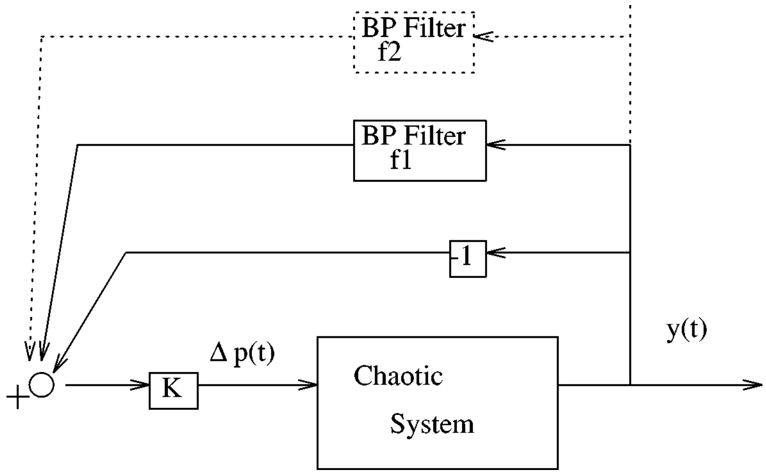

Fig. 1. Block Diagram of the Control Algorithm.

OGY algorithm [1], which stabilizes the UPO by applying occasional, small, well-calculated perturbations to the system parameters.

The above methods are in essence discrete in nature and calculate the perturbation based upon local behavior of the system in a neighborhood of the UPO. This is an advantage, as knowledge about the entire global dynamics is not necessary. However, since control is exercised only occasionally in a small neighborhood of the UPO, the system becomes susceptible to occasional bursts away from the UPO under moderate noise. To overcome this limitation the idea of time continuous control was proposed by Pyragas [3]. Among the two algorithms suggested by Pyragas one required an external periodic signal approximating the UPO, while the other recovered the periodic signal by delay coordinate method. Though various implementations of the second method has been reported, the inspiration behind the present report is to replace the delay element which is difficult and costly to obtain at some time scales.

The present algorithm also achieves control by perturbing the system parameters in proportion to the error signal between the output signal to be controlled and a periodic signal, but the periodic signal is derived from the chaotic attractor itself, by passing the chaotic output of the system through a bank of band pass filters with narrow pass bands. The filters may be simple LTI ones, which can be implemented using resistor, capacitor and opamps only. It has been observed that though LTI filters are unable to filter out a periodic signal from a chaotic one [8], when connected in the above configuration, the whole system can be controlled to periodic orbits.

II. Control Algorithm

Let us consider a dynamical system given by the model

$$\begin{aligned}\dot{X} &= f(X, p)\\ y &= CpX\end{aligned} \tag{1}$$

where, p is a parameter available for perturbation and y is the output signal to be controlled. We assume both y and p to be scalars.

The system is connected in the configuration shown in Fig. 1. The feedback path consists of an inverter and a bank of filters connected in parallel. The filters are band pass type with narrow pass bands, second-order notch filters are found to be sufficient for effective control. The number of filters required depends on the periodicity of the UPO's to be stabilized. To obtain a period-1 output only a single filter would be necessary, while two filters are required to obtain a period-2 output. It may be noted in this context that if only the inverter loop is present, the system gets stabilized to an equilibrium point for an high gain K. To select the pass frequency of the filter, an FFT of the output signal is obtained, which would be typically spread spectrum, with broad peaks centered around frequencies corresponding to the UPO's. We select the pass frequency of the filters (f_i's) to be within this windows. A sufficiently high Q-value is selected for the filters and is assumed to be tunable. If the output of the i_{th} filter is $y_{f_i}(t)$ the perturbation applied to the system parameter p is of the form

$$\Delta p(t) = K\left(\sum y_{f_i}(t) - y(t)\right). \tag{2}$$

The value of gain K is tuned to obtain stabilization.

When stabilization is achieved the output of the filter bank and the system both become periodic and close to each other; also, the perturbation $\Delta p(t)$ becomes extremely small. Therefore, as well as in OGY and Pyragas's method small external force is used for stabilization. Also since the pass frequency of the filters were chosen to be in the same window as that of the UPO's, the stabilized orbit lies in a small neighborhood of the UPO of the original system.

The Lorentz system is used to illustrate the main results for the algorithm. The system equations for the Lorentz system are given by

$$\begin{aligned}\dot{x}_1 &= -x_1 + x_2x_3\\ \dot{x}_2 &= 3(x_3 - x_2)\\ \dot{x}_3 &= -x_1x_2 + rx_2 - x_3.\end{aligned} \tag{3}$$

The state x_2 is selected as the output signal to be controlled and r is the system parameter available for perturbation. The nominal value of r is taken as 26.0.

The second-order filter with transfer function

$$F(s) = \frac{C\omega_0}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

is used in the feedback loop. The spectrum of the output signal is shown in Fig. 2(b). For stabilization of the period-1 orbit a single filter with pass frequency of 1.2 Hz is chosen, which lies in the pass window of the chaotic system. Stabilization is obtained at $Q = 8.0$, $K = 0.52$ and $C = 0.90$. Fig. 3(b) and (a) shows the stabilized output signal and the perturbation in the system parameter, respectively. Fig. 3(c) shows the spectrum of the controlled output.

For stabilization of a period-2 orbit two filters with pass frequencies $f_1 = 1.2$ Hz and $f_2 = 0.4$ Hz are chosen. Stabilization is achieved at $Q_1 = 8.0, Q_2 = 6.0, C_1 = C_2 = 0.9$, with a gain of $K = 0.60$. Fig. 4 shows the stabilized orbit.

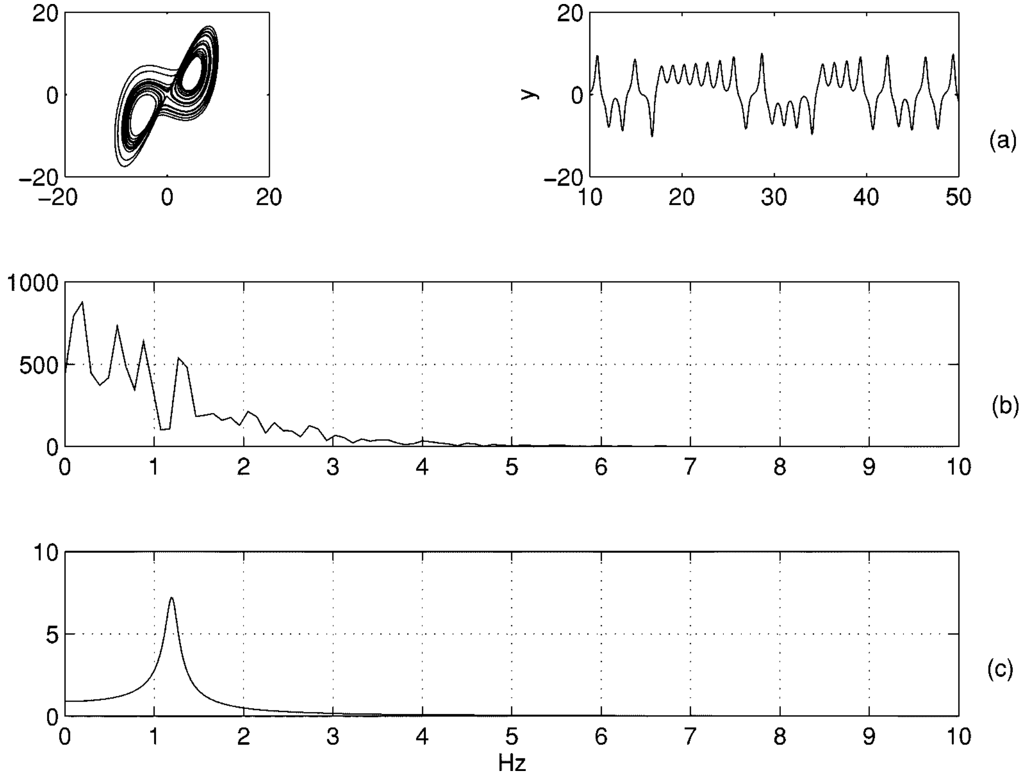

Fig. 2. Dynamics of the uncontrolled Lorentz system. (a) Phase portrait and output (x_2) for the uncontrolled system. (b) Power spectrum of the output over a time scale of 50 s, sampled at 50 Hz, (c) Frequency response of the filter used in feedback path.

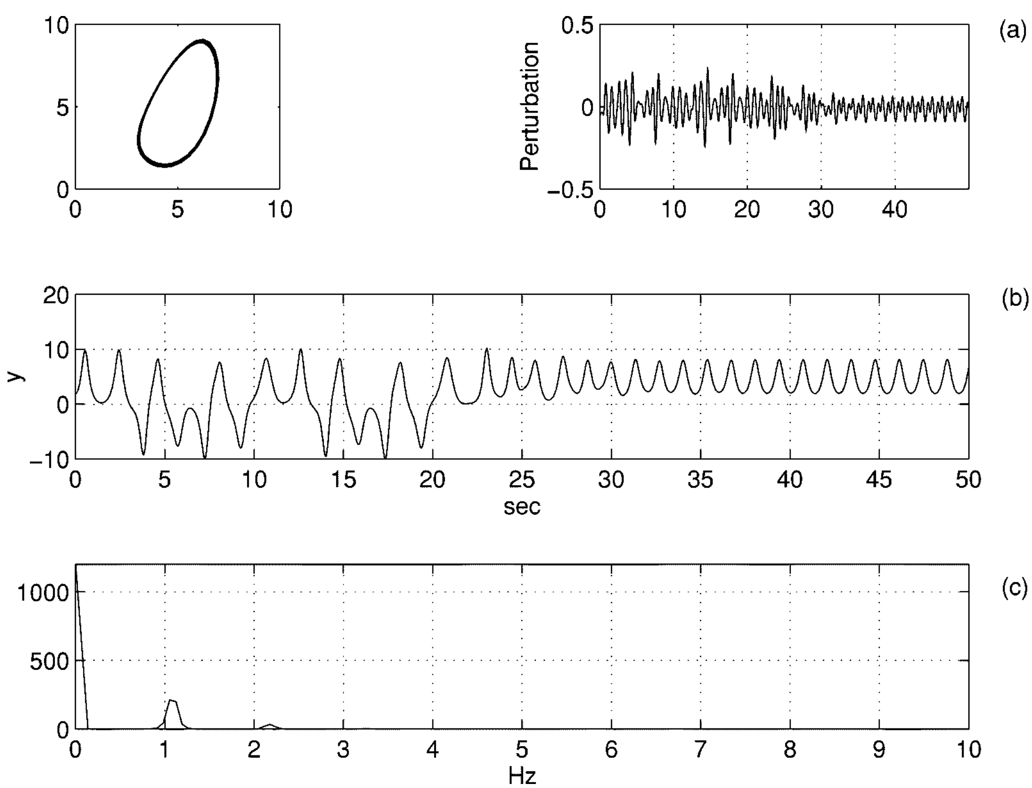

Fig. 3. Controlled period-1 orbit for the Lorentz system: (a) Phase Portrait and perturbation in r, (note that unlike Pyragas's method where perturbation can be large during the transient period, leading to problems like multistabilty, here perturbation is small even during the transients). (b) Output signal. (c) Spectrum of the output after the transients are over, (the peak at dc is due to the dc bias of the output), the stabilized orbit is an *almost* p-1 orbit, a small higher frequency component is present along with the main frequency component at $f \approx 1.2$ Hz.

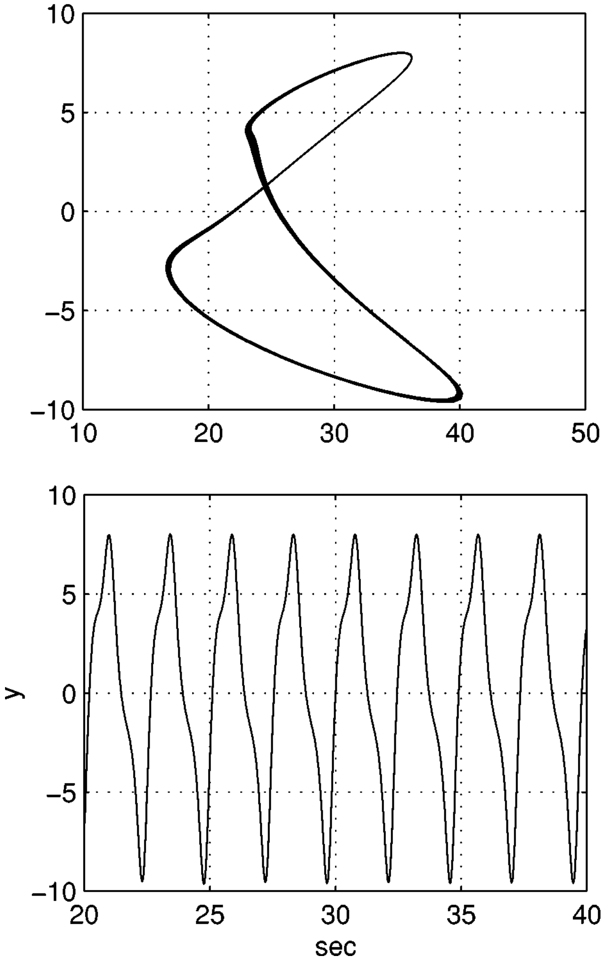

Fig. 4. Dynamics of the controlled period-2 orbit of the Lorentz system. (a) Phase portrait (b) Output (x_2)

Though general validity and sufficiency conditions for the effectiveness of the above algorithm is difficult to prove, it appears that stabilization in the above method is achieved through additional degrees of freedom introduced into the system by the filter in the feedback loop. The filter does not change much the projection of the system dynamics into the original low dimensional state space, but change only the Lyapunov exponent of the UPO. As compared to the delayed feedback method suggested by Pyragas [3], where the system dimension increases to infinity, a finite increase in system dimension occurs here, i.e., the finite dimensional LTI filter (a second-order transfer function for a single filter) approximates the delay element (having a transfer function e^{-Ts}) up to some frequency.

III. Conclusion

The above algorithm offers in a naive form a paradigm in which the problem of control of chaotic systems can also be viewed as that of synchronization of two back to back, mutually coupled system, of which one may be a chaotic system with numerous embedded UPO's and the other may be a LTI or a simpler nonlinear system whose natural dynamics is periodic. There is scope for future studies in using higher order filters and nonlinear systems in the feedback path.

In conclusion, a method of stabilizing chaotic systems approximately to a UPO, by small continuous-time perturbations, is presented. The main advantage of the above method lies in its easy applicability to a wide variety of systems. No complex calculations are involved and the algorithm can be implemented using low-order LTI filters only.

References

[1] E. Ott, C. Grebogi, and J. Yorke, "Controlling chaos," *Phys. Rev. Lett.*, vol. 64, p. 1196, 1990.
[2] C. W. Wu and L. O. Chua, "A unified framework for synchronization and control of dynamical systems," *Int. J. Bifrc. Chaos*, vol. 4, no. 4, p. 979, 1994.
[3] K. Pyragas, "Continuous control of chaos by self controlling feedback," *Phys. Lett. A*, vol. 170, p. 421, 1992.
[4] R. Roy, T. W. Murphy Jr., T. D. Maier, Z. Gills, and E. R. Hunt, "Dynamical control of a chaotic laser: Experimental stabization of a globally coupled system," *Phys. Rev. Lett.*, vol. 68, no. 9, p. 1259, 1992.
[5] G. Chen and X. Dong, "On feedback control of chaotic continuous time systems," *IEEE Trans. Circuit Syst.—1*, vol. 40, p. 591, 1993.
[6] C. Piccardi, "On taming chaos using LTI filters," *IEEE Trans. Circuit Syst.—1*, vol. 43, p. 431, 1996.
[7] M. J. Ogorzalek, "Taming chaos—Part 2: Control," *IEEE Trans. Circuits Syst.—1*, vol. 40, p. 700, 1993.
[8] A. A. Hammad and E. A. Jonkheere, "Taming chaos: A numerical experiment using low order LTI filters," *IEEE Trans. Circuits Syst.—1*, vol. 42, p. 111, 1995.

CMOS Circuits Generating Arbitrary Chaos by Using Pulsewidth Modulation Techniques

Takashi Morie, Souta Sakabayashi, Makoto Nagata, and Atsushi Iwata

***Abstract*—This paper describes CMOS circuits generating arbitrary chaotic signals. The proposed circuits implement discrete-time continuous-state dynamics by means of analog processing in a time domain. Arbitrary nonlinear transformation functions can be generated by using the conversion from an analog voltage to a pulsewidth modulation (PWM) signal; for the transformation, time-domain nonlinear voltage waveforms having the same shape as the inverse function of the desired transformation function are used. The circuit simultaneously outputs both voltage and PWM signals following the desired dynamics. If the nonlinear voltage waveforms are generated by digital circuits and D/A converters with low-pass filters, high flexibility and controllability are obtained. Moreover, the nonlinear dynamics can be changed in realtime. Common waveform generators can be shared by many independent chaos generator circuits. Because the proposed circuits mainly consist of capacitors, switches, and CMOS logic gates, they are suitable for scaled VLSI implementation. CMOS circuits generating arbitrary chaos with up to third-order nonlinearity and two variables have been designed and fabricated using a 0.4 μm CMOS process. Chaos has been successfully generated by using tent, logistic, and Hénon maps, and a chaotic neuron model.**

***Index Terms*—Chaos, CMOS analog integrated circuits, nonlinear circuits, nonlinear functions, pulse width modulation.**

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T. Morie, M. Nagata, and A. Iwata are with Faculty of Engineering, Hiroshima University, Higashi-Hiroshima 739-8527, Japan (E-mail: morie@dsl.hiroshima-u.ac.jp).

S. Sakabayashi is with Fujitsu Limited, Kawasaki 211-8588, Japan.

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