

Synchronization of two Mutually Coupled Duffing – type Circuits

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Abstract—In this paper we have studied experimentally the case of chaotic synchronization of two identical nonlinear electronic circuits. This is a very interesting research area because of its applications to the field of secure communications. The circuit we have used is a second order, Duffing – type, nonlinear electronic circuit driven by a sinusoidal voltage source. The nonlinear element has a cubic i-v characteristic. We have studied the dynamic behavior of the system in the case of the bidirectional coupling via a linear resistor. Both experimental and simulation results have shown that chaotic synchronization is possible.

Keywords—Chaos, Duffing equation, Chaotic synchronization, Bidirectional coupling.

I. INTRODUCTION

Synchronization, among dynamical variables in coupled chaotic systems would appear to be almost an oxymoron as the definition of chaos. Since the beginning of the '90s, many researchers have discussed the synchronization of two coupled chaotic systems [1] – [4]. Synchronization of chaotic systems plays an important role in several research areas. For example, neural signals in the brain are observed to be chaotic and it is worth to consider further their possible synchronization [5]. Other interesting examples may be seen from the working artificial neural networks [6], biological networks [7], coupled chaotic neurons [8], multimode lasers [9], coupled map lattices [10], [11], and coupled electric oscillators [12]. Also, the topic of synchronization has risen great interest as a potential mean in communication [13], [14]. The last few years, a considerable effort has been devoted to extend the chaotic communication applications to the field of secure communications.

Generally, there are two methods of chaos synchronization available in the literature. In the first method, a stable subsystem of a chaotic system could be synchronized with a separate chaotic system, under certain suitable conditions. The second method to achieve chaos synchronization between two

identical nonlinear systems is due to the effect of resistive coupling without requiring to construct any stable subsystem [15] – [17]. As we know from the bibliography, periodically forced synchronized chaotic circuits are much more noise-resistant than autonomous synchronized chaotic circuits.

In this paper we have studied the case of bidirectional coupling of two identical, second order Duffing-type electrical oscillators.

II. THE DUFFING – TYPE CIRCUIT

Duffing's equation,

$$\frac{d^2x_1}{dt^2} + \varepsilon \cdot \frac{dx_1}{dt} + a \cdot x_1 + b \cdot x_1^3 = B \cdot \cos(\omega \cdot t) \quad (1)$$

is one of the most famous and well studied nonlinear non-autonomous equations, exhibiting various dynamic behaviors, including chaos and bifurcations. One of the simplest implementations of the Duffing equation has been presented by Kyprianidis et al. [18]. It is a second order nonlinear circuit, which is excited by a sinusoidal voltage source and contains two op-amps (LF411) operating in the linear region Fig. 1. This circuit has also a very simple nonlinear element, implementing a cubic function of the form

$$i(v) = p \cdot v + q \cdot v^3 \quad (2)$$

which is shown in Fig. 2.

Denoting by x_1 and x_2 the voltages across capacitors C_2 and C_4 respectively, we have the following state equations.

$$\frac{dx_1}{dt} = -\frac{1}{C_2 \cdot R_2} \cdot x_1 + \frac{1}{C_2 \cdot R_3} \cdot x_2 \quad (3)$$

$$\frac{dx_2}{dt} = -\frac{R_0}{C_4 \cdot R_5} \cdot f(x_1) + \frac{V_0}{C_4 \cdot R_5} \cdot \cos(\omega \cdot t) \quad (4)$$

where, $f(x_1) = p \cdot x_1 + q \cdot x_1^3$, is a cubic function.

Finally, from (3) and (4), we take the Duffing equation (1),

$$\text{where, } \varepsilon = \frac{1}{C_2 \cdot R_2}, \quad a = \frac{p \cdot R_0}{C_2 \cdot C_4 \cdot R_3 \cdot R_5}, \quad b = \frac{r \cdot R_0}{C_2 \cdot C_4 \cdot R_3 \cdot R_5}$$

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$$\text{and } B = \frac{V_0}{C_2 \cdot C_4 \cdot R_3 \cdot R_5}.$$

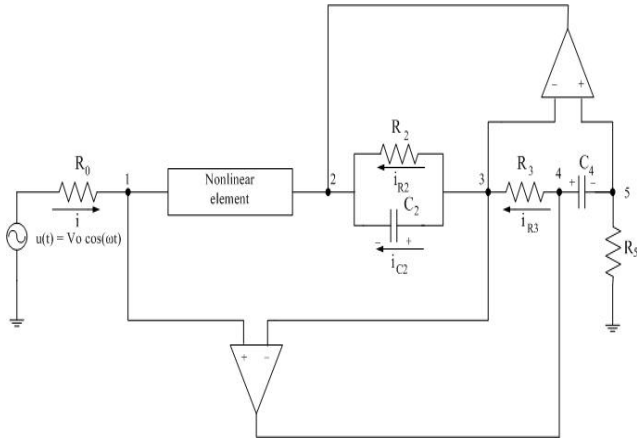


Fig. 1 The electronic circuit obeying Duffing's equation

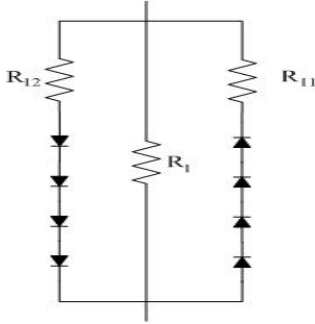


Fig. 2 The nonlinear element implementing the cubic function of the form $i(v) = p \cdot v + q \cdot v^3$

The values of circuit parameters are $R_0 = 2.05\text{k}\Omega$, $R_2 = 5.248\text{k}\Omega$, $R_3 = R_5 = 1\text{k}\Omega$, $R_{11} = R_{12} = 0.557\text{k}\Omega$, $R_1 = 8.11\text{k}\Omega$, $C_2 = 105.9\text{nF}$, $C_4 = 9.79\text{nF}$, $V_0 = 2\text{V}$ and $f = 1.273\text{kHz}$, so the normalized parameters take the following values $a = 0.25$, $b = 1$, $\varepsilon = 0.18$, $\omega = 0.8$ and $B = 20$. The phase portrait of x_2 vs. x_1 is shown in Fig. 3, where we can see that the circuit has a chaotic behavior.

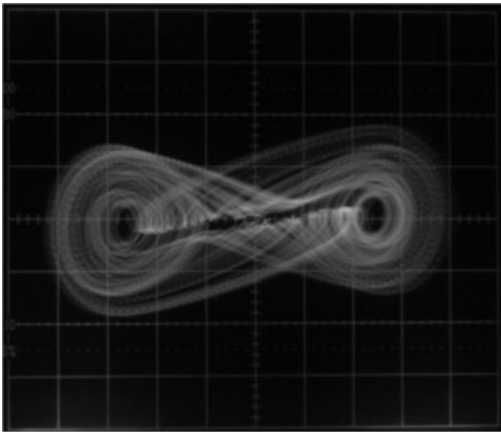


Fig. 3 Experimental phase portrait of x_2 vs. x_1 for $a = 0.25$, $b = 1$, $\varepsilon = 0.18$, $\omega = 0.8$ and $B = 20$ (Horiz. x_1 : $1\text{V}/\text{div.}$, Vert. x_2 : $5\text{V}/\text{div.}$)

III. THE COUPLED SYSTEM

The system of two identical Duffing circuits bidirectionally or two – way coupled via a linear resistor R_C is shown in Fig. 4. The state equations of the system of Fig. 4 has the form of (5) – (8), or the form of (9) – (10), where, $x_1 = v_{C2}$, $x_2 = v_{C4}$,

$x_1' = v_{C2}'$, $x_2' = v_{C4}'$, and $\xi = \frac{R_0}{R_C + 2R_0}$, is the coupling factor.

$$\frac{dx_1}{dt} = -\frac{1}{C_2 R_2} x_1 + \frac{1}{C_2 R_3} x_2 \quad (5)$$

$$\begin{aligned} \frac{dx_2}{dt} = & -\frac{R_0}{C_4 R_5} f(x_1) + \frac{q}{C_4 R_5} \cos(\omega t) - \\ & - \frac{R_0^2}{C_4 R_5 (R_C + 2R_0)} (f(x_1') - f(x_1)) \end{aligned} \quad (6)$$

$$\frac{dx_1'}{dt} = -\frac{1}{C_2 R_2} x_1' + \frac{1}{C_2 R_3} x_2' \quad (7)$$

$$\begin{aligned} \frac{dx_2'}{dt} = & -\frac{R_0}{C_4 R_5} f(x_1') + \frac{q}{C_4 R_5} \cos(\omega t) - \\ & - \frac{R_0^2}{C_4 R_5 (R_C + 2 \cdot R_0)} (f(x_1) - f(x_1')) \end{aligned} \quad (8)$$

$$\begin{aligned} \frac{d^2 x_1}{dt^2} + \varepsilon \frac{dx_1}{dt} + \alpha(1 - \xi)x_1 + b(1 - \xi)x_1^3 + \alpha \xi x_1' + \\ + b \xi (x_1')^3 = B \cdot \cos(\omega t) \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{d^2 x_1'}{dt^2} + \varepsilon \frac{dx_1'}{dt} + \alpha(1 - \xi)x_1' + b(1 - \xi)(x_1')^3 + \alpha \xi x_1 + \\ + b \xi x_1^3 = B \cdot \cos(\omega t) \end{aligned} \quad (10)$$

We have chosen the following values of the normalized parameters, $a = 0.25$, $b = 1$, $\varepsilon = 0.18$, $\omega = 0.8$ and $B = 20$, so the two coupled circuits are in chaotic steady state, as we saw before. The two coupled circuits have also different initial conditions and we study the dynamics of the system, as the coupling coefficient ξ is increased from zero (uncoupled circuits).

IV. CHAOTIC SYNCHRONIZATION

Considering the case, that the two coupled circuits are identical and are driven by signals of the same amplitude, we have studied the phenomenon of chaotic synchronization as the coupling factor ξ is increased. The bifurcation diagram $x_1 - x_1'$ versus ξ is shown in Fig. 5. When the difference $x_1 - x_1'$ becomes equal to zero, this means that the two circuits are in chaotic synchronization.

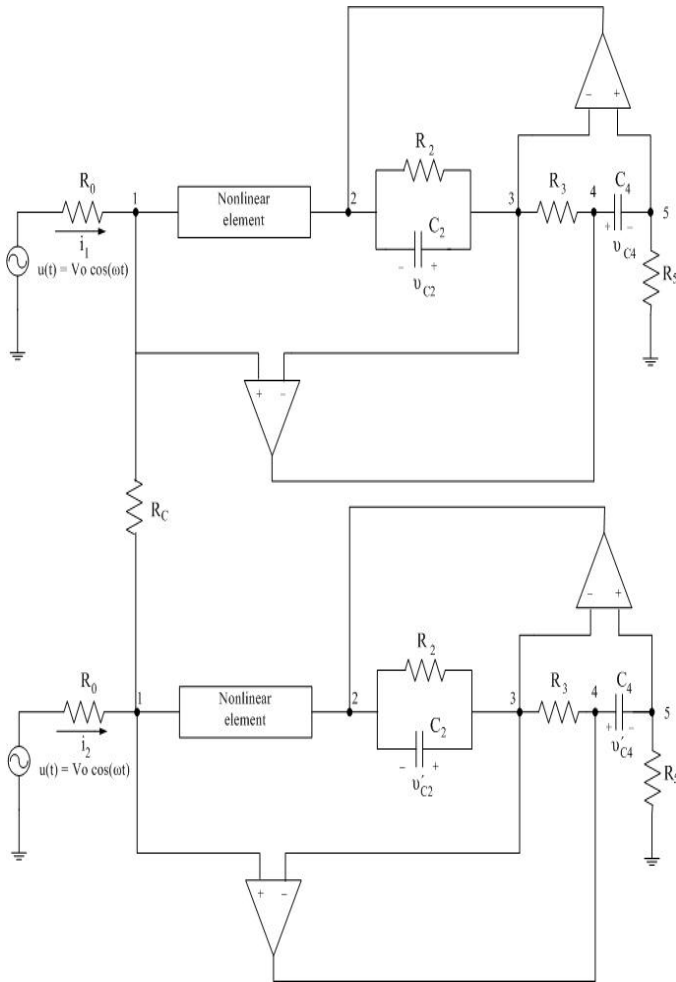


Fig. 4 Two Duffing circuits bidirectionally coupled via a linear resistor R_C

A. The Case $B = 20$

In Figs.6 – 14 we can see the experimental results from the coupled system for various values of the coupling resistor R_C . The system has a variety of dynamical behavior, as we saw at the bifurcation diagram (Fig. 5). We observe that the system appears phase – locked states of period – 1, period – 2, e.t.c. in different ranges of values of the coupling factor ξ (Figs. 6, 8, 9, 12). Also, the system passes from chaotic states (Figs. 7, 10, 11, 13) to a chaotic synchronization (Fig. 16) as we expect from the bifurcation diagram. The phenomenon of chaotic synchronization appears for $\xi > 0.48$. So, the coupled circuits confirmed the theoretical results we took from the simulation of the dynamical system, as we saw in Figs. 6, 11, 12, 14.

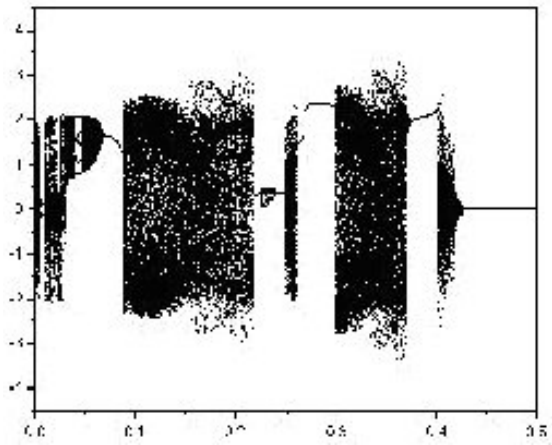
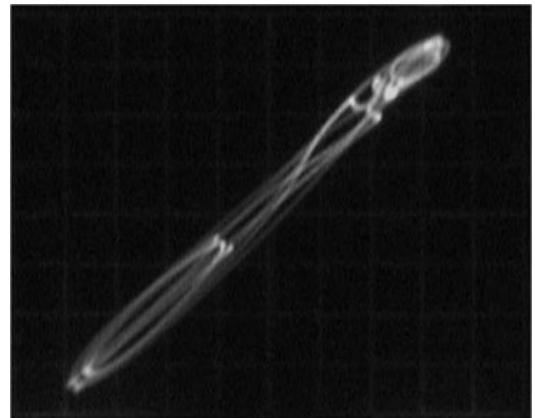
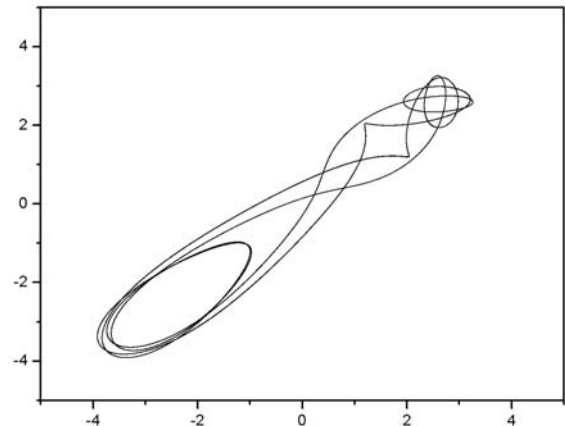


Fig. 5 The bifurcation diagram $x_1 - x_1'$ versus ξ for $a = 0.25$, $b = 1$, $\epsilon = 0.18$, $\omega = 0.8$ and $B = 20$



(a)



(b)

Fig. 6 (a) Experimental phase portrait x_1' versus x_1 (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.) and (b) Theoretical phase portrait x_1' versus x_1 , for $R_C = 182k\Omega$ ($\xi = 0.011$). The system is in period – 2

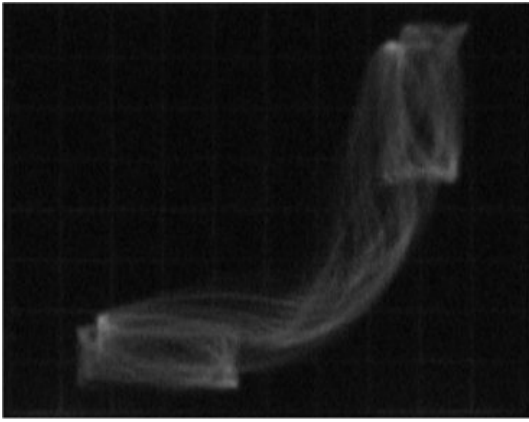


Fig. 7 Experimental phase portrait x_1' versus x_1 for $R_C = 54k\Omega$ ($\xi = 0.035$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic state

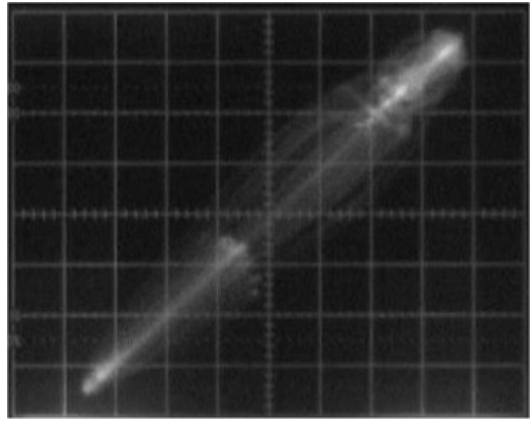


Fig. 10 Experimental phase portrait x_1' versus x_1 for $R_C = 5k\Omega$ ($\xi = 0.23$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic state

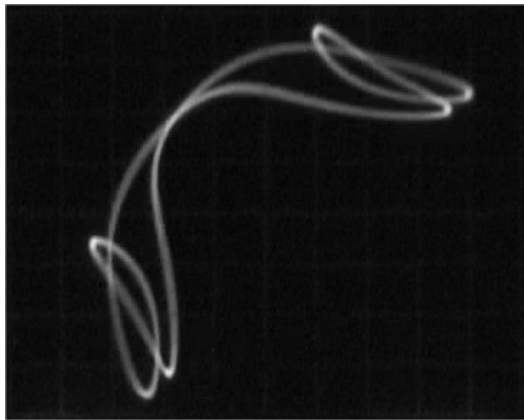
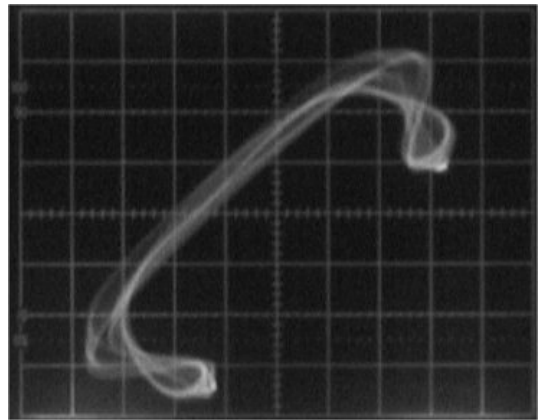


Fig. 8 Experimental phase portrait x_1' versus x_1 for $R_C = 41k\Omega$ ($\xi = 0.08$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in period-1 state



(a)

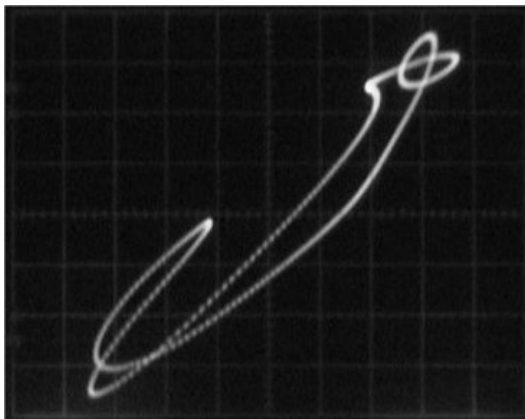
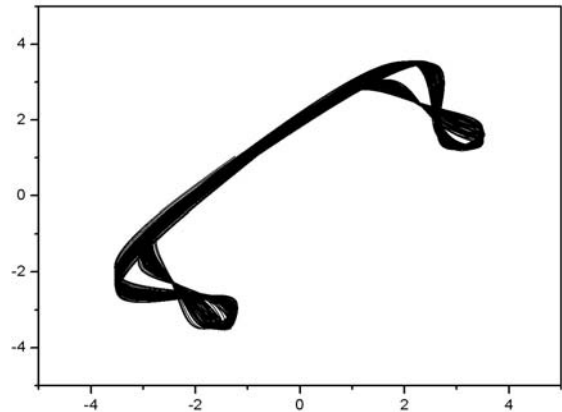
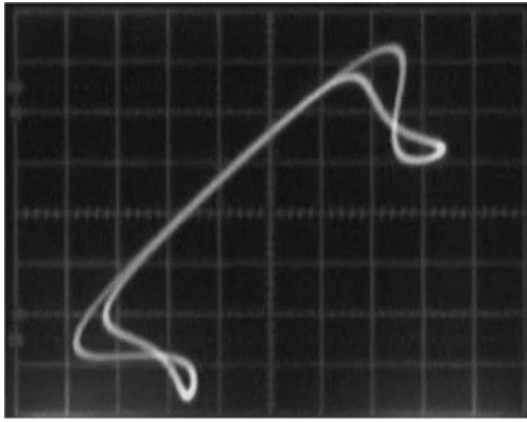


Fig. 9 Experimental phase portrait x_1' versus x_1 for $R_C = 5.2k\Omega$ ($\xi = 0.22$). (Horiz. V_{C2} 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a period - 1 state

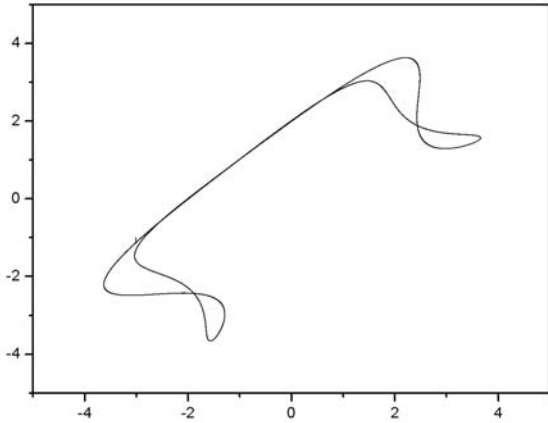


(b)

Fig. 11 (a) Experimental phase portrait x_1' versus x_1 (Horiz. V_{C2} 1V/div., Vert. V_{C2}' : 1V/div.) and (b) Theoretical phase portrait x_1' versus x_1 , for $R_C = 1.3k\Omega$ ($\xi = 0.38$). The system is in a chaotic state

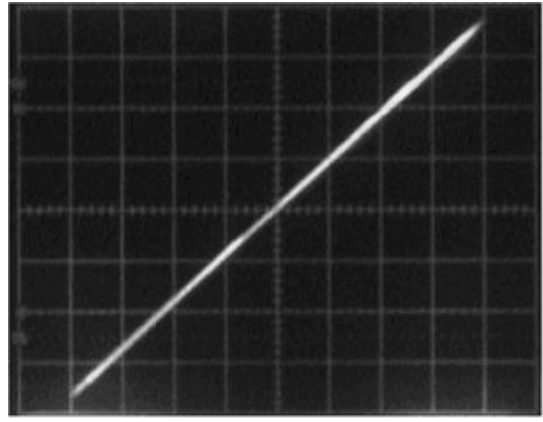


(a)

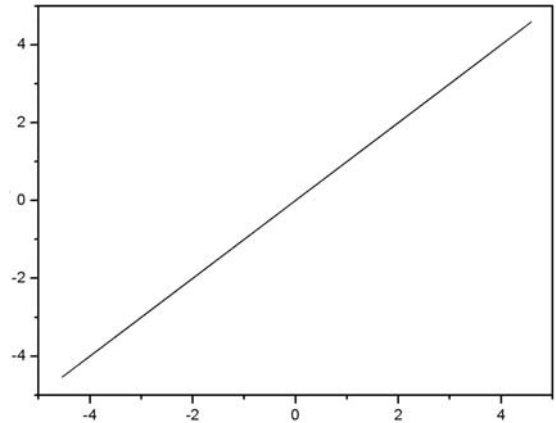


(b)

Fig. 12 (a) Experimental phase portrait x_1' versus x_1 (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.) and (b) Theoretical phase portrait x_1' versus x_1 , for $R_C = 1k\Omega$ ($\xi = 0.4$). The system is in period - 1 state



(a)



(b)

Fig. 14 (a) Experimental phase portrait x_1' versus x_1 (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.) and (b) Theoretical phase portrait x_1' versus x_1 , for $R_C = 170\Omega$ ($\xi = 0.48$). The system is in a chaotic synchronization

B. The Case B = 27

In Fig. 15, the bifurcation diagram $x_1 - x_1'$ versus ξ is shown for $B = 27$. As we can observe, a phase - locked state of period - 2 is created in the ranges of values $0.017 < \xi < 0.022$ and $0.387 < \xi < 0.392$ (Fig. 17). In the range of values $0.212 < \xi < 0.229$ we can see a period - 3 state (Fig. 18). Chaotic synchronization is observed for $\xi > 0.444$ (Fig. 20). Also, in Figs. 16 and 19 we can see the chaotic behavior of the system. Finally we conclude that the system has exactly the same experimental behavior as we expect from the bifurcation diagram.

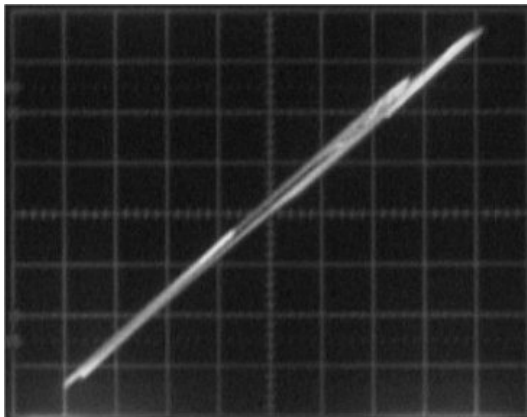


Fig. 13 Experimental phase portrait x_1' versus x_1 for $R_C = 260\Omega$ ($\xi = 0.47$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic state

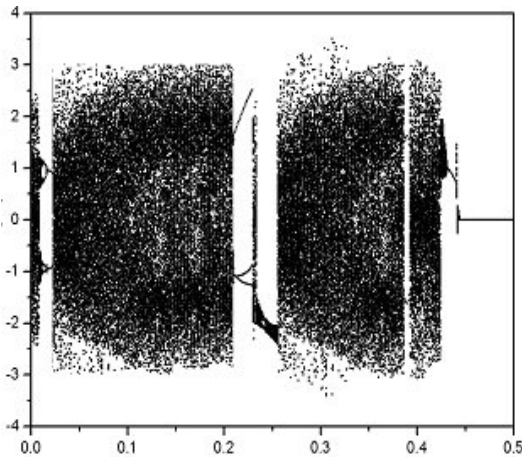


Fig. 15 The bifurcation diagram $x_1 - x_1'$ versus ξ for $a = 0.25$, $b = 1$, $\varepsilon = 0.18$, $\omega = 0.8$ and $B = 27$

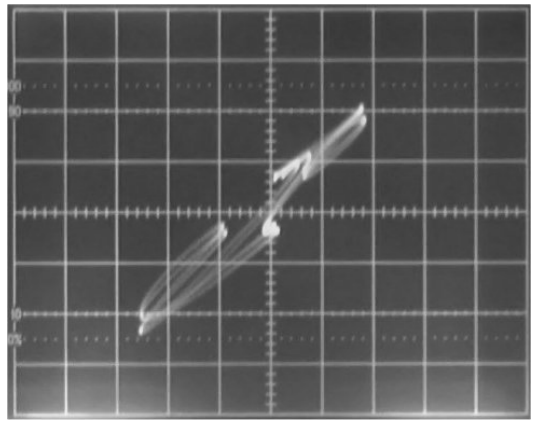


Fig. 18 Experimental phase portrait x_1' versus x_1 for $R_C = 5.2k\Omega$ ($\xi = 0.22$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a period – 3 state

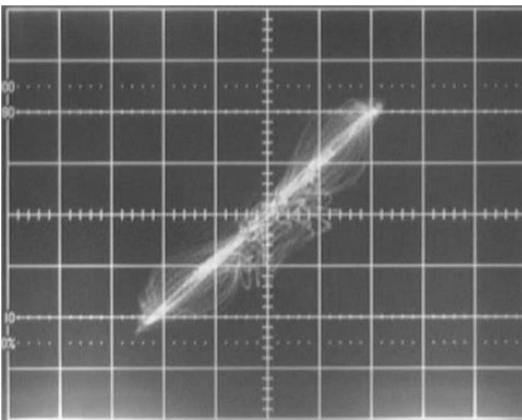


Fig. 16 Experimental phase portrait x_1' versus x_1 for $R_C = 406k\Omega$ ($\xi = 0.005$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic state

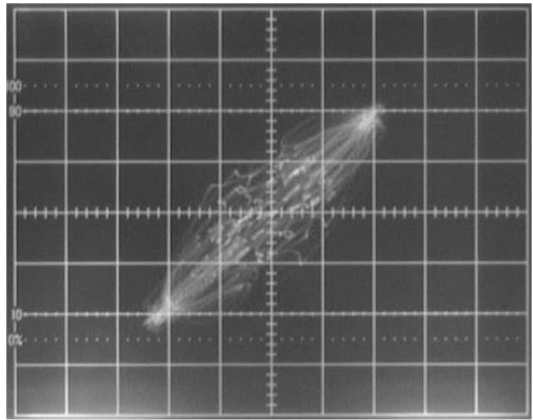


Fig. 19 Experimental phase portrait x_1' versus x_1 for $R_C = 2.7k\Omega$ ($\xi = 0.3$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic state

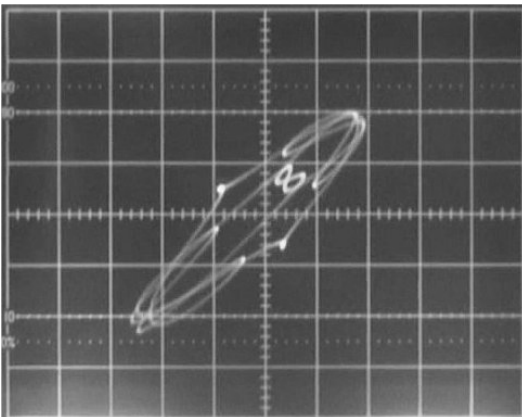


Fig. 17 Experimental phase portrait x_1' versus x_1 for $R_C = 98.5k\Omega$ ($\xi = 0.02$). Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a period – 2 state

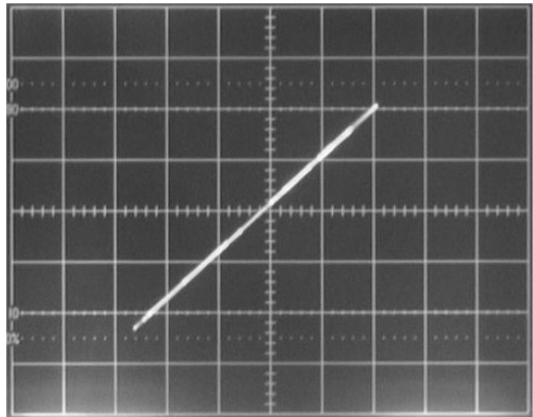


Fig. 20 Experimental phase portrait x_1' versus x_1 for $R_C = 560\Omega$ ($\xi = 0.45$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic synchronization

C. The Case $B = 28.2$

In Fig. 21, the bifurcation diagram $x_1 - x_1'$ versus ξ is shown for $B = 28.2$. As we can observe, a phase-locked state of period – 1 is created in various ranges of values: $0.0187 < \xi < 0.191$, $0.286 < \xi < 0.297$ and $0.368 < \xi < 0.401$ (Figs. 23, 24, 25). In Fig. 22 we can see an example of the chaotic

behavior of the system. Also in Fig. 26 we can observe the chaotic synchronization of the system when the coupling coefficient is greater of 0.402. Finally we conclude again that the system has exactly the same experimental behavior as we expect from the bifurcation diagram.

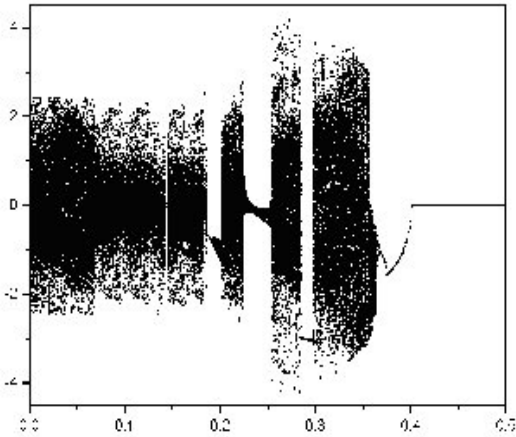


Fig. 21 The bifurcation diagram $x_1 - x_1'$ versus ξ for $a = 0.25$, $b = 1$, $\varepsilon = 0.18$, $\omega = 0.8$ and $B = 28.2$

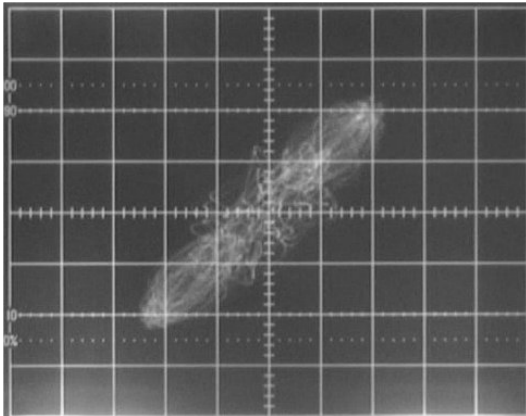


Fig. 22 Experimental phase portrait x_1' versus x_1 for $R_C = 200k\Omega$ ($\xi = 0.01$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic state

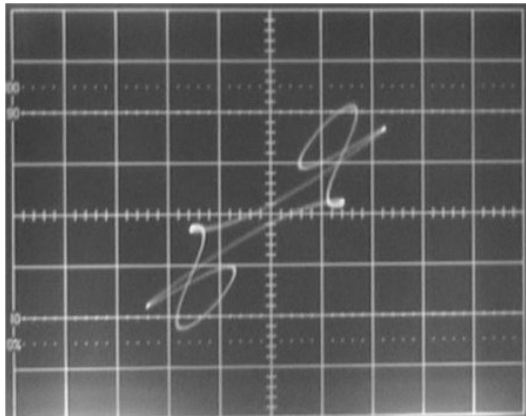


Fig. 23 Experimental phase portrait x_1' versus x_1 for $R_C = 6.75k\Omega$ ($\xi = 0.189$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a period-1 state

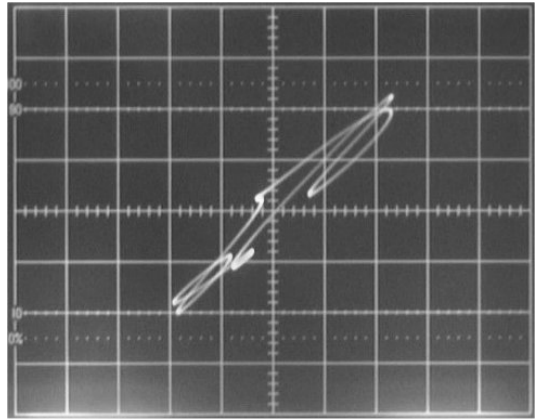


Fig. 24 Experimental phase portrait x_1' versus x_1 for $R_C = 3.1k\Omega$ ($\xi = 0.286$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a period – 1 state

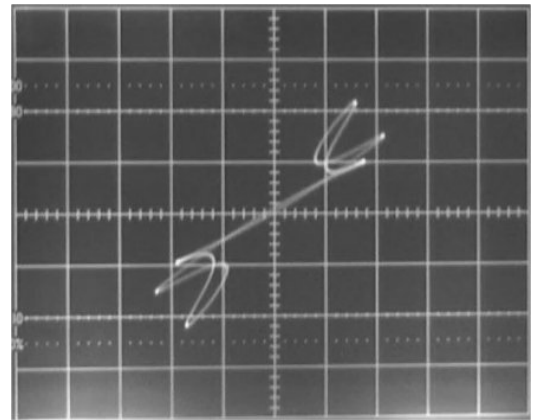


Fig. 25 Experimental phase portrait x_1' versus x_1 for $R_C = 1.2k\Omega$ ($\xi = 0.387$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a period – 1 state

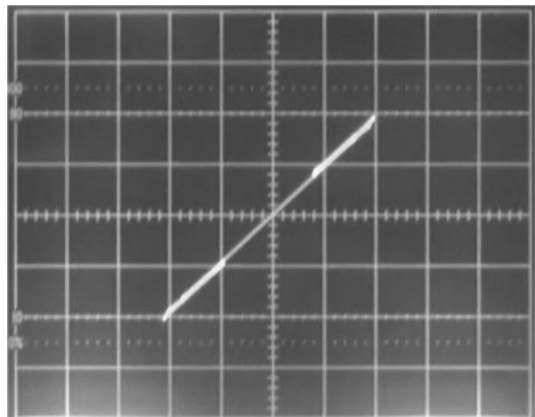


Fig. 26 Experimental phase portrait x_1' versus x_1 for $R_C = 960\Omega$ ($\xi = 0.405$). (Horiz. V_{C2} : 1V/div., Vert. V_{C2}' : 1V/div.). The system is in a chaotic synchronization

V. CONCLUSION

In this paper we have studied the dynamics of two resistively coupled nonlinear Duffing – type electrical oscillators. The two circuits are identical, having chaotic dynamical behavior, as we have found out from both

theoretical and experimental results. We experimentally confirmed the expected behavior of the system for various values of the coupling resistor R_C . We have shown periodic and chaotic states, in different ranges of values of the coupling factor ξ . Finally, we observed a chaotic synchronization when the factor $\xi > 0.48$.

REFERENCES

- [1] R. Brown and L. Kocarev, "A Unifying definition of synchronization for dynamical systems," *Chaos*, vol. 10, 2000, pp. 344–349.
- [2] S. Boccaletti, J. Kurths, G. Osipov, D. L. Valladares, and C. S. Zhou, "The synchronization of chaotic systems," *Phys. Rep.*, vol. 366, 2002, pp.1–101.
- [3] G. Jiang, W. Tang, and G. Chen, "A simple global synchronization criterion for coupled chaotic systems," *Chaos Solitons & Fractals*, vol. 15, no. 5, 2003, pp.925–935.
- [4] C. W. Wu, *Synchronization in coupled chaotic circuits and systems*. World Scientific, 2002.
- [5] P. Tass, M. G. Roseblum, M. G. Weule, J. Kurths, A. Pikovsky, J. Volkman, A. Schnitzler, and H. J. Freund, "Detection of n:m phase locking from noise data: Application to magnetoencephalography," *Phys. Rev. Lett.*, vol. 81, 1998, pp. 3291-3294.
- [6] C. Schafer, M. G. Roseblum, J. Kurths, and H. H. Abel, "Heartbeat synchronized with ventilation," *Nature*, vol. 392, 1998, pp.239-240.
- [7] A. Neiman, Xing Pei, D. Russell, W. Wojtenek, L. Wilkens, F. Moss, H. A. Braun, M. T. Huber, and K. Voigt, "Synchronization of the noisy electroresponsive cells in the paddlefish," *Phys. Rev. Lett.*, vol. 82, 1999, pp. 660–663.
- [8] M. Bazhenov, R. Huerta, M. I. Rabinovich, and T. Sejnowski, "Cooperative behavior of a chain synaptically coupled chaotic neurons," *Physica D*, vol. 116, 1998, pp. 392-400.
- [9] G. D. Van Wiggeren and R. Roy, "Communication with chaotic lasers," *Science*, vol. 279, 1998, pp. 1198-1200.
- [10] Meng Zhan, Gang Hu, and Junzhong Yang, "Synchronization of chaos in coupled systems," *Phys. Rev. E*, vol. 62, 2000, pp. 2963-2966.
- [11] Wang Jinlan, Chen Guangzhi, Qin Tuanfa, Ni Wansun, and Wang Xuming, "Synchronizing spatiotemporal chaos in coupled map lattices via active-passive decomposition," *Phys. Rev. E*, vol. 58, 1998, pp. 3017-3021.
- [12] I. M. Kyprianidis and I. N. Stouboulos, "Chaotic synchronization of two resistively coupled nonautonomous and hyperchaotic oscillators," *Chaos Solitons and Fractals*, vol. 17, 2003, pp. 317-325.
- [13] S. Callegari, R. Rovatti, and G. Setti, "Spectral properties of chaos-based FM signals: Theory and simulation results," *IEEE Trans. Circuits Syst. I*, vol. 50, 2003, pp. 3–15.
- [14] C. K. Tse and F. Lau, *Chaos-based digital communication systems: Operating principles, analysis methods, and performance evaluation*. Berlin, New York: Springer Verlag, 2003.
- [15] I. M. Kyprianidis, Ch. K. Volos, and I. N. Stouboulos, "Suppression of chaos by linear resistive coupling," *WSEAS Trans. Circ. Syst.*, vol. 4, 2005, pp. 527-534.
- [16] I. M. Kyprianidis and I. N. Stouboulos, "Dynamics of two resistively coupled Duffing-type electrical oscillators," *International Journal of Bifurcation and Chaos*, vol.16, no. 6, 2006, pp. 1765-1775.
- [17] I. M. Kyprianidis and I. N. Stouboulos, "Chaotic synchronization of three coupled oscillators with ring connection," *Chaos Soliton and Fractals*, vol.47, 2003, pp. 1349-1351.
- [18] I. M. Kyprianidis, Ch. K. Volos, and I. N. Stouboulos, "Experimental study of a nonlinear circuit described by Duffing's equation," *Science and Engineering*, Journal of Istanbul Kultur University, vol.4, no. 4, December 2006, pp. 45-54.

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- [1] Ch. K. Volos, I. M. Kyprianidis, and I. N. Stouboulos, "Chaotic cryptosystem based on inverse Duffing circuit," *Proceedings of the 5th International Conference on Non-linear Analysis, Non-linear Systems and Chaos (NOLASC 2006)*, Bucharest, Romania, 16-18 October 2006, pp. 92-97.
- [2] Ch. K. Volos, I. M. Kyprianidis, and I. N. Stouboulos, "Bidirectional coupling of two Duffing-type circuits," *Proceedings of the 7th WSEAS International Conference on Systems Theory and Scientific Computation*, Athens, Greece, 24-26 August 2007.
- [3] I. M. Kyprianidis, Ch. K. Volos, I. N. Stouboulos, and J. Hadjidemetriou, "Dynamics of two resistively coupled Duffing-type electrical oscillators," *International Journal of Bifurcation and Chaos*, vol. 16, no. 6, June 2006, pp. 1765-1775.

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- [1] Ch. K. Volos, I. M. Kyprianidis and I. N. Stouboulos, "Experimental Demonstration of a Chaotic Cryptographic Scheme," *WSEAS Transactions on Circuits & Systems*, vol. 5, no. 11, pp.1654-1661, November 2006.
- [2] I. M. Kyprianidis, A. N. Bogiatzi, M. S. Papadopoulou, I. N. Stouboulos, G. N. Bogiatzis and T. Bountis, "Synchronizing chaotic attractors of Chua's canonical circuit. The case of uncertainty in chaos synchronization," *Int. J. Bifurc. Chaos*, vol.16, no. 7, pp. 1961-1976, July 2006.
- [3] I. N. Stouboulos, A. N. Miliou, A. P. Valaristos, I. M. Kyprianidis and A. N. Anagnostopoulos, "Crisis induced intermittency in a fourth-order autonomous electric circuit," *Chaos, Solitons and Fractals*, vol. 33, no. 4, pp.1256-1262, August 2007.

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- [1] I. N. Stouboulos, I. M. Kyprianidis, and M. S. Papadopoulou, "Antimonotonicity and bubbles in a 4th order non driven circuit," *Proceedings of the 5th WSEAS International Conference on Non-Linear analysis, Non-Linear Systems and Chaos*, Bucharest, Romania, October 16-18 2006, pp. 81-86.
- [2] I. N. Stouboulos, I. M. Kyprianidis, and M. S. Papadopoulou, "Experimental study of antimonotonicity in a 4th order nonlinear autonomous electric circuit," *WSEAS Transactions on Circuits & Systems*, Issue 11, vol. 5, November 2006, pp.1662-1668.
- [3] I. N. Stouboulos and I. M. Kyprianidis, "Study of dynamics of a fourth-order autonomous nonlinear electric circuit," *Proceedings of the 13th IEEE International Conference on Digital Signal Processing*, vol. 2, 1997, pp. 715-718