Temperature as a Chaotic Circuit Bifurcation Parameter

Valerii Y. Ostrovskii
Department of Computer Aided Design
Saint Petersburg Electrotechnical University "LETI"
Saint Petersburg, Russia
vyostrovskii@etu.ru

Thalita E. Nazare[1], Samir A. M. Martins, Erivelton G. Nepomuceno[2]
Electrical Engineering Department
Federal University of São João del–Rei
São João del–Rei, Brazil
[1]thalitanazare@gmail.com, [2]nepomuceno@ufsj.edu.br

Abstract*—The number of researches aimed at understanding the chaotic behavior of nonlinear dynamical systems has grown considerably in recent years. The development of electronic circuits that exhibit this type of behavior has been the interest of numerous works in the literature. Among the possible sets of nonlinear systems, the simplest in which one can observe bifurcation phenomena and chaotic behavior, followed by well–controlled experiments, are nonlinear electronic circuits. One of the most widely used tools for analysis and evaluation of chaotic behavior is known as the bifurcation diagram. Generally, in the analysis of these circuits, parameters such as voltage, current and frequency are used to verify their respective behaviors. Variable values of passive components such as resistors and capacitors are also widely used. The temperature has also been used as a bifurcation parameter in resistor, diode and inductor (RLD) circuits. However, there is little attention from the scientific community on temperature as a bifurcation parameter for electronic circuits using operational amplifiers such as the chaotic Jerk circuit. In this sense, this project aims to implement a chaotic Jerk circuit, composed of operational amplifiers, resistors and capacitors, and subject it to different temperature levels, using this variable as an analysis parameter. Thus, at the end of this work it was possible to verify that the temperature variation directly influences the behavior of the investigated system, thus reaching the final objective of the project, presenting that the temperature can be a bifurcation parameter for a chaotic Jerk circuit.

Keywords—chaotic circuit; chaos; jerk dynamics; bifurcation; temperature

I. Introduction

Dynamic systems have been researched since Newton's time, but it was from the works of Lorenz [1] that various numerical experiments [2] were performed to contribute to understanding the behavior of nonlinear dynamic systems [3]. Thus, the number of researches aimed at understanding the chaotic behavior of these systems has grown considerably in recent years [4].

According to Balberg and Arbell [5], the simplest system in which bifurcation phenomena and chaotic behavior can be observed, followed by well–controlled experiments, are nonlinear electronic circuits. As examples, we have the work of Suneel [6], which looks for a simple electronic circuit for the logistic map which according to Ott [7], is the most used model for the study of chaotic systems, as well as the work of Campos–Cantón et al. [8], which makes a simple implementation of the Tent map. Miller and Grassi [9] also use an electronic circuit for discrete map analysis, which in this case is the map of Henon. Thukral et al. [10] using different types of analog circuits that exhibit nonlinear dynamics capable of generating signals that have noise–like frequency spectrum, show that a low–cost spectrum–based secure communication model can be developed using analog circuits.

Matsumoto [11] also features simple electronic circuits that allow confirming phenomena already observed computationally and rigorously proving that the circuit is chaotic, in addition to the fact that it is easily constructed. In many studies, one can already find the importance of comparing physical and computational analysis, such as several works that emerged after the development of the Chua circuit [12]. Recently, these studies have been motivated by the discovery of third order ordinary differential equations whose solutions have chaotic behavior. In the works developed by Sprott [13–15] a new class of chaotic electronic circuits consisting of resistors, capacitors, diodes and operational amplifiers is presented, in which the author presents this comparison between physical and computational results.

Generally, in the analysis of these circuits parameters such as voltage, current and frequency are used to verify their respective behaviors. Variable values of passive components such as resistors and capacitors are also widely used. However, studies by Ji–Chao et al. [16] and Balberg and Arbell [5] make use of temperature variation for different types of nonlinear system analysis, showing that this parameter has a great influence on circuit behavior. Still, there are few works in the literature that address this phenomenon and especially its influence on Jerk dynamics circuits.

Thus, the objective of this work was to analyze the influence of temperature in the chaotic circuit Jerk, composed by operational amplifiers, resistors and capacitors, proposed by Sprott [14], making temperature the variable of interest for analysis. Being the main objective to verify if the behavior

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observed by Balberg and Arbell [5] in an RLD circuit also occurs in Jerk dynamics circuits.

As a tool for the analysis of this behavior, the phase space and an approximation of the bifurcation diagram were used, which is generally used to refer to the qualitative transition from regular to chaotic behavior, changing the control parameter, in this case the temperature, given any initial condition [17]. The bifurcation diagram is used to study the system as a function of its control parameter [18–19], allowing to know regions of the system that converge to bifurcation or even chaos, depending on the parameter [20]. Thus, by analyzing the behavior of the circuit for different temperature values, at the end of the project, it was possible to prove that temperature variation can be a bifurcation parameter for a chaotic Jerk circuit, as observed by Balberg and Arbell [5] in an RLD circuit. Another factor that can be stated is that for periodic regions of the circuit, Lyapunov's greatest exponent is negative.

II. METHODOLOGY

In order to understand how the behavior of Jerk dynamics circuits may be related to temperature variation, the circuit developed in Sprott [14], shown in Fig. 1, was the basis for this project, along with research by Balberg and Arbell [5] that already has influence of temperature in nonlinear circuits.

In this article, at first, it was studied the operation of nonlinear circuits and chaotic Jerk circuits, considering their various configurations and considering the tolerance of each component necessary for its practical implementation. This study was conducted with the support of the base articles, individually analyzing the influence and importance of its components. In order to verify the behavior of these circuits previously, the LTspice simulation software was used.

After this step, a comparison was made between the commercially available components that were compatible as much as possible with the components used by the author. Having made the choice, the first practical step was the implementation of the circuit presented by Fig. 1, in order to collect the data of its behavior when subjected to room temperature.

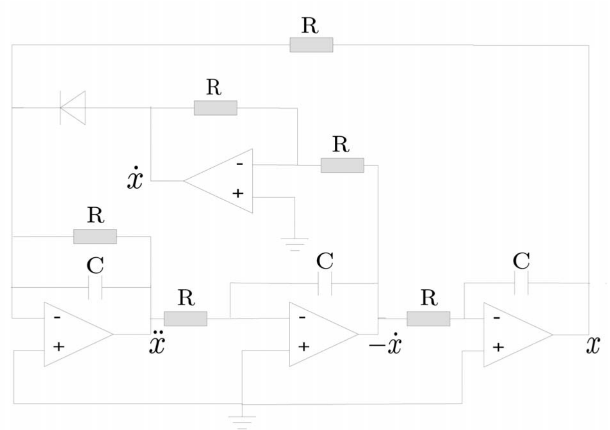

Fig. 3. Chaotic circuit consisting of 1kΩ resistors, operational amplifiers, 1μF capacitors and 1N4001 diode. Source: [14]

In parallel to the literature review and implementation of the circuit analyzed, a greenhouse of controlling the temperature was set up. This container is made of thermal insulation material, with the principle of heating incandescent lamps. Temperature monitoring was performed using NTC sensors and their data were processed via Arduino. Temperature control was also performed, responsible for actuating the actuators and changing the box temperature. Thus, this greenhouse was used to analyze the behavior of the Jerk circuit at different temperature levels, respecting the operational limits of its components.

After data collection, the Matlab software was used to generate the phase spaces for different temperature values. With this tool it was possible to analyze the circuit sensitivity with respect to the initial conditions and observe the period doubling when the temperature acts as a bifurcation parameter. Regarding error propagation, the precautions should follow the guidelines contained in the Institute of Electrical and Electronic Engineering (IEEE) 754–2008, which deals with floating point computation and IEEE 1788–2015 [21–23], on Interval Arithmetic.

III. RESULTS

To previously verify the behavior of the circuit using the components found for implementation, we used the LTspice simulation software, where it was possible to observe that the circuit dynamics was not affected, because the behaviors found were like those presented by the author.

Thus, in order to obtain a process that would guarantee the correct temperature variation and have the lowest possible influence of the ambient temperature, a wood greenhouse with an PI control system was built.

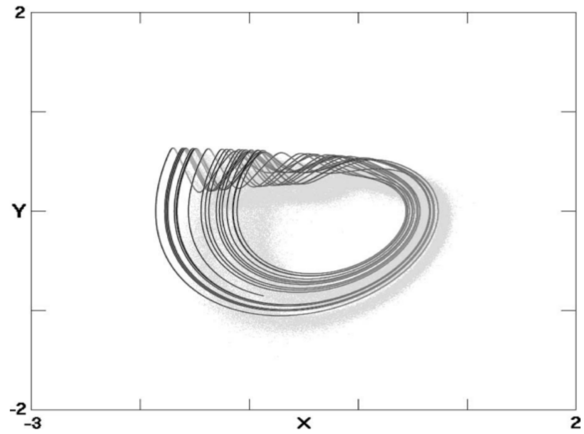

Fig. 4. Phase space by Sprott [14]

The Jerk circuit was implemented in and all voltage data related to system state variables were collected. To analyze and compare the results obtained, the phase space diagram was used for each system behavior at different temperatures. The result presented by Sprott [14] is shown in Fig. 2. Therefore, after collecting all data, the same phase space was developed for different temperatures, considering the same parameters as the author. The results for the temperatures that presented the greatest behavior difference are presented by Fig. 3.

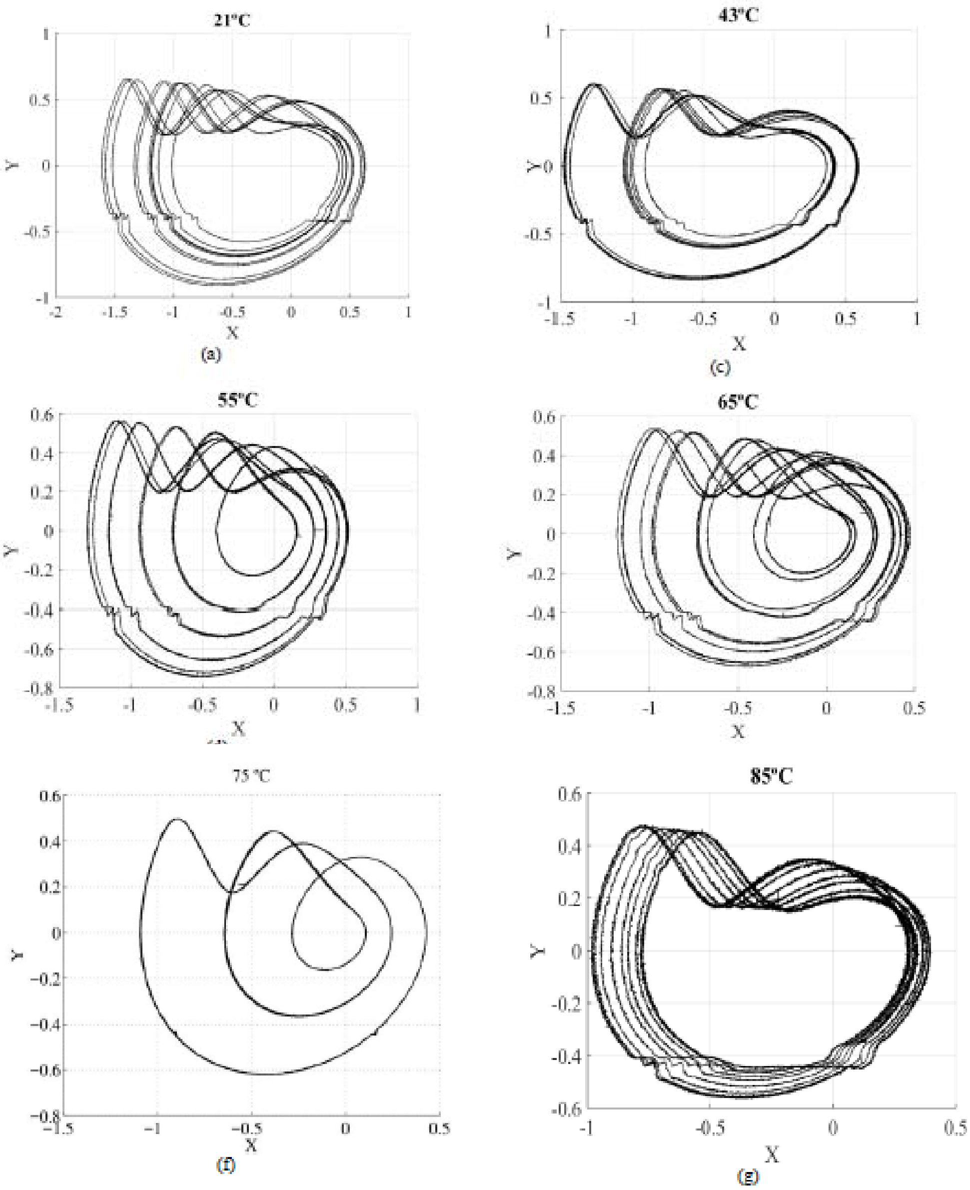

Fig. 3. Phase space representation used to analyze circuit behavior for different temperatures

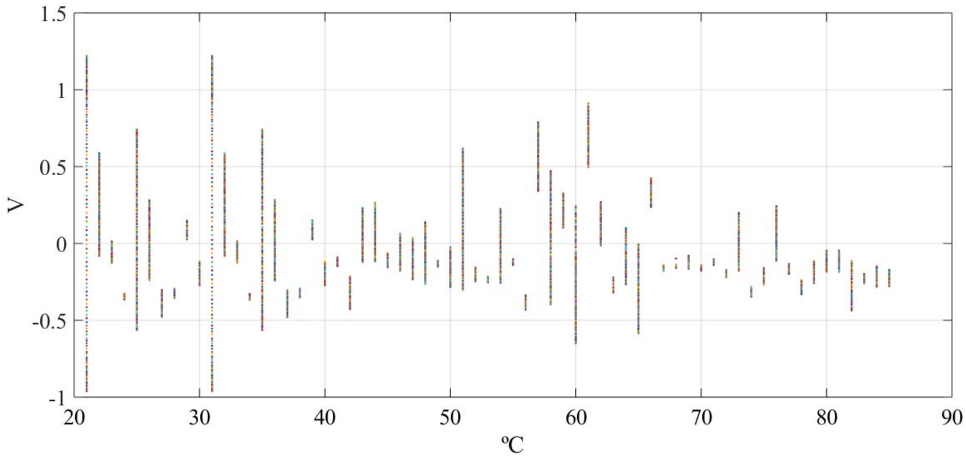

Fig. 4. Circuit output voltage behavior for a temperature range of 21ºC to 85ºC

After all these results, it can be stated that the temperature can be used as a bifurcation parameter for the system. For, the circuit has different temperature–dependent behaviors, for example, at 21ºC has a chaotic behavior, while at 75ºC it changes to a periodic fixed–point three behavior. Finally, Fig. 4 shows the different behaviors of the system according to temperature. Circuit voltage data were collected from one to one degree, between 21ºC and 85ºC, and for each series 5000 points were collected and to construct the diagram in Fig. 4, only the last 500 values were used.

Thus, as temperature values increase, the range of voltage values decreases. Finally, it is also possible to state that, for high temperature values, that is, where there is clear periodicity, the largest Lyapunov exponent is negative.

IV. CONCLUSION

At the end of this work, it was observed that, at first, temperature is rarely a parameter considered effectively in practical work, especially when its effect is not object of study. This can be proven due to the small number of researches that consider this phenomenon. However, following the methodology approached in this project, it was possible to show that its influence does count when analyzing practical experiments. Even though this is not the focus of the many studies found in the literature, it is important to emphasize that when analyzing the results, it should be borne in mind that the behaviors obtained are conditioned to all parameters that may influence the result, including temperature.

Many researches aim to reproduce or are based on results already found by other authors, but, in most cases, this reproduction is not done under the same conditions as the original work. One of the factors that most influence circuit behavior is the limitation of finding the same components used in the original work. However, in the results presented by this project, it was possible to observe that there is a change in behavior at different ambient temperatures. For the phase space that the author presents for the Jerk circuit shown in Fig. 2, even though it has chaotic behavior, is different from the phase space obtained in this work, presented by Fig. 3(a). For both cases, data collection was performed at room temperature and there is no way to state that this difference is due only to the difference in components used or whether it is also due to the temperature difference in each experiment.

Finally, it can be concluded that the objective of the work was achieved, since it was shown that the temperature change influences the behavior of the circuit, taking it from a chaotic to a periodic region. This fact is relevant because, with these results, a new bifurcation parameter is shown for analysis and studies of chaotic circuits. It is believed that the same behavior obtained in this project can be found for different circuit topologies, and it has been proven that the same happens with an RLD circuit.

REFERENCES

[1] Lorenz E., "Deterministic Nonperiodic Flow", Journal of the Atmospheric Sciences, March 1963, pp. 130–141.

[2] Peck S. L., "Simulation as experiment: a philosophical reassessment for biological modeling", Trends in Ecology & Evolution, 2004, vol. 19, pp. 530–534.

[3] Hammel S. M., Yorke J. A., Grebogi C., "Do numerical orbits of chaotic dynamical processes represent true orbits?", Journal of Complexity, June 1987, vol. 3, pp. 136–145.

[4] Fiedler–Ferrara N., Prado C. P. C., "Caos – Uma Introdução", Editora Edgard Blcher, 1994.

[5] Balberg I., Arbell H., "Temperature as a bifurcation parameter in nonlinear electronic circuits", Physical review. E, Statistical physics, plasmas, fluids, and related interdisciplinary topics, January 1994, vol. 49, pp. 110–113.

[6] Suneel M., "Electronic circuit realization of the logistic map", Sadhana, vol. 31, February 2006, pp. 69–78.

[7] Ott E., "Chaos in Dynamical Systems", Cambridge University Press, 2002.

[8] Campos–Cantón I., Campos–Cantón E., Murguía J. S., Rosu H. C., "A simple electronic circuit realization of the tent map", Chaos, Solitons & Fractals, October 2009, vol. 42, pp. 12–16.

[9] Miller D. A., Grassi G., "A discrete generalized hyperchaotic Henon map circuit", Proceedings of the 44th IEEE 2001 Midwest Symposium on Circuits and Systems, 2001, vol. 1, pp. 328–331.

[10] Thukral M. K., Sherpa K. S., Garg K., "Application of Analog Electronic Circuits in Secure Communication: A Review", Springer Singapore, 2018, pp. 675–684.

[11] Matsumoto T., "Chaos in Electronic Circuits", Proceedings of the IEEE, 1987, vol. 75, pp. 1033–1057.

[12] Chua L. O., "The Genesis of Chua's Circuit", Int. J. Electronics Communications, 1992, vol. 46, pp. 250–257.

[13] Sprott J. C., "A new class of chaotic circuit", Physics Letters A, February 2000, vol. 266, pp. 19–23.

[14] Sprott J. C., "A New Chaotic Jerk Circuit", IEEE Transactions on Circuits and Systems II: Express Briefs, April 2011, vol. 58, pp. 240–243.

[15] Sprott J. C., "Algebraically Simple Chaotic Flows", International Journal of Chaos Theory and Applications, January 2000, vol. 5, pp. 1–20.

[16] Ji–Chao Z., Son H., Kim N., Song H. J., "Stability of operation versus temperature of a three–phase clock–driven chaotic circuit", Chinese Physics B, 2013, vol. 22.

[17] Ramadan N., Ahmed H. E. H., Elkamy S. E., El–Samie F. E. A., "Chaos–Based Image Encryption Using an Improved Quadratic Chaotic Map", American Journal of Signal Processing, 2016, vol. 6, pp. 1–13.

[18] Ji Y., Lai L., Zhong S., Zhang L., "Bifurcation and chaos of a new discrete fractional–order logistic map", Communications in Nonlinear Science and Numerical Simulation, April 2018, vol. 57, pp. 352–358.

[19] Potkonjak N. I., "Consideration about a voltammogram as the bifurcation diagram of oscillating electrochemical systems: a case study of the copper|1 M trifluoroacetic acid oscillator", Reaction Kinetics, Mechanisms and Catalysis, February 2018, vol. 123, pp. 115–163.

[20] Monteiro L. H. A., "Sistemas Dinâmicos", Livraria da Física, 2006.

[21] Overton M. L., "Numerical computing with IEEE floating point arithmetic", SIAM, 2001.

[22] IEEE, "IEEE Standard for Floating–Point Arithmetic", IEEE Std 754–2008, 2008, pp. 1–70.

[23] IEEE, "IEEE Standard for Interval Arithmetic", IEEE Std 1788–2015, 2015, pp. 1–97.