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Antimonotonicity, chaos and multiple coexisting attractors in a simple hybrid diode-based jerk circuit

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ABSTRACT

This paper focuses on the dynamics of a modified jerk circuit obtained via replacing the diode bridge memristor in the original jerk circuit introduced in [24] with a first-order hybrid diode circuit. Both memristive diode bridge and first order hybrid diode are frequency dependent component even though the later device doesn't has a pinched hysteresis loop. The analysis is carried out in terms of bifurcation diagrams, graph of Lyapunov exponents, phase portraits, Poincaré section, time series and frequency spectra. The results indicate that, the new circuit exhibits rich dynamic behaviors including multiple coexisting self-excited attractors (e.g. coexistence of two, four or six disconnected periodic and chaotic attractors) and antimonotonicity (i.e. concurrent creation and annihilation of periodic orbits) compared to the original memrisitve jerk circuit. Basins of attraction of various coexisting attractors display extremely complex structures thus justifying jumps between coexisting attractors in experiment. Both PSpice simulations and laboratory experimental measurements are carried out to support the theoretical analyses.

1. Introduction

During the last decades, the discipline of nonlinear dynamical systems and chaos has advanced significantly. The research effort on chaotic systems has progressed starting from theoretical research and controlling of chaos to the utilization of chaotic circuits effectively. Chaos is utilized in various areas of nonlinear science such as information processing, preventing the collapse of power systems, high-performance circuit devices, and liquid mixing with low power consumption [1]. Chaotic circuits have several applications among which multi-frequency active antenna design, chaotic communication, random bit generation, bio-medicine, neural networks, visual sensing, secure communication, spread spectrum communication, low power communication and sonar systems, just to name a few [2–9]. To generate chaotic oscillations, a nonlinear element such as Chua's diode, bipolar junction transistor, JFET, semiconductor diode, Zener diode, Lamba diode, tunnel diode, memristor, nonlinear resistor and hybrid diode (in spite of their intrinsic current-voltage ($i - \upsilon$) characteristic) is used to design the circuit [10–17]. Chua's oscillator has been intensively studied these last years by considering different forms of nonlinearity. The dynamics exhibited by some variants of Chua's circuit includes self-excited attractors, hidden attractors, coexistence of self -existed attractors, coexistence of hidden attractors, antimonotonicity and so on [18–20]. Similarly, recent research works have reported very rich and interesting dynamic behaviors in simple jerk systems. Recall that jerk systems are third-order differential equations of the form $\dddot{x} = J(\ddot{x}, \dot{x}, x)$ where the nonlinear function J is called the "jerk" because it denotes the third-time derivative of x which would correspond to the first-time derivative of acceleration in a mechanical system [21–23]. A series of works concerning the issue of coexisting multiple attractors in simple jerk dynamical systems were carried out by Kengne and collaborators [24–26]. Particularly, in the work of Njitacke and collaborators [24], a modified jerk circuit with memory element (i.e. memristor) has been proposed and the corresponding dynamics investigated in terms of its parameters. Theoretical analyses, software simulations and experimental methods were used to demonstrate the complex phenomena such as period doubling bifurcation, periodic windows, and coexistence of multiple attractors (four coexisting attractors) experienced by the circuit. Motivated by the above mentioned works, this paper focuses on the dynamics of a modified jerk circuit obtained via replacing the diode bridge memristor in the original jerk circuit introduced in [24] with a first-order hybrid diode circuit. Both memristive diode bridge and first order hybrid diode are frequency

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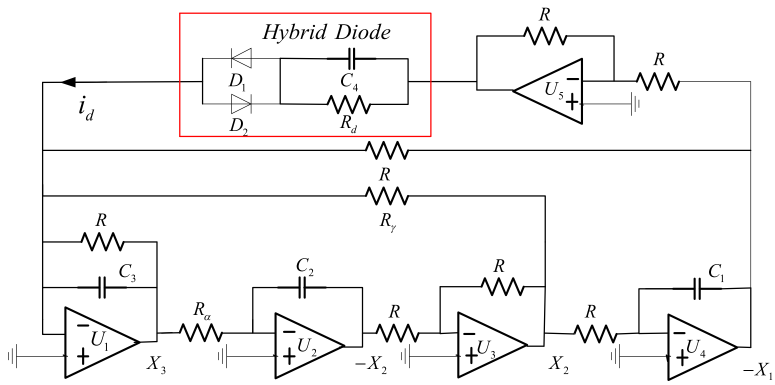

Fig. 1. Electronic realization of the jerk circuit modified by a hybrid diode circuit (see Table 1 for the values of electronic components).

dependent component even though the later device doesn't has a pinched hysteresis loop. Mention that, the hybrid diode has two diodes less than the original memristive diode bridge. More interestingly, the novel hybrid diode based circuit displays richer dynamic behavior (such antimonotonicity and coexistence of six disconnected attractors) compared to the original memristive diode bridge circuit. Also, the goal of this work can be summarized in the following three keys points: a) to carry out a systematic analysis of the modified jerk circuit and explain the chaos mechanism; b) to define the domain in the parameter space in which the proposed model experience multiple coexisting attractors and hysteretic dynamics; c) to carry out an experimental study of the system to support the theoretical predictions. The overall motivation of this paper is to enrich the literature with a novel chaotic system/circuit with multiple coexisting attractors; moreover, we develop useful tools for the practical circuit design of such types of oscillators.

The remainder of this letter is structured as follows. Section 2 presents the modeling process. The electronic structure of the modified jerk circuit with hybrid diode is presented and a suitable mathematical model is derived. In Section 3, analysis tools such as bifurcation diagrams, graph of Lyapunov exponents, phase portraits, Poincaré section, time series and frequency spectra are used to highlight phenomena such as coexistence of multiple attractors and antimonotonicity in the modified circuit. In Section 4, both Pspice simulations and laboratory experimental measurements are carried out to support our analysis. In Section 5, we discuss our results, suggest some potential utilities of the new circuit, and point out some open issues. Finally, some concluding remarks and proposals for future work are given in Section 6.

2. The proposed modified jerk circuit

2.1. Modified jerk circuit by hybrid diode

Fig. 1 represents the circuit diagram of the proposed jerk circuit with hybrid diode. The circuit consists of operational amplifiers, resistors, capacitors and diodes. The part within the red box is the first-order hybrid diode circuit in which a pair of diodes is connected in anti-parallel. Thus, the proposed circuit is a fourth-order nonlinear circuit with four dynamic elements namely C_1, C_2,C_3 and C_4. In order to derive a mathematical model of the circuit in Fig. 1, the voltages across each capacitors are defined respectively as X_1, X_2, X_3 and X_4. The currents flowing through the diodes is defined as I_d. It is important to stress that the current-voltage characteristic $(I-V)$ of the pair of semiconductor diodes D_1 and $D_2(\eta = 1.9$, $V_T = 26$mV, $I_S = 2.682$nA) is obtained from the Shockley diode equation [27,28] as follows:

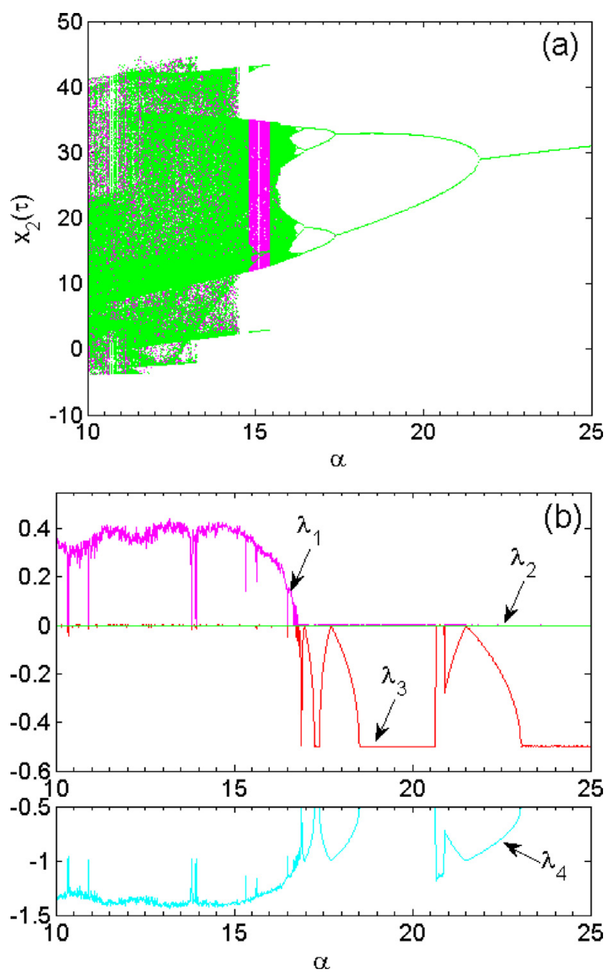

Fig. 2. Bifurcation diagram (a) showing local maxima of the coordinate $x_2(\tau)$ versus $\alpha$and the corresponding graph (b) of largest Lyapunov exponent (λ_i) plotted in the range $10 \le \alpha \le 25$ with $\gamma = 1.66$. A positive exponent $(\lambda_1 > 0)$ indicates chaos while regular states are characterized with negative values of Lyapunov exponent $(\lambda_1 < 0)$. The diagram in magenta is obtained for increasing decreasing values of α starting from the initial point $(0, 0, -1, 0)$ while the one in green is obtained with fixed initial condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$I_d = I_{D_1} - I_{D_2} = I_S[\exp(V_d/nV_T) - 1] - I_S[\exp(-V_d/nV_T) - 1] = 2I_S \sinh(V_d/nV_T) \quad (1)$$

I_S is a reverse bias saturation current, n is a diode ideality factor, V_T is a thermal voltage with $V_d = X_1 - X_4$. Upon, applying Kirch-