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Noise activated dc signal sensor based on chaotic Chua circuit

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ABSTRACT

The noise activated dc voltage signal sensor based on Chua's electronic circuit made from standard electronic components and operating in the chaotic regime where two single scroll attractors coexist is proposed. The crossings between attractors are driven only by the Gaussian noise. The unknown dc target signal is detected and measured via the monitoring of the residence time proportion the sensor stays in one of the two attractors. The dependence of the output time proportion on the input dc target signal voltage and the noise intensity were obtained performing computer simulations. The optimal noise intensity range for detection is indicated and the dependence of the measurement error on the observation time in this range is obtained. The nearly linear output–input relation for the optimal noise level is found.

1. Introduction

The stochastic resonance (SR) is a phenomenon where the presence of internal or input noise is required to achieve an optimal output from nonlinear system [1–3]. In initial studies nonlinear systems like the threshold device generating pulse every time the threshold is crossed or the double-well system with quartic potential driven by weak subthreshold periodic signal subject to additive white noise were considered [4–7]. These system are examples of general systems which exhibit SR, i.e. the two-state systems and the excitable systems. SR was observed and demonstrated in experiments on human vision, hearing, tactile and brain functions and on many other sensory biological systems [8,9]. These observations and experiments evidence that in biological systems noise enhances information transmission and processing. The nonlinear systems with chaotic dynamical behavior have also been used in studies of SR. They served as chaotic source substituting stochastic noise [10,11] or as a variant of the two-state system where chaotic attractors represent system states [12–17]. In the second case SR in electronic Chua's circuit was the most intensively studied both numerically [15,16] and experimentally [17]. SR effect have also been presented for aperiodic subthreshold input signals [18,19]. This phenomenon is termed aperiodic stochastic resonance (ASR). In recent years new form of SR has been introduced under the name of suprathreshold stochastic resonance (SSR) [20]. SSR occurs in a system of identical parallel threshold devices such as comparators or neurons subject to the same input signal, but independent and identically distributed noise. It was shown that if the overall output is the sum of the individual outputs, then SR occurs irrespective of whether the input signal is subthreshold or not. Nowadays the definition of SR is thus extended to phenomena in which the presence of noise or randomness is required to achieve an optimal output from a system.

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Recently, noise activated nonlinear bistable dynamical systems have been proposed as sensors of weak dc or low-frequency signals [21,22]. Usually, in a large class of nonlinear bistable dynamic sensors like a two-state Schmitt trigger [23], magnetic fluxgate sensors [24,25], ferroelectric sensors [25,26] and mechanical sensors e.g. acoustic transducers made with piezoelectric crystals, ceramics, or polymers [26], a known periodic (sinusoidal or triangular) external bias signal is applied to the sensor to drive it between its two stable states corresponding to minima of its potential energy function. The amplitude of the bias signal is large to make sensor response independent of the noise. The target dc signal breaks the symmetry of the potential energy function what can be detected and measured by different techniques. The conventional method (PSD technique) is based on the monitoring of the power spectral density amplitude of the sensor response [24]. It contains only the odd harmonics of the bias signal frequency in the absence of a target signal and all harmonics in the presence of a target signal. The spectral amplitudes of even harmonics are quantifying measures of dc target signal amplitude. The alternative measurement technique is based on the mean residence time difference in two stable steady states of the potential energy function (RTD technique) [22,27,28]. This technique has several advantages compared to the PSD technique, i.e. it provides a very simple and sensitive readout processing scheme, it can be implemented experimentally without complicated feedback electronics and it avoids the knowledge of the computationally demanding power spectral amplitude of the sensor output. Nonlinear sensors often operate in noisy environments, so the noise is present in the physical quantity under measurement. Moreover, current trends go in direction of realizing miniaturized sensors which are cheap and compact. However, the reduction of sensor dimension increases the sensor noise affecting the sensing operations [22]. In the presence of noise crossing events between stable states are controlled by both the noise and added bias signal. The effect of the noise on operation of nonlinear bistable sensors using RTD measurement technique with external suprathreshold time-periodic bias signal controlling switching between the two stable states was described in Ref. [21,25,29,30]. The requirement of large onboard power to provide a high-amplitude suprathreshold bias signal was mitigated by utilizing a low-amplitude subthreshold bias signal and allowing the crossing events to be largely noise controlled. The role of the subthreshold bias signal was to make crossings between stable states to happen near a given times. The individual crossing events driven by the noise and the subthreshold bias signal can occur at different multiples of the bias signal half period, i.e. they can show a skipping behavior. The residence time distribution can be multipeaked in this case what complicates readout scheme. It was shown that for subthreshold bias signal the right amount of the noise improves target signal detectability both using the PSD technique [31–33] and RTD technique [34,35]. The stochastic resonance effect is thus utilized for the optimal operation of such sensors. The noise activated bistable dynamic sensors to detect dc or low-frequency target signal operate in the absence of bias signal [22]. They are based on RTD measurement technique. The crossing events between stable states in these sensors are driven only by the noise. The simplest example of such a sensor is a two-state Schmitt trigger [22]. The noise activated bistable sensors have many advantages like: simple readout scheme, high sensitivity, zero bias signal and good performance in the presence of noise. Their applicability can however be limited by short observation time.

In this paper we propose to use Chua's electronic circuit operating in the chaotic state in which two single scroll attractors coexist as the noise activated bistable dynamic sensor to detect weak dc or low frequency voltage signals. We selected this circuit because it is the simplest circuit that is capable of producing chaos [36,37] easy to build at low cost using standard electronic components [38]. Moreover, both the single Chua's circuit and an array of closely matched Chua's circuits can now be fabricated in a single chip [39], what is important for the sensor application and miniaturization. We assume that only the noise added to the target signal drives the sensor between attractors without the presence of time periodic bias signal. We propose to monitor the proportion of the time the sensor stays in one of the two attractors and use this observable as a quantifier of the target signal. This readout scheme we applied because it is very simple and easy to implement experimentally. We study the operation of the proposed sensor by performing numerical simulations. We present SR effect and we determine the noise intensity range optimal for the sensor operation. There are two significant difficulties in designing a good sensor, i.e. the output–input proportionality and usually disrupting presence of the noise [22]. The presence of the noise is inherent in functioning of the proposed noise activated sensor and we show that there is practically linear dependence between the output time proportion and the input dc target signal voltage for the noise level in the optimal noise range. The performance of noise activated sensors is significantly dependent on the observation time [34]. We show how the measurement error decreases with the observation time for our sensor driven by the optimal noise.

The paper is organized as follows: in Section 2 we present the schematic of the noise activated sensor based on Chua's circuit operating in chaotic region, specify parameters of electronic components, describe dc constant voltage detection strategy and give details about performed computer simulations. We also discuss the dependence of the sensor output, i.e. the time proportion it stays in one attractor, on the noise intensity and dc target signal voltage. In Section 3 we present SR effect and determine the noise intensity range optimal for the sensor operation. We show for the optimal noise level the output–input relation and the dependence of the measurement error on the observation time. Finally, we provide conclusions in Section 4.

2. Sensor description, detection strategy and operating range

The Chua's electronic circuit is the first real physical object in which chaos was observed experimentally [40]. It is made up of one resistor, one inductor, two capacitors and one nonlinear element called Chua's diode characterized by a three-segment piecewise-linear current–voltage curve [36,38]. The Chua's diode can be made using multiple discrete components like