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Changing Attractors Using Synchronization in Chaotic Circuits with Unidirectional Coupling

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Abstract

In recent years, the rapid development of artificial intelligence has led to increased power consumption and rising operational costs, motivating the exploration of alternative approaches. Chaotic circuits, which exhibit nonlinear and bounded dynamics, have attracted attention due to their synchronization properties, similar to those observed in biological systems such as neurons. This study investigates attractor control in ring-shaped networks of chaotic circuits using the Nishio–Inaba circuit. By externally connecting an additional chaotic circuit to the ring, we analyzed changes in attractor shape and average voltage and current values. The results demonstrate that attractor bias can be reversed and propagated throughout the network, suggesting that mixed coupling structures enable effective control of network dynamics.

1. Introduction

In recent years, the development of artificial intelligence has caused issues such as increased power consumption, expansion of data centers, and the resulting rise in operational costs. Although technologies such as reservoir computing and edge computing are being actively explored to address these challenges, new approaches using nonlinear circuits are also gaining attention.

In chaotic circuits, chaotic behavior appears in voltage and current signals. Chaotic phenomena are characterized by nonlinearity, aperiodicity, boundedness, and high sensitivity to initial conditions[1]. Oscillators with bounded dynamics tend to synchronize, and therefore chaotic circuits also exhibit synchronization due to this boundedness[2]. In nature, nonlinear systems such as neurons and heartbeats frequently display similar synchronization behavior. Therefore, chaotic circuits may be able to mimic the behavior of neurons due to these properties. Consequently, using networks of chaotic circuits instead of conventional artificial intelligence systems could enable the prediction of more complex tasks.

In this study, the effects of connecting an external chaotic circuit to a ring-shaped network composed of chaotic circuits in a steady state are investigated. Through this investigation, we examine whether the ring-shaped chaotic circuit can be controlled by using external inputs.

2. Circuit Model

This section discusses the circuit model used in this study. Figure 1 shows the chaotic circuit model which is called Nishio-Inaba Circuit. This circuit model is composed of capacitors, inductors, nonlinear resistors, and negative resistors, and it is known that the voltage and current values exhibit chaotic behavior.

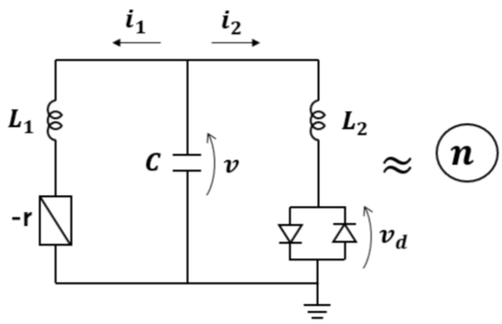


Figure 1: Nishio-Inaba Circuit Model.

The circuit equations for this circuit are described using Kirchhoff's current and voltage laws. Eq. (1) gives the circuit equations of the Nishio–Inaba circuit.

$$\begin{cases} L_1 \dfrac{di_1}{dt} = v + r i_1 \\ L_2 \dfrac{di_2}{dt} = v - v_d \\ C \dfrac{dv}{dt} = -i_1 - i_2. \end{cases} \tag{1}$$

Equation (2) gives the voltage of the nonlinear resistor v_d in Eq. (1). The nonlinear resistor used in the Nishio-Inaba circuit is composed of a bidirectional diode.

$$v_d = \frac{r_d}{2}\left(\left|i_2 + \frac{V}{r_d}\right| - \left|i_2 - \frac{V}{r_d}\right|\right) \tag{2}$$

The circuit equations normalized using normalization parameters are given in Eq. (3).

$$\begin{cases} \dot{x_i} = \alpha x_i + z_i \\ \dot{y_i} = z_i - f(y_i) \\ \dot{z_i} = -x_i - \beta y_i - \displaystyle\sum_{i,j=0}^{n} \gamma_{ij}(z_i - z_j) \end{cases} \tag{3}$$

$$f(y_i) = \frac{\delta}{2}\left(\left|y_i + \frac{1}{\delta}\right| - \left|y_i - \frac{1}{\delta}\right|\right) \tag{4}$$

Equation (4) gives the normalized nonlinear resistor in Eq. (3), where the normalization parameters α, β, δ and γ represent the negative resistance value, inductance ratio, nonlinear resistance value and coupling conductance.

3. System Model

This section discusses the system model used in this study. Figure 2 shows the system model in this study.In this model, one chaotic circuit is regarded as one node. Six circuits are connected in a ring configuration, and one additional circuit that provides disturbances is connected outside the ring.

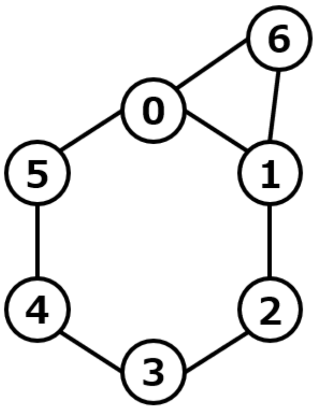


Figure 2: System Model.

In previous studies, two types of attractors were observed in ring-coupled chaotic circuits by combining bidirectional and unidirectional coupling[4]. Therefore, using this model, we investigate the possibility of switching attractors by applying disturbances to the ring-coupled system.

4. Simulation Conditions

This section discusses the simulation conditions in this study. Table 1 shows the values of the parameters used in the Nishio–Inaba circuit equations.

Table 1: Parameters.

α	0.410
β	3.0
δ	470
γ	0.30

Equation (5) gives the initial values of the circuits used in this study. Here, n corresponds to the node number in Fig. 2, and $initial$ is varied from 0.005 to 0.009 in steps of 0.001 to examine the effect of different initial conditions.

$$\begin{aligned} x &= initial * n + 0.010 \\ y &= 0.001 * n + 0.010 \\ z &= 0.001 * n + 0.010 \end{aligned} \tag{5}$$

Furthermore, in this study, the adjacency matrix representing the coupling strength is set according to Eq. (6) for count numbers less than 50,000, according to Eq. (7) for count numbers from 50,000 to less than 300,000, and according to two patterns given by Eq. (8) and (9) for count numbers greater than or equal to 300,000. Here, the count number refers to the number of Runge–Kutta integration steps.

$$\begin{bmatrix} 0 & \gamma & 0 & 0 & 0 & 0 & 0 \\ \gamma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{6}$$

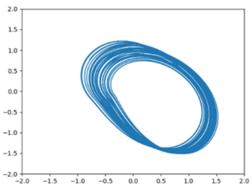
$$\begin{bmatrix} 0 & \gamma & 0 & 0 & 0 & \gamma & 0 \\ \gamma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \gamma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \gamma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} 0 & \gamma & 0 & 0 & 0 & \gamma & 0 \\ \gamma & 0 & 0 & 0 & 0 & 0 & \gamma \\ 0 & \gamma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \gamma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma & 0 & 0 \\ \gamma & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

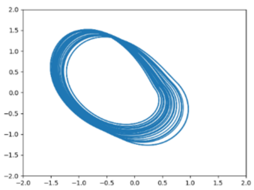
$$
\begin{bmatrix}
0 & \gamma & 0 & 0 & 0 & \gamma & \gamma \\
\gamma & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \gamma & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \gamma & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \gamma & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \gamma & 0 & 0 \\
0 & \gamma & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \quad (9)
$$

5. Simulation Results

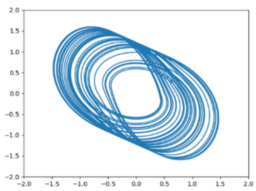
This section presents the results of the simulations conducted in this study. In this study, the chaotic circuits in the system can be broadly classified into three types based on their x–z attractors.



(a) Attractor 1.



(b) Attractor 2.



(c) Attractor 3.

Figure 3: Attractors.

Figure 3 shows three types of attractors. Attractor 3 represents the chaotic trajectory in the uncoupled case. Among these three types, Attractor 1 is shown in blue, Attractor 2 in orange, and Attractor 3 in green. As a classification method, we propose an approach based on the average values.

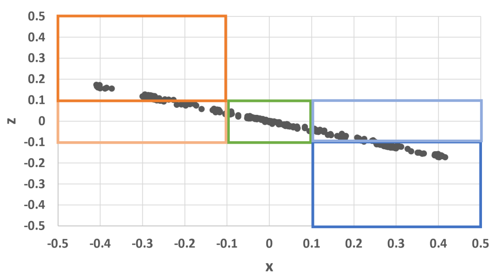


Figure 4: Classification criteria.

Accordingly, in the simulation results, the attractors are classified according to the average values of each variable in the x–z attractors of the chaotic circuits. The classification criteria are shown in Fig. 4. In Fig. 4, the classification is performed using thresholds of ± 0.1. However, there are cases in which the average value of z does not exceed ± 0.1, while the average value of x exceeds ± 0.1. Such states are indicated by light blue and light orange colors.

According to the conditions shown in Fig. 4, the attractors of each node are classified at intervals of 50,000 counts, and the results are presented in Fig. 5 and Fig. 6.

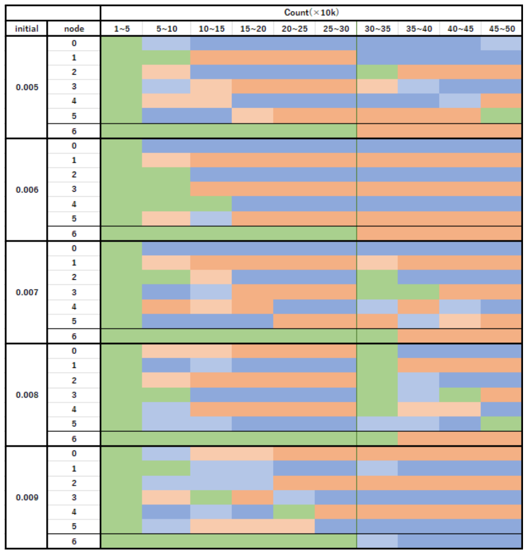


Figure 5: Results for the condition in Eq. (8).

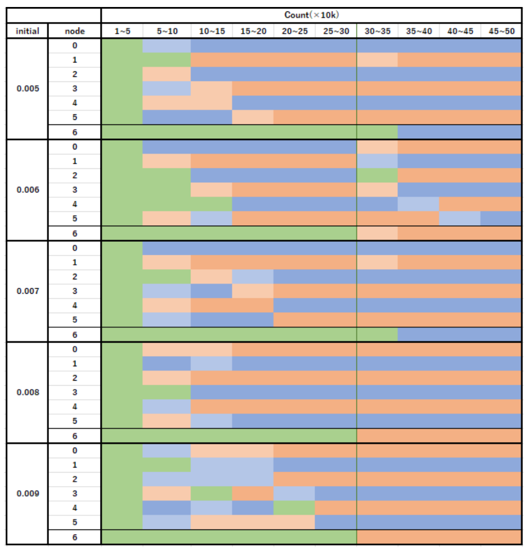


Figure 6: Results for the condition in Eq. (9).

Figure 5 shows the results obtained after a count of 300,000 when the coupling strength matrix given in Eq. (8) is used. It can be seen that, for all nodes, attractors with different characteristics appear alternately in the final state. In addition, the switching of attractors induced by external disturbances, which is the main objective of this study, was observed only when the initial condition parameter $initial$ was set to 0.005 and 0.008.

Figure 6 shows the results obtained after a count of 300,000 when the coupling strength matrix given in Eq. (9) is used. It is observed that, for all nodes, attractors with different characteristics appear alternately in the final state. Furthermore, the switching of attractors induced by external disturbances, which is the main objective of this study, was observed only when the initial condition parameter $initial$ was set to 0.006.

Table 2 summarizes the relationship between the initial conditions and attractor switching based on the results shown in Fig. 4 and 5.

Table 2: Relationship between the initial conditions and attractor.

initial	matrix condition
0.005	Eq. (8)
0.006	Eq. (9)
0.007	-
0.008	Eq. (8)
0.009	-

From the results in Tab. 2, it can be seen that, depending on the initial conditions, there are cases in which the attractor changes in response to external disturbances and cases in which it does not.

6. Conclusions

In this study, we investigated attractor switching induced by externally connected disturbances in ring-coupled chaotic circuits. As a result, it was found that, depending on the initial conditions, the system either converges to its original state even after the disturbance is applied or undergoes a change in its attractor. These results indicate that, by appropriately selecting the initial conditions, it is possible to control the state of a chaotic circuit network, either inducing a change or maintaining the original state. In future work, we plan to increase the number of initial-condition samples to investigate the tendency of initial-condition sensitivity in the Nishio–Inaba circuit.

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