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Smart variable structure control of complex network with time-varying inner-coupling matrix to its equilibrium

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Abstract: The novelty in this paper lies in the establishment of smart controller and suitable multiple sliding mode manifolds according to node chaos dynamics of complex networks with time-varying inner-coupling configuration. The smart variable structure control for asymptotical synchronization to its equilibrium is developed based on the ergodicity characteristic of chaos nodes, without the involvement of linearization and other ideal assumptions. The scheme enables the behavior of complex networks to approach the desired manifolds, and eventually realizes the asymptotical synchronization. Finally, the simulations based on the Lorenz chaos complex network under three topological configurations further verify the robustness and effectiveness of the proposed scheme.

Key words: complex network; synchronization; smart control; variable structure control

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时变内耦合复杂网络的平衡态同步smart变结构控制

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摘要: 当前同步控制问题是复杂网络研究的热点之一. 本文针对具有时变内耦合结构的复杂网络, 利用结点混沌动态的各态历经性, 通过构造合适的滑模面, 提出了smart变结构控制器的设计策略. 该策略可使复杂网络动态行为趋向于所构造的全局吸引区域, 从而最终实现复杂网络在平衡态的渐近同步. 最后, 基于3种不同拓扑结构的Lorenz结点动态的复杂网络进行仿真实验表明该控制方案具有较好的鲁棒性和有效性.

关键词: 复杂网络; 同步; smart控制; 变结构控制

1 Introduction

To gain an insight into the mechanism of complex network operation and even control and prediction of network behavior, complex network systems have been extensively studied recently. Increasing research attention has been drawn to the control and analysis of complex network systems. Complex network systems are ubiquitous, including many natural or man-made systems, such as social network systems, neural network systems, the Internet, logistic network systems, electrical power grids, satellite network guidance systems, and so on. In general, network systems can be represented by means of graphs in mathematical terms where many nodes are inter-connected by directed or undirected edges or links with different topological structures. Currently, main complex networks models are regular networks model, random network model, small-world network model, and scale free network model[1~8].

Collective motions of complex networks have been the subject of considerable interest within the science and technology communities over last decade. Especially, one of the interesting and significant phenomena in complex networks is the synchronization. Recently, synchronization research of complex networks has been reported in the literature[9~21]. The study of the synchronization in a scale-free dynamical network has been

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made, and a positive threshold of coupling strength of scale-free networks has been obtained which can guarantee the synchronization of the network systems in [9]. For the characteristics of small-world dynamical networks, some important concepts such as synchronization matrix, associated feedback system, sensitive and robust edge, have been initially given, and robustness analysis of networks synchronization has been made in [10]. Introducing the coupling delays into complex networks for both continuous-time case and discrete-time case, the synchronization conditions for delay-dependent and delay-independent have been derived in [11], respectively. Several criteria for both robust local and robust global impulsive synchronization for uncertain dynamical networks have been established using the impulsive control systems theory[14]. Based on hybrid control strategy, complex networks of directed time-varying network and undirected time-invariant network with constant edge weights have been studied, and the sufficient conditions for the global exponential and asymptotical synchronization have been developed in [15]. Especially, in [16], a more unified criterion of synchronization for complex network with time-invariant, time-varying and switching configuration has been proposed by using the matrix measure of complex matrices, and an M-synchronization conception is provided firstly for the complex network with time-varying and switching configurations. In [17], the master stability function has been established to decide whether or not any linear coupling arrangement produces stable synchronization dynamics, while variations of desynchronization bifurcation modes have been revealed with change of coupling scheme and coupling strength. Based on master stability function rationale, synchronizablity and synchronization enhancement of some complex networks have been discussed using eigenratio of out-coupling matrix by rewiring links and/or assigning proper weights for the existing links[18~21]. Though, the main methodology of synchronization of complex networks is by means of linearization around the desired equilibrium in these literatures.

The main contribution in this paper is that a novel smart variable structure controller channeling into the corresponding chaos nodes for the synchronization of chaos dynamic complex network systems is initially developed by employing pinning control scheme. Variable structure control is a kind of control strategy that exhibits discontinuity on certain predefined manifolds[22]. Yu has initiated the idea of the smart variable structure control in [23,24]. The main advantages of such control mechanism are robustness and easily realization. On the one hand, variable structure control is robust to certain system parameter variations and external disturbance, which is to be verified by employing time-varying inner matrix in this note. On the other hand, the controller is designed based on the desired sliding mode manifolds. For a general chaos node subsystem of complex networks, multiple sliding mode manifolds are to be established to generate a dimension attraction region which includes the intersection of multiple manifolds. For the sensitive characteristics of chaos systems, we propose a new smart sliding mode control with limited small control magnitude. Besides, motivated by pinning control method introduced in [8,9], smart variable structure controllers pinning to multiple nodes are also to be discussed and tested in the simulation section in this paper.

2 Model description and preliminaries

In general, complex network system consisted of identically linearly and diffusively coupled nodes is considered in most works, with an individual node dynamics as follows

$$\dot{x}_i(t) = f(x_i(t)) + c\sum_{j=1}^{N} a_{ij}\varGamma(t)x_j(t), \qquad (1)$$

where $x_i(t) = (x_{i1}(t), x_{i2}(t), \cdots, x_{in}(t))^{\mathrm{T}} \in \mathbb{R}^n$ is the state of the ith node, $f(\cdot) : \mathbb{R}^n \to \mathbb{R}^n$, c is the coupling strength, $\varGamma(t) = (\varGamma_{ij}(t)) \in \mathbb{R}^{n\times n}$ is a constant 0-1 inner-coupling matrix linking coupled variables with time, $A = (a_{ij})_{N\times N}$ is the out-coupling configuration matrix of the network. As far as out-coupling matrix, it has general form with $a_{ij} = a_{ji} = 1$ if there is a connection node i and node j, and $a_{ij} = a_{ji} = 0$ otherwise.

Remark 1 The variant forms of inner-coupling matrix $\varGamma(t)$ and out-coupling matrix A are discussed here. The time-invariant form has been usually studied, that is, $\varGamma(t) \equiv \varGamma$. In practice, inner-coupling matrix and out-coupling matrix often alter for many special reasons, so it is often time-varying, such as the assumption of the periodic switching[16]. The influence of time-varying out-coupling matrix will be studied in forthcoming publications.

Simply speaking, A is symmetric for an undirected network while A becomes asymmetric if the network is a directed graph. Here assume A is an irreducible symmetric matrix, which means the complex network is connected without isolated clusters. And, the diagonal elements of matrix A are defined as $\sum\limits_{j=1,j\neq i}^{N} a_{ij} = \sum\limits_{j=1,j\neq i}^{N} a_{ji} = -a_{ii},\ i=1,2,\cdots,N.$

Defintion 1 Time-varying inner-coupling matrix sequence IMS_{Γ} is defined as

$$\mathrm{IMS}_{\Gamma}: \{(t_0,\Gamma_0),\cdots,(t_k,\Gamma_k),\cdots\}, \tag{2}$$

where $t_k$is a switching time instance, $k=0,1,\cdots$.

For notation simplicity, represent the network system (1) in the compact form

$$\dot{x}(t) = F(x) + c(A(t)\otimes\Gamma)x(t), \tag{3}$$

where $x(t) = \big(x_1^{\mathrm{T}}(t), x_2^{\mathrm{T}}(t),\cdots,x_N^{\mathrm{T}}(t)\big)$, $F(x) = \big(f^{\mathrm{T}}(x_1), f^{\mathrm{T}}(x_2),\cdots,f^{\mathrm{T}}(x_N)\big)^{\mathrm{T}}$, $\otimes$ denotes the matrix Kronecker product operator.

Defintion 2 The complex network system (3) is called globally asymptotic synchronization to its equilibrium, if there exists the control law $u(t)$ which activates the system (3)

$$\dot{x}(t) = F(x,u(t)) + c(A(t)\otimes\Gamma)x(t). \tag{4}$$

such that

$$x_1(t) = x_2(t) = \cdots = x_N(t) = s \ \text{ as } \ t\to\infty,$$

where s is an equilibrium.

Remark 2 The controllers $u(t)$ in (4) might be pinned for partial nodes in [9], even for only one node discussed in [8]. Here, employing the idea introduced in [7], we will apply a novel smart variable structure control scheme for complex network to observe the asymptotical synchronization behavior by channeling controllers into chaos node dynamics.

Further, denote the state error of ith node as $e_i(t) = x_i(t) - s(t)$. Then the error dynamics is

$$\dot{e}_i = f(s(t)+e_i) - f(s(t)) + c\sum_{j=1}^{N} a_{ij}\Gamma(t)e_j(t). \tag{5}$$

Then the global form of error dynamics is

$$\dot{e}(t) = F(s(t)+e(t)) - F(s(t)) + c(A(t)\otimes\Gamma)e(t), \tag{6}$$

where $e(t) = (e_1^{\mathrm{T}}(t), e_2^{\mathrm{T}}(t)\cdots, e_N^{\mathrm{T}}(t))^{\mathrm{T}}$.

Remark 3 The synchronization analysis of the complex network is most based on the representation through linearization[7~21]

$$\dot{e}_i(t) = J_{\mathrm{f}}e_i(t) + c\sum_{j=1}^{N} a_{ij}\Gamma e_j(t),$$

and the utilization of the non-positive property of eigenvalues of out-coupling matrix A, where J_{f} represents Jocobian matrix of $f(x(t))$ at $x_i(t) = s(t)$. The linearization for node chaos dynamics is not needed in this note.

3 Smart variable structure control

Employing the channel idea in [7], we apply it to the control of complex networks with time-varying inner-coupling case. The design of variable structure control strategy involves selecting a switching manifold and designing a switching control strategy, which guarantee the realization that the switching manifold is reached and maintained. For the sensitive characteristic of chaos systems, the gain of controller can not be a very large magnitude. Therefore, a novel smart sliding mode controller for chaos complex network systems is proposed for the limitation of gain value of sliding mode controller here.

The case to control chaos dynamical systems via complex network to a fixed equilibrium is to investigated. The periodic orbit case for synchronization behavior will be discussed in forthcoming papers. Consider a general chaotic dynamic in (1) represented as

$$\dot{x}_i(t) = f(x_i(t)). \tag{7}$$

The equilibrium set of (7) is determined as

$$M_{\mathrm{s}} = \{x_i(t)\in\mathbb{R}^n | f(x_i(t)) = 0\}. \tag{8}$$

For the chaos property mainly depends on the nonlinear parts of the chaos system, (7) is represented with two parts as follows

$$\begin{cases} \dot{x}_{i1}(t) = l_1(x_i(t)) + \zeta_1(x_i(t)), \\ \quad\vdots \\ \dot{x}_{ip}(t) = l_p(x_i(t)) + \zeta_p(x_i(t)), \\ \dot{x}_{i(p+1)}(t) = l_{p+1}(x_i(t)), \\ \quad\vdots \\ \dot{x}_{in}(t) = l_n(x_i(t)), \end{cases} \tag{9}$$

where $l_k(\cdot)$ is the linear part of the controlled chaos systems, $\zeta_k(\cdot)$ is the nonlinear part of the same one, $k=1,2,\cdots,n$. Assume there exist nonlinear dynamic terms in the p right parts of the system (1). Without loss of generality, suppose they all lie in the preceding p subsystems, which is represented in (9).

Similarly in [7], attach p controller terms $u^{\mathrm{s}}_{ik}(t)$ into these nonlinear terms of $\zeta_k(\cdot)$. Then we have

$$\begin{cases}\dot{x}_{i1}(t)=l_1(x_i(t))+\zeta_1(x_i(t),u^{\mathrm{s}}_{i1}(t)),\\ \quad\vdots\\ \dot{x}_{ip}(t)=l_p(x_i(t))+\zeta_p(x_i(t),u^{\mathrm{s}}_{ip}(t)),\\ \dot{x}_{i(p+1)}(t)=l_{p+1}(x_i(t)),\\ \quad\vdots\\ \dot{x}_{in}(t)=l_n(x_i(t)).\end{cases} \tag{10}$$

The next task includes two aspects. One is to establish manifolds, and the other is to design smart variable structure controllers. According to (8), suppose a chaotic equilibrium or attractor $x^{\mathrm{eq}}\in M_{\mathrm{s}}$.

To stabilize the chaos node, define the set of the p switching manifolds as follows

$$S_i=\left\{(x_{i1},\cdots,x_{in})\in\mathbb{R}^n\,\middle|\,\begin{array}{l}s_{ik}=x_{ik}(t)-x^{\mathrm{eq}}_{ik}=0,\\ k=1,2,\cdots,p\end{array}\right\}. \tag{11}$$

From (11), it is apparent that the chaotic attractor lies in the intersect part of the p multiple manifolds, that is, $x^{\mathrm{eq}}\in S_i$. For each manifold $s_{ik}=0$, considering the influence of the coupling nodes of complex network (5), then (9) is represented as

$$\dot{x}_i(t)=\psi_{ik}(\cdot)+g_{ik}(\cdot,u^s_p(t))+\Xi_i, \tag{12}$$

where

$$\psi_{ik}(\cdot)=\sum_{j=1}^{k-1}(l_j(\cdot)+\zeta_j(\cdot))\,b_j+\sum_{j=k+1}^{p}(l_j(\cdot)+\zeta_j(\cdot))b_j+\sum_{j=p+1}^{n}l_j(\cdot)b_j,$$

$$g_{ik}(\cdot,u^s_{ik})=[l_k(x_i(t))+\zeta_k(x_i(t),u^s_{ik}(t))]b_k,$$

$$\Xi_i=c\sum_{j=1}^{N}a_{ij}\Gamma(t)e_j(t).$$

And $b_1,b_2,\cdots,b_n$ are assumed as the unit vectors in the directions of the n dimension space bases. Ξ_i is supposed as the disturbance term from the coupling nodes of the chaos complex network system. Then obtain the equivalent control

$$u^{\mathrm{eq}}_i(t)\hat{=}\arg_{u^s_{ik}}\{\dot{s}_{ik}=l_k(x_i)+\zeta_k(x_i,u^s_k)+\Xi_{ik}=0\}, \tag{13}$$

where Ξ_{ik} is the kth row entry of the known term Ξ_i, that is, $\Xi_{ik}=c\sum\limits_{j=1}^{N}a_{ij}\Gamma_k(t)e_j(t)$, $\Gamma_k(t)$ is the k row vector.

Design the variable structure controller as follows

$$u^{\mathrm{s}}_{ik}=\begin{cases}u^+,\ s_{ik}>0,\\ u^-,\ s_{ik}<0.\end{cases} \tag{14}$$

Here: restrict the difference and magnitudes of upper control force u^+ and the down control force u^- for the sensitive property of chaos dynamic system. According to the necessary and sufficient condition of sliding mode in [22], it requires the following conditions

$$\lim_{s\to 0^+}\langle\rho_{ik},\psi_{ik}(\cdot)+g_{ik}(\cdot,u^+)+\Xi_i\rangle<0$$

and

$$\lim_{s\to 0^-}\langle\rho_{ik},\psi_{ik}(\cdot)+g_{ik}(\cdot,u^+)+\Xi_i\rangle>0,$$

where $\rho_{ik}$is a norm vector of manifold $s_{ik}=0$, $\langle\cdot,\cdot\rangle$ is an inner product operator. Hence, the attraction region towards the sliding region can be defined as

$$\Omega_{ik}=\Omega^+_{ik}\cup\Omega^-_{ik}, \tag{15}$$

where

$$\Omega^+_{ik}=\left\{x_i(t)\in\mathbb{R}^n\,\middle|\,\begin{array}{r}l_k+\zeta_k+\Xi_{ik}<0,\\ x_{ik}(t)-x^{\mathrm{eq}}_{ik}>0\end{array}\right\},$$

and

$$\Omega^-_{ik}=\left\{x_i(t)\in\mathbb{R}^n\,\middle|\,\begin{array}{l}l_k+\zeta_k+\Xi_{ik}>0,\\ x_{ik}(t)-x^{\mathrm{eq}}_{ik}<0\end{array}\right\}.$$

Then the global attraction region is obtained as

$$\Omega_i=\cup\Omega_{ik}. \tag{16}$$

With multiple sliding mode manifolds, it can easily ensure that the system state will enter the intersection (11) while the system state falls into the global attraction region (16). Moreover, when the partial states approach to their corresponding parts of the unstable equilibrium

$$x_{ik}(t)=x^{\mathrm{eq}}_{ik},\ k=1,2,\cdots,p,$$

the rest parts will reach fast to their corresponding ones of the equilibrium as well under suitable conditions[23]. Similarly in [7], we have the following result.

Theorem 1 Employing the smart variable structure controller (13) and (14), the complex network (1) is globally asymptotic synchronization to its equilibrium, when the system state enters the attraction region (16) if the following autonomous linear subsystem

$$\begin{cases} \dot{x}_{i(p+1)}(t) = l_{p+1}(x_i(t)), \\ \quad \vdots \\ \dot{x}_{in}(t) = l_n(x_i(t)) \end{cases} \tag{17}$$

is asymptotical stable to the manifolds S_i, $i = 1, 2, \cdots, N$.

Remark 4 Motivated by the idea in [8,9], the partial pinning smart variable structure control for the global the synchronization of general complex network can be designed, which mainly depends upon the coupling strength and topological property of complex networks. The simulation for partial nodes pinning variable structure controllers is to provided in next section. But the synchronization analysis of pinning partially sliding mode controllers is still an open problem.

4 Simulation tests

In this section, the Lorenz chaos via complex network is considered. The complex network based on ER random model, star model and ring model here are established with 50 nodes, respectively.

The Lorenz chaos subsystem of the ith node is

$$\begin{cases} \dot{x}_{i1} = \sigma(x_{i2} - x_{i1}), \\ \dot{x}_{i2} = rx_{i1} - x_{i2} - x_{i1}x_{i3}, \\ \dot{x}_{i3} = x_{i1}x_{i2} - bx_{i3}, \end{cases} \tag{18}$$

where σ is called Prandtl number and assumed as $\sigma > 1$, and $r > 1$. There are the three equilibriums which are the origin, $p = [\sqrt{b(r-1)}\ \sqrt{b(r-1)}\ r-1]^{\mathrm{T}}$, and $q = [-\sqrt{b(r-1)}\ -\sqrt{b(r-1)}\ r-1]^{\mathrm{T}}$. The Lorenz system is symmetrical with respect to the x_{i3} axis. Denote $r^* = \dfrac{\sigma(\sigma+b+3)}{\sigma-b-1}$. It is known that p and q are unstable and chaos occurs if $r > r^*$.

Let $\sigma = 10$, $r = 28$, and $b = 8/3$, which means p and q are unstable equilibria, and chaos occurs at the same time. A typical behavior of a Lorenz chaos system is the butterfly effect shown in Fig.1.

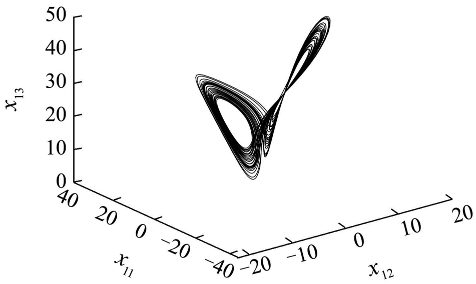

Fig. 1 Lorenz chaos

Now the objective here is to make the synchronization behavior of complex network approach to the unstable equilibrium q. The initial state of the complex network is set with random bounded real for the boundary of the chaos states. Let $c = 2$, and the out-coupling matrix satisfies $\sum\limits_{j=1,j\neq i}^{N} a_{ij} = -a_{ii}$. The IMS_{Γ} is constructed as follows

$$\mathrm{IMS}_{\Gamma} : \{(0, \Gamma_1), (5, \Gamma_2), (10, \Gamma_3)\}, \tag{19}$$

where $\Gamma_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$, $\Gamma_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $\Gamma_3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$, respectively.

Employing the smart variable structure control scheme, we may channel an controller for corresponding chaos node

$$\dot{x}_{i2} = rx_{i1} - x_{i2} - x_{i1}x_{i3}u_i^s.$$

The smart variable structure controller is designed as

$$u_i^s = \begin{cases} 1.55, & s_i > 0, \\ 0.55, & s_i < 0. \end{cases}$$

and the sliding manifolds are designed like this

$$s_i = \{(x(1), x(2), x(3)) | x(2) - p_y = 0\}.$$

As shown above, Fig.2 exhibits synchronization behavior of the complex network by employing the all nodes pinning smart variable structure controllers, which fast approaches the unstable equilibrium. While partial nodes are pinned smart variable structure controllers, without loss of generality, $i = 1, \cdots, 5$, the synchronization behaviors eventually approach the desired synchronization equilibrium shown in Fig.3, which experiences more time.

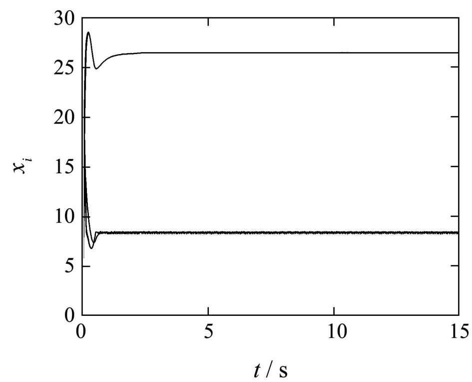

Fig. 2 Trajectories with the all pinning controllers

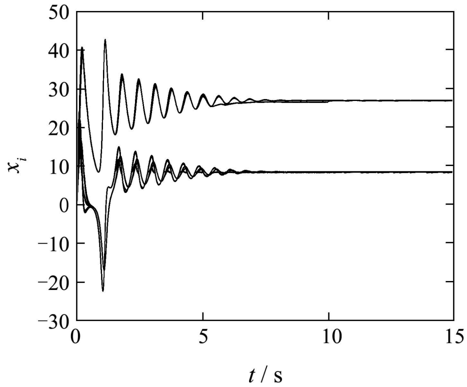

Fig. 3 Trajectories with the partial pinning controllers

In addition, consider two special complex networks such as star and ring topological configure with time-varying inner-coupled matrices IMS_{Γ}. The asymptotical behaviors under the corresponding complex network are shown in Fig.4 and Fig.5, respectively.

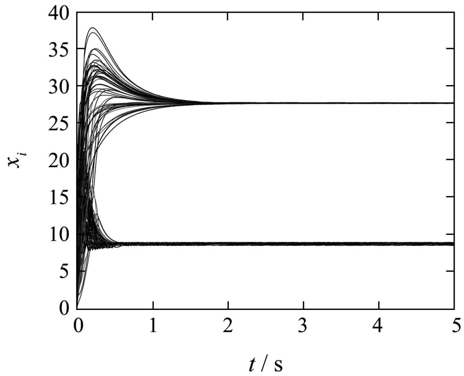

Fig. 4 Trajectories with ring topology configure

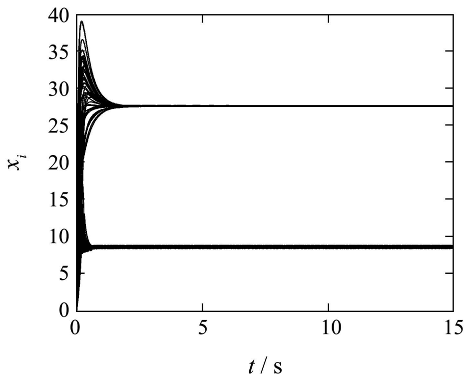

Fig. 5 Trajectories with star topology configure

From the above tests, it is explicitly found that the control scheme proposed here has good robust performance in time-varying inner-coupling situations even with very small control magnitude.

5 Conclusions

In this note, a smart variable structure control strategy was proposed for the synchronization to an unstable equilibrium of chaos complex network. To our knowledge, it is a novel scheme that smart variable structure control was explored in synchronization analysis and control for complex networks. Compared with other synchronization analyses and control methods, the advantages of the smart control scheme are not only robust to time-varying complex network configuration, but also non-involved in local linearization around an unstable equilibrium or attractor. Further research is undertaken to investigate synchronization control for a periodic orbit case by employing the idea proposed here.

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