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Temporary lag and anticipated synchronization and anti-synchronization of uncoupled time-delayed chaotic systems

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Abstract

Without any control scheme and coupling terms, temporary lag and anticipated synchronization and temporary lag and anticipated anti-synchronization are newly discovered in two identical double Mackey–Glass systems with different initial conditions. When all initial conditions are positive, the lag synchronization is obtained. The negative initial values make the time history inverse and temporary lag anti-synchronization occur. The phenomena both appear intermittently.

1. Introduction

Since the first idea of synchronizing two identical chaotic systems with different initial conditions was investigated by Pecorra and Carroll [1], chaos synchronization [2–8] has become an important topic in engineering science. In Ref. [2], this study demonstrates that chaos synchronization between two different chaotic systems using active control has been achieved. The Lorenz, Chen and Lü systems have been controlled to be the new system. In Ref. [3], chaos synchronization of two identical chaotic motions of symmetric gyros is presented. It has been demonstrated that applying four different kinds of one-way coupling conditions can synchronize two identical chaotic systems. In Ref. [4], the dynamic behavior of a symmetric gyro with linear-plus-cubic damping, which is subjected to a harmonic excitation, is studied in this paper. In Ref. [5], synchronization of feedback method in two identical non-autonomous coupled systems has been studied. Then the phase effect of two coupled systems and the transient time in unidirectional synchronization also have been researched. In Ref. [6], the dynamic behavior of electro-mechanical gyrostat system subjected to external disturbance is studied. In Ref. [7], a general scheme is proposed to achieve chaos synchronization via stability with respect to partial variables. Three theorems for synchronization of unidirectional coupled non-autonomous (also autonomous) systems by linear feedback are developed for systems with and without system structure perturbations. In Ref. [8], the dynamic system of the vibrometer is shown to produce regular and chaotic behavior as the parameters are varied. When the system is non-autonomous, the periodic and chaotic motions are obtained by numerical methods. Many effective control schemes have been developed in a

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variety of fields. For example, parametric adaptive control for chaos synchronization has been proposed in Refs. [9–17]. In Ref. [9], the problem of adaptive control and adaptive synchronization for the chaos synchronization of two identical dynamo systems with uncertain two parameters is introduced. In Ref. [10], a more rigorous method (parametric adaptive control) is developed to estimate model parameters by chaos synchronization and a sufficient condition for parameter identification is drawn for the system with parameters in linear form. In Refs. [11,12], a method using MICM is first developed to locate all attractors of a system in a large region of study arbitrarily assigned, which is helpful for the global analysis of the system never studied before. In Ref. [13], two methods are presented to achieve the synchronization: the adaptive control and the Gerschgorin's theorem. The adaptive control and the random optimization method are investigated to achieve parameters identification in Refs. [14–16]. In Ref. [17], two theorems for adaptive synchronization of unidirectional and mutual coupled non-autonomous chaotic systems are derived. By adopting an adaptive law to estimate the Lipschitz constant an adaptive coupling gain is realized. Observer-based control has been proposed in Refs. [18,19]. This paper [18] is dealing with the performances comparison of two multivariable observer-based controllers of a catalytic RFR used to decrease noxious VOC amount released in the atmosphere. In Ref. [19], three control design techniques, adaptive observer-based fuzzy control design, variable structure control algorithm and disturbance attenuation theory are combined together to construct hybrid indirect adaptive observer-based robust tracking control schemes. Variable structure control has been proposed in Refs. [20,21]. A discrete nonlinear sliding mode variable structure approach to implement the mutual synchronization of two globally coupled Henon map lattice (HML) systems is presented in Ref. [20]. A new variable structure control (VSC) scheme to deal with synchronization of chaotic systems with uncertainties is presented in Ref. [21]. Active control has been proposed in Refs. [22–26]. In Ref. [22], they demonstrate that chaos in a Lorenz system of equations can be easily controlled using a sequential controller. In Ref. [23], an adaptive controller is derived based on Lyapunov stability theory in order to overcome the limitation of active control scheme, which can make both Rossler and Chen systems be synchronized in the presence of system's unknown parameters. In Ref. [24], a method generalizing active control to phase and anti-phase synchronization is presented and simulate it by using Lorenz, Rossler, and Chen systems. In Ref. [25], active control theory is using to synchronize two identical or different chaotic systems. The Lü system is controlled to be Lorenz system. The Lü system is controlled to be Chen system. Also, Chen system is controlled to be Lorenz system. The aim of this Letter [26] is to apply active control to synchronize both Rossler and Chen dynamical systems. Anti-control has been proposed in Refs. [27–33]. In Ref. [27], anti-control of chaos for a rigid body has been studied in the paper. For certain feedback gains, a rigid body can easily generate chaotic motion. Basic dynamical behaviors, such as symmetry, invariance, dissipativity and existence of attractor, are also discussed. The dynamic system of the suspended track with moving load system has been studied in Ref. [28]. The synchronization of the master and slave system is studied. In Ref. [30], anti-control of chaos is achieved by adding constant term, periodic term, impulse term, time-delay term and adaptive control. In Ref. [30], chaos anti-control and synchronization of a 2-degrees-of-freedom loudspeaker system are researched by many methods. First, a 2-degrees-of-freedom loudspeaker system model and states equations of motion for it are introduced. Next, the bifurcation diagram and the Lyapunov exponent are expressed by numerical analysis. In Ref. [31], anti-control of chaos is studied via adding a constant torque, a $x|x|$ term, and various periodic waves, such as the square wave, the triangle wave, and the sawtooth wave. In Ref. [32], an autonomous hexagonal centrifugal governor system is studied. It plays an important role in many rotational machines such as diesel engine, steam engine and so on. Two different procedures, linear and nonlinear controllers with certain feedback gain are proposed to anti-control. The periodic and chaotic motion of the autonomous system with time-delay is obtained by the numerical methods such as phase trajectory, time history and power spectrum in Ref. [33]. Nonlinear control has been proposed in Refs. [34–36] and so on. In Ref. [34], modification based on Lyapunov stability theory to design a controller is proposed in order to overcome this limitation. The synchronization can be robustly achieved without the requirement to calculate the conditional Lyapunov exponents. In Ref. [35], the chaotic synchronization of the chaotic system devised by Lü et al. is investigated. A class of novel nonlinear control scheme for the synchronization is proposed, and the synchronization is achieved by the Lyapunov stability theory. In Ref. [36], nonlinear control method is used to synchronize two identical or different chaotic systems, and determine the controller based on Lyapunov stability theory. Then the method is simulated by using two identical Lü systems and two different chaotic systems. The applications of chaos synchronization are implemented extensively including secure communications, chemical, physical, and biological systems and neural networks.

Recently, the concept of synchronization has been extended to the scope, such as generalized, lag, anticipated, phase and anti-synchronization. The basic synchronization called complete synchronization is that the state vectors of the first system $x(t)$ is equal to the state vectors of the second system $y(t)$:$y(t)=x(t)$. The lag synchronization [37] is that the state vector of the second system y delay that of driver system x:$y(t)=x(t-T)$ with positive T. If T is negative, we have anticipated synchronization. If the synchronizations are temporary and intermittent, they are called temporary lag synchronization (TLS) and temporary anticipated synchronization (TAS). Lag anti-synchronization [38] means $y(t)=-x(t-T)$. When T is negative, we have anticipated anti-synchronization. If they are temporary and intermittent, they are called temporary lag anti-synchronization (TLAS) and temporary anticipated anti-synchronization (TAAS) [39].

It is discovered that TLS, TAS and TALS, TAAS appear for two identical double Mackey–Glass systems, without any control scheme or coupling terms, but with different initial conditions.

The rest of this paper is organized as follows. In Section 2, temporary lag and anticipated synchronizations (TLS, TAS) and temporary lag and anticipated anti-synchronization (TALS, TAAS) are described. In Sections 3 and 4, simulations of TLS, TAS, TLAS and TAAS for two identical double Mackey–Glass systems with different initial values are given. Finally, some conclusions are given in Section 5.

2. Temporary lag and anticipated synchronization and temporary lag and anticipated anti-synchronization

Consider the first time-delay chaotic system

$$\dot{x}=f(x,x_\tau,t), \tag{1}$$

and second time-delay chaotic system

$$\dot{y}=f(y,y_\tau,t), \tag{2}$$

where $x,y\in R^n$ are n-dimensional state vectors, $x_\tau=x(t-\tau)$ are corresponding time-delay state vectors, and $f:R^n\to R^n$ defines a vector function in n-dimensional space. The error are defined as $e=x(t-T)-y(t)$. If the following conditions hold, the systems are in temporary lag synchronization:

$$e_i=x_{iT_j}-y_i=0,\quad i=1,2,\dots,p\leqslant n,\quad j=1,2,\dots,m\quad \text{for } t_{iT_{j1}}\leqslant t\leqslant t_{iT_{j2}}, \tag{3}$$

where x_i, y_i are the state vectors of the system, T_j is the time which x_i lag behind y_i in the jth intervals. When T_j is negative, we have temporary anticipated synchronization.

In the case of anti-synchronization, the states of the systems which have opposite signs, the error $e=x(t-T)+y(t)$ will converge to zero. Therefore, we can say the temporary lag anti-synchronization is achieved when the following conditions are satisfied:

$$e_i=x_{iT_j}+y_i=0,\quad i=1,2,\dots,p\leqslant n,\quad j=1,2,\dots,m\quad \text{for } t_{iT_{j1}}\leqslant t\leqslant t_{iT_{j2}}, \tag{4}$$

where x_i, y_i are the state vectors of the system, T_j is the time which x_i lag behind y_i in the jth intervals. When T_j is negative, we have temporary anticipated anti-synchronization.

3. The lag and anticipated synchronization of two identical double Mackey–Glass systems

We consider two double Mackey–Glass systems which consist of two coupled Mackey–Glass equations [40]:

$$\dot{x}_1=\frac{bx_{1\tau}}{1+x_{1\tau}^n}-rx_1,\qquad \dot{x}_2=\frac{bx_{2\tau}}{1+x_{2\tau}^n}-rx_2-x_1, \tag{5}$$

and

$$\dot{y}_1=\frac{by_{1\tau}}{1+y_{1\tau}^n}-ry_1,\qquad \dot{y}_2=\frac{by_{2\tau}}{1+y_{2\tau}^n}-ry_2-y_1. \tag{6}$$

The system is a model of blood production of patients with leukemia. The variables x_1, x_2 are the concentration of the mature blood cells in the blood, and $x_{1\tau}$, $x_{2\tau}$ are presented the request of the cells which is

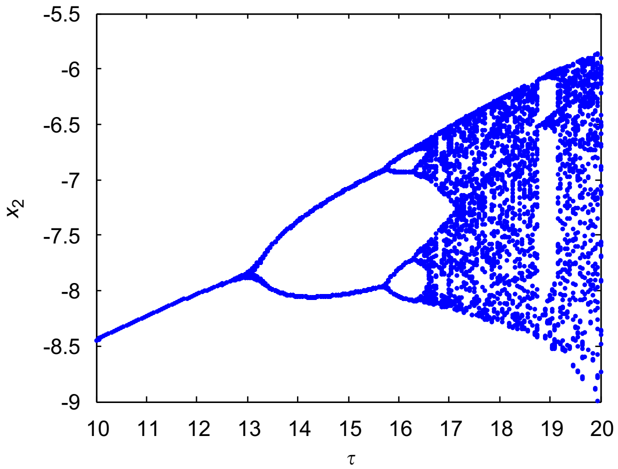


Fig. 1. The phase portraits and the bifurcation diagram for double Mackey–Glass system.

made after τ seconds, i.e. $x_{i\tau} = x_i(t-\tau)$ $(i = 1, 2)$. The time delay τ indicates the difference between the time of cellular production in the bone marrow and of the release of mature cells into the blood. According to the observations, the time τ is large in the patients with leukemia and the concentration of the blood cells becomes oscillatory.

In our study, we keep the delay time fixed in 20 s ($\tau = 20$) and the parameters are shown as follows: $b = 0.2$, $r = 0.1$, and $n = 10$. The system is chaotic in foregoing conditions as shown in Fig. 1 [41]. All the numerical simulations are implemented by Matlab. The initial conditions we choose are constant, i.e. the variable $x(t+\theta)$ maintains a constant for all $\theta \in (-\tau, 0)$.

Fig. 2 shows the time histories of double Mackey–Glass system with initial conditions $(x_{10}, x_{20}) = (0.001, 0.001)$, $(y_{10}, y_{20}) = (0.0015, 0.0015)$, respectively. Because the similar characteristics exist for x_1, y_1 and for x_2, y_2, we only draw the time histories of x_1, y_1 (Fig. 2(a)–(f)) and the time histories of error, $e_1 = x_{1T_j} - y_1$ (Fig. 2(g)–(l)). From Fig. 2, the temporary lag and anticipated synchronizations appear intermittently. Lag synchronizations are more than anticipated synchronization. In Table 1, we marshal the length of the temporary lag (anticipated) synchronization and the lag (anticipated) of x_1 to y_1, which are varied in each intervals. There are four lag synchronous intervals and two anticipated synchronous intervals between 30,000 s. Notice that the longest interval occur at the first interval, about 1200 s. Others are hundreds seconds long.

We also find the trend of decreasing the length of the temporary synchronization with increasing initial conditions. As the initial values increase, the time intervals for temporary lag or anticipated synchronization decrease. Table 2 shows the lengths of the first time interval where the initial values are varied from 0.00001 to 0.1, L_1 and L_2 indicate the length of first temporary synchronization of x_1, y_1 and of x_2, y_2, respectively. From the curve fitting presented in Figs. 3 and 4, the relations between L_1, L_2 and x_{10}, x_{20} are obtained as follows:

$$L_1 = -229.93 \ln(x_{10}) - 262.06, \tag{7}$$

and

$$L_2 = -229.88 \ln(x_{20}) - 261.58. \tag{8}$$

They are essentially identical.

4. The lag and anticipated anti-synchronization of two identical double Mackey–Glass systems

In this section, we add one, two, three or four minus sign to the initial conditions, TLS and TLAS occur alternatively.

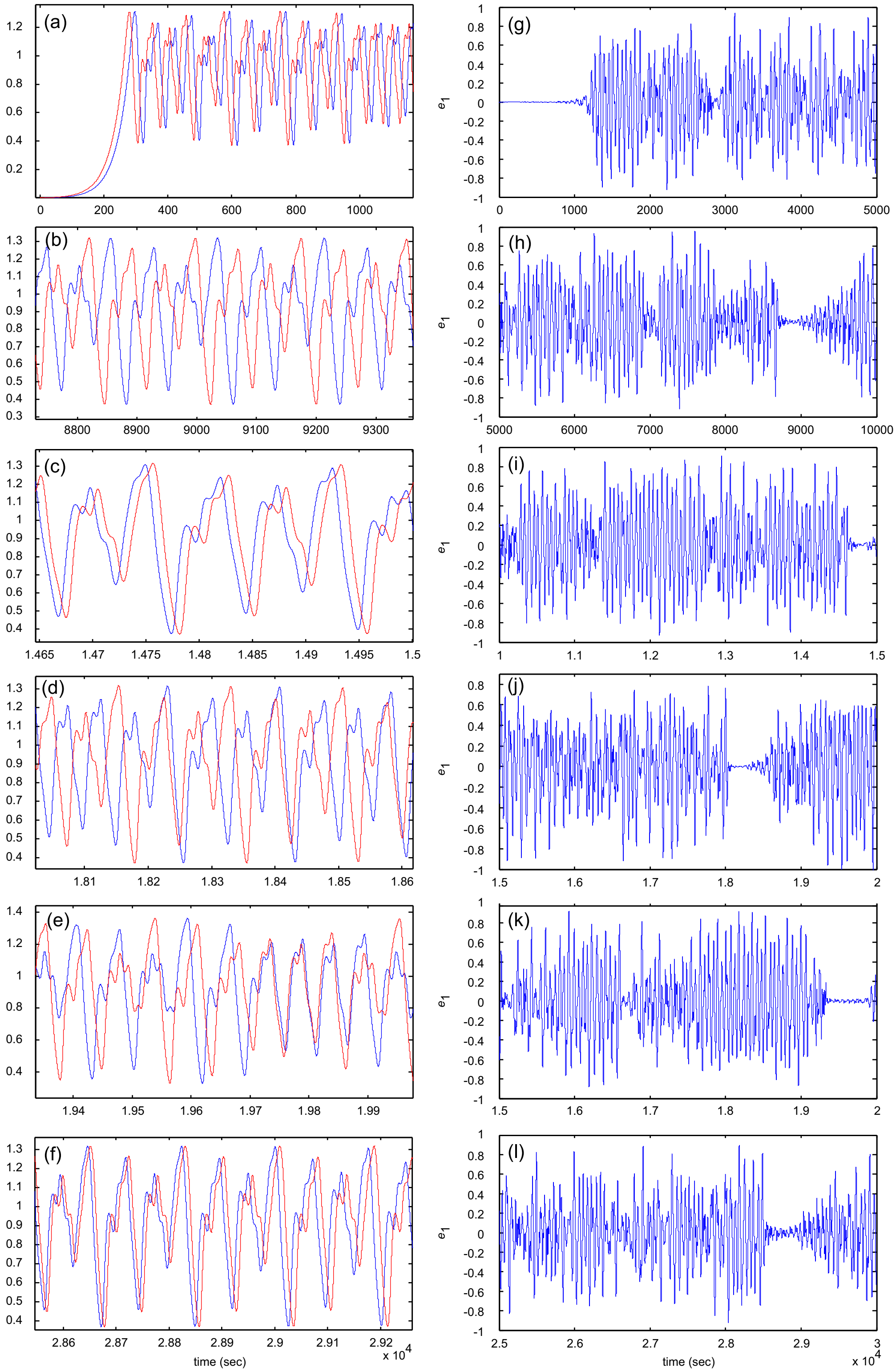


Fig. 2. (a)–(f) The time histories of x_1 (blue) and y_1 (red) and (g)–(l) error $e_1 = x_{1T_j} - y_1$ of double Mackey–Glass systems with initial conditions $(x_{10}, x_{20}) = (0.001, 0.001)$, $(y_{10}, y_{20}) = (0.0015, 0.0015)$.

Table 1
The length of temporary lag (anticipated) synchronization and the lag (anticipated) of x_1, x_2 to y_1, y_2

	x_1, y_1			x_2, y_2		
	Time intervals (s)	Length of temporary synchronization (s)	Lag of x_1 to y_1 (s)	Time intervals (s)	Length of temporary synchronization (s)	Lag of x_2 to y_2 (s)
1	0–1187	1187	17	0–1194	1194	17
2	8730–9215	485	37	8740–9360	620	38
3	14630–15000	370	−8	14640–15010	370	−8
4	18103–18611	508	77	18111–18658	547	77
5	19387–19983	596	55	19390–19990	600	55
6	28580–29010	430	−7	28530–28980	450	−6

Table 2
The lengths of the first time intervals of TLS and TAS where the initial values are varied from 0.00001 to 0.1

Initial conditions ($x_{10} = x_{20}$, $y_{10} = y_{20}$)	L_1	L_2
(10^{-5}, 1.5×10^{-5})	2593	2593
(5×10^{-5}, 7.5×10^{-5})	1759	1759
(10^{-4}, 1.5×10^{-4})	1683	1683
(5×10^{-4}, 7.5×10^{-4})	1806	1806
(10^{-3}, 1.5×10^{-3})	1187	1186
(5×10^{-3}, 7.5×10^{-3})	843	843
(0.01, 0.015)	1031	1033
(0.05, 0.075)	382	382
(0.1, 0.15)	231	231

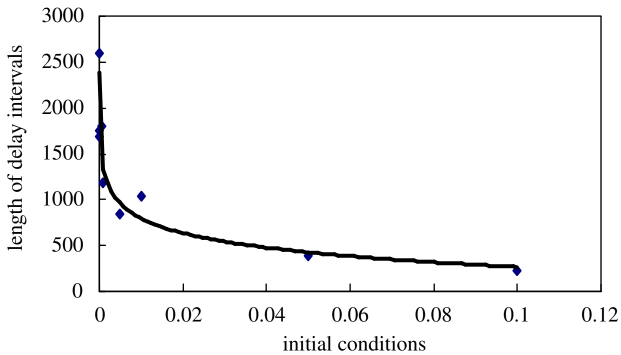


Fig. 3. The curve fitting of initial condition x_0 to the length of temporary lag or anticipated synchronization L_1.

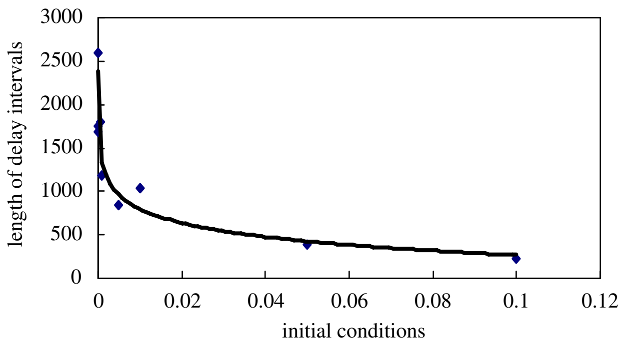


Fig. 4. The curve fitting of initial condition x_0 to the length of temporary lag or anticipated synchronization L_2.

Table 3
The time histories of double Mackey–Glass system with negative initial values

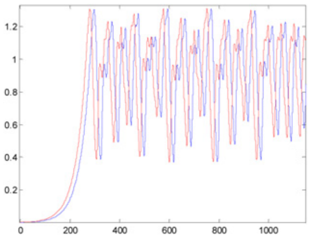
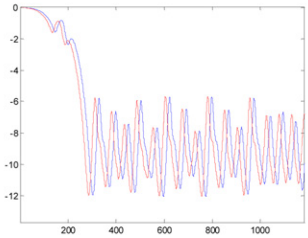
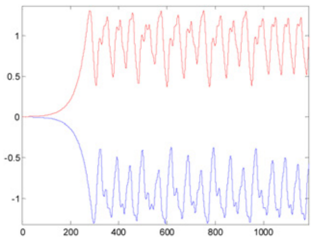
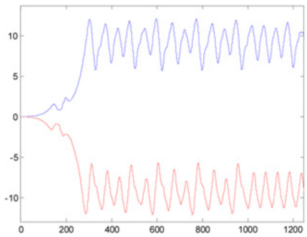
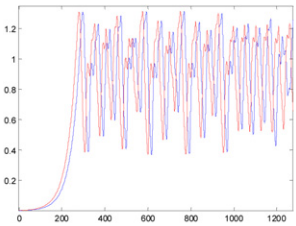
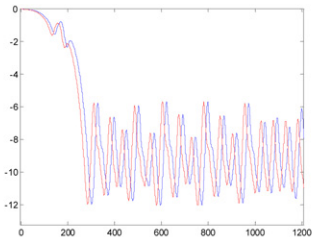
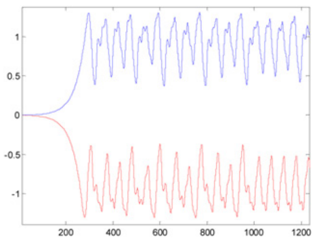
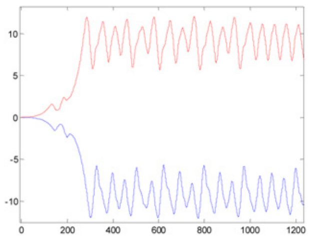
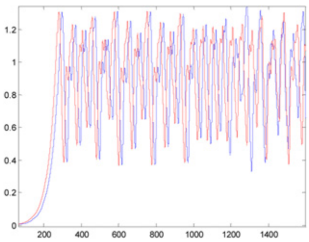
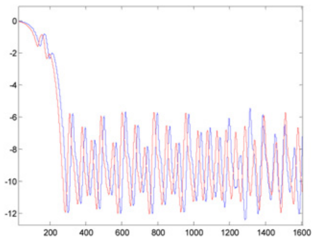
Case	Initial conditions	x_1: blue, y_1: red	X_2: blue, y_2: red
0	(0.001, 0.001), (0.0015, 0.0015)	 Lag synchronization	 Lag synchronization
1	(−0.001, 0.001), (0.0015, 0.0015)	 Lag anti-synchronization	 Lag anti-synchronization
2	(0.001, 0.001), (0.0015, 0.0015)	 Lag synchronization	 Lag synchronization
3	(0.001, 0.001), (−0.0015, 0.0015)	 Lag anti-synchronization	 Lag anti-synchronization
4	(0.001, 0.001), (0.0015, −0.0015)	 Lag synchronization	 Lag synchronization

Table 3 (*continued*)

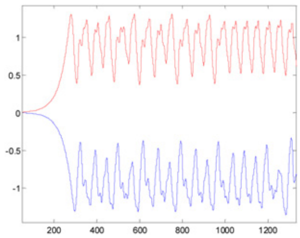
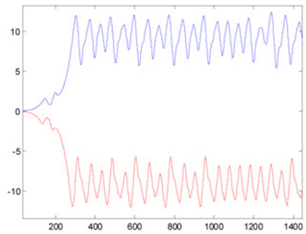
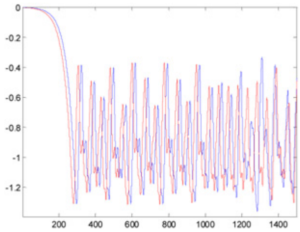
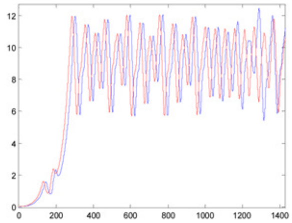
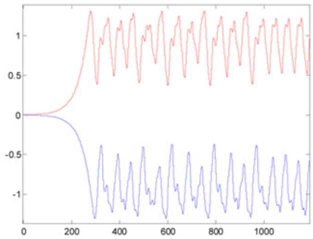
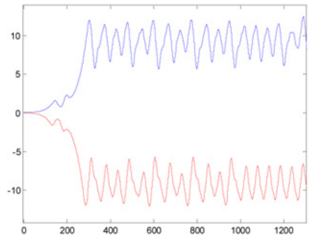
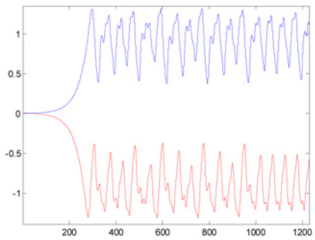
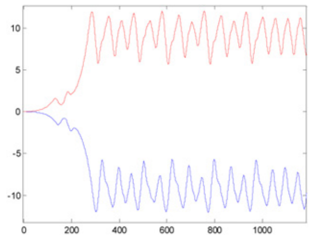
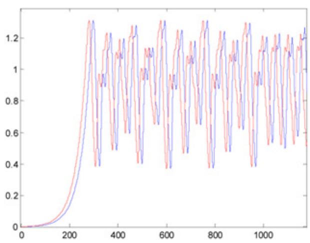
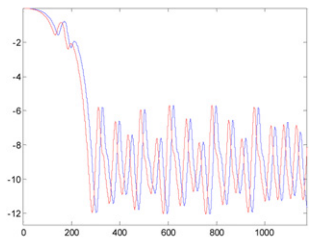
Case	Initial conditions	x_1: blue, y_1: red	X_2: blue, y_2: red
5	(−0.001, −0.001), (0.0015, 0.0015)	 Lag anti-synchronization	 Lag anti-synchronization
6	(−0.001, 0.001), (−0.0015, 0.0015)	 Lag synchronization	 Lag synchronization
7	(−0.001, 0.001), (0.0015, 0.0015)	 Lag anti-synchronization	 Lag anti-synchronization
8	(0.001, −0.001), (−0.0015, 0.0015)	 Lag anti-synchronization	 Lag anti-synchronization
9	(0.001, −0.001), (0.0015, −0.0015)	 Lag synchronization	 Lag synchronization

Table 3 (*continued*)

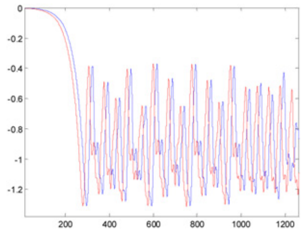
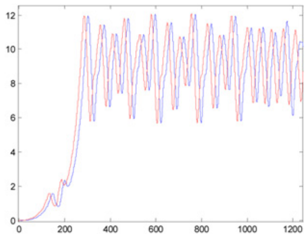
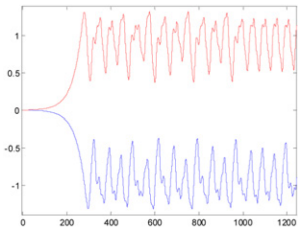
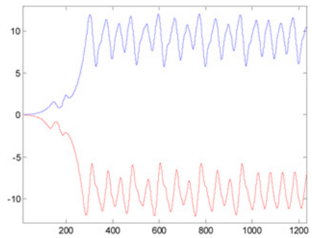
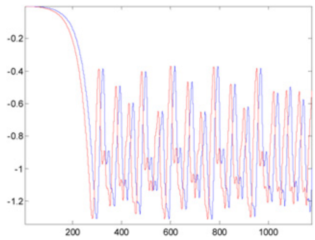
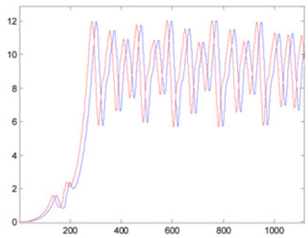
Case	Initial conditions	x_1: blue, y_1: red	X_2: blue, y_2: red
10	(−0.001, −0.001), (−0.0015, 0.0015)	 Lag synchronization	 Lag synchronization
11	(−0.001, −0.001), (0.0015, −0.0015)	 Lag anti-synchronization	 Lag anti-synchronization
12	(−0.001, −0.001), (−0.0015, −0.0015)	 Lag synchronization	 Lag synchronization

Table 3 shows the results of the simulations. There are interesting phenomena. The minus sign makes the original time history inverse but with same magnitude, i.e. two time histories are symmetric to the abscissa. From Case 1–4, it is found that the inverse effect only appears when the initial condition x_{10} or y_{10} is negative. On the contrary, it does not work for x_{20} and y_{20}. The trajectories of x_1 and x_2 are upside down as x_{10} is negative, and the trajectories of y_1 and y_2 show the similar characteristics with negative y_{10}. In these two cases, the lag anti-synchronizations exist. Because the negative initial conditions x_{20}, y_{20} have no influence on the systems, there are still lag synchronizations in Case 2 and 4. Case 5–9 show the results where there are two negative initial conditions at the same time. In Case 5 and 7, only the inverses of x_1 and x_2 occur, so two systems are in lag anti-synchronization. Case 6 and 9 maintain lag synchronization because both trajectories are opposite in the former case and no inversion exists in the latter case. Case 8 shows the lag anti-synchronization where the trajectory of y_1 and y_2 is reversed. Finally, the simulations where there are three and four negative initial values, are presented respectively. It is easy to know that Case 10 is the same as Case 6 and Case 11 and Case 1 are quite alike.

According to the symmetric relations between cases with negative initial conditions and the original cases, the lengths of the lag anti-synchronizations and the lags of x_1 to y_1 are all invariant, just as that in Table 1 which is listed in Section 2.

The time histories and the error dynamics e with initial conditions $(x_{10}, y_{10}) = (-0.001, 0.001)$, $(x_{20}, y_{20}) = (0.0015, 0.0015)$ are shown in Fig. 5. Comparing with Fig. 2, nothing is changed except the inverse of x_1 and y_1.

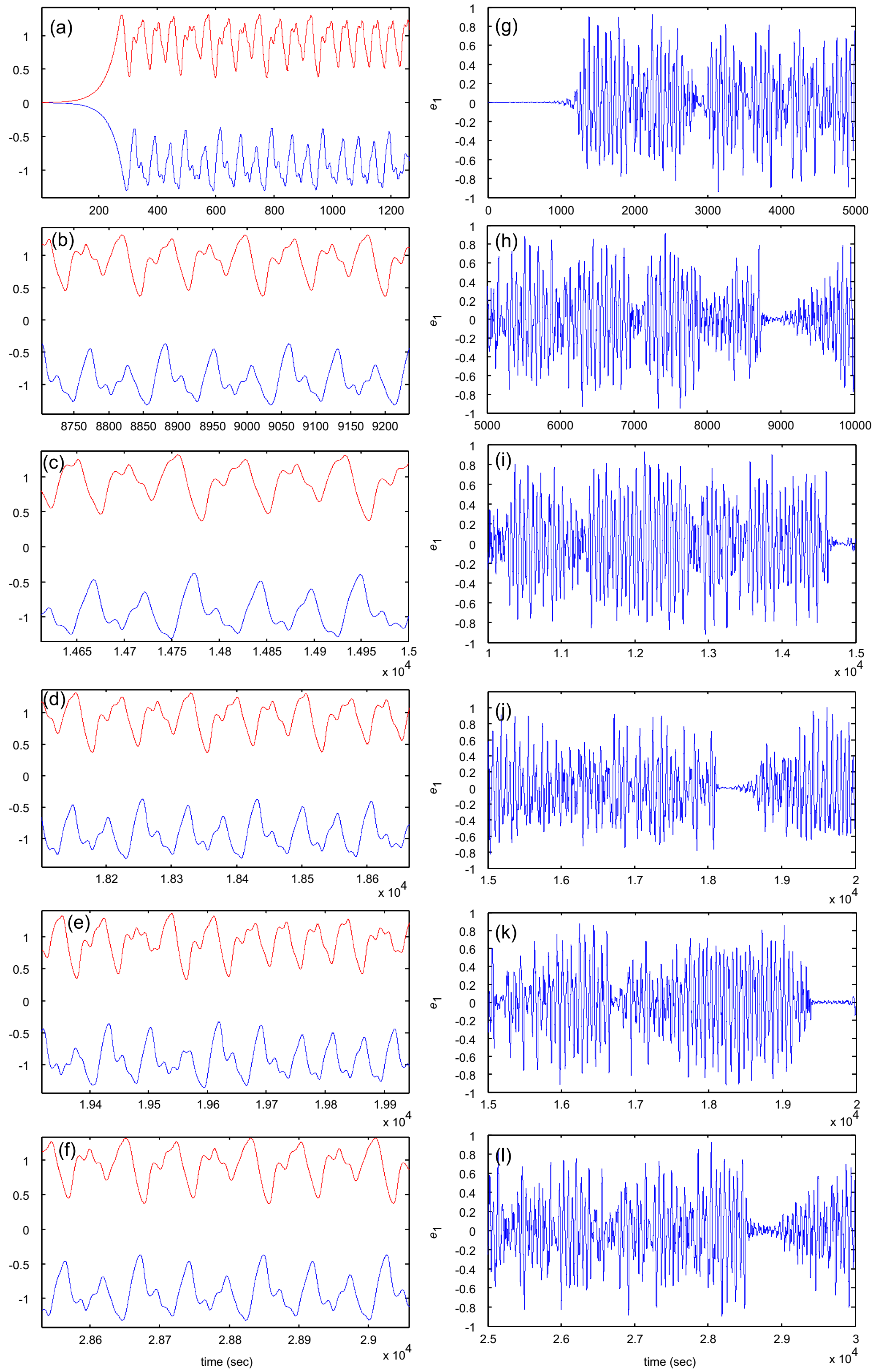


Fig. 5. (a)–(f) The time histories of x_1 (blue) and y_1 (red) and (g)–(l) error $e_1 = x_{1T_j} + y_i$ of double Mackey–Glass systems with initial conditions $(x_{10}, x_{20}) = (-0.001, 0.001)$, $(y_{10}, y_{20}) = (0.0015, 0.0015)$.

5. Conclusions

In this paper, temporary lag or anticipated synchronization and the lag or anticipated anti-synchronization of double Mackey–Glass systems with small and similar initial conditions are discovered. For the first interval of TLS, when all initial values are positive, temporary lag synchronizations are found. The trajectory will be reversed if the initial condition of x_1 or y_1 is negative. In these cases, the lag or anticipated anti-synchronization exists. From the results of simulation, we find six temporary lag (anticipated) synchronization intervals in 30,000 s. The numerical simulations of temporary lag and anticipated synchronization and anti-synchronization are showed in this paper. In fact, our new double Mackey–Glass systems with different delay time τ can be used in transfusion of blood between two persons. Our future work will study model for different persons with different initial conditions in transfusion of blood. The theoretical analysis and its applications should be open for further work in the future.

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