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Sigmoid-function Based Fixed-time Stability of Delayed Nonlinear Dynamic Systems

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Abstract

This paper investigates fixed-time stability of delayed nonlinear dynamic systems. At first, by designing an inequality with sigmoid-function, a new kind of fixed-time stability lemma is constructed. Then, as an application, the new proposed lemma is applied to discuss fixed-time stabilization(FT) for a kind of delayed neural networks. At last, simulations are also given to show the effectiveness of the derived results.

Keywords: fixed-time stability, nonlinear dynamic systems, fixed-time stabilization, sigmoid-function, time delays.

1 Introduction

Convergence time of fixed-time stability is finite and its upper bound is a positive constant [1]. Theoretical results about fixed-time stability have better performance and more accurate, which have some important engineering applications. Therefore, fixed-time stability of linear or nonlinear dynamic systems has attracted widespread interests from scholars in these days, and many interesting works have been reported, e.g., see [2–4].

In 2021, by improving fixed-time stability lemma, Hu *et al.* [5] studied fixed-time synchronization(FS) of complex networks, Aouiti *et al.* [6] investigated fixed-time stabilization(FT) for delayed neural networks with inertial items. In 2023, by using aperiodically switching control, Hu *et al.* [7] discussed FT of the spatiotemporal neural networks with discontinuous right-hand side. In 2024, by using event-triggered control, Zhang *et al.* [8] showed some new results on FS of discontinuous neural networks with time delays and inertial items. In 2026, Zhou *et al.* [9] gave novel results on FT and FS of inertial memristive neural networks with switching control, and Qiao *et al.* [10] studied FS of stochastic impulsive reaction-diffusion complex networks via internal and boundary control.

Noteworthy, the fixed-time stability lemmas used in above works are mainly based on the previous work [1], which usual has two power index terms. In this paper, without using two power index terms, we will use sigmoid-function to construct a kind of

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fixed-time stability lemma. And by using the proposed lemma and designing proper feedback control, FT for a kind of delayed neural networks will be investigated.

The following parts of this paper are: Sigmoid-function based fixed-time stability lemma is built in Section 2. In Section 3, FT of delayed neural networks are discussed via the proposed lemma. In Section 4, simulations are provided. At last, conclusions are showed.

Notations: Let $\Delta = \{1, 2, ..., n\}$, $\mathbf{R}^n$ is Euclidean space in n-dimensional. For $\forall\, z = (z_1, z_2, ..., z_n)^T \in \mathbf{R}^n$, which 1-norm is defined as $\|z\| = \sum_{k=1}^{n} \mid z_k \mid$. And $\mathbf{C}([-\tau, 0], \mathbf{R}^n)$ denotes all continuous function from $[-\tau, 0]$ to $\mathbf{R}^n$, where $\tau = \max_{t\geqslant 0}\{\tau(t)\}$.

2 Sigmoid-function based fixed-time stability

Consider the following delayed nonlinear dynamic systems

$$\frac{\mathrm{d}z(t)}{\mathrm{d}t} = f(t, z(t), z(t-\tau(t))), t \geqslant 0, \tag{1}$$

where $z(t) = (z_1(t), z_2(t), ..., z_n(t))$ is state variable of the systems (1), $f(\cdot) = (f_1(\cdot), f_2(\cdot), ..., f_n(\cdot))$ is nonlinear vector function and $f : \mathbf{R} \times \mathbf{R}^n \times \mathbf{R}^n \mapsto \mathbf{R}^n$, $\tau(t)$ is time delay that satisfies $0 < \tau(t) \leqslant \tau$. The initial values of system (1) are $z_k(s) = \varsigma_k(s) \in \mathbf{C}([-\tau, 0], \mathbf{R}), k \in \Delta = \{1, 2, ..., n\}$.

For the convenience of rest discussion, the following Assumption 1 and Definition 1 of system (1) are given.

Assumption 1. For system (1), the nonlinear function $f_k(\cdot)$ is bounded continuous function and satisfies Lipschitz condition, and $z(t) = 0$ is the origin of system (1), here $k \in \Delta$.

Definition 1. ([8]). Nonlinear dynamic systems (1) is fixed-time stable, if origin of systems (1) is stable, and there is a constant $\mathcal{T}_M > 0$ that settling function $\mathcal{T}(z(0)) \leqslant \mathcal{T}_M$, $\lim_{t\to\mathcal{T}_M} \|z(t)\| = 0$ and $z(t) = 0$ when $t \geqslant \mathcal{T}_M$, where $\mathcal{T}_M$ is called settling-time.

Remark 1. Under Assumption 1, one can easily find that for each initial value, nonlinear dynamic systems (1) has unique solution $z(t)$ that is defined in the interval $[0, +\infty)$.

Now, by using C-regular function definition given in [11] and designing an inequality with sigmoid-function, we give following fixed-time stability Lemma 1 for this paper.

Lemma 1. Suppose there is a C-regular function $\mathbf{V}(\cdot)$, and following with any solutions of (1) that satisfies

$$\frac{\mathrm{d}\mathbf{V}(z(t))}{\mathrm{d}t} \leqslant -\frac{\alpha}{\sigma(\mathbf{V}(z(t)))\Big[1-\sigma(\mathbf{V}(z(t)))\Big]}, \tag{2}$$

where $\alpha > 0, \sigma(\mathbf{V}(z(t))) = 1/[1+\exp(-\mathbf{V}(z(t)))]$, then, systems (1) can get fixed-time stable, and settling-time is

$$\mathcal{T}_M = \frac{1}{2\alpha}. \tag{3}$$

Proof. From (2), we get that $\frac{\mathrm{d}\mathbf{V}(t)}{\mathrm{d}t} < 0$, because $\mathbf{V}(\cdot)$ is C-regular function. So, systems (1) is global asymptotic stable. Let $q = \mathbf{V}(z(t))$, from (2) and [11], we have the following settling-time function

$$\mathcal{T}(z(0)) = \frac{1}{\alpha}\int_0^{\mathbf{V}(z(0))} \sigma(q)\Big[1-\sigma(q)\Big]\mathrm{d}q, \tag{4}$$

because $\sigma'(q) = \sigma(q)[1-\sigma(q)] > 0$, then, one has

$$\begin{aligned}\mathcal{T}(z(0)) \leqslant& \frac{1}{\alpha}\int_0^{+\infty} \sigma(q)\Big[1-\sigma(q)\Big]\mathrm{d}q\\ =&\frac{1}{\alpha}\int_0^{+\infty}\sigma'(q)\mathrm{d}q\\ =&\frac{1}{\alpha}\sigma(q)|_0^{+\infty} = \frac{1}{\alpha}\frac{1}{1+\exp(-q)}|_0^{+\infty}\\ =&\frac{1}{\alpha}(1-\frac{1}{2}) = \frac{1}{2\alpha}.\end{aligned} \tag{5}$$

Now, based on [11], Definition 1 and from (5), one knows that systems (1) can get fixed-time stable, and settling-time is $\mathcal{T}_M = \frac{1}{2\alpha}$. The proof of Lemma 1 is finished.

Remark 2. The authors of this paper try their best to show a new method to realize fixed-time stability of nonlinear dynamic systems, that is, based on Sigmoid-function $\sigma(V(t)) = \frac{1}{1+e^{-V(t)}}$ to derive fixed-time stability, which curve is shown in Figure 1. And under the above inequality (2), one knows that $V(t)$ is a non-increasing monotone function, so, $0 < \sigma(V(t)) < 1$. Therefore, the method used in this paper is completely different from the method of many previous works, such as [1, 6] that has two positive index variables λ, γ in $\dot{V}(t) < -\alpha V^{\lambda}(t) - \beta V^{\gamma}(t)$.

Remark 3. The previous work [8] discussed predefined-time stable of delayed neural networks, in fact, from Lemma 1, if the following inequality holds

$$\frac{\mathrm{d}\mathbf{V}(t)}{\mathrm{d}t} \leqslant -\frac{\mathcal{T}_M}{\mathcal{T}_c}\frac{\alpha}{\sigma(\mathbf{V}(t))\Big[1-\sigma(\mathbf{V}(t))\Big]}, \tag{6}$$

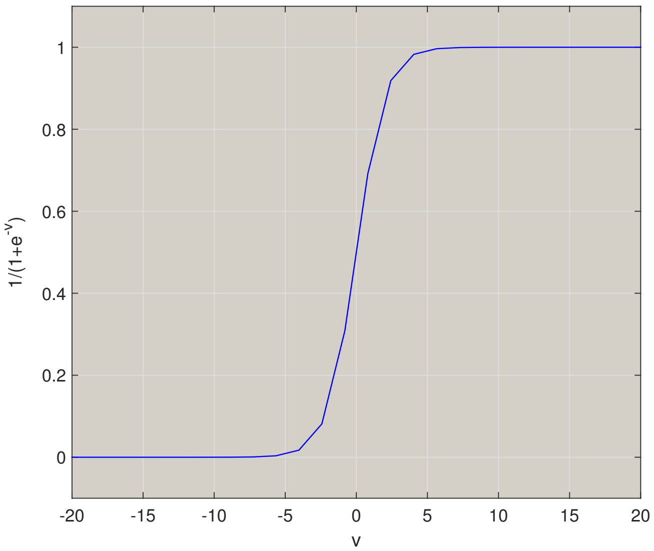

Figure 1. Curve of the Sigmoid-function.

where $\mathcal{T}_c > 0$ and other variables given as above, then, systems (1) can get predefined-time stable, and predefined-time is $\mathcal{T}_c$. Our paper mainly about fixed-time stability of nonlinear dynamic systems, and for more details of predefined-time stability, the readers can see [5] and [8].

3 Application of Lemma 1

In this section, as an application, we choose a kind of delayed neural networks as system (1). And we investigate the FT of the delayed neural networks based on Lemma 1.

Consider the following delayed neural networks

$$\begin{aligned}\frac{\mathrm{d}z_k(t)}{\mathrm{d}t} = -d_k z_k(t) &+ \sum_{p=1}^{n} a_{kp} g_p(z_p(t)) \\ &+ \sum_{p=1}^{n} b_{kp} g_p(z_p(t-\tau(t))) \\ &+ \sum_{p=1}^{n} c_{kp} \int_{t-\tau(t)}^{t} g_p(z_p(s))\mathrm{d}s, \quad (7)\end{aligned}$$

where $d_k > 0$, $z_k(t)$ is the state of the k^{th} neural, a_{kp}, b_{kp}, c_{kp} are connect weights, $g_p(\cdot)$ is the nonlinear feedback function, $\tau(t)$ is defined as in (1), and initial values of systems (7) are $z_k(s) = \psi_k(s) \in \mathbf{C}([-\tau, 0], \mathbf{R}), t \geqslant 0, k, p \in \Delta$.

From Assumption 1, one has the following Assumption 2 for delayed neural networks (7).

Assumption 2. For system (7), the nonlinear feedback function $g_p(\cdot)$ is continuous function, which satisfies $g_p(0) = 0$ and for $\forall\ o_1, o_2 \in \mathbf{R}$ that

$$|g_p(o_1) - g_p(o_2)| \leqslant \mathcal{L}_p|o_1 - o_2|,\ |g_p(o_1)| \leqslant \mathcal{W}_p\,, \quad (8)$$

where $\mathcal{L}_p > 0, \mathcal{W}_p > 0$.

If delayed neural networks (7) is unstable, here, we consider its following stabilization model

$$\begin{aligned}\frac{\mathrm{d}z_k(t)}{\mathrm{d}t} = -d_k z_k(t) &+ \sum_{p=1}^{n} a_{kp} g_p(z_p(t)) \\ &+ \sum_{p=1}^{n} b_{kp} g_p(z_p(t-\tau(t))) \\ &+ \sum_{p=1}^{n} c_{kp} \int_{t-\tau(t)}^{t} g_p(z_p(s))\mathrm{d}s \\ &+ u_k(t), \qquad (9)\end{aligned}$$

where $u_k(t)$ is the control input, which is designed as follows:

$$\begin{aligned}u_k(t) = &- \gamma_k z_k(t) - \frac{\alpha_k \mathrm{sign}(z_k(t))}{\sigma(\mathbf{V}(t))\Big(1 - \sigma(\mathbf{V}(t))\Big)} \\ &- \delta_k \mathrm{sign}(z_k(t)), \qquad (10)\end{aligned}$$

and $\gamma_k, \alpha_k, \delta_k > 0$, $\mathbf{V}(t) = \sum_{k=1}^{n} \mid z_k(t) \mid$.

Now, we give the following Theorem 1 about FT of delayed neural networks (7) with control (10).

Theorem 1. Under Assumption 2 and control (10), and the following conditions hold

$$-d_k - \gamma_k + \sum_{p=1}^{n} \mathcal{L}_k |a_{pk}| < 0, \quad (11)$$

$$-\delta_k + \sum_{p=1}^{n} \mathcal{W}_p \Big(|b_{kp}| + \tau|c_{kp}|\Big) < 0, \quad (12)$$

then, delayed neural networks (7) gets FT, and settling-time is $\mathcal{T}_M = \frac{1}{2\alpha}$,

where $\alpha = \min_{1 \leqslant k \leqslant n}\{\alpha_k\}$.

Proof. Consider C-regular function as follows:

$$\mathbf{V}(t) = \sum_{k=1}^{n} \mid z_k(t) \mid . \quad (13)$$

Now, along the solutions of systems (9), and by using chain-rule [12], then, from (13), one gets

$$\begin{aligned}
\frac{\mathrm{d}\mathbf{V}(t)}{\mathrm{d}t}\Big|_{(9)} &= \sum_{k=1}^{n} \dot{z}_k(t)\,\mathrm{sign}(z_k(t)) \\
&= \sum_{k=1}^{n} \mathrm{sign}(z_k(t))\Big[-d_k z_k(t) + \sum_{p=1}^{n} a_{kp} g_p(z_p(t)) \\
&\quad + \sum_{p=1}^{n} b_{kp} g_p(z_p(t-\tau(t))) \\
&\quad + \sum_{p=1}^{n} c_{kp}\int_{t-\tau(t)}^{t} g_p(z_p(s))\mathrm{d}s + u_k(t)\Big] \\
&= \sum_{k=1}^{n} \mathrm{sign}(z_k(t))\Big[-d_k z_k(t) + \sum_{p=1}^{n} a_{kp} g_p(z_p(t)) \\
&\quad + \sum_{p=1}^{n} b_{kp} g_p(z_p(t-\tau(t))) \\
&\quad + \sum_{p=1}^{n} c_{kp}\int_{t-\tau(t)}^{t} g_p(z_p(s))\mathrm{d}s \\
&\quad - \gamma_k z_k(t) - \frac{\alpha_k\,\mathrm{sign}(z_k(t))}{\sigma(\mathbf{V}(t))(1-\sigma(\mathbf{V}(t)))} \\
&\quad - \delta_k\,\mathrm{sign}(z_k(t))\Big] \\
&\leqslant \sum_{k=1}^{n}\Big[-d_k|z_k(t)| + \sum_{p=1}^{n}|a_{kp}|\,|g_p(z_p(t))| \\
&\quad + \sum_{p=1}^{n}|b_{kp}|\,|g_p(z_p(t-\tau(t)))| \\
&\quad + \sum_{p=1}^{n}|c_{kp}|\,\Big|\int_{t-\tau(t)}^{t} g_p(z_p(s))\mathrm{d}s\Big| \\
&\quad - \gamma_k|z_k(t)| - \frac{\alpha_k}{\sigma(\mathbf{V}(t))(1-\sigma(\mathbf{V}(t)))} \\
&\quad - \delta_k\Big],
\end{aligned} \tag{14}$$

by using Assumption 2 and from (14), one has

$$\begin{aligned}
\frac{\mathrm{d}\mathbf{V}(t)}{\mathrm{d}t}\Big|_{(9)} &\leqslant \sum_{k=1}^{n}\Big[-d_k|z_k(t)| + \sum_{p=1}^{n}\mathcal{L}_P|a_{kp}||z_p(t)| \\
&\quad + \sum_{p=1}^{n}\mathcal{W}_p\Big(|b_{kp}| + \tau|c_{kp}|\Big) \\
&\quad - \gamma_k|z_k(t)| - \frac{\alpha_k}{\sigma(\mathbf{V}(t))\Big(1-\sigma(\mathbf{V}(t))\Big)} - \delta_k\Big] \\
&= \sum_{k=1}^{n}\Big[(-d_k - \gamma_k + \sum_{p=1}^{n}\mathcal{L}_k|a_{pk}|)|z_k(t)| \\
&\quad - \delta_k + \sum_{p=1}^{n}\mathcal{W}_p\Big(|b_{kp}| + \tau|c_{kp}|\Big) \\
&\quad - \frac{\alpha_k}{\sigma(\mathbf{V}(t))\Big(1-\sigma(\mathbf{V}(t))\Big)}\Big].
\end{aligned} \tag{15}$$

Under conditions (11) and (12), from (15), one obtains

$$\begin{aligned}
\frac{\mathrm{d}\mathbf{V}(t)}{\mathrm{d}t}\Big|_{(9)} &\leqslant \sum_{k=1}^{n}\Big[-\frac{\alpha_k}{\sigma(\mathbf{V}(t))\Big(1-\sigma(\mathbf{V}(t))\Big)}\Big] \\
&\leqslant -\frac{\alpha}{\sigma(\mathbf{V}(t))\Big(1-\sigma(\mathbf{V}(t))\Big)}.
\end{aligned} \tag{16}$$

Now, by using Lemma 1, one gets that the delayed neural networks (7) gets FT with control scheme (10), and settling-time is $\mathcal{T}_M = \frac{1}{2\alpha}$. The proof of Theorem 1 is completed.

If $c_{pk} = 0, p, k \in \Delta$, then, the stabilization model (9) is changed into

$$\begin{aligned}
\frac{\mathrm{d}z_k(t)}{\mathrm{d}t} &= -d_k z_k(t) + \sum_{p=1}^{n} a_{kp} g_p(z_p(t)) \\
&\quad + \sum_{p=1}^{n} b_{kp} g_p(z_p(t-\tau(t))) \\
&\quad + u_k(t),
\end{aligned} \tag{17}$$

where $u_k(t)$ is the control input as given in (10).

For (17), and from Theorem 1, we has the following Corollary 1.

Corollary 1. Under Assumption 2 and control (10), and the following condition (11) hold and

$$-\delta_k + \sum_{p=1}^{n}\mathcal{W}_p|b_{kp}| < 0, \tag{18}$$

then, delayed neural networks (17) is fixed-time stable, and settling-time is $\mathcal{T}_M = \frac{1}{2\alpha}$.

Remark 4. From Figure 1, one can find that the control input (10) do not produce extremely large control inputs near the zero, so, we believe that the fixed-time stability results of this paper still holds when the control input is bounded. And in this paper, we only discuss a simple application, that is, FT of delayed neural networks, we believe that our results can be used to discuss fixed-time stability for other more complex nonlinear dynamic models, such as circuit systems, switched systems and neural networks with inertial items, complex-valued or reaction-diffusion terms.

4 Example simulations

Example 1. Discuss two-dimensional delayed neural networks as follows:

$$\begin{aligned}\frac{\mathrm{d}z_k(t)}{\mathrm{d}t} &= -d_k z_k(t) + \sum_{p=1}^{2} a_{kp} g_p(z_p(t)) \\ &\quad + \sum_{p=1}^{2} b_{kp} g_p(z_p(t-\tau(t))) \\ &\quad + \sum_{p=1}^{2} c_{kp} \int_{t-\tau(t)}^{t} g_p(z_p(s))\mathrm{d}s, \\ &\quad t \geqslant 0, \end{aligned} \tag{19}$$

where $d_1 = d_2 = 1, \tau(t) = \frac{\exp(t)}{1+\exp(t)}, g_p(z_p(t)) = \tanh(z_p(t)), k, p = 1, 2$, and other parameter values are given as in Table 1.

Table 1. Parameter values of delayed neural networks (19).

a_{11}	a_{12}	b_{11}	b_{12}	c_{11}	c_{12}
2	-0.1	-1.5	-0.1	-0.01	0.01
a_{21}	a_{22}	b_{21}	b_{22}	c_{21}	c_{22}
-5	2.5	-3	-2.5	0.01	-0.01

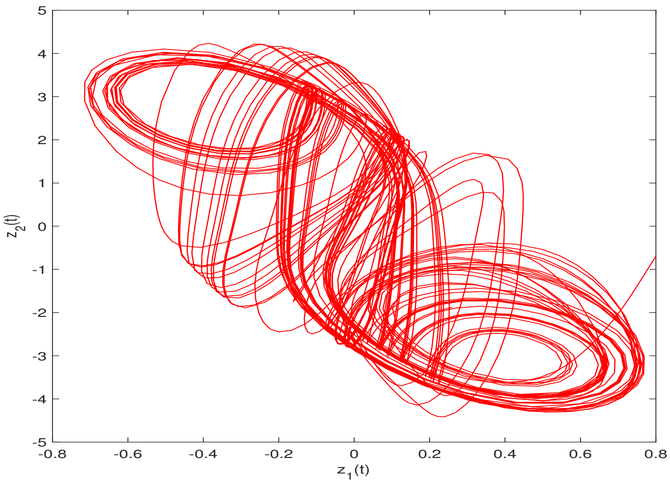

Figure 2. Chaotic behaviors of delayed neural networks (19).

We select the initial values of delayed neural networks (19) are $z_1(s) = 0.8, z_2(s) = -0.7, \forall s \in [-1, 0)$, and delayed neural networks (19) exist chaotic behaviors, which is showed in Figure 2. Without control, state

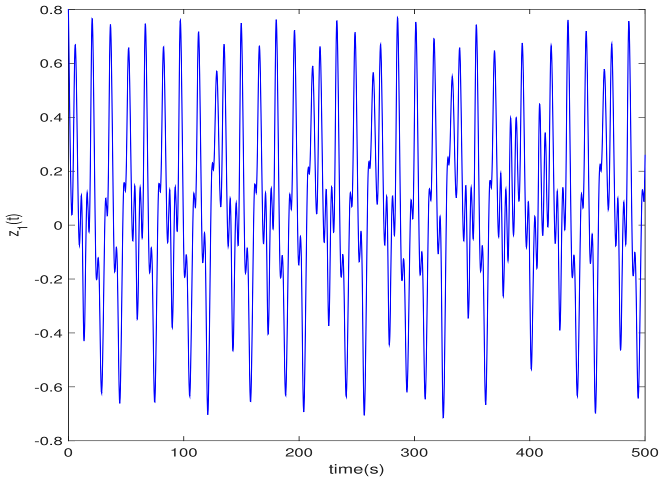

Figure 3. State trajectory $z_1(t)$ of system (19) without control.

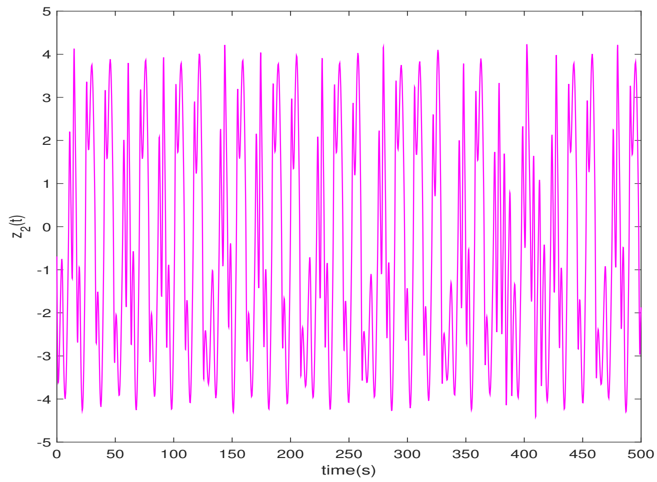

Figure 4. State trajectory $z_2(t)$ of system (19) without control.

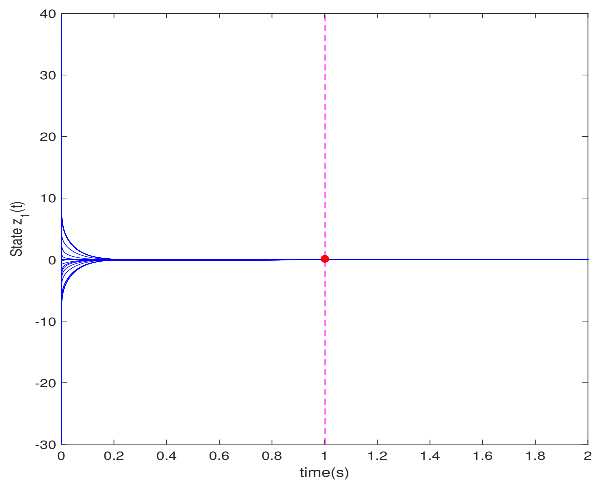

Figure 5. State trajectories $z_1(t)$ of system (19) with control (10).

trajectories $z_1(t), z_2(t)$ of delayed neural networks (19) are displayed in Figures 3 and 4, respectively.

Now, we can easily get $\mathcal{L}_1 = \mathcal{L}_2 = \mathcal{W}_1 = \mathcal{W}_2 = \tau = 1$, and choose $\gamma_1 = \gamma_2 = 7, \delta_1 = 1.7, \delta_2 = 5.6, \alpha_1 = \alpha_2 = 0.5$, then, one has $\alpha = 0.5$ and

$$-d_1 - \gamma_1 + \sum_{p=1}^{2} \mathcal{L}_1 |a_{p1}| < 0,$$
$$-d_2 - \gamma_2 + \sum_{p=1}^{2} \mathcal{L}_2 |a_{p2}| < 0,$$
$$-\delta_1 + \sum_{p=1}^{2} \mathcal{W}_p \Big(|b_{1p}| + |c_{1p}| \Big) < 0,$$
$$-\delta_2 + \sum_{p=1}^{2} \mathcal{W}_p \Big(|b_{2p}| + |c_{2p}| \Big) < 0,$$

so, all conditions of Theorem 1 are hold, then, from Theorem 1, we get delayed neural networks (19) is fixed-time stable with control input (10). And settling-time $\mathcal{T}_M = 1$, randomly selecting 30 initial values in interval $[-50, 50]$ and under control (10), state trajectories $z_1(t), z_2(t)$ of delayed neural networks (19) are fixed-time stable, which are displayed in Figures 5 and 6, respectively.

Remark 5. From above analysis, one finds control (10) has sign$(\cdot)$, to avoid chattering phenomenon, we use $\tanh(w \cdot (\cdot))$ stands for sign$(\cdot)$ in the simulation, where w is a big positive constant. In our simulation, we choose $w = 20$, that is, we use $\tanh(20 \cdot z_k(t))$ substitutes sign$(z_k(t))$ in our simulations.

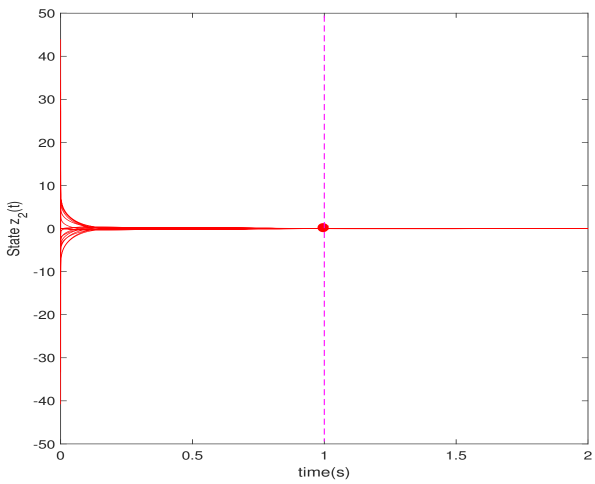

Figure 6. State trajectories $z_2(t)$ of system (19) with control (10).

5 Conclusions

Based on sigmoid-function, a new kind of fixed-time stability Lemma 1 was constructed. And FT of a kind of delayed neural networks was investigated by using the proposed Lemma 1. Compared with some previous works, our fixed-time stability Lemma 1 does not have two power index terms, which is more convenient for practical applications. And our results can be used to discuss fixed-time stability and synchronization for other general nonlinear dynamic systems, which will be further investigated in our future works.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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