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Research Article

Practical Stability for Conformable Time-Delay Systems

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This article investigates the practical exponential stability and design problems of conformable time-delay systems. Sufficient conditions that confirm the practical exponential stability and design of the proposed class of systems are given by utilizing an adequate Lyapunov–Krasovskii functional (L-KF). These conditions are expressed in the form of linear matrix inequalities (LMI) which could be solved by using solvers in LMI Toolbox of MATLAB. Two numerical examples are given to illustrate the applicability of the proposed results.

1. Introduction

The concepts of fractional derivation and fractional integration are often associated to Riemann and Liouville, while the question of the generalization of the notion of the derivative of fractional orders is older since 1695. More than 300 years later, we are only beginning to overcome the difficulties. Many famous researchers have studied this subject such as Leibniz and L'Hôpital (1695), Fourier (1822), Abel (1823), Liouville (1832), Riemann (1847), and Ross (1975). During the past three decades, more interest has been attracted to fractional calculus and other fields of application have diversified. In recent years, fractional differential equations (FDEs) have found applications in many problems in physical. As in most of the time, these equations cannot be solved exactly except when we know some particular solutions or else we refer to the study of existence and uniqueness of solutions using some fundamental theorems of functional analysis (the Banach contraction theorem) for the other FDEs (Riemann–Liouville and Caputo) (see [1–15]).

The derivations and the integrations of the integer order are interpreted physically and geometrically in a clear way in general. The shortcomings of these interpretations have been recognized in several international conferences on fractional calculus. The absence of an answer to this question has rendered the theory of fractional derivation and integration very mysterious. Therefore, there was always one of the open problems. Fractional differentiation and integration are generalizations of integer-order differentiation and integration.

For this, it would be very interesting to have the physical and geometric interpretations of the fractional-order operators which will provide a place for classical interpretations of whole-order derivations and integrations. The physical interpretation of fractional integration and differentiation relies on the use of two types of time: the cosmic time and individual time; on the other hand, the classical differential and integral calculus is based on the use of the mathematical time.

Khalil et al. [1] introduced a new fractional derivative called the fractional conformable derivative. This new concept is very interesting. Later, this theory is developed by Abdeljawad in [8], who gave the definitions of the conformable derivatives to the left and to the right of the higher order, the exponential functions, the Gronwall transformation inequality, and the Laplace transformation for conformable fractional calculus.

Indeed, there are a few works on the study of the practical stability of conformable FDEs (see [9, 11]). To the best of our knowledge, there is no existing work about the practical stability of conformable systems with delays, and motivated by the previous works in the literature, our article covers this gap by using the LMI method.

The main highlights of this article are as follows:

(i) A L-KF for the conformable time-delay systems is proposed.

(ii) Study the exponential practical stability and design for a class of conformable time-delay systems.

(iii) Using the LMI technique to show our main results.

The content of this article are organized as follows: Section 2 is devoted to some preliminary definitions. In Section 3, we prove our main results. In Section 4, we present two applicable examples to illustrate our results.

2. Preliminaries

Notations used are as follows: I represents the identity matrix, $\|.\|$ stands for the Euclidean norm of a vector, $\mathrm{Sym}(\Theta)$ and $\mathrm{diag}(\Theta,\Theta)$ refer to $\Theta+\Theta^T$ and $\begin{bmatrix}\Theta & 0\\ 0 & \Theta\end{bmatrix}$, respectively. $\lambda_{\min}(\Theta)$ and $\lambda_{\max}(\Theta)$ stand for the minimum and the maximum eigenvalues of Θ, respectively.

Definition 1. [8] Given a function ξ defined on $[l,\infty]$, then the conformable fractional derivative starting from l of ξ of the order β is defined by

$$T_l^{\beta}\xi(\chi)=\lim_{\varsigma\longrightarrow 0}\frac{\xi\left(\chi+\varsigma(\chi-l)^{1-\beta}\right)-\xi(\chi)}{\varsigma}, \tag{1}$$

for all $\chi>l$, $\beta\in(0,1)$. If $T_l^{\beta}\xi(\chi)$ exists $\forall\chi\in(l,b)$ for some $b>l$ and $\lim_{\chi\longrightarrow l^+}T_l^{\beta}\xi(\chi)$ exists, then by definition

$$T_l^{\beta}\xi(l)=\lim_{\chi\longrightarrow l^+}T_l^{\beta}\xi(\chi). \tag{2}$$

Remark 1. If $l=0$, the definition of the conformable fractional derivative and integral above will be reduced to the result in [1].

Seeking simplicity, we note $T^{\beta}:=T_0^{\beta}$.

Let us consider the following fractional system:

$$\begin{aligned}T^{\beta}\xi(\chi)&=F(t,\xi(\chi),\xi(\chi-\tau)),\chi\geq 0,\\ \xi(\chi)&=\varphi(\chi),\chi\in[-\tau,0],\end{aligned} \tag{3}$$

where $\xi(\chi)\in\mathbb{R}^n$ is the state vector, τ stands for time delay, and $\varphi(\chi)$ is the initial condition.

Definition 2. The system (3) is called practically exponentially stable (p.e.s) with the convergence rate δ, if there are positive scalars C, δ, and ϱ such that

$$\|\xi(\chi)\|\leq C\|\varphi\|E_{\beta}(-\delta,\chi)+\varrho,\forall\chi\geq 0, \tag{4}$$

where $E_{\beta}(-\delta,\chi)=e^{-\delta\chi^{\beta}}$.

3. Exponential Practical Stability and Stabilization Criteria

In this section, the following time-delay system with the conformable derivative is considered.

$$\begin{aligned}T^{\beta}\xi(\chi)&=G\xi(\chi)+H\xi(\chi-\tau)+M\nu(\chi)+h(\chi),\chi\geq 0,\\ \xi(\chi)&=\varphi(\chi),\chi\in[-\tau,0],\end{aligned} \tag{5}$$

where $\xi(\chi)\in\mathbb{R}^n$ is the state vector, τ stands for time delay, $\nu(\chi)\in\mathbb{R}^m$ is the control input, $\varphi(\chi)$ is the initial condition, $G,H\in\mathbb{R}^{n\times n}$, $M\in\mathbb{R}^{n\times m}$, and $h(\chi)\in\mathbb{R}^n$.

Assumption 1. Suppose that the function $h(\chi)$ is bounded $\|h(\chi)\|<\alpha$.

Firstly, we study the stability analysis of the system (5) when the control input $\nu(\chi)=0$.

Theorem 1. *Under Assumption 1, for given positive scalars σ and υ, if there exist positive definite matrices P and Q such that the following LMI is satisfied:*

$$\begin{bmatrix}\mathrm{Sym}(PG+\sigma P)+Q & PH & P\\ * & -e^{-2\sigma\frac{\tau^{\beta}}{\beta}}Q & 0\\ * & * & -\upsilon I\end{bmatrix}<0, \tag{6}$$

then the system (5) is p.e.s. with the convergence rate σ.

Proof. Let us consider the L-KF

$$V\left(\xi_{\chi}\right)=\xi^T(\chi)P\xi(\chi)+\int_{\chi}^{\chi+\tau}s^{\beta-1}e^{2\sigma\left(s^{\beta}/\beta-\chi^{\beta}/\beta-\tau^{\beta}/\beta\right)}\xi^T(s-\tau)Q\xi(s-\tau)\mathrm{d}s. \tag{7}$$

For $\chi>0$, we get

$$
\begin{aligned}
T^{\beta}V\left(\xi_{\chi}\right) &= 2\xi^{T}(\chi)P\left(T^{\beta}\xi(\chi)\right) + \chi^{1-\beta}\Big((\chi+\tau)^{\beta-1}e^{2\sigma\left((\chi+\tau)^{\beta}/\beta-\chi^{\beta}/\beta-\tau^{\beta}/\beta\right)}\xi^{T}(\chi)Q\xi(\chi),\\
&\quad -\chi^{\beta-1}e^{-2\sigma\tau^{\beta}/\beta}\xi^{T}(\chi-\tau)Q\xi(\chi-\tau),\\
&\quad -2\sigma\chi^{\beta-1}\int_{\chi}^{\chi+\tau}s^{\beta-1}e^{2\sigma\left(s^{\beta}/\beta-\chi^{\beta}/\beta-\tau^{\beta}/\beta\right)}\xi^{T}(s-\tau)Q\xi(s-\tau)\mathrm{d}s\Big),\\
&\leq 2\xi^{T}(\chi)P\left(T^{\beta}\xi(\chi)\right) + \xi^{T}(\chi)Q\xi(\chi) - e^{-2\sigma\tau^{\beta}/\beta}\xi^{T}(\chi-\tau)Q\xi(\chi-\tau)\\
&\quad -2\sigma\int_{\chi}^{\chi+\tau}s^{\beta-1}e^{2\sigma\left(s^{\beta}/\beta-\chi^{\beta}/\beta-\tau^{\beta}/\beta\right)}\xi^{T}(s-\tau)Q\xi(s-\tau)\mathrm{d}s,\\
&\leq 2\xi^{T}(\chi)P\left(G\xi(\chi)+H\xi(\chi-\tau)+h(\chi)\right)^{T} + \xi^{T}(\chi)Q\xi(\chi) - e^{-2\sigma\tau^{\beta}/\beta}\xi^{T}(\chi-\tau)Q\xi(\chi-\tau),\\
&\quad -2\sigma\int_{\chi}^{\chi+\tau}s^{\beta-1}e^{2\sigma\left(s^{\beta}/\beta-\chi^{\beta}/\beta-\tau^{\beta}/\beta\right)}\xi^{T}(s-\tau)Q\xi(s-\tau)\mathrm{d}s.
\end{aligned}
\tag{8}
$$

then

$$
\begin{aligned}
T^{\beta}V\left(\xi_{\chi}\right) + 2\sigma V\left(\xi_{\chi}\right) &\leq 2\xi^{T}(\chi)PG\xi(\chi) + 2\xi^{T}(\chi)PH\xi(\chi-\tau) + 2\xi^{T}(\chi)Ph(\chi) + 2\sigma\xi^{T}(\chi)P\xi(\chi) + \xi^{T}(\chi)Q\xi(\chi)\\
&\quad - e^{-2\sigma\tau^{\beta}/\beta}\xi^{T}(\chi-\tau)Q\xi(\chi-\tau).
\end{aligned}
\tag{9}
$$

It is obvious that for any positive scalar υ, we have

$$
2\xi^{T}(\chi)Ph(\chi) \leqslant \upsilon\|h(\chi)\|^{2} + \frac{1}{\upsilon}\|P\xi(\chi)\|^{2}. \tag{10}
$$

Since $\|h(\chi)\| < \alpha$, we get

$$
2\xi^{T}(\chi)Ph(\chi) \leqslant \upsilon\alpha^{2} + \frac{1}{\upsilon}\xi^{T}(\chi)PP\xi(\chi). \tag{11}
$$

Then,

$$
T^{\beta}V\left(\xi_{\chi}\right) + 2\sigma V\left(\xi_{\chi}\right) \leq \vartheta(\chi)^{T}\Xi\vartheta(\chi) + \upsilon\alpha^{2}, \tag{12}
$$

where

$$
\Xi = \begin{bmatrix} \mathrm{Sym}(PG+\sigma P) + Q + \frac{1}{\upsilon}PP & PH \\ * & -e^{-2\sigma\frac{\tau^{\beta}}{\beta}}Q \end{bmatrix}, \vartheta(\chi) = \begin{bmatrix} \xi(\chi) \\ \xi(\chi-\tau) \end{bmatrix}. \tag{13}
$$

By applying the Schur complement, (6) is equivalent to $\Xi < 0$ which implies that

$$
T^{\beta}V\left(\xi_{\chi}\right) + 2\sigma V\left(\xi_{\chi}\right) \leq \upsilon\alpha^{2}. \tag{14}
$$

According to Lemma 1 in [11], there exists $\mu > 0$ such that

$$
V\left(\xi_{\chi}\right) \leq V(\phi)E_{\beta}(-\delta,\chi) + \mu, \tag{15}
$$

where $\mu = \alpha^{2}\nu/2\sigma\beta$.

Furthermore, it is clear from (7) that

$$
\begin{aligned}
V(\phi)E_{\beta}(-2\sigma,\chi) &\leq \left(\lambda_{\max}(P) + \frac{\tau^{\beta}}{\beta}\lambda_{\max}(Q)\right)\|\phi\|^{2}E_{\beta}(-2\sigma,\chi).\\
V\left(\xi_{\chi}\right) &\geq \lambda_{\mathrm{mim}}(P)\|\xi(\chi)\|^{2}.
\end{aligned}
\tag{16}
$$

Then, we get

$$
\|\xi(\chi)\| \leq \sqrt{\frac{\left(\lambda_{\max}(P) + \tau^{\beta}/\beta\lambda_{\max}(Q)\right)}{\lambda_{\min}(P)}}\|\phi\|E_{\beta}(-\sigma,\chi) + \sqrt{\frac{\mu}{\lambda_{\min}(P)}}. \tag{17}
$$

The proof is completed. □

Secondly, we study the stabilization problem of the system (5) based on the following feedback controller:

$$\nu(\chi) = F\xi(\chi), \tag{18}$$

where $F \in \mathbb{R}^{m\times n}$ is the gain of the feedback controller.

In this case, the closed-loop system is expressed as follows:

$$\begin{aligned} T^{\beta}\xi(\chi) &= (G + M \times F)\xi(\chi) + H\xi(\chi-\tau) + h(\chi), \chi \geq 0, \\ \xi(\chi) &= \phi(\chi), \chi \in [-\tau, 0]. \end{aligned} \tag{19}$$

Theorem 2. *Under Assumption 1, for given positive scalars σ and η, if there exist positive definite matrices X and R, a matrix Y such that the following LMI is satisfied:*

$$\Psi = \begin{bmatrix} \mathrm{Sym}(GX + MY + \sigma X) + R + \eta I & HX \\ * & -e^{-2\sigma\frac{\tau^{\beta}}{\beta}}R \end{bmatrix} < 0, \tag{20}$$

then the closed-loop system (19) is p.e.s with the convergence rate σ. Furthermore, the feedback control gain matrix is obtained by using the relation $F = YX^{-1}$.

Proof. Following a similar line in the proof of Theorem 1, we get that for any positive scalar υ, we have

$$T^{\beta}V(\xi_{\chi}) + 2\sigma V(\xi_{\chi}) \leq \vartheta^{T}(\chi)\Gamma\vartheta(\chi) + \upsilon\alpha^{2}, \tag{21}$$

where

$$\Gamma = \begin{bmatrix} \mathrm{Sym}(PG + PMF + \sigma P) + Q + \frac{1}{\upsilon}PP & PH \\ * & -e^{-2\sigma\tau^{\beta}/\beta}Q \end{bmatrix}. \tag{22}$$

Define $\eta = 1/\upsilon$, $X = P^{-1}$, $R = P^{-1}QP^{-1}$, and $Y = FP^{-1}$, we get

$$T^{\beta}V(\xi_{\chi}) + 2\sigma V(\xi_{\chi}) \leq \vartheta^{T}(\chi)\mathrm{diag}(P,P)\Psi\mathrm{diag}(P,P)\vartheta(\chi) + \upsilon\alpha^{2}. \tag{23}$$

The rest is similar to the proof of Theorem 1. □

Remark 2. In [16], the authors have studied the practical exponential stability of system (5) for the case when $\beta = 1$.

Remark 3. This work presents the first attempt for practical exponential stability and stabilization for conformable time-delay systems. When restricted to $\beta = 1$, the major contribution of this work compared with [16] is that $\xi(\chi)$ converges to a ball of radius $\Delta = \alpha\sqrt{\upsilon/2\sigma\beta\lambda_{\min}(P)}$ which can be minimized by adjusting the parameter υ.

4. Illustrative Examples

4.1. Example 1. In this subsection, we examine a class of system that can be described by the following model:

$$T^{\beta}\xi(\chi) = \begin{bmatrix} 0 & 1 \\ -\omega^{2} & -2\delta\omega \end{bmatrix}\xi(\chi) + \begin{bmatrix} 0 & 0 \\ \rho & 0 \end{bmatrix}\xi(\chi-\tau) + \begin{bmatrix} 0 \\ M\sin(\chi) \end{bmatrix}, \tag{24}$$

where $\omega = 3.1321, \delta = 1.6762, M = 0.3,$ and $\rho = 0.32$.

Applying Theorem 1, we get a feasible solution by choosing $\beta = 0.9, \tau = 0.5, \upsilon = 230,$ $\sigma = 0.95$, $P = \begin{bmatrix} 14.8903 & 7.9744 \\ 7.9744 & 7.4048 \end{bmatrix}$, and $Q = \begin{bmatrix} 53.6000 & 54.3918 \\ 54.3918 & 55.7061 \end{bmatrix}$. Now, we take the initial condition $\phi(\chi) = [\,2\ \ -3\,]^{T}$ and $\forall\chi \in [\,-0.5\ \ 0\,]$. The evolution of system states and their phase diagram are shown in Figures 1 and 2, respectively.

Now, we take $\beta = 1, \omega = 3.1321, \delta = 1.6762, M = 0.1, \rho = 0.32,$ and $\tau = 0.5$. The objective is to compute Δ the radius of the ball in which $\xi(\chi)$ converges. Table1lists the computation results.

From Table 2, it can be seen that the radius Δ can be minimized by adjusting the parameter υ.

Remark 4. It is noticed that the LMI conditions in Theorem 1 can be infeasible for the ordinary case ($\beta = 1$) and feasible for some $\beta < 1$.

For example, we choose $\tau = 8$, $\sigma = 0.4$, and $\upsilon = 10$. If $\beta = 1$, Theorem 1 fails to test the practical exponential stability. However, we obtain the following set of the feasible

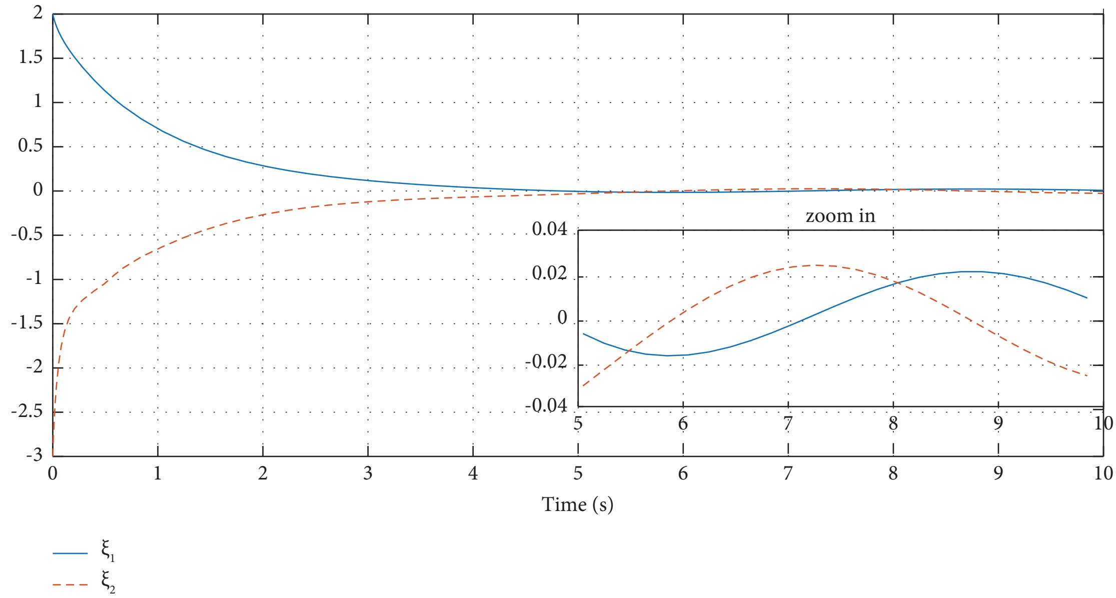

Figure 1: Evolution of system states ξ_1 and ξ_2.

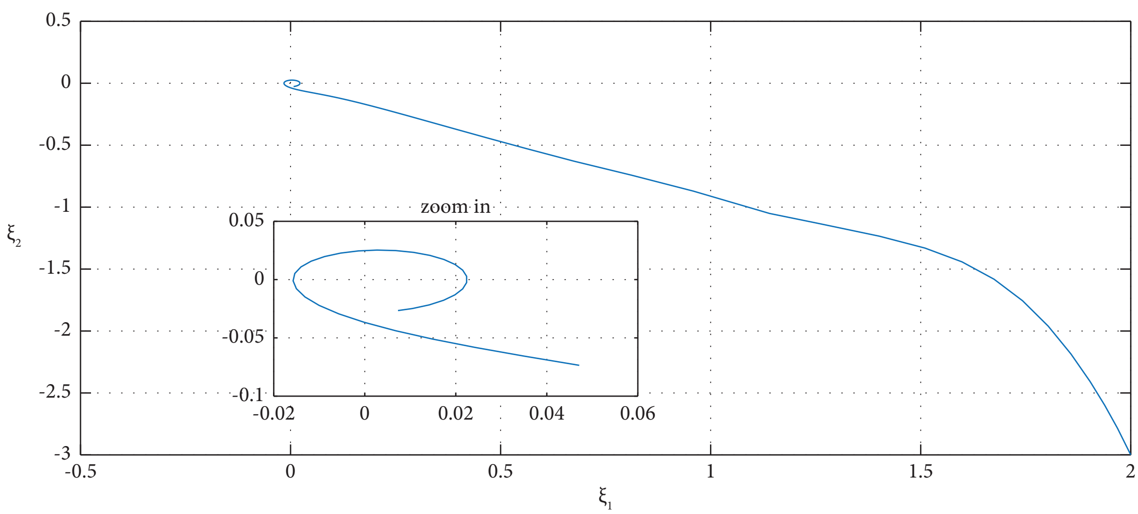

Figure 2: Behavior in the $\xi_1 - \xi_2$ plane for Example 1.

Table 1: Controller gain for various σ.

σ	F
0.1	$F = \begin{bmatrix} -4.1314 & -0.5507 \end{bmatrix}$
0.5	$F = \begin{bmatrix} -4.0365 & -0.8756 \end{bmatrix}$
1.99	$F = \begin{bmatrix} -28.0115 & -0.9866 \end{bmatrix}$

Table 2: Comparison results of Δ for Example 1.

Methods	Δ
[16]	0.585
Theorem 1 for $v = 0.1$	0.510
Theorem 1 for $v = 5$	0.506
Theorem 1 for $v = 10$	0.499

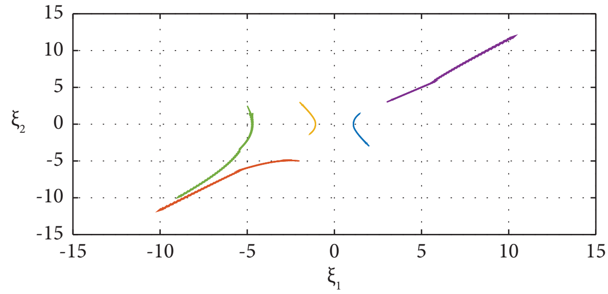

FIGURE 3: Behavior in the $\xi_1 - \xi_2$ plane for Example 2 without control.

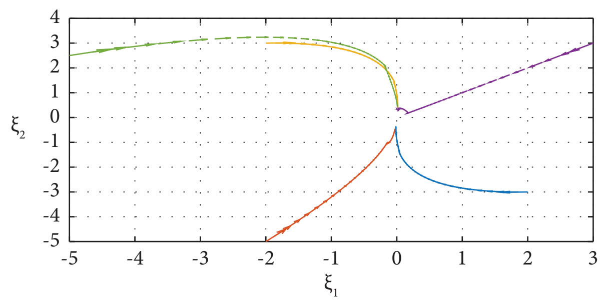

FIGURE 4: Behavior in the $\xi_1 - \xi_2$ plane for Example 2 with control.

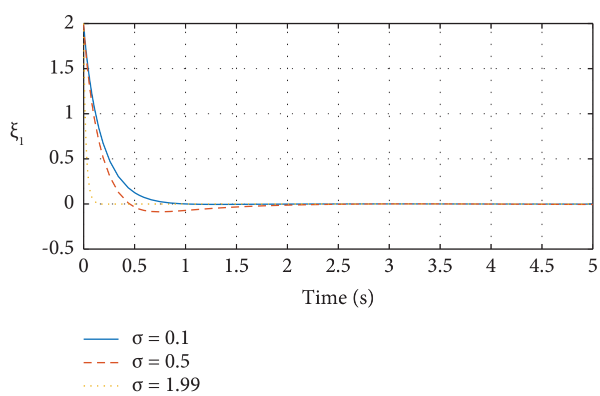

FIGURE 5: The evolution of state ξ_1 for $\sigma = 0.1$, $\sigma = 0.5$, and $\sigma = 1.99$.

solution for $\beta = 0.7$, $P = \begin{bmatrix} 4.0478 & 1.2695 \\ 1.2695 & 1.3331 \end{bmatrix}$, and $Q = \begin{bmatrix} 4.5322 & 4.1400 \\ 4.1400 & 5.9155 \end{bmatrix}$.

4.2. Example 2. Consider a model of the form

$$T^{\beta}\xi(\chi) = \begin{bmatrix} 0 & 1 \\ 2 & -1 \end{bmatrix}\xi(\chi) + \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}\xi(\chi - \tau) + \begin{bmatrix} 1 \\ 1 \end{bmatrix}\nu(\chi) + \begin{bmatrix} 0 \\ 0.1\sin(\chi) \end{bmatrix}. \tag{25}$$

The behavior of the open-loop system (25) without input ($\nu(\chi) = 0$) is shown in Figure 3. It is seen that system (25) is unstable.

By solving the LMI conditions in Theorem 2 for $\beta = 0.9, \tau = 0.5, \eta = 0.12$, and $\sigma = 0.95$, we get the following control gain: $F = \begin{bmatrix} -4.9423 & -0.8446 \end{bmatrix}$. Figure 4 shows the behavior of the closed-loop system for the same initial conditions in Figure 3.

Now, we compute the controller gains F for different values of σ with the choice of $\beta = 0.9$ and $\tau = 0.5$. Table 2 lists the computation results.

The evolution of the system state ξ_1 is shown in Figure 5 for various σ.

5. Conclusion

This article discusses the exponential practical stability and design of time-delay conformable systems. Some sufficient conditions are presented to show the exponential practical stability by using an appropriate L-KF and the LMI method. Finally, two illustrative examples are presented to show the applicability of our main result. In the future, combining with the work in [17], we can extend our work to conformable time-varying delay systems.

Data Availability

No data were generated or analyzed during the current study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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