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A Sufficient Condition for the Global Exponential Stability of Uncertain Interval Continuous-Time Systems

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ABSTRACT

This paper investigates the stability of a class of uncertain interval continuous-time dynamic systems. Combining linear algebra and time-domain analysis, we derive a sufficient condition for a class of uncertain interval continuous time systems to achieve global exponential stability. We also derive the exponential convergence rate of such uncertain interval systems. Finally, a computer numerical simulation example is provided to illustrate and verify the correctness of the main theorem.

KEYWORDS: *Global exponential stability, interval systems, continuous-time systems, exponential convergence rate.*

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1. INTRODUCTION

In recent years, stability analysis and robust controller design for interval systems have been extensively discussed and researched; see, for example, [1]-[8] and the references therein. Based on practical needs, the uncertainty within the system should be taken into account, which also increases the difficulty of stability analysis.

This paper proposes a simple criterion for guaranteeing global exponential stability for a class of uncertain interval continuous-time systems. Furthermore, the exponential convergence rate of such uncertain interval continuous-time systems is calculated. Finally, several numerical computer simulation results are presented to illustrate the effectiveness of the main theorem.

This paper is structured as follows: Chapter 1 is an introduction to uncertain interval continuous-time systems, Chapter 2 is an analysis of the global exponential stability of uncertain interval continuous-time systems, Chapter 3 is the computer numerical simulation results of uncertain interval continuous-time systems, and Chapter 4 is the conclusion.

This paper will use the chaotic characteristics of the laser dynamic system to design a new master-slave chaotic secure communication system. Based on the control theory, it is deduced that such a secure communication system can achieve the goal of global exponential tracking. Besides, the guaranteed exponential convergence rate of this secure communication system will be calculated simultaneously. Finally, several computer simulation results will demonstrate the effectiveness of this main theorem. In particular, throughout the paper, $\|x\| := \sqrt{x^T \cdot x}$ represents the Euclidean norm of the column vector x, and $|a|$ represents the absolute value of a real number a.

2. DYNAMIC SYSTEMS DESCRIPTION AND MAIN RESULTS

Terminology and notation

$\Re^n$ the n-dimensional real space;

$|a|$ the modulus of a complex number a;

$\left[\underline{a}, \overline{b}\right]$ the set of $\left\{x \middle| \underline{a} \le x \le \overline{b}\right\}$;

A^T the transport of the matrix A;

$\|x\|$ the Euclidean norm of the vector $x \in \Re^n$;

$\mathrm{Re}(\lambda)$ the real part of a complex number λ.

In this paper, we consider the following uncertain interval continuous-time dynamic systems:

$$\begin{bmatrix} \Delta b_1 \cdot x_1'(t) \\ \Delta b_2 \cdot x_2'(t) \\ \Delta b_3 \cdot x_3'(t) \\ \vdots \\ \Delta b_n \cdot x_n'(t) \end{bmatrix} = \begin{bmatrix} \Delta a_{1,1} & \Delta a_{1,2} & \Delta a_{1,3} & \cdots & \Delta a_{1,n} \\ \Delta a_{2,1} & \Delta a_{2,2} & \Delta a_{2,3} & \cdots & \Delta a_{2,n} \\ \Delta a_{3,1} & \Delta a_{3,2} & \Delta a_{3,3} & \cdots & \Delta a_{3,n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta a_{n,1} & \Delta a_{n,2} & \Delta a_{n,3} & \cdots & \Delta a_{n,n} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ \vdots \\ x_n(t) \end{bmatrix}, \tag{1}$$

for $t \ge 0$. Besides, $x(t) := [x_1(t) \quad x_2(t) \quad \cdots \quad x_n(t)]^T \in \Re^{n \times 1}$ is the state vector, Δb_i and $\Delta a_{i,j}$ represent the uncertain parameters of the systems, with $\Delta b_i \in \left[\underline{b_i}, \overline{b_i}\right]$, $\Delta a_{i,j} \in \left[\underline{a_{i,j}}, \overline{a_{i,j}}\right]$, and $0 \notin \left[\underline{b_i}, \overline{b_i}\right]$, $\forall\, i, j \in \{1,2,3,\cdots,n\}$. For the sake of convenience, we define the following parameters:

$$\alpha_1 := Max\left(\frac{\Delta a_{1,1}}{\Delta b_1}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{1,j}}{\Delta b_1}\right| - Max\left|\frac{\Delta a_{1,1}}{\Delta b_1}\right|, \tag{2.1}$$

$$\alpha_2 := Max\left(\frac{\Delta a_{2,2}}{\Delta b_2}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{2,j}}{\Delta b_2}\right| - Max\left|\frac{\Delta a_{2,2}}{\Delta b_2}\right| \tag{2.2}$$

$$\alpha_3 := Max\left(\frac{\Delta a_{3,3}}{\Delta b_3}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{3,j}}{\Delta b_3}\right| - Max\left|\frac{\Delta a_{3,3}}{\Delta b_3}\right| \tag{2.3}$$

$\vdots$

$$\alpha_{n-1} := Max\left(\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{n-1,j}}{\Delta b_{n-1}}\right| - Max\left|\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right|, \tag{2.n-1}$$

$$\alpha_n := Max\left(\frac{\Delta a_{n,n}}{\Delta b_n}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{n,j}}{\Delta b_n}\right|; - Max\left|\frac{\Delta a_{n,n}}{\Delta b_n}\right|; \tag{2.n}$$

$$\beta_1 := Max\left(\frac{\Delta a_{1,1}}{\Delta b_1}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{j,1}}{\Delta b_j}\right| - Max\left|\frac{\Delta a_{1,1}}{\Delta b_1}\right|, \tag{3.1}$$

$$\beta_2 := Max\left(\frac{\Delta a_{2,2}}{\Delta b_2}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{j,2}}{\Delta b_j}\right| - Max\left|\frac{\Delta a_{2,2}}{\Delta b_2}\right|, \tag{3.2}$$

$$\beta_3 := Max\left(\frac{\Delta a_{3,3}}{\Delta b_3}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{j,3}}{\Delta b_j}\right| - Max\left|\frac{\Delta a_{3,3}}{\Delta b_3}\right|, \tag{3.3}$$

$\vdots$

$$\beta_{n-1} := Max\left(\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{j,n-1}}{\Delta b_j}\right| - Max\left|\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right|, \tag{3.n-1}$$

$$\beta_n := Max\left(\frac{\Delta a_{n,n}}{\Delta b_n}\right) + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{j,n}}{\Delta b_j}\right| \; Max\left|\frac{\Delta a_{n,n}}{\Delta b_n}\right|; \tag{3.n}$$

$$\overline{\alpha} := Max\{\alpha_1, \alpha_2, \alpha_3, \cdots, \alpha_n\}, \tag{4.1}$$

$$\overline{\beta} := Max\{\beta_1, \beta_2, \beta_3, \cdots, \beta_n\}. \tag{4.2}$$

The definition of the uncertain continuous-time interval systems (1) as globally exponentially stable systems is as follows.

Definition 1.
The uncertain continuous-time interval systems (1) are said to be globally exponentially stable if there exist two positive constants K and τ satisfying

$$\|x(t)\| \le K \cdot e^{-\tau t}, \quad \forall\, t \ge 0.$$

Meanwhile, the positive number τ is called the exponential convergence rate.

Now, we are in a position to present the main result for the global exponent stability of uncertain continuous-time interval systems (1).

Theorem 1.
The uncertain continuous-time interval systems (1) are globally exponentially stable provided that

$$\delta := \min\left\{\overline{\alpha}, \overline{\beta}\right\} < 0. \tag{5}$$

At the same time, the guaranteed exponential convergence rate is given by

$$\alpha = -\delta - \varepsilon, \tag{6}$$

where ε is any positive number such that $\varepsilon < -\delta$.

Proof. Clearly, the uncertain continuous-time interval systems of (1) can be rewritten into the following types.

$$\frac{dx(t)}{dt}=\begin{bmatrix}\frac{\Delta a_{1,1}}{\Delta b_1} & \frac{\Delta a_{1,2}}{\Delta b_1} & \cdots & \frac{\Delta a_{1,n}}{\Delta b_1}\\ \frac{\Delta a_{2,1}}{\Delta b_2} & \frac{\Delta a_{2,2}}{\Delta b_2} & \cdots & \frac{\Delta a_{2,n}}{\Delta b_2}\\ \vdots & \vdots & \vdots & \vdots\\ \frac{\Delta a_{n,1}}{\Delta b_n} & \frac{\Delta a_{n,2}}{\Delta b_n} & \cdots & \frac{\Delta a_{n,n}}{\Delta b_n}\end{bmatrix}_{n\times n}\cdot x(t)$$

$$:=\Delta H\cdot x(t)$$

where $\Delta H=\begin{bmatrix}\frac{\Delta a_{1,1}}{\Delta b_1} & \frac{\Delta a_{1,2}}{\Delta b_1} & \cdots & \frac{\Delta a_{1,n}}{\Delta b_1}\\ \frac{\Delta a_{2,1}}{\Delta b_2} & \frac{\Delta a_{2,2}}{\Delta b_2} & \cdots & \frac{\Delta a_{2,n}}{\Delta b_2}\\ \vdots & \vdots & \vdots & \vdots\\ \frac{\Delta a_{n,1}}{\Delta b_n} & \frac{\Delta a_{n,2}}{\Delta b_n} & \cdots & \frac{\Delta a_{n,n}}{\Delta b_n}\end{bmatrix}$. Let λ and $\begin{bmatrix}y_1\\ y_2\\ \vdots\\ y_n\end{bmatrix}$ are the eigenvalue and eigenvector of the uncertain matrix of ΔH, respectively. Thus, one has $\Delta H\cdot\begin{bmatrix}y_1\\ y_2\\ \vdots\\ y_n\end{bmatrix}=\lambda\begin{bmatrix}y_1\\ y_2\\ \vdots\\ y_n\end{bmatrix}$. Obviously, it can be readily obtained that

$$\sum_{j=1}^{n}\frac{\Delta a_{i,j}}{\Delta b_i}\cdot y_j=\lambda y_i,\ \forall\, i\in\{1,2,3,\cdots,n\}.$$

$$\Rightarrow\ \left(\lambda-\frac{\Delta a_{i,i}}{\Delta b_i}\right)y_i=\left(\sum_{j=1}^{n}\frac{\Delta a_{i,j}}{\Delta b_i}\cdot y_j\right)-\frac{\Delta a_{i,i}}{\Delta b_i}y_i,\quad \forall\, i\in\{1,2,3,\cdots,n\}.$$

$$\Rightarrow\ \left|\lambda-\frac{\Delta a_{i,i}}{\Delta b_i}\right|\cdot|y_i|\le-\left|\frac{\Delta a_{i,i}}{\Delta b_i}\right|\cdot|y_i|+\sum_{j=1}^{n}\left|\frac{\Delta a_{i,j}}{\Delta b_i}\right|\cdot|y_j|,\ \forall\, i\in\{1,2,3,\cdots,n\}.$$

It results that

$$\left|\lambda-\frac{\Delta a_{1,1}}{\Delta b_1}\right|\le-\left|\frac{\Delta a_{1,1}}{\Delta b_1}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{1,j}}{\Delta b_1}\right|,$$

if $Max\{|y_1|,|y_2|,|y_3|,\cdots,|y_n|\}=|y_1|$;

or

$$\left|\lambda-\frac{\Delta a_{2,2}}{\Delta b_2}\right|\le-\left|\frac{\Delta a_{2,2}}{\Delta b_2}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{2,j}}{\Delta b_2}\right|,$$

if $Max\{|y_1|,|y_2|,|y_3|,\cdots,|y_n|\}=|y_2|$;

or

$$\left|\lambda-\frac{\Delta a_{3,3}}{\Delta b_3}\right|\le-\left|\frac{\Delta a_{3,3}}{\Delta b_3}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{3,j}}{\Delta b_3}\right|,$$

if $Max\{|y_1|,|y_2|,|y_3|,\cdots,|y_n|\}=|y_3|$;

$\vdots$

or

$$\left|\lambda-\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right|\le-\left|\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{n-1,j}}{\Delta b_{n-1}}\right|,$$

if $Max\{|y_1|,|y_2|,|y_3|,\cdots,|y_n|\}=|y_{n-1}|$;

or

$$\left|\lambda-\frac{\Delta a_{n,n}}{\Delta b_n}\right|\le-\left|\frac{\Delta a_{n,n}}{\Delta b_n}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{n,j}}{\Delta b_n}\right|,$$

if $Max\{|y_1|,|y_2|,|y_3|,\cdots,|y_n|\}=|y_n|$.

Based on the above, we can further deduce that

$$\mathrm{Re}(\lambda)\le\frac{\Delta a_{1,1}}{\Delta b_1}-\left|\frac{\Delta a_{1,1}}{\Delta b_1}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{1,j}}{\Delta b_1}\right|,$$

or $\mathrm{Re}(\lambda)\le\frac{\Delta a_{2,2}}{\Delta b_2}-\left|\frac{\Delta a_{2,2}}{\Delta b_2}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{2,j}}{\Delta b_2}\right|,$

or $\mathrm{Re}(\lambda)\le\frac{\Delta a_{3,3}}{\Delta b_3}-\left|\frac{\Delta a_{3,3}}{\Delta b_3}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{3,j}}{\Delta b_3}\right|,$

$\vdots$

or $\mathrm{Re}(\lambda)\le\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}-\left|\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{n-1,j}}{\Delta b_{n-1}}\right|,$

or $\mathrm{Re}(\lambda)\le\frac{\Delta a_{n,n}}{\Delta b_n}-\left|\frac{\Delta a_{n,n}}{\Delta b_n}\right|+\sum_{j=1}^{n}\left|\frac{\Delta a_{n,j}}{\Delta b_n}\right|.$

These show that

$$\mathrm{Re}(\lambda)\le Max\left(\frac{\Delta a_{1,1}}{\Delta b_1}\right)-Max\left|\frac{\Delta a_{1,1}}{\Delta b_1}\right|+\sum_{j=1}^{n}Max\left|\frac{\Delta a_{1,j}}{\Delta b_1}\right|=\alpha_1, \tag{7.1}$$

or

$$\mathrm{Re}(\lambda)\le Max\frac{\Delta a_{2,2}}{\Delta b_2}-Max\left|\frac{\Delta a_{2,2}}{\Delta b_2}\right|+\sum_{j=1}^{n}Max\left|\frac{\Delta a_{2,j}}{\Delta b_2}\right|=\alpha_2, \tag{7.2}$$

or

$$\mathrm{Re}(\lambda)\le Max\frac{\Delta a_{3,3}}{\Delta b_3}-Max\left|\frac{\Delta a_{3,3}}{\Delta b_3}\right|+\sum_{j=1}^{n}Max\left|\frac{\Delta a_{3,j}}{\Delta b_3}\right|=\alpha_3, \tag{7.3}$$

$\vdots$

or

$$\begin{aligned}\operatorname{Re}(\lambda) &\le Max\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}} - Max\left|\frac{\Delta a_{n-1,n-1}}{\Delta b_{n-1}}\right| \\ &\quad + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{n-1,j}}{\Delta b_{n-1}}\right| \\ &= \alpha_{n-1},\end{aligned} \tag{7.n-1}$$

Or

$$\begin{aligned}\operatorname{Re}(\lambda) &\le Max\frac{\Delta a_{n,n}}{\Delta b_{n}} - Max\left|\frac{\Delta a_{n,n}}{\Delta b_{n}}\right| \\ &\quad + \sum_{j=1}^{n} Max\left|\frac{\Delta a_{n,j}}{\Delta b_{n}}\right| \\ &= \alpha_{n}.\end{aligned} \tag{7.n}$$

From (7) and (4.1), one has

$$\operatorname{Re}(\lambda) \le \overline{\alpha}. \tag{8}$$

Using the same analysis process and combining the fact that matrices ΔH^T and ΔH have the same eigenvalues, we can also deduce that

$$\operatorname{Re}(\lambda) \le \overline{\beta}. \tag{9}$$

As a consequence, from (5), (8), and (9), we have $\operatorname{Re}(\lambda) \le \delta < 0$. This means that the uncertain continuous-time interval systems (1) with (5) are globally exponentially stable with guaranteed exponential convergence rate $\alpha = -\delta - \varepsilon$, where ε is any positive number with $\varepsilon < -\delta$. This completes the proof.

3. NUMERICAL SIMULATIONS

Consider the following uncertain continuous-time interval systems:

$$\Delta b_1 \frac{dx_1(t)}{dt} = \sum_{j=1}^{4} \Delta a_{1,j} \cdot x_j(t), \tag{10.1}$$

$$\Delta b_2 \frac{dx_1(t)}{dt} = \sum_{j=1}^{4} \Delta a_{2,j} \cdot x_j(t), \tag{10.2}$$

$$\Delta b_3 \frac{dx_1(t)}{dt} = \sum_{j=1}^{4} \Delta a_{3,j} \cdot x_j(t), \tag{10.3}$$

$$\Delta b_4 \frac{dx_1(t)}{dt} = \sum_{j=1}^{4} \Delta a_{4,j} \cdot x_j(t), \tag{10.4}$$

where

$$\Delta b_1 \in [1,2],\ \Delta a_{1,1} \in [-10,-9],\ \Delta a_{1,2} \in [1,2], \tag{10.5}$$

$$\Delta a_{1,3} \in [-1,0],\ \Delta a_{1,4} \in [0,1], \tag{10.6}$$

$$\Delta b_2 \in [-2,-1]\ \Delta a_{2,1} \in [0,1], \tag{10.7}$$

$$\Delta a_{2,2} \in [9,10],\ \Delta a_{2,3} \in [-1,0], \tag{10.8}$$

$$\Delta a_{2,4} \in [-2,-1],\ \Delta b_3 \in [2,3], \tag{10.9}$$

$$\Delta a_{3,1} \in [-2,-1],\ \Delta a_{3,2} \in [3,4], \tag{10.10}$$

$$\Delta a_{3,3} \in [-12,-11],\ \Delta a_{3,4} \in [-1,0], \tag{10.11}$$

$$\Delta b_4 \in [-3,-2],\ \Delta a_{4,1} \in [-1,0], \tag{10.12}$$

$$\Delta a_{4,2} \in [1,2],\ \Delta a_{4,3} \in [2,3], \tag{10.13}$$

$$\Delta a_{4,4} \in [10,11]. \tag{10.14}$$

Comparing system (1) and system (10), it can be readily obtained that $n = 4$. From (10) with (2)-(4), it is easy to see that

$$\alpha_1 = \alpha_2 = \frac{-1}{2},\ \alpha_3 = \frac{-1}{6},\ \alpha_4 = \frac{-1}{3},$$

$$\beta_1 = -2,\ \beta_2 = \frac{1}{2},\ \beta_3 = \frac{-1}{6},\ \beta_4 = \frac{1}{6},\quad \overline{\alpha} = \frac{-1}{6},\ \overline{\beta} = \frac{1}{2}.$$

Therefore, by Theorem 1, the uncertain continuous-time interval systems (10) are globally exponentially stable, in view of $\delta = \min\{\overline{\alpha}, \overline{\beta}\} = \frac{-1}{6} < 0$. Besides, from (6) and selecting $\varepsilon = \frac{1}{15}$, the guaranteed exponential convergence rate of the uncertain continuous-time interval systems (10) can be calculated as $\alpha = 0.1$. The typical state trajectories of the uncertain continuous-time interval systems (10) are shown in Figure 1 and Figure 2. As shown in Figure 1 and Figure 2, all state variable signals of uncertain continuous-time interval systems of (10) will eventually approach zero.

4. CONCLUSION

In this paper, a class of uncertain interval continuous-time dynamic systems has been studied. Combining linear algebra and time-domain analysis, a sufficient condition for a class of uncertain interval systems to achieve global exponential stability has been derived. In addition, the exponential convergence rate of the above uncertain interval systems has also been calculated in detail. At last, some computer numerical simulation results have been provided to show and verify the correctness of the main theorem.

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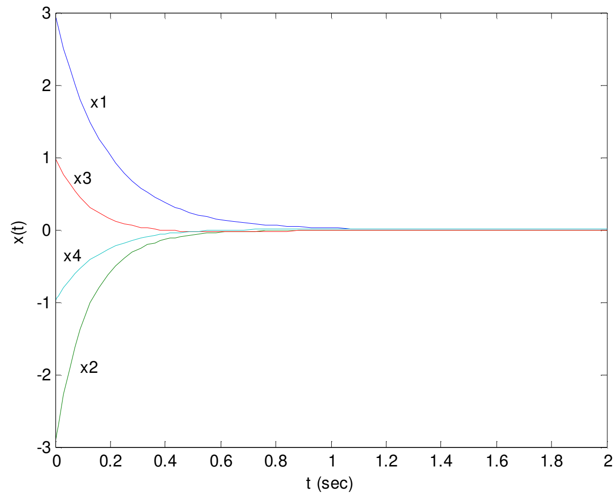

Figure 1: Typical state trajectories of the uncertain continuous-time interval systems of (10) with $x(0)=[3 \quad -3 \quad 1 \quad -1]^T$.

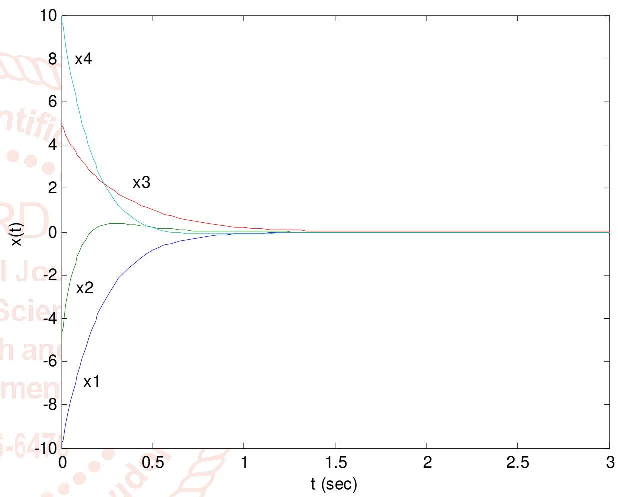

Figure 2: Typical state trajectories of the uncertain continuous-time interval systems of (10) with $x(0)=[-10 \quad -5 \quad 5 \quad 10]^T$.