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MODEL REFERENCE SHAPE ASYMPTOTIC TRACKING CONTROL FOR LINEAR SYSTEMS

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Abstract. *By employing the concept of shape variable proposed, this paper is concerned with the issue of shape asymptotic tracking for a class of linear systems, where the shape asymptotic tracking is described by using the rigid motion. Considering the uncertainties, model reference adaptive control approach is introduced into control design. Compared with the existing results, the advantage of this paper is that the shape tracking control is considered for multi-variables linear systems based on the model reference method with the general model matching condition. By the Lyapunov theory, the shape asymptotic tracking controller is synthesized, which ensures that the shape of the controlled linear system can track asymptotically the shape of the reference system, and the boundedness of all other signals in the closed-loop system is also guaranteed. Finally, a simulation example is utilized to verify the effectiveness of the proposed controller.*
Keywords: Model reference adaptive control, Linear systems, Shape variable, Shape asymptotic tracking, Rigid motion

1. **Introduction.** Shape is a geometric concept to describe the curved contour of a curve, which has been widely applied in the research of natural science and practical engineering [1–3]. In recent years, many research achievements based on shape concept have emerged in the field of intelligent transportation [4], image retrieval [5], object detection and recognition [6], remote sensing images [7], medical images [8] and so on. Utilizing the concept of shape to pedestrian detection, Suhr and Jung [4] proposed a practical backover warning system via a wide-angle rearview camera. Chuang et al. [8] presented an adaptive texture-based active shape model method for segmenting the tendon and synovial sheath. As can be seen, it is of great significance to research engineering issues by utilizing the concept of shape.

Inspired by the above observations, the shape may be also employed in control theory to describe the dynamical feature of the control system in the state space, and thus the shape of the state trajectory can be controlled to track a given goal shape. In the past decade, there were some research results to investigate the shape in control theory [9–16]. Wang and Han [10] proposed the control issue of the shape of the control system trajectory curve and the reference trajectory curve shape congruence. Then, the two-dimensional planar shape congruence control approach for a class of nonlinear systems with two-input was presented by employing the property of the signed curvature. On the basis of the differential geometry knowledge of plane curves and space curves, Huang et al. [12, 13]

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proposed the concept of shape synchronization in chaotic systems. The shape of the driven system state trajectory and the shape of the response system state trajectory complete synchronization was achieved by the presented controller, which was constructed by utilizing the property of curvature. Considering the issue of the shape control for a swarm of robots, Cheah et al. [16] developed the region-based shape controller, which can form various shapes of the desired region by selecting the appropriate objective functions. However, the issue of the shape of the control system trajectory is not considered in [16]. Meanwhile, the controllers are developed in [10,12,13] with the assumption that the system state trajectory curve is regular. However, the presented approaches are not suitable for the non-regular system state trajectory curve. Thus, how to remove the assumption that the system state trajectory curve is regular is still an open issue remaining for further research.

On the other hand, in order to improve the robustness of the developed control schemes, the uncertainties of model matching should be considered. To handle such issue, the model reference adaptive control (MRAC) has been developed, and many achievements have been reported [17–25]. On the basis of Lyapunov stability theory, Cheng et al. [19] proposed a model reference adaptive sliding mode control scheme for a class of multi-input and multi-output (MIMO) dynamic systems with model mismatch and external interference, and the state tracking of the control system was achieved. Based on the traditional model reference adaptive method, Xie et al. [21] developed the composite anti-disturbance model reference adaptive control strategy for a class of switched systems with parameter uncertainties and multiple disturbances, and the state tracking of the control system was achieved effectively. The above research achievements mainly focus on the issue of the state tracking of the control system and the reference system. However, the shape tracking the issue of the control system state trajectory and the reference system state trajectory is not considered. Thus, how to employ the model reference adaptive control method of the shape tracking control design of the control system and the reference system is an issue worth further research.

Motivated by the above discussions, this paper is to describe the similarities and differences in the shape of curves from the viewpoint of rigid body motion (rotation and translation); thus, it avoids the assumption by which the curve is regular. Then, the shape asymptotic tracking controller is developed for a class of linear systems. The main contributions of this paper are summarized as follows.

1) Utilizing the property of rigid motion, the concept of shape asymptotic tracking is proposed for the linear system based on the shape variables. Then, the model matching condition of the traditional one is extended.

2) By using the model reference adaptive method, the adaptive controller is synthesized such that the goal of shape asymptotic tracking is achieved effectively, and all signals in the closed-loop system can be ensured to be bounded.

The remaining parts of this paper are organized as follows. The problem formulation and preliminary results are provided in Section 2. The control design procedures of shape asymptotic tracking controller and stability analysis are presented in Section 3. Section 4 provides the simulation example to verify the presented results. Finally, a conclusion is given in Section 5.

2. Problem Formulation and Preliminary Results.

2.1. Problem formulation.

A class of linear system is considered as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

where $x(t) = [x_1(t), \ldots, x_n(t)]^T \in R^n$ is the system state, and $u(t) \in R^m$ denotes the control input; $A \in R^{n\times n}$ is the system matrix and $B \in R^{n\times m}$ denotes the gain matrix.

Definition 2.1. *The state variables $x_1(t)$ and $x_2(t)$ of the control system (1) are called shape variables, and its trajectory by $r(t) = [x_1(t), x_2(t)]^T$ in the phase plane is named as shape trajectory curve of the control system (1).*

Remark 2.1. *The shape variables can be regarded as the position coordinates or attitude angle of the physical system, for instance, the position coordinates of automatic guided vehicle system [26] and the attitude angle of inverted pendulum system [27].*

Consider the reference system as follows:

$$\dot{x}_r(t) = A_r x_r(t) + B_r y_r(t) \tag{2}$$

where $x_r(t) = [x_{r1}(t), \ldots, x_{rn}(t)]^T \in R^n$ is the state of reference system, and $y_r(t) \in R^m$ is the given bounded continuous input signal of the reference system; $A_r \in R^{n\times n}$ denotes the system matrix and $B_r \in R^{n\times m}$ is the gain matrix.

Definition 2.2. *The state variables $x_{r1}(t)$ and $x_{r2}(t)$ of the reference system (2) are called reference shape variables, and its trajectory by $r_r(t) = [x_{r1}(t), x_{r2}(t)]^T$ in the phase plane is named as shape trajectory curve of the reference system (2).*

Remark 2.2. *The reference shape variables can be regarded as states of actual physical reference system or the desired system's states.*

Definition 2.3. *The shape trajectory curve of the control system (1) after a rigid motion could be asymptotically congruent to the shape trajectory curve of the reference system (2), that is, $\lim_{t\to\infty} [r_r(t) - Qr(t) - p_1] = 0$, where $Q \in R^{2\times 2}$ and $p_1 \in R^2$ denote the orthogonal matrix and constant vector respectively. It means that the shape asymptotic tracking of the control system (1) and reference system (2) is achieved, and the controller is called as the shape asymptotic tracking controller.*

Remark 2.3. *The orthogonal matrix Q not only represents the case of rigid motion, i.e., $|Q| = 1$, but also includes the case of $|Q| = -1$.*

To achieve shape asymptotic tracking of the control system (1) and reference system (2), the following matrix $E \in R^{n\times n}$ and vector $P \in R^n$ are given:

$$E = \begin{bmatrix} Q & \mathrm{O}_{2\times(n-2)} \\ \mathrm{O}_{(n-2)\times 2} & I_{(n-2)} \end{bmatrix} \tag{3}$$

$$P = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} \tag{4}$$

where $Q \in R^{2\times 2}$ is the orthogonal matrix, and $I_{(n-2)} \in R^{(n-2)\times(n-2)}$ is the identity matrix; $\mathrm{O}_{2\times(n-2)} \in R^{2\times(n-2)}$ and $\mathrm{O}_{(n-2)\times 2} \in R^{(n-2)\times 2}$ denote the zero matrices; $p_1 \in R^2$ and $p_2 \in R^{n-2}$ are the constant vectors. When $n = 2$, E and P denote $E = Q \in R^{2\times 2}$ and $P = p_1 \in R^2$, respectively.

With the matrix E, vector P and Definition 2.3, it is seen that if the following equality is satisfied, the shape asymptotic tracking in Definition 2.3 can be obtained.

$$\lim_{t\to\infty} [x_r(t) - Ex(t) - P] = 0 \tag{5}$$

Remark 2.4. *From (5), it clearly shows that the shape asymptotic tracking of the shape trajectory curve of the control system (1) and reference system (2) is achieved, while the trajectory curve of the remaining states of the control system (1) and reference system (2) tend to be congruent. Further, the general asymptotic tracking is a special case of the shape asymptotic tracking, that is $\lim_{t\to\infty} [x_r(t) - x(t)] = 0$ where E and P denote identity matrix and zero vector, respectively.*

2.2. **Main results.** Considering the control system (1), let $\bar{x} = Ex + P$, and then the following auxiliary system can be obtained:

$$\begin{aligned}\dot{\bar{x}} &= E\dot{x} \\ &= E\left(Ax + Bu\right) \\ &= EA\left(E^{-1}\left(Ex + P\right) - E^{-1}P\right) + EBu \\ &= EAE^{-1}\bar{x} - EAE^{-1}P + EBu \\ &= \bar{A}\bar{x} + \bar{B}u - \bar{C}\end{aligned} \tag{6}$$

where $\bar{x}(t) = [\bar{x}_1(t), \dots, \bar{x}_n(t)]^T \in R^n$, $\bar{A} = EAE^{-1}$, $\bar{B} = EB$, $\bar{C} = EAE^{-1}P$.

Therefore, the shape asymptotic tracking in Definition 2.3 can be transformed as $\lim\limits_{t\to\infty} [x_r(t) - \bar{x}(t)] = 0$.

Definition 2.4. *Let the matrix $S = (s_{ij}) \in R^{g\times l}$ and $W = (w_{ij}) \in R^{q\times v}$, the Krionecker product of S and W [28], denoted by $S \otimes W$, is defined as the partitioned matrix $S \otimes W = \begin{pmatrix} s_{11}W & s_{12}W & \cdots & s_{1l}W \\ s_{21}W & s_{22}W & \cdots & s_{2l}W \\ \vdots & \vdots & & \vdots \\ s_{g1}W & s_{g2}W & \cdots & s_{gl}W \end{pmatrix}$ where $S \otimes W \in R^{gq\times lv}$.*

Definition 2.5. *Let the matrix $S = (s_{ij}) \in R^{g\times l}$ and vector $s_i = [s_{1i}, s_{2i}, \dots, s_{gi}]^T, i = 1, 2, \dots, l$, the vec $(\bullet)$ operator transformation constructs a vector by stacking columns of a matrix [28], that is, $vec\,(S) = [s_1, s_2, \dots, s_l]^T$.*

According to Definition 2.4 and Definition 2.5, the following property is given in [28], and the following lemma is true.

Lemma 2.1.

$$vec\,(S\Xi W) = \left(W^T \otimes S\right) vec\,(\Xi) \tag{7}$$

where $\Xi \in R^{l\times q}$.

To synthesize the control system design in Section 3, the following assumptions are presented.

Assumption 2.1. *The control signal of the reference system is bounded and continuous, and the matrix A_r is Hurwitz stable.*

Assumption 2.2. *Considering the control system (1) and reference system (2), there are existing matrix $E \in R^{n\times n}$, vector $P \in R^n$, $H \in R^m$, matrix $K^* \in R^{m\times m}$ and $F^* \in R^{m\times n}$ satisfying the following model matching condition:*

$$E^{-1}A_r - AE^{-1} = BF^* \tag{8}$$

$$E^{-1}B_r = BK^* \tag{9}$$

$$BH = AE^{-1}P \tag{10}$$

From Assumption 2.1, for any given positive definite matrix Φ, the following Lyapunov equation has a unique positive definite matrix solution Θ:

$$A_r^T\Theta + \Theta A_r = -\Phi \tag{11}$$

Remark 2.5. *With Lemma 2.1, Equations (8) and (9) can be transformed as follows:*

$$\left(A_r^T \otimes I_n - I_n \otimes A\right) vec\left(E^{-1}\right) = \left(I_n \otimes B\right) vec\left(F^*\right) \tag{12}$$

$$\left(B_r^T \otimes I_n\right) vec\left(E^{-1}\right) = \left(I_m \otimes B\right) vec\left(K^*\right) \tag{13}$$

The solutions are discussed as follows.

1) If the matrix E is given, then Equations (12) and (13) can be regarded as linear equations for $vec(F^*)$ and $vec(K^*)$; thus, the sufficient condition for solutions to (12) and (13) is shown as follows:

$$\begin{cases} rank\left[\left(A_r^T \otimes I_n - I_n \otimes A\right) vec\left(E^{-1}\right), \left(I_n \otimes B\right)\right] = rank\left(I_n \otimes B\right) \\ rank\left[\left(B_r^T \otimes I_n\right) vec\left(E^{-1}\right), \left(I_m \otimes B\right)\right] = rank\left(I_m \otimes B\right) \end{cases} \tag{14}$$

Under the above condition, F^* and K^* can be obtained by solving Equations (12) and (13).

2) If F^* and K^* are given, then Equations (12) and (13) can be regarded as the linear equation for $vec(E^{-1})$, and thus the sufficient condition for solutions to (12) and (13) is shown as follows:

$$rank\begin{bmatrix} \left(A_r^T \otimes I_n - I_n \otimes A\right) & \left(I_n \otimes B\right) vec\left(F^*\right) \\ \left(B_r^T \otimes I_n\right) & \left(I_m \otimes B\right) vec\left(K^*\right) \end{bmatrix} = rank\begin{bmatrix} \left(A_r^T \otimes I_n - I_n \otimes A\right) \\ \left(B_r^T \otimes I_n\right) \end{bmatrix} \tag{15}$$

Under the above condition, the matrix E satisfying the condition is obtained by solving Equations (12) and (13).

3) By the given adjustable vector H and matrix E, then Equation (10) can be regarded as the linear equation for P, and the sufficient condition for solutions to (10) is $rank(BH, AE^{-1}) = rank(AE^{-1})$. On this condition, P can be obtained by solving Equation (10). Particularly, $P = EA^{-1}BH$ when the matrix A is invertible.

In order to make the proposed scheme more intuitive, a block diagram of model reference shape asymptotic tracking control is presented in Figure 1.

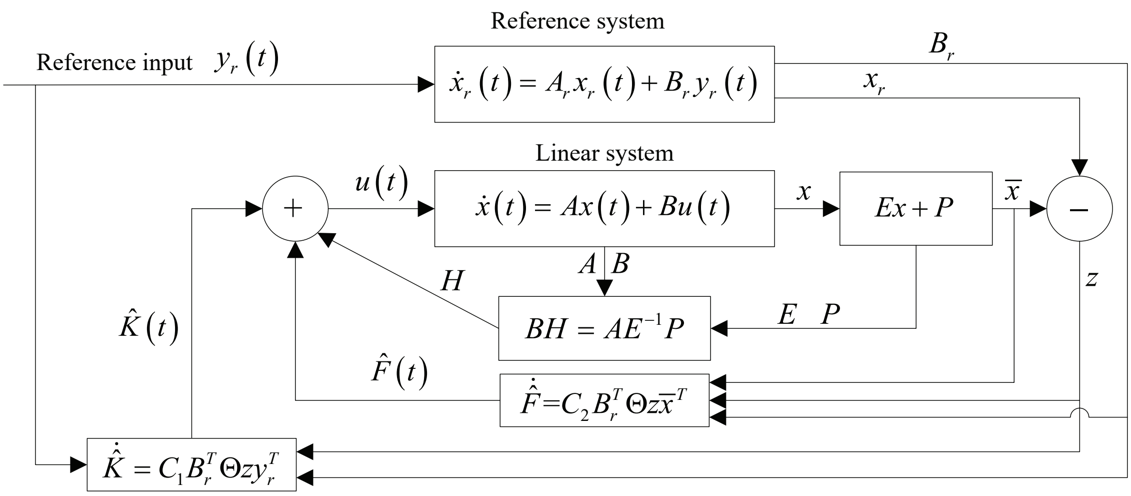

Figure 1. Diagram of model reference shape asymptotic tracking control

In Figure 1, $\hat{K} = \hat{K}(t)$ and $\hat{F} = \hat{F}(t)$ denote the estimation matrices of K^* and F^* in (8) and (9), and development procedures of adaptive laws $\dot{\hat{K}}$ and $\dot{\hat{F}}$ are presented in Section 3.

3. **Control Design and Stability Analysis.** The control objective of this paper is to synthesize the shape asymptotic tracking controller for the control system (1). With the controller, shape asymptotic tracking of the control system (1) and reference system (2) can be achieved, and all signals in the closed-loop system are ensured to be bounded.

To achieve the above control objective, the following shape asymptotic tracking controller is proposed:

$$u(t) = \hat{K}(t)y_r(t) + \hat{F}(t)\bar{x}(t) + H \tag{16}$$

where H is the adjustable vector satisfying (10). $\hat{K} = \hat{K}(t)$ and $\hat{F} = \hat{F}(t)$ are the estimation matrices of K^* and F^* in (8) and (9).

The adaptive laws are proposed as follows:

$$\dot{\hat{K}} = C_1 B_r^T \Theta z y_r^T \tag{17}$$

$$\dot{\hat{F}} = C_2 B_r^T \Theta z \bar{x}^T \tag{18}$$

where $C_1 = \Gamma_1\big((K^*)^{-1}\big)^T$, $C_2 = \Gamma_2\big((K^*)^{-1}\big)^T$. $\Gamma_1 \in R^{m\times m}$ and $\Gamma_2 \in R^{m\times m}$ are the designed adjustable positive definite matrices.

The tracking error is denoted as $z = x_r - \bar{x}$. Then, with Equations (2), (6) and (16), the following error system can be obtained:

$$\begin{aligned} \dot{z} &= \dot{x}_r - \dot{\bar{x}} \\ &= A_r z + \left(A_r - \bar{A} - \bar{B}\hat{F}\right)\bar{x} + \left(B_r - \bar{B}\hat{K}\right) y_r - \bar{B}H + \bar{C} \end{aligned} \tag{19}$$

Further, the following result can be obtained with Assumption 2.2:

$$\begin{aligned} \dot{z} &= A_r z + B_r(K^*)^{-1}\left(F^* - \hat{F}\right)\bar{x} + B_r(K^*)^{-1}\left(K^* - \hat{K}\right) y_r \\ &= A_r z + B_r(K^*)^{-1}\tilde{F}\bar{x} + B_r(K^*)^{-1}\tilde{K} y_r \end{aligned} \tag{20}$$

where $\tilde{K}$ and $\tilde{F}$ denote the estimation errors of $\tilde{K} = K^* - \hat{K}$ and $\tilde{F} = F^* - \hat{F}$, respectively.

Theorem 3.1. *Consider the control system (1) and the reference system (2), if Assumptions 2.1 and 2.2 are satisfied, the shape asymptotic tracking controller (16) with the adaptive update laws (17) and (18) can ensure that the shape of the control system (1) tracks asymptotically the shape of the reference system (2), and all other signals in the closed-loop system are bounded.*

Proof: Consider the following Lyapunov function candidate:

$$V = \frac{1}{2}\left[z^T\Theta z + tr\left(\tilde{K}^T\Gamma_1^{-1}\tilde{K}\right) + tr\left(\tilde{F}^T\Gamma_2^{-1}\tilde{F}\right)\right] \tag{21}$$

The time derivative of V is given by:

$$\dot{V} = \frac{1}{2}\left[\dot{z}^T\Theta z + z^T\Theta\dot{z} + tr\left(\dot{\tilde{K}}^T\Gamma_1^{-1}\tilde{K} + \tilde{K}^T\Gamma_1^{-1}\dot{\tilde{K}}\right) + tr\left(\dot{\tilde{F}}^T\Gamma_2^{-1}\tilde{F} + \tilde{F}^T\Gamma_2^{-1}\dot{\tilde{F}}\right)\right] \tag{22}$$

Substituting (19) into (22) yields:

$$\begin{aligned} \dot{V} &= \frac{1}{2}\left[z^T\left(A_r\Theta + \Theta A_r\right)z\right] + z^T\Theta B_r(K^*)^{-1}\tilde{F}\bar{x} + z^T\Theta B_r(K^*)^{-1}\tilde{K}y_r \\ &\quad + \frac{1}{2}tr\left(\dot{\tilde{K}}^T\Gamma_1^{-1}\tilde{K} + \tilde{K}^T\Gamma_1^{-1}\dot{\tilde{K}}\right) + \frac{1}{2}tr\left(\dot{\tilde{F}}^T\Gamma_2^{-1}\tilde{F} + \tilde{F}^T\Gamma_2^{-1}\dot{\tilde{F}}\right) \\ &= \frac{1}{2}\left[z^T\left(A_r\Theta + \Theta A_r\right)z\right] + tr\left[\left(y_r z^T\Theta B_r(K^*)^{-1} - \dot{\hat{K}}^T\Gamma_1^{-1}\right)\tilde{K}\right] \\ &\quad + tr\left[\left(\bar{x}z^T\Theta B_r(K^*)^{-1} - \dot{\hat{F}}^T\Gamma_1^{-1}\right)\tilde{F}\right] \end{aligned} \tag{23}$$

Substituting (17) and (18) into (23), it follows that:

$$\dot{V} = -\frac{1}{2}z^T\Phi z \tag{24}$$

The result (24) shows that closed-loop system is stable. Thus, $z(t)$, $\hat{K}(t)$ and $\hat{F}(t)$ are bounded. The boundedness of the state vector x_r can be obtained from Assumption 2.1. Then, the state vector x can be bounded, and the boundedness of the control signal u

can be obtained from (16). Hence, the boundedness of all signals in the closed-loop is guaranteed. From (19), this further implies that $\dot{z}$ is bounded. According to the Barbalat Lemma [29], $\lim_{t\to\infty} z(t) = 0$ can be obtained. Theorem 3.1 is established.

4. **Simulation Study.** In this section, a numerical example is presented to show the effectiveness of the proposed controller. The Matlab software is used for simulation. The matrices A, B, A_r, B_r and the vector H are generated randomly by the Matlab program, where the vector H satisfies Assumption 2.2. Then, reference system input is chosen as $y_r = \begin{bmatrix} a\sin(t) & b\cos(t) & c\sin(t) \end{bmatrix}^T$, where the parameters a, b and c are generated randomly in Matlab.

According to method 1) in Remark 2.5, the procedures of solving matrices K^* and F^* are shown as follows.

(I) Giving the matrix E, generate matrices A, B, A_r, B_r and the vector H randomly. Then, utilize Equation (14) to determine whether Equations (12) and (13) satisfy the sufficient condition for solutions. If it is not satisfied, generate the matrices again till the sufficient condition for solutions is satisfied, else continue to (II);

(II) Utilizing the matrices A, B, A_r, B_r and the vector H, solve the matrix Equations (12) and (13), and then obtain the matrices K^* and F^*;

(III) With the vector H and matrix E, determine whether Equation (10) satisfies the sufficient condition for solutions. If it is not satisfied, return to (I), else solve Equation (10) to obtain the vector P.

Simulation results are shown in Figures 2-6, where Figure 2 shows the shape trajectory curve of the control system and the reference system, Figure 3 shows the trajectory of tracking error, Figure 4 shows the trajectory of control signals, Figure 5 and Figure 6 show the trajectories of adaptive control signals.

From Figure 2 and Figure 3, it clearly shows that the shape trajectory curves of the control system and the reference system are asymptotically congruent, while the position is different. It means that the shape trajectory curves of the control system and the shape trajectory curves of the reference system can achieve asymptotic congruence through a suitable rigid motion, namely, shape asymptotic tracking of the control system and the reference system is achieved. Then, from Figure 4 to Figure 6, it shows that control signals and adaptive laws are bounded. The above simulation results show that the

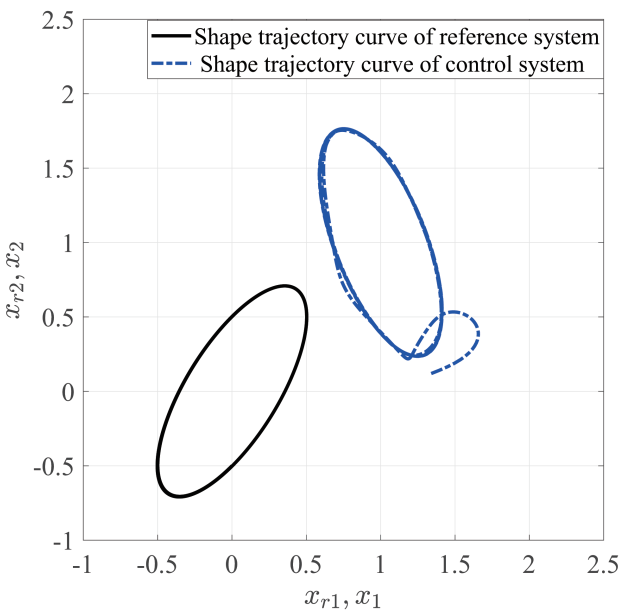

FIGURE 2. System state phase curve

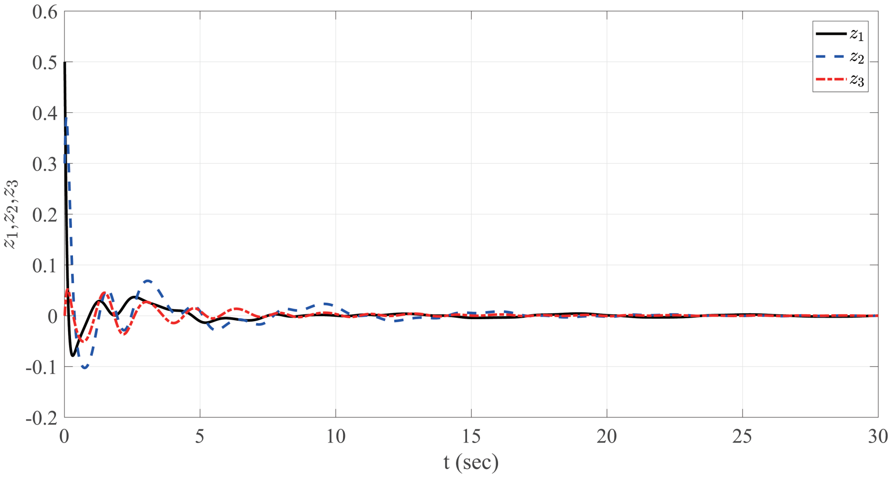

FIGURE 3. Shape tracking error time response curve

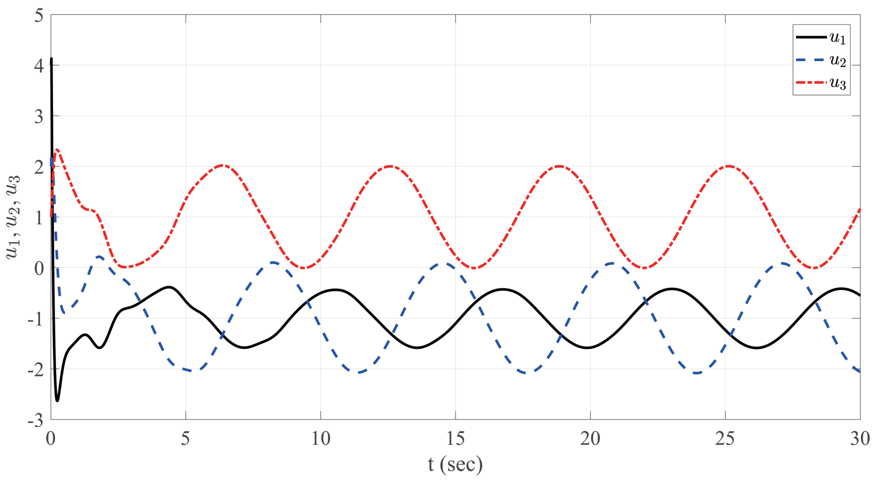

FIGURE 4. Control signal time response curve

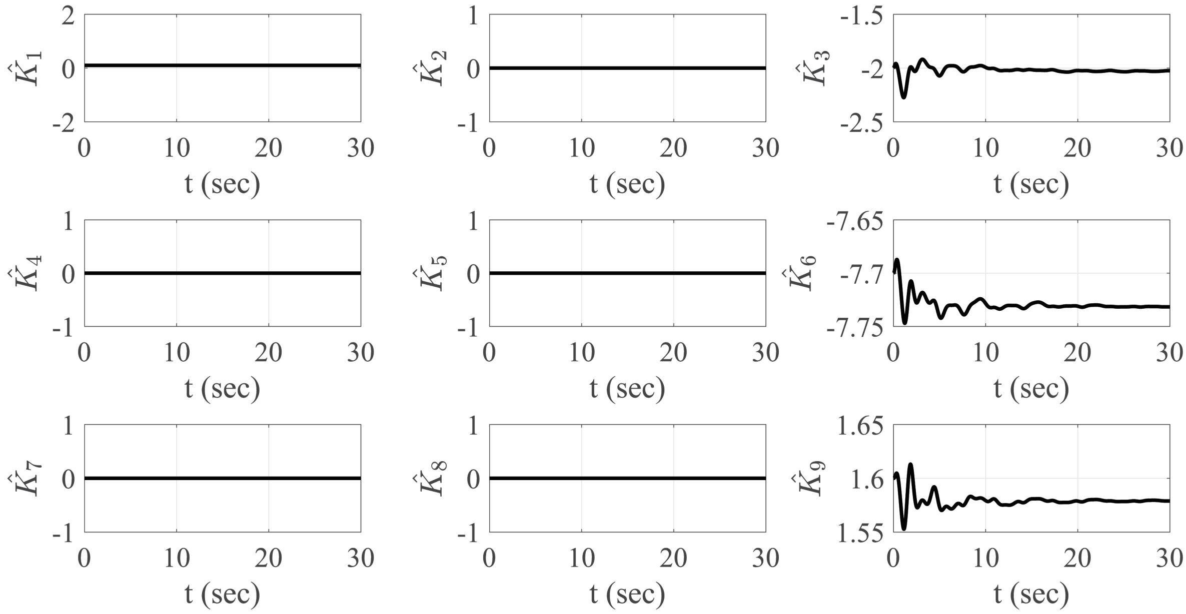

FIGURE 5. Adaptive law $\hat{K}$ time response curve

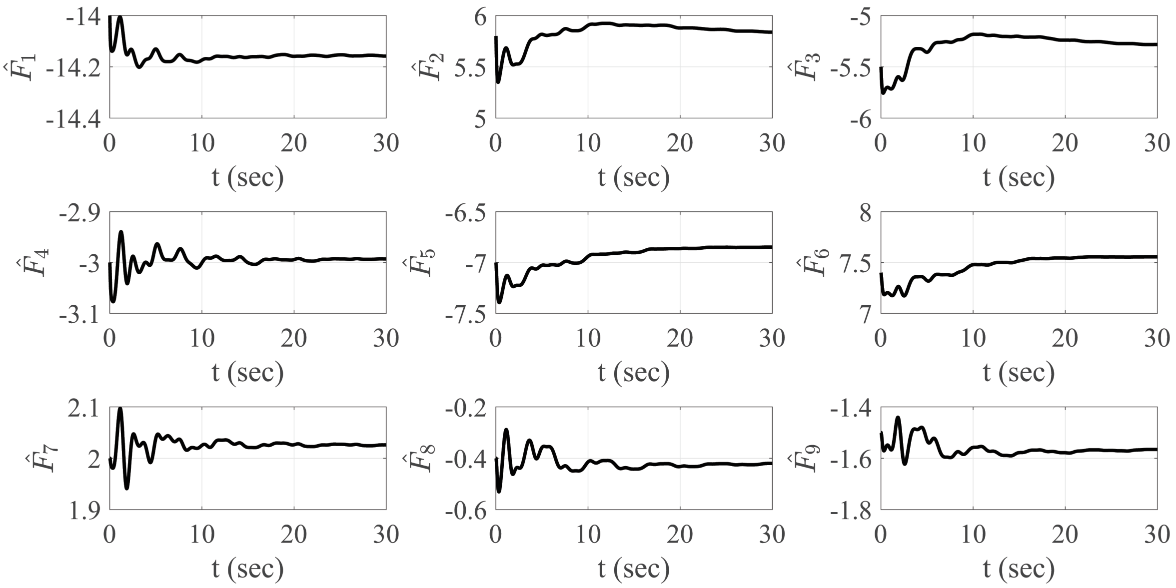

Figure 6. Adaptive law $\hat{F}$ time response curve

proposed shape asymptotic tracking controller can achieve shape asymptotic tracking of the shape trajectory curves of the control system and the reference system effectively.

5. Conclusions.

In this paper, the model reference based shape asymptotic tracking has been researched for a class of linear system. The results show that the shape asymptotic tracking controller can effectively achieve the shape asymptotic tracking of the control system and the reference system under a suitable model matching condition. Simultaneously, all other signals in the closed-loop system can be guaranteed bounded. Consider most nonlinear system can be approximated as linear systems; thus, the developed results are also effective for nonlinear system. It is worth noting that the traditional control approaches are not suitable for shape asymptotic tracking control of linear systems, which will be a new research topic.

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