

AIRSHIP ATTITUDE TRACKING SYSTEM *

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Abstract: The attitude tracking control problem for an airship with parameter uncertainties and external disturbances was considered in this paper. The mathematical model of the airship attitude is a multi-input/multi-output uncertain nonlinear system. Based on the characteristics of this system, a design method of robust output tracking controllers was adopted based on the upper-bounds of the uncertainties. Using the input/output feedback linearization approach and Liapunov method, a control law was designed, which guarantees that the system output exponentially tracks the given desired output. The controller is easy to compute and complement. Simulation results show that, in the closed-loop system, precise attitude control is accomplished in spite of the uncertainties and external disturbances in the system.

Key words: airship; uncertain nonlinear system; feedback linearization; simulation

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Introduction

The airship attitude control system is a subsystem of airship control system and is the important precondition for the airship's stable running. In the practical situation, some parameters of the airship are not known exactly. Moreover, while the airship runs, several disturbances torques such as the wind field and the buoyancy inevitably act on the airship. All these elements constitute the uncertainties of the airship attitude system. The existence of the uncertainties makes the airship's stable running, precise guiding difficult. Therefore, it is significant to study the robust control problem of the airship attitude tracking system. In this paper, the mathematical model of the airship attitude was established. Applying input/output feedback linearization and Liapunov method, the tracking controller for the airship attitude nonlinear system was designed in the presence of parameter variations and external disturbances. The proposed control law compensates for the uncertainties and guarantees the exponential convergence of the output tracking error.

1 Mathematical Model of Airship Attitude

From the 6DOF dynamic model of the airship in Refs.[1,2], we can get the mathematical model of the airship attitude as follows:

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$$\begin{aligned}
\begin{bmatrix} \dot{\vartheta} \\ \dot{\psi} \\ \dot{\phi} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} &= \begin{bmatrix} -r \sin \phi + q \cos \phi \\ \frac{1}{\cos \vartheta} (r \cos \phi + q \sin \phi) \\ p + \tan \vartheta (r \cos \phi + q \sin \phi) \\ \frac{I_{xz}^2 - I_z(I_y - I_z)}{-I_x I_z + I_{xz}^2} r q - \frac{I_{xz}(I_x + I_z - I_y)}{-I_x I_z + I_{xz}^2} p q + \frac{I_z}{-I_x I_z + I_{xz}^2} Z_G G_a \cos \vartheta \sin \phi \\ \frac{I_z - I_x}{I_y} r p - \frac{I_{xz}}{I_y} (p^2 - r^2) - \frac{1}{I_y} Z_G G_a \sin \vartheta \\ \frac{I_{xz}(I_x - I_y + I_z)}{-I_x I_z + I_{xz}^2} r q + \frac{-I_{xz}^2 - I_x(I_x - I_y)}{-I_x I_z + I_{xz}^2} p q + \frac{I_{xz}}{-I_x I_z + I_{xz}^2} Z_G G_a \cos \vartheta \sin \phi \end{bmatrix} \\
&+ \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{-I_x I_z + I_{xz}^2} & 0 & 0 \\ 0 & \frac{1}{I_y} & 0 \\ 0 & 0 & \frac{1}{-I_x I_z + I_{xz}^2} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{T_{d1}}{-I_x I_z + I_{xz}^2} \\ \frac{T_{d2}}{I_y} \\ \frac{T_{d3}}{-I_x I_z + I_{xz}^2} \end{bmatrix}, \quad (1)
\end{aligned}$$

where p, q, r are angular velocities about Ox, Oy and Oz , respectively; ϑ, ψ, ϕ are pitch, yaw and roll angles, respectively; I_x, I_y, I_z are moments of inertia about Ox, Oy and Oz , respectively; I_{xz} is the product of inertia about the plane of xOz ; I_x, I_y, I_z, I_{xz} include the added mass; Z_G is the distance from the Center of Gravity to the Center of Volume in the direction of z ; G_a is the weight of the airship; T_{d1}, T_{d2}, T_{d3} are the disturbances torques; u_1, u_2, u_3 are the input control torques.

The system parameters are uncertain during the course of running. It is assumed that

$$\begin{aligned}
I_x &= I_x^* + \Delta I_x; & I_y &= I_y^* + \Delta I_y; \\
I_z &= I_z^* + \Delta I_z; & I_{xz} &= I_{xz}^* + \Delta I_{xz},
\end{aligned}$$

where $I_x^*, I_y^*, I_z^*, I_{xz}^*$ are the known nominal values of inertia; $\Delta I_x, \Delta I_y, \Delta I_z, \Delta I_{xz}$ are the uncertain parts of inertia.

Select the state variables as $\mathbf{x} = [\vartheta, \psi, \phi, p, q, r]^T$. The output as $\mathbf{y} = [y_1, y_2, y_3]^T = [\vartheta, \psi, \phi]^T$. From the mathematical model (1), we get the following state equations:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}) + \Delta \mathbf{F}(\mathbf{x}) + [\mathbf{G}(\mathbf{x}) + \Delta \mathbf{G}(\mathbf{x})]\mathbf{u}, \\ \mathbf{y} = \mathbf{h}(\mathbf{x}), \end{cases} \quad (2)$$

where

$$F(x) = \begin{bmatrix} -r \sin \phi + q \cos \phi \\ \frac{1}{\cos \vartheta} (r \cos \phi + q \sin \phi) \\ p + \tan \vartheta (r \cos \phi + q \sin \phi) \\ \frac{I_{xz}^2 - I_z^*(I_y^* - I_z^*)}{-I_x^* I_z^* + I_{xz}^{*2}} r q - \frac{I_{xz}^*(I_x^* + I_z^* - I_y^*)}{-I_x^* I_z^* + I_{xz}^{*2}} p q + \frac{I_z^*}{-I_x^* I_z^* + I_{xz}^{*2}} Z_G G_a \cos \vartheta \sin \phi \\ \frac{I_z^* - I_x^*}{I_y^*} r p - \frac{I_{xz}^*}{I_y^*} (p^2 - r^2) - \frac{1}{I_y^*} Z_G G_a \sin \vartheta \\ \frac{I_{xz}^*(I_x^* - I_y^* + I_z^*)}{-I_x^* I_z^* + I_{xz}^{*2}} r q + \frac{-I_{xz}^2 - I_x^*(I_x^* - I_y^*)}{-I_x^* I_z^* + I_{xz}^{*2}} p q + \frac{I_{xz}^*}{-I_x^* I_z^* + I_{xz}^{*2}} Z_G G_a \cos \vartheta \sin \phi \end{bmatrix},$$

$$\Delta F(x) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \left(\frac{I_{xz}^2 - I_z(I_y - I_z)}{-I_x I_z + I_{xz}^2} - \frac{I_{xz}^2 - I_z^*(I_y^* - I_z^*)}{-I_x^* I_z^* + I_{xz}^{*2}} \right) r q \\ - \left(\frac{I_{xz}(I_x + I_z - I_y)}{-I_x I_z + I_{xz}^2} - \frac{I_{xz}^*(I_x^* + I_z^* - I_y^*)}{-I_x^* I_z^* + I_{xz}^{*2}} \right) p q \\ + \left(\frac{I_z}{-I_x I_z + I_{xz}^2} - \frac{I_z^*}{-I_x^* I_z^* + I_{xz}^{*2}} \right) Z_G G_a \cos \vartheta \sin \phi + \frac{T_{d1}}{-I_x I_z + I_{xz}^2} \\ \left(\frac{I_z - I_x}{I_y} - \frac{I_z^* - I_x^*}{I_y^*} \right) r p - \left(\frac{I_{xz}}{I_y} - \frac{I_{xz}^*}{I_y^*} \right) (p^2 - r^2) - \left(\frac{1}{I_y} - \frac{1}{I_y^*} \right) Z_G G_a \sin \vartheta + \frac{T_{d2}}{I_y} \\ \left(\frac{I_{xz}(I_x - I_y + I_z)}{-I_x I_z + I_{xz}^2} - \frac{I_{xz}^*(I_x^* - I_y^* + I_z^*)}{-I_x^* I_z^* + I_{xz}^{*2}} \right) r q \\ + \left(\frac{-I_{xz}^2 - I_x(I_x - I_y)}{-I_x I_z + I_{xz}^2} - \frac{-I_{xz}^2 - I_x^*(I_x^* - I_y^*)}{-I_x^* I_z^* + I_{xz}^{*2}} \right) p q \\ + \left(\frac{I_{xz}}{-I_x I_z + I_{xz}^2} - \frac{I_{xz}^*}{-I_x^* I_z^* + I_{xz}^{*2}} \right) Z_G G_a \cos \vartheta \sin \phi + \frac{T_{d3}}{-I_x I_z + I_{xz}^2} \end{bmatrix},$$

$$\Delta G(x) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{-I_x I_z + I_{xz}^2} - \frac{1}{-I_x^* I_z^* + I_{xz}^{*2}} & 0 & 0 \\ 0 & \frac{1}{I_y} - \frac{1}{I_y^*} & 0 \\ 0 & 0 & \frac{1}{-I_x I_z + I_{xz}^2} - \frac{1}{-I_x^* I_z^* + I_{xz}^{*2}} \end{bmatrix},$$

$$G(x) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{-I_x^* I_z^* + I_{xz}^{*2}} & 0 & 0 \\ 0 & \frac{1}{I_y^*} & 0 \\ 0 & 0 & \frac{1}{-I_x^* I_z^* + I_{xz}^{*2}} \end{bmatrix}, \quad h(x) = \begin{bmatrix} \vartheta \\ \psi \\ \phi \end{bmatrix}.$$

2 Robust Controller Design

Consider a class of uncertain nonlinear systems of the following form:

$$\begin{cases} \dot{x} = f(x) + \Delta f(x) + [G(x) + \Delta G(x)]u, \\ y = h(x), \end{cases} \quad (3)$$

where $x \in R^n$ is the system state vector; $u, y \in R^m$ are system input and output vectors, respectively; $\Delta f(x)$ and $\Delta G(x)$ represent system uncertainties; $G(x) = [g_1(x), \dots, g_m(x)]$; $\Delta G(x) = [\Delta g_1(x), \dots, \Delta g_m(x)]$; $h(x) = [h_1(x), \dots, h_m(x)]^T$, $f(x)$, $\Delta f(x)$, $g_i(x)$ and $\Delta g_i(x)$ are smooth vector fields; $h_i(x)$ is a smooth scalar function.

2.1 Input/output linearization^[3,4]

The nominal system of the system (3) is described by the form:

$$\begin{cases} \dot{x} = f(x) + G(x)u, \\ y = h(x). \end{cases} \quad (4)$$

Definition 1 For the nominal system (4), if the following conditions are satisfied for all $x \in R^n$ in the neighborhood of x^0 :

- (i) $L_{g_j} L_f^{k_i} h_i(x) = 0$ for all $1 \leq i, j \leq m$ for all $k_i < r_i - 1$,
- (ii) The $m \times m$ matrix

$$B(x) = \begin{bmatrix} L_{g_1} L_f^{r_1-1} h_1(x) & \cdots & L_{g_m} L_f^{r_1-1} h_1(x) \\ L_{g_1} L_f^{r_2-1} h_2(x) & \cdots & L_{g_m} L_f^{r_2-1} h_2(x) \\ \cdots & \cdots & \cdots \\ L_{g_1} L_f^{r_m-1} h_m(x) & \cdots & L_{g_m} L_f^{r_m-1} h_m(x) \end{bmatrix}$$

is nonsingular at $x = x^0$. Then the system (4) is said to have the relative degree $r = \sum_{i=1}^m r_i$,

where r_i is the sub-relative degree of the i -th output $y_i = h_i(x)$.

For the uncertain nonlinear system (3), the following standard assumptions are introduced.

Assumption 1 The uncertainties in the system (3) satisfy the matching condition. That is, there exist two smooth functions $D(x) : R^n \rightarrow R^m$ and $E(x) : R^n \rightarrow R^{m \times m}$, such that, for all $x \in R^n$,

$$\Delta f(x) = G(x)D(x), \quad \Delta G(x) = G(x)E(x). \quad (5)$$

Assumption 2 Each element of the desired output $\mathbf{y}_d = [y_{d1}, \dots, y_{dm}]^T$ and its first $r_i (i = 1, \dots, m)$ derivatives are all bounded. That is, these exist $b_d > 0$,

$$\left\| [y_{d1}, y_{d1}^{(1)}, \dots, y_{d1}^{(r_1)}, \dots, y_{dm}, y_{dm}^{(1)}, \dots, y_{dm}^{(r_m)}] \right\| \leq b_d.$$

In this paper, it is assumed that the system (4) has the relative degree $r = n$. Then according to the differential geometry theory^[3,4], there exists a following local diffeomorphism $\mathbf{T}(\mathbf{x})$,

$$\mathbf{T}(\mathbf{x}) = \boldsymbol{\xi} = [\boldsymbol{\xi}_1, \dots, \boldsymbol{\xi}_m]^T, \quad (6)$$

where $\boldsymbol{\xi}_i = [h_i(\mathbf{x}), L_f h_i(\mathbf{x}), \dots, L_f^{r_i-1} h_i(\mathbf{x})]^T$.

Under the above-mentioned coordinate transform and the input transform $\mathbf{v} = \mathbf{A}(\mathbf{x}) + \mathbf{B}(\mathbf{x})\mathbf{u}$, the system (3) can be transformed into the following normal form:

$$\begin{cases} \dot{\boldsymbol{\xi}} = \mathbf{A}\boldsymbol{\xi} + \mathbf{B}[\mathbf{B}(\mathbf{x})\mathbf{D}(\mathbf{x}) - \mathbf{B}(\mathbf{x})\mathbf{E}(\mathbf{x})\mathbf{B}^{-1}(\mathbf{x})\mathbf{A}(\mathbf{x}) + (\mathbf{I}_m + \mathbf{B}(\mathbf{x})\mathbf{E}(\mathbf{x})\mathbf{B}^{-1}(\mathbf{x}))\mathbf{v}], \\ \mathbf{y} = \mathbf{C}\boldsymbol{\xi}, \end{cases} \quad (7)$$

where $\mathbf{A}(\mathbf{x}) = [a_1(\mathbf{x}), \dots, a_m(\mathbf{x})]^T$, $a_i(\mathbf{x}) = L_f^{r_i} h_i(\mathbf{x})$, \mathbf{I}_m is the identity matrix, $\mathbf{A} = \text{diag}\{\mathbf{A}_i\}$, $\mathbf{B} = \text{diag}\{\mathbf{B}_i\}$, $\mathbf{C} = \text{diag}\{\mathbf{C}_i\}$, $i = 1, \dots, m$.

$$\mathbf{A}_i = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}_{r_i \times r_i},$$

$$\mathbf{B}_i = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix}_{r_i \times 1}, \quad \mathbf{C}_i = [1 \quad 0 \quad \cdots \quad 0]_{1 \times r_i}.$$

It is clear that the linearizing control law of the system (4) is as follows:

$$\mathbf{u} = \mathbf{B}^{-1}(\mathbf{x})(-\mathbf{A}(\mathbf{x}) + \mathbf{v}). \quad (8)$$

2.2 Robust controller constructing^[5-8]

Conveniently, make $\mathbf{Y}_r = [y_{d1}^{(r_1)}, y_{d2}^{(r_2)}, \dots, y_{dm}^{(r_m)}]^T$ and define the error vector as $\mathbf{e} = [e_1, \dots, e_m]^T$, where $\mathbf{e}_i = [e_{i1}, \dots, e_{iri}]^T$, $i = 1, \dots, m$, and the tracking errors and their derivatives are

$$e_{i1} = y_i - y_{di}, \dots, e_{iri} = y_i^{(ri-1)} - y_{di}^{(ri-1)}. \quad (9)$$

From Eq.(8) and Eq.(9), the error equation of the system (7) is expressed as

$$\begin{aligned} \dot{\mathbf{e}} &= \mathbf{A}\mathbf{e} + \mathbf{B}[-\mathbf{Y}_r + \mathbf{B}(\mathbf{x})\mathbf{D}(\mathbf{x}) - \mathbf{B}(\mathbf{x})\mathbf{E}(\mathbf{x})\mathbf{B}^{-1}(\mathbf{x})\mathbf{A}(\mathbf{x}) \\ &\quad + (\mathbf{I}_m + \mathbf{B}(\mathbf{x})\mathbf{E}(\mathbf{x})\mathbf{B}^{-1}(\mathbf{x}))\mathbf{v}]. \end{aligned} \quad (10)$$

Since the pair (\mathbf{A}, \mathbf{B}) is controllable, there exists the feedback matrix $\mathbf{K} = \text{diag}\{\mathbf{K}_i\}$, where $\mathbf{K}_i = [k_{i1}, \dots, k_{iri}]$, $i = 1, \dots, m$, such that the latent roots of the matrix $\mathbf{A} - \mathbf{BK}$ have negative real parts.

The following assumption for the uncertainties is given.

Assumption 3 *There exist two non-negative continuous functions $\rho_1(\mathbf{x})$ and $\rho_2(\mathbf{x})$, such that, for all $\mathbf{x} \in R^n$,*

$$\|B(\mathbf{x})D(\mathbf{x}) - B(\mathbf{x})E(\mathbf{x})B^{-1}(\mathbf{x})A(\mathbf{x}) + B(\mathbf{x})E(\mathbf{x})B^{-1}(\mathbf{x})(-K\mathbf{e} + \mathbf{Y}_r)\| \leq \rho_1(\mathbf{x}), \quad (11)$$

$$\|I_m + B(\mathbf{x})E(\mathbf{x})B^{-1}(\mathbf{x})\|_{i_\infty} \geq \rho_2(\mathbf{x}) > 0, \quad (12)$$

where $\|\cdot\|$ denotes the two-norm in R^m , and $\|\cdot\|_{i_\infty}$ means the induced infinite norm in $R^{m \times m}$ space.

To make the system output exponentially track the desired output \mathbf{y}_d and compensate for the effect of the uncertainties on the system, the following control signal \mathbf{v} is constructed according to the respective compensation principle.

$$\mathbf{v} = \mathbf{v}_1 + \mathbf{v}_2, \quad (13a)$$

$$\mathbf{v}_1 = \mathbf{Y}_r - K\mathbf{e}, \quad (13b)$$

$$\mathbf{v}_2 = -\gamma(\mathbf{x}) \frac{B^T P \mathbf{e} \rho_1(\mathbf{x})}{\|B^T P \mathbf{e} \rho_1(\mathbf{x})\| + \varepsilon e^{-\alpha t}}, \quad (13c)$$

where $\gamma(\mathbf{x}) = \rho_1(\mathbf{x})/\rho_2(\mathbf{x})$, ε and α are given constants, with $\varepsilon > 0$ and $\alpha > 2/\lambda_{\max}(\mathbf{P})$, $\lambda_{\max}(\mathbf{P})$ is the maximum latent value of \mathbf{P} , and \mathbf{P} is a positive definite symmetric matrix, which is a solution to the following Liapunov equation:

$$(\mathbf{A} - \mathbf{BK})^T \mathbf{P} + \mathbf{P}(\mathbf{A} - \mathbf{BK}) = -2\mathbf{I}_n. \quad (14)$$

Theorem 1^[6] *If the system (3) satisfies Assumptions 1–3, then under the control laws (8) and (13), for the arbitrary initial values and the arbitrary bounded desired output \mathbf{y}_d , the system output \mathbf{y} exponentially tracks the desired output \mathbf{y}_d .*

3 System Simulations

Consider the airship attitude nonlinear system (2). The system output is $\mathbf{y} = [\vartheta, \psi, \phi]^T$. The control objective is to track the desired trajectory,

$$\mathbf{y}_d = [1 - e^{-0.372t}(\sin(0.372t) + \cos(0.372t))]\mathbf{d},$$

where $\mathbf{d} = [5, 9, 10]^T$ deg. The nonlinear system (2) can be transformed into the partially linear system in Eq.(7) via the diffeomorphism Eq.(6). It is easy to verify that the system satisfies Assumptions 1–3. Thus one can use the designed control laws (8) and (13) to simulate.

For numerical computation, the following system parameters are selected:

$$\begin{aligned} \mathbf{T}_d &= \begin{bmatrix} 200 \sin 2\pi t + T_{1rd} \\ 200 \cos 2\pi t + T_{2rd} \\ 150 \cos 2\pi t + T_{3rd} \end{bmatrix} \text{ N} \cdot \text{m}, \\ I_x &= 833.222 \text{ kg} \cdot \text{m}^2, \quad I_y = 13229.521 \text{ kg} \cdot \text{m}^2, \\ I_z &= 12856.753 \text{ kg} \cdot \text{m}^2, \quad I_{xz} = 1047.665 \text{ kg} \cdot \text{m}^2, \end{aligned}$$

where the random number $T_{ird}(i = 1, 2, 3)$ has a mean of 0 and standard deviation 10.

$$\begin{aligned} \Delta I_x &= 0.5(1 + \sin(0.1t))0.2I_x, & \Delta I_y &= 0.5(1 + \sin(0.1t))0.3I_y, \\ \Delta I_z &= 0.5(1 + \sin(0.1t))0.3I_z, & \Delta I_{xz} &= 0.5(1 + \sin(0.1t))0.5I_{xz}. \end{aligned}$$

Use the proposed control law to simulate, where the control law parameters are selected as $k_{ij} = 4$ ($i = 1, 2, 3; j = 1, 2$), $\varepsilon = 0.01$ and $\alpha = 3$. Let the initial states be $[\vartheta, \psi, \phi]^T = [10, 18, -10]^T$ deg; $[p, q, r]^T = [10, 10, 10]^T$ deg/s.

The simulation results are shown in Figs.1–5. The system output trajectories are shown in Fig.1, where the desired output is displayed in the dashed lines. It is seen from these figures that the airship attitude can track the desired attitude well and the control is continuous in the presence of the parameter uncertainties and the external disturbances.

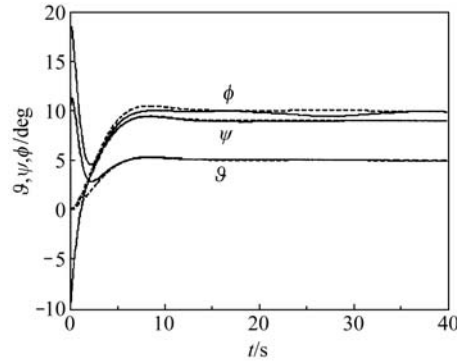


Fig.1 The attitude angle trajectory

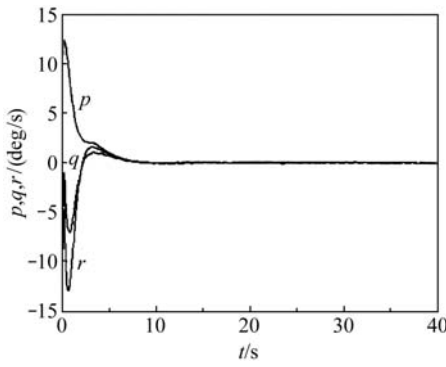


Fig.2 The attitude angular velocity trajectory

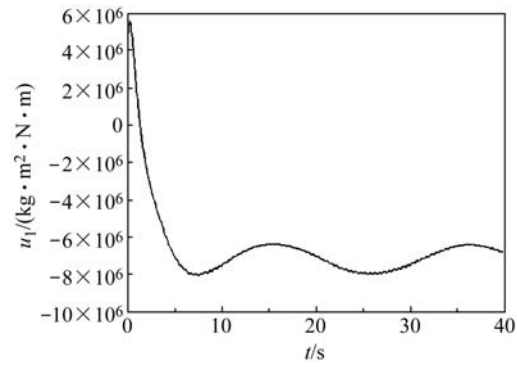


Fig.3 The control torque trajectory (u_1)

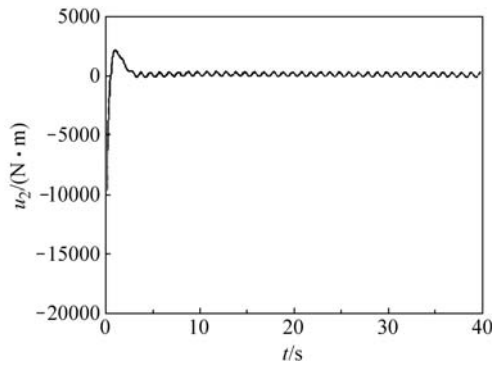


Fig.4 The control torque trajectory (u_2)

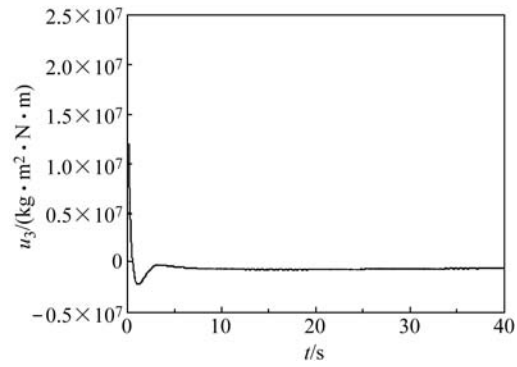


Fig.5 The control torque trajectory (u_3)

4 Conclusions

The nonlinear tracking control problem for airship attitude was studied in this paper. A controller design scheme based on the upper-bounds of uncertainties was adopted. In this control

scheme, the nonlinear system was transformed into the partially linear system first. Then the controller is designed based on Liapunov method. Under this control law, the airship attitude exponentially tracks the desired attitude in spite the existence of parameter uncertainties and the external disturbances. Simulation results show that the designed control is available and effective.

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