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Pitch Channel Control of Airship with Adaptive Sliding Mode

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Abstract

Based on the nonlinear model of airship pitch channel, a kind of sliding mode control method is designed without any prior information about airship parameters. The adaptive turning law is adopted to solve the unknown information of airship in model. So the whole information for controller can used are only the measurement of pith angle and its angle speed. Detailed simulation are done for two situations such as airship flying with big trust and small trust Numerical simulation results shows that the airship can fly smooth and safe. Especially, the controller can use the same group of parameters during all kinds of above flying conditions. So it shows that the proposed method is reasonable and effective.

Keywords: *airship, pitch channel, adaptive, sliding mode*

1. Introduction

Coming into 21th century, the value of Near-Space has aroused people's attention greatly, and Near-Space Vehicles are very concerned by people, and then the airship with many excellences becomes popular research subject in international [1-8]. Among the key technologies applied in development of the airship, the design of Auto-control system is the most important one , and the development of the airship will be a challenge mission because of its especial complexity [9-17].

Previous work in paper [1-3] discussed the model of airship and its PID control. It is easy to make a conclusion that PID control is still the most useful method until now. It has many advantages such as it is very simple and effective and trustful. But in this paper, a kind of adaptive sliding mode method is used in the design of controller for airship’s pitch channel. With the simulation analysis we found that it is also very effective. It almost has the same swiftness and robustness characters as the PID control method. And it is worth to point out that the adaptive strategy is used to solve the uncertainties of the model of airship, so it is different from PID control method. So it is also a effective method for the analysis and controller design of complex flying object. Especially, this method is more convenient than PID method to cope with high order system and uncertainties and nonlinearities.

2. Model Description

Based on the previous work, the pitch channel model of airship can be described as follows:

$$M\dot{x} = f(x) + g(x)u \tag{1}$$

And $x = [u \quad w \quad q \quad \theta \quad x \quad z]$, M satisfies:

$$M^{-1} = \begin{bmatrix} a_{11} & & a_{13} & & & \\ & a_{22} & & & & \\ a_{31} & & a_{33} & & & \\ & & & 1 & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \tag{2}$$

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The definition of a_{ij} see the definition of M in previous work.

Choose the expect value of all states u, w, q, θ, x, z are $u^d, w^d, q^d, \theta^d, x^d, z^d$, Define the error variable $e = x - x^d$, $\dot{e} = \dot{x}$, then it hold:

$$M\dot{e} = f(x) + g(x)u \tag{3}$$

Use the inverse matrix of M:

$$\dot{e} = M^{-1} f(x) + M^{-1} g(x)u \tag{4}$$

To make it convenient for reading, some functions can be written as follows:

$$f(x) = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix}, \quad g(x) = \begin{bmatrix} 0 & 1 \\ k_1 & 0 \\ k_2 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad u = [u_1 \quad u_2]^T \tag{5}$$

Where:

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix} = \begin{bmatrix} -(m+m_{33})wq + Q[C_{X1}\cos^2\alpha + C_{X2}\sin(2\alpha)\sin(\alpha/2) \\ (m+m_{11})qu + ma_z q^2 + Q[C_{z1}\cos(\alpha/2)\sin(2\alpha) + C_{z2}\sin(2\alpha) + C_{z3}\sin(\alpha)\sin(|\alpha|)] \\ -ma_z wq(-rv) + Q[C_{M1}\cos(\alpha/2)\sin(2\alpha) + C_{M2}\sin(2\alpha) + C_{M3}\sin(\alpha)\sin(|\alpha|)] - a_z \sin\theta W \\ q \\ u\cos\theta + w\sin\theta \\ -u\sin\theta + w\cos\theta \end{bmatrix}$$

Define:

$$M^{-1} f(x) = \begin{bmatrix} f_{a1} \\ f_{a2} \\ f_{a3} \\ f_{a4} \\ f_{a5} \\ f_{a6} \end{bmatrix} = \begin{bmatrix} a_{11} f_1 + a_{13} f_3 \\ a_{22} f_2 \\ a_{31} f_1 + a_{33} f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix} \tag{6}$$

And,

$$g(x)u = \begin{bmatrix} u_2 \\ k_1 u_1 \\ k_2 u_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

Then the system can be written as follows:

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{x} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} f_{a1} \\ f_{a2} \\ f_{a3} \\ f_{a4} \\ f_{a5} \\ f_{a6} \end{bmatrix} + \begin{bmatrix} a_{11}u_2 + a_{13}k_2u_1 \\ a_{22}k_1u_1 \\ a_{31}u_2 + a_{33}k_2u_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

3. Adaptive Sliding Mode Control of Attitude

Assume the velocity of airship is a constant, it means that the power of airship is a constant, and the control objective is to design a controller such that the pitch angle can trace a constant, without lost generality, assume the pitch angle is $\theta^d = 2/57.3$, define the sliding mode as:

$$s_1 = c_1(\theta - \theta^d) + q \tag{9}$$

And solve the derivatives of s_1:

$$\dot{s}_1 = c_1 q + \dot{q} = c_1 q + a_{31} f_1 + a_{33} f_3 + a_{31} u_2 + a_{33} k_2 u_1 \tag{10}$$

Consider the separation design method and use u_1 to control the height of airship and use u_2 to control the flying distance of airship, then assume u_1 is a constant and design.

$$u_1 = -k_0 s_1 - \hat{k}_1 s_1 - \hat{k}_2 q - \hat{k}_3 - \hat{k}_4 u_2 \tag{11}$$

Then,

$$\dot{s}_1 = c_1 q + a_{31} f_1 + a_{33} f_3 + a_{31} u_2 + a_{33} k_2 (-\hat{k}_1 s_1 - \hat{k}_2 q - \hat{k}_3 - \hat{k}_4 u_2) \tag{12}$$

And arrange it as:

$$\begin{aligned} \dot{s}_1 = & -a_1 s_1 + (c_1 - a_{33} k_2 \hat{k}_2) q + (a_{31} f_1 + a_{33} f_3 - a_{33} k_2 \hat{k}_3) \\ & + (a_{31} - a_{33} k_2 \hat{k}_4) u_2 + (a_1 - a_{33} k_2 k_0 - a_{33} k_2 \hat{k}_1) s_1 \end{aligned} \tag{13}$$

Define:

$$c_1 - a_{33} k_2 \hat{k}_2 = \tilde{k}_2 \tag{14}$$

Then,

$$\dot{\tilde{k}}_2 = -a_{33} k_2 \dot{\hat{k}}_2 \tag{15}$$

Also define:

$$\tilde{k}_3 = a_{31} f_1 + a_{33} f_3 - a_{33} k_2 \hat{k}_3 \tag{16}$$

Where,

$$k_{3a} = (a_{31} f_1 + a_{33} f_3)' \tag{17}$$

And define:

$$\tilde{k}_4 = a_{31} - a_{33} k_2 \hat{k}_4 \tag{18}$$

Also define:

$$\tilde{k}_1 = a_1 - a_{33} k_2 k_0 - a_{33} k_2 \hat{k}_1 \tag{19}$$

And arrange the sliding mode as:

$$\dot{s}_1 = -a_1 s_1 + \tilde{k}_2 q + \tilde{k}_3 + \tilde{k}_4 u_2 + \tilde{k}_1 s_1 \tag{20}$$

Design the turning law of adaptive parameter,

$$\dot{\hat{k}}_1 = \Gamma_1 s_1 s_1 \tag{21}$$

Also design the turning law of adaptive parameter estimation.

$$\dot{\hat{k}}_4 = \Gamma_4 u_2 s_1 \tag{22}$$

And design the estimation value as:

$$\dot{\hat{k}}_2 = \Gamma_2 s_1 q \tag{23}$$

At last, design turning law for $\hat{k}_3$.

$$\dot{\hat{k}}_3 = \Gamma_3 s_1 \tag{24}$$

Choose the whole Lyapunov function as:

$$V_a = \frac{1}{2} s_1^2 + \sum_{i=1}^{4} \left[\frac{1}{2 \Gamma_i a_{33} k_2} (\tilde{k}_i)^2 \right] \tag{25}$$

And solve its derivatives as:

$$\dot{V}_a = -a_1 s_1^2 + \frac{1}{\Gamma_3 a_{33} k_2} \tilde{k}_3 k_{3a} \tag{26}$$

Where:

$$\tilde{k}_3 = a_{31} f_1 + a_{33} f_3 - a_{33} k_2 \hat{k}_3 \tag{27}$$

Then the system can be stable with the assumption that the control parameter a_1 is big enough. So consider given interval $|x| < d$ around state x, since $|k_{3a}|$ is bounded , then there exists a a_1 big enough that makes the derivatives of Lyapunov function is small than zero. It also means that the system can be stable.

4. Numerical Simulation

Now the numerical simulation is done to show the rightness of above design. To make the velocity to be a constant, design a velocity controller first. To make it simple and also without infect the real control effect, we can assume the power of airship to be a constant, so we design $u_2 = 5000$, now the velocity of airship is about $20m/s$. And if we choose $u_2 = 10000$, the velocity of airship can be $30m/s$ around. The simulation result is as follows.

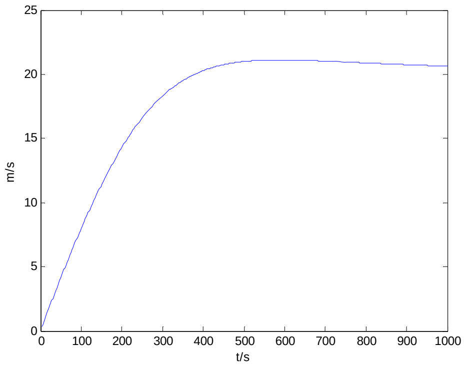

Figure 1. Forward Velocity

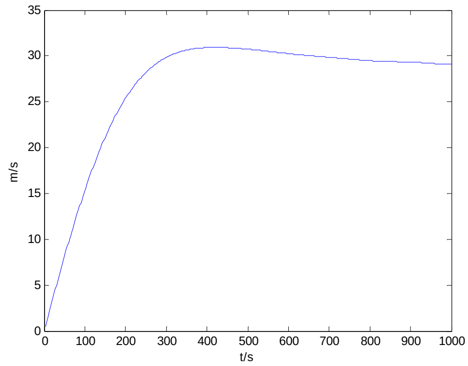

Figure 2. Forward Velocity

Base on the assumption that the forward speed of air can be a stable constant, the tracing controller of a given pitch angle of airship can be designed as follows. The control effect of given pitch angle $\theta^d = 2/57.3$ and $\theta^d = -10/57.3$ is given as follow figures, where the control parameters is designed as follows: $c1 = 1$, $k_0 = 0.3$, $\Gamma_1 = 0.001$, $\Gamma_2 = 0.005$, $\Gamma_3 = 0.002$, $\theta^d = 2/57.3$.

So the conclusion can be made according to the above curves. The airship can climb from 0 m to 1700m in 2000 s with a given pitch angle 2 degree. And the curve of actuator is smooth and the pitch angle only has one overshoot without chatters.

Considering increasing the power and the forward speed to verify the effectiveness of the pitch angle controller, choose $u_2 = 10000$, assume the initial height is 1, and the expected pitch angle is 20 degree, the control parameter is keep the same as above, the simulation result is show as below figures.

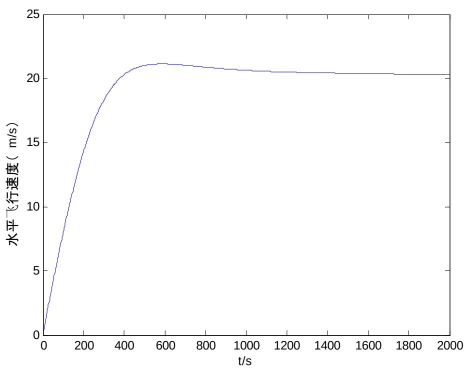

Figure 3. Forward Velocity

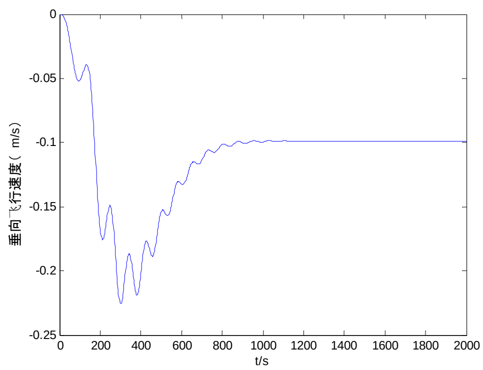

Figure 4. Vertical Velocity

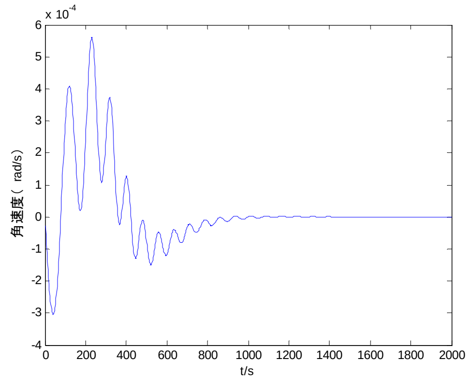

Figure 5. Angle Velocity

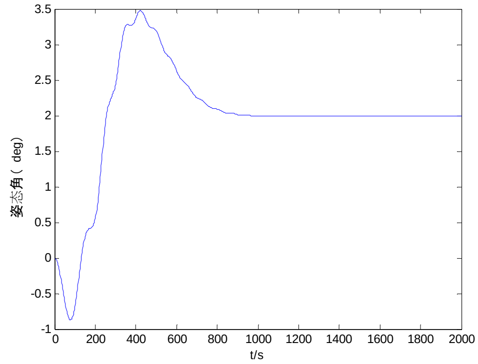

Figure 6. Pitch Angle

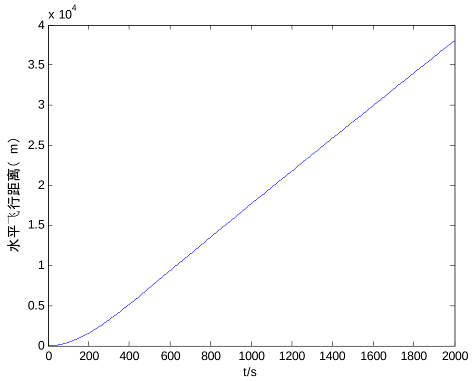

Figure 7. Flying Distance

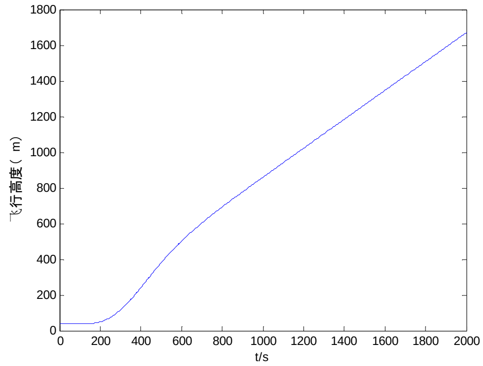

Figure 8. Height

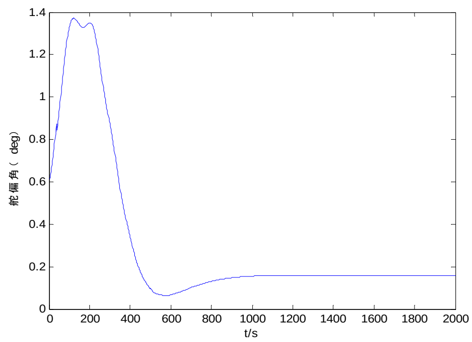

Figure 9. Actuator Angle

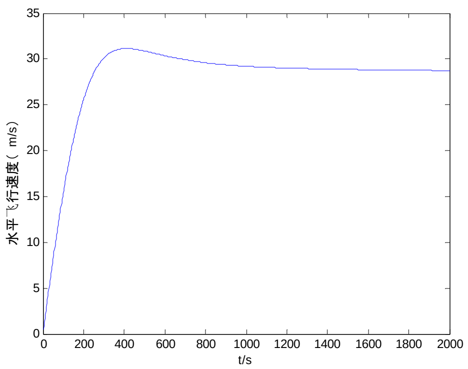

Figure 10. Forward Velocity

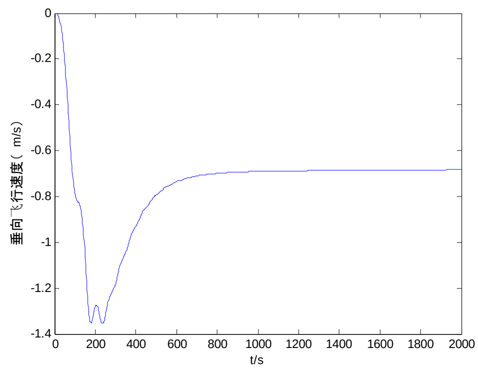

Figure 11. Vertical Velocity

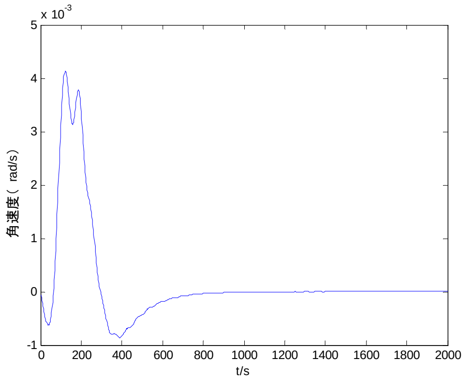

Figure 12. Angle Velocity

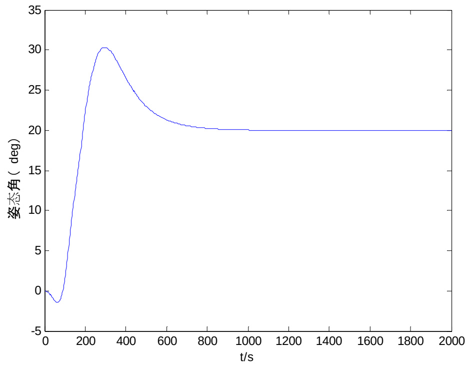

Figure 13. Pitch Angle

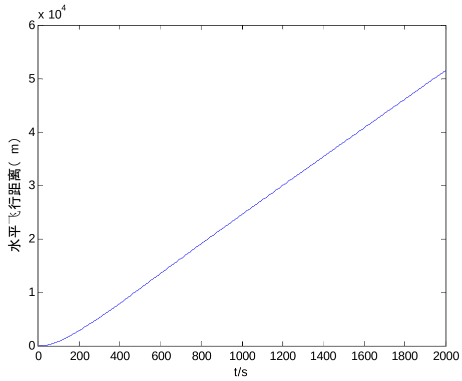

Figure 14. Flying Distance

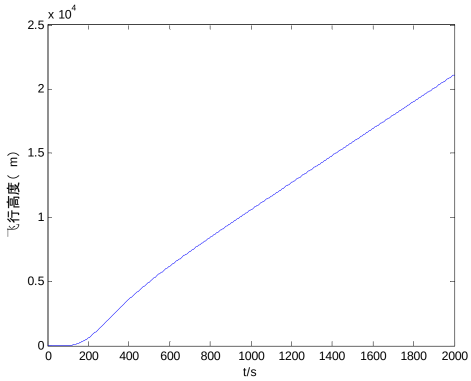

Figure 15. Height

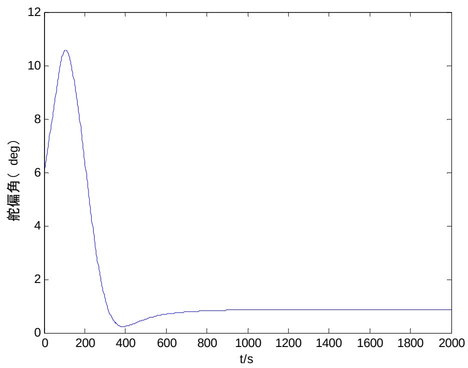

Figure 16. Actuator Angle

We can find that the forward speed of airship is still stable and it is about $27m/s$, and the airship can also fly with a smooth response with a big pitch angle, where the max actuator angle is small than 11 degree. Also the climbing speed is increased and the it can reach 21000m height in 2000s.

5. Conclusion

Considering the above two situations that flying ship flies with big trust and small trust, all the controller parameters can be keep the same without any turning. And all flying processes are very smooth and safe, so the whole control effect is satisfactory. It testifies that the method proposed in this paper is effective for airship pitch channel control.

What is worthy pointing out is that the whole controller only used the pitch angle and its speed without any other special information about the airship structure or parameters. So it means that the adaptive method is effective to cope the unknown functions in the whole airship models. And the controller parameters are not necessary to change during different flying condition. It means that the propose adaptive sliding mode control method is reasonable for airship control.

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