Disturbance-Observer-Based Sliding-Mode Attitude Control of Rotation-Isolating Rudder with Ultrasonic Motor

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Abstract. Rotation-isolating rudder is a type of correction mechanism widely used in two-dimensional trajectory correction projectile. In this paper, we focus on its attitude servo system, develop a disturbance-observer-based sliding-mode control method, and prove the asymptotic stability of the control method. Based on the single-axis turntable established, we test the rolling attitude control performance of the rotation-isolating rudder, and the experimental result shows the effectiveness of the control method developed.

1. Introduction

Trajectory correction projectile is a sort of simple guided ammunition. During the flight, the actual trajectory and the ideal trajectory are compared, and the error of the comparison is used to generate the command to control the correction mechanism to perform the corresponding action, which produces the correction force to change its trajectory[1,2].

Rotation-isolating rudder is a typical type of correction mechanism. When it works, the rotation motion of the rudder is isolated from the spin motion of the projectile, and the rolling attitude of the rudder is controlled by the servo, which changes the aerodynamic force of the correction projectile, so as to correct its trajectory. At present, in the related research of the servo equipped with the rotation-isolating rudder, the permanent magnet synchronous motor is mainly used as the executive motor[3,4]. However, the rotor of that kind of motor has large inertia, long response time and needs to be used with reducer under heavy load, which makes it difficult to achieve high position control performance in the projectile with limited space.

Traveling-wave rotary ultrasonic motor (hereinafter referred to as ultrasonic motor) is a new type of micro-motor, which uses the inverse piezoelectric effect of piezoelectric materials to stimulate the slight vibration of the elastomer in ultrasonic frequencies, and converts the vibration into the rotational motion of the rotor through the friction between the stator and the rotor, thereby driving the load. This kind of motor has the advantages of small size, fast response, high control accuracy, good electromagnetic compatibility and can run at low speed and high torque without reducer, so it can be considered as the executive motor of the rotation-isolating rudder to overcome the shortcomings of permanent magnet synchronous motor. However, the current research largely focuses on the mechanical properties and structural design[5-7], and less attention is paid to the attitude control technique of the rotation-isolating rudder based on ultrasonic motor, which is the key step to realize the trajectory correction function. Therefore, it is necessary to conduct research on this aspect, providing technical support for the design and application of the correction mechanism based on similar principles.
2. Dynamic mathematical model of the servo system

The rotation-isolating rudder studied in this paper is mainly equipped with individual anti-tank rocket projectile, and its overall layout is shown in figure 1. The rotation-isolating rudder is installed at the tail of the rocket projectile, and can rotate around the longitudinal axis of the projectile driven by the ultrasonic motor.

![Figure 1. Individual anti-tank rocket projectile](image1)

In order to control the motion of the rotation-isolating rudder with respect to the inertial space, the overall structure of servo system is designed, which is shown in figure 2. Motor driver, ultrasonic motor and rotation-isolating rudder constitute the drive system.

When the servo system works normally, in each control period, the servo controller receives the latest roll angle $\gamma$ of the rotation-isolating rudder from the attitude sensor, calculates the latest motor angular velocity $\omega$ through the output signal of the photoelectric encoder, and combines these information with the command signal $\gamma_d$ from the projectile computer as input. Based on the control method, the control input $u$ required by the motor driver in next control period is updated, and the control input $u$ is amplified by the motor driver to adjust the motor angular velocity $\omega$, so as to drive the rotation-isolating rudder to overcome the disturbance of the spin angular velocity $\omega'$ of the rocket projectile and track the command signal $\gamma_d$ swiftly.

Since the ultrasonic motor contains nonlinear and dispersive processes such as piezoelectric energy conversion and friction transfer, the obtained model, whether theoretical model or equivalent circuit, is not convenient for the actual servo control. Therefore, in this paper, drive system is regarded as a black box, the input and output of which can be measured in the open loop situation. By using the technique of system identification, the dynamic mathematical model of the whole servo system is obtained

\[
\begin{align*}
\frac{d\gamma}{dt} &= \omega + \omega' \\
\frac{d\omega}{dt} &= \alpha \\
\frac{d\alpha}{dt} &= -pw - q\alpha + ru + f(\alpha)u + g(t)
\end{align*}
\]

(1)

where $\alpha$ is motor angular acceleration, parameters $p = 15600$, $q = 397.4$, $r = 1.06 \times 10^4$, $f(\alpha) = 177.6\alpha$, and $g(t)$ represents the model uncertainty caused by time variation.

For the convenience of the subsequent design of control method, we define the state of the servo system $x = [x_1, x_2, x_3]^T = [\gamma, \omega, \alpha]^T$, the mismatched disturbance $d_1(t) = \omega'$ and the matched disturbance $d_2(t) = f(\alpha)u + g(t)$, then the mathematical model of the whole servo system can be rewritten as

\[
\begin{align*}
\dot{x}_1 &= x_2 + d_1(t) \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= -px_2 - qx_3 + ru + d_2(t)
\end{align*}
\]

(2)
In the servo system, the roll angle of the rotation-isolating rudder can be measured by the attitude sensor, and motor angular velocity can be calculated by the output waveform of the photoelectric encoder. However, no sensor is used to measure motor angular acceleration. Therefore, state $x_1$ and $x_2$ are measurable, but state $x_3$ is unmeasurable.

3. Disturbance-observer-based sliding-mode control method

3.1. Observer design

To estimate the mismatched disturbance $d_i(t)$ in the mathematical model, high gain observer 1 is designed

$$\begin{align*}
\dot{x}_1 &= \hat{x}_2 + \hat{d}_i(t) + h_{11}(x_1 - \hat{x}_1) \\
\dot{x}_2 &= h_{12}(x_1 - \hat{x}_1)
\end{align*}$$

where $\hat{x}_1$ and $\hat{d}_i(t)$ are estimation of roll angle of the rotation-isolating rudder and spin angular velocity of the rocket projectile, respectively, and parameters $h_{11} = \frac{a_{11}}{e_1}$, $h_{12} = \frac{a_{12}}{e_1}$.

When $e_1$ is small enough, the state equation of the estimation error of observer 1 can be written as

$$\begin{align*}
\dot{\hat{x}}_1 &= -h_{11}\hat{x}_1 + \hat{x}_2 \\
\dot{\hat{d}}_i(t) &= -h_{12}\hat{x}_1
\end{align*}$$

where the estimation error $\hat{x}_1 = x_1 - \hat{x}_1$ and $\hat{d}_i(t) = d_i(t) - \hat{d}_i(t)$. To ensure the asymptotic stability of observer 1, the real part of all roots of characteristic equation $s^2 + \alpha_{11} s + \alpha_{12} = 0$ must be less than zero[8].

To estimate the unmeasurable state $x_3$ and the matched disturbance $d_2(t)$, high gain observer 2 is designed

$$\begin{align*}
\dot{x}_3 &= \hat{x}_2 + h_{21}(x_2 - \hat{x}_2) \\
\dot{\hat{x}}_3 &= -p\hat{x}_2 - q\hat{x}_3 + ru + \hat{d}_2(t) + h_{22}(x_2 - \hat{x}_2) \\
\dot{\hat{d}}_2(t) &= h_{23}(x_2 - \hat{x}_2)
\end{align*}$$

where $\hat{x}_2$, $\hat{x}_3$ and $\hat{d}_2(t)$ are estimation of motor angular velocity, motor angular acceleration and total disturbance of nonlinearity and time variation, respectively, and $h_{21} = \frac{a_{21}}{e_2}$, $h_{22} = \frac{a_{22}}{e_2}$, $h_{23} = \frac{a_{23}}{e_2}$.

When $e_2$ is small enough, the state equation of the estimation error of observer 2 can be written as

$$\begin{align*}
\dot{\hat{x}}_2 &= -h_{21}\hat{x}_2 + \hat{x}_3 \\
\dot{\hat{x}}_3 &= -h_{22}\hat{x}_2 \\
\dot{\hat{d}}_2(t) &= -h_{23}\hat{x}_2
\end{align*}$$

where the estimation error $\hat{x}_2 = x_2 - \hat{x}_2$, $\hat{x}_3 = x_3 - \hat{x}_3$ and $\hat{d}_2(t) = d_2(t) - \hat{d}_2(t)$. To ensure the asymptotic stability of observer 2, the real part of all roots of characteristic equation $s^3 + \alpha_{21}s^2 + \alpha_{22}s + \alpha_{23} = 0$ must be less than zero.

3.2. Controller design

Under the feedforward compensation of mismatched disturbance, we define the sliding-mode surface as
\[ s = c_1 e + c_2 \left[ x_2 - \dot{x}_d + \dot{d}_1(t) \right] + \dot{x}_1 - \ddot{x}_d \]  
(7)

where \( x_{id} \) is the state of command singal \( y_d \), and the error of roll angle \( e = x_1 - x_{id} \).

Combining (2), the derivative of (7) is

\[
\dot{s} = c_1 \dot{e} + c_2 \dot{x}_2 + c_2 \dot{\dot{d}}_1(t) + \dot{x}_1 - c_2 \dot{x}_{id} - \ddot{x}_{id}
\]

\[ = ru + (c_1 - p) x_2 + (c_2 - q) x_3 + c_d \dot{d}_1(t) + c_d \dot{d}_2(t) - c_1 \ddot{x}_{id} - c_2 \ddot{x}_{id} - \ddot{x}_{id} \]
(8)

The control law is designed as

\[
u = -\frac{1}{r} \left[ k \text{sgn}(s) + (c_1 - p) x_2 + (c_2 - q) \dot{x}_3 + c_d \dot{d}_1(t) + c_d \dot{d}_2(t) - c_1 \ddot{x}_{id} - c_2 \ddot{x}_{id} - \ddot{x}_{id} \right]
\]  
(9)

Consider a candidate Lyapunov function as

\[ V = \frac{1}{2} s^2 \]  
(10)

Take the switching gain \( k > \left| c_1 h_2 \ddot{x}_1 + h_2 \ddot{x}_2 + (c_2 + q) \ddot{x}_3 + c_1 \ddot{d}_1 + \ddot{d}_2 \right| \), where \( \ddot{x}_1 = \sup_{t \geq t_0} \ddot{x}_1(t) \), \( \ddot{x}_2 = \sup_{t \geq t_0} \ddot{x}_2(t) \), \( \ddot{x}_3 = \sup_{t \geq t_0} \ddot{x}_3(t) \), \( \ddot{d}_1 = \sup_{t \geq t_0} \ddot{d}_1(t) \), \( \ddot{d}_2 = \sup_{t \geq t_0} \ddot{d}_2(t) \), then when \( t > t_0 \), Combining (4), (6), (8) and (9), yields
Formula (11) indicates that after time $t_0$, under the control law designed, the sliding-mode surface defined above converges to $s = 0$ in finite time. Therefore, with the block diagram of control system shown in figure 3, the servo is able to control the rotation-isolating rudder to track the command signal asymptotically.

4. Experiment

4.1. Single-axis turntable

In order to test the roll attitude control performance of the rotation-isolating rudder, a single-axis turntable is established. This experimental platform is mainly composed of hand wheel, rotation-isolating rudder, attitude sensor, ultrasonic motor, photoelectric encoder 1, longitudinal axis of the projectile, servo controller, motor driver, slip ring and photoelectric encoder 2, as shown in figure 4. The attitude sensor is installed inside the rotation-isolating rudder, and the photoelectric encoder 1 is installed in the shell of the ultrasonic motor.

![Figure 4. Single-axis turntable](image)

The experimental platform simplifies the parts that is not related to the rotation-isolating rudder, so the rocket projectile is just represented by the longitudinal axis of the projectile. The hand wheel, the motor shell and the rotor of the slip ring are directly installed on the longitudinal axis of the projectile. The photoelectric encoder 2 is connected with the longitudinal axis of the projectile through the coupling. At the same time, the servo controller and the motor driver are also connected with the longitudinal axis of the projectile through the support plate. The rotation-isolating rudder is installed on the hollow output shaft of the ultrasonic motor and can rotate relative to the rocket projectile through the rolling bearing.

During the experiment, the hand wheel is turned to simulate the spin motion of rocket projectile. The servo controller can directly output the analog voltage as the control input of the motor driver, receive and record the roll angle of the rotation-isolating rudder collected by the attitude sensor, and calculate and record the motor speed and the spin speed of the rocket projectile through the encoder 1 and the encoder 2.
4.2. Experimental result

| $k$  | $c_1$ | $c_2$ | $\varepsilon_1$ | $\alpha_{11}$ | $\alpha_{12}$ | $\varepsilon_2$ | $\alpha_{21}$ | $\alpha_{22}$ | $\alpha_{23}$ |
|------|-------|-------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $2\times10^4$ | 250   | 25    | 0.01            | 1              | 0.35           | 0.1            | 1              | 50             | 800            |

The sinusoidal signal with offset of 0°, amplitude of 90° and period of 2s is taken as the command signal, and the controller and observer parameters are shown in table 1. The experimental data recorded in the first 10s were intercepted, the result of which is shown in figure 5.

![Figure 5. Experimental result](image)
5. Conclusion
The experimental result shows that when the disturbance-observer-based sliding-mode control method is adopted, the estimated spin speed of the rocket projectile by disturbance observer is in good agreement with its actual value. Meanwhile, in the experiment, the servo can control the rotation-isolating rudder to move periodically according to the command signal, which indicates that the servo system has achieved excellent motion control performance.

References
[1] YANG Huijuan, HUO Pengfei, HUANG Zheng. Overview of Correction Executive Mechanism on Trajectory Correction Projectile[J]. Journal of Sichuan Ordnance, 2011, 32(01): 7-9. (in Chinese)
[2] XIA Bin, ZHOU Liang. Trajectory Correction Projectile and Analysis on the Key Technologies for the Trajectory Correction Process[J]. National Defense Science & Technology, 2013, 34(03): 27-34. (in Chinese)
[3] ZHANG Dongxu. Research on the Rolling Controlled Two-dimensional Trajectory Correction Mechanism[D]. Beijing Institute of Technology, 2015. (in Chinese)
[4] CUI Yebing. Research on Rolling Control Technology of Guided Artillery Rocket’s Fixed Canard Rudder[D]. Nanjing University of Science and Technology, 2014. (in Chinese)
[5] CHEN Haipeng, YAO Junfei, HE Honglin. An Adjustable Speed System Using Ultrasonic Motor for High Spin-Stabilized Projectile[J]. Journal of Vibration, Measurement & Diagnosis, 2020, 40(01): 122-126+207. (in Chinese)
[6] YAO Junfei. Design and Test of Actuator Based on Ultrasonic Motor Braking Mechanism[D]. Nanjing University of Aeronautics and Astronautics, 2018. (in Chinese)
[7] WANG Nan. Hollow Ultrasonic Motor and Its Application in Actuator[D]. Nanjing University of Aeronautics and Astronautics, 2019. (in Chinese)
[8] Khalil H, Praly L. High-gain observers in nonlinear feedback control[J]. International Journal of Robust and Nonlinear Control, 2014, 24(6): 991-992.