Design and Signal Delay Analysis of Spinning Missile Electric Rudder Control System

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Abstract. In order to meet the requirements of ultra-small special-purpose missiles for miniaturization, high dynamic characteristics and low signal delay of the missile-mounted rudder, and to reduce the working pressure of the navigation computer control system, a digital electric rudder control system based on MCU and H-bridge integrated power drive chip was designed and implemented. The system uses the Texas Instruments C2000 high-performance MCU as the core control unit to process the single-channel rudder position feedback signal. After the fuzzy position PID algorithm calculation, the control signal is output in the form of pulse width modulation (PWM) waveform, and the rudder control is completed by the DRV8872 power drive chip. Aiming at the problem of phase delay in missile attitude control system, the reason of delay is analyzed from the perspective of system composition. The phase delay formula is derived through theoretical calculation and sine sweep test. A method based on navigation computer deviation compensation is proposed. It has been proved by experiments that the rudder control system has good dynamic response capability and has good compensation effect on system signal delay.

1. Introduction

In order to meet the requirements of ultra-small special-purpose missiles for miniaturization, high dynamic characteristics and low signal delay of the missile-mounted rudder, and to reduce the working pressure of the navigation computer control system, a digital electric rudder control system based on MCU and H-bridge integrated power drive chip was designed and implemented. The system uses the Texas Instruments C2000 high-performance MCU as the core control unit to process the single-channel rudder position feedback signal. After the fuzzy position PID algorithm calculation, the control signal is output in the form of pulse width modulation (PWM) waveform, and the rudder control is completed by the DRV8872 power drive chip. Aiming at the problem of phase delay in missile attitude control system, the reason of delay is analyzed from the perspective of system composition. The phase delay formula is derived through theoretical calculation and sine sweep test. A method based on navigation computer deviation compensation is proposed. It has been proved by experiments that the rudder control system has good dynamic response capability and has good compensation effect on system signal delay.

Since the spinning missile continues to rotate at a fixed frequency around its longitudinal axis, its pitch angle and yaw angle are coupled, which requires decoupling and phase compensation for channel decoupling. In the previous research, Luoqi Chen calculated the influence of rudder delay on the control system, using the feedforward correction method for decoupling, but this method needs to obtain relevant information such as flight speed, rotate speed and altitude [2], which is difficult in engineering application; Yanchao Bi analyzed the rudder delay characteristic in the quasi-elastic coordinate system, and the relationship between the lag angle and the corresponding phase angle [3], but didn’t propose...
compensation scheme; Jianqiao Yu determined the rudder signal delay time by the normal acceleration delay [4], but didn’t consider the case that there is delay in the input command signal.

Based on the actual engineering project of single-channel spinning missile, this paper analyses the reason of delay during the process of command transmission and execution from the perspective of the overall composition of the navigation-rudder control system. The delay time of control system is quantitatively determined by sine sweeping, hence a corresponding deviation compensation algorithm is proposed. Hardware-in-the-loop simulation test has achieved good compensation results.

2. Control system overall plan
In essence, the missile rudder is a typical position servo control system. The overall structural block diagram of the electric rudder control system is shown in Fig.1. The rudder is composed of a DC brush motor, a reduction gear set, rudder wings, an angle sensor, etc., and one motor drives two rudder wings simultaneously, which are respectively installed on the opposite sides of the missile.

![Figure 1. Rudder system overall block diagram](image)

Considering the working environment of small spinning missile, this scheme uses single channel control to reduce the volume of the rudder system. The control mode adopts a sinusoidal swing control law, and the rudder control system adopts outputs PWM waveform to control the speed of the motor. The potentiometer is used as the rudder deflection angle sensor, and the core control logic is the position closed loop feedback control based on the discrete PID algorithm.

3. Control system hardware design
The rudder control circuit realizes functions of secondary power conversion, serial bus communication, and control signal generation and amplification, and analog signal conversion. The function is realized by three modules: power supply, system control and motor drive. Chip selection and circuit design are based on miniaturization, high precision, and low power consumption principle.

The control circuit uses MCU as the core processor to realize functions of serial bus communication, command transmit-receive, rudder wings angle detection, and fuzzy PID calculation. The control module block diagram is shown in Fig.2.
As the core of the rudder control system, the processor adopts Texas Instruments high-performance MCU TMS320F28035, which features operating frequency up to 60 MHz, abundant on-chip resources, and optimized structure for real-time control. It can output up to four channels high-precision PWM simultaneously. For the miniaturized design requirements, the smallest 56-pin VQFN package (very-thin quad flat no-lead package) was selected, and the planar size was only 6.75 × 6.75mm.

The motor drive unit amplifies the power of PWM signal with the H-bridge power circuit, and controls the motor to drive the rudder shaft to rotate. In order to ensure the one-way transmission of the PWM signal from the control unit to the drive unit, and to avoid the high-frequency noise reverse coupling caused by the motor operating, a high-speed opt coupler is used for isolation between the two units.

The motor driver uses Texas Instruments single-channel H-bridge DC motor driver DRV8872. The driver implements bidirectional control of the motor through four N-channel MOSFETs with peak currents up to 3.6A. In current decay mode, the motor speed can be adjusted by inputting a pulse width modulated (PWM) waveform. When both inputs are asserted low, the DRV8872 will go into sleep mode, which helps reduce power consumption. The DRV8872 also features a current regulation function that limits the output current to a certain level, reducing power consumption and preventing motor burnout. The driver does not require a large-capacity capacitor to maintain voltage stability, which is beneficial for servos that require repeated start and stop of the motor.

4. Control system software design

The rudder control software implements functions of serial bus communication, analog to digital conversion, core control algorithm implementation, and control signal output. The main process of software work is shown in Fig.3.
RS422 serial bus communication works by interrupt receiving and polling transmission. It only enters the interrupt when the host computer command signal arrives, which avoids occupying the MCU calculation cycle repeatedly.

The AD sampling program reads the latest angle sensor signal in the buffer before each PID control is performed, ensuring the accuracy of the angle control.

The control algorithm uses discrete fuzzy PID as the core algorithm. Combined with the sinusoidal control law of the spinning missile, each sinusoidal cycle is equally divided into 60 position points, and each point is executed \( \frac{33}{n} \) (\( n \) is the rotational speed) times of discrete PID. By optimizing the algorithm structure, the adjacent PID interval time is compressed to 500\( \mu \)s, which ensures the control precision and the smoothness of the sinusoid.

5. Analysis and compensation of control signal delay

5.1. Spinning missile sinusoidal control law

The sinusoidal control law of the spinning missile uses the sinusoidal signal of the same frequency \( \omega \) as the missile spins to control the rudder wings for periodic deflection [5]. The equivalent control force generated by one rotation is used to control the attitude of the missile body, as shown in the Fig.4.

**Figure 4.** Sinusoidal control law control model

Assume that the rudder axis coincides with the z axis of the missile, the frequency of the rudder surface is \( \omega \), the amplitude is \( A \), the initial phase is \( \theta_0 \), then the rudder angle at time \( t \) is

\[
\delta(t) = A \sin(\omega t + \theta_0)
\]  

(1)

The component of the rudder angle in the quasi-elastic coordinate system satisfies

\[
\begin{bmatrix}
\delta_y \\
\delta_z
\end{bmatrix}
= \begin{bmatrix}
\cos(\omega t) & -\sin(\omega t) \\
\sin(\omega t) & \cos(\omega t)
\end{bmatrix}
\begin{bmatrix}
0 \\
1
\end{bmatrix}
= \begin{bmatrix}
-A \sin(\omega t) \\
A \cos(\omega t)
\end{bmatrix}
\]  

(2)

After a full period of deflection, the equivalent rudder bias is

\[
\bar{\delta}_y = \frac{\omega}{2\pi} \int_{0}^{2\pi/\omega} \delta_y \, dt = -0.5A \cos \theta_0
\]  

(3)

\[
\bar{\delta}_z = \frac{\omega}{2\pi} \int_{0}^{2\pi/\omega} \delta_z \, dt = 0.5A \sin \theta_0
\]  

(4)
\( \delta y \) and \( \delta z \) are the equivalent rudder deviations in the y and z directions of the quasi-elastic coordinate system, and the aerodynamic resultant force formed by the rudder bias is the equivalent control force of one period, which can be expressed as a vector form

\[
\vec{F}_{\text{sin}} = \frac{1}{2} QSC_n^\delta A \exp(-j \theta_0) \tag{5}
\]

Where Q is the dynamic pressure of the missile; S is the equivalent area of the rudder surface; \( C_n^\delta \) is the normal force coefficient of the rudder surface.

It can be concluded that the amplitude A and the initial phase \( \theta_0 \) of this sinusoidal motion respectively determine the amplitude and direction of the equivalent control force \( F_{\text{sin}} \).

The complete missile attitude control system consists of a geomagnetic sensor, a navigation computer, a rudder control computer, and an electric rudder [6]. The navigation computer calculates the steering input command signal based on the missile attitude, the predetermined trajectory and the roll angle data measured by the geomagnetic sensor, and transmits it to the rudder control computer in the form of sine wave amplitude, phase and frequency; the rudder control computer uses the position PID algorithm to calculate and generate motor control signal in the form of PWM wave at the beginning of a spinning cycle. The entire control process is shown in Fig.5.

![Figure 5. Missile attitude control process](image)

Let the total time delay generated by the attitude control process of the missile be \( t \), then the actual phase of the sinusoidal yaw in one gyro period can be expressed as \( \theta = \theta_0 + \Delta \theta \), where \( \theta_0 \) is the ideal initial phase and \( \Delta \theta \) represents the additional phase due to the signal delay, which can be expressed as \( \Delta \theta = 2\pi \omega t \). The actual equivalent control force produced by the sinusoidal swing at this time is expressed as:

\[
\vec{F}_{\text{sin}} = \frac{1}{2} QSC_n^\delta A \exp[-j(\theta_0 + \Delta \theta)] \tag{6}
\]

That is, the signal delay affects the direction of the equivalent control force, causing the actual deflection direction of the missile to deviate from origin direction.

5.2 Control signal input and response delay analysis

The geomagnetic sensor can calculate the current roll angle information of the rotating missile by measuring the relative position of the earth's magnetic field and the missile. Due to the sampling frequency of the geomagnetic sensor and the data transmission speed limit, there is a time delay \( t_1 \) from the sampling to the calculation of the rolling angle data. In this process, the missile has been rotated by an angle relative to the initial position of the measurement, so the roll angle obtained by the geomagnetic sensor lags behind the real body position.

After receiving the roll angle data of the geomagnetic sensor, the navigation computer calculates the command information of the current cycle steering yaw according to the flight track information. This
calculation process also has a hysteresis, which is recorded as \( t_2 \). The delay generated by the data communication between the navigation computer and the rudder control computer via serial bus is recorded as \( t_3 \).

After receiving the command signal from the navigation computer, the rudder control computer compares with the position of the rudder wings feedback by the potentiometer, and obtains a control signal in the form of PWM through the position PID algorithm to complete the control of the electric rudder. The signal delay generated by this process is recorded as \( t_4 \).

### 5.3. Control signal delay time calibration

The geomagnetic sensor currently used in the navigation computer has a sampling frequency of 100 Hz. When the spinning frequency is maintained between 1 and 15 Hz, the delay due to the operating of the geomagnetic sensor is about 10 ms. this delay time can be effectively reduced by increasing the sensor sampling frequency.

For the rest of the delay time \( t_2 + t_3 + t_4 \), the rudder system can be calibrated by sine sweeping. For the single-channel sinusoidal steering control system proposed in this paper, the delay calibration is performed in the full operating frequency band width at intervals of 0.5 Hz with 10° amplitude. The curve is fitted by least squares method as Fig.6.

![Figure 6. Linear fitting curve](image)

It can be calculated that in the operation frequency band width, the servo phase delay has good linearity. The rotational speed and rudder system phase delay meets the linear regression equation below:

\[
\theta' = 0.0558\pi \omega + 0.0117\pi
\]  

(7)

Because the phase delay is related to the delay time, which is \( t = \frac{\theta'}{2\pi\omega} \). The rudder system delay time at an amplitude of 10° is

\[
t_2 + t_3 + t_4 = \left(27.9 + \frac{5.85}{\omega}\right)\text{ms}
\]  

(8)

Where is the gyro frequency.

According to the above analysis, the total delay time of the missile body attitude control system is
\[ t = (10 + 27.9 + \frac{5.85}{\omega}) \text{ ms} \]  

(9)

5.4. Control signal delay advance compensation algorithm

During the low-speed (<10 Hz) spinning of the missile, the phase delay of the missile attitude control system caused by the command delay is relatively stable, and has a linear relationship only with the rotational speed of the missile. Based on this relationship, this paper proposes a control system delay deviation compensation method, that is, when the navigation computer generates the electric rudder control command, the current phase delay is calculated in combination, and the delay is compensated in the form of phase. Thereby the possible phase delay is compensated in advance, and the signal delay that exists in the control system forms an equivalent control force with an accurate direction. Through the turntable test, the effect of the deviation compensation algorithm can be visually analyzed.

6. Control system performance test

6.1. Dynamic performance test

The hardware system designed based on this scheme is shown in Fig.7. Using the rudder dynamic performance test software to analyze the performance of the rudder control system, the test report is generated as Table 1

![Figure 7. Rudder control circuit](image)

Table 1. Rudder performance test report

| Number | Test Items                      | Design specs | Measured value |
|--------|--------------------------------|--------------|----------------|
| 1      | Bandwidth f/Hz                  | 1~15         | 1~15           |
| 2      | Maximum rudder angle A/°         | \( \geq 12 \) | \( \pm 15 \)   |
| 3      | Maximum angular velocity V/°/s  | \( \geq 480 \) | 672.01         |
| 4      | Zero deviation \( \epsilon/° \) | \( \leq 0.2 \) | \( \pm 0.16 \) |
| 5      | Non-sensitive area \( \theta/° \) | \( \leq 0.2 \) | \( \pm 0.2 \)  |
| 6      | Time domain characteristics     | Rise time tr/ms | \( \leq 50 \) | 28             |
|        |                                | Overshoot \( \sigma/\% \) | \( \leq 10 \) | 7.8            |
| 7      | Frequency domain characteristics | Bandwidth BW/Hz | \( \geq 14 \) | 14             |
| 8      | Single continuous working time t/s |             | \( \geq 40 \) | 60             |

The test results show that the electric rudder control system based on this scheme meets the dynamic and static performance design indicators. In terms of characterizing the time domain characteristics of dynamic characteristics, the addition of discrete fuzzy PID algorithm significantly improves the rise time and overshoot of the system, making the design of this set of electric electric rudder control system extremely suitable for strict performance requirements of repeated start and stop, forward and reverse rotation of the motor.
6.2. Turntable test
In order to ensure the effectiveness of the rudder control test, it is necessary to carry out hardware-in-the-loop test analysis on the operating condition of the rudder control system under rotating conditions. In this test, the rudder control system is fixed on the high-speed turntable for rotation, the control command and feedback data are recorded, the cooperative control capability of the navigation-rudder control system is verified, and the working condition of the rudder control system is analyzed. Fig.8 shows the phase and speed commands received by the rudder system and the PID count and AD data during the servo execution.

The recorded data shows that the rudder system starts to execute according to the command after receiving the rudder control command. After performing 120 times of PID control, the rudder wings performs two cycles of sinusoidal motion, and the actual amplitude, initial phase and speed are all equivalent to the commands, which meets the requirements of the rudder system. At the same time, the command response delay of the attitude control system after applying the deviation compensation has been reduced to 12 ms, and the compensation algorithm is effectively verified.

7. Conclusion
Based on the concept of modular design, this paper proposes a design scheme of high-performance missile electric rudder control system. By selecting high-performance MCU, AD conversion chip and power driver chip on the hardware, using fuzzy PID intelligent control algorithm and optimizing control logic, the rudder control system perfectly meets the dynamic features demand of the small-scale rotating missile. At the same time, to solve the problem of the equivalent control force direction deviation caused by the command delay of the missile attitude control system, this paper analyzes each module from the system perspective, and obtains the delay time by quantitative calculation and sine sweep calibration. The conclusion is that there is a single proportional relationship between signal delay and the rotational speed of the missile. A signal delay compensation method based on navigation computer deviation compensation is also proposed. The research results of this paper have been tested by dynamic test, turntable test and flight test, showing good dynamic characteristics and extremely low system signal delay.
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