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Research on roll control of fixed-wing dual-spin missile correction assembly

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Abstract: Aiming at the input disturbance and model uncertainty problems of the roll channel of the correction component of the fixed-wing dual-rotating missile, a two-degree-of-freedom roll channel control method based on H-loop shaping is designed. By modeling the electrical system and mechanical system of the correction component, the calculation method of the electromagnetic control torque of the actuator is obtained. By using theoretical analysis and experimental tests, the modeling method of the aerodynamic torque and roll damping torque of the correction component is studied, so as to obtain the roll channel control model, and a two-degree-of-freedom roll channel controller based on H-loop shaping is designed to realize roll angle control. The results of semi-physical simulation experiments show that the method of establishing the roll channel control model by analyzing the electrical system and mechanical system of the correction component is feasible, and the designed roll channel controller can achieve accurate roll angle control.

Keywords: fixed wing; double-spinning missile; roll control; actuator; trajectory correction

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Roll Control of Course Correction Fuze for Dual-Spin Projectile with Fixed-Canards

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Abstract: In order to solve the input disturbance and model uncertainty problems of the roll

channel of the course correction fuze (CCF) for dual-spin projectile with fixed-canards, a two- degree-of-freedom roll channel control method based on H. loop shaping was proposed. Through the modeling of electrical and mechanical systems of the CCF, the calculation method of the electromagnetic control torque of the actuator was researched. Based on theoretical analysis and experimental test, the modeling method of the aerodynamic torque and the rolling damping torque of the CCF were studied, and then the roll channel control model was obtained. A two-degree-of- freedom roll channel controller based on H. loop shaping was designed to control the roll angle of the CCF. Hardware-in-the-loop simulation experiments show that it is feasible to establish the roll channel control model by analyzing the electrical and mechanical systems of the CCF, and the designed roll channel controller can achieve accurate roll angle control.

Key words: fixed canard; dual-spin projectile; roll control; actuator; trajectory correction

The demand for low-cost, high-precision and low-collateral-damage guided ammunition in modern warfare has promoted the development of simple conventional guided ammunition. The common method of simple guidance of conventional ammunition is to replace the conventional fuze with a correction fuze[1], and use the canard layout double-spinning bomb[3] as a simple correction fuze.

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A type of ammunition in which the correction fuze is connected to the main body of the projectile by a bearing group, which rotates around the longitudinal axis of the projectile at low speed and high speed respectively, thus providing suitable working conditions for the correction fuze and maintaining the dynamic stability of the projectile.

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The dual-rotation layout brings new problems to the dynamics and actuator design of the corrected missile. Costello et al. studied the linearization theory of the projectile of the dual-rotation missile and discussed the stability problem of the dual-rotation missile. The Franco-German Saint-Louis Institute [5-7] conducted a systematic study on the modeling, stability and guidance control of the dual-rotation missile. Xu Nuo et al. [8] analyzed the angular motion characteristics and stability of the dual-rotation missile based on the dynamic model of the fixed-wing dual-rotation missile. Xu Nuo et al. also analyzed the bifurcation characteristics of the nonlinear dynamics of the dual-rotation missile and studied the influence of system parameters on the dynamic bifurcation characteristics. Cheng Jie et al. studied the working conditions of the electromagnetic actuator of the dual-rotation missile, modeled the canard and bearings, and verified the design conditions of the electromagnetic actuator using ballistic parameters. They studied the rolling channel characteristics of the dual-rotation missile, established the dynamic model of the dual-rotation channel, and reversely estimated the model parameters through transient numerical calculation and dynamic wind tunnel tests, and conducted flight tests to verify the model prediction results. Gu Tingting et al. [12] used a method combining numerical simulation and experimental testing to establish a dynamic response model of the electromagnetic torque of the motor based on the time domain characteristics of the step response of the dual-rotation actuator. The aerodynamic torque and roll damping torque models were obtained through flight tests, and then the roll control response model of the dual-rotation missile correction component was established. As mentioned above, although there has been great progress in the research on the roll channel modeling of dual-rotation missiles at home and abroad, the key electromagnetic control torque in the model is mostly studied by the reverse analysis method of the test results. The results obtained in this way cannot fundamentally reflect the characteristics of the electromagnetic torque change. The difficulty in modeling the electromagnetic control torque from the electrical principle is that it is necessary to conduct a detailed electromagnetic analysis of the actual working conditions of the coaxial motor of the actuator. At present, previous research work has less modeling of the electrical principle of the motor of the roll channel actuator, and even less research on the relationship between the motor's ability to generate electromagnetic control torque and the flight parameters of the missile. Therefore, the established roll channel model cannot accurately reflect the actual state of the controlled object. Therefore, the designed roll channel controller is applied to the actual The system may produce control errors.

Therefore, this paper first introduces the principle of roll channel control of the correction component of the fixed-wing dual-rotation missile according to the characteristics of the fixed-wing dual-rotation missile; then, through the analysis of the torque on the correction component, especially the analysis of the electromagnetic torque generated by the motor in the generator mode, the dynamic model of the roll channel of the correction component is established; then, according to the characteristics of input disturbance and model uncertainty in the dynamic model of the roll channel, a two-degree-of-freedom H-loop shaping roll channel controller is designed, which can suppress input disturbance and have sufficient robustness to model uncertainty, and can ideally track the reference input; finally, the designed roll channel controller is experimentally verified through semi-physical simulation experiments.

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1 Roll control principle of fixed-wing dual-spin missile correction assembly

Compared with the conventional canard layout double-rotating missile, in order to reduce costs and simplify the structure, the fixed-wing double-rotating missile adopts fixed-angle rudders, as shown in Figure 1. The double-rotating missile is divided into two parts: the front body and the rear body. The front body is a low-speed rotating part with two pairs of fixed canard rudders, that is, the correction component part. The rear body is the main part of the missile body. Rudder blades 1 and 3 form a pair of differential kinetic energy, which can provide a derotating torque for the front body; rudder blades 2 and rudder blades 4 form a pair of control rudders, which are used to generate control force and control torque. When trajectory correction is not required, the front body rotates freely at a low speed in the opposite direction relative to the rear body under the action of the differential rudder, and the average effect on trajectory correction is approximately 0; when the trajectory needs to be corrected, the front body controls the roll angle according to the correction instruction under the action of the axial motor.

Rudder blade 2 (4)

Rudder piece 1

Rudder piece 1

Rudder piece 4

Rudder piece 2

precursor

posterior body

√ Rudder piece 3

Rudder piece 3

Fig. 1 Schematic diagram of actuator of dual-spin projectile

with fixed-canards

The forebody roll angle control scheme is shown in Figure 2. The onboard GPS, inertial measurement unit (IMU) and geomagnetic sensor provide the projectile's position, velocity, acceleration and attitude information to the onboard computer. The onboard computer calculates the forebody roll angle command required for trajectory correction according to the correction control algorithm, and resolves it into a command sequence and sends it to the correction mechanism control board. The Hall sensor used to measure the relative angle between the forebody and the rear body also continuously sends the angle feedback sequence to the correction mechanism control board. The embedded computer in the correction mechanism control board obtains the control electromagnetic torque required for roll angle control according to the command sequence and feedback sequence and the forebody roll angle control strategy, and resolves the torque into the duty cycle of the PWM signal output to the MOS tube to control the motor to generate the corresponding electromagnetic torque to achieve roll angle control. The generation mechanism and process of the electromagnetic torque are shown in Figure 3. The coil winding in the figure corresponds to the permanent magnet synchronous motor in Figure 2, D₁~D. is a diode, R is a power resistor, Q is a MOS tube, and the permanent magnet synchronous motor works in the generator state, using the extremely high relative speed between the front and rear bodies of the double-rotating spring to generate electrical energy. The three-phase rectifier bridge rectifies the three-phase AC output of the motor into DC. When the PWM signal is at a low level, the DC path is cut off, no current is generated in the entire circuit, and the motor does not generate electromagnetic torque; when the PWM signal is at a high level, the DC path is turned on, and the circuit

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When there is current flowing in the motor, the motor will generate the maximum braking electromagnetic torque. Therefore, by adjusting the duty cycle of the PWM signal, the motor can be made to output any electromagnetic torque between zero and the maximum braking electromagnetic torque to achieve the front body roll angle control.

instruction sequence

GPS

missile-borne computer

embedded computer

Three-phase rectifier bridge

NOSE

Feedback sequence chicken

PWM

geomagnetic sensor

Hall sensor

MOS tube

Correction mechanism control panel

Figure 2 Block diagram of the front body roll angle control scheme

Permanent magnet synchronous motor

Power Resistor

Fig. 2 Block diagram of control scheme for the roll angle of the forward body

ID

R

D

D

b

PWM

ID

D

D

coil winding

Three-phase rectifier bridge

Figure 3 Braking circuit schematic

Fig. 3 Schematic diagram of the braking circuit

As mentioned above, the forebody roll angle control is realized by controlling the electromagnetic torque. The schematic diagram of the forebody roll torque is shown in Figure 4. The torques on the forebody are: the control electromagnetic torque T, generated by the motor in the correction mechanism; the reverse aerodynamic torque T, generated by the fixed differential kinetic energy; the aerodynamic damping torque generated by rolling, where is the forebody speed, is the aerodynamic damping torque coefficient, the forebody roll damping torque, is the roll damping torque between the front and rear bodies, the speed and the positive direction of each torque are shown in Figure 4, where is the defined forebody roll angle, yer and r are the coordinate axes of the fixed plane coordinate system, and the dynamic model of the forebody roll channel will be obtained by analyzing the dynamic characteristics of the dual-rotor correction mechanism.

2 Corrected component roll channel modeling

2.1 Correction component torque analysis

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The key to the dynamic modeling of the rolling channel of the correction component is to model the torque of the correction component. First, the most critical electromagnetic control torque is modeled. The principle of electromagnetic torque generation is shown in Figure 3. The following analysis shows the form of the maximum braking electromagnetic torque when the PWM signal always maintains a high level. It is assumed that the diodes D~D and MOS tube Q in Figure 3 are ideal devices. At the same time, the rectifier bridge in the figure is a principle rectifier bridge, and various filtering measures in actual engineering are not added. However, the analysis of the principle rectifier bridge can reflect the mechanism of electromagnetic torque generation.

For the three-phase full-wave rectifier bridge in Figure 3, when Q is turned on, only one group of diodes is turned on at each moment, and the current flows from the phase with the highest motor potential through one of the diodes D1~D, flows through the load resistor R and the MOS tube Q, and then flows through one of D~D to the phase with the lowest potential. Assuming that the potential of phase 1 is the highest and the potential of phase 6 is the lowest during a certain period of time, D and D are turned on. The equivalent circuit diagram of the braking circuit during this period is shown in Figure 5, where R is the internal resistance of each phase winding of the motor, L is the synchronous inductance, and is the current in the loop. The ideal diodes D and D are omitted in the figure.

R

L

RL

R

L

Figure 5 Equivalent circuit diagram of the braking circuit when D and D are turned on

Fig. 5 Equivalent braking circuit model when D, and D, conduct

P

0

2

T

Figure 4 Schematic diagram of the front body rolling moment (from the tail to the head)

Fig. 4 Schematic diagram of roll moments of the forward body(viewed from the rear)

Figure 6 Schematic diagram of three-phase winding coordinate system

Fig. 6 Schematic diagram of the three-phase winding

coordinate system

The braking circuit model is established in the three-phase winding coordinate system. The three-phase winding coordinate system is shown in Figure 6. The magnetic axes of a, b and the three-phase winding are used as the coordinate system, and the intersection of the three magnetic axes is used as the origin. Each coordinate axis differs by 120° in space. Assuming the permanent magnet flux is λ, the permanent magnet

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The sum of the flux of the body and the three-phase winding is =COS (0-0) -,COS(-+ㅈ), A = A. cos(--) (1)

Where 10000 is the relative electrical angular velocity between the front and rear bodies, is the number of pole pairs, is the relative mechanical angular velocity between the front and rear bodies: 0. is the initial electrical angular position of the magnetic axis of the permanent magnet relative to the magnetic axis of the phase winding. According to electromagnetic theory, the sum of the induced electromotive force e,er of the three-phase windings a, b and c is e= dλ dt = sin(at) da-sin(-80+), (2) {eb = dt dλ =-sin(01 - Θε Let: =-, by the trigonometric function and the difference product formula, we can get ea - Bed, cos(at - 0+중). e- (3) For the equivalent circuit diagram of D and D at the time shown in Figure 5, there is di 2(R+L.)+R = ৯ Assume that the steady-state value of is sb = Lasin (w-0++0). Substituting equation (5) into equation (4), eliminating and we can get i- 2(R+R)+(L) sin(wat-00++), where (4) (5) (6)

L00 = arccos √(R+R)+(L.) (7)

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By analyzing the conduction sequence of the circuit path in the three-phase rectifier bridge according to formula (2), it can be obtained that the diodes in the three-phase rectifier bridge are periodically turned on. Each cycle can be divided into 6 time periods. The current in this period flows from the working phase to the y phase in the form of xy. Then the conduction sequence of the three-phase rectifier bridge can be represented by Figure 7.

Work

Good

Stare

Fig. 7 Schematic diagram of three-phase rectifier bridge conduction sequence

Formula (8) calculates the maximum braking electromagnetic torque corresponding to time period ① in Figure 7. The same method can be used to calculate the form of the maximum braking electromagnetic torque corresponding to time periods ② to ⑥. The calculation results show that the maximum braking electromagnetic torque changes periodically, and the change period is the duration of each time period. In fact, by observing that the voltage change law of each time period is exactly the same, the same conclusion can be drawn. Therefore, it is sufficient to study the change law of the maximum braking electromagnetic torque corresponding to time period ①. 60 yuan/2 can be taken, so the time corresponding to time period ① is 1=0~T/6, where T-2 yuan/ is the electrical cycle. In the time period =0~T/6, the maximum and minimum values ​​that can be obtained, that is, the maximum and minimum values ​​of the maximum braking electromagnetic torque of all time periods are as shown in formula

(9) 和式(10) shown, 3 my poly T= 4 (1+sin ). (9) (R+R)+(L)

T= X 3 ρωλί 4(R+R)+(L) [sin(+)+sing]. (10)

The average value of the maximum braking electromagnetic torque is the average of the maximum and minimum values.

According to the principle of electromechanical energy conversion, D, and D can be obtained. The expression of the maximum braking electromagnetic torque during the conduction period is:

T 00 3 roll 4√(R+R)+(L) X [sin(2001-200+2+)+sin 4]. (8)

In order to study the variation law of the maximum braking electromagnetic torque, we can first

T- 3 roll X 4(R+R)+(L) [(1+sin(+))+ sin ]. (11)

Generally speaking, L≪R+R, so if we ignore

The L00 term in formula (11) can be simplified to: Το 1.3125 ρωλί 1 R+R (12)

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Therefore, the average maximum braking electromagnetic torque is approximately equal to the distance between the front and rear bodies.

The relative speed is proportional to R(t), and inversely proportional to R+R. From the above analysis results, it can be obtained that in the braking circuit of the generator mode, the braking electromagnetic torque provided by the motor is fluctuating, and the angular frequency of the fluctuation is 600 η. After obtaining the design parameters of the motor, the maximum, minimum and average values ​​of the fluctuation can be calculated by equations (9) to (11) respectively. In the subsequent forebody roll channel control, when the duty cycle of the PWM signal is k(t), it is considered that the electromagnetic control torque output by the motor can be estimated by the following equation:

Tk() T

(13)

The estimation of electromagnetic control torque in formula (13) ignores the electromagnetic torque fluctuation, which needs to be considered in the design of the forebody roll angle control strategy. The remaining torques of the correction component are analyzed below. The reverse aerodynamic torque T is generated by the differential rudder. 1 T. = pSlv C, (14)

Where: p is the atmospheric density; S is the reference area; is the reference length; v is the projectile velocity 18, is the average tilt angle of the differential kinetic energy; C is the derivative of the rolling moment coefficient generated by the differential kinetic energy relative to the fixed rudder tilt angle, which can be solved by CFD simulation or wind tunnel test. The parameters used to calculate the aerodynamic rolling damping moment are:

b₁ = SC

2

(15)

Where C is the derivative of the roll damping moment coefficient generated by the canard roll relative to the canard roll angular velocity, which can be solved by the aerodynamic engineering method Datcom.

The front body rolling damping torque T is mainly generated by the front and rear body connecting bearing group, which is divided into two parts: viscous damping torque and rolling friction torque, which can be expressed as T₁=cv(PA-Pp)+CFxsgn(PA-P),

(16)

Where: cv is the viscous damping torque coefficient; pa is the front body speed; sgn is the sign function; CR is the rolling friction torque coefficient; F is the normal force acting on the bearing, which can be expressed as:

FAX. 702 (17)

Where: mp is the mass of the front body; ma is the mass of the rear body; m is the total mass of the projectile; X and X are the projections of the combined external forces on the front body and rear body of the double-rotating projectile in the fixed plane coordinate system, respectively. The viscous damping moment coefficient and the rolling friction moment coefficient can be estimated by experimental methods.

So far, the modeling of the moment of the correction component has been completed. Next, the dynamic model of the rolling channel of the correction component is derived.

2.2 Modified component rolling channel dynamics model

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In the rolling channel of the double-spinning missile correction component, the rolling attitude of the correction component is the result of the combined action of the electromagnetic control torque T, the reverse aerodynamic torque T, the aerodynamic damping torque and the rolling damping torque T. The front body roll angle is defined as shown in Figure 4, and the roll motion of the correction component can be expressed as

Py

T. +T+bpp-T

(18)

Where is the axial moment of inertia of the correction component. When the roll angle control torque calculated by the roll channel controller is T, the controller needs to use the reverse aerodynamic torque T obtained in Section 2.1. The aerodynamic damping torque, and the roll damping torque T model are used to obtain the estimated values ​​of the above torques, which are written as, and (bp) respectively. Then the electromagnetic control torque required for roll angle control is calculated as

TT+T-T-(bp).

(19)

Then according to the electromagnetic torque model obtained in Section 2.1, the duty cycle of the PWM signal to be output is obtained. The electromagnetic control torque output value estimation module in the controller represented by Equation (19) is written as T. (T.TTbp.), Then from equation (18), the block diagram of the correction component roll control model is obtained, as shown in Figure 8.

Fig. 8 Block diagram of the roll control model for the course correction fuse

Pr

The motor outputs the required electromagnetic torque T.

The resultant torque is T in Figure 8. The error between T and

The estimated errors of torque T, T and (あか) and electromagnetic control

The fluctuation of the braking torque T and the output error can be unified

Expressed as input disturbance, for roll channel control, ignoring input disturbance

The model of the controlled object obtained after the operation can be expressed by the transfer function G(s).

shown as

G(s) = s(Is-b₁)

Or let x = [P], and get the system state space model

1 x = x+

y- [01]x.

(20)

(21)

The ideal controlled object model obtained above is simple, but

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The key control issues that need to be addressed in the designed roll channel controller are the input disturbance and model uncertainty issues of the real controlled object. Therefore, based on the controlled object model, a roll channel controller that can suppress input disturbances, has sufficient robustness to model uncertainty, and can ideally track the reference input will be designed.

3 Correction Component H Loop Shaping Two-DOF Roll Channel Controller Design

The H-loop shaping method originated from Dr. Hyde's doctoral thesis and has been successfully applied to multiple industrial fields. This method essentially synthesizes a single-degree-of-freedom controller, which has the disadvantage that it cannot strictly meet the requirements of command tracking. Limebeer et al. introduced a second degree of freedom in the controller and expanded the problem into a standard H optimization problem. This dynamic two-degree-of-freedom solution uses the feedback part of the controller to meet the requirements of disturbance suppression and robust stability. At the same time, a pre-filter controller is added to the controller to force the system closed-loop response to track the output of the reference model to achieve the purpose of reference input tracking. This section applies the two-degree-of-freedom H\_loop shaping controller method to the design of the correction component roll channel controller.

The structure of the two-degree-of-freedom H\_loop shaping controller can be represented by Figure 9. In general, the control problem is to shape the controlled object G into G=GW, then decompose the shaped object into G=M,N,, and then seek the stabilizing controller K=[KK] for the standardized coprime decomposition form of G to minimize the H norm of the transfer function from the signal [r] to [u ye] in Figure 9. This problem can be transformed into a general control composition problem, and the suboptimal H\_controller can be obtained using the H\_standard synthesis method and the y-iteration method.

K (22) and, [K

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Where: is the reference input after scale transformation; is the measured output. The closed-loop transfer function T of the inner loop parallel to the reference model T has the form of formula (23):

TI-GK)G,K, the purpose of the pre-filter K, is to ensure (23)

(24) In this way, the expected response characteristics in the time domain are introduced into the controller design process, where is a scalar parameter. In the optimization design, better model matching performance can be obtained by increasing its value.

This will correspondingly reduce the robustness of the system.

0 I

Define the generalized object P as in Equation (25), and transform the two-DOF controller design problem into the form of standard control configuration,

0

0 MG

TPMG,

P

P12

PP

22

pl

0 0

0

MG

(25)

Assume that the object G to be shaped has the following minimum state space realization with respect to the reference model transfer function:

G. (26) So the generalized object P can be realized as A B B, T D

A,

0

0 (BD + Z,CR1/2B,

0

A.

B.

0

0

0

0

0

0

I

C,

0

0

1/2

D,

C

D.

PR

AM

0

0

did not

0

0

C

0

0

R

D.

and

pl

N.

M

(27)

Fig. 9

K

T

Figure 9 Block diagram of two-DOF H-loop shaping controller

Block diagram of two-degree-of-freedom controller

based on H. loop shaping

The stabilization controller K-[KK], K, is the pre-filter

The controller K is the feedback controller, and the control signal is the formula (22)

form.

Among them, R-I+D.D., and Z, is the generalization of G

The only positive solution of Riccati equation (28) is S, =

I+DD..

(A-BS DIC)Z+Z(A-BS DIC)-

ZCRCZ,+B,SB=0.

(28)

At this point, the two-degree-of-freedom controller design problem is transformed into a standard

H\_suboptimal control problem, that is, given a y>, find a stabilizing control

Controller K makes

|| F(P,K) || <c.

(29)

The control problem represented by equation (29) can be solved by using the standard H comprehensive method:

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The controller K is solved by the method. To simplify the calculation, this paper uses the Robust Control Toolbox provided by Matlab to solve the control problem. Usually, the controller order obtained is high, and the controller needs to be reasonably reduced.

Since the optimized controller cannot guarantee steady-state gain matching, a constant matrix W is needed to scale the controller K so that the closed-loop transfer function T to the output y accurately matches the steady-state gain of the reference model T. The constant matrix W can be obtained by the following formula:

WHAT(5)T(8)

(30)

The steady-state gain matching controller is K-[KW K], and the final two-degree-of-freedom H-loop shaping controller is shown in Figure 10.

IN

| Two-degree-of-freedom controller

IN

G

K

Figure 10 Block diagram of the final two-DOF H\_loop shaping controller

Fig. 10 Block diagram of the final two-degree-of-freedom controller based on H. loop shaping

For comparison, a two-degree-of-freedom perturbation is introduced.

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The block diagram of the classical loop shaping roll channel controller is shown in Figure 11, where K is the input disturbance suppression controller and K is the reference input tracking controller. The classical loop shaping controller is designed by shaping the loop transfer function and only considers the input disturbance suppression problem. The control effects of the two controllers will be given as a comparative reference in the simulation experiment part.

K

G

this

G

Figure 11 Block diagram of the two-degree-of-freedom disturbance rejection classic loop shaping controller

Fig. 11 Block diagram of the two-degree-of-freedom controller based on classical loop shaping

4 Analysis of semi-physical simulation experiment results

In order to verify the accuracy of the roll channel control model and whether the roll channel controller can accurately correct the roll angle control of the component, a simulation experiment based on a ground semi-physical simulation platform is designed. The experiment is based on a high-speed turntable test system designed by the Servo Technology Institute of Beijing Institute of Technology. The turntable is shown in Figure 12.

Motorized spindle

Conductive slip ring

Motorized spindle drive

Torque sensor

Correction mechanism to be tested

Permanent magnet synchronous motor

Permanent Magnet Synchronous Motor Driver

Industrial computer

Figure 12 High-speed turntable test system

Fig. 12 High-speed rotating platform test system.

The high-speed turntable test system is mainly composed of a high-speed electric spindle and driver, a conductive slip ring, a permanent magnet synchronous motor and driver, a torque sensor, an industrial computer, a test bench and corresponding supporting facilities. The correction component to be tested rotates at high speed under the drive of the high-speed electric spindle to simulate the high-speed rolling motion of the rear body of the projectile; the torque sensor can measure the torque between the front and rear bodies of the correction component. When conducting the rolling channel control experiment of the correction component, the torque sensor is removed and the front body of the correction component is directly connected to the permanent magnet synchronous motor through a coupling; the motion card in the industrial computer is connected to the test bench.

Generate motion instructions to the permanent magnet synchronous motor driver, and the permanent magnet synchronous motor drives the driver to simulate the movement of the front body under the aerodynamic torque.

The rolling damping torque T and the average value of the maximum braking electromagnetic torque obtained by the high-speed turntable test system are shown in Table 1 at different relative speeds between the front and rear bodies. For comparison, the table also gives the theoretical calculation results of T obtained by the modeling method in Section 2. The theoretical calculation results of T are consistent with the turntable test results.

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Table 1 Torque measurement and calculation results

Tab. 1 Measurement and calculation results of torque

T measurement value/ (Nm)

T/(Nm)

Speed(rs)

Measured value

Calculated value

After removing the command angle, the roll angle error curve under the two-degree-of-freedom H-loop shaping roll channel controller is shown in Figure 13, and the roll angle error curve under the classic loop shaping controller is shown in Figure 14.

50

0.025 6

0.0720

0.082

200

100

0.026 9

0. 108 8

0.113

150

0.028 7

0.165 0

0.163

200

0.0310

0.205 5

0.211

100

250

0.033 5

0.276 6

0.281

After conversion calculation, the ideal controlled object model under the semi-physical simulation turntable experimental conditions is obtained as follows:

G(s) - 7 692.3 (0.946 2x+1)'

(31)

error/()

-100

0

For the controlled object model, the classic loop shaping controller result obtained by the controller design method given in Section 3 is shown in Equation (32). The reduced-order two-degree-of-freedom H-loop shaping roll control is

The controller result is shown in equation (33), K. (s) 0.028 48+1, 0.085x+1' K, (s) = 0.05(0.18+1) 0.01s+1

-200, 2000

2

8

10

Figure 13 Error of H-loop shaping controller under fixed roll angle command

Fig. 13 Control error of the H. loop shaping controller with constant roll angle instruction

200

(32)

W₁(s) = 0.05(0.1x+1) ,W, 2.384 8. 0.01s+1 K₁(s) = 0.301 52(0.010985+1) (0.02307s+1) (7.34 × 10+1) (0.005 343s+1) (0.088 9s+1)' K₂(3) = -0.719 44(0.009645s+1) (0.1323s+1)

100

(7.319×10s+1) (0.005 396x+1)(0.1006s+1)\*

(33)

The designed two-degree-of-freedom H loop shaping roll channel control

The controller converts the program into an executable computer program and writes it into the correction component.

In order to compare the control effect, the classic circuit

The shaping controller is also converted into an executable computer program.

Semi-physical simulation is used to test the control effects of the two controllers.

Due to the characteristics of the correction component, the roll angle of the front body only needs to be

So two semi-physical simulations are designed.

Experiment, the front body roll angle command of experiment 1 is fixed, and the front body roll angle command of experiment 2 is fixed.

The angle command changes 90° at regular intervals to observe the step response.

In experiment 1, after the experimental equipment is prepared, set the electric spindle speed

After the speed reaches 150r/s, start the electric spindle. After the speed of the electric spindle stabilizes,

The motion card in the control machine gives instructions to make the front body simulate the movement under the aerodynamic torque.

Then the correction component roll channel control board starts to power on.

Control the front body to stabilize to the specified angle, maintain about 88 degrees, and then gradually close

Each system completes an experimental process, and the signal of the entire experimental process

The actual roll angle is transmitted to the industrial computer and recorded by the conductive slip ring.

error(\*)

0

-100

-200

2

10

Figure 14 Error of the classic network shaping controller under fixed roll angle command

Fig. 14 Control error of the classical loop shaping controller with constant roll angle instruction

Before the correction component roll channel control board is powered on,

The circumferential rotation of the forebody and the roll angle errors of the two controllers

The curve changes approximately periodically between -180° and 180°; the control panel works

After that, the roll angle error quickly approaches 0°, as shown in Figures 13 and 14.

Comparing the control error curves of the two controllers, it can be seen that the fixed angle refers to

Under the command, after entering the steady state, the control errors of the two controllers are both within 5°

Within, it meets the performance requirements, but the control effect of H controller is better

Good, the error curve fluctuates less,

After the completion of experiment 1, experiment 2 was started. In experiment 2, the roll angle command was kept at 3.58 and then changed by 90°. Each experiment was conducted for about 208 times. After the experiments of the two controllers were completed, the industrial computer recorded the experimental data. After the actual roll angle was subtracted from the command angle, the roll angle error curves of the two controllers were shown in Figures 15 and 16, respectively.

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error(")

200

150

100

50

0

-50

-100

-150

-200

5

10

15

20

s

Figure 15 Error of H loop shaping controller under variable roll angle command

Fig. 15 Control error of the H loop shaping controller with variable roll angle instruction

error/(\*)

200

100

0

-100

-200

2

4

6

8 10

12

Figure 16 Error of the classic loop shaping controller under variable roll angle command

Fig. 16 Control error of the classical loop shaping controller with variable roll angle instruction

As shown in Figures 15 and 16, at the moment when the command angle changes by 90° each time, the controlled angular error fluctuates instantaneously. Theoretically, the two-degree-of-freedom H-loop shaping controller of the meter shows its superiority in disturbance suppression and robustness to model uncertainty under both fixed roll angle command and variable roll angle command.

The movement should be close to 90°. As can be seen from the figure, in actual situations, when the command angle changes

At the moment of change, the control angle error changes slightly more complicated, and the front body switches the command

Jitter may occur at the moment of the controller, which is difficult to achieve in the controller engineering implementation.

To avoid, for each command angle, both controllers can make

The angle error decreases rapidly, and after entering the steady state, the control error is within 5°C.

However, as can be seen from the figure, under the variable roll angle command, the H controller

The control effect is better and the error curve fluctuation is smaller. Therefore, this paper sets

5Conclusion

A two-degree-of-freedom rolling channel control method based on H\_loop shaping is designed. The feasibility and control effect of the control method are verified through semi-physical simulation experiments. The following conclusions are drawn:

① Modify the electrical and mechanical systems of the rolling channel of the component

The electromagnetic control torque of the correction mechanism is calculated based on the model. The aerodynamic torque and roll damping torque of the correction component are modeled by theoretical analysis and experimental test, thus obtaining the roll channel control model of the correction component. The dynamic model reflects the characteristics of input disturbance and model uncertainty in the roll channel. The semi-physical simulation experiment verifies that the modeling method is feasible.

② Aiming at the characteristics of input disturbance and model uncertainty in the dynamic model of the roll channel of the correction component, a two-degree-of-freedom H-loop shaping roll channel controller is designed, which can suppress input disturbance, has sufficient robustness to model uncertainty, and can ideally track the reference input. The feasibility and accuracy of the control method are verified through semi-physical simulation experiments, and compared with the classic loop shaping controller. The semi-physical simulation experimental results show that the loop shaping controller designed in this paper has better control effect.

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Table 5 Summary of comparison results

Detection tools

KLEE

SHUT DOWN

Tab. 5 Compare Results

False positive/false negative %

Discover the program

defect/%

0

13.3

17.8

3.3

time out/ %

mistake/ %

7.1

10.7

0

6.7

From the results, we can see that compared with KLEE, ABAZER-SE has no timeout and has lower false negatives and false positives. Among them, 16, 25, and 51 of the bench-marks have false positives, mainly because they report all possible unsafe locations in the tested code as defects.

4 Conclusion

Static symbolic execution technology has been a research hotspot in recent years and can be used for software automated testing, vulnerability detection and path analysis []. Similar to these studies, the tool ABAZER-SE developed in this paper also

The method of combining static analysis with symbolic execution is adopted. The main difference is that ABAZER-SE is built on GCC AST. Compared with CIR, AST contains more source code information. In addition, in the implementation process, solutions such as using specific structures to handle uncertain addresses are proposed to solve some challenges faced in static symbolic execution. The defect detection tool ABAZER-SE designed and implemented in this paper is based on static symbolic execution. It improves the accuracy of defect detection by removing unreachable paths. The experimental results prove the effectiveness of this method. Future work includes adding parsing of other operators and adding detection of more defect types.

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