A DOUBLE-LOOP ROLL SPEED CONTROL OF A NONLINEAR DYNAMIC SYSTEM WITH CONSTRAINED INPUTS AND COMPLICATED DISTURBANCES

Tingting YIN[1, 2], Zhong YANG[1*], Ruisheng SUN[2], Fangxiu JIA[3], Youlong WU[4]

As for the high-dynamic nonlinear tracking conditions of the rudder roll speed control systems, the conventional single closed-loop control methods usually fail to solve the input constraints, the specified parameter uncertainties and uncertain nonlinear problems, such as nonlinear frictional dynamics, non-modeled external disturbances, high frequency electromagnetic dynamic responses, and so on. To solve these limitations, under the premise of considering the upper constraints of dynamic control force, a novel speed dynamic tracking strategy based on double closed-loop control architecture is proposed. Firstly, based on the dynamic systematic model, the direct predictive controller, combined with the extended state observer, is established as the inner loop to improve the control response characteristics and accuracy. Meanwhile, based on the upper constraints of the dynamic control force and the changing trend of the control target, a new tracking system reference trajectory is automatically estimated and generated online to optimize the stability and transient performance for the outer loop. Simulation results show that the proposed double closed-loop speed tracking control system can not only meet the dynamic tracking accuracy of the system, but also solve the problems of limited control constraints and complicated disturbances in practical engineering applications.

Keywords: Double-loop Control Structure; Nonlinear Dynamic System; Direct Predictive Control; Extended State Observer; Online Trajectory Planning.

1. Introduction

The two-dimensional trajectory correction problem is simplified into the one-channel roll control problem by the application of the fixed rudder canards,

[1] School of Intelligent Science and Control Engineering, Jinling Institute of Technology, Nanjing 211169, China, email: yintingting@jit.edu.cn
[*]Corresponding Author. Prof., School of Intelligent Science and Control Engineering, Jinling Institute of Technology, Nanjing 211169, China, email: yz@jit.edu.cn
[2] Prof., School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing 210094, China, email: srscom@163.com
[3] Ass. Prof., ZNDY of Ministerial Key Laboratory, Nanjing University of Science and Technology, Nanjing 210094, China, email:jiafangxiu@126.com
[4]Ass. Prof., School of Electronic and Information Engineering, Jinling Institute of Technology, Nanjing 211169, China, email: youlong_wu@jit.edu.cn

which is popularly favored in fields of low-cost guidance improvement of active weapons and equipment [1-3].The rudder roll system is a typical highly nonlinear system, where the time-varying nonlinear characteristics from trajectories and actuators, systematic modeling uncertainties from parameter perturbations, frictions and aerodynamic torque ripples, un-modeled external disturbances are all included [4]. Meanwhile, there are also uncertain nonlinearities in electromagnetic response dynamics, such as inconsistency in the parameters and high-frequency dynamic responses of each trajectory correction execution component [5, 6].

With the extensive research of the fixed-rudder dual-spin trajectory correction projectile, the nonlinearities and disturbances mentioned above have become the most obvious limiting factors of roll control performance for effective and reliable trajectory corrections, leading to the instability or performance degradation of the control strategy designed with the ideal nominal system model [7, 8]. Therefore, it is necessary to seek a more effective control algorithm to estimate and eliminate the system disturbance, so as to realize the fast, high-precision and robust control of the fixed-rudder control system.

As for the roll speed control loop, the responsiveness and stability are the two most concerned requirements. Regarding the tracking stability performance for the nonlinear systems with modeling uncertainties and un-modeled disturbances, the strong-robust strategies, like the adaptive back-stepping method [9], the variable structure control method [10], the fuzzy logic system [11], the neural networks [12] as well as the sliding mode controllers [13] are successively proposed but easily over limited, failing to systematically solve the state measurement noises and control input constraints. The neural network has a large amount of calculation limiting the response speed and the discontinuous function in sliding mode control is easy to cause chattering, which both contradicts with the actual control requirements.

In order to improve the responsiveness performance of the nonlinear tracking systems, different strategies and methods have been proposed. Linear theory based algorithms evolved from basic PID technologies, for example, self-tuning PID control, feed-forward compensated PID, are not appropriate for the specified highly nonlinear rudder roll control system [14, 15]. Direct predictive control (DPC) is a control method based on model prediction of state quantities, which shows good potential in terms of fast response performance, however, the DPC method requires a highly accurate model since subtle model deviations often lead to deviations in the DPC control results [16-18].

Aiming to balance the contradictory demands for fast response and stable tracking, a new double-loop roll speed control of an uncertain and highly nonlinear dynamic system with constrained input and complicated disturbances is proposed. Online correction of the DPC model containing errors according to real-time feedback is an effective way to achieve fast and accurate tracking where the extended state observer (ESO) provides a feasible framework [19]. As the essential design inputs for real-time control parameter computation, the ESO corrected dynamic model can be also introduced into the upper limit model for prediction, therefore the control output is preprocessed by the control force boundaries, greatly reducing the amount of complicated online computation.

Therefore, a novel double-loop roll speed control, where control performance and real-time response are both taken into account, is proposed. The rest of this paper is organized as follows. Section 2 provides problem formulations and preliminaries. Section 3 gives the double-loop roll speed controller design. In Section 3, a simplified inner-loop ESO based DPC controller design, treated as the inner loop, is presented first. Meanwhile Outer-loop online reference trajectory planner, as the outer loop, is presented afterwards. Simulations are conducted in Section 4 to illustrate the effectiveness of the proposed two loop scheme. Section 5 draws the conclusions of this work.

2. Problem formulations and preliminaries

2.1 System descriptions

The considering rudder roll speed control system of the dual-spin projectile, which possesses self-contained constraints and external disturbances, follows the dynamic speed commands to spin around the projectile axis under the combined action of the electromagnetic control torque M_{ctrl}, aerodynamic torzongque M_{aero} and the rotational friction torque M_{damp}, as shown in Fig 1, where f_d refers to other un-modeled interferences, such as modeling errors, unexpected airflow disturbances, and so on.

The rolling dynamics equation can be expressed as:

$$J\frac{d\omega}{dt} = M_{aero} + M_{ctrl} + M_{damp} + f_d(\omega, t) \tag{1}$$

Where J is the known moment of inertia, ω is the output of the rudder roll system.

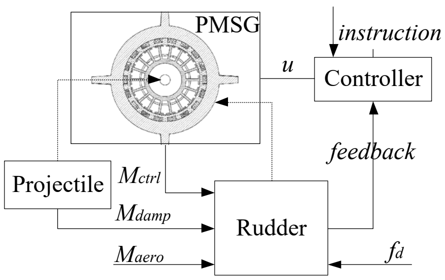


Fig 1 The rudder roll system of the dual-spin projectile

Note that the aerodynamic torque as well as the friction torque has been modeled properly by simulations and experiments in the following form:

$$M_{aero} = \frac{\rho v^2 Sd}{2}\left(C_{l\delta} \cdot \delta_s + C_{l\omega} \cdot \frac{\omega R}{v} \right) \tag{2}$$

$$M_{damp} = C_f \left| F_c \right| sign(\omega - \omega_P) \tag{3}$$

Where ω_P is the to-be-measured roll speed of projectile body, ρ is the atmospheric density, v, S and d are respectively the velocity, reference area and diameter of the projectile body, $C_{l\delta}$ and $C_{l\omega}$ denote the torque coefficients of the static steering torque and dynamic roll damping torque. C_f is the bearing friction damping coefficient, which can be obtained through ground tests. F_c denotes the axial force, relating to the mass ratio of between rudder and body.

The PMSG (permanent magnetic synchronous generator) based dual-spin electromagnetic actuator is applied to output the required electromagnetic control torque M_{ctrl}, which is corresponding to the to-de-designed constrained control input parameter u. Since the electrical response speed is much higher than the mechanics, based on the performance test data of PMSG, reasonably ignoring the high-frequency response characteristics of current loop, the dynamic equation of electromagnetic control torque response is given where K_n denotes the actual measured and verified torque coefficients.

$$M_{ctrl} = f(u, \omega, \omega_P, K_n, t) \approx u K_n(\omega_P - \omega) \tag{4}$$

Therefore,

$$J\frac{d\omega}{dt} = K_n \cdot u\left(\omega_P - \omega\right) + \frac{\rho v^2 SdC_{l\delta} \cdot \delta_s}{2} + \frac{\rho vSdC_{l\omega}R\omega}{2} - C_f \left| F_c \right| sign(\omega - \omega_P) + d(t) \tag{5}$$

In order to facilitate the controller design, the state variable is defined as $x_I=\omega$, and time varying variable $x_R=\omega_P - \omega$. Consequently, the strict-feedback nonlinear dynamic nonlinear system is established in the following form.

$$J\dot{x}_1 = K_n x_R \cdot u + \frac{1}{2}\rho v^2 SdC_{l\delta}\delta_s + \frac{1}{2}\rho vSdC_{l\omega}Rx_1 + C_f \left| F_c \right| sign(x_R) + d(t) \tag{6}$$

To further simplify the above formula, the following equations can be obtained by introducing parameter matrix $\boldsymbol{\theta}=[\theta_1,\ldots,\theta_n] \in \boldsymbol{R}^n$ and continuous functions f_i ($f_1 = \omega_P - x_1$, $f_2 = \rho v^2 C_{l\delta}$, $f_3 = \rho v C_{l\omega}$, $f_4 = -\left| F_c \right| sign(\omega - \omega_P)$):

$$\begin{aligned} &J\dot{x}_1 = \theta_1 f_1 u + \theta_2 \cdot f_2 + \theta_3 \cdot f_3 \cdot x_2 + \theta_4 \cdot f_4 + d(t) \\ &y = x_1 \end{aligned} \tag{7}$$

Where $y=x_1$ is the specified state variable to be controlled and y can be only measured indirectly by the projectile spin speed ω_P and the relative roll speed between rudder and projectile body x_R.

As the actual control input to be designed for the nonlinear system, u is limited within a certain range due to unavoidable dead-zone circumstances and design principle shortages. Therefore, the corresponding electromagnetic torque also represents strong nonlinearities and input constraints,

$$u = \begin{cases} u_M & u > u_M \\ u & else \\ u_L & u < u_L \end{cases} \tag{8}$$

Where u_L refers to the dead-zone limitations and u_M represents the upper bound of torque output capacity of the designed electromagnetic actuator.

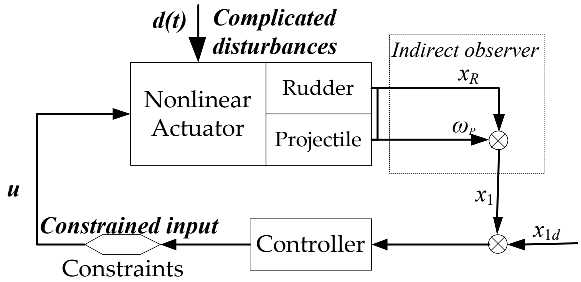


Fig 2 the rudder roll speed control scheme

From the above analysis, the primary objective of this paper is to propose a stable double-loop controller to track the desired time-varying nonlinear speed curve as shown in Fig 2. Necessary dynamic predictions and compensations for observing errors and modeling bias should be considered in the inner loop to ensure the control rapidity and stability. Meanwhile, a practical reference trajectory considering the input constraints and structural response limitations is important to be outlined, which in beneficial to balance the relationship of the plant output and the objective curve. In general, the proposed controller can not only optimize the constraints and nonlinearities, but also improve the dynamic response behaviors and accuracy performances.

In order to complete the controller design, the following assumptions need to be made:

Assumption1. The external disturbances $d(t)$ are bounded, i.e.,

$$|d(t)| \le D \tag{9}$$

where D refers to positive constants.

Assumption2. The roll control instruction $x_{1d}(t)$ is given and bounded.

Assumption3. The set of parameters $\boldsymbol{\theta}$ are bounded in the known range $[\boldsymbol{\theta}_{min}\ \boldsymbol{\theta}_{max}]$, that is,

$$\boldsymbol{\theta}_{min} = [\theta_{1min}, \ldots, \theta_{nmin}] \le [\theta_1, \ldots, \theta_n] \le [\theta_{1max}, \ldots, \theta_{nmax}] = \boldsymbol{\theta}_{max} \tag{10}$$

2.2 Direct predictive control

For the time-varying and non-equal interval sampling problem for the high transient nonlinear application, under the condition that the speed update time is unpredictable, a direct predictive control method to reach the control target at the desired time point is adopted.

On the basis of desired control time interval T and speed control instruction $x^*(k)$, the reference trajectory of speed control shown in Fig 3 is selected in combination with cost function $J(k)$, while $J(k)$ is defined as the difference between the predicted state value and control instruction:

$$J(k) = \left| x_p(t_k + T) - x^*(k) \right| \tag{11}$$

where $x_p(t_k + T) = \int_{t_k}^{t_k+T} \dot{x}_1(u,t)dt$.

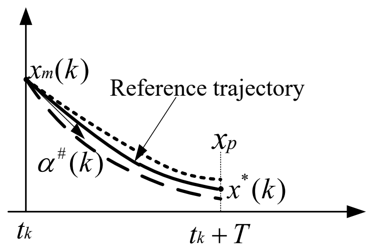


Fig 3 the direct predictive control based reference trajectory determination

The determination principle for reference trajectory $x_p^{\#}(t_k + T)$ should be content with:

$$\left| x_p^{\#}(t_k + T) - x^*(k) \right| \square \min_{u \in U}(\left| x_p(t_k + T) - x^*(k) \right|) \tag{12}$$

It can be inferred that the corresponding control input parameter $u^{\#}$ is determined according to the reference trajectory as well as the dynamic roll characteristic equations. Consequently, the control quality of direct predictive control method completely depends on the accuracy of dynamic models and state observations.

The uncertainty of system dynamic model parameters, un-modeled interference and observation errors all have negative impacts on the accuracy and stability of the control system, and even cause system divergences. To deal with this defect, an extended state observer can be introduced to correct model deviations and observation errors, thereby improving the stability and accuracy of the control system.

3. Double-loop roll speed controller design

Inspired by the concept of the reference trajectory planner, we propose a dual-loop control architecture to address a complex class of tracking control problems involving system uncertainty, uncertain nonlinearity, state quantity observation noise, system modeling errors, and limited control inputs. Fig 4 briefly outlines the specific structure of the designed controller.

1) In the inner loop, the direct predictive controller can make full use of the rough system model to improve the control response speed. Under the premise of fully considering the system observation error and external disturbance, DPC cooperates with the extended state observer to complete the real-time estimation of the system modeling error and external disturbances. Finally, the DPC and ESO based inner loop aims to realize the real-time tracking of the nonlinear system in the continuous time domain.

2) In the outer loop, the reference trajectory x_{1r} fed into the inner tracking controller is generated by online planning, thereby minimizing the transient performance within the range of predictive control capabilities. Here, the reference trajectory is realized in the continuous time domain where a reference trajectory tracking regulator is proposed to coordinate the contradiction between the available adjustment capability and the required tracking capability of the system, which enhances the greater adaptability relative to the proposed dual-loop system.

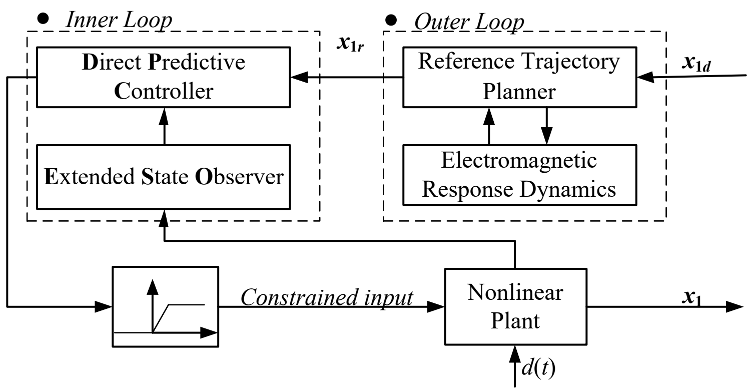


Fig 4 the proposed double-loop rudder roll speed control

In summary, the proposed double-loop control strategy provides a feasible framework to deal with the uncertain nonlinear dynamic system involving system uncertainty, uncertain nonlinearity, state quantity observation noise, system modeling errors, and limited control inputs.

3.1 Simplified inner-loop ESO based DPC controller design

Based on the above analysis, the inner loop will solve the problem of nonlinearity and modeling uncertainty in the canard roll system. Based on the more accurate dual-rotation channel parameter identification model and the dynamic response model of the electromagnetic actuator obtained from the previous test, and a nonlinear model predictive control strategy based on extended state observer is proposed. The overall disturbance of the system is estimated by \ an designed output-feedback-type ESO and compensated in a feedforward manner to reduce the influence of model uncertainty and disturbance on the tracking performance.

As aforementioned, the roll speed states are disturbed or noised, such that an extended state observer needs to be constructed to estimate the accurate roll information and modeling errors based on the rough measurements and models. At first, the dynamic systematic function is derived where the overall disturbances $\Delta(t)$ is included. $\Delta(t)$ can be inferred as bounded.

$$J\dot{x}_1 = \theta_{1n} f_1 u + \theta_{2n} \cdot f_2 + \theta_{3n} \cdot f_3 \cdot x_1 + \theta_{4n} \cdot f_4 + \Delta(t) \tag{13}$$

Where $\boldsymbol{\theta}_n = \begin{bmatrix} \theta_{1n} & \theta_{2n} & \theta_{3n} & \theta_{4n} \end{bmatrix}^{\mathrm{T}}$ refers to the approximate parameters based on preliminary tests and simulations. It is worth noting that $\Delta(t)$ includes the modeling uncertainties and un-modeled disturbances, $\Delta(t)=\left(\theta_1 - \theta_{1n}\right) f_1 u + \left(\theta_2 - \theta_{2n}\right) f_2 + \left(\theta_3 - \theta_{3n}\right) \cdot f_3 \cdot x_1 + \left(\theta_4 - \theta_{4n}\right) f_4 + d(t)$, and its deviation is denoted as bounded functions $h(t)$.

In order to reduce the negative influences from the model parameter uncertainties and un-modeled disturbances in the systematic dynamic equations, the roll speed x_1 and disturbance $\Delta(t)$ are both observed as to-be-estimated states $\boldsymbol{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^{\mathrm{T}}$, that is $x_2 = \Delta(t)$.

To proceed, a simple real-time feedback-based form of observer is introduced to evaluate the states and disturbances and is given [20].The state estimation $\hat{\boldsymbol{x}} = \begin{bmatrix} \hat{x}_1 & \hat{x}_2 \end{bmatrix}^{\mathrm{T}}$ can be approximated where ω_0 represents the bandwidth of the designed observer.

$$\begin{aligned} &J\dot{\hat{x}}_1 = \theta_{1n} f_1 u + \theta_{2n} \cdot f_2 + \theta_{3n} \cdot f_3 \cdot x_1 + \theta_{4n} \cdot f_4 + \hat{x}_2 - 2\omega_0 (\hat{x}_1 - x_1) \\ &\dot{\hat{x}}_2 = -\omega_0^2 (\hat{x}_1 - x_1) \end{aligned} \tag{14}$$

By subtracting the ESO equation from the original strictly feedback nonlinear system, the transient formulation of the observation error system can be obtained as follows:

$$\begin{cases} \dot{\tilde{x}}_1 = x_2 - 2\omega_0 \tilde{x}_1 \\ \dot{\tilde{x}}_2 = h(t) - \omega_0^2 \tilde{x}_1 \end{cases} \tag{15}$$

Where $\tilde{x}_1 = \hat{x}_1 - x_1, \tilde{x}_2 = \hat{x}_2 - x_2$.

Remark 1: If $h(t)$ is bounded, the observed state evaluation $\hat{\boldsymbol{x}} = [\hat{x}_1 \quad \hat{x}_2]^{\mathrm{T}}$ is bounded, then the designed extended state observer converges to converges to a very small range.

By substituting the ESO equations into the DPC controller, the cost function for the inner loop is rewritten.

$$J(k) = \left|\hat{x}_p(t_k + T) - x^*(k)\right| \tag{16}$$

Where $\hat{x}_p(t_k + T) = \int_{t_k}^{t_k+T} \dot{\hat{x}}_1(u,t)dt$.

The new determined reference trajectory $x_p^{\#}(t_k + T)$ is constructed as:

$$\left|x_p^{\#}(t_k + T) - x^*(k)\right| \square \min_{u \in U}(\left|\hat{x}_p(t_k + T) - x^*(k)\right|) \tag{17}$$

Remark 2: If $\tilde{x}_1 \to 0$, the error of DPC, $z_1 = x_1(t_k + T_1) - x^*(k) = \hat{x}_1(t_k + T_1) - x^*(k) - \tilde{x}_1(t_k + T_1)$ also converges to zero.

In the selection process of parameter u, there are a large number of rotation speed prediction integral operations and repeated operations with different u values. In order to meet the real-time control under high observation update rate, the algorithm needs to be simplified. According to the dynamic equation of rudder roll and the previous ballistic test data, the time-varying parameters show strong time-varying nonlinearity in the full ballistic range, but in the very short measurement update interval T (taking satellite data 0.1s as an example) , the change of f_2 and f_3 is less than 0.017. Meanwhile, the speed of the projectile is much higher than the speed of the canard and the rate of change of the projectile speed is also less than 0.0025. Consider the changing trends of the real-time nonlinear variables in the extremely short updating intervals(less than 0.05 seconds), the local linear simplification of dynamic functions $f_1,\ldots,f_4$ is proved to be reasonable.

Then, the original observer during DPC control interval $[t_k \quad t_k + T]$ becomes:

$$\begin{aligned} J\dot{\hat{x}}_1 = {} & \theta_{1n} \cdot \left(\frac{f_1(t_k + T) - f_1(t_k)}{T}(t - t_k) + f_1(t_k)\right)u + \theta_{2n} \cdot \left(\frac{f_2(t_k + T) - f_2(t_k)}{T}(t - t_k)\right. \\ & \left. + f_2(t_k)\right) + \theta_{3n} \cdot \left(\frac{f_3(t_k + T) - f_3(t_k)}{T}(t - t_k) + f_3(t_k)\right) \cdot x_1 \\ & + \theta_{4n} \cdot \left(\frac{f_4(t_k + T) - f_4(t_k)}{T}(t - t_k) + f_4(t_k)\right) + \hat{x}_2 - 2\omega_0(\hat{x}_1 - x_1) \end{aligned} \tag{18}$$

With necessary simplifications, the above expression can be rewritten as:

$$\dot{\hat{x}}_1 = (\lambda_1 u + \lambda_2)t + \lambda_3 u + \lambda_4 \tag{19}$$

After Integral operations, the predicted state value based on the current ESO evaluations is obtained.

$$\hat{x}_p(t_k + T) = \hat{x}_1(t_k) + \frac{(\lambda_1 u + \lambda_2)t^2 \big|_{t_k}^{t_k+T}}{2} + \left(\lambda_3 u + \lambda_4\right)T \tag{20}$$

The traversal optimization problem is transformed into a directly solved problem for control input *u*.

$$\hat{x}_p(t_k + T) = x^*(k) \tag{21}$$

The engineering algorithm is derived based on the change characteristics of the time-varying function and reasonable linear approximation processing within a very short interval of the rotation speed updating cycle. On the basis of maintaining the performance of the original algorithm, the complicated integral operation is converted into the calculation of the quadratic function, meanwhile, the traversal optimization problem of repeated operations is converted into a direct solution problem, which greatly reduces the amount of online calculations.

However, in the condition that $\hat{x}_p(t_k + T) > x^*(k) \quad u = u_{\max}$ or $\hat{x}_p(t_k + T) < x^*(k) \quad u = u_{\min}$, the above equation has no appropriate solutions. In order to avoid this situation, the effective pre-processing of restricted control parameters is required. Taking the known output capability boundary of the electromagnetic actuator into consideration, an outer-loop online reference trajectory planning strategy based on the dynamic response characteristics of the electromagnetic actuator is effective to avoid the unsolvable inner loop conditions.

3.2 Outer-loop online reference trajectory planning

The control trajectory often lacks full consideration of the dynamic system performance and the limited control ability due to limited control input parameters. Therefore, for the actual control system, how to make necessary corrections to the control trajectory according to the systematic characteristics is very beneficial for improving the transient and steady state performance.

For the high dynamic nonlinear rudder roll control system, the upper limit of the electromagnetic torque of the PMSG based actuator is determined by the relative roll speed between high dynamic nonlinear projectile and the control object (the duck rudder). According to the results of the previous research on the electromagnetic torque characteristic modeling, it can be concluded that the relationship between the threshold value of the electromagnetic torque and the above parameters can be obtained by setting u=$u_{\max}$ as

$$M_{ctrl} \in \left[K_n(\omega_P - \omega)u_{\min} \quad K_n(\omega_P - \omega)u_{\max} \right] \tag{22}$$

Then the dynamic output characteristic threshold of the controlled object can be obtained.

$$\begin{aligned} J\dot{x}_{1\max} &= \theta_1 f_1 u_{\max} + \theta_2 \cdot f_2 + \theta_3 \cdot f_3 \cdot x_2 + \theta_4 \cdot f_4 + d(t) \\ J\dot{x}_{1\min} &= \theta_1 f_1 u_{\min} + \theta_2 \cdot f_2 + \theta_3 \cdot f_3 \cdot x_2 + \theta_4 \cdot f_4 + d(t) \end{aligned} \tag{23}$$

To proceed, the maximum variation coefficient of roll state based on designed observer can be derived:

$$\begin{aligned} \dot{\hat{x}}_{1\max} &= (\lambda_1 u_{\max} + \lambda_2)t + \lambda_3 u_{\max} + \lambda_4 \\ \dot{\hat{x}}_{1\min} &= (\lambda_1 u_{\max} + \lambda_2)t + \lambda_3 u_{\min} + \lambda_4 \end{aligned} \tag{24}$$

Thereby, the control instructions beyond transient control capabilities can be re-designed considering available control ability, especially the high-transient commands, such as step instruction, are smoothly corrected and achievable.

$$x_{1r}(k+1) = \begin{cases} x_{1r}(k) + \int_{t(k)}^{t(k+1)} \dot{\hat{x}}_{1\max}\, dt & \dot{x}_{1d}(k) > \dot{\hat{x}}_{1\max} \\ x_1(k+1) & else \\ x_{1r}(k) + \int_{t(k)}^{t(k+1)} \dot{\hat{x}}_{1\min}\, dt & \dot{x}_{1d}(k) < \dot{\hat{x}}_{1\min} \end{cases} \tag{25}$$

The external control loop based on the output torque limit of the electromagnetic actuator can effectively predict and deal with the situation that the control targets exceed the control capabilities, avoiding the control output hysteresis caused by the redundant calculation of the inner loop, and effectively improving the control system response time and dynamic performance.

4. Simulations with Experimental data

In this part, the proposed control strategy is introduced into a dynamic system with constrained inputs, complicated nonlinearities and disturbances. In order to demonstrate its feasibility and effectiveness of the proposed controller, based on the test data of the 107mm shot test platform, the simulation test was completed combined with the real-time canard roll angle rate control command.

The dynamic model, exploited to verify the designed control structure, takes the external ballistic characteristics of a 155mm high-spin projectile as input, shown in Table 1, while the step speed control instruction is given as follows.

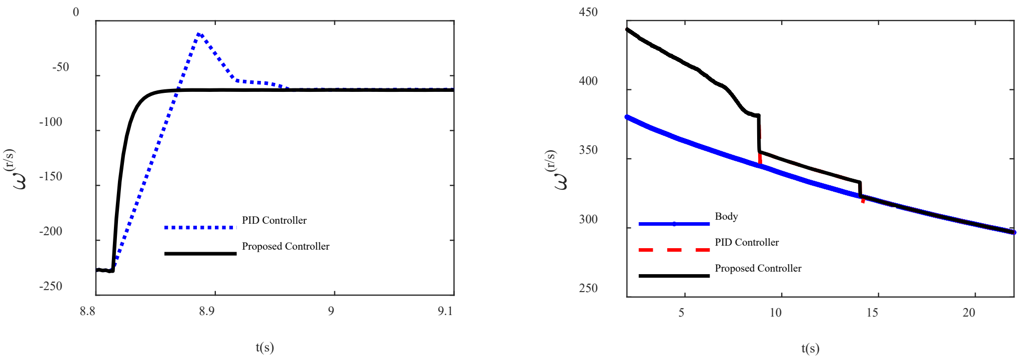
$$x_1(d) = \begin{cases} -10*2\pi & 8.81 \le t < 14 \\ 0 & t > 14 \end{cases} \tag{26}$$

Table 1

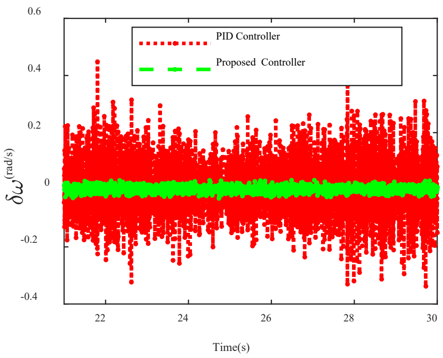
Simulation parameters of the roll speed control system

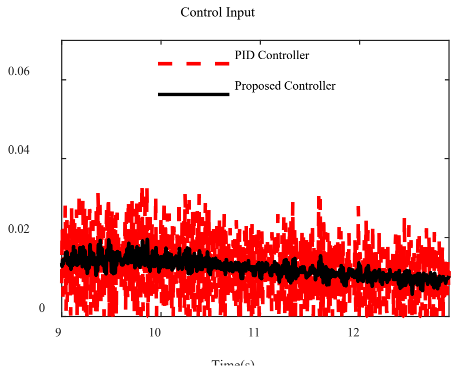
System Parameters	Value
J/kg·m^2	2.757e-4
S/ m^2	0.0189
d/m	0.1550
H/m	0
x_0/m·s^{-1}	$0.6 \cdot \omega_{p0}$
δ/°	4
Kn/kg ·m^2·s^{-1}	2.865e-4

In addition, the system disturbances and measurement noises are respectively determined as limited random and white noises. The classic PID controller is selected to conduct comparative simulations of rudder roll speed control where the response speed, stability and accuracy of the fixed canard roll control are evaluated to verify the applicability of the control algorithm proposed in this paper, afterwards, the simulation results are plotted in Fig 5. As for the proposed control structure, in order to reduce the online calculation amount of the control system, on the basis of analyzing the variation characteristics of the parameters, the limit analysis method of the control torque capability of the outer loop is used to quickly deal with the over-limit problem, and the inner loop control structure is used to update the speed within a very short time interval. The time-varying parameters are linearized, and the complicated integral optimization problem is simplified to a function to directly solve the problem.



(a) (b)





(c) (d)

Fig 5 simulation results based on experimental data

The corresponding curve of the controlled rudder roll speed under two different controllers are demonstrated in Fig 5(a), and the timeliness and stability of the proposed controller are well documented where the response time is improved by 97% from 0.1s to 0.03s. From the control overshoot that affects the system stability, the controller proposed in this paper can both successfully suppress the controlled variable at two control instruction release time points, as shown in Fig 5(b). It can be inferred from Fig 5 (c) that the double-loop controller designed in this paper shows better accuracy and stability, the maximum speed control error of the system is reduced by about 93% from 0.44rad/s to 0.03rad/s, and the RMSE value of the tracking error is also reduced by about 93% from 0.18rad/s to 0.013 rad/s. It's obvious in Fig 5 (d) that during the time period (9~13s) with strong nonlinear changes, the input parameters of the proposed control architecture show a more stable and effective output, which lays a reliable foundation for the stable and fast control of the system.

From the dynamic response verification results and above statistical analysis, it can be seen that the rudder roll control algorithm proposed in this paper can fully improve the dynamic response time of the canard, and at the same time, the dynamic response curve is more stable, which breaks through the conventional PID control algorithm in controlling the dynamic rate and overshoot. From the control steady state verification results and the dynamic curve of the system control parameter u, it can be concluded that the roll control algorithm proposed in this paper can effectively reduce the measurement error of the observed quantity, thereby avoiding the measurement error and jitter. The control amount is reduced, and the control accuracy and stability have been greatly improved. The double-loop rudder roll control algorithm proposed in this paper can meet the needs of actual roll control in terms of dynamic response performance, control response time and steady-state accuracy, having strong feasibility and superiority.

It can be known from above results and analysis, the proposed double-loop roll speed controller of a nonlinear dynamic system with constrained inputs and complicated disturbances, which consists of simplified ESO and DPC based inner loop and Electromagnetic torque model based outer loop, ensures advanced control performances in the condition of sufficient real-time computation capability. The simulation results show that the method can compensate for the nonlinearity and uncertainty existing in the rudder roll system, greatly reducing the complexity of the original algorithm, and showing strong robustness and good tracking performance.

5. Conclusions

In this paper, aiming at the nonlinear problems such as nonlinear ballistic elements, frictional perturbation, aerodynamic parameter disturbance and unmodeled dynamics in the fixed canard double-rotation ballistic correction rudder roll system, taking the fixed canard as the research object, a novel double-loop roll speed control of a nonlinear dynamic system with constrained inputs and complicated disturbances has been proposed. The proposed double-loop control strategy achieves a balance between solving nonlinear problems and limited control input through two closed-loop control structures. In the inner loop, simulations results based on experimental data demonstrate that the advanced effectiveness and better robustness for nonlinear uncertainties, modeling errors, measuring disturbances are promised by ESO and DPC based simplified controller. Meanwhile, in the outer loop, necessity of trajectory planner for control parameter preprocessing based on electromagnetic torque capability prediction model is verified. Simulation results demonstrate that the applicability of the proposed control structure can be certificated by the smoother control input, faster control responses, smaller tracking errors and better nonlinear adaptability. In our future research work, we will consider the necessary nonlinear modeling correction strategies in more practical applications with complicated dynamic and disturbed issues.

Acknowledgement

This work was supported by the Start-up research fund for the high-level talents of Jinling Institute of Technology (jit-b-202112).

REFERENCES

[1] *Cui Y B, Chen X , Xu J*. Research on Single Channel Rolling Control for Fixed Canard Rudder. Applied Mechanics and Materials, 2013, 433-435:1150-1153.

[2] *Yin T, Jia F, Yu J*. Research on Roll Control System for Fixed Canard Rudder of the Dual-Spin Trajectory Correction Projectile. Wireless Personal Communications, 2018(2):1-16.

[3] *Yu W, Wang X M, Yu J Y*. Influence of control strategy on stability of dual-spin projectiles with fixed canards. Defence Technology, 2018, 14(6):11.

[4] *Yin T , Jia F, Jiyan Y U , et al*. Robust Adaptive Control of Roll Position of Fixed Rudder for Dual-spin Projectile with Improved LuGre Friction Model. Acta Armamentarii, 2019.

[5] *Cheng J, Yu J Y, Wang X M, et al*. Research on Working Condition of Electromagnetic Actuator of Trajectory Correction Projectile with Decoupled Canards. Acta Armamentarii, 2014, 35(12):2010-2015.

[6] *Zhang Y , Peng L , Xiao L , et al*. Research on control scheme of dual-spin projectile with fixed canards// IEEE International Conference on Mechatronics & Automation. IEEE, 2016.

[7] *Zhang X, Yao X, Yang Z, et al.* Analysis of angular motion of dual-spin projectile with fixed-canards under period average control. Acta Aeronautica et Astronautica Sinica, 2019.

[8] *Cheng, Shen, Deng*. Novel Aiming Method for Spin-Stabilized Projectiles with a Course Correction Fuze Actuated by Fixed Canards. Electronics, 2019, 8(10):1135.

[9] *Mullen J, Bailey S C C, Hoagg J B*. Filtered dynamic inversion for altitude control of fixed-wing unmanned air vehicles. Aerospace Science & Technology, 2016, 54:241-252.

[10] *Lu P, Kampen E J V, Visser C D, et al*. Aircraft fault-tolerant trajectory control using Incremental Nonlinear Dynamic Inversion. Control Engineering Practice, 2016, 57:126-141.

[11] *Hui-Song G , Lu L , X Jin-Lin, et al.* Research on the shift prediction of electric tractor test bench based on fuzzy control[J]. UPB Scientific Bulletin, Series D: Mechanical Engineering, 2019, 81(1):143-154.

[12] *Yang Y , Liu Q , Yue D , et al.* Predictor-Based Neural Dynamic Surface Control for Bipartite Tracking of a Class of Nonlinear Multiagent Systems. IEEE Transactions on Neural Networks and Learning Systems, 2021, PP(99):1-12.

[13] *Adir V G , Stoica A M , Whidborne J F* . Sliding Mode Control of a 4Y Octorotor. UPB Scientific Bulletin, Series D: Mechanical Engineering, 2012, 74(4):37-52.

[14] *Truong D Q, Ahn K K.* Force control for hydraulic load simulator using self-tuning grey predictor – fuzzy PID. Mechatronics, 2009, 19(2):233-246.

[15] *Zhao X , Yang J , Yu C* . Wet clutch shifting process with adaptive fuzzy control. UPB Scientific Bulletin, Series D: Mechanical Engineering, 2018, 80(3):89-102.

[16] *Yan S , Chen J , Yang T , et al.* Improving the Performance of Direct Power Control Using Duty Cycle Optimization. IEEE Transactions on Power Electronics, 2018:1-1.

[17] *Zhang Y, Jiao J, Xu D.* Direct Power Control of Doubly Fed Induction Generator Using Extended Power Theory Under Unbalanced Network. IEEE Transactions on Power Electronics, 2019, PP(12):1-1.

[18] *Corts P, Rodrguez J, Antoniewicz P, et al.* Direct Power Control of an AFE Using Predictive Control. IEEE Transactions on Power Electronics, 2008, 23(5):2516-2523.

[19] *Pawar S N, Chile R H, Patre B M.* Predictive extended state observer-based robust control for uncertain linear systems with experimental validation. Transactions of the Institute of Measurement and Control, 2021(23):014233122110025.

[20] *Yin T T, Jia F X, Ji-Yan Y U, et al.* Direct Model Predictive Rotating Speed Control for Rudder in Dual-Spin Projectile with Output-Feedback Extended State Observer. Transactions of Beijing Institute of Technology, 2019.