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Fuzzy Fractional Order $PI^{\lambda}D^{\mu}$ Controller Design Based on Correction Projectile System

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Abstract

The control system for correction projectile is a strongly nonlinear and time-varying complicated system. Conventional PID controller has been widely used in the control system of ammunition. But it cannot achieve highly control effect because of the complexity and uncertainty of system model. With fuzzy control and fractional order control theory, this paper puts forward a fuzzy fractional order controller through taking correction projectile as controlled object. On one hand, self-adaptive adjustment to the parameters can be realized because fuzzy control is not dependent on the control model; on the other hand, better control effect can be brought by using fractional order controller to control integer order system. Simulation results show that the the fuzzy fractional order $PI^{\lambda}D^{\mu}$ controller demonstrates the better time domain response characteristics compared with the fractional order $PI^{\lambda}D^{\mu}$ controller and the conventional PID controller, and can be used to improve the robustness of the system in the correction projectile system control.

***Keywords**: fuzzy control; fractional order $PI^{\lambda}D^{\mu}$ controller; correction projectile; Oustaloup algorithm; fuzzy logic*

1. Introduction

Correction projectile refers to making correction on the ballistic deflection once or more in a certain ballistic range after the projectile coming out of the muzzle, so as to improve hit precision. It is quasi-exact guided ammunition with high benefit and low cost which is different from the uncontrollable conventional ammunition and the high-cost ammunition that can hit the target accurately. Correction projectile becomes one of the important aspects in the field of ammunition development in recent years because of its high quality and low cost. Control system in projectile design is the key to the correction effect. And the design of the controller affects the performances of control system. It is the foundation of the realization of the control system. In the previous smart ammunition control system, conventional PID controller with the characteristics of clear physical meaning, simple structure and good robustness is widely used. However, with the development of smart weapons and ammunition towards high precision and high speed, the model of control system becomes more and more complex, and the performance requirements are increasingly high. As a result, it is hard for the traditional PID controller to achieve satisfactory.

In recent years, fractional order control arises more and more attention from scholars, who apply the theory to practical problems. Fractional calculus is the theory studying on arbitrary order of differential and integral, and is the extension of the integer order

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calculus. It can realize the control result with better robustness than the integer order control. It applies to both the fractional order system and the integer order system [1][2][3]. Fractional order $PI^{\lambda}D^{\mu}$ controller has two more adjustable parameters, λ and μ, than the integer order controller. It increases the regulation range and can improve the control quality of integer order control system. Scholars have gradually realized the advantages of fractional order controller. References [4] and [5] have applied the fractional calculus to the flight control field, respectively designed fractional order controller of hypersonic aircraft and guided projectile what has obtained better robustness and stronger anti-interference performance compared with PID controller, and been able to eliminate static error better. By use of the fuzzy control method, online self-adaptive parameter adjustment can be realized through fuzzy reasoning according to the actual situation of the system. Reference [6] has designed the flight control system of missile patrol by using fuzzy control method. References [7] and [8] have designed fuzzy fractional order controllers respectively according to the integer order and fractional order object model, and have carried on the numerical simulation analysis.

The capability and utility of conventional PID controller has increased to a good extent due to its hybridization with fuzzy logic controllers (FLC) [9]. Reference [10] points out that it provides a flexible and model-free approach to control engineers for designing a controller based on their own intuitions for the systems with uncertainties and nonlinearities. Reference [11] has designed the Fractional Order Fuzzy Proportional-Integral-Derivative (FOFPID) controller for a two-link planar rigid robotic manipulator for trajectory tracking problem.

With the advantages of fuzzy control and the fractional order theory, this paper puts forward a kind of system design method based on fuzzy fractional order control through taking the correction projectile model as the control object. With the characteristics of fractional order controller, the system increases the parameter tuning range and improves the control quality. At the same time, it can achieve the purpose of independence of the control object and on-line parameter tuning.

2. The Mathematical Model of Correction Projectile

Control mechanism of two-dimensional correction projectile includes corresponding control mechanisms controlling the movement direction, rolling direction and movement speed of the projectile, *etc*. Pulse thrust or servo are often used to control two-dimensional correction projectile. In this paper, the author adopts a type of canard correction projectile model as shown in Figure 1. In the process of the projectile flying to the target, two-dimensional correction to the control system can be made by the use of canard rudder plate aerodynamic characteristics, so as to make the movement path of the projectile be more close to the trajectory of presupposition.

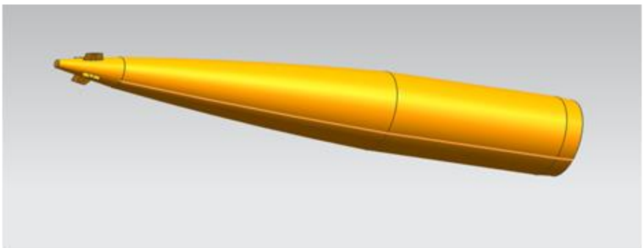

Figure 1. Structure of Two-Dimension Correction Projectile

The movement of the correction projectile flying in the air is a very complicated process. To describe it, six degree of freedom trajectory differential equations is needed.

We need to establish and simplify guided projectile, six degree of freedom motion equations to be a correction projectile mathematical model [12]. The coupling among the channels is usually neglected when designing correction projectile. The research is done separately in the pitch and lateral channels. In this paper, the author takes the pitch channel as the example to design the control law. Assuming the projectile taking unpowered flight (T=0) and the gravity, the rotation of the earth and other factors are neglected, then the simplified model for the pitch channel is as follows:

$$\begin{cases} m\dot{v} = -X - mg\sin\theta \\ mv\dot{\theta} = Y - mg\cos\theta \\ \dot{x} = v\cos\theta \\ \dot{y} = v\sin\theta \\ \dot{\theta} = \omega_z \\ \theta = \vartheta - \alpha \end{cases} \tag{1}$$

Among them, X is the aerodynamic drag, Y is the aerodynamic lift, θ is the trajectory inclination angle, ϑ is the projectile axial pitch angle, α is the angle of attack, J_z is the moment of inertia, ω_z is the rotating angular velocity.

The model is simplified into linear equations by using the small perturbation method, the simplified longitudinal perturbation equations of motion are as follows:

$$\begin{cases} \Delta\ddot{\vartheta} + a_{22}\Delta\dot{\vartheta} + a_{24}\Delta\alpha = -a_{25}\Delta\delta_z \\ \Delta\dot{\theta} - a_{34}\Delta\alpha = a_{35}\Delta\delta_z \\ \Delta\vartheta = \Delta\theta + \Delta\alpha \end{cases} \tag{2}$$

The transfer function corresponding to the model is:

$$G(s) = \frac{\Delta\vartheta(s)}{\Delta\delta_z(s)} = \frac{a_{25}s + a_{25}a_{34} - a_{24}a_{35}}{s^3 + (a_{22} + a_{34})s^2 + (a_{24} + a_{22}a_{34})s} \tag{3}$$

Among them, $a_{22} = -\frac{M_z^{\omega_z}}{J_z}$ is the damping force coefficient, $a_{24} = -\frac{M_z^{\alpha}}{J_z}$ is the static undetermined dynamic coefficient, $a_{25} = -\frac{M_z^{\delta_z}}{J_z}$ is the manipulation of power coefficient,

$a_{34} = \frac{Y^{\alpha}}{mv}$ is the normal dynamic coefficient , $a_{35} = \frac{Y^{\delta_z}}{mv}$ is the rudder surface dynamic coefficient.

3. Fractional Order PIλDμ Controller

3.1. Structure of Fractional Order $PI^{\lambda}D^{\mu}$ Controller

Fractional order controller makes the differential and integral orders of the integer order PID controller into any real number. The output of the fractional order controller in time domain can be expressed as[8]

$$u(t) = k_p e(t) + k_i D^{-\lambda} e(t) + k_d D^{\mu} e(t) \tag{4}$$

In the formula, $D^{-\lambda}$ and D^{μ} are the basic operators of fractional calculus, $e(t)$ is the input error value; k_p is the roportional control parameters, k_i is the integral control parameters, k_d is the differential control parameters; λ and μ are the integral order number and the fractional order number of the controller, they can be any real numbers.

After transform of Laplace, the transfer function of the fractional order $PI^{\lambda}D^{\mu}$ is obtained as follows:

$$G_f(s)=\frac{U(s)}{E(s)}=k_p+k_i s^{-\lambda}+k_d s^{\mu} \tag{5}$$

While λ=1, μ=1, it is integer order PID controller; While λ=1, μ=0, it is integer order PI controller; While λ=0, μ=1, it is integer order PD controller. Fractional order controller has better flexibility than the integer order PID controller. By choosing different λ and μ, the system can obtain better frequency response characteristics, among them, the integral order λ effects the steady precision of the system, and the static error of the system can be reduced by adjusting parameter λ; differential order μ effects the overshoot of the system, and the performance of the closed-loop control system can be improved by adjusting parameter μ.

As the fractional system or controller cannot be directly implemented in software simulation, we need to realize it by making discretization or approximation of differential and integral operators, namely the method of digital realization is needed to complete the design of the fractional order controller, and the precision of the digital realization affects the design of the fractional order controller directly. The digital realization method of the fractional order controller includes two main kinds of methods to calculate the numer: z-domain numerical method and the time-domain numerical method[13][14][15]. And in the time-domain numerical method, the Oustaloup algorithm is easy to realize in engineering, being able to fit fractional calculus with high accuracy in the frequency range, so it is a better digital realization algorithm for fractional calculus. With Oustaloup rejector[16], the fractional calculus S^{α} can be fitted in the frequency domain. This is a kind of approximation method to realize fractional order controller. Among them, the transfer function of the rejector is:

$$S^{\alpha}=K\prod_{k=1}^{N}\frac{s+w_k'}{s+w_k} \tag{6}$$

The pole zero and gain of the rejector are ,

$$w_k'=w_b w_u^{(2k-1-\alpha)/N} \tag{7}$$

$$w_k=w_b w_u^{(2k-1+\alpha)/N} \tag{8}$$

Among them, $K=w_h^{\alpha}$, $w_u=\sqrt{w_h/w_b}$ (w_b, w_h)is fitting frequency interval, N is the order of the rejector.

The structure of the fractional order controller is as shown in Figure 2:

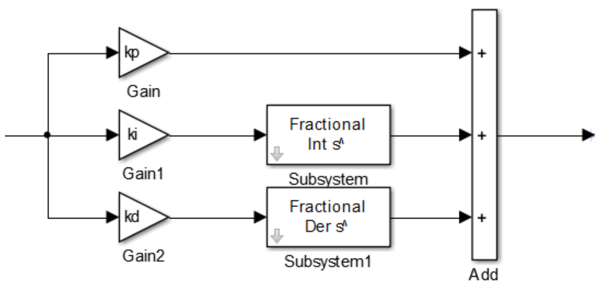

Figure 2. Structure of Fractional Order $PI^{\lambda}D^{\mu}$ Controller

3.2. Parameter Characteristics of Fractional Order $PI^{\lambda}D^{\mu}$ Controller

Because there exists two more parameters in the fractional order controller, parameter tuning becomes complicated, thus the tuning method by integer order controller parameter is no longer suitable. The parameter tuning method of the fractional order controller is different from that of the integer order PID controller. It mainly includes dominant pole placement method, amplitude margin and phase margin quantity method, optimization method, *etc*. In this paper, the author uses the optimization method of ITAE standards to adjust the parameters of the fractional order controller.

$$J = ITAE = \int_0^{t_f} t\left|e(t)\right|dt = \int_0^{t_f} t\left|r(t) - y(t)\right|dt \tag{9}$$

In the formula: r(t) is the expected value of the closed loop system, y(t) is the output value of the closed loop system.

In the process of fractional order controller optimization, we continuously change the order of the fractional order, and after a lot of experiments, suitable controller parameters λ and μ are obtained. Because these exists two more degrees of freedom in the fractional order controller than that in the integer order controller, thus more parameters need to be fitted, we change the parameters λ and μ to find suitable parameters first, then determine the parameters k_P, k_i, k_d by optimization method.

4. Fuzzy Fractional Order $PI^{\lambda}D^{\mu}$ Controller

Neither the integer order controller nor the fractional order controller has the function of parameter self-tuning, we introduce fuzzy control rules[17] to find out the relations between error *e*, error rate of change e_c and the three parameters of fractional order $PI^{\lambda}D^{\mu}$ controller. According to different *e* and e_c , adjust the parameters k_P, k_i, k_d on line, so as to improve the control effect.

4.1. Fuzzy Control Rules

Fuzzy controller is suitable for uncertain systems or nonlinear systems. It has a strong robustness on the parameter changes of the controlled object, as well as strong ability to suppress outside interference. In this paper, the author uses the two-input three-output controller structure, namely that the input is angle error *e* and angle error change e_c , the output is adjusting parameters k_P, k_i, k_d. The relationship between output variables and input variables is determined through the establishment of fuzzy rules. Divide each variable into 7 fuzzy states with the corresponding language variables {NL，NM，NS，ZO，PS，PM，PL}. They mean negative big, negative medium, negative small, zero, positive medium positive small and positive big, respectively. The discourse domain of *e* and e_c is set as [-6，6], the discourse domain of k_P and k_d is set as [-3，3], the discourse domain of k_i is set as [-0.1，0.1]. Membership functions for the triangular type and Gauss type are chosen for fuzzy language variable value, and the membership functions for the input and output variables are shown in Figure 3.

Selection principle of control quantity is: when the error is very big, eliminating the error as soon as possible is the standard for the selection of the control quantity; and when the error is small, maintaining the stability of the system and reducing the overshoot are the standards for selecting control quantity. In this paper, the author uses Mamdani reasoning model which includes 49 control rules, if-then statement is used in Matlab simulation, control rules are shown in Table 1:

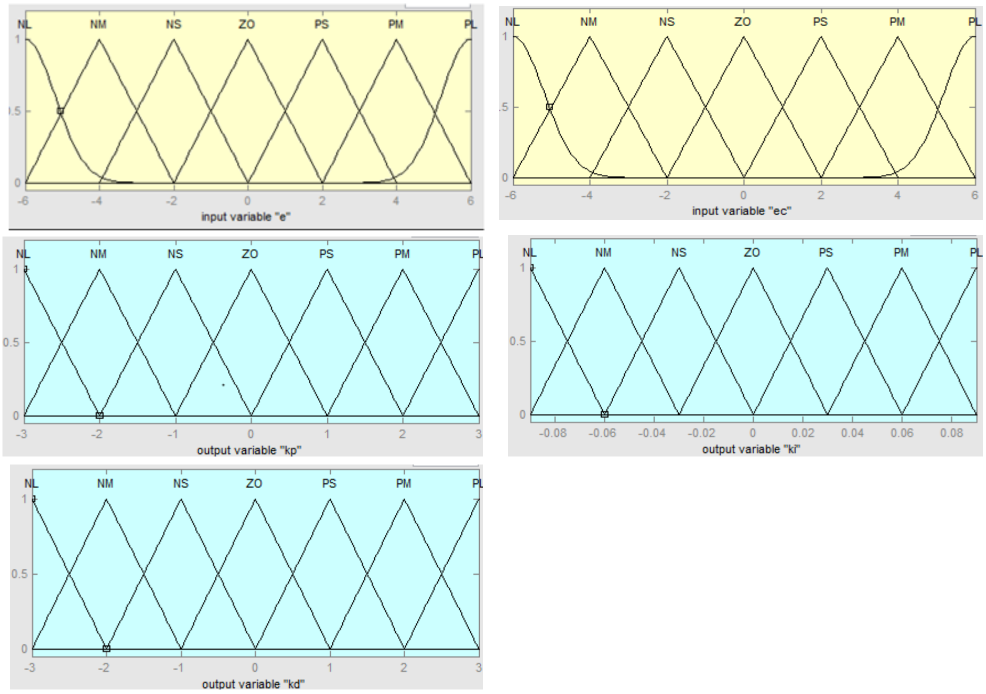

Figure 3. Membership Degree Fuzzy Subset of Input and Output

Table 1. Fuzzy Control Rule Table

e_c / e	NL	NM	NS	ZO	PS	PM	PL
NL	PL/NL/PS	PL/NL/PS	PM/NL/ZO	PM/NM/ZO	PS/NM/ZO	PS/ZO/PL	ZO /ZO/PL
NM	PL/NL/PS	PL/NL/NS	PM/NM/NS	PS/NM/NS	PS/NS/ZO	ZO/ZO/NS	ZO/ZO/PM
NS	PM/NL/ZO	PM/NM/NS	PM/NM/NS	PM/NS/NS	ZO/ZO/ZO	NS/PS/PS	NM/PS/PS
ZO	PM/NM/ZO	PS/NM/NS	PM/NS/NS	ZO/ZO/NM	NM/PS/ZO	NM/PM/PS	NM/PM/PM
PS	PS/NM/ZO	PS/NS/ZO	ZO/ZO/ZO	NM/PS/ZO	NS/PS/ZO	NM/PM/PS	NM/PS/PS
PM	PS/ZO/PL	ZO/ZO/NS	NS/PS/PS	NM/PM/PS	NM/PM/PS	NL/PM/PS	NL/PL/PS
PL	ZO/ZO/PL	ZO/ZO/PM	NM/PS/PS	NM/PM/PM	NM/PS/PS	NL/PL/PS	NL/PL/PL

4.2. Structure of Fuzzy Fractional Order $PI^{\lambda}D^{\mu}$ Controller

Differing from the fractional order controller which uses optimization method ITAE criterion to adjust the controller parameters, the fuzzy adaptive fractional order control has two inputs, respectively the error and error change rate that can make on-line real-time correction to the parameters with fuzzy reasoning, and then assign the parameters to the fractional order controller. With the characteristics of the fuzzy controller and the fractional order controller, a fuzzy fractional order controller is set up to realize on-line control of data model. The structure diagram of the controller is shown in Figure 4:

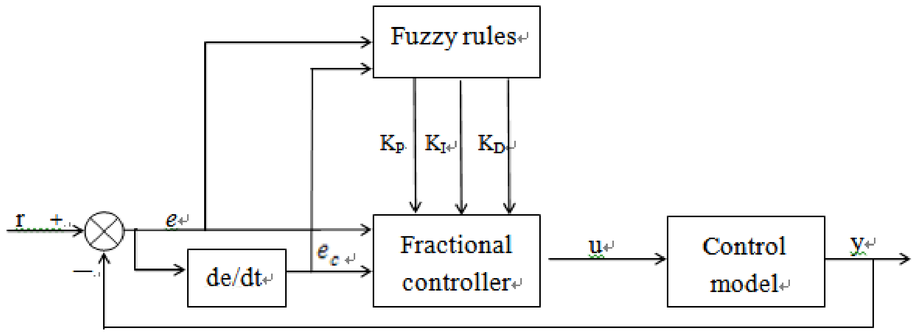

Figure 4. Structure Of Fuzzy Fractional Order Pi^λd^μ Controller

Among them, the relationships between parameters in the controller are as follows:

$$k_p = k_{p0} + \Delta k_p$$
$$k_i = k_{i0} + \Delta k_i \qquad (10)$$
$$k_d = k_{d0} + \Delta k_d$$

In the formula, k_{p0} k_{i0} and k_{d0} are the initial parameters of the fractional order controller in the fuzzy fractional order controller, and are obtained by the the parameter tuning method of integer order controller. For λ and μ of the fractional order controller, their influences on the control system are needed to be considered. With the experience and references, the values of λ and μ are among [0,2], after simulation, the values are determined: μ=0.9, λ=0.6. This is obtained by fuzzy reasoning of the fuzzy controller. Then by different e and e_c , k_p 、 k_i and k_d are adjusted on line.

The work steps of the fuzzy fractional order controller are as follows:

5. Assign zero to the initial values of e and e_c , and assign values to k_{p0}、k_{i0} and k_{d0} ;
6. Calculate the current values of Δk_p , Δk_i and Δk_d by fuzzy rule;
7. Obtain the current values of k_p k_i and k_d by using formula (10);
8. Put k_p、 k_i and k_d into formula (4) and (6),then u_m and y_m at the time of m are got;
9. Then using the formula $e_m = r_m - y_m$ and $e_{cm} = r_{cm} - y_{cm}$, then e_m and e_{cm} at the time of m are got;
10. Returning to step2， adjust and .

5. Simulation Experiment

Use Simulink in the software Matlab to set up control system, and apply the fuzzy fractional order controller to the pitch channel model of the correction projectile. For the integer order shell model, design the integer order controller, the fractional order controller and the fuzzy fractional order controller respectively, take the unit step response signal as the input signal. Among them, according to reference [7] which is about the the change range of the parameters influence on the control system, after repeated simulation adjusting, the parameters of the fractional order controller are set as $k_p = 0.9$, $k_i = 0.6$, $k_d = 0.1$,μ=0.9, λ=0.4, the parameters of the integer order controller are set after optimization as $k_p = 0.9$, $k_i = 0.6$, $k_d = 0.2$.

Making comparative analysis on the 3 kinds of controllers, we can get system step response curve under different controllers as shown in Figure 5. The time domain index corresponding to the various controllers are as shown in Table 2. Figure 5 and Table 2 show that we can control the controlled object by using integer order PID controller, so that the response curve tends to be stable, but the overshoot of the system is large. The control effect of fractional order $PI^{\lambda}D^{\mu}$ controller (FOPID) on the controlled object is better then that of the integer order controller, and the overshoot is reduced. And from the step response curve, the overshoot of the control model under fuzzy fractional order $PI^{\lambda}D^{\mu}$ controller (FFOPID) is 5.9%, and the adjusting time is 3.85. By contrast, the performance index is greatly reduced, which means more stable. The results of variation in ITAE to FOFPID,FOPID and PID controllers are listed in Figure 6. This shows that fuzzy fractional order controller has better control performance on integer order controlled object than the other two kinds of controllers.

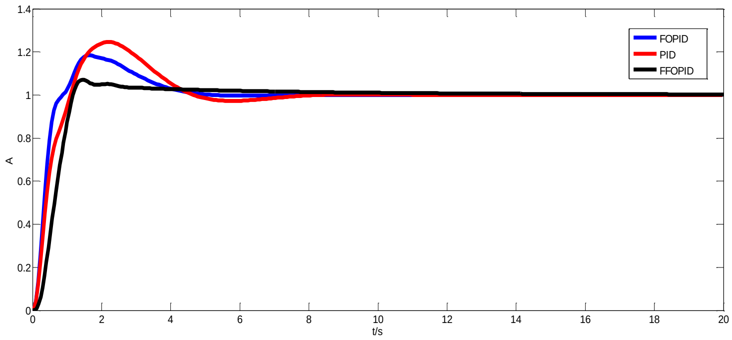

Figure 5. Step Response Comparison of Controller

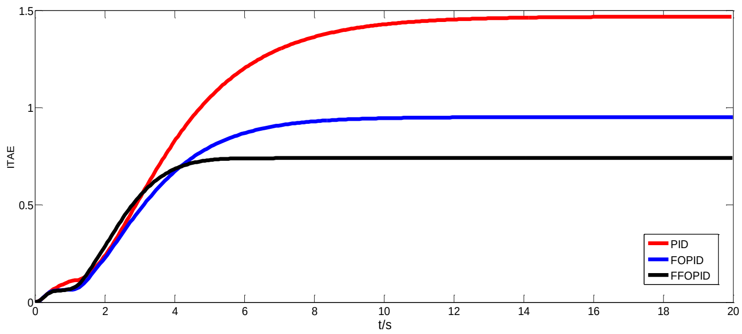

Figure 6. Variaton in ITAE for Controllers

Table 2. Time Domain Indices of Three Controllers

Controller Types	Rise Time t_r/s	Adjustment Time t_s/s	Overshoot M_p/%	J_{ITAE}
PID	2.26	7.85	25.8	1.48
FOPID	1.59	7.60	19.2	0.95
FFOPID	1.38	3.85	5.9	0.73

In order to test the anti jamming performance of the control system, we make simulation analysis on the control effects of PID controller, FOPID controller and FFOPID controller respectively. When the simulation time is 10s, put step interference of 0.2mm amplitude to the control system to simulate uncertainty effect factors in the process of missile flight. Figure 7 shows that, under the disturbed scenario, the overshoot of the integer order PID controller is bigger, and more time needs to be adjusted if needed to complete adjustment in 6s. Compared with PID controller, the overshoot of the fractional order $Pi^{\lambda}D^{\mu}$ controller is smaller. And the fuzzy fractional order $PI^{\lambda}D^{\mu}$ controller has the smallest overshoot as well as the best inhibitory effect on interference, least stable error and stronger stability. Therefore, in the interference condition, using the fuzzy fractional order controller to control the integer order control object is able to obtain stronger anti-interference and robustness, and eliminate the static error better.

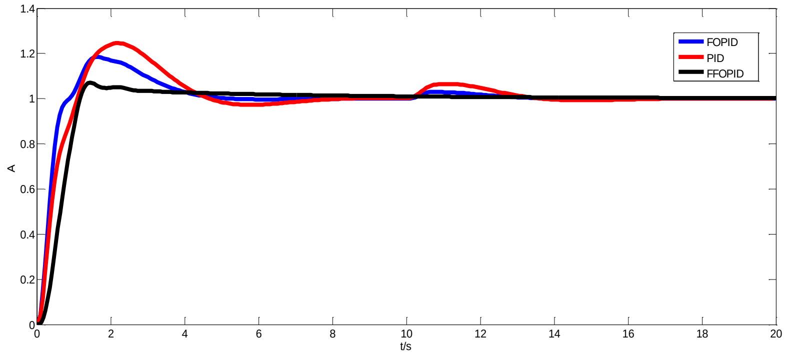

Figure 7. Step Response Curve Comparison after Adding Interference

6. Conclusion

By the mathematical model of the projectile as the control object, this paper puts forward fuzzy fractional order $PI^{\lambda}D^{\mu}$ controller and applies it to the pitch control system of the correction projectile. Through a combination of fractional calculus and the principle of fuzzy control, the author uses the Oustaloup approximation algorithm digital to realize the fractional order controller, determine the fuzzy rules, and set up the structure of fuzzy fractional order controller. For the correction projectile model, detailed design steps and numerical simulation realization of fuzzy fractional order $PI^{\lambda}D^{\mu}$ controller are described. The result shows that: fuzzy fractional order controller introduces fuzzy rules and realizes on-line self-adaptive adjustment, then obtains the optimal parameters of the controller. Compared with fractional order $PI^{\lambda}D^{\mu}$ controller and integer order PID controller, fuzzy fractional order $PI^{\lambda}D^{\mu}$ controller has significantly smaller system overshoot and faster convergence speed, these are conducive to improve the control effect of the system. In the same interference condition, fuzzy fractional order $PI^{\lambda}D^{\mu}$ controller achieves a better anti-interference ability than the other two controllers.

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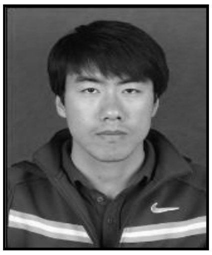

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