Simulation of Networked Control Systems Based on Single Neuron Adaptive PID with Smith Predictor

Haitao Zhang, Jinbo Hu, Guifang Wu and Wenshao Bu

***Abstract*—Single neuron control system not only has simple structure and strong robustness, but also can adapt to the systems affected by interference. At the same time, Smith predictor is characterized by predicting the dynamic characteristics of time-delay systems. Aimed at the problem of time delay in networked control systems, a kind of controller based on improved single neuron adaptive PID with new Smith predictor is presented. It utilizes the self-learning and self-adaptive ability of single neuron, and Smith predictive compensation characteristics. The network based control for a DC motor is simulated in Matlab. The simulation result shows that the control algorithm based on improved Single Neuron adaptive PID with new Smith predictor can effectively improve the robustness and adaptability of networked control systems.**

***Index Terms*—Networked control systems， Time delay， Single neuron， Smith predictor**

I. INTRODUCTION

A networked control system is one of the new technologies in the field of computer control. Since it has the advantage of sharing information resources, easy extension and maintenance, high reliability and flexibility, it has been a development trend of complex control systems and remote control systems [1-2]. In networked control system, the data and information are transmitted through the network, which will lead to time delay of network. Time delay can result in system performance degradation, and even make system become instable.

At present, the research results of networked control systems mainly include two aspects: control and network. In terms of control, the research content mainly includes controller design, control algorithm design and system stability research. Kumar etc. proposed a modified Smith predictor which uses Markov approach and Kalman estimation algorithm in networked control system [3]. Aslam designed the event-triggered fuzzy filter for Takagi-Sugeno fuzzy systems subject to deception attacks under the stochastic multiple time-varying delays [4]. Abate etc. proposed a novel networked control system based on fuzzy logic and an existing wM-Bus at 169-MHz infrastructures for gas metering so as to preserve the effectiveness of the Cathodic protection system [5].

A kind of control algorithm based on improved single neuron adaptive PID with new Smith predictor is proposed in the paper. Because of the existence of forward delay and feedback delay, a new Smith predictor is adopted. In addition, single neuron controller is used so as to solve the problem that is generated by the inaccuracy of controlled object model. Single neuron controller has the ability of self-learning and self-adaption. It can automatically adjust the PID parameters, and achieve the optimal control of networked control system. The performance of proposed algorithm is better than traditional PID controller. Furthermore, it shows excellent adaptability in the control of the nonlinear and complex objects.

II. THE STRUCTURE OF NETWORKED CONTROL SYSTEM

The networked control systems are also called network based control systems. The networked control system is a fully networked distributed control system, which is a closed loop feedback control system connected through the network [6-7]. Specifically, the networked control system uses the network as the transmission medium. It realizes the information exchange among sensors, controllers and actuators, and realizes resource sharing and remote monitoring. The networked control system is generally composed of controller, controlled object and communication networks.

A typical block diagram of networked control system is shown in Fig. 1. Data is transmitted among the controller, actuator and sensor via a shared communication network, which will cause the network transmission delay. So there are essentially three kinds of time delays in the system. τ_{sc} is the time delay from the sensor to the controller, τ_{ca} is the time from the controller to the actuator, and τ_c is the calculation delay in the controller.

Since τ_c is very small, it is generally considered to be merged into τ_{ca} , so the system delay is expressed

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as $\tau = \tau_{sc} + \tau_{ca}$.

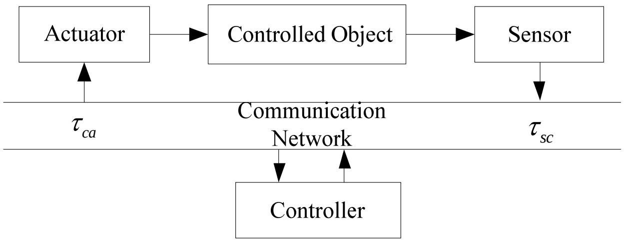

Fig. 1. A typical block diagram of networked control systems

There is time delay in the control loop, and the time delay is uncertain. With the change of the controlled object model, the data sampling value is uncertain, and the signals of the forward and feedback channels are both added with random time delay. Random time delay makes the system slower in response, larger in overshoot and longer in adjustment time. When the time delay is too large, it will affect the stability of the system.

III. THE CONTROL ALGORITHM OF NEW SMITH PREDICTOR

A. The principle of classic Smith predictive compensation

In 1957, the classical Smith predictive control scheme was proposed to deal with the pure time delay in the closed loop control system. On the basis of simple PID control, predictive compensation is used to make the closed loop characteristic equation free of pure delay. Smith predictive control improves the stability of the whole system. It theoretically solves the control problem of time-delay systems, but there are some shortcomings in practical control systems [8]. The block diagram of Smith predictive control system is shown in Fig. 2.

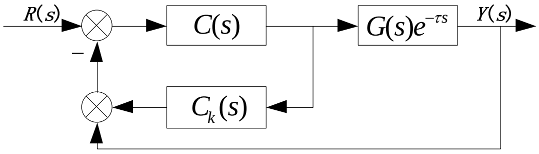

Fig. 2. The block diagram of Smith predictive control system

In Fig. 2, the closed loop transfer function of the system is as follows:

$$\frac{Y(s)}{R(S)} = \frac{C(s)G(s)e^{-\tau s}}{1 + C(s)C_k(s) + C(s)G(s)e^{-\tau s}} \tag{1}$$

In Eq. (1), $C(s)$ is the transfer function of controller, $G(s)e^{-\tau s}$ is the transfer function of controlled object which contains pure time delay. $C_k(s)$ is the transfer function of predictive compensation model. In order to make the characteristic equation of the closed loop system does not contain pure time delay. Then Smith predictor should meet Eq. (2).

$$C_k(s) = G_m(s)(1 - e^{-\tau_m s}) \tag{2}$$

When $G_m(s) = G(s)$ and $\tau_m = \tau$, the closed loop transfer function of system is simplified, the following conclusion is obtained:

$$\frac{Y(s)}{R(S)} = \frac{C(s)G(s)e^{-\tau s}}{1 + C(s)G(s)} \tag{3}$$

The system characteristic equation is expressed as the following:

$$1 + C(s)G(s) = 0 \tag{4}$$

In the system, $G(s)$ is the controlled object, and its output is the feedback signal, so the feedback signal can be received τ seconds in advance. Therefore, this control method is called predictive compensation control. Its closed loop characteristic equation does not contain pure time delay, so the Smith predictor eliminates the possibility of system instability caused by time delay. Thus the method can significantly improve the control performance of the system.

However, the classical Smith predictive compensation control method is only applicable to the traditional feedback control system with known controlled object model and constant system delay.

But the system studied in this paper is a closed loop feedback control system based on network. Because the network induced delay may be random, time-varying and uncertain, the system delay cannot be deterministic or known constant. The networked control system is related to network topology, communication protocol, network loading and packet size. It is difficult or impossible to get an accurate delay prediction or identify accurate mathematical model of controlled objects [9]. The classical Smith predictor cannot fully meet the requirements of networked control systems.

B. The Principle of New Smith Predictor

Smith predictor can predict the dynamic characteristics of time-delay system. The controller can receive the delayed controlled quantity in advance by using the predictor. The controller can take action in advance, so as to reduce overshoot and accelerate the adjustment process [10]. However, in networked control systems, due to the time-varying and uncertainty of time delay, it is almost impossible for the traditional Smith predictor to establish an accurate time delay prediction model. When the signal is transmitted, there will be "null sampling" or "multi sampling" due to the existence of time delay. Only using the traditional Smith predictor will produce compensation error and affect the stability of the system. Therefore, a new Smith predictor is proposed, which can realize dynamic compensation control [8].

Fig. 3 shows the structure of a networked control system with a new Smith predictor.

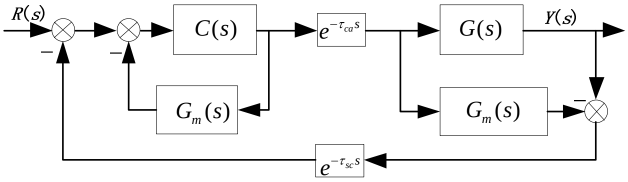

Fig. 3. The block diagram of networked control system with new Smith predictor

In Fig. 3, $C(s)$ is the transfer function of controller, $G(s)$ is the transfer function of controlled object. Then the closed loop transfer function of the system is as follows:

$$\frac{Y(s)}{R(S)}=\frac{C(s)e^{-\tau_{ca}s}G(s)}{1+C(s)G_m(s)+C(s)e^{-\tau_{ca}s}(G(s)-G_m(s))e^{-\tau_{sc}s}} \tag{5}$$

Its characteristic equation is as follows:

$$1+C(s)G_m(s)+C(s)e^{-\tau_{ca}s}(G(s)-G_m(s))e^{-\tau_{sc}s}=0 \tag{6}$$

In Eq. (6), it includes the controlled object $G(s)$ and the predicted model $G_m(s)$, and doesn't include the predicted model of time delay τ_{ca} and τ_{sc}.

When the system satisfies $G_m(s)=G(s)$, Eq. (5) is simplified and the following relation is obtained:

$$\frac{Y(s)}{R(s)}=\frac{C(s)e^{-\tau_{ca}s}G(s)}{1+C(s)G(s)} \tag{7}$$

Its characteristic equation is as follows:

$$1+C(s)G(s)=0 \tag{8}$$

In this case, the block diagram of the networked control system could be simplified to Fig. 4.

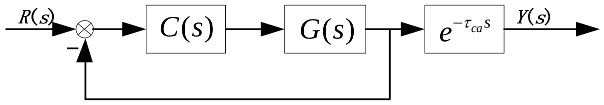

Fig.4. The simplified block diagram of new Smith predictor

The Eq. (8) shows that all exponential delay terms affecting stability have been removed from the closed loop characteristic equation, so the performance of the control system will be improved [11].

Because the networked delay is sometimes variable and uncertain, the system just using the new Smith predictor cannot obtain satisfactory results. It is necessary to introduce other effective control methods to overcome the adverse effects of network delay.

IV. THE NETWORKED CONTROL SYSTEM WITH SINGLE NEURON ADAPTIVE PID AND NEW SMITH PREDICTOR

A. *The Single Neuron adaptive PID control*

As the basic unit of neural network, neurons have self-learning and self-adaptive ability. The control system is constructed by neurons, and the algorithm is simple, easy to implement, and has good robustness. In addition, the most prominent feature is that the system does not need to accurately identify the structure and parameters of the controlled object [12]. Therefore, the design of the single neuron adaptive controller does not need an accurate controlled object model.

Considering these characteristics of single neuron, we introduce an adaptive PID algorithm based on single neuron and apply it to the system with a new Smith predictor. The method improves the performance of networked control system by combining the advantages of single neuron and new Smith predictor.

The single neuron model has been applied to PID control systems. Fig. 5 is the block diagram of single neuron adaptive PID control systems.

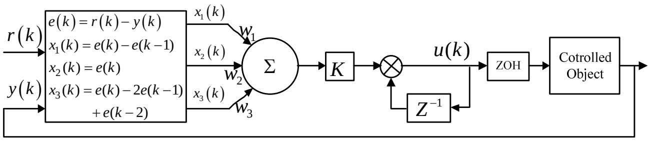

Fig.5. The block diagram of single neuron adaptive PID

In Fig. 5, k represents the sampling time, $r(k)$ and $y(k)$ are the input and output of the system respectively, and meet $e(k)=r(k)-y(k)$. ZOH is a zero order holder. The control quantity is generated by the neuron related to self-learning [13]. $x_1(k)$, $x_2(k)$ and $x_3(k)$ are inputs of the neuron, which satisfy the following relationship:

$$\begin{aligned}x_1(k)&=e(k)-e(k-1)\\x_2(k)&=e(k)\\x_3(k)&=e(k)-2e(k-1)+e(k-2)\end{aligned} \tag{9}$$

w_1, w_2 and w_3 are respectively the weight values of the input $x_1(k)$, $x_2(k)$ and $x_3(k)$.

K is the proportional coefficient of neuron, and $K>0$, then the output of the controller can be expressed as:

$$u(k)=u(k-1)+K\sum_{i=1}^{3}w_i(k)x_i(k) \tag{10}$$

K is the proportional coefficient of the neuron. The learning method of weight value adopts the supervised Hebb learning rule.

$$\begin{aligned}w_1(k+1)&=w_1(k)+\eta_P e(k)x_1(k)\\w_2(k+1)&=w_2(k)+\eta_I e(k)x_2(k)\\w_3(k+1)&=w_3(k)+\eta_D e(k)x_3(k)\end{aligned} \tag{11}$$

where η_P, η_I and η_D are the learning rates of proportion, integration, and differentiation respectively. Different learning rates η_P, η_I and η_D are adopted for proportion, integral and differential to adjust different weight coefficients.

The single neuron adaptive PID control method realizes the adaptive control of the system by adjusting the weight coefficient. To ensure the convergence and robustness of the learning method, we normalize equations (10) and (11) to obtain the following expression:

$$u(k)=u(k-1)+K\sum_{i=1}^{3}w_i\,'(k)x_i(k) \tag{12}$$

$$w_i\,'(k)=w_i(k)/\sum_{i=1}^{3}\|w_i(k)\| \tag{13}$$

B. *The Improved Single Neuron adaptive PID control*

In Eq. (11), the weight updating doesn't consider the output of single neuron controller. In order to suppress the large weight fluctuation caused by the change of control quantity, the control quantity is added in the weight updating equations. The improved weight updating method is as follows:

$$\begin{aligned}w_1(k+1)&=w_1(k)+\eta_P e(k)x_1(k)u(k)\\w_2(k+1)&=w_2(k)+\eta_I e(k)x_2(k)u(k)\\w_3(k+1)&=w_3(k)+\eta_D e(k)x_3(k)u(k)\end{aligned} \tag{14}$$

In addition, $x_3(k)$ is the differential of deviation $e(k)=r(k)-y(k)$, and large input change can will cause large fluctuation of $x_3(k)$. So the differential forward is introduced into single neuron control system. Considering the above reasons, Eq. (9) can be improved as follows:

$$\begin{aligned} x_1(k) &= e(k)-e(k-1) \\ x_2(k) &= e(k) \\ x_3(k) &= y(k)-2y(k-1)+y(k-2) \end{aligned} \tag{15}$$

Using the output quantity $y(k)$ instead of $e(k)$ in $x_3(k)$, the sudden change of the reference input $r(k)$ will not affect $x_3(k)$. So the control quantity generated by the differential of deviation $e(k)$ will be eliminated.

On the other hand, for the single neuron control algorithm, the coefficient K in Eq. (12) reflects the adjusting amplitude. For large deviations, the adjusting amplitude is also large to satisfy the requirement of system rapidity. And for small deviations, the adjusting amplitude is also small to satisfy the requirement of system stability [14]. Hence, the coefficient K can be designed as the function of deviation $e(k)$. Utilizing practical experience and Matlab simulation, the parameter K can be adjusted using the following equation:

$$K=\mu\left|e(k)\right|^{\alpha} \tag{16}$$

In Eq. (16), the variables α and μ are both constants, and $\alpha<1$. The parameters μ and α are selected by practical experience and Matlab simulation. Generally, if a larger μ is selected, the system rapidity will be better, but overshoot of the system will be greater. If the smaller α is selected, the system stability will be better. On the contrary, the larger α is not conductive to the stability of the system; the smaller μ is not conductive to the rapidity of the system.

C. The Single Neuron adaptive PID control with new Smith Predictor

The single neuron adaptive PID controller is an improvement of the traditional PID controller. It overcomes the sensitivity of the traditional PID control to the changes of the model parameters of the controlled object. It also has better learning ability and is easy to ensure the real-time performance of the system [15]. Therefore, under the control of single neuron adaptive PID controller, the networked control system can obtain better control effect than traditional PID controller

New Smith predictor can eliminate the influence of time delay in the networked control system. The single neuron adaptive PID controller can use the self-learning ability and adaptability of neuron to adjust three parameters of PID online, so the controlled object can obtain better stability. Hence the combination of the single neuron adaptive PID and new Smith predictor not only has excellent adaptability and strong controllability, but also has strong dynamic characteristics. The block diagram of the networked control system with new smith predictor and single neuron adaptive PID is shown in Fig. 6.

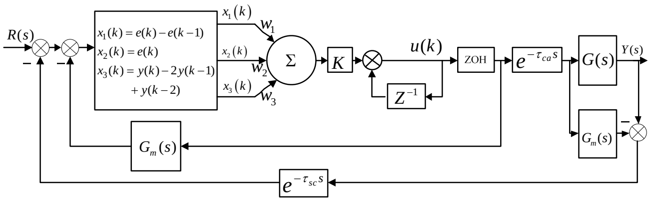

Fig. 6. The block diagram of networked control system with new smith predictor and improved single neuron adaptive PID

V. SIMULATION RESULTS

In order to verify the effectiveness of the proposed method, the DC motor is simulated in Matlab [16]. The transfer function of the DC motor is described as follows:

$$G(s)=\frac{2029.826}{(s+26.29)(s+2.296)} \tag{17}$$

A. Simulation of precise object model

The sampling period T=10ms, the reference input R=50rad/s. The time delay in forward and feedback channel is generated by gauss random generator in Simulink toolbox, and its variance is 0.000001. The initial values of neuron weights are $w_1(0)=w_2(0)=w_3(0)$=0.1, the learning rate of neurons are η_P =5, η_I =0.03, and η_D =1.5. For the fixed proportional coefficient, K =0.2; for adaptive proportional coefficient, $K=0.05\left|e(k)\right|^{0.1}$. Using simple PID method, PID control with Smith predictor method, single neuron adaptive PID with new Smith predictor method, and improved single neuron adaptive PID with new Smith predictor method respectively, the step responses are observed under random delay with different mean values. For observing the effect of time delay τ, the simulation experiments are carried out under three different random delays with mean values of $\tau=5ms$, $\tau=10ms$ and $\tau=15ms$ respectively.

The desired speed is 50rad/s, and the step responses are shown in Fig. 7, Fig. 8 and Fig. 9. The dimensions of vertical axis and horizontal axis variables in the following figures are respectively angular velocity and time.

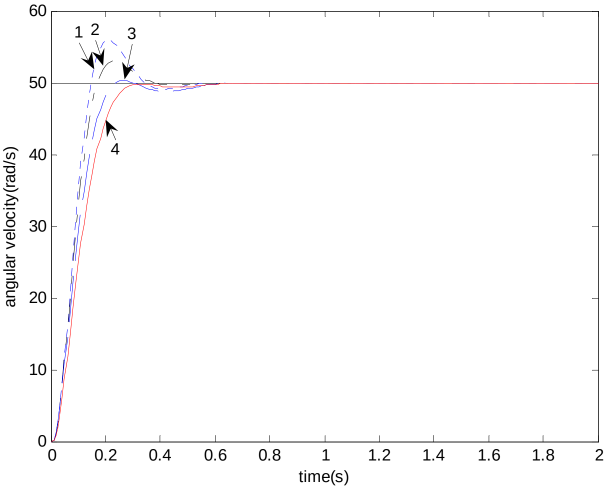

Fig. 7. Step response with time delay $\tau=5ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

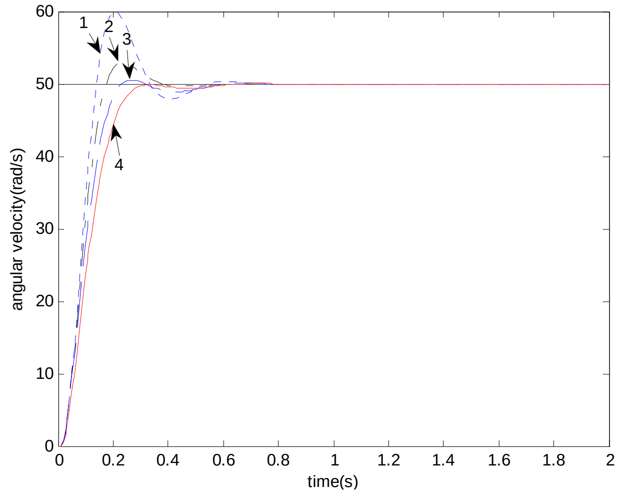

Fig. 8. Step response with time delay $\tau = 10ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

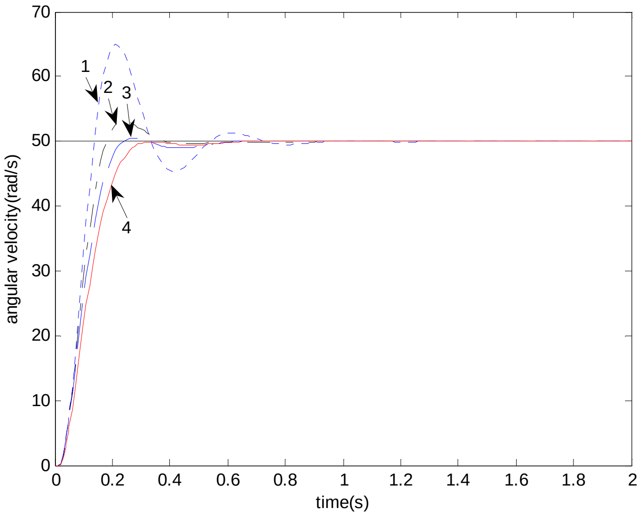

Fig. 9. Step response with time delay $\tau = 15ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

Simulation results show that although the overshoot of the traditional PID algorithm is large, all algorithms can reach a stable state. With the increase of time delay, the control effects of these methods are obviously different. In the case of simple PID control, the response curve produces obvious oscillation. Although the system reaches a stable state, the adjustment time becomes longer and the overshoot becomes larger. However, the other three methods can still achieve stability quickly, and the response speed is basically not affected by the time delay. In addition, although the response speed of the improved single neuron algorithm with the new Smith predictor is a little slower, it basically has no overshoot.

During the simulation, the interference is added to the controller output at 1 second. The Pulse generator chosen from the Sources module library is used to generate interference, and parameters of Pulse generator are: the Pulse height is 20, the Pulse period is 20 seconds, and the Pulse width is 0.2 seconds. The step responses with the interference are shown in Fig. 10, Fig.11 and Fig. 12.

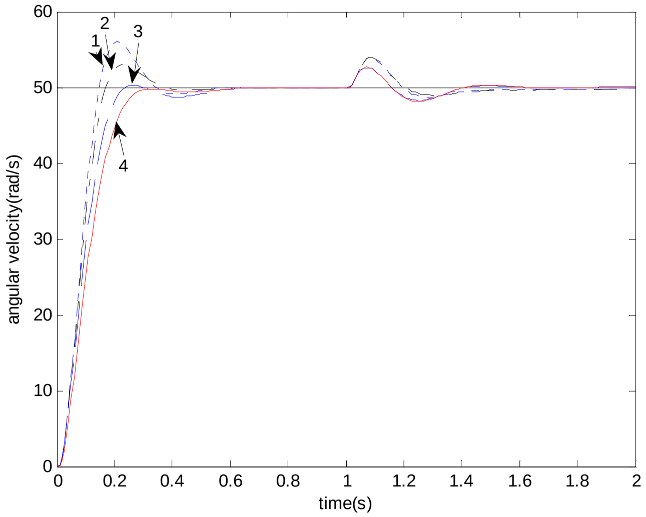

Fig. 10. Step response with disturbance and time delay $\tau = 5ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

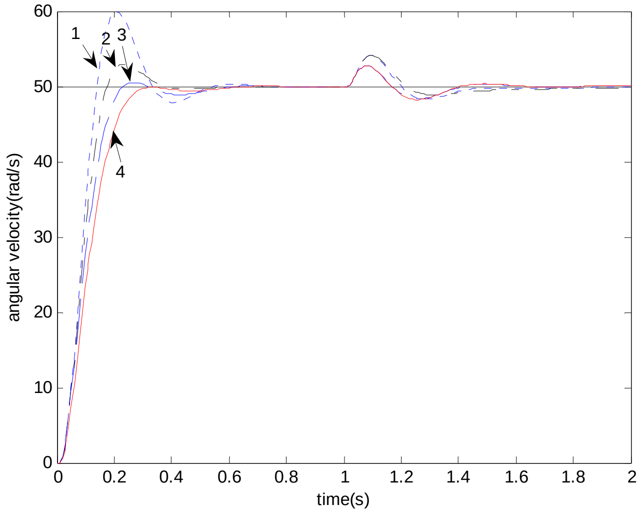

Fig. 11. Step response with disturbance and time delay $\tau = 10ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

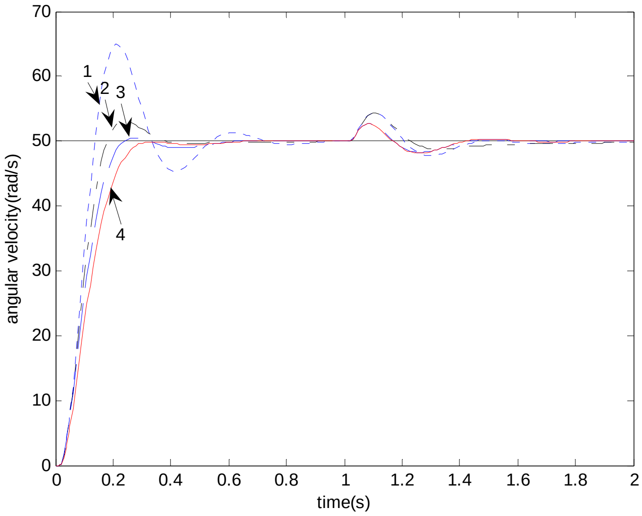

Fig. 12. Step response with disturbance and time delay $\tau = 10ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

The simulation results show that all algorithms have overshoot after adding interference, but can return to a stable state. However, the improved single neuron algorithm with a new Smith predictor has less overshoot and can return to the stable state faster.

B. Simulation of imprecise controlled object model

In fact, the theoretical model and the actual model of the controlled object do not exactly match. Assuming that the actual controlled object model is different from Eq. (17), its transfer function is as follows:

$$G(s)=\frac{2029.826}{(s+25)(s+2.296)} \tag{18}$$

The simulation experiments are carried out for this model under same conditions. The desired speed is still 50rad/s, and the step responses are shown in Fig. 13, Fig. 14 and Fig. 15.

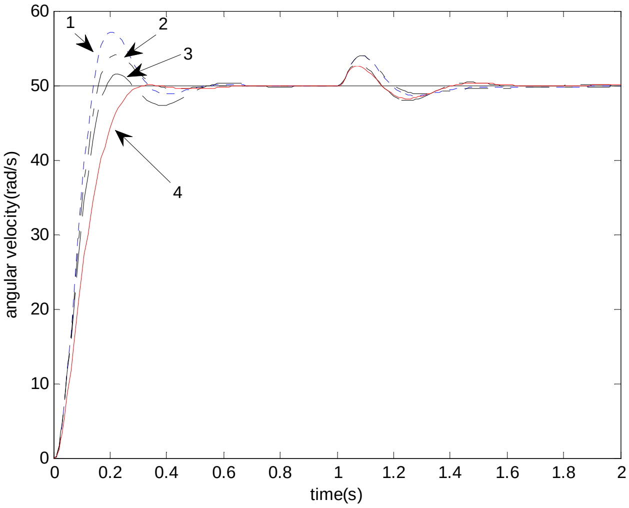

Fig. 13. Step response with disturbance and time delay $\tau = 10ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

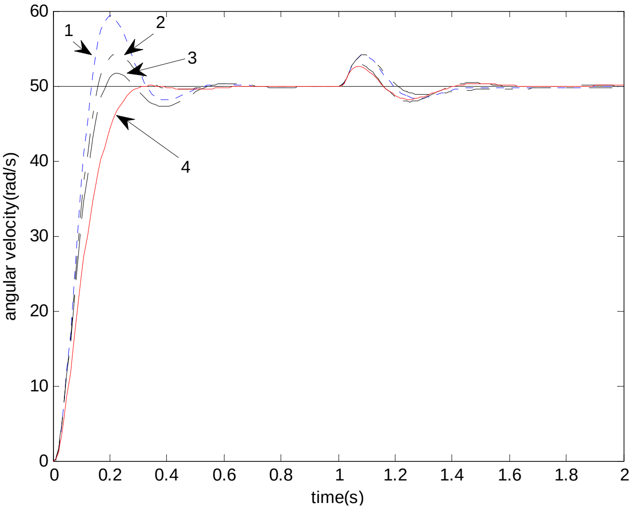

Fig. 14. Step response with disturbance and time delay $\tau = 10ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

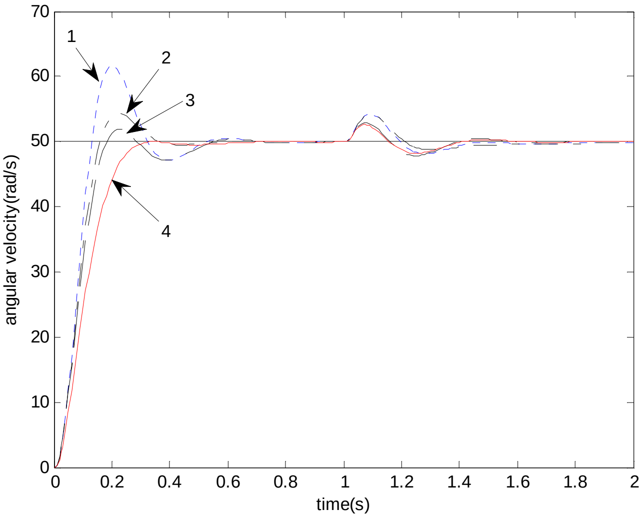

Fig. 15. Step response with disturbance and time delay $\tau = 15ms$

1-PID; 2-PID control with Smith predictor; 3- single neuron adaptive PID with new Smith predictor; 4- improved single neuron adaptive PID with new Smith predictor

The simulation results show that all algorithms have overshoot after using imprecise controlled object model, but can return to a stable state. However, the improved single neuron algorithm with a new Smith predictor has less overshoot and can return to the stable state faster.

C. Simulation Summary

Compared with other three methods, the improved single neuron adaptive PID with new Smith predictor has the advantages of high control accuracy, small overshoot, short adjustment time and strong anti-interference ability. The single neuron adaptive PID realizes the automatic adjustment of control parameters. The new Smith predictor realizes that the forward channel delay from the controller to the actuator is removed from the closed loop system, and the feedback channel delay from the sensor to the controller is completely eliminated from the control system. Thus the performance of the whole control system is improved. Therefore, the control method based on improved single neuron adaptive PID and new Smith predictor can effectively meet the requirements of networked control system.

VI. CONCLUSION

In this paper, the simulation model of networked control system is established by Matlab, and the simulation research is carried out by using the control algorithm of improved single neuron adaptive PID with new smith predictor. The simulation result shows that this control algorithm possesses stable output, short adjustment time and strong robustness, and can meet the requirements of networked control system.

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