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Servo control system of electric cylinder based on feed forward prediction

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ABSTRACT

In this paper, combining feed forward DMC and PID control algorithm is applied to the servo system of electric cylinder. Considering for the servo control system of electric cylinder, a PID controller based on dynamic matrix control (DMC) feed forward is designed with utilizing the quickness and adaptive characteristics of dynamic matrix predictive control by combining the DMC algorithm with PID controller, which could obtain online control for the servo control system of electric cylinder and realize the rapid and real-time control. Simulation results show that the servo control system of electric cylinder has better static and dynamic performance.

Key words: electric cylinder; DMC predictive control; PID control; feed forward

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INTRODUCTION

The static and dynamic tension-compression as well as torsion test about the specimen can be accomplished by the high precision multi-function torsion testing machine that is an important test equipment for evaluating the performance of shaft parts, which has important significance in research of materials and structure[1-2]. At present, The common driver ways mainly include hydraulic drive, motor drive, pneumatic drive and electric cylinder drive, etc[3-5]. However, the demand for the purity of oil is higher and the working performance are susceptible to temperature. Besides, there are high requirements and expensive price about maintaining hydraulic system and manufacturing elements. It is difficult to carry out fault diagnosis. The air compressibility is big and the stability as well as efficiency of the pneumatic system are low in the pneumatic drive. In addition, the transmission is inaccurate and exhaust noise is big so that the output power is small[6-8]. The Electric cylinder control is drived through the control of the servo motor, and liquid such as oil and gas is not necessary as a medium to transfer power in the process of the Electric cylinder control. It effectively avoided to produce the system errors as a result of oil leak, which results in that the experiment data is not accurate and the control accuracy is not high. Compared with the electro-hydraulic servo valve control system, the performance of the electric control system is not affected by the environment, temperature, the polluted hydraulic valve and the factors of fluid medium. etc. In addition, the connection between servo motor and servo drive is convenient as well as quick, which can ignore the effects of the complex oil pump, piping and the cooling system and other ancillary facilities in the hydraulic system.

Electric cylinder servo motor is usually controlled by PID control. The PID control algorithm is currently widely used in automatic control of thermal objects with simple principle, high universality. As thermal objects with large delay, large inertia, nonlinear and uncertainty characteristics, dynamic characteristics has been changing along with the change of operation condition. The classic PID is difficult to deal with complex control system requirements. For the most advanced and intelligent control theory, due to the particularity of electric power production and the unique requirements of safety and reliability, its application in the electric power production is slow. So it is necessary to research the control method that keeps simple structure of the classic PID, and the thermal objects still have a strong adaptability with the parameter changing and external disturbance in the method. For the research of the large delay, parameters system for boiler main steam temperature model, there is not yet publicly literature that has researched traditional PID improving from the perspective of control history in the world. This paper has improved the traditional incremental PID controller introducing historical information based on the qualitative analysis of the delay system inverse dynamics, redefining the new correct reference quantity instead of the original reference.

The control principle of PID is simple, easy setting as well as using, easy and the adjusting performance indicators is not very sensitive to the slight changes of the controlled object. But PID controller could achieve a satisfactory effect only under the premise of getting good parameters setting. Smith predictive control method can make the controller action in advance, thus offsetting the effects of time delay characteristics, reducing the overshoot and improving the stability of the system as well as accelerating the adjustment process and improving the rapidity of the system. But Smith predictive control has two main shortcomings: (1) the robustness is not guaranteed with the object's properties changed; (2) when there is interference, it can not be overcomed. For the servo system of electric cylinder with the characteristics of nonlinear, uncertainty, time-varying and interference, it is necessary to seek a new control strategy combined with PID control in order to meet the requirements of control performance in the servo system.As an important kind of predictive control algorithm, dynamic matrix control (DMC) has been widely used in the field of modern control[9]. The dynamic step response of the system is employed as the prediction model, and then the historical information and the future inputs of the system are utilized to predict the future outputs. The ill-posed caused by model errors or environmental disturbances is avoided through rolling optimization replacing the global optimization. In this paper, PID controller based on feedforward DMC is applied to design and analysis the servo control system of electric cylinder. DMC algorithm uses the object's dynamic step response function as the prediction model, which does not rely on accurate mathematical model. The rolling optimization is adopted to realize the optimization of control input at the current moment. The numerical simulation results have verified the effectiveness of the PID controller based on feedforward DMC by proposed in this paper.

The research working is as follows: firstly, in terms of the existing servo system of electric cylinder, the function and characteristics of the original composition in the system and interference factors with the system's working influenced are analyzed to determine the transfer function of the system. Secondly, a PID controller based on feedforward DMC is designed to ensure that the system has good stability and robustness with complicated conditions of the system's parameters changing as well as external load disturbance and cross interference. Finally, MATLAB software is applied to obtain the system's simulation and the three coefficient of PID are setted by Ziegler-Nichols setting method, which achieves a better control effect about the system by gradually changing the various parameters of the controller.

WORKING PRINCIPLE AND MATHEMATICAL MODEL

Electric cylinder is driven by the servo motor and then decelerated by the synchronous belt, driving the ball screw rotating, then making the nut on the screw do linear movement, finally driving electric cylinder piston moving. Electric cylinder can be roughly divided into three parts of servo motor, synchronous belt, and ball screw. Movement flow chart is shown in Fig. 1.

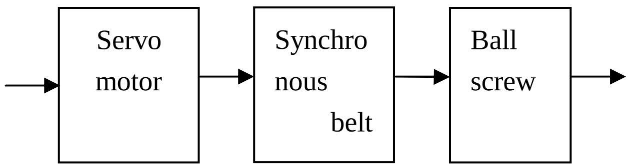

Fig. 1: The process program of electric cylinder

In this paper, the mechanism modeling method is adopted to establish the accurate mathematical model of the servo control system of electric cylinder.

The open loop transfer function of the servo control system of electric cylinder is shown in the Eq. (1):

$$G(s)=G_1(s)G_2(s)=\frac{K_vK_i}{s(1+T_ms)}=\frac{K}{s(1+T_ms)} \quad (1)$$

where the measured static magnification is taken as K=486（rpm/v）and the median value of time constant in the system is Tm=0.46 s. The block diagram of the servo control system of electric cylinder is obtained according to the mathematical models of each part derived by above method, which is shown in Fig. 2.

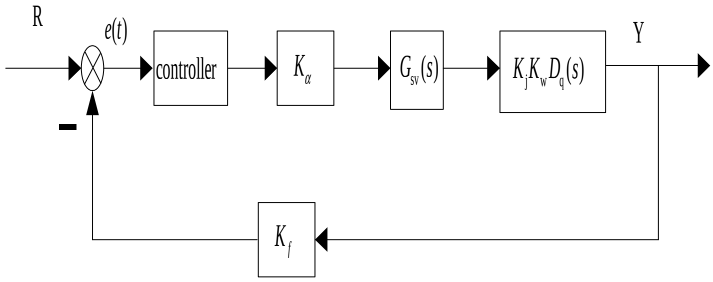

Fig. 2: The block diagram of the servo control system of electric cylinder

Thus, the whole transfer function of the servo control system of electric cylinder is as follows (mathematical model) :

$$G_{sv}(s)=\frac{X_v(s)}{\Delta I(s)}=\frac{486K_1/130}{0.46k_2s^2+s} \quad (2)$$

K1 and K2 change in the range of [0.9, 1.1] in Eq. (2).

DESIGN OF PID CONTROLLER BASED ON FEEDFORWARD DMC

Establishing the feedforward DMC algorithm

This paper has adopted DMC as the feedforward controller of the system. The input R of the servo control system of electric cylinder is optimized in advance combined with a PID feedback controller.

DMC algorithm adopts the step response function with the object as the prediction model. After a unit step signal is added to the input of the system, the dynamic step response coefficient at each sampling time is $a_i=a(iT)$, i=1,2,…,N respectively. N is the length of the time domain with the model.

According to the proportion and superposition principle of the linear system, the input increments $\triangle u(k+j)$, $j=0,1,\cdots,M-1$ with groups of M are input to the system from the kth moment, the predictive output at the P moment in the future is the sum of the output without any control increments and the outputs when the M control increments is applied individually to the system, namely:

$$y_M(k+1|k)=y_0(k+1|k)+a_1\Delta u(k) \quad (3a)$$

$$y_M(k+2|k)=y_0(k+2|k)+a_2\Delta u(k)+a_1\Delta u(k+1) \quad (3b)$$

…

$$y_M(k+P|k)=y_0(k+P|k)+a_P\Delta u(k)+\cdots+a_{P-M+1}\Delta u(k+M-1) \quad (3c)$$

Eq. (3) is written in vector form as follows:

$$Y_M(k+1)=Y_0(k+1)+A\Delta U(k) \quad (4)$$

In Eq.(4), $\Delta U(k)=[\Delta u(k),\Delta u(k+1),\cdots,\Delta u(k+M-1)]^{\mathrm{T}}$, P is the time length with rolling optimization, M $(M\le P\le N)$ is the length of control time domain and A is $P\times M$ matrix made up of the step response coefficients, which is as follows:

$$A=\begin{bmatrix} a_1 & 0 & \cdots & 0 \\ a_2 & a_1 & \ddots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ a_P & a_{P-1} & \cdots & a_{P-M+1} \end{bmatrix}_{P\times M} \quad (5)$$

The rolling optimization objective function is adopted for DMC. For every kth moment, the optimal controlling law in control time-domain *M* in the future is selected to make the predictive values in the time-domain *P* in the future as close as possible to the output values. The optimal controlling law is determined by the following quadratic performance index:

$$\min J(k)=\sum_{i=1}^{P} q_i\left[y_r(k+i)-y_M(k+i\mid k)\right]^2+\sum_{j=1}^{M} r_j\Delta u^2(k+j-1) \quad (6)$$

Where, q_i and r_j are the weight coefficients, which stands for the inhibition of the tracking error and control values changing respectively.

Eq.(6) is written in vector form as follows:

$$\min J(k)=\left\|Y_r(k+1)-Y_M(k+1)\right\|_Q^2+\left\|\Delta U(k)\right\|_R^2 \quad (7)$$

where, $Y_r(k+1)=\left[y_r(k+1),\ldots,y_r(k+P)\right]^{\mathrm{T}}$ are the desired output values at *P* sampling time in the future; *Q* is the matrix of error coefficients and *R* is the control matrix, which is as follows respectively:

$$Q=diag[q_1,q_2,\ldots,q_P],\ R=diag[r_1,r_2,\ldots,r_M] \quad (8)$$

Differentiating Eq.(7) with respect to $\Delta U(k)$, and ordering $dJ(k)/d\Delta U(k)=0$,the optimal controlling law can be obtained:

$$\Delta U(k)=(A^TQA+R)^{-1}A^TQ\left[Y_r(k+1)-Y_0(k+1)\right] \quad (9)$$

We only need to determine the control incremental $\Delta u(k)$ at the current moment. However, $\Delta U(k)=[\Delta u(k),\Delta u(k+1),\cdots,\Delta u(k+M-1)]^{\mathrm{T}}$ is given by the Eq. (9). At the next moment, $\Delta u(k+1)$ is obtained by the same optimization method, and this is the "rolling optimization" strategy. By Eq. (9), the optimal value of $\Delta u(k)$ at the current moment is as follows:

$$u(k)=u(k\text{-}1)+\Delta u(k) \quad (10)$$

In the Eq. (10), $\Delta u(k)=[1,0,\cdots,0](A^TQA+R)^{-1}A^TQ\left[Y_r(k+1)-Y_0(k+1)\right]$.

Feedback PID controller

The conventional PID controller is widely used in industrial process control because of simple algorithm, convenient setting as well as strong robustness, high reliability and the advantages of not needing object's precise mathematical model. This paper adopts the incremental PID controller to realize on-line control of the servo control system of electric cylinder and the control law can be described as follows:

$$u_{\mathrm{PID}}(k)=u_{\mathrm{PID}}(k\text{-}1)+K_p(e(k)-e(k-1))+K_ie(k)+K_d(e(k)-2e(k-1)+e(k-2)) \quad (11)$$

In the Eq.(11), K_p, K_i and K_d are proportion coefficient, integral time constant and differential time constant respectively. $e(k)$ is the difference between the expected values and real output values at *k* moment.

By combining the feedforward DMC algorithm with PID feedback controller in above, the controller design of the servo control system of electric cylinder can be established as shown in Fig.3:

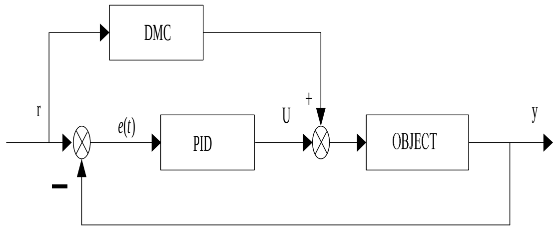

Fig. 3: The controller design of the servo control system of electric cylinder

Thus, the general optimal input value at *k* moment with the system is as follows:

$$u_{\text{sum}}(k)=u_{\text{PID}}(k)+u(k) \quad (12)$$

Setting PID controller parameter

In fact, the control effects satisfying the control system can be achieved with the parameter setting about the PID controller by adjusting the three parameters K_p, $K_I$and K_D to match the controller features and characteristics of the controlled object. For the control of the pure lag industrial process, the common industrial setting method of PID parameters is: the stable boundary method (critical proportion band method). The integral and differential effect are removed under the condition of the closed-loop system and then make the system produce persistent oscillation under the action of pure proportioner. The critical gain K_p and critical shock T at this period are utilized according to the experience formula and correction proposed by the Ziegler and Nichols shown in the Tab. 1and the three parameters of PID can be obtained from the Tab. 1.

Tab. 1: Parameter setting formula of the critical proportion band method

	K_p	K_I	K_D
P	$0.5K_p$		
PI	$0.455K_p$	$0.535K_p$	
PID	$0.6K_p$	$1.2K_p$	$0.075K_p$

THE SIMULATION RESULTS OF ELECTRIC CYLINDER SERVO CONTROL SYSTEM

It is important to study the stability of the servo system. When the servo system of electric cylinder running steady, it seems to be expected that the outputs can track inputs accurately or repeat the inputs as far as possible. Namely, the steady-state tracking accuracy with the system is required as a result of getting the steady-state error as small as possible.

The response results of step input

When given a unit step disturbance, the system simulation of the step response is obtained by using MATLAB software and the PID parameters are optimized by the critical proportion band method. Then, the dynamic step response coefficients of dynamic matrix predictive control can be obtained in the Fig.4 and the results of the system simulation of the step response are shown in Fig.5 and Fig.6 respectively.

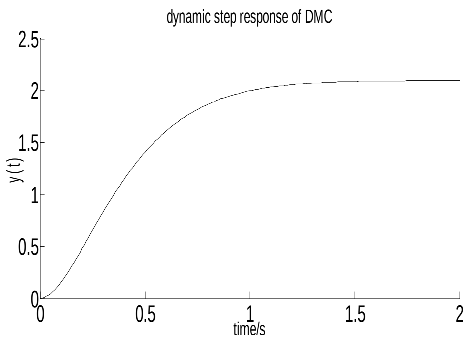

Fig. 4: The curve of dynamic step response coefficients with DMC

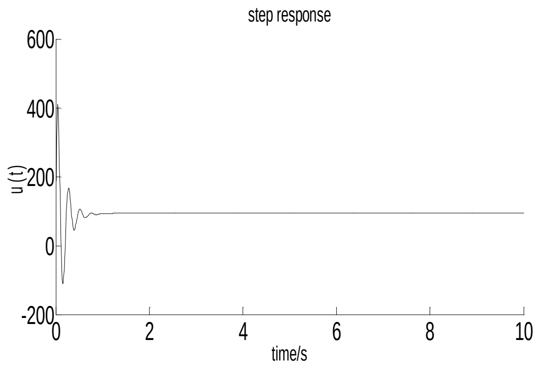

Fig. 5: The input curve of step response with feedforward DMC - PID controller

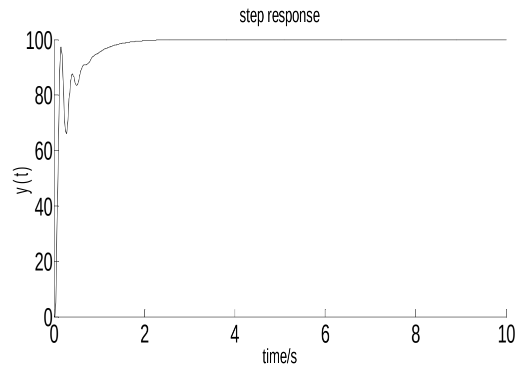

Fig. 6: The output curve of step response with feedforward DMC - PID controller

As can be seen from the Fig. 5 and Fig. 6, the system steady-state error is smaller and the adjust time is within 2 s by utilizing the feedforward DMC - PID controller. The speed of system response is quick, which meets the design requirements of the servo control system of electric cylinder.

The response results of pilse input

When given a unit impulse disturbance, the use of MATLAB software simulation system of the step response.The system simulation of the step response is obtained by using MATLAB software keeping the PID parameters same and the impulse responses of the system control values as well as the outputs are observed and the results are shown in Fig.7 and Fig.8 respectively

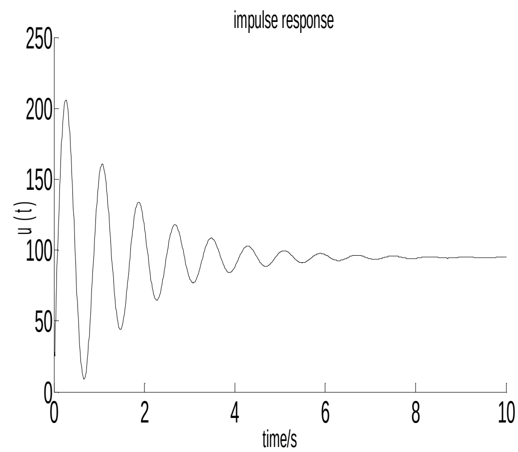

Fig. 7: The input curve of step response with feedforward DMC - PID controller

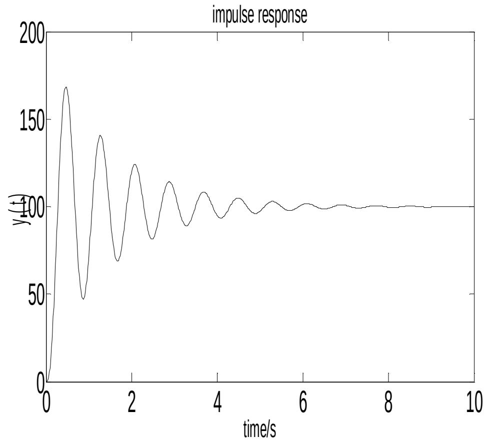

Fig. 8: The output curve of step response with feedforward DMC - PID controller

As can be seen from the Fig. 7 and Fig. 8, the steady-state error of the system is relatively smaller through using the feedforward DMC-PID controller. although the adjustment time is relatively longer, the system can still achieve a stable state in the oscillation after a period of time and basically meet the design requirements of the servo system of electric cylinder.

CONCLUSION

In this paper, combining feedforward DMC and PID control algorithm is applied to the servo system of electric cylinder. Simulation results show that the control algorithm designed by this paper and the servo amplifier can meet the requirements of the servo system. The control algorithm has the biggest advantage of not depending on the precise mathematical model and can effectively restrain the disturbance of the outside, which make the servo system has better quickness, accuracy and
stability.

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