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Position Servo Control for a Direct-Drive Actuator Based on Genetic Algorithm

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Abstract: A novel position control strategy for a Brushless DC motor (BLDC) drive is proposed in this paper. Brushless DC motor, which is widely used in the field of Direct Drive servo Actuator (DDA) with superior performance, possesses fast transient response and high accuracy. Nevertheless, there are such uncertainties as unpredictable flow torques and estimated errors of the BLDC model in this system, which may influence the accuracy and the rapid response of the control. So in this paper, genetic algorithm is applied to the position loop. Simultaneously, in order to improve the rapidness of the whole system, position and velocity double closed-loop system is compared with position and current double closed-loop system. Experimental results validate the scheme proposed can attenuate the influences by the uncertainties of the model sharply. The genetic algorithm used in the position loop can ensure the system's stability and the accuracy of the position response. While tracking the same step response the step rise time of the double closed loop structure of the position and current reduced more than 25% compared with that of the double closed loop structure of the position and velocity.

Keywords: Brushless DC motor (BLDC), Digital Signal Processor (DSP), Direct-Drive Actuator (DDA), doubles loops, Genetic Algorithm (GA), robustness

INTRODUCTION

Direct Drive Actuator (DDA), which has such good features as high-frequency response, large flow high-power density and excellent anti-contamination characteristics, is extensively adopted in the research and application fields of modern industrial automation, military, chemical industry, aviation and aerospace, etc (Jin *et al*., 2006). Traditionally, DDA is actualized by hydraulic drive with complex mechanical transmission mechanism, which causes complexity in mechanical structure, bulkiness in volume, slow responses, low positioning precision and dynamic performance (Buchnik and Rabinovici, 2004). As a result, great attention has been paid to the Brushless DC (BLDC) motor (Li *et al*., 2005), which greatly simplifies the mechanical structure and improves the precision and response speed. BLDC motors are currently utilized in a multitude of industrial applications such as in robotics, guided vehicles, mining, steel mills and traction. The BLDC motors can improve the system reliability and reduce the electrical sparkle (Wai, 2001).

In many industrial drives, advanced digital control strategies for the control of BLDC drives with a conventional position controller (Stewart and Kadirkamanathan, 2001). Proportional-Integral-Derivative (PID) controller has gained the widest acceptance in high-performance servo systems (Chiang and Su, 2005). Generally, the position controller of the BLDC motor is requested to have a rapid and accurate response for the reference, regardless of whether a load disturbance is imposed and the plant's parameters vary. However, the conventional PID control scheme has a steady-state error and a long recovery time when a load disturbance is imposed (Muciente *et al*., 2010). The conventional PID control scheme cannot obtain good position response.

There have been numerous methods to optimize the parameters of the PID controllers, including time domain optimizations, frequency domain shaping and genetic algorithms. GA is an iterative search and optimization algorithm based on natural selection and genetic mechanism. It is an optimization method inspired by Darwin's reproduction and survival of the fittest individual Chen *et al*. (1995). This algorithm looks for the fittest individual from a set of candidate solutions called population. The population is exposed to crossover, mutation and selection operators to find the fittest individual. The fitness function assesses the quality of every individual in evaluation process. The selection operator ensures the fittest individuals for the next generation. The crossover and mutation operators are used for variety of populations. This algorithm does not need any accurate initial information. So in this paper, a novel control strategy with the parameters optimized by GA is proposed (Chilali and Gahinet, 1996).

The rest of this paper is organized as follows: the model of a DDA system is established and the structure

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of the double-loop system is proposed, genetic algorithm into the control system and in experimental results a hardware structure of motor control based on Digital Signal Processor (DSP) is given. The experimental results clearly demonstrate the effectiveness of the proposed scheme and ascertain the rapidness of the position and current double closed-loop system.

In this paper, a novel position control strategy for a Brushless DC motor (BLDC) drive is proposed. Brushless DC motor, which is widely used in the field of Direct Drive servo Actuator (DDA) with superior performance, possesses fast transient response and high accuracy. Nevertheless, there are such uncertainties as unpredictable flow torques and estimated errors of the BLDC model in this system, which may influence the accuracy and the rapid response of the control. So in this paper, genetic algorithm is applied to the position loop. Simultaneously, in order to improve the rapidness of the whole system, position and velocity double closed-loop system is compared with position and current double closed-loop system. Experimental results validate the scheme proposed can attenuate the influences by the uncertainties of the model sharply. The genetic algorithm used in the position loop can ensure the system's stability and the accuracy of the position response. While tracking the same step response, the step rise time of the double closed loop structure of the position and current reduced more than 25% compared with that of the double closed loop structure of the position and velocity.

MODELING OF DIRECT DRIVE ACTUATOR SYSTEM WITH BRUSHLESS DC MOTOR

As is shown in Fig. 1, the whole system consists of a brushless DC motor, a hydraulic system, an intelligent motor controller and a position sensor. The valve has outstanding features of high response due to the compact and powerful rotational motor, BLDC. It drives the spool and gives the feedback of the spool position (Yavuz, 2007).

In the ideal condition the three phase voltage equations in a matrix for the BLDC motor are represented as:

$$\begin{pmatrix} U_a \\ U_b \\ U_c \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{pmatrix}\frac{d}{dt}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad (1)$$

where,

u_a, u_b & u_c : The stator phase voltage
r : The winding resistor
i_a, i_b & i_c : The line current
e_a, e_b & e_c : The back EMFs of the phases
L : The self-inductance
M : The mutual inductance
D : The differential operator

Furthermore, the above equation can be simplified as:

$$u = r' i + L\frac{di}{dt} + k_e\omega \quad (2)$$

where,

u = The terminal voltage
i = The phase current
r' = The equivalent phase winding resistance
L' = The equivalent phase inductance
K_e = The back electromotive force constant
ω = The motor speed

And the mechanical equation of the BLDC motor is given as:

$$T_e - T_L = J\frac{d\omega}{dt} + P\omega \quad (3)$$

$$T_e = k_t i \quad (4)$$

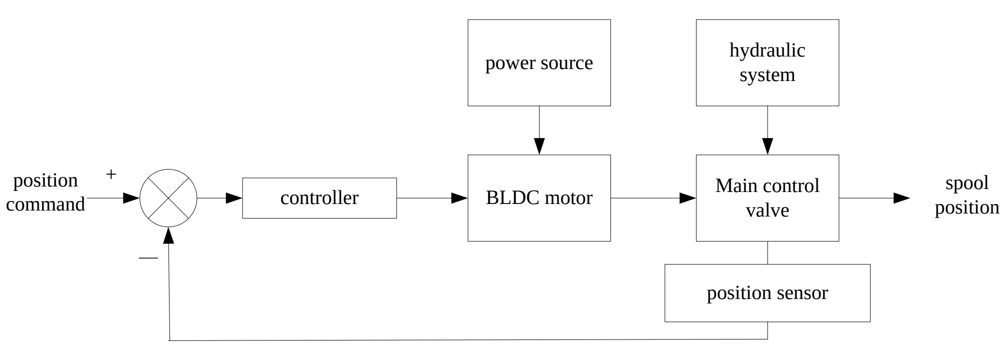


Fig. 1: The structrure of the DDA system

$$\frac{d\theta}{dt} = \omega \tag{5}$$

where,

T_e = The electromagnetic torque
T_L = The load torque
J = The inertia of the motor
k_t = The motor torque constant
P = The viscous coefficient
θ = The motor mechanical angular velocity

The load of the motor is mainly the flow torque, including the transient flow torque and static flow torque. The working environment of the DDA in this paper is 29 Mpa in this study. According to the structural parameters of the flat valve, the transient flow torque and the static flow torque can be given as:

$$T_1 = \begin{cases} 0.075 f & \theta \geq 0 \\ 0.0567 f & \theta < 0 \end{cases}$$

$$f = \begin{cases} 0 & |\theta| \leq 0.48° \\ 0.5\left[1.25 - \left(\dfrac{1.35}{\sin|\theta|} - 12\right)\tan|\theta|\right]^2 \cot|\theta| & 0.48° \leq |\theta| \leq 0.72° \\ 2\left[1.25 + 8\tan|\theta| - \dfrac{1.35}{\cos|\theta|}\right] \square \left[12\tan|\theta| + 1.25 + \dfrac{1.35}{\cos|\theta|}\right] & 0.72° < |\theta| \leq 12.62° \\ 10 - 0.5\left[1.25 - 8\tan|\theta| + \dfrac{1.35}{\cos|\theta|}\right]^2 \cot|\theta| & 12.62° < |\theta| \leq 15° \end{cases} \tag{6}$$

where,

θ_1 : The turned angle of the flat valve
f : The fluid force which is sustained by the spool

The speed of the liquid changes when it flows through the valve port. It leads to the flow force which is caused by the change of the momentum of the heart valve tank and the valve chamber annular. Because the static flow torque is influenced by the hydraulic oil pressure, the fluctuations of the source pressure, the machining and assembly errors due to transient fluid torque. So it is hard to determine the specific equation. The presence of the transient fluid torque has a great impact on the whole system.

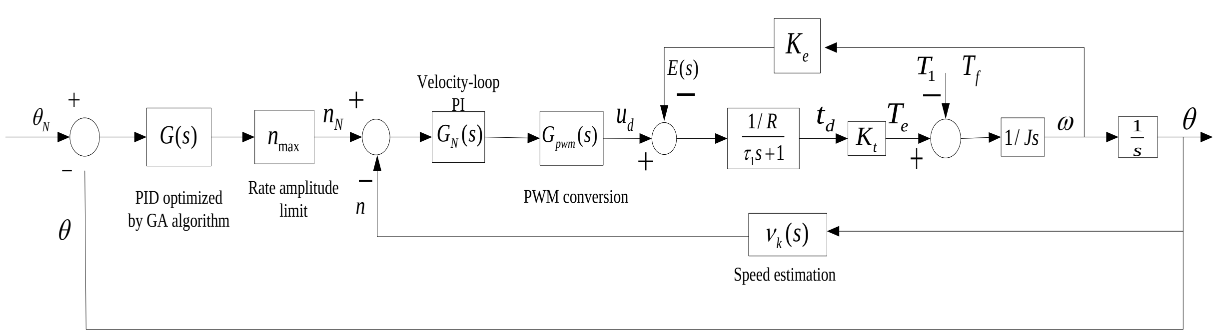
The traditional tripple-loop structure, including the current loop, velocity loop and the position loop is hard to satisfy the rapidness of the DDA. So double-loop structure is proposed in this paper, including the position and current double closed-loop structure and the position and velocity double closed-loop structure. Figure 2 shows the position and velocity double closed-loop structure. Figure 3 shows the position and current double closed-loop structure.

The transfer function of the position and velocity double closed-loop system can be simplified as:

$$w_1(s) = \left[ak_p k_i k_s k_t\left(s + \frac{\beta k_{ip}}{ak_p}\right)\right] / [IR_{\tau_1} s^4 + J(R + k_i k_s)s^3 + k_e k_t s^2 + ak_p k_i k_s k_t s + \beta k_{ip} k_i k_s k_t] \tag{7}$$

The transfer function of the position and current double closed-loop system can be simplified as:

$$w_1(s) = \left[ak_p k_n k_s k_t\left(s + \frac{\beta k_{ip}}{ak_p}\right)\right] / [RJ_{\tau_1} s^4 + RJs^3 + (k_e + k_n k_s)s^2 + ak_p k_n k_s k_t s + \beta k_{ip} k_n k_s k_t] \tag{8}$$



θ_N —Position given; θ— Position feedback; n_N — Speed given; n —Speed feedback; τ_1 —Electromagnetic time constant, $\tau_1 = (L-M)/R$;

K_e— Back-EMF constant; u_d terminal voltage; $E(s)$— Back-EMF; i_d Current feedback .

Fig. 2: The position and velocity double closed-loop structure

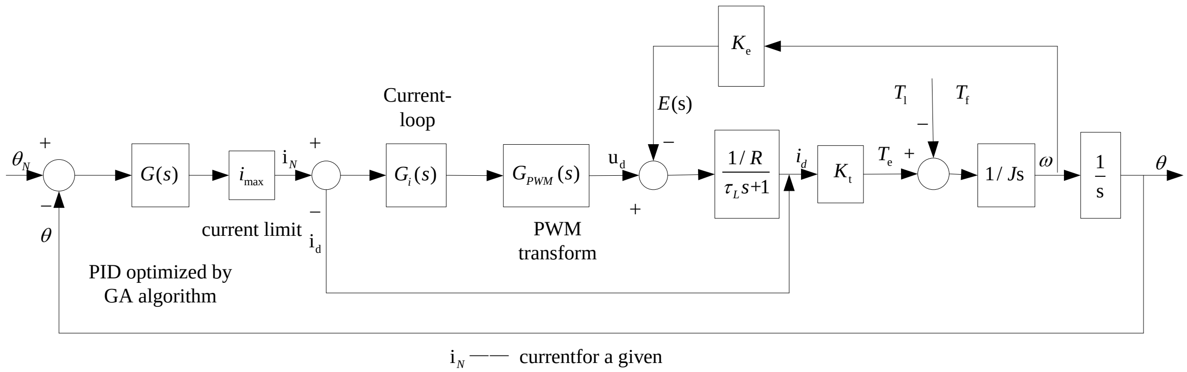


Fig. 3: The position and current double closed-loop structure

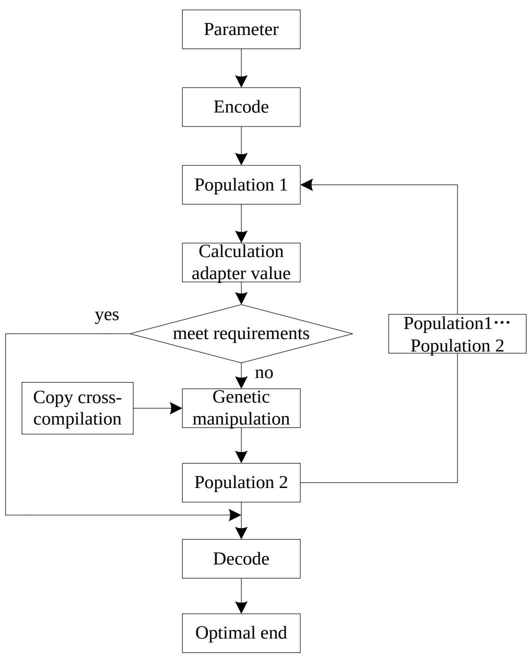


Fig. 4: Control diagram of the algorithm proposed in this paper

THE PROPOSED CONTROL SCHEME

As discussed above, there are both static flow torque and transient flow torque in DDA. It is needed to seek for the scheme to attenuate the influences of the torques. GA has many better performances with less computational burden and excellent robustness (Jury, 1965).

Fitness value determines genetic probability of genetic algorithm. Deduction and other subsidiary information are not demanded, so there is little dependence on problem. No limitation is asked to the function that may be an explicit function or an implicit function. Figure 4 shows the control diagram of the algorithm proposed in this paper. Figure 5 gives the schematic of system implementation.

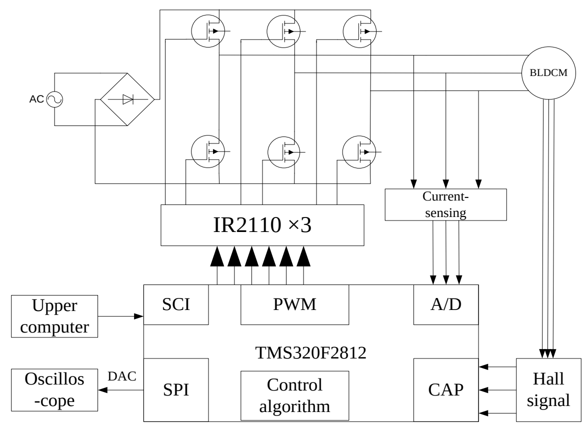


Fig. 5: Schematic of system implementation

The optimization of the GA is as follows:

1. **Code the parameters:** Two level hierarchic chromosome configurations describe network parameters and topology. Control genee level denotes network topology using binary codes, 0 and 1 separately corresponding dormancy and activation of this unit. A population of binary strings will be generated randomly.
2. Circulating fitness function *F* (*n*) for every individual *n* in the current population *N*.
3. Create a new population by repeating following steps until the new population is complete Combination of qualitative and quantitative (human and robot):

- **Selection:** Select two parent chromo-somas from a population according to their fitness (the better fitness, the bigger chance to be selected).
- **Crossover:** With a crossover probability crossover the parents to form a new offspring (children). If no

crossover was performed, offspring is an exact copy of parents.

- **Mutation:** With a mutation probability mutate new offspring at each locus (position in chromosome).
- **Accepting:** Place new offspring in a new population.

4. Use new generated population for a further run of algorithm.
5. If the end condition is satisfied, stop and return the best solution in current population.
6. Go to step 2.

EXPERIMENTAL RESULTS

To verify the correctness and feasibility of the proposed scheme for the BLDC, a complete experimental system was built. The experiential results are compared with those of the PID controller. Simultaneously, the position and velocity double closed-loop system is compared with position and current double closed-loop system.

The specifications of the BLDC are shown in Table 1.

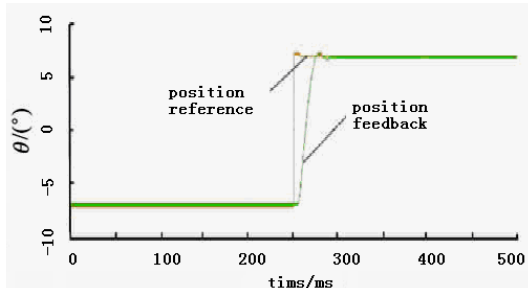
The experiment is realized by a floating-point 150 MHz DSP TMS320LF2812. Experiments are carried out using the DSP-based BLDC motor drive system. The sampling period for the position controller, speed controller and current controller are chosen to be 100, 50 and 25 us, respectively.

At the time of 250 ms, a position reference is given and different systems are applied to the experiment. From the Fig. 6 that the rising time is longer while using the position and the velocity double closed-loop system. It illustrates that when the motor is controlled by the proposed scheme, there is little overshot and rising time is also very short (40 ms). The step rise time of the double closed loop structure of the position and current reduced more than 25% compared with that of the double closed loop structure of the position and velocity.

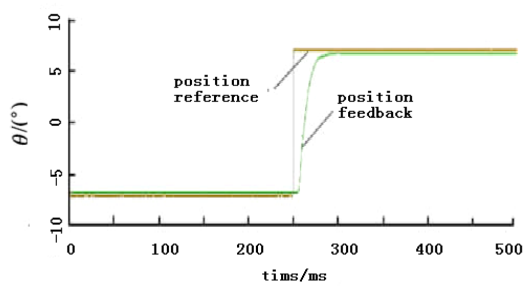
In this experiment a position reference of sinusoidal waveform is given. And the proposed control algorithm is applied to Fig. 7a. PID control algorithm is applied to Fig. 7b. There are some uncertainties that the quality of the moving coil might change when the valve is working. Figure 7a and b show the desired and actual

Table 1: Specifications of the BLDC

Parameters	Quantity
Rated voltage (V)	28
Phase resistor (Ω)	2.1
Mutual inductance (mH)	3.1
Self inductance (mH)	0.5
Rated speed (r/min)	600
Controlling cycle of the current loop (us)	25
Controlling cycle of the position loop (us)	100
Controlling cycle of the velocity loop (us)	50
Rotation inertia (Kg*m^2)	2.1*10^{-6}
EMF coefficient V/ (rad/s)	0.114

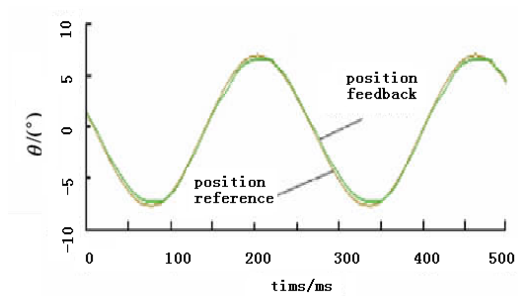


(a)

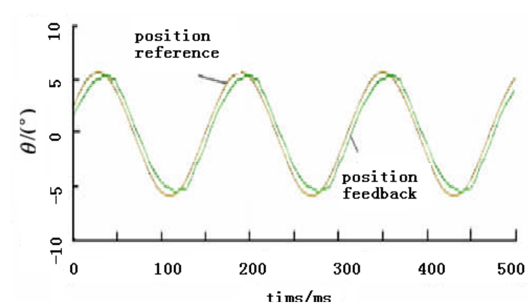


(b)

Fig. 6: The comparison between the position and current double closed-loop system and the position and the velocity double closed-loop system



(a)



(b)

Fig. 7: Robustness of different algorithms

trajectories of the spool displacement when the quality shifts during the working process. It illustrates that the proposed control scheme shows better robustness. The trajectory curve shows only little difference when the quantity of the moving coil is varying. The static and performances of BLDC are greatly improved after the scheme is applied.

CONCLUSION

This paper has proposed a dynamic model of DDA and has put forward a novel control scheme according to this model. In the algorithm, GA is applied to the system, which has strong robustness. Simultaneously, a hardware structure of motor control system based on f Digital Signal Processor (DSP) is implemented to realize the proposed algorithm. Experimental results validate the scheme proposed can attenuate the influences by the uncertainties of the model sharply. While tracking the same step response, the step rise time of the double closed loop structure of the position and current reduced more than 25% compared with that of the double closed loop structure of the position and velocity.

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