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High Speed Motion Control System With Predictive Observer and Its Parameters Optimization

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Abstract: The traditional control of high speed motion control system usually employs feedforward control to provide phase advance. In this paper, we proposed a predictive observer to compensate phase lags in the feedback loop. By employing the observer, the velocity and the position controller can be designed as for a plant does not have phase lag elements. Then, loop gains can be enlarged and motion speed can be improved. There are two sets of parameters need to be set, the controller's and the observer's. We applied least square algorithm for model estimation and simplex method for controller auto tuning. The algorithms were tested in simulations. The results show that the motion performance is extremely improved by the predictive observer. The accuracy of the estimated model has errors less than 2.5%. The preferred motion performance can be got according to the auto-tuned control parameters which implies that the strategy for parameters setting works well.

Keywords: high speed, predictive observer, least square, simplex method, auto tuning, phase lead, motion control

1 Introduction

With the continuous improvement of process efficiency, high speed motion control system is increasingly widely used. Linear motor or voice coil motor is the most suitable actuator for high speed motion control system [1]. This is because it has many advantages such as large torque or force outputs, less transmission mechanism with little friction and little precision loss. It can provide high acceleration to realize high speed motion. This mechanism with linear motor has its inherent properties. Its bandwidth is high which is usually beyond hundreds of Hz. It is very sensitive to disturbances and high frequency resonances [2]. In the control system, the typical three-loop control is still the mostly-used control framework in industry. To achieve a high speed motion and a good tracking performance, gains of the control loop should be as high as possible. However, higher loop gains will destroy the system stability [2]. It usually takes the designer lots of time to get a balance between fast response and enough margin of stability. It gets more hardly especially the control loop hasn't enough stability margin.

To get more stability margin, it is usually via employing additional control law such as feedforward control [3,4,5], disturbance observer [6,7,8,9], velocity observer [10,11] and etc.. The feedforward control compensates the phase in the forward control loop. It is sensitive to plant uncertainties and easily causes high frequency vibration. An effective complement is to employ a disturbance observer. The observer is used to compensate for the load disturbance, and furthermore, the nonlinear friction and cogging effects. Stability margin can be indirectly enlarged by reducing disturbances but only in a small scale. The advantage of velocity observer is to avoid the measuring noise caused by quantization of derivative of measured positions. It is usually used in the velocity estimation at low speed.

To get good response when the control structure is fixed, it is via optimization of the control parameters. such as auto-tuning technique based on gradient method [12,13,14], iterative learning control strategy [15,16] and simplex auto-tuning method [17]. Because of its intuitive architecture, simple programming and without complex matrix operations, simplex auto-tuning method is widely used in optimization design of PID parameters [18,19,20].

In the servo control system, the three-loop control is

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realized in motion controller and servo drive. Usually, the position and velocity control loops are realized in motion controller and the current loop is realized by servo drive or servo amplifier. In the control structure, there are many phase lag elements limit the bandwidth. The current loop is itself a low-pass filter. Also, there are command filters between velocity loop and current loop. In digital control, the time delay is always existing. It comes from calculations, signal transformations and sampling. A control structure with these phase lags is shown in Fig. 1(a). $F_v(s)$, $F_c(s)$ and $F_m(s)$ represent filters in velocity loop, current loop and measurement respectively. τ_* represents the corresponding time delay. These phase lags can be simplified as a first-order low-pass filter and a pure time delay as shown in Fig.1(b). The transfer function of $F(s)$ is

$$F(s) = \frac{1}{1+T_i s}. \quad (1)$$

where, T_i is the time constant. $F(s)$ is the simplified model of filters and current loop controller. The transfer function of $P(s)$ is

$$P(s) = \frac{1}{Ms}. \quad (2)$$

where, M is the mass of the load. In the model of $P(s)$, we ignored the friction. Therefore, the model of phase lags is

$$L(s) = \frac{e^{-\tau s}}{1+T_i s}. \quad (3)$$

The phase lag elements produce more phase lags at higher frequency range. For example, $L(s)$ will introduce 37.8^o of phase lag at 300 Hz for $\tau = 0.125ms$ and $T_i = 0.24ms$. Obviously, the phase lag elements limit the bandwidth and slow down the system's response.

In this paper, we propose a predictive observer and its parameters optimization methods. The predictive observer provides a way to compensate phase lags in the feedback loop to provide phase advance. Distinguished with feedforward control, the inner loop stability can be enhance and bandwidth of control loop can be improved. The observer has two sets of parameters, the model and the compensator. Therefore, there are several sets of parameters need to be set, the parameters of observer and controller. We employ least square estimation to calculate the model and complex auto-tuning algorithm to tune the controller. This paper is centered around the predictive observer and its parameters' setting. The testing of these algorithms is performed in simulation. The paper is organized as follows. In Section 2, the control structure with predictive observer is proposed. The setup of simulation environment and the implementation of the control system are also introduced. The mathematical tools such as least square estimation, simplex algorithm for tuning PID controller and commonly used optimization criterions are formulated in Section 3. In Section 4, we proposed the method of applying the mathematical tools in setting the parameters of our

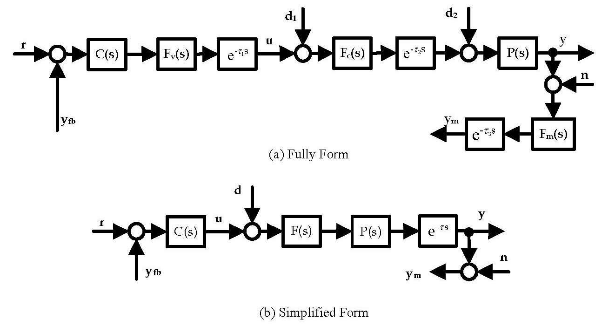

Fig. 1: Phase lags in the open loop of a general servo control system. $F_v(s)$, $F_c(s)$, $F_m(s)$ and $F(s)$ are filters. τ_1, τ_2, τ_3 and τ are time delays.

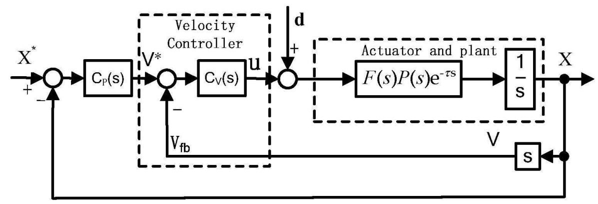

Fig. 2: Traditional Servo Control Structure.

proposed control structure. In the simulations, the simplex auto-tuning algorithm is used in pre-tuning and re-tuning the controller. The auto tuned results are illustrated and the algorithm for model estimation is also test. The results shows that the predictive observer can extremely improve the motion performance and the proposed auto setting strategy works well.

2 Servo control system with predictive observer

2.1 Servo control system description

In a traditional servo control system, a multi-axis motion controller realizes the position and velocity loop controller. A servo drive or amplifier realizes the current controller. In the feedback, a linear encoder is used to measure the position signal. The velocity is estimated by derivative of position.

2.1.1 Traditional servo control structure

The structure of traditional servo control system is shown in Fig. 2. $C_p(s)$ and $C_v(s)$are position loop controller and velocity loop controller respectively. X^* and V^* are position and velocity command. The control command is

u and the disturbance is d. V_{fb} is estimated by derivative of measured position X. Therefore, the transfer function of velocity loop is

$$G_v^T(s)=\frac{F(s)e^{-\tau s}P(s)C_v(s)}{1+F(s)e^{-\tau s}P(s)C_v(s)}. \tag{4}$$

The transfer function of position loop is

$$G_p^T(s)=\frac{C_p(s)\frac{1}{s}\frac{F(s)e^{-\tau s}P(s)C_v(s)}{1+F(s)e^{-\tau s}P(s)C_v(s)}}{1+C_p(s)\frac{1}{s}\frac{F(s)e^{-\tau s}P(s)C_v(s)}{1+F(s)e^{-\tau s}P(s)C_v(s)}}. \tag{5}$$

Design of $C_v(s)$ and $C_p(s)$ should consider fast response, enough margin of stability and maximized disturbance rejection ability. However, higher gains of $C_v(s)$ and $C_p(s)$ give fast response but greater noise susceptibility and often, lower margins of stability. The noise rejection characteristics, the disturbance rejection characteristics and the command following characteristics are coupled with design of $C_v(s)$ and $C_p(s)$. In many applications, designers usually spend a lot of time to get a balance between these characteristics. It gets more hardly especially the control loop hasn't enough bandwidth. According to Eq.(4) and Eq.(5), the phase lag elements $F(s)e^{-\tau s}$ presents in the denominator of the transfer function. It means that they will affect the poles of the closed loop transfer function and will limit the bandwidth of the control system.

2.1.2 Traditional PPI control

PPI control is the most used control law in servo control. PPI means the position controller is a proportional control (P-control) and velocity controller is a proportional and integral control (PI-control). Therefore, $C_v(s)$ and $C_p(s)$ have the transfer function as

$$C_v(s)=(1+\frac{1}{T_v s})K_v,\ \ C_p(s)=K_p. \tag{6}$$

PI-control used in velocity controller is to get a non-steady-state-error velocity control and a good velocity following. P-control used in position control is to get a fast response and good tracking of the position references. The most stiffness of the control system comes from the velocity controller and position controller. It's better to set the gains of $C_v(s)$ and $C_p(s)$ as high as possible, i.e., K_p and K_v. However, the presentation of $F(s)e^{-\tau s}$ in $G_v^T(s)$ and $G_p^T(s)$ will limit the gains of K_p and K_v.

2.2 The predictive observer

In this section, we will propose a position and velocity predictive observer to eliminate the limitation of loop gains caused by $F(s)e^{-\tau s}$.

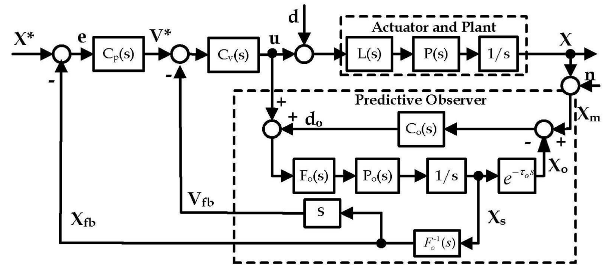

Fig. 3: Diagram of Control System With Position Predictive Observer.

2.2.1 Control structure with predictive observer

The control structure with the position predictive observer is shown in Fig. 3. In the observer, $P_o(s)$ and $F_o(s)$ are models of $P(s)$ and $F(s)$. τ_o is nominal value of τ. $C_o(s)$ is the compensator of the observer. X_o and d_o are estimated position and disturbance respectively. $F_o^{-1}(s)$ is the inverse of $F_o(s)$.

If the feedback using X_s, the predictive observer is a modified smith predictor [21,22]. $F(s)$ is invertible. So, we take the output of $F_o^{-1}(s)$ as controller's feedback. Then, the closed loop transfer function of velocity loop is

$$G_v(s)=\frac{C_v(s)P(s)F(s)e^{-\tau s}}{1+C_v(s)P_o(s)\frac{1+\frac{1}{s}F(s)e^{-\tau s}P(s)C_o(s)}{1+\frac{1}{s}F_o(s)e^{-\tau_o s}P_o(s)C_o(s)}}. \tag{7}$$

The closed loop transfer function of position loop is

$$G_p(s)=\frac{\frac{1}{s}C_p(s)G_v(s)}{1+\frac{\frac{1}{s}C_p(s)C_v(s)P_o(s)+\frac{1}{s}C_p(s)G_v(s)\frac{1}{s}P_o(s)C_o(s)}{1+P_o(s)C_v(s)+\frac{1}{s}P_o(s)F_o(s)C_o(s)}}. \tag{8}$$

2.2.2 Predictive ability

If the model are correct, i.e.,

$$F_0(s)e^{-\tau_o s}=F(s)e^{-\tau s}, P_0(s)=P(s) \tag{9}$$

the velocity loop transfer function in Eq.(7) can be simplified as

$$G_v(s)=\frac{C_v(s)P(s)}{1+C_v(s)P_o(s)}F(s)e^{-\tau s}. \tag{10}$$

The position loop transfer function in Eq.(8) can be simplified as

$$G_p(s)=\frac{C_p(s)\frac{1}{s}\frac{C_v(s)P_o(s)}{1+C_v(s)P_o(s)}}{1+C_p(s)\frac{1}{s}\frac{C_v(s)P_o(s)}{1+C_v(s)P_o(s)}}F(s)e^{-\tau s}. \tag{11}$$

From Eq.(10) and Eq.(11), we can find out that the phase lag elements $F_o(s)e^{-\tau_o s}$ will not present in the

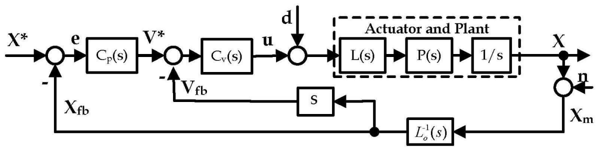

Fig. 4: Equivalent Diagram of Control System With Predictive Observer.

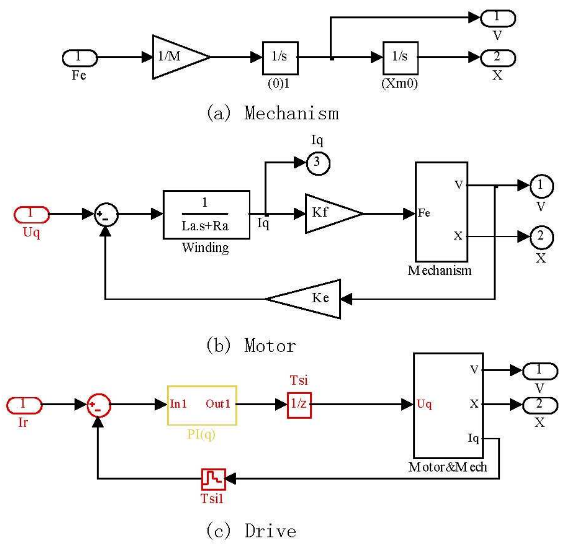

Fig. 5: Simulation models of mechanism, motor and drive.

denominator of the closed-loop transfer function. The control structure can be the same as the diagram shown in Fig.4. They have the same input-output equation. The predictive observer performs the function of $L^{-1}(s)$. With this predictive ability, it compensates the phase lags caused by $L(s)$. Therefore, the design of position and velocity controller can be no longer consider the phase delay elements. The gains of $C_v(s)$ and $C_p(s)$ can be set higher. The inner loop stability can be enhance and the bandwidth of control loop can be improved.

2.3 Setup of simulation environment

Simulation is the most effective way to test a proposed method. It also reduces development cycles and security risks. In this section, we setup the simulation environment for performing the proposed control system and test our proposed methods.

The simulation model is a realistic servo control system of XY-table in wire bonder. The mechanism of a realistic XY-table is a generalized parallel structure. The actuator is voice coil motor produced by Tamagawa. Its force constant is 43 N/A. The back EMF is 43 $V/(m/s)$. The armature resistance and inductance are 3.5 *Ohms* and 4 *mH* respectively. Its peak force can be up to 430 N. The total load of X-axis is 3.73 Kg. The feedback is a position signal measured by a linear encoder with resolution of 0.5 *um*. The drive is a CDHD series of high performance servo drive produced by Servotronix. The drive realizes the current loop with a PI control. The sample time of current loop is 31.25 *us*. The velocity control loop and position control loop is realized in GTS series motion controller produced by Googoltech. The sample times of position and velocity control loop are 250 *us* and 62.5 *us* respectively.

The simulation is performed in Matlab and the model is setup in Simulink by straight forward. The simulation model of mechanism, motor and drive are as shown in Fig.5.

2.4 Implementation of the control system

According to the theory of predictive observer, we implement the control system with the position predictive observer. The diagram of implementation is shown in Fig.6. The model of $P(s)$ and $L(s)$ are in Eq.(2) and Eq.(3). M_o, τ_o and T_{io} are nominal value of M, τ and T_i respectively. k_1, k_2, k_3 and k_4 are parameters of the compensator $C_o(s)$. There is an integration element in the compensator to get a non-steady-state error response. In realization, the delay time τ_o is realized by several zero-order holders. The control law is the traditional PPI control with position loop gain K_p, velocity loop gain K_v and velocity integration time constant T_v.

In the Simulink, the integration $1/s$ is realized by function block of discrete-time integrator. The difference s is realized by function block of discrete difference. The low pass filter $1/(1+T_{io}s)$ is realized by function block of discrete filter with the transfer function as

$$G_f(z) = \frac{T_s}{T_s + 2T_{io}} \frac{1+z^{-1}}{1+\frac{T_s-2T_{io}}{T_s+2T_{io}}z^{-1}}. \qquad (12)$$

where, T_s is sample time. All of these function blocks are running at sample time of 62.5 *us*. The time delay is usually two or three times of sample time of velocity control loop [15]. Here, $e^{-\tau_o s}$ is realized by two zero order holder, i.e., the time delay is fixed as 125 *us*. Therefore, there are three sets of parameters in the control system, the model, the compensator and the controller.

3 Mathematical tools

3.1 Least square estimation

Least square estimation is the mostly used method in system identification [23]. For a linear single input and single output system, it has the function $y = f(x)$. The goal of identification is to determine the formula

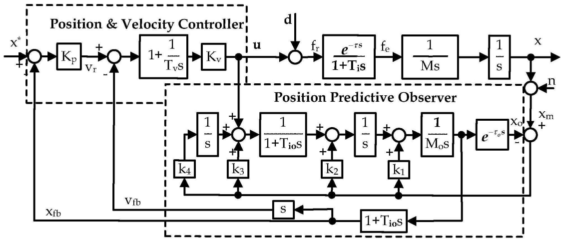

Fig. 6: Implementation of Control System With Predictive Observer.

$y = f(x)$. Firstly, $f(x)$ is parameterized by physical modeling. Then, a set of data points $(x_1,y_1),...,(x_N,y_N)$ are produced by experiment. At last, one employs the least square estimation to get parameters of $f(x)$.

There is experimental error in the measured data point (x_k,y_k). It is also called residuals and represented as e_k. It is satisfied that

$$y_k = f(x_k) + e_k \;\text{ for }\; 1 \le \mathrm{k} \le \mathrm{N}. \tag{13}$$

To measure how far the data point (x_k,y_k) lies from the curve $y = f(x)$, there are several norms can be used related to the residuals e_k as in Eq.(13).

$$\text{Maximum error}: \; \mathrm{E}_\infty(\mathrm{f}) = \max_{1\le \mathrm{k} \le \mathrm{N}} \{|\mathrm{f}(\mathrm{x_k}) - \mathrm{y_k}|\}. \tag{14}$$

$$\text{Average Error}: \; E_1(f) = \frac{1}{N}\sum_{k=1}^{N} |f(x_k) - y_k| \tag{15}$$

$$\text{Root mean square error}: \; E_2(f) = \left(\frac{1}{N}\sum_{k=1}^{N} |f(x_k) - y_k|^2\right)^{1/2} \tag{16}$$

A best-fitting is found by minimizing one of the quantities in Eq.(14-16). When minimizing norm $E_2(f)$, the estimation method is called least square estimation.

In order to deal with the general case, we define the information vector φ_k composed of the experimental data, the parameter vector θ for the parameterized model. Then, Eq.(13) can be represented as

$$y_k = \varphi_k^T \theta + e_k \;\text{ for }\; 1 \le \mathrm{k} \le \mathrm{N}. \tag{17}$$

To minimize $E_2(f)$ is same as to minimize $E_2^2(f)$. Then, we can get the error criterion function is

$$J(\theta) = \sum_{k=1}^{N} \left| y_k - \varphi_k^T \theta \right|^2. \tag{18}$$

To minimize $J(\theta)$, we should find a $\hat{\theta}$ to meet the differential of $J(\hat{\theta})$ equals to zero. This yields the estimation $\hat{\theta}$ of θ,

$$\hat{\theta} = \left(\sum_{k=1}^{N} \varphi_k \varphi_k^T\right)^{-1} \sum_{k=1}^{N} \varphi_k y_k. \tag{19}$$

3.2 Simplex algorithm

Simplex algorithm is a method for minimizing an objective function in N dimensional space. The simplex is a special polytope of $N+1$ vertices in N dimensions. The examples of simplex are triangle on a plane and a tetrahedron in three-dimensional space. The PID tuning based on simplex is to minimize an objective function of a tetrahedron in three-dimensional space. Simplex method has four basic deformations, reflection, expansion, contraction and reduction. The following are the iterative algorithm steps of simplex method to tuning PID parameters.

1) Initial simplex algorithm: According to an initial value of PID parameters, the initial point m_4 is determined. And initial the length of simplex side h, the expansion coefficient p, shrink coefficient q, performance accuracy ε, maximum search times M and feasible region Q.

2) Calculate the points: Let $j = 0$, calculate the others points by $m_i = m_4 + hZ_i$, $i = 1,2,3$, where, z_i is basis of N dimension space. If m_i is in Q, go to (3). Otherwise, decrease h and repeat (2).

3) Order: According to the objective function $f(m_i)$, remark the worst point m_h, the worse point m_g, the better point m_m and the best point m_l.

4) Reflection: Let $j = j+1$. If $(f(m_m) - f(m_l))/f(m_l) \le \varepsilon$, jump to (7). Otherwise, if $j \ge M$, the search fails. If $j < M$, determine the reflected point m_r of m_h on the plane $m_g m_m m_l$. If m_r is in Q, go to (5), otherwise, contract the simples by $m_r = (1-q)m_h + m_r$ until m_r is in Q.

5) Expansion: If $f(m_r) < (m_g)$, expand the simplex by $m_e = (1-p)m_h + pm_r$ until m_e is in Q. If $f(m_e) < f(m_r)$, replace m_h by m_e, otherwise, replace m_h by m_r. Go to (3).

6) Contraction: If $f(m_r) \ge f(m_g)$, contract simplex by $m_s = (1-q)m_h + m_r$. If $F_s < F_g$, replace m_h by m_s, go to (3). otherwise, reduce simplex by $m_i = (m_i + m_l)/2$, $i = 1,2,3,4$, back to (3).

7) Output result: End the iteration and output the result.

3.3 Optimization criterion

The complex method has an objective function $f(m)$. The objective function is an optimization criterion which can be represented as a mapping of the wanted performance such as rising time, overshoot and settling time, etc. In motion control, the tracking error $e(t)$ is the most important information to determine the performance. Therefore, most of the optimization criterion are functions of $e(t)$. The following are the commonly used optimization criterion.

1) Integral of squared error criterion (ISE)[20]:

$$ISE = \sum_{0}^{L} e^2(k). \tag{20}$$

2) Integral of absolute error criterion (IAE)[20]:

$$IAE = \sum_{0}^{L} |e(k)|. \qquad (21)$$

3) Integral of time-weighted squared error criterion (ITSE)[26]:

$$ITSE = \sum_{0}^{L} ke^2(k). \qquad (22)$$

4) Integral of time-weighted absolute error criterion (ITAE)[24,25]:

$$ITAE = \sum_{0}^{L} k|e(k)|. \qquad (23)$$

5) Generalized integral of squared error criterion (GISE)[27]:

$$GISE = \sum_{1}^{L} (e^2(k)+\rho(e(k)-e(k-1))^2). \qquad (24)$$

6) Generalized integral of time-weighted squared error criterion (GITSE)[20]:

$$GITSE = \sum_{1}^{L} k(e^2(k)+\rho(e(k)-e(k-1))^2). \qquad (25)$$

In PID optimization, the most used criterions are ITAE. With different objective performance, the optimization criterion will be different. Therefore, the choosing of criterion depends on the wanted performance. Generally, ITAE is for lower overshooting and smooth tracking, and GITSE is for both fast settling and lower overshooting [20].

4 Setting of parameters

There are several sets of parameters. These sets of parameters should be set step by step. Before employing the predictive observer, the traditional PPI controller should be tuned at first and then the system can get a good response. This work is a preparation for tuning the observer. The second step is to set the model's parameter and then, the compensator. Based on the observer, the PPI controller should be re-tuned at last.

4.1 Parameter setting of PPI control

Based on the control structure, the controller has three parameters, K_p, K_v and T_v. Since simplex algorithm easily goes into locally optimum, the simplex algorithm needs to be refined.

The plant has the transfer function with $P(s)L(s)$. When tuning the PPI controller, the phase lag elements $L(s)$ can be simplified as 1. Then, the closed velocity control loop has the transfer function

$$G_v(s) = \frac{K_v(T_v s+1)}{MT_v s^2 + K_v T_v s + K_v}. \qquad (26)$$

Usually, the velocity loop is tuned as a second order system. It will have the form

$$G_v(s) = \frac{K_v(T_v s+1)}{MT_v(s^2 + 2\varepsilon\omega_v s + {\omega_v}^2)}. \qquad (27)$$

where, ω_v is the natural frequency of velocity loop and ε is the damping coefficient. Then, K_v, T_v and ω_v has the relationship as

$$K_v = 2M\varepsilon\omega_v, \ \ T_v = 4\varepsilon^2 M/K_v. \qquad (28)$$

The mass of load M is invariable. Therefore, if the damping coefficient ε is fixed, the PPI control can be simplified as two parameters. Since the most stiffness of the control loop comes from the velocity loop, the velocity loop usually set as a over-damped system such that $\varepsilon \geq 1$. When employing simplex method, the simplex can use a triangle on a plane. The steps of simplex algorithm is similar as the PID auto-tuning. The flowchart is shown in Fig.7.

4.2 Model estimation

In the predictive observer, the model of platform should be as correct as possible. Then, the predictive ability of the observer can work well as proposed. With a correct model, the observed position signal X_o will have the same profile as X_m. Also, the profile of dX_o/dt and dX_m/dt will be the same. To identify whether the model is correct, the compensator of the observer should be shut down and then compare the profile of V_o and V_m which represents dX_o/dt and dX_m/dt respectively.

As introduced in the implementation of the observer, the transfer function from u to X_o in discrete-time will be,

$$v(k) = \frac{T_s}{T_s+2T_{io}} \frac{1+z^{-1}}{1+\frac{T_s-2T_{io}}{T_s+2T_{io}}z^{-1}} \frac{1}{M_o} \frac{T_s}{1-z^{-1}} z^{-2}u(k) \qquad (29)$$

where $v(k) = \frac{X_o(k)-X_o(k-1)}{T_s}$.

From Eq.(29), we can get

$$v(k)-v(k-1) = A(v(k-1)-v(k-2))+Bu(k-1) \qquad (30)$$

where, $A = \frac{T_s-2T_{io}}{T_s+2T_{io}}$ and $B = \frac{T_s}{T_s+2T_{io}}\frac{T_s}{M_o}$.

Let $y_k = v_m(k)-v_m(k-1)$, $\varphi_k = [y(k-1)\ u(k-1)]^T$, $\theta = [A\ B]^T$ and $e_k = y_k-(v(k)-v(k-1))$, we can get the same form as in Eq.(17). According to Eq.(19), the value of θ can be estimated if we have a series data of $u(k)$ and $v_m(k)$. Then, we can get estimated value of M_o and T_{io} as

$$\hat{T}_{io} = \frac{1-A}{2(1+A)}T_s, \ \ \hat{M}_o = \frac{T_s}{T_s+2T_{io}}\frac{T_s}{B}. \qquad (31)$$

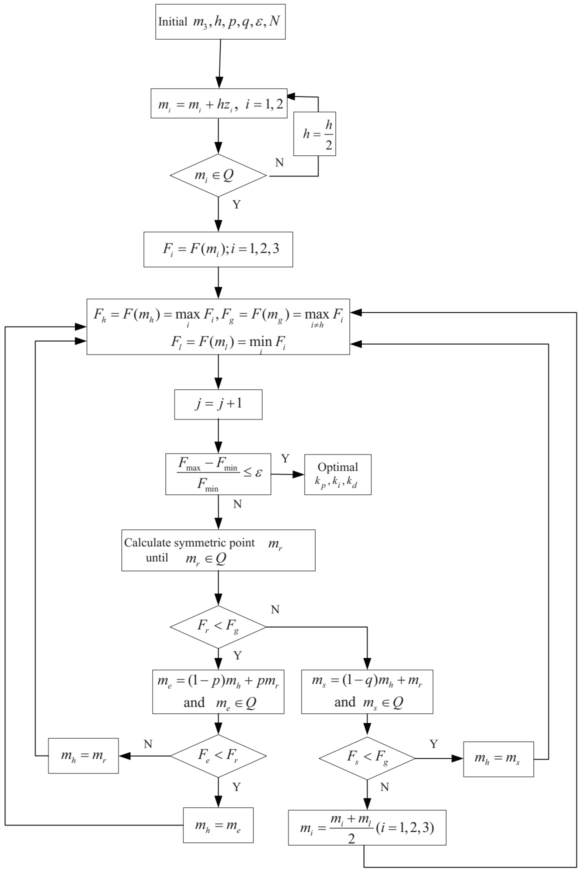

Fig. 7: Flowchart of auto-tuning PPI controller by simplex method.

4.3 Parameter setting of the compensator

As in Fig.3, the transfer function from u to X_o is

$$G_{X_o u}(s) = \frac{L_o(s)P_o(s)}{1 + C_o(s)L_o(s)P_o(s)}. \quad (32)$$

Since the $C_o(s)$ is designed for the nominal model of $P(s)L(s)$, its gain can be set higher. By ignoring $e^{-\tau_o s}$, the characteristic polynomial of Eq.(32) is

$$ch(s) = (1 + T_{io}s)(M_o s + K_1)s^2 + K_2(1 + T_{io}s)s + K_3 s + K_4 \quad (33)$$

Usually, the bandwidth of motion control system using linear motor should beyond 200 Hz. The bandwidth of is set at 300 Hz to provide enough bandwidth and avoid high frequency noises. Then, we set all of the four eigenvalues at $w_o = 2 * \pi * 300$, i.e., let $ch(s) = T_{io}M_o(s + w_o)^4$. Then, we get

$$k_1 = 4\omega_o M_o - M_o/T_{io}$$
$$k_2 = 6\omega_o^2 M_o - k_1/T_{io}$$
$$k_3 = 4{\omega_o}^3 T_{io}M_o - k_2$$
$$k_4 = \omega_o^4 T_{io}M_o. \quad (34)$$

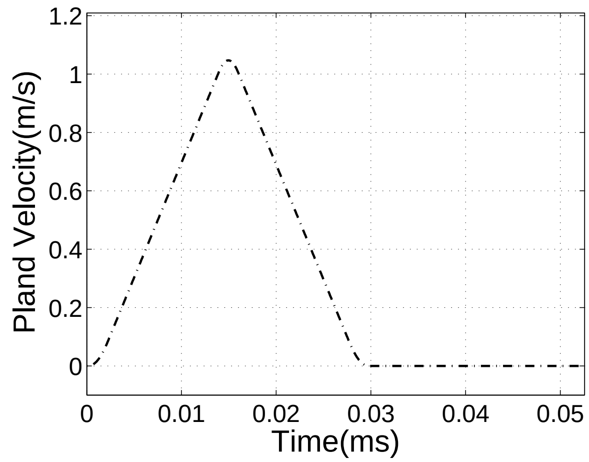

Fig. 8: Planned Velocity Profile of the Motion.

5 Simulations

In this section, we test the proposed algorithms via simulations. The simulations follow these steps, pre-tuning PPI controller with traditional control structure, estimating the model parameters, re-tuning the PPI control parameters with proposed position predictive observer. The purpose of pre-tuning PPI controller is to get a normal motion. Then, the observer's parameter can be set based on the information of the motion. At last, the PPI controller would be re-tuned after employing the position predictive observer. In the simulations, a common used motion is a 15 *mm* point to point motion. The motion has the planed velocity profile as shown in Fig.8. The planned acceleration is 78.4 m/s^2, and the planned motion consumes 29.7 *ms*.

5.1 Pre-tuning PPI controller

The procedure of this step is performed on simplex auto-tuning method. Generally, the procedure to manually tune PPI controller is from inner loop to outer loop. When tuning the velocity loop, the actual velocity should follow the command very well. It is also preferred that there is less vibrations in the actual velocity during the motion. When tuning the position loop, the tracking performance should be good. That means the settling time should be as less as possible. It is also preferred that there is no overshoot and no vibrations after the motion. These performances decide the choose of optimization criterion. Therefore, the criterions for tuning the velocity loop is ITAE and the criterions for tuning the position loop is a

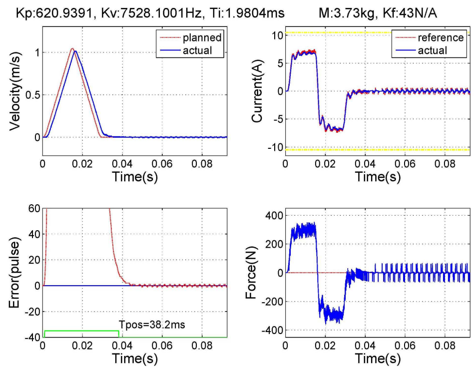

Fig. 9: Simplex auto-tuning result for traditional PPI control when $W_v = 1$.

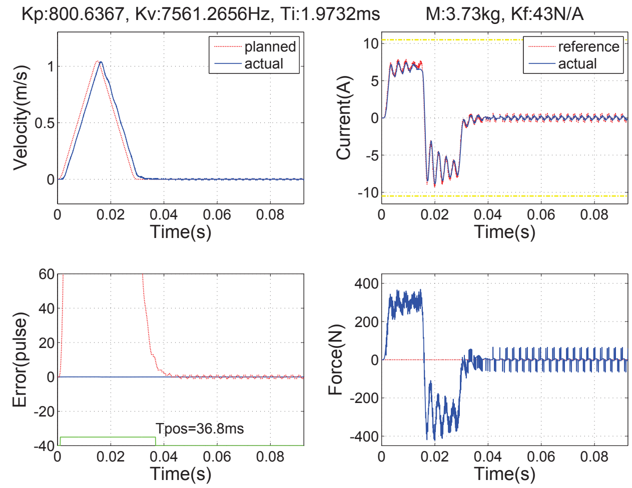

Fig. 10: Simplex auto-tuning result for traditional PPI control when $W_v = 0.5$.

modified GITSE. Therefore, the objective function F_{PPT} for position controller and velocity controller is

$$f_p(e_p) = \sum_{1}^{L} k(\rho_1(k)e_p^2(k) + \rho_2(k)(e_p(k) - e_p(k-1))^2)$$

$$f_v(e_v) = \sum_{0}^{L} k\,|e_v(k)|$$

$$F_{PPI}(e_p, e_v) = f_p(e_p) + W_v f_v(e_v) \tag{35}$$

where, W_v is a weighting factor of $f(e_v)$. It balances the performances of position loop and velocity loop. ρ_1 and ρ_2 are weighting factors for e_p and de_p/dt respectively.

According to Fig.7, serial parameters should be initialed. m_3 is set at $(1,1)$. The initial the length of simplex side $h = 500$, the expansion coefficient $p = 2$, shrink coefficient $q = 0.5$, performance accuracy $\varepsilon = 0.02$, maximum search times $M = 100$ and feasible region $Q = \{(K_p, K_v)|K_x \in R^+, x = p, v\}$. We set $\rho_1(k) = 1, \rho_2(k) = 10$ when $k < 29.6/Ts$ and $\rho_1(k) = 10, \rho_2(k) = 1$ when $k \geq 29.6/T_s$. This is for the different performance between during motion and after motion. During the motion, we want there are less vibrations. After the motion, we want there are less errors.

When we set $W_v = 1$, the auto-tuned result is shown in Fig.9. The results of parameters are $K_p = 620.9$, $K_v = 7528.1$, $T_i = 1.98$. The band of error is set as 10 *pulse*. Then, the time consuming is $Tpos = 38.2$ *ms*. The iterative times of the simplex algorithm is 13.

When we set $W_v = 0.5$, the auto-tuned result is shown in Fig.10. The iterative times of the simplex algorithm is 13. The results of parameters are $K_p = 800.6$, $K_v = 7561.1$, $T_i = 1.97$. The time consuming is $Tpos = 36.8$ *ms*. When reduce W_v, K_p is enlarged and the settling time is reduced.

When we set $W_v = 1$, the auto-tuned result is shown in Fig.11. The iterative times of the simplex algorithm is 14. The results of parameters are $K_p = 425.9$, $K_v = 9531.3$,

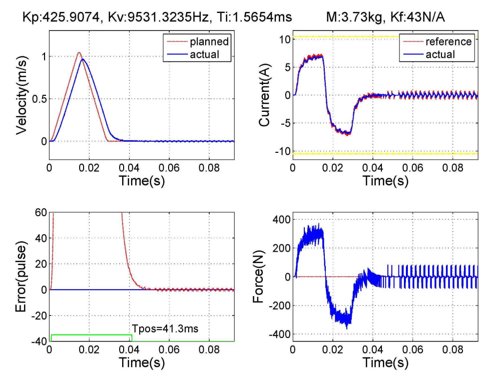

Fig. 11: Simplex auto-tuning result for traditional PPI control when $W_v = 1$.

$T_i = 1.565$. The time consuming is $Tpos = 41.3$ *ms*. When enlarge W_v, K_v is enlarged and the settling time is increased. Compared with Fig.10 and Fig.11, the vibrations of velocity during the motion is reduced by enlarge W_v.

5.2 Parameters setting of the observer

We use the result shown in Fig.11 to set the parameters of the observer. We take the record of u and X_m. V_m is get by derivative of X_m. Then, we can write the data sequence of $(u(k), v(k)$. According to the estimation algorithms, we get the estimated values are $M_o = 3.8131$ *kg* and $T_io = 0.2657$ *ms*. Comparing with $M = 3.73$ *kg*, there is only 2.23% errors in the estimation of M_o. By setting the parameter into the observer and keep the compensator

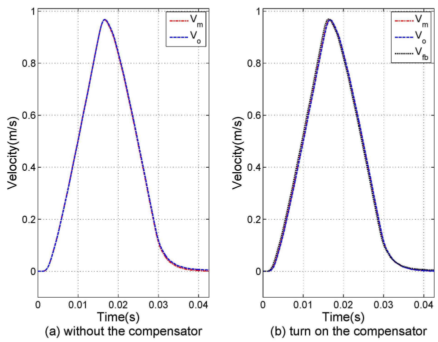

Fig. 12: Profile of V_m and V_o

open, we get the profile of V_m and V_o as shown in Fig.12(a). We can see that they have very littler difference in the end of the motion. After set $\omega_o = 300Hz$ and turn on the compensator, we get the profile of V_m and V_o as shown in Fig.12(b). The two profiles coincide together. This means the observer estimate the actual velocity correctly. The profile of feedback velocity V_{fb} comes earlier than V_m. It means the feedback velocity V_{fb} estimated by the predictive observer has more phase advance than V_m.

5.3 Re-tuning PPI controller

After employing the observer, the PPI controller is re-tuned also by the simplex method. Here, we set $W_v = 1$. The auto-tuned result is shown in Fig.13. The iterative times of the simplex algorithm is 13. The results of parameters are $k_p = 1495.5$, $k_v = 92476.9$, $T_i = 0.1613$. The time consuming is $Tpos = 30.8\ ms$. After using the position predictive observer, the settling time is extremely reduced. The loop gains enlarged by many times. These benefits are from the predictive observer providing an extremely phase advance. When we set $W_v = 0.1$, the position time only take $29.5ms$ as shown in Fig.14. The actual position goes into error band before the ending of the planned motion.

6 Conclusions

In this paper, we proposed a position predictive observer and it's parameters setting methods. The predictive observer provides a way to compensate phase lags in the feedback loop. It can provide lots of phase advance so that the loop gains can be improved and the settling time can be extremely reduced. With least square model estimation, the model parameter of the observer can be set correctly. With simplex auto-tuning method, the controller can be well tuned and then the wanted motion performance can be got.

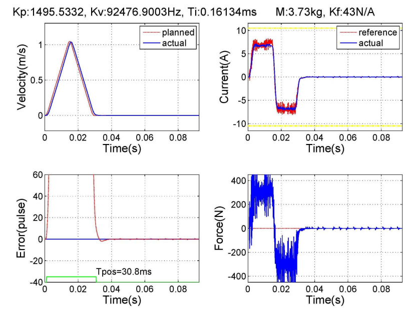

Fig. 13: Simplex auto-tuning result for PPI control with predictive observer when $W_v = 1$.

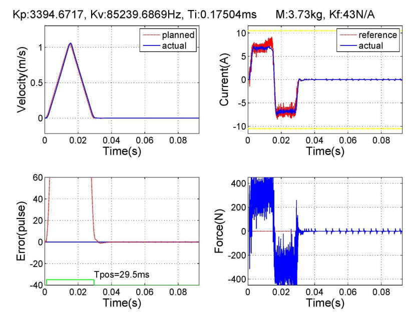

Fig. 14: Simplex auto-tuning result for PPI control with predictive observer when $W_v = 0.1$.

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