

Disturbance Observer-Based Motion Control for a Simple Direct Drive System

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Abstract—Direct drive system is the driving part that is directly connected to the driven part without using a gearbox. The advantages of direct drive system are frictionless, high efficiency, noise reduction and high torque, produced at low speed. However, the direct drive motor system has its limitation, which is sensitive to the disturbance and parameter variation. In this paper, a proportional derivative controller with disturbance observer (PDDO) is designed to achieve high positioning performance of the direct-drive system in the presence of mass and disturbance force variations. The direct-drive system in this paper is driven using voice coil motor. The disturbance observer controller is relatively easier to design than the other advanced controllers and often shows higher robust to the disturbance force and model parameter change, as compared to the conventional controller. The positioning performance of PDDO controller is evaluated and compared with a PID controller, which is designed to have similar sensitivity as the PDDO control. The positioning performance of the controllers is examined in the presence of different mass and disturbance force. Overall, the PDDO has demonstrated better robust performance as compared to the PID controller.

Index Terms—Direct Drive System; Voice Coil Motor; PD Controller with Disturbance Observer (PDDO); Robust performance.

I. INTRODUCTION

Nowadays, the direct drive system has been widely used for robots arm, machine tools, chip mounters, semiconductor manufacturing system, precision milling machines, precision assembly robots and so on [1]. In direct drive system, there is no gearbox or ball screw between the driving part and driven part, hence the friction between the driving part and driven part is reduced.

Direct drive motor is the driving part that is directly connected to the driven part without using a gearbox. The concept of direct drive system is shown in Figure 1(b). In Figure 1(a), there is a gear between the driving and driven part in a conventional motor, while in Figure 1(b), there is no gear between the driving and driven part. In other words, the driving part is directly connected to driven part. Voice coil motor (VCM) is one of the examples of direct drive motor that is widely used in the industry, especially for ultra- or nano positioning systems, such as hard disk drive system [2], direct drive valve system [3] and X-Y planar nano-motion table system [4]. The structure of voice coil motor is shown in Figure 2 [5]. There is a permanent magnet at the fixed coil part (stator). When the current is supplied, the magnet is energized

and induced the current to move the rotor. Therefore, there is non-contact between rotor and stator in VCM. The advantages of direct drive system are that of free from friction, easy to realize for precise, high speed and safe motion [6]. Unfortunately, direct drive system is always sensitive to disturbance and parameter variation. Without the connection of gearbox in the direct drive system, the friction element becomes low, leading to low damper and low stiffness. Hence, the system becomes more sensitive in the presence of small changes in parameter.



Figure 1(a): Motor with gear

Figure 1(b): Direct drive motor

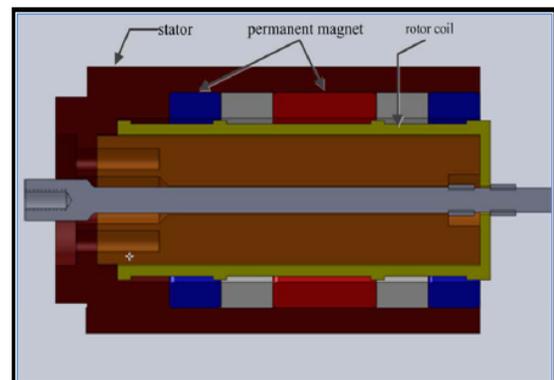


Figure 2: Mechanical structure of VCM [5]

Due to the physically low damping characteristics of the direct drive system, researchers have devoted to propose high robustness controller as the solution to provide better disturbance rejection characteristic. Butler et al. [7] has proposed an adaptive time-optimal position controller for a

direct drive DC motor with a design based on the model reference adaptive approach, where the controller guarantees approximate time-optimal behavior of the motor if a step input is applied, independent of the load inertia and the magnitude of the step input. Besides that, S.K. Jong et al. [8] has proposed a robust digital position control of brushless direct drive motor, which employed a linear quadratic controller with load torque observer. The advantage of this controller is that the disturbance can be rejected. This observer contains current, where the measured current is generally too noisy to be used in a digital controller or an observer. On the other hand, an asymptotically stable adaptive observer based on a deadbeat observer is considered to be able to overcome the problems of unknown parameters, torque disturbances and a small chattering effect for a permanent magnet synchronous motor in [9]. After that, a torque controller [10] is used to eliminate the torque ripple. The limitation of torque controller is quite a complex approach and it merely reduces the torque ripple. In addition, acceleration feedback control is proposed by J.D. Han et al. [11]. This controller can eliminate the torque disturbance, but the high gain acceleration feedback control is needed. Sliding mode controller (SMC) also widely applies in the direct drive system. SMC has less sensitivity to the disturbance force and parameter variations. However, the noise caused by SMC will affect the system performance [12]. However, the design procedures of those above-mentioned advanced controllers are complicated, require accurate model parameters, and time-consuming. Until now, the reliability and applicability of those advanced controllers in the industry are still at a poor level, as compared to the conventional controllers.

Conventional controllers have faced limitations to perform high positioning performance that requires high demanding requirement from the industry nowadays. In order to reduce the sensitivity of the direct drive motor to parameter variations and disturbance, disturbance observer (DOB) was introduced by K. Ohnishi et al. [13, 14]. The advantages of the disturbance observer are its robustness against parameter variations and simple structure [14, 15]. DOB can estimate the unknown disturbance and has low sensitivity to disturbance: In other words, the control system is robust. However, it still has a disadvantage, which is the noise of the estimated disturbance influences the position response. A low pass filter is added at the state feedback of the DOB to reduce the noise. Internal Model Controller (IMC) is different from the disturbance observer controller (DOB) in terms of the stability and disturbance rejection principle and the different loop structure, where these differences reflect the system robustness for both IMC and DOB.

In this paper, proportional derivative with disturbance observer (PDDO) control is proposed as a controller to provide better disturbance rejection characteristic, low sensitivity to disturbance, yet easy to design. In PDDO control structure, the disturbance observer is used to estimate the disturbance and parameter variation of the plant and PD controller is used to compensate the transient performance of the system. The direct-drive system used to clarify the usefulness of the PDDO control is driven by voice coil motor. The proposed controller is validated in positioning and tracking performance. Besides, the robustness of the PDDO

controller is evaluated experimentally in the presence of mass and disturbance force variations.

This paper is organized as follows: Section II derives the system modelling of the VCM and Section III explains the design procedure of the PDDO controller. Section IV discusses the simulation results and discussion while Section V summarizes this paper.

II. SYSTEM MODELLING

Figure 3 shows the 1-DOF non-contact air-slide mechanism that driven by voice coil motor (VCM). When the current is supplied, the magnet is energized. The current is induced and the moving part starts to move linearly. There is no contact between moving part and fixed part. In order to change it into a contact mechanism, a plastic is added at the moving part by using grease. Thus, when the moving part moves, little friction coefficient is generated. The transfer function of the system is determined by using dynamic model as shown in Figure 4. The block diagram of the system is shown in Figure 5.

Equation of motion:

$$M\ddot{x}(t) + b\dot{x}(t) = f(t) \quad (1)$$

where:

$$f(t) = K_m I_a(t) \quad (2)$$

Rewrite Equation (1):

$$M\ddot{x}(t) + b\dot{x}(t) = K_m I_a(t) \quad (3)$$

Transfer function of the system in frequency domain is:

$$\frac{X(s)}{I_a(s)} = \frac{K_m}{Ms^2 + bs} \quad (4)$$

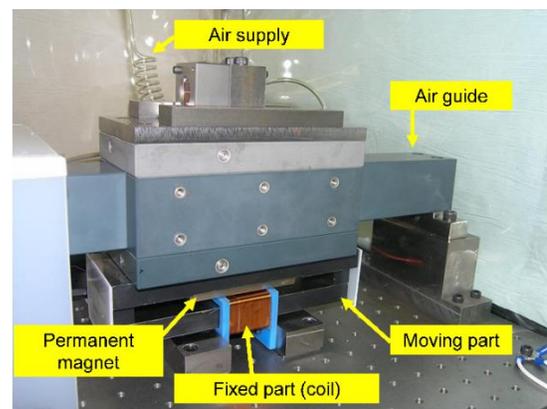


Figure 3: 1-DOF air slide mechanism. [16]

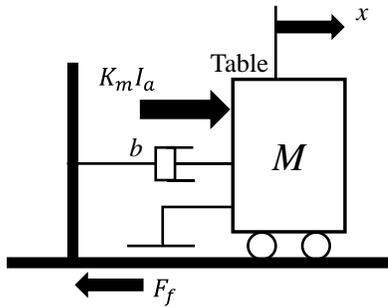


Figure 4: Dynamic model of system

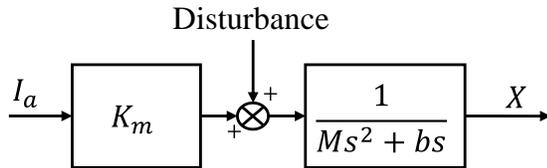


Figure 5: Block diagram of 1-DOF positioning system

III. CONTROLLER DESIGN

To design the PDDO controller, the procedures begin with the nominal plant, $G_{pn}(s)$ determination. To model the nominal plant, a general second-order model is first considered:

$$G_{pn}(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (5)$$

where the poles, S_d are set according to desired specifications such that the overshoot percentage of the system is 2% and the settling time is 0.5 seconds. The equation of the poles, S_d is given as:

$$s_d = -\sigma \pm j\omega_d \quad (6)$$

In Figure 6, the block diagram of PDDO is presented. To design the observer, the observer gain, L and state feedback, K is determined with Ackermann's formula. With the Ackermann's formulation, the observer gain, L and state feedback, K are given as:

$$L = [1024 \quad 48]^T \quad (7)$$

$$K = [0 \quad 1] \quad (8)$$

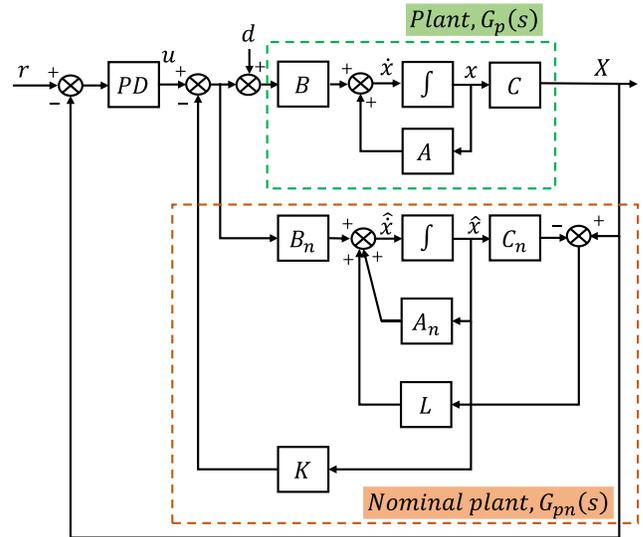


Figure 6: Block diagram of PDDO

To design the low-pass filter, $Q(s)$, the cut-off frequency of the system is determined by using frequency response that shown in Figure 7. The cut-off frequency of the system is 0.8685 rad/sec. The transfer function of filter [17] is determined by using the Equation (9), where g is the cut-off frequency of the system.

$$Q(s) = \frac{g}{s + g} \quad (9)$$

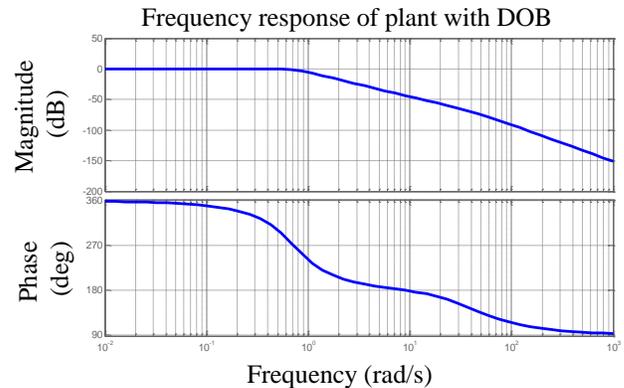


Figure 7: Frequency response of system with DOB

PD controller is designed by using root locus method to achieve the design specification, settling time, T_s is 0.5 seconds, and percent of overshoot, %OS is 2%. The observer poles must be two to five times faster than the controller poles to make sure that the estimation error can be reduced to zero quickly [18]. The estimation error is defined as the difference between the x and \hat{x} . As shown in Figure 6, the desired observer poles is set to four times faster than the desired close loop poles in order to reduce the estimation error. The block diagram of DOB can be represented in the form that is shown in Figure 8 by using block reduction method [19].

To examine the robustness of PDDO, PDDO controller is tested with different mass, force coefficient, disturbance force

(step and sine wave) and input (sine wave and triangular wave). Besides that, the transient performance of PDDO is compared with PID controller.

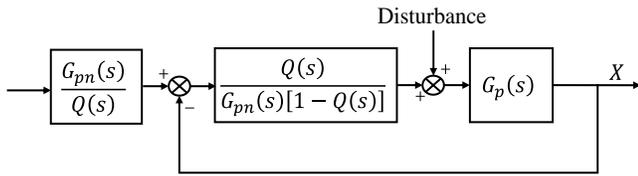


Figure 8: Block reduction of DOB structure

IV. SIMULATION RESULTS AND DISCUSSION

This paper presents the simulation work and it is done using MATLAB Software. The motor variables and parameters are defined in Table 1. PID and PDDO (PD with disturbance observer) controllers are designed in order to compare the performance of each controller in term of transient performance. The required settling time, T_s is set to 0.5 seconds and percent of overshoot, %OS, is 2%.

Table 1
Parameters of direct drive system

Variable	Unit	Parameters
Force constant, K_m	N/A	6.12
Mass of the system, M	kg	10.5
Friction of the system, b	Ns/m	9.3

The transfer function of the plant:

$$G_P(s) = \frac{6.12}{10.5s^2 + 9.3s} \tag{10}$$

Represent the transfer function in state space observer canonical form:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ &= \begin{bmatrix} -0.8857 & 0 \\ 1 & 0 \end{bmatrix} x + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u \end{aligned} \tag{11}$$

$$\begin{aligned} y &= Cx \\ &= \begin{bmatrix} 0 & 0.5829 \end{bmatrix} x \end{aligned} \tag{12}$$

The system is observable since the rank of the observability matrix, O_M is equal to the order of the system. It is calculated as follows:

$$O_M = \begin{bmatrix} C \\ CA \end{bmatrix} = \begin{bmatrix} 0 & 0.5829 \\ 0.5829 & 0 \end{bmatrix} \tag{13}$$

$$rank = 2 \text{ (observable)} \tag{14}$$

In order to validate the PDDO controller, the PID controller is designed for comparison purposes using the same sensitivity as PDDO. PID controller is designed using root locus method. The design specification is similar to the PD controller, which are the settling time, T_s is 0.5 second, and the percentage of overshoot, %OS is 2%.

The dominant poles:

$$S_d = -\sigma \pm j\omega_d = -8 + j6.4182$$

$$\begin{aligned} G_{PID}(s) &= \frac{15.2302(s^2 + 7.0605s + 0.69605)}{s} \\ &= 107.5328 + \frac{14.6286}{s} + 15.2302s \end{aligned} \tag{15}$$

The gain of PID controller, $K_p=107.5328$, $K_i=14.6286$, and $K_d=15.2302$ as shown in equation (15). Figure 9 shows the frequency response PD after the gain adjusted and PID. The gain of PD controller, K_p and K_d are adjusted in order to have the same frequency response for both systems with PD and PID. It is noted that the adjusted gain value of PD controller are $K_p=107.43$ and $K_d=15.22$ and it was used in all experiments in order to compare the positioning performance of system with PID. The transfer function of PD controller after gain adjusted,

$$G_{PD}(s) = 15.22s + 107.43 \tag{16}$$

$$G_P(s) = \frac{6.12}{10.5s^2 + 9.3s} \tag{17}$$

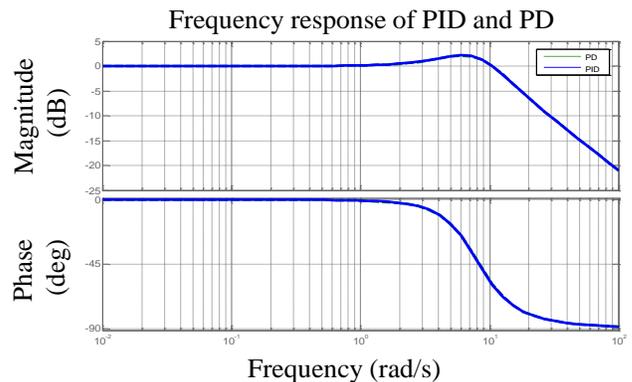


Figure 9: Frequency response of PD after adjusted and PID

Figure 10 shows the output response of system with PID and PDDO. The reference input is step input with amplitude 1 mm and default mass (10.5 kg) and force coefficient (0.35 N) are used. Swiftness of response is represented by the rise time while the closeness of response to desired response is represented by the overshoot and settling time [20]. The accuracy of the both control system are examined in term of steady state error, e_{ss} . Table 2 shows the transient performance of system with PID and PDDO. The rise time of the PDDO is better than PID, which means that the response of system with PDDO is faster than PID. However, the percent of overshoot

of PDDO is greater than PID.

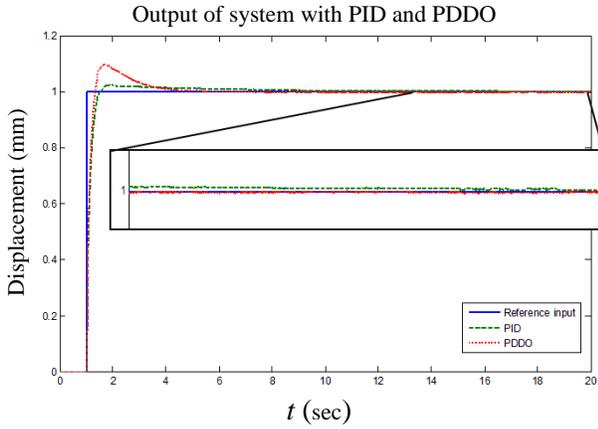
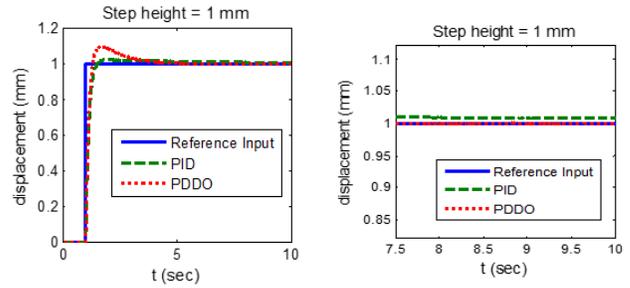


Figure 10: Output performance of PID and PDDO

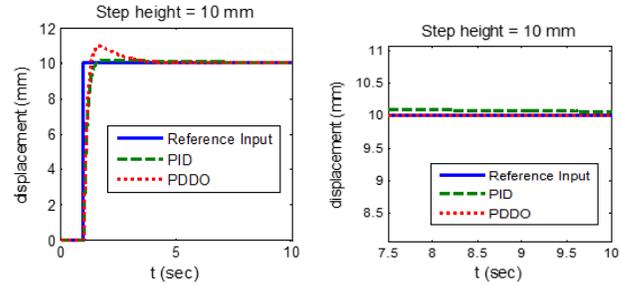
Table 2
Transient performance of system with PID and PDDO

PID				PDDO			
T_r (s)	T_s (s)	OS (%)	e_{ss}	T_r (s)	T_s (s)	OS (%)	e_{ss}
0.28	1.45	3	0.01	0.24	1.3	10	0

The system with PID and PDDO are tested with different amplitude step input, mass and force coefficient. Different amplitude is tested with the step input and the mass and force coefficient is 10.5 kg and 0.35 N respectively. Figure 11(a) shows the output of system with PID and PDDO with different amplitude (1 and 10). As shown in Figure 11(b), PID still has a steady state error when the amplitude changes, the overshoot of the PDDO is higher than PID as observed in Figure 11(a).



(a): Simulated positioning performance of 1mm step input with its magnified view.



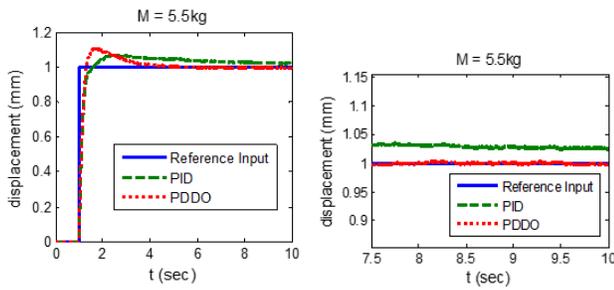
(b): Simulated positioning performance of 10mm step input with its magnified view.

Figure 11: Comparative simulated positioning performance of PDDO and PID controllers.

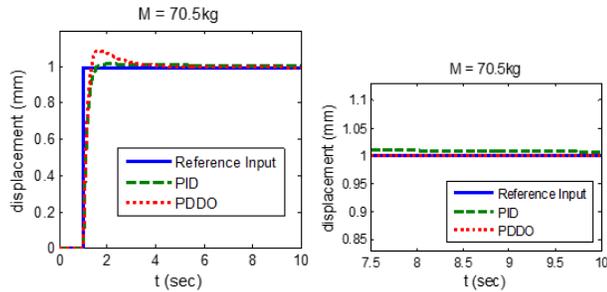
For robust performance, it can be divided into two types of analysis, that are mass variations (5.5 kg and 70.5 kg) and force variations (0.35 N and 1.40 N). The reference input is 1 mm step input and the force coefficient is constant, 0.35 N. Figure 12(a) shows the output of system with PID and PDDO. As observed, the overshoot of PDDO is still higher than the PID, while the PID has steady state error when the mass changes. The steady state error is magnified in Figure 12(b). Table 3 shows the transient performance with PID and PDDO. When the mass is increased, the rise time and settling time of PDDO remains the same while PID becomes longer. The response of PID becomes slower when mass is increased. The observer poles of disturbance observer is set four times faster than the close loop poles, therefore the estimation error can be reduced to zero quickly.

Table 3
Transient performance of system when mass changed

Mass (kg)	PID				PDDO			
	T_r (s)	T_s (s)	OS (%)	e_{ss}	T_r (s)	T_s (s)	OS (%)	e_{ss}
5.5	0.23	1.44	7	0.03	0.23	1.3	10	0
70.5	0.27	1.49	2	0.01	0.24	1.3	10	0



(a): Simulated positioning performance of 5.5kg mass with its magnified view.



(b): Simulated positioning performance of 70.5kg mass with its magnified view.

Figure 12: Comparative simulated positioning performance of PDDO and PID controllers with different mass.

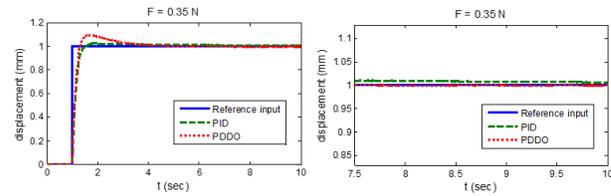
The force coefficient is changed (0.35 N and 1.40 N) in order to observe the positioning performance of system with PID and PDDO. The reference input is 1 mm step input and mass of this system, 10.5 kg is used in this experiment. Figure 13(a) shows the output response of the system with PID and PDDO. The response of PID still shows a steady state error and PDDO still has overshoot higher than PID.

The steady state error of PID is higher compared to PDDO shown in Figure 13(b). Table 4 shows the transient performance of system with PID and PDDO when the force coefficient changes. When the force increases, the settling time and rise time of PDDO is remain unchanged. Similar to the variation mass, PID controller always has the accuracy problem, which is a steady state error.

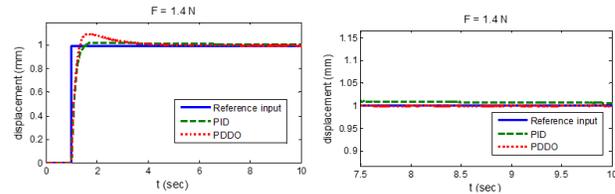
Table 4
Transient performance of system when force coefficient changed

Force (N)	PID				PDDO			
	T_r (s)	T_s (s)	OS (%)	e_{ss}	T_r (s)	T_s (s)	OS (%)	e_{ss}
0.35	0.28	1.45	3	0.01	0.24	1.3	10	0
1.40	0.27	1.40	3	0.01	0.24	1.3	10	0

For point-to-point experiment, although the overshoot of PDDO is higher than PID, the steady state error of PDDO is zero as compared to PID. In other words, the PDDO can perform better than PID in point-to-point experiment, steady state of PDDO is always zero when there is parameter variations. As observed, the positioning performance of PDDO is not affected by the variation of mass and force coefficient compare to PID.



(a): Simulated positioning performance of 0.35N force with its magnified view.



(b): Simulated positioning performance of 1.4N force with its magnified view.

Figure 13: Comparative simulated positioning performance of PDDO and PID controllers with different force coefficient.

V. CONCLUSION

As a conclusion, the point-to-point positioning performance of PDDO is better than PID in term of steady state error. When the parameters change, PID always has a steady state error, while the positioning performance of PDDO is not affected by variation of mass and force coefficient as compared to PID.

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