Smith Predictor with Simple Control Scheme for Higher Order Systems

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Abstract

A simple control scheme with smith predictor connection is proposed in this paper for time delay higher order systems. The control scheme is simply integral (I) controller with Proportional Derivative(PD)-Sliding mode controller(SMC). The initial values for the P,I, and D parameters are taken from the reduced model of the higher order system. Additional feedback sliding mode control (FSMC) is also used to reduce the effect of uncertainty in the prediction time delay values. A number of examples are tested and compared with other control methods like robust PID controller with smith predictor and Direct synthesis method with smith predictor to illustrate the efficient performance for the proposed control scheme.

مستقرئ (Smith) باستخدام مخطط سيطرة بسيط للانظمة عالية الرتبة

الخلاصة

في هذا البحث تم طرح مخطط مسيطر بسيط مع متنبيء **(SMITH)** للانظمة العالية المستوى ذات التاخير الزمني. مخطط السيطرة هو ببساطة مسيطر تكاملي **((I) Integral)** مع مسيطرات انزلاقية تناسبية اشتقاقية **PD))** **(Proportional+Derivative)**. القيم الاولية لمعلمات التناسب والتكامل والاشتقاق اخذت من النموذج البسيط المصغر للانظمة عالية الرتبة. تم ايضا استخدام اسلوب سيطرة انزلاقية اضافي **(SMC)** لغرض تقليل تاثير الشك في قيم وقت تاخير التنبأ. تم اختبار عدد من الامثلة ومقارنتها مع طرق السيطرة الاخرى مثل مسيطر تناسبي-تكاملي- اشتقاقي **(PID)** وطريقة التركيب المباشر لتوضيح الاداء الكفوء لمخطط السيطرة المقترح.

Keywords: Model reduction method, higher order systems, PID controller, Smith predictor, SMC, time delay.

1- Introduction

In industrial and chemical practice, higher order systems and large time delay processes, such as some thermal systems are difficult to control. Much research has been devoted to control performance enhancement for such systems in industry.

Control methods based on conventional unity feedback control structure and (PID) controller has been systematically developed[1,2]. In general a higher order system is reduced to a low order rational form plus a time delay. It is well known that the smith predictor(SP) control structure is more effective for industrial processes with large time delay compared with a conventional

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unity feedback control structure[3]. The utility of employing the (SP) versus conventional (PI) control for a control loop containing time delays in both the forward and feedback paths has been examined [4]. By using the Integral-Squared-Error(ISE) performance specifications, the ideally optimal (SP) controller is analytically derived according to the nominal high-order system model, which inevitably results in the higher order controller[5].

2-The Proposed Control scheme

The block-diagram for the proposed control scheme is shown in Fig.(1).

Where

- $G_h(s)$: the transfer function for the higher order plant.
- $u(s)$: the control action signal.
- $G_r(s)$: reduced second order model for the higher order system.
- e^{-ds}: The actual time delay.
- $e^{-d_p s}$: The predicted time delay.
- SMC: Feedback time delay sliding mode controller.
- $E_1(s)$: The error signal for the controlled system with time delay.
- $E_2(s)$: The error signal for the reduced system without time delay.
- $E_y(s)$: The error signal between the actual output and the predicted output.

Each part in this proposed control scheme can be explained by the following subsections:

2.1 Reduce The Higher Order System To 2nd Order System

It is often desirable and sometimes necessary, for analysis and design purpose to reduce the order of the transfer function of a higher order systems. It is necessary of model reduction technique is to provide a simplified model, which is computationally simpler to handle than the original higher order system. Several methods available for reducing the order of a transfer function [6,7,8]. All these methods are based on the concept that the dynamical behavior of system is determined by the poles nearest to the imaginary axis, i.e. dominant poles. However, many practical control systems do not have dominant poles, the above methods can not be used in general. Manigandan[9] suggested a method for reducing the order of transfer function by matching a combination of time-moment and Markov parameters of the original and a reduce model (2nd –order reduce model) systems. Where the nth order system $G_h(s)$ is equated to the 2nd order reduced model $G_r(s)$ with unknown parameters, so that

$G_h(s)= G_r(s)$, or

$$\frac{a_0+a_1s+a_2s^2+\ldots+a_{n-1}s^{n-1}}{b_0+b_1s+b_2s^2+\ldots+b_ns^n}=\frac{d_0+d_1s+d_2s^2+\ldots+d_{k-1}s^{k-1}}{e_0+e_1s+e_2s^2+\ldots+e_ks^k} \quad \ldots(1)$$

The unknown parameters (d_0,d_1,e_0,e_1,e_2) are determined by taking d_0=1 or e_0=1. for more details about the Manigandan method see ref.[9].

2.2 The Integral-Sliding Mode Pd Controller

The block-diagram for this controller is shown in Fig.(2). Where(α_1) is user design parameter, $x = (T_d s + 1)$ is sliding function, and K_s is sliding gain.

According to direct synthesis approach [10], which is used for first order plant, the equations for proportional gain K_p, integral gain K_i, and derivative gain K_d are[10]:

$$K_p = \frac{T}{K.\lambda} \qquad \text{…(2a)}$$

$$K_i = \frac{K_p}{T_i} \qquad \text{…(2b)}$$

$$K_d = K_p.T_d \qquad \text{…(2c)}$$

Where: T is the reduce first order plant model time constant, λ is a user specified closed loop time constant, and K is the gain of the first order plant model, and the integral time T_i=T, while the derivative time is chosen as T_d=T_i/4.

Note, since the reduced model $G_r(s)$ which is used in this paper is a 2nd order plant model and PID controller parameters with direct synthesis of ref.[10] are driving for a first order plant (not for the 2nd order model $G_r(s)$) therefore the $G_r(s)$ should be again reduce to first order model before calculate the PID controller parameters K_p, T_i, K_i, T_d, and K_d PID, let us refer to the reduce first order plant model as $G_f(s)$. In other word, the SMC can be use a discontinuity of the signum function, saturation function, or a sigmoid tan hyperbolic function.

Here in this paper, we use the nonlinear $\tanh(x.\alpha_1)$ function in the $u_s(s)$. This function give smooth output values between (-1 to 1) dependent on the values of the input x and the user design parameter α_1, the value of the sliding gain K_s is determine according to the following two suggested cases:-

Case #1:

If the higher order or the reduced transfer function contain zeros in his numerator then the sliding gain K_s will taken equal to the proportional gain K_p.

Case #2:

If the numerator of the reduced transfer function has no zeros or has small plant gain K then the sliding gain $K_s = \beta.K_p$. Where β is suitable constant value selected by the designer.

The purpose of using SMC with PD controller is to make the proportional gain K_p variable and this led to improve the performance of this controller. With this new PD-SMC, the equation for the control action $u(s)$ became:

$$u(s) = \left[\frac{K_i}{s} + K_s(\tanh(x\alpha_1) \right] \qquad \text{…(3)}$$

2.3 The Feedback Sliding Mode Controller(Fsmc)

Since the actual time delay is unknown, therefore $e^{-d_p s}$ (predication time delay) is assumed with boundary condition is

$$d_{\min} \le d_p \le d_{\max} \qquad \ldots(4)$$

when the difference between the actual time delay and the prediction one is become large, this lead to increase the oscillation and hence the system become unstable in addition to give bad performance by increase the steady state error(E_{ss}). Therefore in order to compensate this difference, a simple (SMC) controller is suggested to be used in the feedback path as shown in Fig.(3).

Where(α_2) is user design parameter (it is suggested to be less than or equal to one).

3. Simulation Results

With Matlab-Simulink, four higher order examples are tested and compared with the robust PID (R-PID) controller that explained in [11] with smith predictor connection, the direct synthesis PID [10] (DR-PID) method with smith predictor connection, and with the proposed scheme (PS-PID) of Fig.(1) to show which controller among them gives best performance and sure the stability when the difference between the actual and the predication time delay become large.

The purpose for selected four tested examples is to explained the ability of Manigandan method in reduce any higher order transfer function to second order or to first order transfer function, also to test the efficiency of the PS-PID method with different examples. Note the control parameters for the R-PID are obtained for the reduced 2nd plant model, while the control parameters for the DR-PID and the PS-PID are obtained for the reduced first order plant model. The Matlab-Simulink connection for the PS-PID is as explained in Fig.(1), the R-PID with smith predictor and the DR-PID with smith predictor are also connected as shown in Fig.(1) but without SMC in the feedback bath.

- ***Example* #1:** consider the fourth order transfer function which is given by[9]:

$$G_h(s) = \frac{2400 + 1800s + 496s^2 + 28s^3}{240 + 360s + 204s^2 + 36s^3 + 2s^4} \qquad \ldots(5)$$

According to Manigandan method with Eq.(1), the reduced second order model is obtained as:

$$G_r(s) = \frac{410.256 + 14s}{41.0256 + 29.5897s + s^2} \qquad \ldots(6a)$$

and the reduced first order model is obtained as: $G_f(s) = \dfrac{1}{0.1 + 0.0687s}$ ..(6b)

The control parameter for the robust, direct synthesis, and the proposed control scheme are given in Table.(1). Note the control parameters for the robust PID are obtained according to method that is explained in [11] model with natural frequency $\omega_n = 8$ rad/sec, damping ratio $\zeta = 1$, and with settling time t_s=0.5 sec.

The simulation results for this example with time delay d=0.4 sec. and different predicted time delay d_p=(0.3, 0.7, 1) sec. are shown in Fig.(4), while Fig.(5) shows the simulation results for this example with time delay d=0.7 sec. and different predicted time delay d_p=(0.3, 0.7, 1) sec.

- ***Example* #2:** consider the third order transfer function which is given by:

$$G_h(s) = \frac{1}{(s+1)(2s+1)(3s+1)} \quad \ldots(7)$$

With Manigandan method, the reduced second order model is obtained as:

$$G_r(s) = \frac{1}{1+6s+11s^2} \quad \ldots(8a)$$

and the reduced first order model is obtained as:

$$G_f(s) = \frac{1}{1+6s} \quad \ldots(8b)$$

With control parameters for the compared methods in Table(2), the control parameters for the robust PID are obtained with natural frequency $\omega_n = 0.62$ rad/sec, damping ratio $\zeta = 1$, and with settling time t_s=6.45 sec.

The simulation results for this example with time delay d=0.5 sec. and different predicted time delay d_p=(0.3, 0.8, 1.5) sec. are shown in Fig.(6).

- ***Example* #3:** consider the eighth order transfer function which is given by[9]:

$$G_h(s)=\frac{194480+482964s+511812s^2+278376s^3}{17760+45952s+24469s^2+7669s^3+1558s^4}$$

$$\cdots\frac{+82402\ s^4+13285\ s^5+1086\ s^6+35\ s^7}{+1558\ s^5+220\ s^6+21\ s^7+s^8}$$

the reduced second order model is obtained by applying Manigandan method as [9]:

$$G_r(s)=\frac{410.21+35s}{36.63+1.436s+s^2} \quad \ldots(10a)$$

Also by applying Manigandan method, the reduced first order model is obtained as:

$$G_f(s)=\frac{1}{0.08929+0.02857s} \quad \ldots(10b)$$

the control parameter are given Table (3). The control parameters for the robust PID are obtained with natural frequency $\omega_n=8$ rad/sec, damping ratio $\zeta=1$, and with settling time t_s=0.5 sec.

The simulation results for this example with time delay d=0.1 sec. and different predicted time delay d_p=(0.08, 0.1, 0.15) sec. are shown in Fig.(7).

- ***Example* #4:** consider the fourth order transfer function which is given by[4]:

$$G_h(s)=\frac{126}{100+180s+97s^2+18s^3+s^4} \quad \ldots(11)$$

the reduced second order model is obtained by applying Manigandan method as:

$$G_r(s)=\frac{1.29}{1.031+1.8s+s^2} \quad \ldots(12a)$$

and the reduced first order model is obtained as:

$$G_f(s)=\frac{1}{0.7992+1.39s} \quad \ldots(12b)$$

The control parameter are given in Table(4), the control parameters for the robust PID are obtained with natural frequency $\omega_n=1$ rad/sec, damping ratio $\zeta=1$, and with settling time t_s=4 sec.

The simulation results for this example with time delay d=1 sec and different predicted time delay d_p=(0.5, 1.2, 2) are shown in Fig.(8).

From the response of the four simulated examples, we can see the following notes:

1-The original close loop systems without (controller or smith predictor) are unstable for any small time delay values like in Ex.1 and Ex.3, or bad response with higher oscillations and large rising time t_r and settling time t_s as in Ex.2 and Ex.4.

2-The response of the all four simulated examples with (R-PID and smith predictor) or with (DS-PID and smith predictor) when d is fixed and different d_p values, show that these controller maintain the system stability but some times the oscillation increase (as in Ex.1 with R-PID and smith predictor) when the difference between the actual d and the predicted time delay d_p increase and hence this can be led to make the system unstable, also the performance of the all simulated examples with R-PID and smith predictor is less efficiency than the performance of these examples with the DS-PID and smith predictor.

3-The response of the all four simulated examples with the propose controller scheme (PS-PID) when d is fixed and different d_p values, show that the system is stay stable even when the difference between the d and d_p increase because this scheme compensate the difference between the actual and the predicted time delays by the feedback SMC, in other wise the performance of the all simulated examples with this scheme except Ex.3(which is nearly equivalent to the performance with the DS-PID and smith predictor) is more efficiency than the with the other compared method.

4. Conclusions

In this paper a smith predictor with simple controller scheme for time delay higher order systems is proposed, this scheme consist from two controller, the first feed forward controller is Integral – sliding mode PD controller, in this controller the values of proportional gain K_p, the integral time T_i, and the derivative time T_d are determined by the direct-synthesis method. The second controller is a feedback sliding mode controller, this controller is used to reduce the effect of the error E_y which introduce due to the difference between the original plant with the original time delay and the reduced 2nd plant model with the predicted time delay. Four higher examples are tested by robust PID controller with smith predictor connection, direct synthesis PID controller with smith predictor connection, and the proposed scheme PID with smith predictor connection, the performance of tested examples illustrates the efficiency of the proposed controller scheme.

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Table (1):control parameter of Ex.1

Type of controller	K_p	T_i	K_i	T_d	K_d
Robust PID (R-PID)	0.259	0.087	2.961	0.378	0.098
Direct synthesis DR-PID	0.236	0.687	0.343	0.171	0.040
Proposed scheme PS-PID	0.236	0.687	0.3435	0.171	----
SMCs parameters	α_1	α_2	β	K_s	
	1	0.6	1	0.236	

Table (2):control parameter of Ex.2

Type of controller	K_p	T_i	K_i	T_d	K_d
R- PID	8.09	3.088	2.62	0.734	5.935
DR-PID	1.414	6	0.2357	1.5	2.1210
PS-PID	1.414	6	0.2357	1.5	----
SMC parameters	α_1	α_2	β	K_s	
	1.5	0.6	35.361	50	

Table (3):control parameter of Ex.3

Type of controller	K_p	T_i	K_i	T_d	K_d
R-PID	0.867	0.1514	0.7752	---	0.0388
DR-PID	1.1931	1.7392	0.6860	0.4348	0.5188
PS-PID	1.1931	1.7392	0.6860	0.4348	----
SMC parameters	α_1	α_2	β	K_s	
	0.4	0.4	3.1	3.6986	

Table(4):control parameter of Ex.4

Type of controller	K_p	T_i	K_i	T_d	K_d
R-PID	0.4584	0.152	3.0283	0.0855	0.0392
DR-PID	0.15	0.32	0.4688	0.08	0.0120
PS-PID	0.15	0.32	0.4688	0.08	----
SMC parameters	α_1	α_2	β	K_s	
	1.5	0.5	1	0.15	

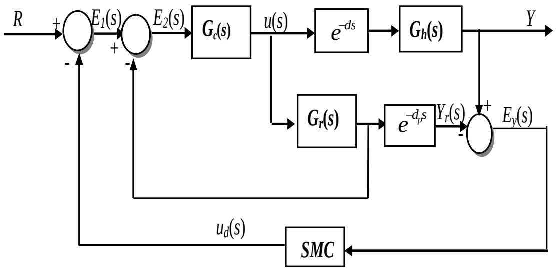


Figure.(1):the suggested smith control scheme.

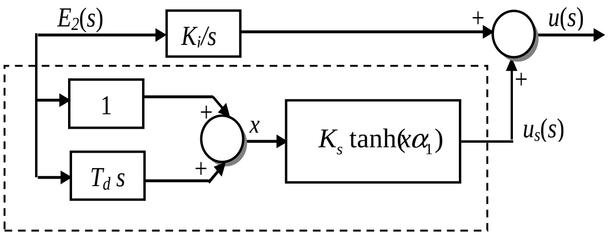


Figure.(2): The integral-sliding mode PD controller.

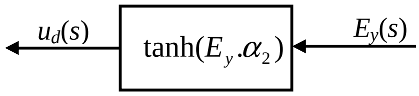
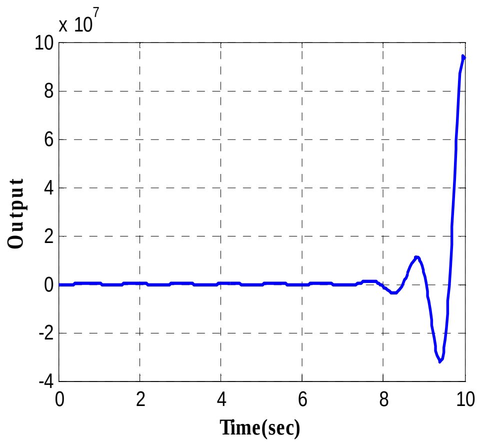
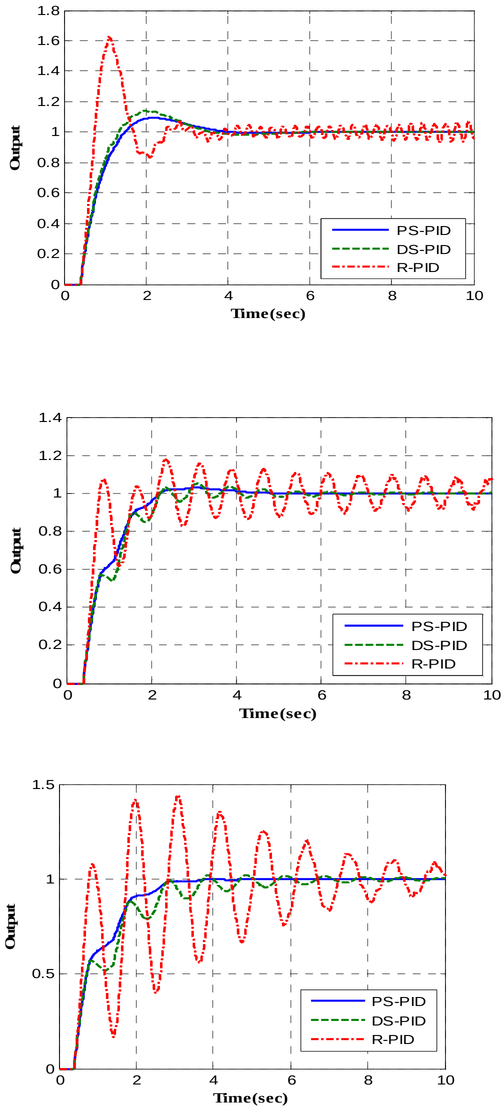


Figure.(3): the suggested feedback sliding mode controller.



(a)

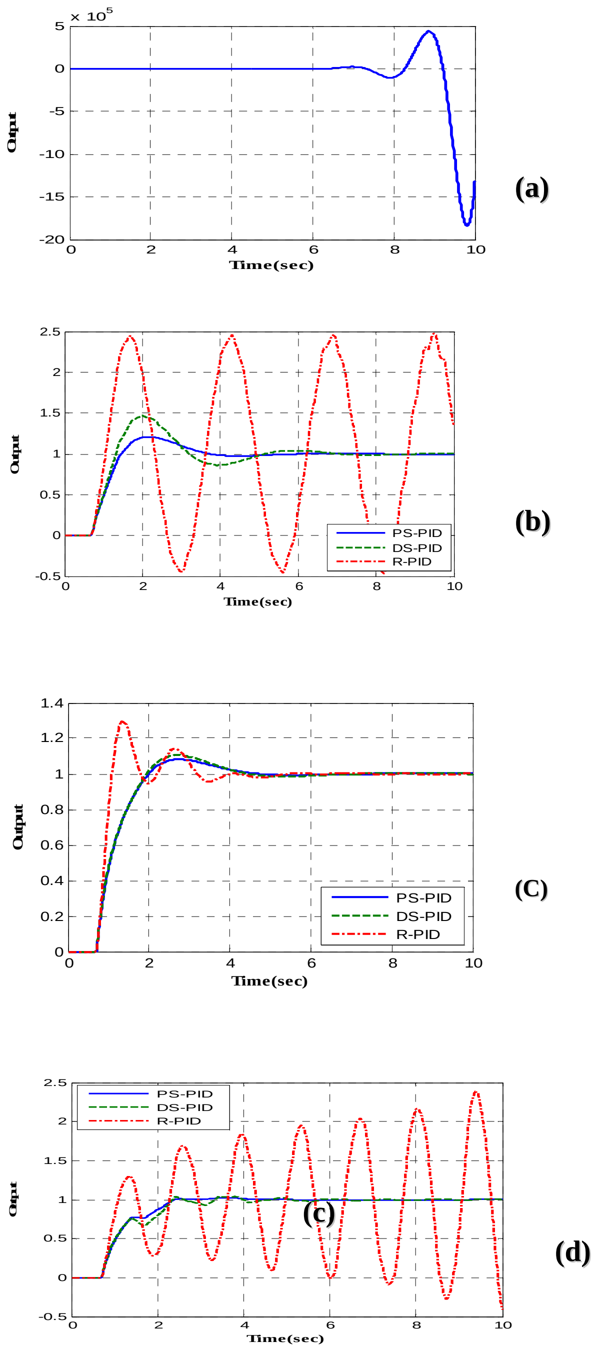


(b)

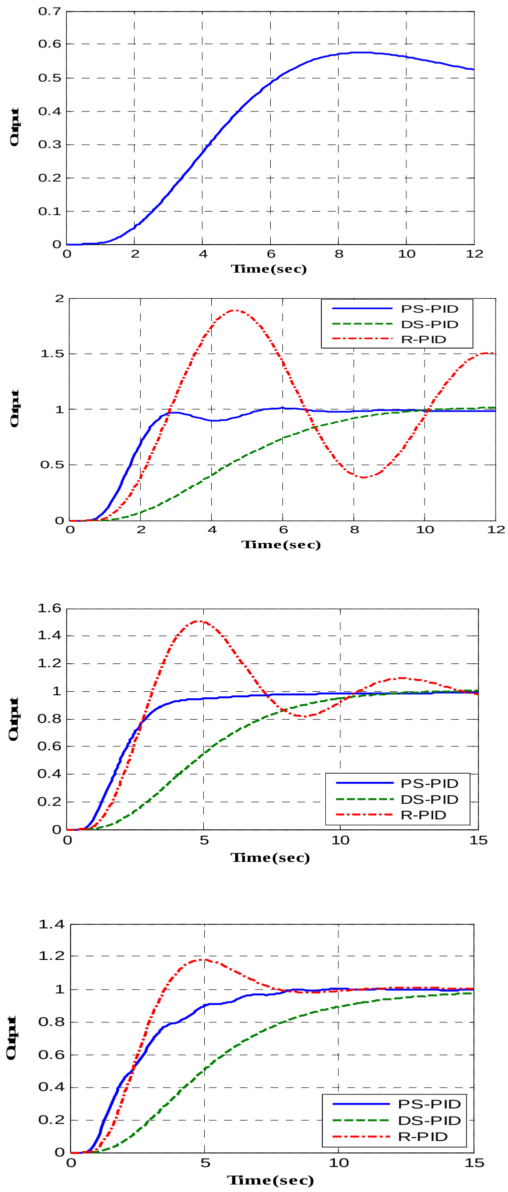
(c)

(d)

Figure(4):the output response for Ex.1. with *d*=0.4 sec., (a): without controller. (b): with controller and d_p=0.3 sec., (c): with controller and d_p=0.7 sec., (d): with controller and d_p=1 sec., .



Figure(5):the output response for Ex.1. with *d*=0.7 sec., (a): without controller. (b): with controller and d_p=0.3 sec. (c): with controller and d_p=0.7 sec. (d): with controller and d_p=1 sec.



(a)

(b)

(c)

(d)

Figure(6):the output response for Ex.2. with *d*=0.5 sec., (a): without controller. (b): with controller and d_p=0.3 sec. (c): with controller and d_p=0.8 sec. (d): with controller and d_p=1.5 sec.

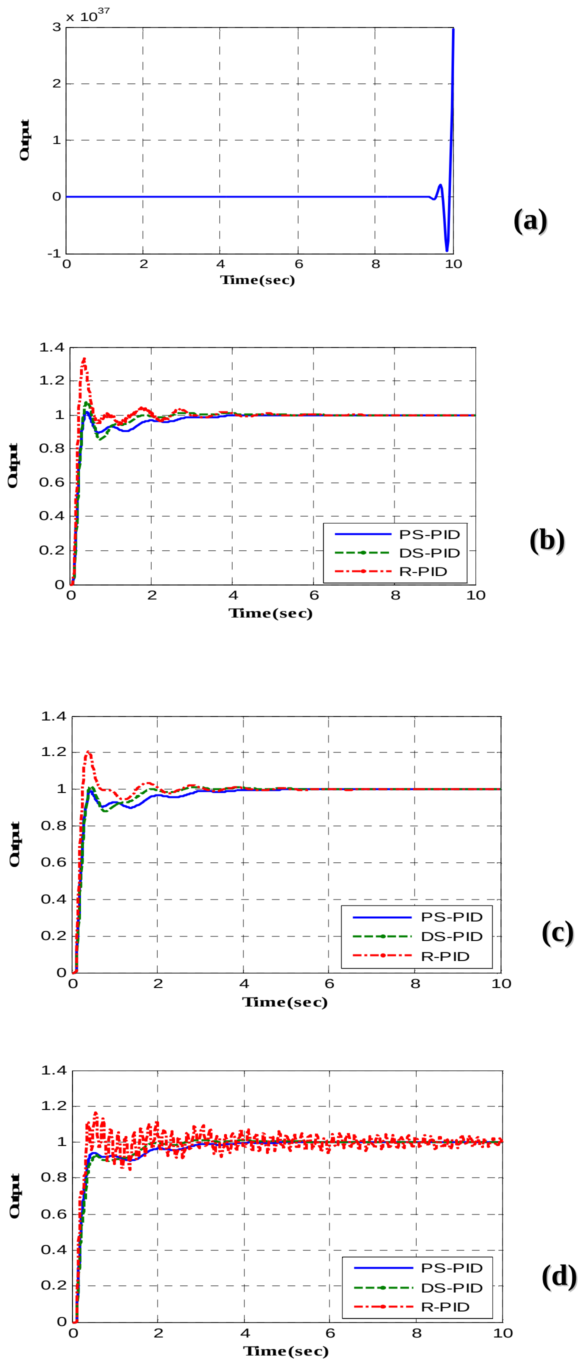


Figure (7):the output response for Ex.3. with d=0.1 sec., (a): without controller. (b): with controller and d_p=.08 sec. (c): with controller and d_p=0.1 sec. (d): with controller and d_p=0.15 sec.

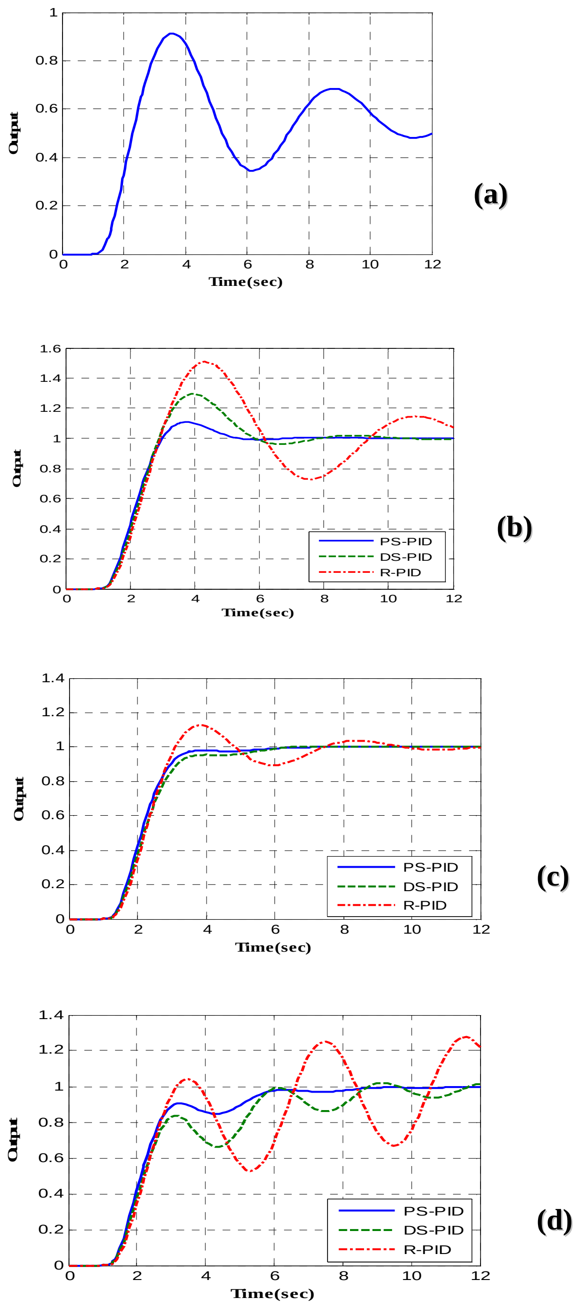


Figure (8):the output response for Ex.4. with d=1 sec., (a): without controller. (b): with controller and d_p=0.5 sec. (c): with controller and d_p=1.2 sec. (d): with controller and d_p=2 sec.