Robust adaptive controller design for excavator arm

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ABSTRACT

This paper presents a robust adaptive controller that does not depend on the system parameters for an excavator arm. Firstly, the model of the excavator arm is demonstrated in the Euler-Lagrange form considering with overall excavator system. Next, a robust adaptive controller has been constructed from information of state error. In this paper, the stability of overall system is mathematically proven by using Lyapunov stability theory. Also, the proposed controller is model free then the closed loop system is not affected by disturbances and uncertainties. Finally, the simulation is executed in Matlab/Simulink for both presented scheme and the PD controller under some conditions to ensure that the proposed algorithm given the good performances for all cases.

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1. INTRODUCTION

Nowadays, robots are used commently in the industries because of their versatility and efficiency [1-3]. The automatic remote control of the robot plays a significant role in real-life application, such as nuclear field, construction, and rescue missions. For the excavator robot, in order to perform a specific duty, it needs to complete at least two tasks: determining a feasible path from its initial location to the destination and then executing the task through control algorithm that has to be designed. According to these requirements, the tracking control problem for the excavator robot system is constantly receiving the interesting of scientists. The earlier research work mainly focused on modelling work including kinematic and dynamic model, modelling of interaction between the machine and the environment, and parameter identification [4-10]. Modelling and parameter identification during the operation of machine is very helpful for the real-time monitoring and remote control.

About the control design, during the earlier stage of study on excavator, impedance control is considered as a popular control. In [11], a position-based impedance controller is presented on mini-excavator. In [12-13], authors present detail of robust impedance control for hydraulic excavator. The impedance control suits to apply for excavator because it can deal with both free and constrain motion [13]. However, the algorithm is quite complicated. Recently, many modern control techniques are used in trajectory control of excavator arm. In [14], an adaptive controller is presented in controlling excavator arm. The stability of system is ensured through mathematical proof and verified by simulation results. However, the simulation as well as the explanation of simulation results is quite poor. In [15-16], the fuzzy controllers are employed to solve the tracking control problem of the excavator. In these type of controllers, the information about the system does not require. However, the stability of the overall system is not shown in the mathematic. Nowadays, the PID controller still being used widely in the practice because of its simplify. However, tuning of the PID gains to adapt with the change of working conditions is difficult and depending on the personal experiences. In recent times, in order to deal with this problem, some optimization techniques such as artificial neural network (ANN), ant colony optimization (ACO), etc., have been applied to optimize the PID parameters. In [17], an genetic algorithm (GA) is used to determine the PID gains for trajectory tracking control of robotic excavator. The presented scheme gave the good performances in comparison with some given methods. However, the gotten results still have problems needed to be discussed.

In this paper, a robust adaptive controller is proposed for excavator arm system. The structure of controller consists of two parts: the first part is responsible for keeping the stability of the system and the second part is used for adapting with the unknown parameters. Therefore, the proposed controller has ability to cancel the effect of the uncertainties as well as to keep the tracking error go to zero. Also, the presented controller is simple so it is easy to implement. The feasible of the algorithms is demonstrated by Lyapunov stability theory and verified through simulation models. The simulation is executed in MATLAB/Simulink for both presented scheme and the PD controller under some conditions to ensure that the proposed algorithm given the good performances for all cases.

2. CONTROLLER DESIGN FOR EXCAVATOR ARM

2.1. Modelling of excavator arm

Consider an excavator system with structure as Figure 1. The system consists of two subsystems: the base is used to move the entire system on the $x_0O_0y_0$, plane and the arm is used for movement in the $z_0O_0y_0$ and $z_0O_0x_0$ planes. This paper concern mainly on the motion control of excavator arm, so the base part and the rotation around O_0z_0 axis are considered unchanged.

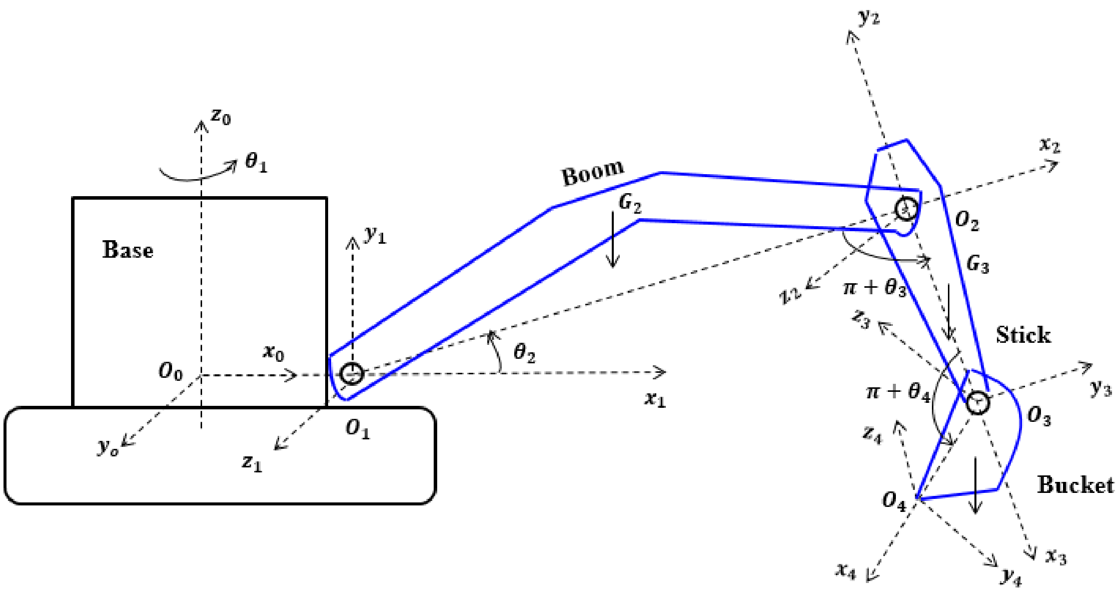

Figure 1. Schematic diagram of an excavator

The Euler-Lagrange model of excavator arm during the digging process corresponding to the coordinates of each join as shown in Figure 1 is as follow [18]:

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) + B(\dot{\theta}) = \Gamma\tau - F_L \tag{1}$$

where $\theta = [\theta_2 \quad \theta_3 \quad \theta_4]$ is the position of each joint in the joint space, $D(\theta)$ represents inertial part, $C(\theta,\dot{\theta})$ is the Coriolis and centripetal effects, $G(\theta)$ is the gravity part, $B(\dot{\theta})$ represents frictions; Γ is the corresponding input matrix, $\tau = [\tau_1 \quad \tau_2 \quad \tau_3]$ specifies the torques acting on the shaft of 3 joints, F_L represents the interactive torques. The formulas of above parts are given by the following expressions:

$$D(\theta)=\begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix},\ C(\theta,\dot{\theta})=\begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix},\ \Gamma=\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

$$G(\theta)=\begin{bmatrix} G_2 & G_3 & G_4 \end{bmatrix},\ B(\dot{\theta})=\begin{bmatrix} B_{bo}\dot{\theta}_2 & B_{st}\dot{\theta}_3 & B_{bu}\dot{\theta}_4 \end{bmatrix}, \tag{3}$$

where:

$$\begin{aligned}
&D_{33}=I_{bu}+M_{bu}r_4^2 \\
&D_{22}=D_{33}+I_{st}+M_{st}r_3^2+M_{bu}\left[a_3^2+2a_3r_4\cos\left(\theta_4+\alpha_4\right)\right] \\
&D_{11}=D_{22}+I_{bo}+M_{bo}r_2^2+M_{st}\left[a_2^2+2a_2r_3\cos\left(\theta_3+\alpha_3\right)\right] \\
&\qquad +M_{bu}\left[a_2^2+2a_2a_3c_3+2\,\mathrm{a}_2\mathrm{r}_4\cos\left(\theta_{34}+\alpha_4\right)\right] \\
&D_{23}=D_{32}=D_{33}+M_{bu}a_3r_4\cos\left(\theta_4+\alpha_4\right) \\
&D_{13}=D_{31}=D_{23}+M_{bu}a_2r_4\cos\left(\theta_{34}+\alpha_4\right) \\
&D_{12}=D_{21}=D_{13}+I_{st}+M_{st}\left[r_3^2+a_2r_3\cos\left(\theta_3+\alpha_3\right)\right] \\
&\qquad +M_{bu}\left[a_3^2+a_2a_3c_3+a_3r_4\cos\left(\theta_4+\alpha_4\right)\right] \\
&C_{11}=-M_{st}a_2r_3\dot{\theta}_{23}\sin\left(\theta_3+\alpha_3\right)-M_{bu}a_2a_3\dot{\theta}_{23}s_3-M_{bu}a_2r_4\dot{\theta}_{234}\sin\left(\theta_{34}+\alpha_4\right) \\
&C_{12}=-M_{st}a_2r_3\dot{\theta}_{23}\sin\left(\theta_3+\alpha_3\right)-M_{bu}a_2a_3\dot{\theta}_{23}s_3-M_{bu}a_2r_4\dot{\theta}_{234}\sin\left(\theta_{34}+\alpha_4\right) \\
&C_{13}=-M_{bu}a_2r_4\dot{\theta}_{234}\sin\left(\theta_{34}+\alpha_4\right) \\
&C_{21}=a_2\dot{\theta}_2\left[M_{bu}a_3s_3+M_{st}r_3\sin\left(\theta_3+\alpha_3\right)\right]-M_{bu}a_3r_4\dot{\theta}_{234}\sin\left(\theta_4+\alpha_4\right) \\
&C_{22}=-M_{bu}a_3r_4\dot{\theta}_{234}\sin\left(\theta_4+\alpha_4\right) \\
&C_{23}=-M_{bu}a_3r_4\dot{\theta}_{234}\sin\left(\theta_4+\alpha_4\right) \\
&C_{31}=M_{bu}r_4\dot{\theta}_2\left[a_2\sin\left(\theta_{34}+\alpha_4\right)+a_3\sin\left(\theta_4+\alpha_4\right)\right]+M_{bu}a_3r_4\dot{\theta}_3\sin\left(\theta_4+\alpha_4\right) \\
&C_{32}=M_{bu}a_3r_4\sin\left(\theta_4+\alpha_4\right) \\
&C_{33}=0 \\
&G_2=\left(M_{bu}+M_{st}\right)ga_2c_2+M_{bo}gr_2\cos\left(\theta_2+\alpha_2\right) \\
&G_3=M_{bu}ga_3c_{23}+M_{st}gr_3\cos\left(\theta_{23}+\alpha_3\right) \\
&G_4=M_{bu}gr_4\cos\left(\theta_{234}+\alpha_4\right)
\end{aligned}$$

2.2. Robust adaptive controller design

Define the error signal:

$$e=\theta_d-\theta \tag{4}$$

where θ_d is desired value of θ. The filtered error surface is chosen as

$$\begin{aligned}
&x=\dot{\theta}-\dot{\theta}_d+\Upsilon e \\
&\dot{x}=\ddot{\theta}-\ddot{\theta}_d+\Upsilon\dot{e}
\end{aligned} \tag{5}$$

where $\Upsilon = diag(\Upsilon_1, \Upsilon_2, \Upsilon_3) > 0$

Based on (5), (1) can be written as

$$\begin{aligned} D(\theta)\dot{x} &= -C\left(\theta,\dot{\theta}\right)x - M(\theta)\ddot{y} - C\left(\theta,\dot{\theta}\right)\dot{y} - G(\theta) - B\left(\dot{\theta}\right) - F_L + \Gamma\tau \\ &= -C\left(\theta,\dot{\theta}\right)x - \Phi_m^T\varphi_m + \Gamma\tau \end{aligned} \tag{6}$$

where $\dot{y} = \dot{\theta}_d - \Upsilon e$, $\Phi_m = \left[D(\theta) \quad C\left(\theta,\dot{\theta}\right) \quad B\left(\dot{\theta}\right) \quad G(\theta) \quad F_L\right]^T$, $\varphi_m = [\ddot{y} \quad \dot{y} \quad 1 \quad 1 \quad 1]^T$. Asuming that $\|\Phi_m\| = \left[\|D(\theta)\| \quad \left\|C\left(\theta,\dot{\theta}\right)\right\| \quad \left\|B\left(\dot{\theta}\right)\right\| \quad \|G(\theta)\| \quad \|F_L\|\right]^T \le \left[\rho_1 \quad \rho_2 + \rho_3\left\|\dot{\theta}\right\| \quad \rho_4\left\|\dot{\theta}\right\| \quad \rho_5 \quad \rho_6\right]^T$ and ρ_i (i = 1,2,3,4,6) are unkown positive constans.

Consider the following theorem. **Theorem**: If there exist the scalars ρ_i (i = 1,2,3,4,6) so that $\|\Phi_m\| = \left[\|D(\theta)\| \quad \left\|C\left(\theta,\dot{\theta}\right)\right\| \quad \left\|B\left(\dot{\theta}\right)\right\| \quad \|G(\theta)\| \quad \|F_L\|\right]^T \le \left[\rho_1 \quad \rho_2 + \rho_3\left\|\dot{\theta}\right\| \quad \rho_4\left\|\dot{\theta}\right\| \quad \rho_5 \quad \rho_6\right]^T$ then the following controller and adaptation law can make the dynamic error go to zero.

$$\begin{aligned} \Gamma\tau &= -Kx - \sum_{k=1}^{6} \frac{x\hat{\rho}_k\varphi_k^{\,2}}{\|x\|\varphi_k + \varepsilon_k} \\ \dot{\hat{\rho}}_k &= \frac{\eta_k\|x\|^2\varphi_k^{\,2}}{\|x\|\varphi_k + \varepsilon_k} - \eta_k^{'}\hat{\rho}_k, k = 1,\ldots,6 \end{aligned} \tag{7}$$

where K = diag(k_1, k_2, k_3) with $k_i > 0$ (i = 1, 2, 3), $\eta_k^{'} > 0, \varepsilon_k > 0$ are constant, ζ = diag (ζ_1, ζ_2, ζ_3) > 0, $\varphi = \left[\|\ddot{\chi}\| \quad \|\dot{\chi}\| \quad \left\|\dot{\theta}\right\|\|\dot{\chi}\| \quad \left\|\dot{\theta}\right\| \quad 1 \quad 1\right]^T$

Proof: Choose the Lyapunove function:

$$V = \frac{1}{2}x^T D(\theta)x + \sum_{k=1}^{6}\frac{1}{2\eta_k}\tilde{\rho}_k^2 \tag{8}$$

where $\tilde{\rho}_k = \rho_k - \hat{\rho}_k$, $\hat{\rho}_k$ are estimated values of ρ_k, η_k *is* positive constant.

The time derivative of Lyapunov function using (6) is as

$$\begin{aligned} \dot{V}_1 &= -x^T\left[C\left(\theta,\dot{\theta}\right) - \frac{1}{2}\dot{D}(\theta)\right]x + \sum_{k=1}^{6}\frac{1}{\eta_k}\tilde{\rho}_k\dot{\tilde{\rho}}_k + +x^T[-D(\theta)\ddot{y} - C\left(\theta,\dot{\theta}\right)\dot{y} \\ &\quad - G(\theta) - B\left(\dot{\theta}\right) - F_L + \Gamma\tau] \\ &= x^T\left(-\Phi_m^T\varphi_m + \Gamma\tau\right) - \sum_{k=1}^{6}\frac{1}{\eta_k}\tilde{\rho}_k\dot{\hat{\rho}}_k \end{aligned} \tag{9}$$

Substituting (7) into (9), it is obtained:

$$\begin{aligned}
\dot{V} &= -x^T Kx - x^T \Phi_m^T \varphi_m - x^T \sum_{k=1}^{6} \frac{x\hat{\rho}_k \varphi_k^2}{\|x\|\varphi_k + \varepsilon_k} - \sum_{k=1}^{6} \frac{\|x\|^2 \tilde{\rho}_k \varphi_k^2}{\|x\|\varphi_k + \varepsilon_k} + \sum_{k=1}^{6} \frac{\eta_k'}{\eta_k} \tilde{\rho}_k \hat{\rho}_k \\
&\le -x^T Kx + \|x\|\|\Phi_m^T \varphi_m\| - \sum_{k=1}^{6} \frac{\|x\|^2 \rho_k \varphi_k^2}{\|x\|\varphi_k + \varepsilon_k} + \sum_{k=1}^{6} \frac{\eta_k'}{\eta_k} \tilde{\rho}_k \hat{\rho}_k \\
&\le -x^T Kx + \|x\|\Phi^T \varphi - \sum_{k=1}^{6} \frac{\|x\|^2 \rho_k \varphi_k^2}{\|x\|\varphi_k + \varepsilon_k} + \sum_{k=1}^{6} \frac{\eta_k'}{\eta_k} \tilde{\rho}_k \hat{\rho}_k \\
&\le -x^T Kx + \sum_{i=1}^{6} \rho_k \varepsilon_k + \sum_{k=1}^{6} \frac{\eta_k'}{\eta_k} \tilde{\rho}_k \hat{\rho}_k \\
&\le -x^T Kx - \sum_{k=1}^{6} \frac{\eta_k'}{2\eta_k} \tilde{\rho}_k^2 + \sum_{i=1}^{6} (\rho_k \varepsilon_k + \frac{\eta_k' \rho_k^2}{2\eta_k}) \\
&\le -\lambda_{min}(K)\|x\|^2 - \sum_{k=1}^{6} \frac{\eta_k'}{2\eta_k} \tilde{\rho}_k^2 + \delta \\
&\le -\mu V + \delta
\end{aligned} \tag{10}$$

where $\mu = \min[\lambda_{min}(K), \eta_k' / 2\eta_k] / \max[(D(\theta)), 1/\eta_k] > 0$

$$\Phi = [\rho_1 \quad \rho_2 \quad \rho_3 \quad \rho_4 \quad \rho_5 \quad \rho_6]^T, \ \delta = \sum_{k=1}^{6} (\rho_k \varepsilon_k + \frac{\eta_k' \rho_k^2}{2\eta_k}) \tag{11}$$

Multiplying (10) by $e^{\mu t}$ gives:

$$\frac{d}{dt}(Ve^{\mu t}) \le \delta e^{\mu t} \tag{12}$$

Integrating (12) leads to the following inequality:

$$0 < V(t) < \left(V(0) - \frac{\delta}{\mu}\right)e^{-\mu t} + \frac{\delta}{\mu} < V(0) + \frac{\delta}{\mu} \tag{13}$$

Based on above results and Barbalat's lemma, all error signals will go to zero when time goes to infinite-time.

3. SIMULATION RESULTS

To evaluate the correctness and suitability of the proposed robust adaptive controller, the algorithm was set and simulated in Simulink software with an excavator system given parameters as the following [18]:

Mbo=1566; Mst=735; Mbu=432; Mload=500;
Ibo=14250.6; Ist=727.7; Ibu=224.6;
a2=5.16; a3=2.59; r2=2.71; r3=0.64; r4=0.65;
Bbo=0.02; Bst=0.02; Bbu=0.02;

The parameter for the control law is chosen by practical method (trial–and–error): Υ =diag (1), K=diag ($2\text{x}10^6$, $1.5\text{x}10^6$, 10^5), η_k=1, η_k'=0.01, ε_k=0.1

With the purpose of comparison, the simulation is exercuted for both proposed controller and PD controller [15].The simulation has been conducted for three cases:

- **Case 1**: The parameters of system are rated, the machine works without payload.
- **Case 2**: The parameters of system are rated, the machine works with full payload.
- **Case 3**: The parameters of model change, the machine works will full payload.

In each case, the results were compared with the response of PD controller which was mentioned in [18]. Simulation results for Case 1, Case 2, and Case 3 are shown in Figure 2, 3 and 4, respectively. In these figures, the solid line (Theta$_d$) represents the reference value of and dashed line (Theta) is for real value of θ.

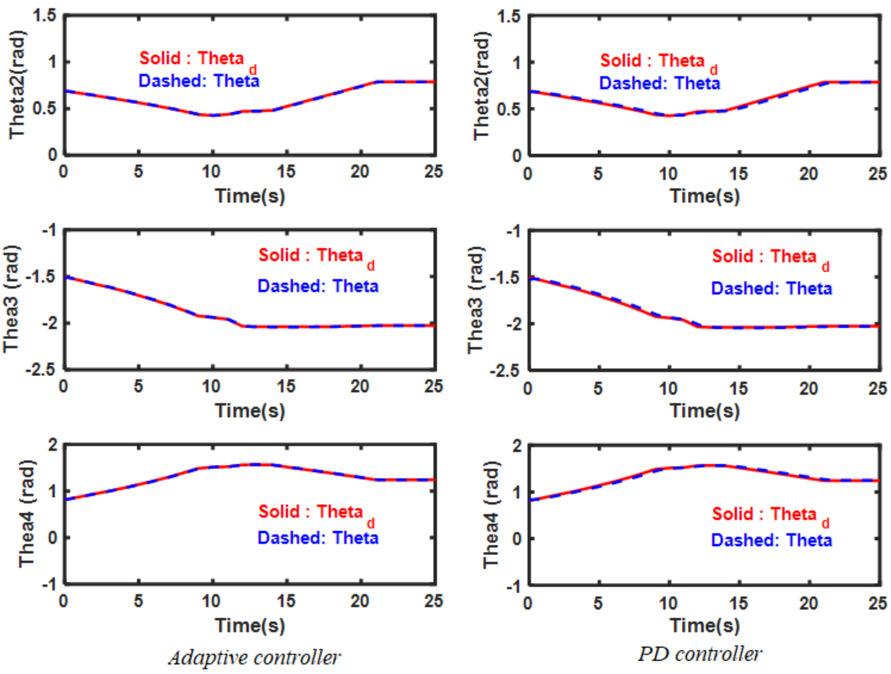

Figure 2 System responses under condition of without payload and rated system parameters

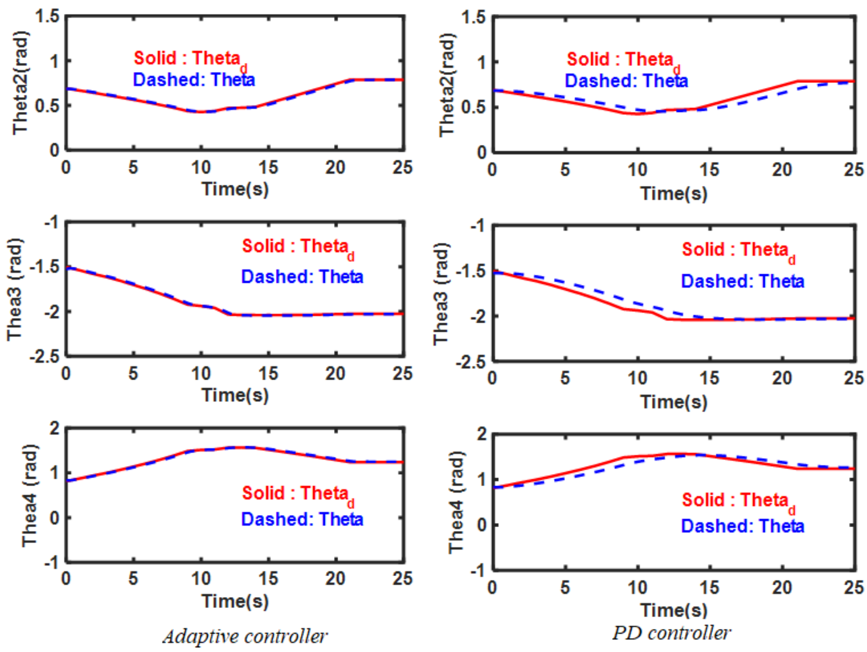

Figure 3. System responses under condition of full payload and rated system parameters

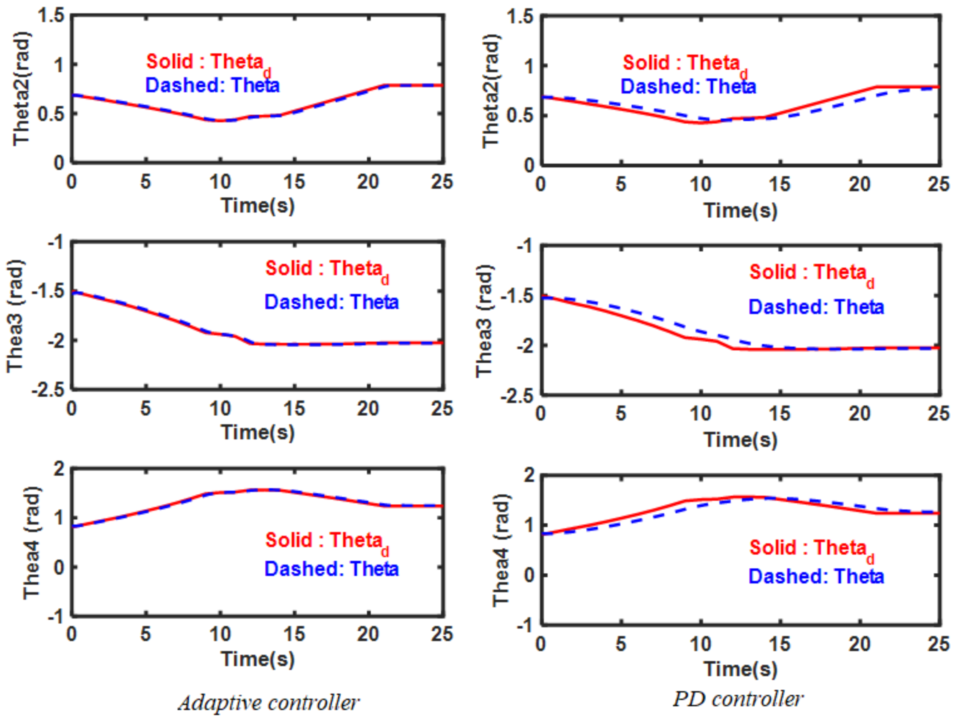

Figure 4. System responses under condition of full payload and system parameters variation

In Figure 2, when system works without load and the parameters of model is rated, the position response of joints by using proposed controller and PD controller is absolutely tracked to desired value, and the tracking error is trivial. In the second case (Figure 3), the system parameters remain unchanged but the excavator work with full payload. The adaptive controller gives the position response of joints almost no deviation from desired trajectory, while the PD controller gives a tracking error about 0.05 rad. In case system works with full payload and the parameter of system change (Figure 4), the results obtained for the adaptive controller are still relatively good. The PD controller gives a maximal tracking error about 0.15 rad.

From the simulation results, it can be seen that the PD controller can make the system only work well when the elements of system are determined. When the system has load disturbance, the tracking error appears (0.05 rad) and will increase to 0.15 rad if the system is affected by addition disturbances. This is proved that the PD controller will increase tracking error when system has disturbance. Meanwhile, for adaptive controller, the responses of system under condition of system uncertainties as well as payload noise are so good.

4. CONCLUSION

This paper has presented the robust adaptive controller that does not depend on the system model for excavator arm. The controller has simple structure, easy to implement but still guarantees good performances to the uncertainty of the system. The stability and suitability of the controller were demonstrated by Lyapunov stability theory and examined through simulation. The simulation results show that all joints of excavator arm absolutely track to desired value even if there is the effect of the load disturbance and the impact of the uncertainties of system model.

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