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Adaptive Control for A Class of Linear Systems with Matching Uncertainties and Its Application to Ship Steering

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Abstract

The purpose of this paper is to present an adaptive control for a class of linear systems with matching uncertainties. Firstly, a class of linear systems with matching uncertainties is recommended. Secondly, an adaptive control algorithm for the class is proposed based on the upper bounds of the uncertainties. Then, applying Lyapunov stability theory and linear matrix inequality method, we prove that the adaptive control algorithm can guarantee the closed–loop system to converge exponentially with a prescribed degree towards a residual ball around the equilibrium. Finally, the proposed algorithm is verified with the simulation on a cargo ship steering. The simulation result shows that the system with the proposed algorithm is asymptotically stable and its tracking error can approach to zero.

Keyword: matched uncertainties, linear systems, adaptive control, ship steering

I. Introduction

In daily language, "to adapt" means to change behaviors to conform to new circumstances. An adaptive controller is thus a controller with adjustable parameters and a mechanism for adjusting the parameters that can modify its behavior in response to changes in the dynamics of the process and the character of the disturbances [1]. Numerous articles have been written on the studies on adaptive control [1,2,3]. There are kinds of methods to adjust the parameters of various controllers for different systems [3,4,5,6,7]. But most of the controllers are focused on nonlinear systems in recent years and some methods are too complex to be used in real-time systems. However, there are many systems that can be controlled with linear controllers through linearization in the real systems, so the linear systems are worthy to be studied.

In the studies on linear systems with matching uncertainties, linear matrix inequality (LMI) is an effective method for the robust control for uncertain systems [3,4,8]. And yet some of the obtained controllers are very conservative and may be too strong as lacking adaptation, so they would need more energy. Moreover, if the controller structure of the system is inconsequential and if any special measure is not been taken, the system may tremble, which is very harmful.

In recent years there has been a growing interest in the need for designing adaptive systems to solve problems in ship steering control in order to improve fuel efficiency and reduce wear on ship components [1]. Ship steering control involves various forms of uncertainties and nonlinearities, but we can use the linear model of ship steering through linearization to design an adaptive controller with LMI.

In this paper, we introduce a class of linear systems with matching uncertainties. With Lyapunov stability theory and linear matrix inequality method [3,8], an adaptive control algorithm is proposed based on the upper bounds of the uncertainties by on-line estimating the process parameters. Moreover, residual ball around the equilibrium is taken according to the system in case of the system tremble. In order to verify the adaptive control algorithm, simulation on a cargo ship steering is taken with the adaptive control algorithm as a controller. The adaptive controller, by contrast with an optimal PD controller, will show reasonable results in the simulation control of nonlinear ship steering model. The simulation results show that the adaptive control algorithm is asymptotic stable in the large scope for the obtained closed loop system.

II. Problem formulation and assumption

Consider the uncertain linear system with matching uncertainties as following form:

$$\dot{x}(t) = (A + \Delta A(s(t))x(t) + (B + \Delta B(s(t))u(t) + Cw(t) \tag{1}$$

where $t \in R^+$, $x(t) \in R^n$ is the state variable, $u \in R^m$ is the control input, $n \geq m \geq 1$, $s(t) \in \Omega_1 \subset R^p$ is the state uncertain vector, $v(t) \in \Omega_2 \subset R^l$ is control input uncertain vector, $w(t) \in \Omega_3 \subset R^q$ is environment disturbance uncertainty vector, and Ω_1, Ω_2 and Ω_3 are compact sets and Lebesgue measures in R^p, R^l, R^q. Matrices A, B and C are constant ones with proper dimensions. Matrices ΔA and ΔB are matching uncertainties under the known structure A and B respectively with proper dimensions. C is matching uncertainty. The following assumptions are introduced for system (1):

Assumption 1: For the matching uncertainty in system (1), (A, B) is controllable.

Assumption 2: Let $D(s(t))$, $E(v(t))$ be matrices in R^p, R^l with appropriate dimensions, and F be constant matrix respectively. Then the admissible uncertainties are assumed to be of the form

$$\begin{cases} \Delta A(s(t)) = BD(s(t)) \\ \Delta B(s(t)) = BE(v(t)) \\ \quad C = BF \end{cases} . \tag{2}$$

Substitute (2) into (1), and we obtain

$$\dot{x}(t) = Ax(t) + B((I + E(v(t)))u + D(s(t))x(t) + Fw(t)) .$$

Let $\eta(x, s(t), v(t), w(t)) = D(s(t))x + E(v(t)))u + Fw(t)$,

and we have

$$\dot{x}(t) = Ax(t) + B(u + \eta(x, s(t), v(t), w(t))) \ . \tag{3}$$

Assumption 3: Supposing that $\|D(s(t))\|$, $\|E(v(t))\|$, $\|F(w(t))\|$ have upper bounds, having constants $\theta_1 = \max_{s(t)\in\Omega_1} \| D(s(t)) \| \geqslant 0$, $0 \leqslant \theta_2 = \max_{v(t)\in\Omega_2} \| E(v(t)) \| < 1$, $\theta_3 = \max_{w(t)\in\Omega_3} \| Fw(t) \| \geqslant 0$,

and letting $\Theta = [\theta_1,\ \theta_2,\ \theta_3]^{\mathrm{T}}$, $\psi(x,t) = [\| x \|,\ \| u \|,\ 1]^{\mathrm{T}}$,

the flowing inequation comes into existence

$$\| \eta \| \leqslant \Theta \psi(x,t) = \theta_1 \| x \| + \theta_2 \| u \| + \theta_3 \ . \tag{4}$$

Our aim may be described as follows:

Under the assumptions of 1, 2 and 3, derive an adaptive robust quadratic stable adaptive control algorithm with the property of the uniformly ultimate bound for the obtained closed-loop system with the unknown parameters θ_1, θ_2, θ_3.

III. Adaptive control algorithm design

Under uncertain liner system with assumption 1, there exists a real symmetric positive matrix P and a constant $\rho > 0$ satisfying the RICCATI equation

$$A^{\mathrm{T}}P + PA - \rho PBB^{\mathrm{T}}P = -Q,$$

where Q is a positive definite matrix chosen by designer.

Supposing that θ_1, θ_2 and θ_3 are unknown, $\hat{\theta}_1$, $\hat{\theta}_2$ and $\hat{\theta}_3$ are the estimates of θ_1, θ_2 and θ_3 respectively, $\tilde{\theta}_1 = \theta_1 - \hat{\theta}_1, \tilde{\theta}_2 = \theta_2 - \hat{\theta}_2$ and $\tilde{\theta}_3 = \theta_3 - \hat{\theta}_3$ are the estimate error of θ_1, θ_2 and θ_3, we have $\dot{\tilde{\theta}}_1 = \dot{\theta}_1 - \dot{\hat{\theta}}_1 = -\dot{\hat{\theta}}_1, \dot{\tilde{\theta}}_1 = \dot{\theta}_1 - \dot{\hat{\theta}}_1 = -\dot{\hat{\theta}}_1$, $\dot{\tilde{\theta}}_3 = \dot{\theta}_3 - \dot{\hat{\theta}}_3 = -\dot{\hat{\theta}}_3$.

So we have the following form of inequation (4):

$$\begin{aligned}
&\|\eta\| \leqslant \Theta\psi(x,t)\\
&= \hat{\theta}_1\|x\| + \hat{\theta}_2\|u\| + \hat{\theta}_3 + \theta_1\|x\| + \theta_2\|u\| + \theta_3 - (\hat{\theta}_1\|x\| + \hat{\theta}_2\|u\| + \hat{\theta}_3)\\
&= \hat{\theta}_1\|x\| + \hat{\theta}_2\|u\| + \hat{\theta}_3 + \tilde{\theta}_1\|x\| + \tilde{\theta}_2\|u\| + \tilde{\theta}_3\\
&= \hat{\Theta}\psi(x,t) + \tilde{\Theta}\psi(x,t),
\end{aligned}$$

where $\hat{\Theta} = [\hat{\theta}_1,\ \hat{\theta}_2,\ \hat{\theta}_3]^{\mathrm{T}}$, and $\tilde{\Theta} = [\tilde{\theta}_1,\ \tilde{\theta}_2,\ \tilde{\theta}_3]^{\mathrm{T}}$.

Therefore, we suppose that the adaptive control algorithm scheme is

$$u = -\frac{\rho\|PBx\| + 2\hat{\theta}_1\|x\| + 2\hat{\theta}_3}{2(1-\hat{\theta}_2)}\frac{PBx}{\|PBx\|}. \tag{5}$$

We will prove the adaptive control algorithm scheme can guarantee the closed–loop system to converge exponentially with a prescribed degree towards a residual ball around the equilibrium.

Proof: Choose Lyapunov candidate function as following form:

$$V = x^{\mathrm{T}}Px + \tilde{\Theta}^{\mathrm{T}}\Gamma^{-1}\tilde{\Theta},$$

where $\Gamma > 0$ is diagonal matrix chosen by designer.

Under the controller (5), we have

$$\begin{aligned}
\dot{V} &= \dot{x}^{\mathrm{T}}Px + x^{\mathrm{T}}P\dot{x} + \dot{\tilde{\Theta}}^{\mathrm{T}}\Gamma^{-1}\tilde{\Theta} + \tilde{\Theta}^{\mathrm{T}}\Gamma^{-1}\dot{\tilde{\Theta}}\\
&= x^{\mathrm{T}}APx + x^{\mathrm{T}}PAx + 2(B^{\mathrm{T}}Px)^{\mathrm{T}}(u+\eta) + 2\tilde{\Theta}^{\mathrm{T}}\Gamma^{-1}\dot{\tilde{\Theta}},
\end{aligned}$$

where $\dot{\tilde{\Theta}} = [\dot{\tilde{\theta}}_1,\ \dot{\tilde{\theta}}_2,\ \dot{\tilde{\theta}}_3]^{\mathrm{T}}$.

Consider the following facts $B^{\mathrm{T}}Px\eta \leqslant \|B^{\mathrm{T}}Px\|\|\eta\|$ and $\|\eta\| \leqslant \Theta\psi(x,t)$, thus,

$$\dot{V} \leqslant x^{\mathrm{T}}APx + x^{\mathrm{T}}PAx + 2(B^{\mathrm{T}}Px)^{\mathrm{T}}u + 2\|B^{\mathrm{T}}Px\|(\hat{\Theta}\psi(x,t) + \tilde{\Theta}\psi(x,t)) + 2\tilde{\Theta}^{\mathrm{T}}\Gamma^{-1}\dot{\tilde{\Theta}}. \tag{6}$$

Substituting (5) into (6), (6) can be rewritten as

$$\begin{aligned}
\dot{V} \leqslant{}& x^{\mathrm{T}}APx + x^{\mathrm{T}}PAx - 2(B^{\mathrm{T}}Px)^{\mathrm{T}}\frac{\rho\|PBx\| + 2\hat{\theta}_1\|x\| + 2\hat{\theta}_3}{2(1-\hat{\theta}_2)}\frac{PBx}{\|PBx\|}\\
&+ 2\|B^{\mathrm{T}}Px\|(\hat{\Theta}\psi(x,t) + \tilde{\Theta}\psi(x,t)) + 2\tilde{\Theta}^{\mathrm{T}}\Gamma^{-1}\dot{\tilde{\Theta}}\\
={}& x^{\mathrm{T}}APx + x^{\mathrm{T}}PAx - \rho x^{\mathrm{T}}PBB^{\mathrm{T}}Px + \rho x^{\mathrm{T}}PBB^{\mathrm{T}}Px - 2(B^{\mathrm{T}}Px)^{\mathrm{T}}\frac{\rho\|PBx\| + 2\hat{\theta}_1\|x\| + 2\hat{\theta}_3}{2(1-\hat{\theta}_2)}\frac{PBx}{\|PBx\|}\\
&+ 2\|B^{\mathrm{T}}Px\|\left(\hat{\theta}_1\|x\| + \hat{\theta}_2\left\|-\frac{\rho\|PBx\| + 2\hat{\theta}_1\|x\| + 2\hat{\theta}_3}{2(1-\hat{\theta}_2)}\frac{PBx}{\|PBx\|}\right\| + \hat{\theta}_3 + \tilde{\Theta}\psi(x,t)\right) + 2\tilde{\Theta}^{\mathrm{T}}\Gamma^{-1}\dot{\tilde{\Theta}}.
\end{aligned}$$

Owing to $A^{\mathrm{T}}P + PA - \rho PBB^{\mathrm{T}}P = -Q$, previous inequation can be obtained as

$$\dot V \leqslant -x^{\mathrm T}Qx+\rho x^{\mathrm T}PBB^{\mathrm T}Px-2\|PBx\|\frac{\rho\|PBx\|+2\hat\theta_1\|x\|+2\hat\theta_3}{2(1-\hat\theta_2)}$$
$$+2\|B^{\mathrm T}Px\|(\hat\theta_1\|x\|+\hat\theta_2\|\frac{\rho\|PBx\|+2\hat\theta_1\|x\|+2\hat\theta_3}{2(1-\hat\theta_2)}\|+\hat\theta_3\ +\tilde\Theta\psi(x,t))+2\tilde\Theta^{\mathrm T}\Gamma^{-1}\dot{\tilde\Theta}$$
$$=-x^{\mathrm T}Qx+\rho x^{\mathrm T}PBB^{\mathrm T}Px+2\|B^{\mathrm T}Px\|(\hat\theta_1\|x\|-(1-\hat\theta_2)\frac{\rho\|PBx\|+2\hat\theta_1\|x\|+2\hat\theta_3}{2(1-\hat\theta_2)}\|+\hat\theta_3+\tilde\Theta\psi(x,t))$$
$$+2\tilde\Theta^{\mathrm T}\Gamma^{-1}\dot{\tilde\Theta}$$
$$=-x^{\mathrm T}Qx+\rho x^{\mathrm T}PBB^{\mathrm T}Px-\rho\|PBx\|^2\ +2\|B^{\mathrm T}Px\|\tilde\Theta\psi(x,t)+2\tilde\Theta^{\mathrm T}\Gamma^{-1}\dot{\tilde\Theta}$$
$$=-x^{\mathrm T}Qx+2\|(B^{\mathrm T}Px)^{\mathrm T}\|(\tilde\Theta\psi(x,t))+2\tilde\Theta^{\mathrm T}\Gamma^{-1}\dot{\tilde\Theta}\ .$$

Owing to $\lambda_{\min}(Q)\|x\|^2\leqslant x^{\mathrm T}Qx$, we get

$$\dot V\leqslant-\lambda_{\min}(Q)\|x\|^2\ +2\|PBx\|(\tilde\Theta\psi(x,t))+2\tilde\Theta^{\mathrm T}\Gamma^{-1}\dot{\tilde\Theta}. \tag{7}$$

Setting $\dot{\tilde\Theta}=-\|(B^{\mathrm T}Px)^{\mathrm T}\|\Gamma\psi(x,t)$, with

$\dot{\tilde\theta}_1=\dot\theta_1-\dot{\hat\theta}_1=-\dot{\hat\theta}_1\ ,\dot{\tilde\theta}_2=\dot\theta_2-\dot{\hat\theta}_2=-\dot{\hat\theta}_2\ ,\dot{\tilde\theta}_3=\dot\theta_3-\dot{\hat\theta}_3=-\dot{\hat\theta}_3$,

we obtain $\hat\Theta=\Gamma\int_0^t\|(B^{\mathrm T}Px)^{\mathrm T}\|\psi(x,t)dt$.

Thus, the expression (7) is given as $\dot V\leqslant-\lambda_{\min}(Q)\|x\|^2$.

Therefore, it follows from Lyapunov theorem that the system (3) is asymptotically stable.

With the control schemer, the system would be trembling when $\|PBx\|$ is close to zero. So we set a small value ε as the least limited value of $\|PBx\|$, that is if $\|PBx\|<\varepsilon$, the controller output u is zero vector before the system trembling. A residual ball around the equilibrium can be obtained according to the system consequently.

IV. Simulations study on ship steering

To verify the feasibility of the proposed adaptive control algorithm scheme, we use ship steering simulation as example.

The uncertainty process in ship steering linear model with matching uncertainties [2] is defined by the equation as following:

$$(T_0+\Delta T)\ddot\varphi+\dot\varphi=(K_0+\Delta K)\delta+w, \tag{8}$$

where φ is the ship course and δ is the rudder angle, $T_0=T'L/V_0$, $K_0=K'L/V_0$ are nominal parameters that are of the ship design velocity V_0, L is the ship length, K', T' are the dimensionless parameters of the ship, ΔT, ΔK are variety of T_0, K_0 respective, and w is the model uncertainty including parameters and the disturbance uncertainties of the system.

Equation (8) can be rewritten as

$$\ddot\varphi=-\frac{1}{T+\Delta T}\dot\varphi+\frac{(K+\Delta K)}{T+\Delta T}\delta+\frac{1}{T+\Delta T}w\ .$$

On account of $-\frac{1}{T_0+\Delta T}=-\frac{1}{T_0}+\frac{\Delta T}{T_0+\Delta T}$,

$$\frac{K_0+\Delta K}{T_0+\Delta T}=-\frac{1}{T_0}+\frac{T_0\Delta K-K_0\Delta T}{T_0(T_0+\Delta T)},$$

setting

$$a_1 = \frac{\Delta T}{T_0(T_0 + \Delta T)}, b_1 = \frac{T_0 \Delta K - K_0 \Delta T}{T_0(T_0 + \Delta T)}, c_1 = \frac{1}{T_0 + \Delta T},$$

$$x_1 = \varphi,\ x_2 = \dot{\varphi}, u = \delta,$$

we get next form for Equation (8)

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -1/T_0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ K_0/T_0 \end{bmatrix} u + \begin{bmatrix} 0 & 0 \\ 0 & a_1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b_1 \end{bmatrix} u + \begin{bmatrix} 0 \\ c_1 \end{bmatrix} w\ .$$

So we have the same form as equation (1), i.e.

$$\dot{x} = Ax + \Delta Ax + Bu + \Delta Bu + Cw,$$

where

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -1/T_0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ K_0/T_0 \end{bmatrix}, C = \begin{bmatrix} 0 \\ c_1 \end{bmatrix},$$

$$\Delta A = \begin{bmatrix} 0 & 0 \\ 0 & a_1 \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{K_0}{T_0} \end{bmatrix} \begin{bmatrix} 0 & a_1 \cdot \dfrac{T_0}{K_0} \end{bmatrix},$$

$$\Delta B = \begin{bmatrix} 0 \\ b_1 \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{K_0}{T_0} \end{bmatrix} \begin{bmatrix} b_1 \cdot \dfrac{T_0}{K_0} \end{bmatrix},$$

$$C = \begin{bmatrix} 0 \\ c_1 \end{bmatrix} = \begin{bmatrix} 0 \\ \dfrac{K_0}{T_0} \end{bmatrix} \begin{bmatrix} c_1 \cdot \dfrac{T_0}{K_0} \end{bmatrix}.$$

Let $D = \begin{bmatrix} 0 & a_1 \dfrac{T_0}{K_0} \end{bmatrix}, E = \begin{bmatrix} b_1 \cdot \dfrac{T_0}{K_0} \end{bmatrix}, F = \begin{bmatrix} c_1 \cdot \dfrac{T_0}{K_0} \end{bmatrix},$

then we get $\Delta A = BD, \Delta B = BE, C = BF$.

Thus, the equation (8) can be modified as $\dot{x} = Ax + B((I + E)u + DX + Fw)$, which is the same form as equation (3).

In the simulation, the rudder is simulated by a small close-loop servo, which is expressed in next equation

$$T_E \dot{\delta}_E = K_E \delta_E - \delta,$$

where T_E=2.5s is rudder time constant, K_E=1 is the gain of rudder, δ is real rudder angle, $|\delta| \leqslant 35^{\circ}$, $|\dot{\delta}| \leqslant 3^{\circ}/\mathrm{s}$, δ_E is command rudder angle.

We take a cargo ship [3] with the length 126m and displacement 14,500 tons as an example to conduct a simulation research, and compare with an optimal PD control scheme. The dimensionless parameters of the ship are $K' = 7.9269$, $T' = 13.88$, so the simulation parameters are $K_0 = 0.42, T_0 = 261.73$ when ship velocity at design 7.2m/s.

To verify the feasibility of the proposed the adaptive control algorithm scheme, we take the nonlinear ship responded model [2]

$$T\ddot{\varphi} + \dot{\varphi} + a_3\dot{\varphi}^3 = k\delta + \omega$$

as the simulation model, where $T = T' L/V$, V is the real speed of the ship. For the ship, we take a_3=30.

There are two maneuvering situations in ship steering control system that are ship course change and ship course keeping. At the stage of ship course change, it is expected that there is quickly and smoothly turning property. At the stage of course keeping, ship should sail along the scheduled course exactly. It isn't allowed that there is an accumulated error. And in any environment disturbance the ship course system's anti-jamming property should be better.

Figs. 1 to 4 show the simulation for the ship course changing from 0° to 10° with speed at 5 m/s without environment disturbing under the control of adaptive control algorithm and PD respectively.

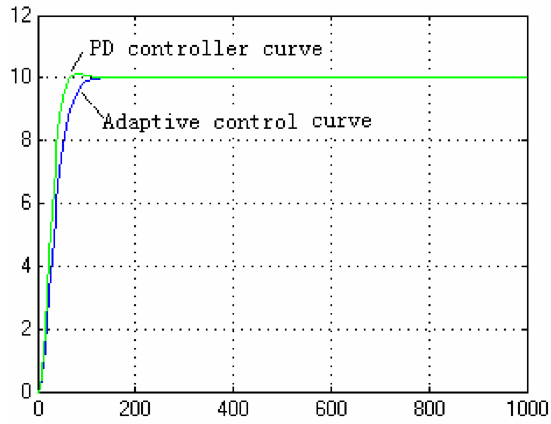

Fig. 1. Simulations result for ship course change from 0° to 10° from 0 to 1000 sec (ship speed at 5 m/s)

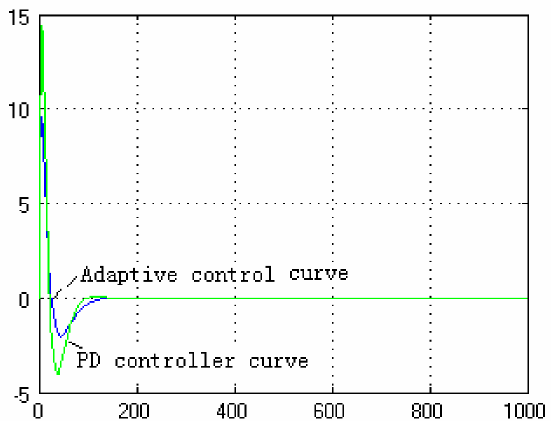

Fig. 2. Simulation results for rudder angle in course change from 0° to 10° from 0 to 1000 sec (ship speed at 5 m/s)

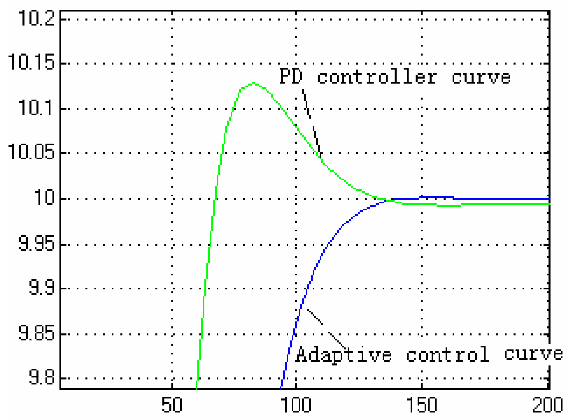

Fig. 3. Partial enlargement of fig. 1 from 0 to 200 sec

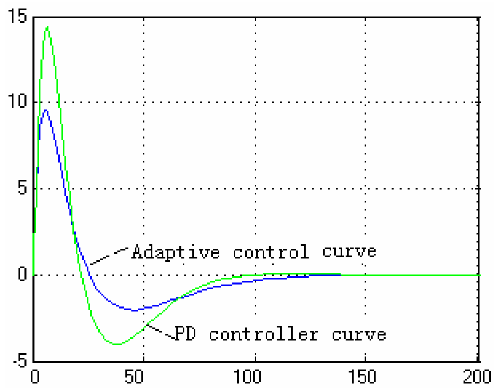

Fig. 4. Partial enlargement of fig. 2 from 0 to 200 sec

Fig.1 shows the result for ship course change and fig.2 shows the rudder angle change in the course change. In order to know the detail of the changing, figs. 3 and 4 zoom in from 0 to 200 sec of fig.1 and fig.2 respectively. From figs. 1 to 4, we can see that the response speed of adaptive control is slower than PD control, but over adjustment is smaller than PD control, and rudder angle change is smother than PD control. Moreover, the static state error of adaptive control is also smaller than PD control. Thus, we will have the thought that the adaptive control may be better than PD control in the control characters.

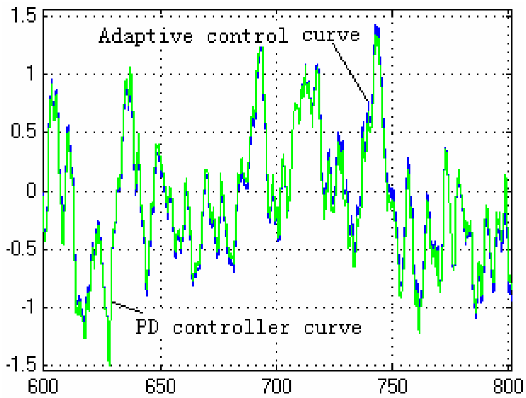

Fig.5. Simulation results for ship course keeping at 0° from 600 to 800 sec
(ship speed at 7.2 m/s, under environment disturbing.)

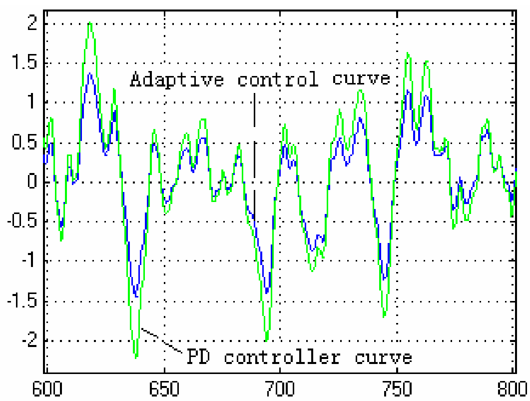

Fig. 6. Simulation results for rudder angle change in course keeping from 600 to 800 sec
(ship speed at 7.2m/s, under environment disturbing.)

In the simulation, in order to simulate environment disturbance, we take white noise instead. Figs. 5 to 6 show the ship course keeping with 0° at designed speed of 7.2 m/s with environment disturbing under the control of adaptive control algorithm and PD respectively.

From fig. 5, we can know that the results precision of course keeping of the two controls are very similar. However, fig. 6 tells us that the extent of rudder angle change in the adaptive control system is smaller than in a PD control system. So we also think that the adaptive control may be better than PD control in control characters.

Therefore, based on the above discussions we can draw the conclusion that the control result of the adaptive control is better than PD control. And the algorithm is simpler, so it can be used in real-time control and needs less energy.

V. Conclusion

In this paper, a class of linear systems with matching uncertainties is presented. An adaptive control for the class of linear systems with matching uncertainties is put forward. The adaptive control performs better by compared its performance in its control system with an optimal PD control's performance in ship steering simulation, so the adaptive control proposed is reasonable. Of course there are some aspects are needed to improve on the system in later study. We will study on identification and filter to the uncertainties style of the systems in order to apply more reasonable control method, and will also investigate the adaptive fuzzy controllers using a combination of neural networks and fuzzy logical control or genetic algorithm.

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