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Adaptive decoupling control based on online identification and simulation

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ABSTRACT

Many complex control processes are interconnected MIMO process, and because the actual systems are influenced by many factors, the system model parameters are also changed. According to the system of the coupling and changeable, this paper puts forward a kind of online identification based on adaptive decoupling control strategy which is used in the actual control system. This control strategy uses a recursive forgetting factor and parameter identification algorithm based on model matching of zero frequency. When system is operating in closed-loop control conditions, process parameters are identified online. Based on the model to design the controller and the decoupling device, and the relative control loop is decoupled. To the actual system, two coupled loop is simulated and experimented. The results show that this method is effective to improve the coupling effect of the system, improve the stability and robustness of the control system.

KEYWORDS

Decoupling; Identification; Adaptive; Online; Control.

INTRODUCTION

Many complex control processes are interconnected MIMO process, one of the inputs will affect the other outputs, and an output will also be affected by the other inputs. When the correlation between the variables is very serious, even with the best variable pairs, it also can not obtain the satisfied control effect. Especially when the correlation degrees in the control system are same, the control is more difficult. Therefore, the system with strong coupling must be decoupled in its control system. This can make the strong coupling system become mild coupling or without coupling system. The decoupling method of coupling system have the main diagonal matrix decoupling and feed forward compensation decoupling method. The diagonal matrix decoupling and feed forward compensation decoupling control is designed based on an accurate model of controlled object, so lack the exact model or parameter variable of control process is difficult to achieve satisfactory results. Using diagonal matrix and a feed forward compensation decoupling must established the object model, when the actual objects changed, the parameters of decoupling controller model should also changes. Therefore, the decoupling control of coupling syetem, must be online identified of the controlled system.

Many object models can be approximated by a first order and time delay model, we can identify the model parameters from the experiment. But in many cases, mathematical model of the controlled system is difficult to determine in advance[1]. Even the mathematical model was identified in a contain condition, but if the condition changes, the dynamic parameters and the model structure is also changed. The adaptive control system can measure the state of the system. Use performance or parameters compare with the operation indexes and expected indexes of the current system, through online identification and change the controller parameters[2-4]. Then the system parameters can adapt the changes. The adaptive controllers changed its structure, parameters and then make a decision or the adaptive law based on the change of control action. In this way, it can maintain the stability of the control system and the normal control function.

This paper aimed at the above problems, think about a interconnected MIMO system, and because the actual system is influenced by many factors, the system model parameters are also changed. According to the system of the coupling and changeable, this paper puts forward a kind of online identification based on adaptive decoupling control strategy which is used in the real system. This control strategy uses a recursive forgetting factor and parameter identification algorithm based on model matching of zero frequency. When system is operating in closed-loop control conditions, process parameters are identified online. Based on the model to design the controller and the decoupling device, and the relative control loop is decoupled. Then designed PID regulator according to ISTE standard, this can make the tuning of on-line controller design become superior. To the actual system, two coupled loop is simulated and experimented. The results show that this method is effective to improve the coupling effect of the system, improve the stability and robustness of the control system.

RECURSIVE ONLINE IDENTIFICATION METHOD

Discretization of continuous system

Many object models are approximated first-order inertial and lag link system, so they can be expressed as：

$$G(s) = G_0(s)e^{-\tau s} = \frac{K}{1+Ts}e^{-\tau s} \tag{1}$$

Where K is amplification factor, T is the time constant, τ is lag time.

In order to carry on the online identification of the system model through computer, it must be discredited the mathematic model. Usually we can use a sampling switch and a zero order holder in continuous system. If the sampling period is represented as T_c, the zero order holder can be expressed as:

$$G_T(s) = \frac{1 - \exp(T_c \cdot s)}{s} \tag{2}$$

For convenience, assume that lag time τ is an integer multiple of the sampling period.

Let $d = \tau / T_c$ **(3)**

d is a positive integer.

Use z transfer, the system model is transformed into discrete models, such as:

$$G(Z) = z(\frac{1-e^{T_c s}}{s} \cdot \frac{Ke^{-\tau s}}{1+Ts}) = Kz(\frac{1}{s} - \frac{1}{s+1/T})(1-z^{-1})z^{-d} = K\frac{z^{-d}(1-e^{-T_c/T})}{z-e^{-T_c/T}} \tag{4}$$

Let $a = e^{-T_c/T}$ **(5)**

$$b = K(1-a) \tag{6}$$

Then

$$G(Z) = \frac{B(z^{-1})}{A(z^{-1})} z^{-d}$$

$$= \frac{bZ^{-1}}{1-aZ^{-1}} Z^{-d} \tag{7}$$

Using difference equation, the system can be described as:

$$y(k+1) = ay(k) + bu(k-d) \tag{8}$$

That is

$$y(k+1) = ay(k) + bu(k)Z^{-d} \tag{9}$$

Make

$$k = k+1 \tag{10}$$

Then

$$y(k) = ay(k-1) + Z^{-d} bu(k-1) \tag{11}$$

In the identification system, a, b are the process parameters of the mathematical model, d is the delay parameter. According to input and output data of actual system, we can identification a, b and d in real-time. Then according to equation (3) (5) (6), obtained amplification factor K, time constant T and lag time τ in the mathematical model of the system.

Zero frequency model matching method

Identification method of ordinary can easily identify the two time-varying parameters a and b in the system, but it is difficult to identify the system delay parameters d .

Unfolding the molecule $B(Z^{-1})\cdot Z^{-d}$ of $G(Z)$ as a polynomial form $B_i(Z^{-1})$, that is:

$$B_i(Z^{-1}) = b_1 Z^{-1} + b_2 Z^{-2} + \cdots + b_i Z^{-i} ,$$

$$(i = 1, 2, 3, \cdots) \quad \textbf{(12)}$$

Where $i-1$ is the longest possible delay, then the identification system model $G(Z)$ can be converted to the form $G_i(Z)$:

$$G_i(Z) = \frac{B(z^{-1})}{A(z^{-1})} z^{-d}$$

$$= \frac{B_m(z^{-1})}{A(z^{-1})}$$

$$= \frac{b_1 Z^{-1} + b_2 Z^{-2} + \cdots + b_i Z^{-i}}{1 - aZ^{-1}} \quad (i = 1, 2, 3, \cdots) \quad \textbf{(13)}$$

In $G_i(Z)$, the parameters need to be identified are as follows:

$$\hat{\theta} = [\hat{a}, \hat{b}_1, \hat{b}_2, \cdots, \hat{b}_i]^T \quad \textbf{(14)}$$

Among it, $\hat{a}, \hat{b}_1, \hat{b}_2, \cdots, \hat{b}_i$ will be identified. When the vector $\hat{\theta}$ is estimated, the estimated parameters in the denominator of $G(Z)$ is a in $G_i(Z)$. Then analysis the frequency characteristic in $B(Z^{-1})\cdot Z^{-d}$ and $B_i(Z^{-1})$, let $z = e^{j\omega}$, when the frequency $\omega = 0$, the zero order and first-order derivative in $B(Z^{-1})\cdot Z^{-d}$ and $B_i(Z^{-1})$ are equal, such as

$$B(z^{-1})z^{-d}\Big|_{z=e^{j\omega}} = B_i(z^{-1})\Big|_{z=e^{j\omega}} \quad \textbf{(15)}$$

$$\frac{dB(z^{-1})z^{-d}\Big|_{z=e^{j\omega}}}{d\omega} = \frac{dB_i(z^{-1})\Big|_{z=e^{j\omega}}}{d\omega} \quad \textbf{(16)}$$

From above, we can derive the parameters b and d as follows, the relationship between parameters b 、 d and $G_i(Z)$ is:

$$\hat{b} = \sum_{m=1}^{i} \hat{b}_m \quad \textbf{(17)}$$

$$\hat{d} = [(\sum_{m=1}^{i} i \times \hat{b}_i) / \sum_{m=1}^{i} \hat{b}_i] - 1 \quad \textbf{(18)}$$

For $\hat{d}$ is an integer, it is necessary to rounding of $\hat{d}$. The b and d are parameters in molecular $G(Z)$, which can be obtained through the formula (17) (18).

Thus, the identification of three parameters in the system model can finally be transformed into the online identification of the parameters $\theta = [a, b_1, b_2, \cdots, b_i]^T$ in $G_i(Z)$.

Recursive algorithm plus with forgetting factor

For the identification of the system data can be successive obtained in real-time, recursive algorithm is for the identification system. When the system is working, we can get the observation of new data. On the basis of the previous estimation results, using the new observation data, introduced previous estimation results. Then based on the recursive algorithm and previous data, we can recursion the new parameter estimation. So again, with the introduction of new data step by step, we can estimate the parameters, until get the satisfactory accuracy.

Let $$\begin{cases} h(k) = [-y(k-1), u(k-1), u(k-2), \cdots, u(k-i)]^T \\ \theta = [a, b_1, b_2, \cdots, b_i]^T \qquad k = 1, 2, \cdots L (L = i + 1) \end{cases} \quad \textbf{(19)}$$

The error in generalized model is the difference of process model and the reference model, that is:

$$e(k) = y(k) - h^T(k)\theta(k) \quad \textbf{(20)}$$

Parameter identification are used input and output datas $h(k)$ and $y(k)$ to determine the estimates $\hat{\theta}(k)$ of the parameters θ at the moment k, the criterion function is:

$$J(\theta)\Big|_{\theta=\hat{\theta}} = e^2(k)\Big|_{\theta=\hat{\theta}} \to \min \quad \textbf{(21)}$$

Mathematical expressions of recursive identification algorithms is,

$$\begin{cases} \hat{\theta}(k) = \hat{\theta}(k-1) + K(k)[y(k) - h^T(k)\hat{\theta}(k-1)] \\ K(k) = \dfrac{P(k-1)h(k)}{1 + h^T(k)P(k-1)h(k)} \\ P(k) = [I - K(k)h^T(k)]P(k-1) \end{cases} \quad \textbf{(22)}$$

Where

$$P^{-1}(k) = H_k^T H_k$$

$$= \sum_{i=1}^{k} h(i)h^T(i) \quad \textbf{(23)}$$

But with the increase of k, $P(k)$, $K(k)$ become more and more small. In formula (23), the ability of the correction $\hat{\theta}$ become more and more weak, that means the new input/output data is weakly tracking the function value of estimation the parameters. This can get the result, parameter estimation is difficult to close to the true value. When the true parameter is time varying, the algorithm can not track the changes, so that the real time identification will be failure. A method to solve this problem is introduced the recursive forgetting factor, using recursive algorithm with a forgetting factor to solve it.

We can use the performance index function as: $J=(Y-H\hat{\theta})W(Y-H\hat{\theta})$ **(24)**

Where, W is weighted diagonal matrix, $W=\begin{bmatrix}\lambda(1) & & & 0\\ 0 & \lambda(2) & & 0\\ & & \ddots & \\ 0 & & & \lambda(N)\end{bmatrix}$ **(25)**

N is the observed data set, λ is the forgetting factor and $0<\lambda\leq 1$. Then the recursive algorithm of forgetting factor is:

$$\begin{cases}\hat{\theta}(k)=\hat{\theta}(k-1)+K(k)[y(k)-h^T(k)\hat{\theta}(k-1)]\\ K(k)=P(k-1)h(k)[h^T(k)P(k-1)h(k)+\lambda(k)]^{-1}\\ P(k)=\dfrac{1}{\lambda(k)}[I-K(k)h^T(k)]P(k-1)\end{cases}$$ **(26)**

When $\lambda(k)=1$, the recursive algorithm with forgetting factor is simplified into the general recursive algorithm.

Therefore, when the system is working, it can be identified with the recursive method and the algorithm matched of zero frequencys based on forgetting factors.

ADAPTIVE DECOUPLING CONTROLLER DESIGN

Feedforward compensation decoupling method

Feedforward compensation decoupling method is used to design a decoupling network according to the invariance principle, so as to relieve the coupling relation in the system. A two input-two output system is shown in Figure 1, we can eliminate the coupling effect using the invariance principle.

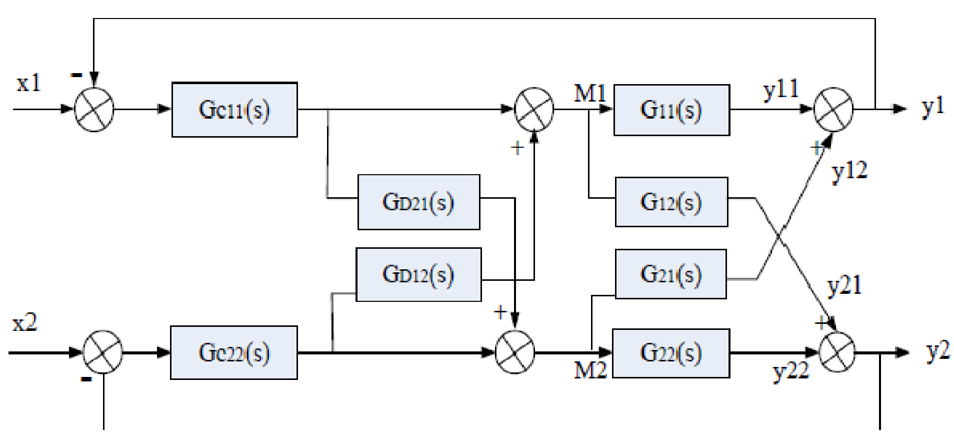

Figure 1: Feed-forward compensation decoupling method system

Make

$$\begin{cases} y_{11} + y_{12} = 0(M_2 \neq 0) \\ y_{21} + y_{22} = 0(M_1 \neq 0) \end{cases} \quad (27)$$

Then

$$\begin{cases} G_{12}(s) + G_{D12}(s)G_{11}(s) = 0 \\ G_{21}(s) + G_{D21}(s)G_{22}(s) = 0 \end{cases} \quad (28)$$

The mathematical model can obtained for the feedforward decoupling compensator as:

$$\begin{cases} G_{D12}(s) = -\dfrac{G_{12}(s)}{G_{11}(s)} \\ G_{D21}(s) = -\dfrac{G_{21}(s)}{G_{22}(s)} \end{cases} \quad (29)$$

So, we can see, with the feed-forward compensation decoupling, two-dimensional system shown in Figure 1 will become two single loop control systems. Feed-forward compensation decoupling method is relatively simple to use, it easy to decoupling the coupled system, and this method is also very effective.

PID controller

The PID controller output is[5]:

$$u(t) = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(t)dt + K_p T_d \frac{de(t)}{dt} \quad (30)$$

So we can get the PID controller[6-9] transfer function as:

$$G_c(s) = \frac{U(s)}{E(s)}$$

$$= K_p + \frac{K_p}{T_i} \cdot \frac{1}{s} + K_p T_d s$$

$$= K_p + K_i \cdot \frac{1}{s} + K_d s \quad (31)$$

Where：

$$\begin{cases} K_i = \dfrac{K_p}{T_i} \\ K_d = K_p T_d \end{cases} \quad (32)$$

The parameters setting method of PID controller are so many[10-12], but in this paper, the parameters of the PID controller will be designed using the optimization index weighted time, based on the ISTE index, that can be designed as:

$$J = \int_0^{\infty} [te(t)]^2 dt \rightarrow \min \tag{33}$$

For a specific group of k, τ, T, ISTE for optimal PID controller parameters tuning formula is obtained for：

$$\begin{cases} K_p = \dfrac{1.042}{k}(\dfrac{\tau}{T})^{-0.897} \\ T_i = \dfrac{T}{0.987 - 0.238(\tau/T)} \\ T_d = 0.385T(\dfrac{\tau}{T})^{0.906} \end{cases} \tag{34}$$

From above, we can see, if the parameters of the system model is obtained, we can design the optimal PID controller.

Adaptive decoupling controller

Because the traditional method of decoupling control excessively depends on the precise model of system, the application in the system has limitations. So if the dynamic changing ststem is large, prior models also not accurately, the control effect of the system will be significantly reduced, and even cause the system instability. So we need to turn it to maintain the control performance requirement on it.

The idea of design adaptive controllers and the parameter tuning is: when the system structure is determined, but the parameters are changed; Online identification of the parameters of the system can be added with adaptive performance. Using the identification results and tuning formulas, tuning the parameters of PID controller online. When the change of system model parameter exceeds a certain range, the identification procedure identify the system, adjusting the parameters by the followed data.

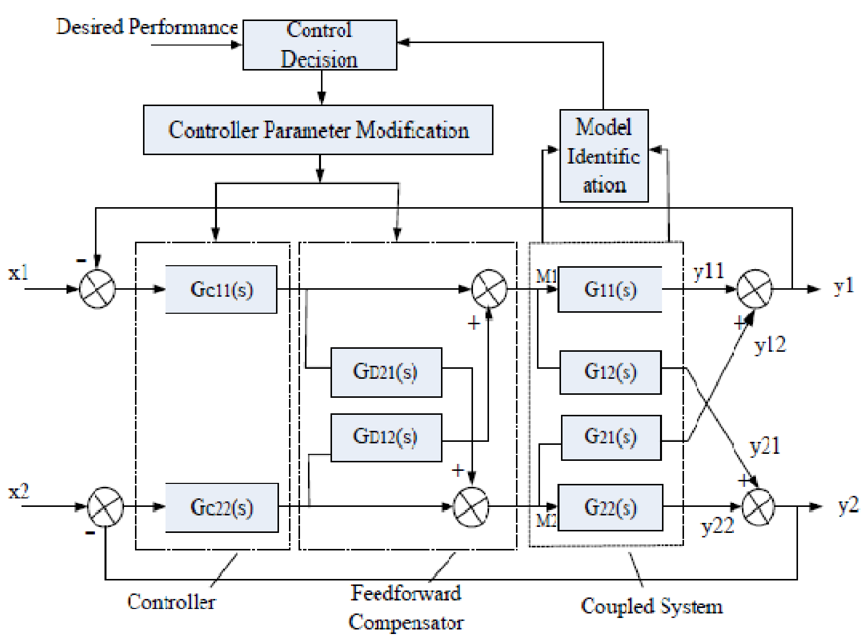

Figure 2: Adaptive decoupling controller

Then designed. The adaptive controller is composed of 4 parts, which are identification unit, decision making unit, parameter setting unit and a controller unit. The composed structure is shown in Figure 2. We can design a adaptive decoupling controller based on it.

Algorithm steps

To sum up, the adaptive decoupling control algorithm of the simulation calculation steps are as follows:

1) Determine the sampling period T_c and the initial parameters.

2) According to formula (19), get the input vector $h(k)$;

3) According to formula (22), estimate the new characteristics parameter vector $\theta(k+1)$ of the reference object model.

4) According to the estimated system parameters, get a, b, d, then use the formula (3) and (5) (6), calculate K, T, τ;

5) According to formula (32) (34), calculate PID controller parameters; According to formula (29), calculate the feedforward decoupling compensator;

6) According to formula (30), calculate controlled quantity u (t), and control the system.

7) Let $k=k+1$, return to step 2).

ANALYSIS OF SIMULATION EXPERIMENTS AND RESULTS

The mathematical model of the controlled object

We can set the controlled system model as:

$$W(s)=\frac{Y(s)}{U(s)}=\begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix},$$

Where

$$G_{11}(s)=G_1(s)=\begin{cases} \dfrac{28}{45s+1}e^{-3s}, 0<t<100 \\ \dfrac{44}{50s+1}e^{-4s}, 100\le t<200 \end{cases}, \quad G_{22}(s)=G_2(s)=\begin{cases} \dfrac{44}{55s+1}e^{-3s}, 0<t<100 \\ \dfrac{48}{60s+1}e^{-4s}, 100\le t<200 \end{cases}$$

$$\begin{cases} G_{12}(s)=G_3(s)=\dfrac{22}{42s+1}e^{-3s}, 0<t<200 \\ G_{21}(s)=G_4(s)=\dfrac{-24}{44s+1}e^{-3s}, 0<t<200 \end{cases}$$

The sampling period is 1s in the process of simulation, the simulation time is 200s.

Then we can see,

$$\begin{cases} a_1=0.978, b_1=0.6154, d_1=3, 0<t<100 \\ a_1=0.9802, b_1=0.8713, d_1=4, 100\le t<200 \\ a_3=0.9765, b_3=0.5412, d_3=3, 0<t<200 \\ a_4=0.9775, b_4=-0.5393, d_4=3, 0<t<200 \\ a_2=0.9782, b_2=0.7928, d_2=3, 0<t<100 \\ a_2=0.9854, b_2=0.7007, d_2=4, 100\le t<200 \end{cases}$$

Adaptive decoupling control simulation structure

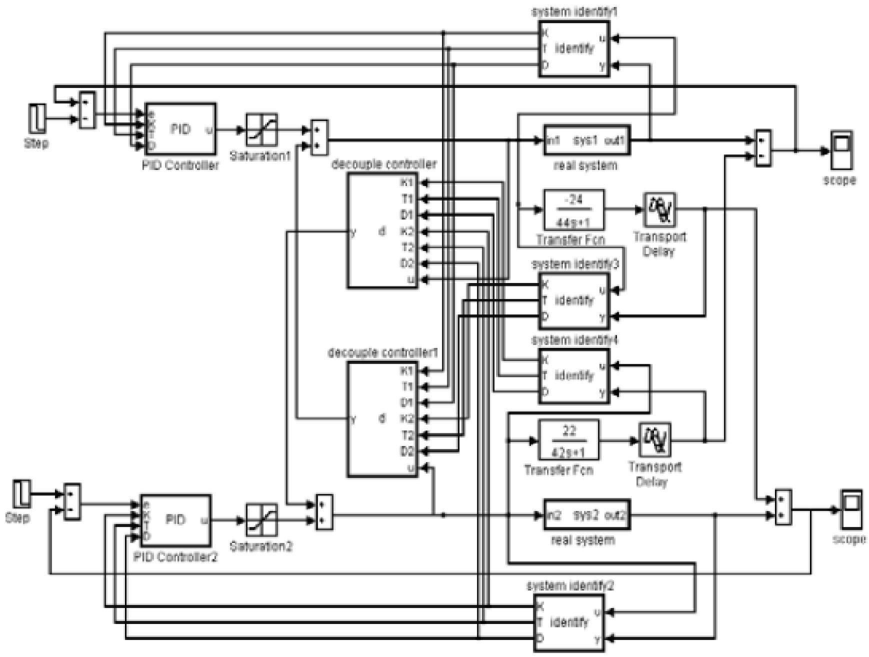

Figure 3: Adaptive decoupling control simulation structure

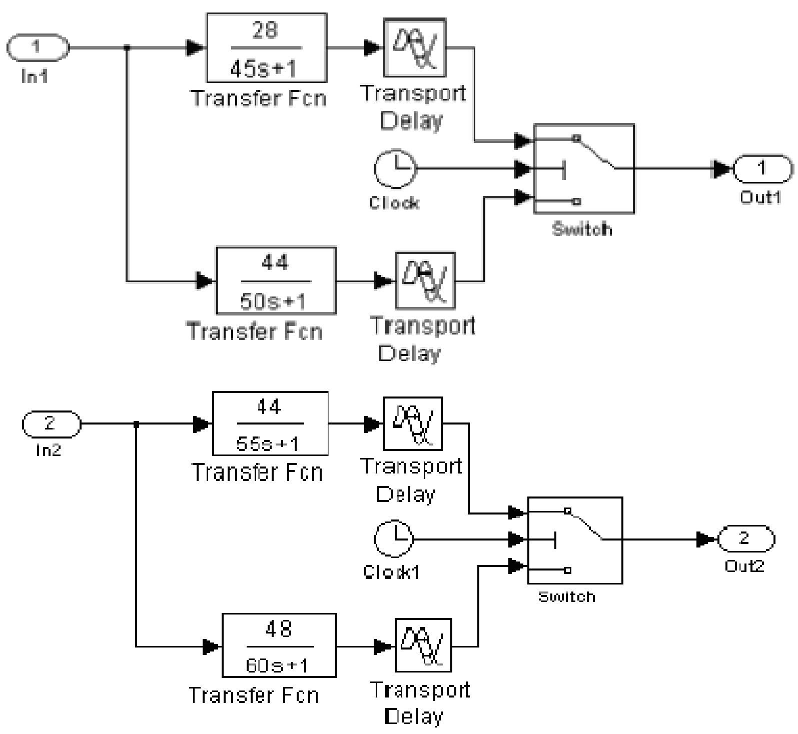

Figure 4: Simulation system structure

Used the softwar silmulink for simulation. We can design the simulation system. Adaptive decoupling control simulation structure is shown in Figure 3, Among it sys1 and sys2 are shown in Figure 4. TansferFcn is model identification part of the system, using the input and output of system, it can identify the model parameters K, T, D. That is the amplification coefficient K, time constant T and lag time τ in mathematical model of the system. PID controller and decouple controller corresponding to the real PID controller and the feedforward decoupling compensator. The parameters of PID controller, feedforward compensation function and decouple controller are determined with the identified K T, D.

Simulation experiments

When simulation begin, the sampling time $T_c = 1s$, the controller output limiter is 0≤u (t)≤2, initial value $\theta(0) = [332]$, the covariance matrix $P(0) = 10^5 I_4$. Simulation will be ended at 200s. The system parameter estimation value is shown in Figure 5 and Figure 8.

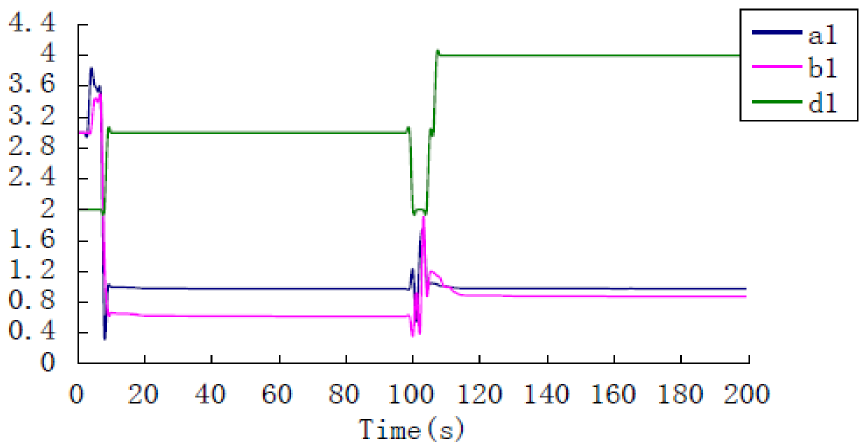

Figure 5: Parameter estimation value in system1

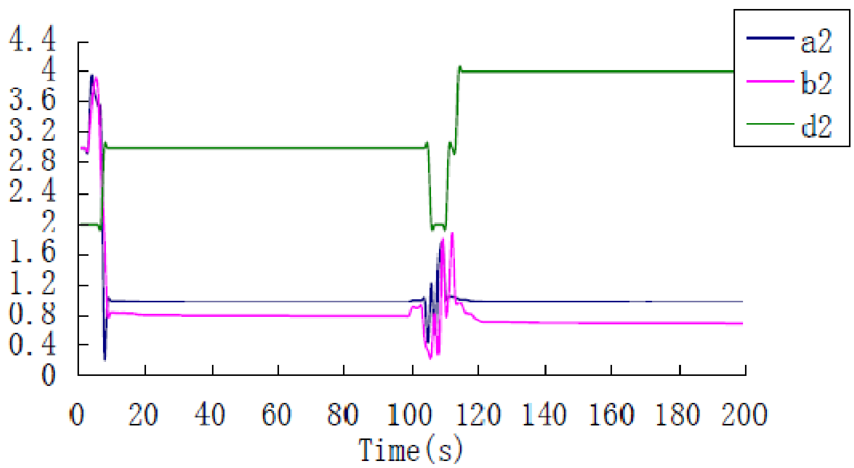

Figure 6: Parameter estimation value in system2

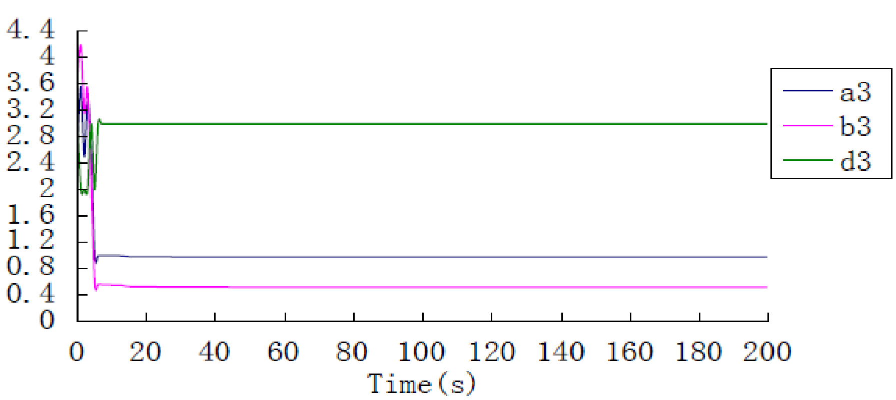

Figure7: Parameter estimation value in system3

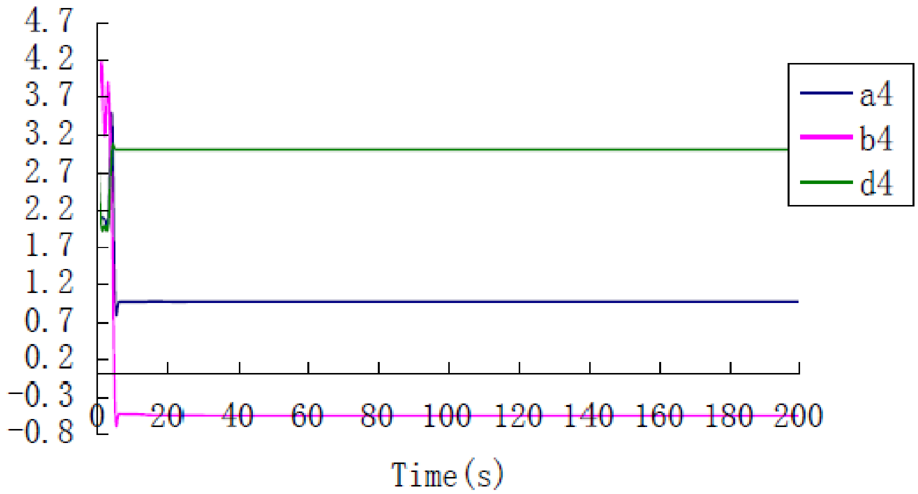

Figure 8: Parameter estimation value in system4

The PID parameters tuning curve of PID controller is shown in Figure 9 and Figure 10. The system response is shown in Figure 11 and Figure 12

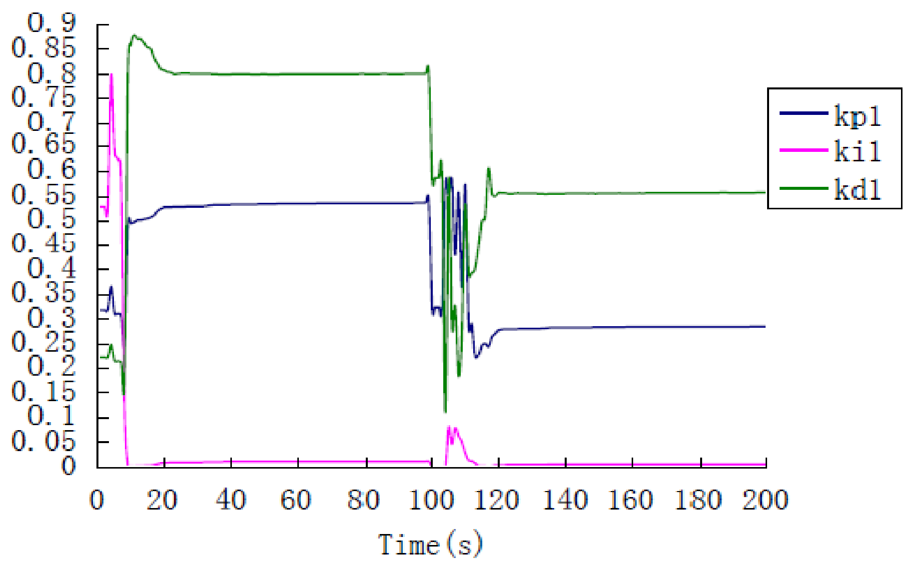

Figure 9: PID controller1 parameters tuning

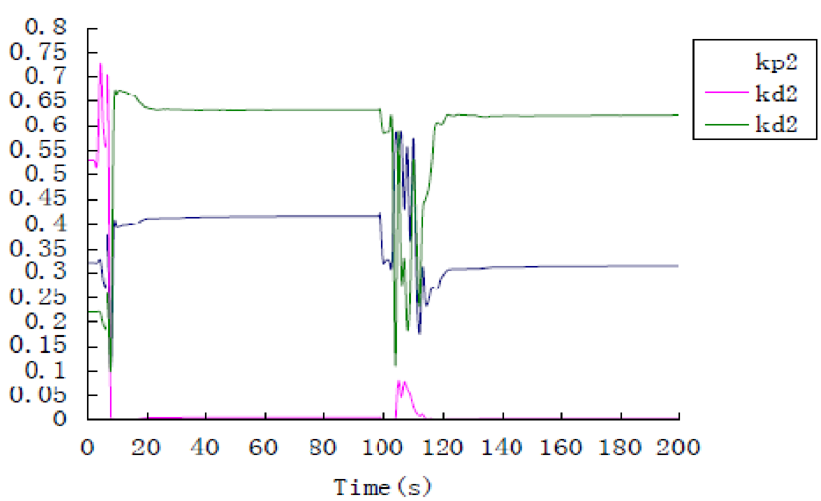

Figure 10: PID controller2 parameters tuning

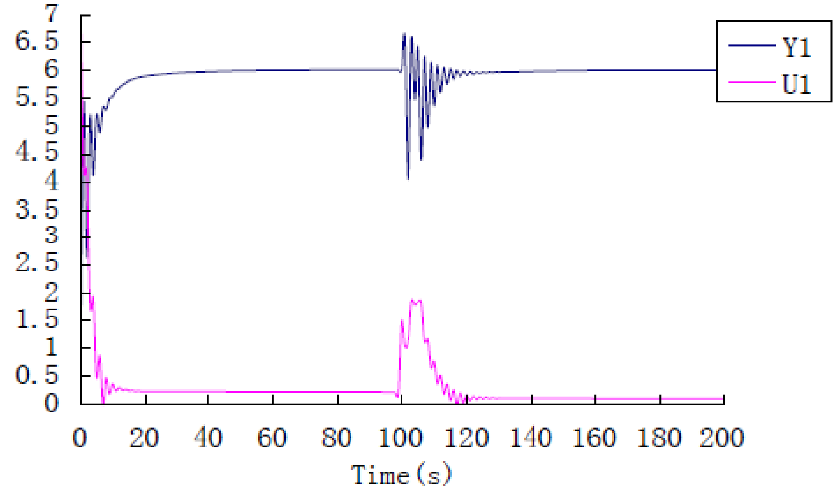

Figure 11: System1 response

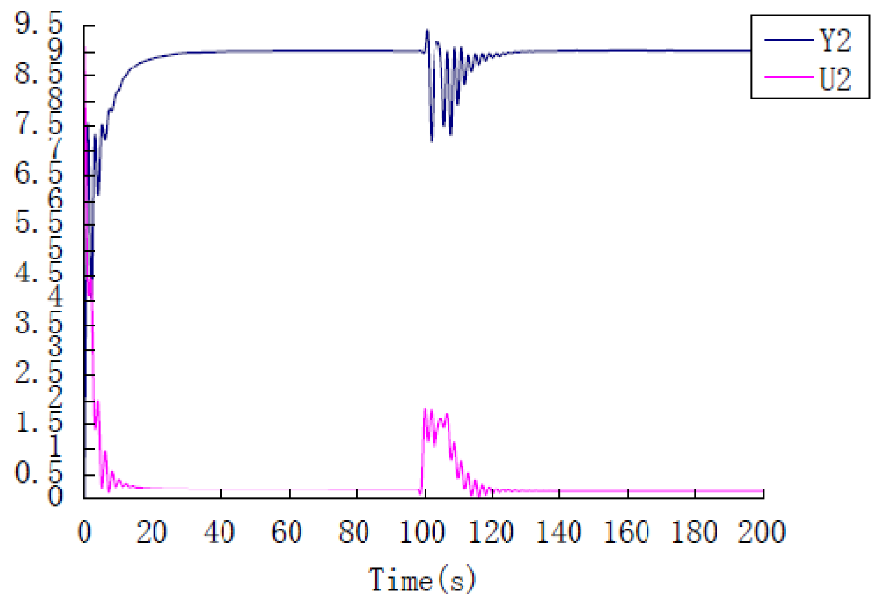

Figure 12: System2 response

From above, we can see, when the system begin to run, it can well estimate the parameters. The parameters are easily obtained, the system can achieve a better control effect. When the system is running to the 100s, we change the system input, the system is in the second operating state. When the parameters changed, the control system appeared oscillation, but after a period of adjustment, the output of the system tends to the new set value. That is, the system can be controlled through online identification, the parameters of the controller can be modified. We can effective control of the system. The control system has a better adaptive ability.

Through the simulation, we can clearly see the change of system parameters, the change of the controller parameters. Also we can see the change of controller output and the control parameters of the system. From the simulation, we can know that this method has a certain ability to adapt the change of system. The control effect is good.

CONCLUSION

Many control system are coupling system. For the actual system is influenced by many factors, the parameters are always changed. Adaptive control system use the input and output signals, on-line identified the mathematical model, and then modified control strategy, change the control role of regulator, until the control performance index is optimal. Add an adaptive decoupling compensator in the coupling system can effectively improve the relationship between the coupling system. This can ensure the normal operation of the system.

The adaptive decoupling control system using a recursive method and parameter identification algorithm that matching zero frequency model based on the forgetting factor, it can identify system parameters in real time. It keep the traditional control effect by feedforward compensation decoupling, at the same time, can get better control effect under the condition of variable object characteristic parameters.

This method can not only recognize the system parameters in real time, it also can change the parameters of the controller in real time. This makes the controller adapt the change of system parameters. In the actual system, it can follow the change of environment and the change of system structure. So, it has a strong robustness. PID controller can change the parameters on-liner. Use two coupled system for simulation and experiment. The results show that this method can effective improved the coupling effect of the system, improve the stability and robustness of the control system.

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