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热连轧板宽板厚的实用自抗扰解耦控制

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摘要: 针对热连轧板宽板厚多变量系统存在强耦合、大时滞和随机不确定等难题, 提出了一种线性自抗扰动态解耦方案. 考虑到系统的大时滞问题, 在常规的降阶扩张状态观测器(ESO)之前, 增加了一个纯时滞环节. 为了把所设计的实用自抗扰控制(ADRC)与常规PID控制器进行公平比较, 各控制器的最佳参数均采用变尺度混沌优化方法得到. 仿真结果表明, 优化后的ADRC不仅具有较好的解耦性能, 而且对模型参数的不确定性和外扰具有较强的鲁棒性和参数适应性.

关键词: 多变量系统; 动态解耦; 自抗扰控制; 时滞系统; 不确定系统

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A practical decoupling control solution for hot strip width and gauge regulation based on active disturbance rejection

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Abstract: To deal with the strong interactions between loops, large time-delay and random uncertainties in the multivariable system of the hot rolling mill, we propose a solution of active disturbance-rejection control (ADRC). In this solution, a time-delay unit is added before the conventional reduced-order extended-state observer. For the fair comparison of the proposed ADRC and the conventional PID controller, parameters of each algorithm are obtained by using the mutative-scale chaotic optimization method. Simulation results show that the optimized ADRC not only has better decoupling performance, but also provides higher robustness and adaptability against the model-parameter uncertainties and external disturbances.

Key words: multivariable systems; dynamic decoupling; active disturbance rejection control; delay systems; uncertain systems

1 Introduction

Recently, there has been a strong demand for high-dimensional accuracy of hot rolling mills in the worldwide market[1]. The dimensional properties of hot rolling mills are the thickness, width length, and flatness, etc. With the successful improvement of the strip gauge and crown accuracy, the strip width performance becomes increasingly important. The conventional direct width control is mainly performed by the roughing mill (RM). To reduce width fluctuation and deviation, many kinds of roughing automatic width control (RAWC) systems have been developed. With the increasingly higher requirements of strip steel rolling yield, the conventional RAWC technology is being replaced by direct width control performed at the finishing mill (FM). A new finishing automatic width control (FAWC) system has been developed by modifying inter-stand tension[2]. The importance and necessity of the FAWC technology has attracted much attention, but adjusting the tension will cause thickness variations at the same time. It is necessary to find a simple and effective decoupling algorithm for the width and gauge multivariable control (WGMC) system to meet the requirements of high-precision (strip thickness error should be less than 0.004 mm) and high-speed (sample time is less than 1 ms and strip speed could reach 30 m/s). In ad-

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dition, there are many other complex characteristics in this system, such as large time delay, time-varying dynamics, random uncertainty, and nonlinearity, etc.

It is very difficult to solve these problems by using the existing control theories directly. It is well established that the challenging control problems in the iron and steel process can all be viewed as disturbance rejection problems and the concept of disturbance can be expanded to include internal disturbances (parameter uncertainties and unmodeled dynamics), and external disturbances (load disturbance and cross-couplings) as suggested by Prof. Han[3]. The basic idea of active disturbance rejection control (ADRC) technique is that the total disturbances are estimated by extended state observer (ESO) in real time and actively compensated by state-error-feedback (SEF) control law for uncertain system. Due to its disturbance rejection capabilities and robustness, ADRC has been widely applied[4].

In view of the complex characteristics of double-input double-output (DIDO) uncertain systems with large time delay, two kinds of ADRC, nonlinear ADRC[5] and linear ADRC (LADRC)[6], were proposed for the WGMC system respectively. Compared to the nonlinear ADRC, the linear ADRC is easier to implement and it has many potential applications. Both of them are based on the unique principle of ADRC for large time delay[7] and uncertain system with time delay[8], where time delay transfer function is often approximated to a first order inertia system and ADRC is designed to control a high order system without time delay. But it increases the order of ADRC and the number of tuning parameters.

In order to make it simple to use, easy to tune and energy-efficient for industrial applications, a practical ADRC solution was proposed for monitor AGC system with large time delay through order reduction in both the plant model and the state observer[9] according to the reduced order ESO design for first order inertia system[10].

Based on the idea of delayed observer for time delay system, such as the chain observer[11], cascade high gain predictors with delayed output[12], and linear stand ESO plus time delay to synchronize the delayed signal[13], the practical ADRC solution for single-input single-output (SISO) system[9] will be extended to the decoupling control for width and gauge DIDO systems with delayed reduced order ESO.

The rest of this paper is organized as follows. The mathematical model of WGMC system is given in Section 2. A practical decoupling solution for WGMC system based on ADRC is proposed in Section 3. Simulation results are shown in Section 4. Finally some conclusions are drawn from the above work in Section 5.

2 Mathematical model of WGMC system

It is difficult to install the X ray meter at the stand because of the high temperature rolling environment, cost and maintenance, etc. X ray width and gauge meter are usually installed only at the exit of the FM in China and there is a long distance from the central line of the last stand to the meters, resulting in a large transportation time delay of each stand[1]:

$$\tau_j = \sum_{j=5}^{m-1} \frac{L}{v_j} + \frac{L_m}{v_m}, \tag{1}$$

where j, m, L, v_j, L_m and v_m are stand number, total stand number, length of inter-stand strip, the jth stand exit strip speed, length of strip between the last stand and meters, the last stand exit strip speed respectively.

The width spread of the FM comes mainly from two deformation phenomena: natural width spread near deformation zone, and creep width fluctuation due to the inter-stand tension variation. For monitor FAWC system, strip width largely depends on inter-stand tension (the back tension), and it is also affected by temperature, steel, and the front tension, etc. According to the analysis of rolling theory, the system has highly nonlinear and complicated characteristics, which make it difficult to establish an accurate models. The model is usually got by linearization around the nominal operating point. So it can be approximated as first order plus time delay (FOPTD):

$$\Delta w_j(s) = \frac{K_{1j}}{T_j s + 1}(\Delta\sigma_{j-1}(s) + d_{1j}(s))\mathrm{e}^{-\tau_j s}, \tag{2}$$

where model gain $K_{1j} = \dfrac{\partial w_j}{\partial \sigma_{j-1}}$, time constant $T_j = L/v_j$. Δ, w_j, σ_{j-1}, d_{1j} stand for small deviations from steady-state operating point, measured exit strip width, inter-stand strip unit tension between $j-1$th stand and jth stand, unknown load disturbance respectively. K_{1j} has many uncertainty factors which mainly depends on the product of strip width and gauge, jth exit temperature and the steel grade, etc.

The model of monitor AGC system can also be approximated as FOPTD:

$$\Delta h_j(s) = \frac{K_{2j}}{T_j s + 1}(\Delta S_j(s) + d_{2j}(s))\mathrm{e}^{-\tau_j s}, \tag{3}$$

where model gain $K_{2j} = M_j/(M_j + Q_j)$, elastic modulus $Q_j = -\dfrac{\partial P_j}{\partial h_j}$. h_j, S_j, d_{2j}, M_j and P_j are measured exit strip thickness, roll gap, unknown load disturbance, mill modulus and rolling force respectively. M_j is often approximated as a constant only related to the strip width and the back up roll diameter. Q_j is of random uncertainty or time-varying which mainly depends on the rolling material, such as temperature, the steel grade, and strip width, etc.

Although the width of FM adjusted by inter-stand tension is effective, the inter-stand tension variation can adversely affect strip thickness accuracy very much. The coupling model can be approximated as FOPTD as well:

$$\Delta h_j(s) = \frac{K_{21j}}{T_j s + 1} \left(\Delta\sigma_{j-1}(s) + d_{1j}(s)\right) \mathrm{e}^{-\tau_j s}, \quad (4)$$

where model gain $K_{21j} = \dfrac{\partial h_j}{\partial \sigma_{j-1}}$.

The closed hydraulic looper and tension control (HLTC) system is even more complicated, but most of their inertia is very small and can be approximated as a first order fast inertia system

$$\frac{\Delta\sigma_{j-1}(s)}{\Delta\sigma_{Rj-1}(s)} = \frac{1}{T_{1j}s + 1}, \quad (5)$$

where σ_{Rj-1} and T_{1j} are inter-stand strip unit tension reference and time constant of the HLTC system respectively.

The closed hydraulic automatic position control (HAPC) system consists of controller, servo amplifier, servo valve, hydraulic cylinder, and position sensor, etc[14]. It is difficult to analyze with the complicated theoretical model. For most of the units are of small inertia, it can also be approximated as a first order fast inertia system

$$\frac{\Delta S_j(s)}{\Delta S_{Rj}(s)} = \frac{1}{T_{2j}s + 1}, \quad (6)$$

where S_{Rj} and T_{2j} are roll gap reference and time constant of the HAPC system respectively.

Using Eqs.(1)–(6), the WGMC system for the last stand of FM near the steady-state operating point can be obtained (subscript j is omitted)

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} + \begin{bmatrix} D_{11}(s) & D_{12}(s) \\ D_{21}(s) & D_{22}(s) \end{bmatrix} \begin{bmatrix} d_1(s) \\ d_2(s) \end{bmatrix}, \quad (7)$$

where

$$G_{11}(s) = \frac{K_1}{(T_1 s + 1)(T s + 1)} \mathrm{e}^{-\tau s},$$

$$G_{12}(s) \approx 0,$$

$$G_{21}(s) = \frac{K_{21}}{(T_1 s + 1)(T s + 1)} \mathrm{e}^{-\tau s},$$

$$G_{22}(s) = \frac{K_2}{(T_2 s + 1)(T s + 1)} \mathrm{e}^{-\tau s},$$

$$D_{11}(s) = \frac{K_1}{T s + 1} \mathrm{e}^{-\tau s}, \quad D_{12}(s) \approx 0,$$

$$D_{21}(s) = \frac{K_{21}}{T s + 1} \mathrm{e}^{-\tau s}, \quad D_{22}(s) = \frac{K_2}{T s + 1} \mathrm{e}^{-\tau s},$$

where measured output y_1, y_2 represent Δw, Δh, and controlled input u_1, u_2 represent $\Delta\sigma_{\mathrm{R}}$, ΔS_{R} respectively.

3 ADRC decoupling for WGMC system

For SISO system, the basic idea of ADRC is to use an ESO to estimate the internal and external disturbances in real time. Then, through disturbance rejection, the originally complex and uncertain plant dynamics is reduced to a simple cascade integral plant, which can be easily controlled. The principle of ADRC is detailed in [4].

As for the multivariable-input multivariable-output (MIMO) system, the dynamic interaction between loops can also be treated as external disturbance, which can be tracked and estimated by ESO in each main loop[3]. Through estimated dynamic interaction compensated by the controller law, a normal SISO ADRC is then designed for each main loop.

The architecture of standard ADRC often consists of three units: tracking differentiator (TD), ESO and SEF control law. To have a fast transient response for the large time delay plant, TD is omitted for the proposed ADRC.

Although traditional ESO and SEF are usually consists of nonlinear function structure, the same control result can also be achieved by linear ADRC (LADRC), since the WGMC system can respond very fast and furthermore, LADRC is much easier to be realized.

3.1 Model order reduction of WGMC system

ADRC is a unique design concept that aims to accommodate not only external disturbances but also unknown internal dynamics in a way that control design can be carried out in the absence of a detailed mathematical model, as most classical and modern design methods require. So the model can be simplified. The error between the simplified model and real model can be seen as disturbance and actively compensated by ADRC.

Due to $T_i \ll T$ in Eq.(7), the smaller inertia unit of each main loop can be omitted in engineering according to the characteristics of the WGMC system. Through model order reduction in Eq.(7), the transfer function of each main loop is simplified as FOPTD:

$$y_i(s) = \frac{b_i}{s + a_i} \left(u_i(s) + d_i(s) + c_i(s)\right) \mathrm{e}^{-\tau_i s}, \quad (8)$$

where $b_i = K_i/T$, $a_i = 1/T$, c_i is the equivalent dynamic interaction from another loop, i denotes each main loop, $i = 1, 2$.

3.2 Reduced order LESO plus time delay design

The ESO was first proposed by Han[3] for on-line estimating the total disturbance, which lumps together the internal dynamics uncertainty and the external disturbance.

To facilitate the design of ADRC, the transfer function (8) should be written into differential equation.

There are various approximation of the time delay

$e^{-\tau s}$, such as the Pade approximation. However, since ADRC is not predicated on an accurate model of the plant, the time delay $e^{-\tau s}$ is often approximated to a first order inertia for ADRC design, then ADRC can be designed to control a higher order system without time delay. But this approximation increased the order of ADRC and the number of tuning parameters.

Let the unknown total disturbance of each main loop be

$$f_i(\cdot) = -a_i \cdot y_i(t) + b_i(d_i(t-\tau_i) + c_i(t-\tau_i)) + b_i \cdot u_i(t-\tau_i) - b_{0i} \cdot u_i(t), \tag{9}$$

where the estimated coefficient b_{0i} is a rough approximation of b_i.

Then the transfer function of each main loop (8) is transformed into the following differential equation:

$$\dot{y}_i(t) = f_i(\cdot) + b_{0i} \cdot u_i(t). \tag{10}$$

For Eq.(10), state of each main loop should be reconstructed to estimate the real state, let the first state

$$x_{1i} = y_i. \tag{11}$$

In order to estimate the unknown total disturbance $f_i(\cdot)$ of each main loop, another state variable x_{2i}, that is, extended state variable, is defined

$$x_{2i} = f_i(\cdot) = \dot{y}_i(t) - b_{0i} \cdot u_i(t). \tag{12}$$

Then Eq.(10) can be rewritten from differential equation to state space equation

$$\begin{cases} \dot{x}_{1i}(t) = x_{2i}(t) + b_{0i} \cdot u_i(t), \\ \dot{x}_{2i}(t) = h_i(\cdot), \\ y_i(t) \ = x_{1i}(t), \end{cases} \tag{13}$$

where $h_i(\cdot) = \dot{f}_i(\cdot)$ is unknown function.

For the plant (13), second order ESO is often designed to obtain the extended state for disturbances compensation according to conventional ADRC. However there is a redundancy when the first state x_{1i} can be measured directly. Using the measured width and gauge outputs y_i, a reduced order ESO, namely first order ESO, is employed to reduce complexity based on the principle of ADRC to control first order inertia plant[10].

Based on the idea of delayed observer for time delay systems[11–12], a time delay unit for each main loop is added to delay the controlled input u_i before it goes into the reduced order ESO, which could synchronize the signals that go into the observer and let it provide meaningful estimations of the total disturbances[13].

The reduced order linear extended state observer plus time delay (ROLESOPTD) for each main loop (13) is constructed in the form of

$$\dot{z}_{2i}(t) = -\omega_{0i}(z_{2i}(t) - \dot{y}_i(t)) - \omega_{0i} \cdot b_{0i} \cdot u_{0i}(t-\tau_i), \tag{14}$$

where z_{2i} is the estimation of extended state variable of each observer; observer gain or bandwidth $\omega_{0i} > 0$ depends on the convergent rate of the ESO; τ_{0i} stands for the estimation of actual time delay.

In order to avoid intensifying measurement noises by direct numerical differentiation of signal y_i in Eq.(14), a new state is defined as

$$z_i(t) = z_{2i}(t) - \omega_{0i} \cdot y_i(t). \tag{15}$$

Therefore, Eq.(14) may be rewritten as

$$\dot{z}_i(t) = -\omega_{0i}(z_i(t) + \omega_{0i} \cdot y_i(t)) - \omega_{0i} \cdot b_{0i} \cdot u_i(t-\tau_i). \tag{16}$$

So the estimation of total disturbance is

$$z_{2i}(t) = z_i(t) + \omega_{0i} \cdot y_i(t). \tag{17}$$

If ω_{0i}, b_{0i} are selected appropriately, then the total disturbance $f_i(\cdot)$ of each main loop can be closely tracked by z_{2i}, namely

$$z_{21}(t) \to f_1(\cdot),\ z_{22}(t) \to f_2(\cdot). \tag{18}$$

3.3 Control law design

Since the total disturbance $f_i(\cdot)$ of each main loop can be accurately estimated in real time based on the input-output signals of the plant, it can be rejected if its estimation z_{2i} is used to compensate in the control action. Then the control law of each main loop can be designed as

$$u_i = \frac{u_{0i} - z_{2i}}{b_{0i}}. \tag{19}$$

Substituting Eq.(19) into the plant (10), it may be reduced approximately to a unit gain cascade plant:

$$\dot{y}_i = f_i(\cdot) - z_{2i} + u_{0i} \approx u_{0i}. \tag{20}$$

Then it will be easy to design a perfect control law by state error feedback.

Inheriting from PID based on error-based feedback control, the controlled input u_{0i} often employs a nonlinear combination to simulate manual's control strategy which has intelligent function in a sense. To satisfy the rapid requirement of the large time delay plant and the easy of use. A simple proportional (P) controller may be employed as

$$u_{0i} = k_{\mathrm{p}i} \cdot e_i, \tag{21}$$

where error $e_i = r_i - y_i$; r_i is the reference signal; $k_{\mathrm{p}i}$ is the controller gain to be tuned.

3.4 Simulation ADRC

For WGMC plant (7), combining reduced order linear extended state observer plus time delay (ROLESOPTD), proportional (P) controller, the proposed ADRC decoupling solution for DIDO system takes the form as shown in Fig.1. Suffix 1 and 2 stand for the width loop and gauge loop, respectively.

3.5 Tuning ADRC

The proposed ADRC for each main loop has only 4 adjustable parameters: estimated time delay τ_{0i}, estimated coefficient b_{0i}, observer bandwidth ω_{0i}, and controller bandwidth $k_{\mathrm{p}i}$. τ_{0i} is the accurate estimation of actual time delay, which had better be updated according to the set-up value of rolling speed during each control period. b_{0i} is usually known to designers, or it is a rough approximation of the actual process coefficient b_i.

Using the parameterization technique proposed in [13, 15],

$$\omega_{0i} = \alpha_i \cdot k_{\mathrm{p}i}, \tag{22}$$

where the ratio α_i is often chosen from two to thirty between performance and noise-sensitivity.

So $k_{\mathrm{p}i}$ becomes the only tuning parameter of each main loop. It can be tuned roughly using, for example, the pole-placement, placing the closed-loop pole around $-a_i$.

To get the optimum control performance, $k_{\mathrm{p}i}$ can be tuned by intelligent optimization methods, such as the mutative scale chaos optimization method based on Logistic map[6].

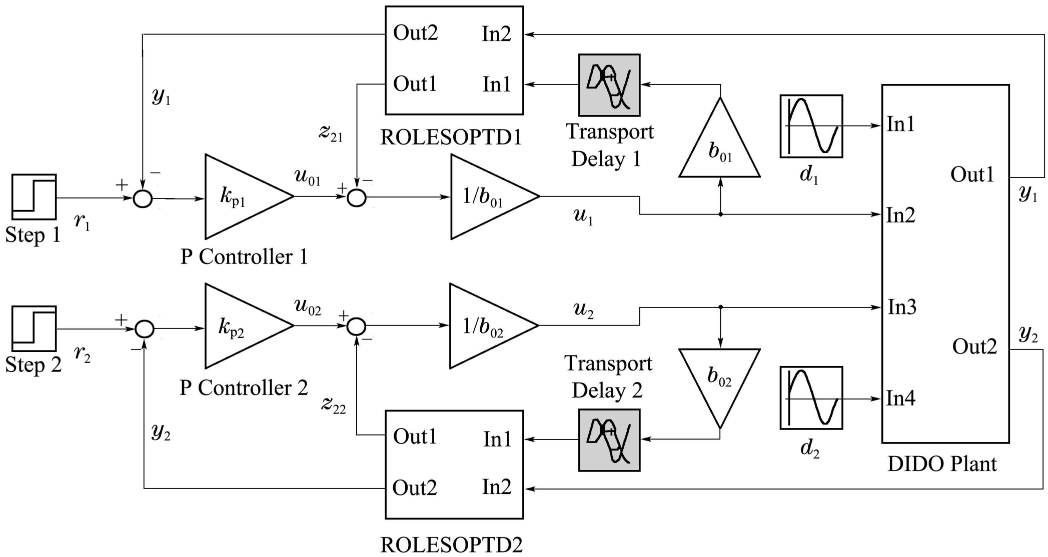

Fig. 1 Block diagram of practical ADRC decoupling for DIDO system

The iterative form of Logistic map is defined as

$$x_{k+1} = \lambda \cdot x_k(1 - x_k), \tag{23}$$

where x_k is the kth value of the map, $x_k \in (0, 1)$; k denotes the number of iteration; λ represents the branch parameter or control parameter, $\lambda \in [1, 4]$.

Obviously, x_k is defined on the open set because 0 is a known fixed point and 1 maps to 0. Note that the initial value should be kept away from other fixed points, such as 0.25, 0.50, 0.75.

According to chaotic dynamical system theory, when $3.569945672 < \lambda \leqslant 4$, Logistic map (23) works completely in a chaos state. In order to move through the whole search space, $\lambda = 4$ is often chosen in chaos optimization because it is of full map.

In general, performance index are often adopted as the objective function for the design of control system, such as the integral absolute error (IAE), the integral of squared error (ISE), the integral of time-weighted squared error (ITSE), and the integral time absolute error (ITAE), etc. According to the characteristics and requirements of WGMC system, the objective function of optimization is selected as

$$J = \min t_{\mathrm{s}}(\sigma\% \leqslant 2\%), \tag{24}$$

where t_{s} is the settling time; overshoot $\sigma\%$ is constrained to be smaller than 2% (instead of 5%) to meet the high-precision design requirements of hot strip rolling.

4 Simulation studies

Take the last stand of hot strip rolling as an example, the nominal plant parameters of the WGMC system (7): $K_1 = -1$, $T = 0.5$, $T_1 = 0.02$, $K_{21} = -0.1$, $T_2 = 0.01$, $M = 5800\,\mathrm{kN/mm}$, $Q \approx 31006\,\mathrm{kN/mm}$, $v_m = 12\,\mathrm{m/s}$, $L_m = 6\,\mathrm{m}$, then the pure transportation time delay $\tau = 0.5\,\mathrm{s}$.

The configuration parameters of simulation: ode1 (Euler) is selected for solver options, fixed-step is set 0.01 s, the model approximation error of solver can be treated as disturbance.

According to the nominal plant parameters of the WGMC system, the controller parameters of the proposed ADRC for each main loop: $\tau_{0i} = \tau$, $b_{0i} = K_i/T$, $\alpha_{01} = 10$, $\alpha_{02} = 20$. The optimized parameters: $k_{\mathrm{p}1} = 2.660$, $k_{\mathrm{p}2} = 2.645$.

The performance of the proposed ADRC is compared with classical PID. Since the parameters of PID tuned by Z–N method would result in a bigger overshoot, they are also optimized by the above chaos optimization method. To have a fair comparison, the objective function is the same as the proposed ADRC. The optimized parameters of classical PID for each main loop: $K_{\mathrm{P}i} = 0.57/K_i$, $K_{\mathrm{I}i} = 0.97/K_i$, $K_{\mathrm{D}i} = 0.002/K_i$.

In the following simulation results, solid line and dotted line represent the proposed ADRC and classical PID respectively.

4.1 Unit step response and decoupling

For the nominal system, a unit step as the set point is exerted respectively for each main loop. The simulation results are shown in Figs.2–3. Because both parameters of ADRC and PID are optimized by the same objective function, both of them have good tracking ability with the overshoot less than 2% and no steady-state error. Compared with PID, t_{s} and ITAE of ADRC for the width loop is decreased by about 31% and 46%, respectively, according to the data in Table 1. In Table 1, ADRC1 and PID1 stand for the first loop (width loop), ADRC2 and PID2 stand for the second loop (gauge loop), respectively.

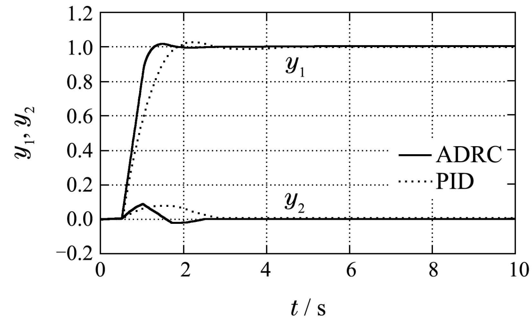

Fig. 2 Unit step response of nominal case ($r_1 = 1, r_2 = 0$)

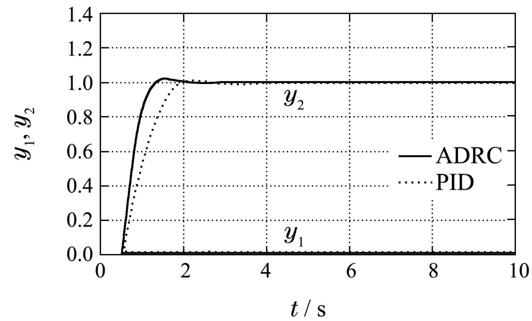

Fig. 3 Unit step response of nominal case ($r_1 = 0, r_2 = 1$)

Compared to the performance index of PID in Table 1, when a unit step is only exerted for width loop as shown in Fig.2, t_{s} and ITAE of ADRC for the gauge loop is decreased by about 42% and 59%, respectively, according to the data in Table 1. It can be seen that the gauge variations coupled by the tension adjustment is largely eliminated and the decoupling performance could well meet the design requirements due to the dynamical decoupling of ADRC.

Table 1 Performance comparison of unit step response

		ADRC1	PID1	ADRC2	PID2
Nominal case	σ / %	1.99	1.72	–	–
	t_{s} / s	1.20	1.75	1.43	2.46
	ITAE	34.68	64.62	7.20	17.38
K_1 decreased by 30%	σ / %	1.47	0	–	–
	t_{s} / s	1.77	4.31	1.64	3.01
	ITAE	56.68	151.44	8.32	30.47
T decreased by 10%	σ / %	0.18	0.09	–	–
	t_{s} / s	2.03	3.32	1.39	2.43
	ITAE	35.09	65.65	6.56	17.31

4.2 Disturbance rejection

To test the disturbance rejection of the nominal system in the presence of external disturbance, a sinusoidal load disturbance signal with 30% of amplitude, frequency 0.06 Hz is exerted at the width loop without changing any controller parameters of ADRC and PID. The simulation results are shown in Figs.4–5. The magnitude of external disturbances which affect the strip width and gauge are reduced by about 55% and 75% respectively in comparison with PID. Although both ADRC and PID are parameter-optimized with the same objective function, the disturbance rejection of ADRC is much better than the classical PID due to the compensation for disturbance of ESO (including the dynamic coupling).

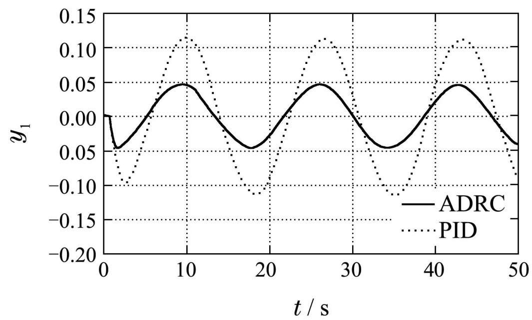

Fig. 4 Disturbance rejection performance of width loop

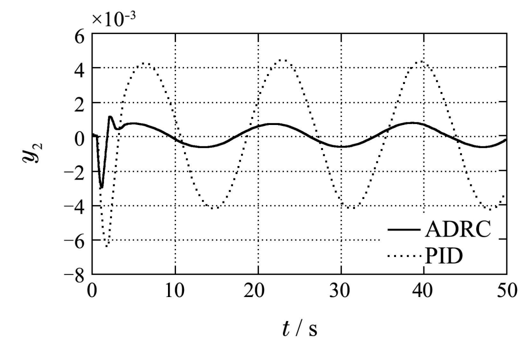

Fig. 5 Disturbance rejection performance of gauge loop

4.3 Robustness to parametric uncertainty

Model parameters are of random uncertainty or time-varying affected by many factors, for example, model gain K_1 is mainly resulted from material rolling conditions including the product of strip width, $m-1$th exit temperature, and the steel grade, etc.

As the proposed ADRC is designed by the maximum model gain, K_1 is decreased by 30%. A unit step as the set point is exerted for width loop without changing any controller parameters of the proposed ADRC and PID. The simulation results are shown in Fig.6. Compared to the performance indices of PID in Table 1, t_s and ITAE of ADRC for width loop are decreased by about 59% and 63%, respectively; and the two performance indices for decoupling of the gauge loop are decreased by about 46% and 73%, respectively. It can be seen that unit step response and decoupling performance of the proposed ADRC is more robust to the parameter uncertainty of model gain.

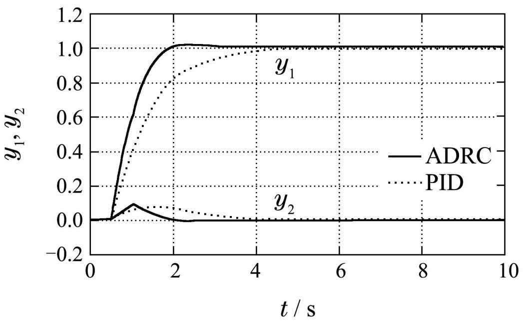

Fig. 6 Unit step response with K_1 decreased by 30%

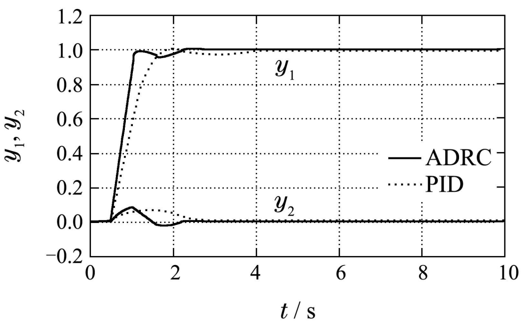

Fig. 7 Unit step response with T decreased by 10%

Model time constant has also many random uncertainty or time-varying factors. Because the proposed ADRC is designed by the maximum time constant, for example, T is decreased by 10%. A unit step as the set point is exerted for width loop without changing any controller parameters of the proposed ADRC and PID. The simulation results are shown in Fig.7. Compared to the performance indices of PID in Table 1, t_s and ITAE of ADRC for the width loop are decreased by about 39% and 47%, respectively; and the two performance indices for decoupling of the gauge loop are decreased by about 43% and 62%, respectively. It can be seen that the tracking and decoupling performance of the proposed ADRC is more robust to the parameter uncertainty of model time constant, and it is able to adapt to the time-varying characteristics of the rolling process.

5 Conclusions

Based on ADRC, a decoupling solution for the uncertain WGMC system with large time delay is proposed. Through order reduction in both the plant model and the state observer, the interaction between the main loops is viewed as disturbance and is estimated by a linear extended state observer of only first order plus time delay, and compensated by the controller law of each main loop. The simulation results show that the ADRC solution with optimized parameters has better performance than the conventional PID controller. These demonstrate that the proposed ADRC is practical and very effective in dealing with the coupling effects, uncertainties, time delay and other external disturbances.

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