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A novel DMC-based predictive PID controller and its tuning

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Abstract: This paper proposes a novel PID control scheme equipped with predictive property based on dynamic matrix control(DMC) algorithm. DMC computes the manipulated variable through minimizing a cost function of expected future errors. Next, a DMC-based predictor is constructed to predict the output values at the future time instant. The predicted future errors are used in a PID controller to generate the actual control actions. The DMC-based predictor and the PID controller are well tuned to provide the design parameters. Compared with the conventional PID and DMC control, simulation results demonstrate the better output responses, particularly in disturbance rejection performance.

Key words: predictive control; PID control; dynamic matrix control(DMC); controller tuning

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一种基于DMC的新型预测PID控制器及其整定

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摘要: 本文提出一种基于动态矩阵控制(DMC)算法预测特性的新型PID控制方法. 在考虑将来的输出期望偏差罚函数最小的前提下, 由DMC计算出控制变量的值. 继而构造基于DMC的预估器用以预测将来时刻的系统输出. 根据将来时刻的多步预测偏差, PID控制器产生当前时刻的实际控制增量. 文中也给出了基于DMC的预估器及PID控制器的参数整定方法. 仿真结果表明, 与常规的PID控制和DMC控制相比, 所提方法具有良好的控制性能, 扰动抑制尤其优良.

关键词: 预测控制; 比例–积分–微分控制; 动态矩阵控制; 控制器整定

1 Introduction

In industrial process control, the PID control algorithm is the most widely used even up to 90 percentages. The conventional PID algorithm is simple, and easily to be implemented. Although only with three tuning parameters (proportional, integrating, and differentiating coefficients), the PID control generally meets the control performance specifications very well[1]. However in case of long dead time in the process model, the system output response will be slower than that with no dead time when considering the same PID controller parameters[2,3]. The presence of dead time impairs closed-loop performance[1,4,5]. There are some dead time compensation strategies[5], such as Smith predictor, which can provide good performances. But because of their robustness they can not be extensively used in practice.

Predictive control algorithm is one of the advanced control strategies that have had a significant impact on industrial control. It predicts the error values of the reference input and the process output so as to calculate the actual manipulated variable. Due to predictive algorithms are essentially internal model based and can intrinsically compensate the dead times of process, they can provide good performance even in case of long dead time[6]. Consequently, the combination of PID and predictive control maybe obtain their both properties: good performance and easily parameters tuning of PID, and good dead time compensation characteristics and easily tackling constraints of predictive control[7∼10]. In case of systems containing long dead time significantly

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faster control performance can be achieved with predictive control than with PID control. Also in case of known future reference trajectory predictive control provides better tracking properties. Nevertheless it is difficult to introduce advanced control algorithms in practice, as PID algorithms also work well, and generally control problems can be solved with them. In recent years some work on predictive PID has been investigated. Miller proposed a new predictive PID control law which is mathematically equivalent to generalized predictive control(GPC) with a steady state weighting term[7,8]. The idea of predictive PID controllers was systematically initiated by Katebi and Moradi[11] and Johnson and Moradi[10]. They utilized the future knowledge of the reference and prediction based on the process model to improve the control quality and tune PID controllers. F. Arousi proposed PI control algorithms equipped with predictive properties and applied to an aperiodic process approximated by a first order model with dead time[12]. All these methods need to design a series of PID controllers, and the control structures are also very complex.

This paper provides a novel PID control scheme equipped with predictive property based on dynamic matrix control(DMC) algorithm. DMC computes the manipulated variable through minimizing a cost function considering expected future errors. Next a DMC-based predictor is constructed to predict the output values of future times. The predicted future errors gather into a PID controller to produce the actual control variable. The DMC-based predictor and the PID controller with a two-degree-of-freedom(2DOF) form are tuned to provide the suitable design parameters. The appropriate tuning parameters can provide good control performance and high robustness.

2 Proposed predictive PID control

2.1 Control structure

Smith predictor has the property of predicting the output response which ahead of the actual process. So the controller can excited the control action ahead of the system output. The principle is captured by Fig.1, which shows a process model $g_0(s)\mathrm{e}^{-Ls}$ containing a dead time L. The controller is given by $g_\mathrm{c}(s)$, usually with a PID form, and there is an internal loop involving a process model representation $g_\mathrm{m}(s) = g_{\mathrm{m}0}(s)\mathrm{e}^{-L_\mathrm{m}s}$. The predictor based on an internal model is shown in Fig.1. In case of no model mismatching, the nominal model is same as the actual model, that is $g_{\mathrm{m}0}(s) = g_\mathrm{m}(s)$, $L_\mathrm{m} = L$. The predictor is to provide the future output value ahead of the dead time L. If we can utilize the future several or more error values it maybe results in the better process output performance.

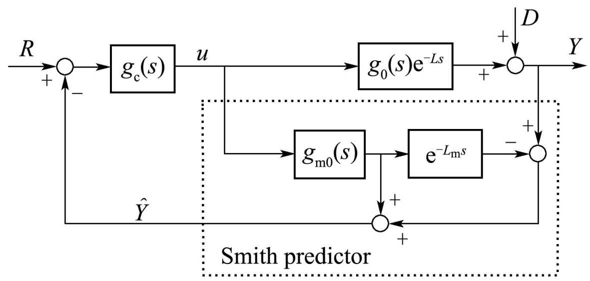


Fig. 1 Smith predictor block diagram

A predictive PID controller considers a predicted value of the error signal. Therefore it can provide faster performance than the traditional PID controller in case of long dead time. An extension of the predictive PID controller is when a series of the predicted error values are taken into account, the controller outputs are calculated from the difference of the predicted reference signal values and the predicted values of the output signal in a given prediction horizon.

Due to DMC can provides the predictive output values ahead of the current output value using a step test model, we can construct a predictor based on the DMC principle. The block diagram of the proposed structure is shown in Fig.2. Note that we employee a description in a discrete form. Here $\hat{e}(k+i|k)$ denotes the predicted value of the error signal i step ahead over the current time of k. $r(k+i|k)$ is the reference signal, and $\hat{y}(k+i|k)$ is the predicted output signal i step ahead over the current time of k. (For simplicity, in the rest paper the current time mark k will be omitted in the expressions for all predicted values.) And $i = 1, 2, \cdots, M$, where M is the predictive output time horizon. The error weighting factors is presented with w_i $(i = 1, 2, \cdots, M)$. $\hat{e}(k)$ denotes the sum of the weighted predictive errors at the current time k. The controller needs an operation in advance of an prediction to eliminate the error and the oscillation of the output responses. Namely, the error is predicted not only by the error in control period but also by the difference between the model output and the reference input at the time points of future, and then the appropriate output is calculated.

Considering the dead time L of the process, the output values should be zero in the range between the current time of k and the next times of $k+d$, where $d = L/T_{\mathrm{s}}$, in which T_{s} denotes the sampling time. Therefore the weight coefficients $w_i(i = 1, 2, \cdots, M)$ all are zeros, while the other $M-d$ weight coefficients can be chosen according to the predictive requirements. In particular, if $M = d+1$, there is only one predictive output after the dead time. This case is similar as Smith predictor shown in Fig.1. Thus we can look the proposed structure in Fig.2 as a multi-step extensive version of Smith predictive structure.

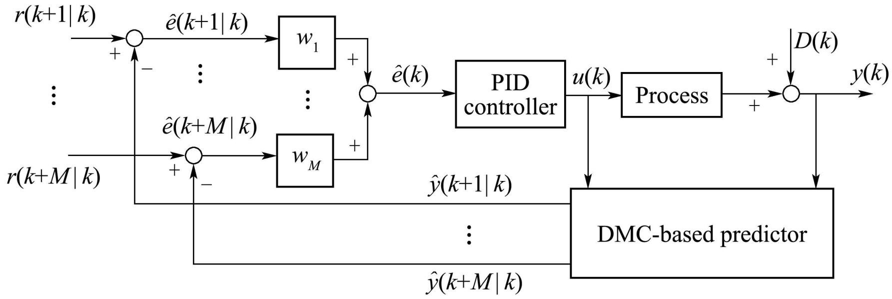


Fig. 2 The proposed predictive PID control structure

2.2 DMC-based predictor

Dynamic matrix control is one of the commonly used model predictive control(MPC) strategy based on the step response model in the industry, which calculates moves on the manipulated variables that will minimize an objective function involving the error between set-points and future projections of controlled variables. Future control moves $\Delta\bar{U}(M\times 1)$ are given as

$$\Delta\bar{U} = (A^{\mathrm{T}}A + \gamma I)^{-1}A^{\mathrm{T}}(Y_r - Y_{\mathrm{past}} - D), \quad (1)$$

where $A(P\times M)$ is the Toeplitze matrix of the step response coefficients of the process. The control moves are penalized by coefficient γ. A small value should be chosen for γ if faster response is required. $Y_r(P\times 1)$ represents a smooth form of the reference input. Usually a first order filter $1/(\alpha s+1)$ with the coefficient α is employed to determine Y_r through the input reference R. $Y_{\mathrm{past}}(P\times 1)$ indicates future behaviors of the process based on its previous inputs. $D(P\times 1)$ represents any existing mismatch, disturbance, and noise in the system which can be viewed as a lumped disturbance. Appropriate values should be selected for design parameters P (prediction horizon), M (control horizon), γ (control move weighting coefficient), and α (input filter coefficient).

In the range of prediction horizon P, the predicted system output is

$$\hat{Y}(k) = \hat{Y}_0(k) + A\Delta\bar{U}(k), \quad (2)$$

where $k = 1, 2, \cdots, P$, $\hat{Y}_0(k)$ is the prediction output value vector at the time of k without the control action in the range of prediction horizon P, and

$$\hat{Y}(k) = [\hat{y}(k+1)\ \hat{y}(k+2)\ \cdots\ \hat{y}(k+P)]^{\mathrm{T}},$$
$$\hat{Y}_0(k) = [\hat{y}_0(k+1)\ \hat{y}_0(k+2)\ \cdots\ \hat{y}_0(k+P)]^{\mathrm{T}},$$
$$\Delta\bar{U}(k) = [\Delta\bar{u}(k+1)\ \Delta\bar{u}(k+2)\cdots\ \Delta\bar{u}(k+M)]^{\mathrm{T}}.$$

Therefore the predicted output after the current time point k can be expressed as

$$\hat{y}(k+d+i) = \\ [h_{i-1}\ h_{i-2}\ \cdots\ h_1]\begin{bmatrix}\Delta\bar{u}(k+1)\\ \Delta\bar{u}(k+2)\\ \vdots\\ \Delta\bar{u}(k+i-1)\end{bmatrix} + \\ [f_1[d+i]\ f_2[d+i]]\begin{bmatrix}y(k)\\ y(k-1)\end{bmatrix} + \\ [h_i\ h_{i+1}\ \cdots\ h_{i+d}]\begin{bmatrix}\Delta u(k)\\ \Delta u(k-1)\\ \vdots\\ \Delta u(k-d)\end{bmatrix}. \quad (3)$$

The first term on the right side of the above equation gives the forced response, while the second and the third terms give the free response. If there is no dead time, i.e. $d = 0$, the last term on the right side of the equation is missing. $h_1, h_2, \cdots$ are the points of the step response, and $f_1[d+i]$, $f_2[d+i]$ are the coefficients in row $d+i$ of the following f_1 and f_2 vectors[12]:

$$f_1 = [\frac{h_2}{h_1} \quad \frac{h_3}{h_1} \quad \frac{h_4}{h_1} \quad \cdots]^{\mathrm{T}}. \tag{4}$$

$$f_2 = [\frac{(1-\frac{h_2}{h_1})h_2}{h_1} \quad \frac{(1-\frac{h_2}{h_1})h_3}{h_1} \quad \frac{(1-\frac{h_2}{h_1})h_4}{h_1} \quad \cdots]^{\mathrm{T}}. \tag{5}$$

The points of the step response can be calculated from the parameters in the transfer function of the process.

2.3 Predictive PID controller

Generally, the form of a classical discrete PID controller is

$$u(k) = k_{\mathrm{p}}e(k) + k_{\mathrm{i}}\sum_{i=1}^{k} e(i) + k_{\mathrm{d}}[e(k) - e(k-1)], \tag{6}$$

where e denotes the error signal at the current time k and k_{p}, k_{i}, k_{d} are the coefficients of the proportional, the integral and the differential components, respectively. Taking the difference on both sides of Equation (6) at step k and $(k-1)$ leads to

$$\begin{aligned}&\Delta u(k) = u(k) - u(k-1) = \\ &(k_{\mathrm{p}} + k_{\mathrm{i}} + k_{\mathrm{d}})e(k) + (-k_{\mathrm{p}} - 2k_{\mathrm{d}})e(k-1) + \\ &k_{\mathrm{d}}e(k-2).\end{aligned} \tag{7}$$

Applying the algorithm on a future error signal $(d+i)$ ahead of the actual time point the corresponding control increment $\Delta u(k)$ is obtained as

$$\begin{aligned}\Delta u(k) = &(k_{\mathrm{p}} + k_{\mathrm{i}} + k_{\mathrm{d}})\hat{e}(k+d+i) + \\ &(-k_{\mathrm{p}} - 2k_{\mathrm{d}})\hat{e}(k+d+i-1) + \\ &k_{\mathrm{d}}\hat{e}(k+d+i-2).\end{aligned} \tag{8}$$

Where $\hat{e}(k+d+i)$ represents the predicted error signal $d+i$ ahead of the current time point k, d denotes the dead time steps, and $i = 1, 2, \cdots$. So at the current time point k, the relation of the process controller action increment and the future average error vector can be denotes:

$$\Delta u(k) = K\begin{bmatrix} r(k+d+i) - \hat{y}(k+d+i) \\ r(k+d+i-1) - \hat{y}(k+d+i-1) \\ r(k+d+i-2) - \hat{y}(k+d+i-2) \end{bmatrix}, \tag{9}$$

where $K = [(k_{\mathrm{p}} + k_{\mathrm{i}} + k_{\mathrm{d}}) \ (-k_{\mathrm{p}} - 2k_{\mathrm{d}}) \ k_{\mathrm{d}}]$ is the PID controller parameter vector that should be tuned.

3 Tuning rules

The proposed structure can be viewed as an extension of Smith predictor, and the predictor is based on DMC receding optimized model. In order to get good control performance, the parameters of PID controller and DMC-based predictor should be appropriately tuned.

Guidelines to select appropriate values for design the parameters P(prediction horizon), M(control horizon), γ(control move weighting coefficient), and α(pole of the reference input filter) could be found in the literature[13].

Most practical industrial processes can be approximated well by a first order plus dead time(FOPDT) model. As in most cases the step response of the system can be measured easily even within industrial circumstances, the FOPDT model can be identified by some data processing techniques such as the least square method. A good, but slow control of this process can be achieved by a PI controller for a FOPDT model[1]. As for the parameters tuning of PI controller, there are some general methods such as Ziegler-Nichols, Tyreus-Luyben methods as well as method of trial and error according to experience.

Denote the FOPDT model as $\frac{k}{Ts+1}\mathrm{e}^{-Ls}$, where k, T, and L represent the constants of gain, inertia time, and pure delay. Since PI control commonly presents a slower response for a FOPDT process, we employee a particular two-degrees-of-freedom PID (2DOF-PID) control structure in Fig.3, in which $F(s)$ and $C(s)$ are the input filter and the PID controller correspondingly. In the standard from using a low pass filter the 2DOF-PID scheme is with the forms as follows:

$$F(s) = \frac{1 + b\tau_{\mathrm{i}} + c\tau_{\mathrm{i}}\tau_{\mathrm{d}}s^2}{1 + \tau_{\mathrm{i}} + \tau_{\mathrm{i}}\tau_{\mathrm{d}}s^2}. \tag{10}$$

$$C(s) = \frac{k_{\mathrm{p}}}{\tau_{\mathrm{i}}}\frac{1 + \tau_{\mathrm{i}}s + \tau_{\mathrm{i}}\tau_{\mathrm{d}}s^2}{s(1 + s\tau_{\mathrm{f}})}. \tag{11}$$

Where k_{p}, τ_{i}, τ_{d} represent the three tuning parameters aforementioned of the PID controller, and τ_{f} is the time constant of the input filter, and b and c are of the weight coefficients of 2DOF controller.

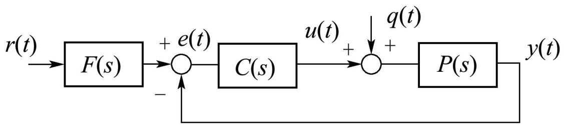


Fig. 3 Two-degrees-of-freedom PID control structure

Table 1 shows the tuning formula for the standard filtered 2DOF-PID. The final tuning of the PID controller will depend on the particular situation. If possible, the best compromise between performance and robustness should be obtained by tuning b or c using some knowledge of the real process and the uncertainties. However, it is important to note that, in practice, when only poor information about the uncertainties is available, a simple tuning rule must be used. For practitioners, this rule should be a good starting point in a real time tuning procedure. If $b = 0.8$ and $c = 1$ are chosen, they commonly offer delay margins greater than 30 percentage of the nominal dead time and a closed loop response with small overshoot[5]. The appropriate b and c can improve the robustness of the 2DOF-PID controller.

Table 1 Parameter tuning

k_{p}	τ_{i}	τ_{d}	τ_{f}	b	c
$\dfrac{0.35(L+2T)}{kL}$	$T+\dfrac{L}{2}$	$\dfrac{LT}{L+2T}$	$0.15L$	0.8	1

Taking into account that the nominal model is represented by $P_n(s)$, a way to define robustness in case of model mismatching is by using the maximum sensitivity M_{s} defined as[1]

$$M_{\mathrm{s}} = \max_{w} \left|1 + C(\mathrm{j}w)P_n(\mathrm{j}w)\right|^{-1}. \qquad (12)$$

Note that $C(\mathrm{j}w)P_n(\mathrm{j}w)$ is a tangent to a disc centered on the -1 point with a radius of $1/M_{\mathrm{s}}$. Normally M_{s} uses the values between 1.2 and 2.0 for a good compromise of control performance and robustness. For the controller parameters for the FOPDT model in Table 1 the maximum sensitivity M_{s} usually in a suitable range[5], which presents the good values for an initial tuning of the 2DOF-PID controller.

4 Simulation results

Consider a heat exchanger for controlling the temperature of a chemical reactor of Fig.4. In this process steam is used for heating water. An increment in the steam flow (F_{s}) produces an increment in the outlet water temperature T. On the other hand, an increment in the water flow (F_{w}), regulated by V_1, produces a decrement in T. Due to the pipe length a significant dead time is observed in the dynamics. The control objective is to maintain the temperature of the reactor at a constant set-point by varying the amount of steam supplied to the heat exchanger via the control valve. This must be done while the reactor is subject to step changes in the temperature of the liquid inlet flow.

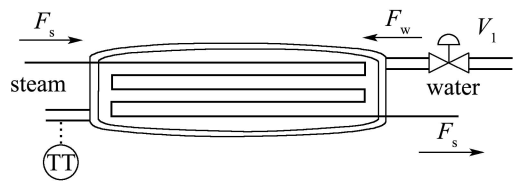


Fig. 4 Heat-exchanger

Consider the water flow F_{w} is used as a manipulated variable to control the temperature T. The transfer function between F_{w} and T can be represented by

$$P(s) = \frac{\mathrm{e}^{-14.7s}}{21.3s+1}.$$

Consider that the steam flow F_{s} is used as a disturbance to control the temperature T and the transfer function between them is denoted as

$$D(s) = \frac{\mathrm{e}^{-35s}}{25s+1}.$$

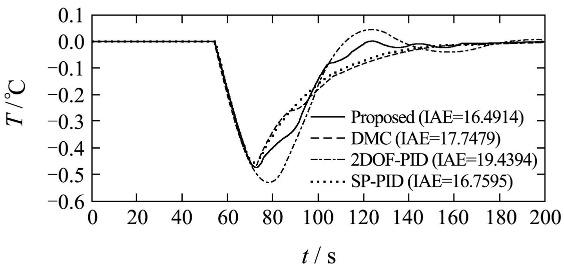
In order to illustrate the better control performance under the proposed predictive PID (P-PID) control method, the comparisons are implemented with that under the other widely used control schemes: the DMC scheme and the PID control scheme, the latter including 2DOF-PID and PID with Smith predictor (SP-PID). The parameters of the controllers are listed in Table 2.

Considering the dead time of the process is $L = 14.7$ s, we choose the control horizon $M = \dfrac{L}{T_{\mathrm{s}}} + 4$, in which T_{s} denotes the sampling time. As for SP-PID control, the integral time τ_{i} is chosen equal to the time constant of the plant $\dfrac{k}{Ts+1}\mathrm{e}^{-Ls}$, and gain k_{p} is chosen proportional to the inverse of the gain of the plant[3]. Thus $\tau_{\mathrm{i}} = T$ and $k_{\mathrm{p}} = \dfrac{x}{k}$, in which x is tuned by simulation. In order to get a high controller gain we chose $x = 10$ in the simulation case. In the proposed P-PID and 2DOF-PID control schemes the controller parameters are tuned following the rule in Table 1. By Equation (12) the maximum sensitivity $M_{\rm s} = 1.323$ can be computed which presents a good trade-off between performance and robustness.

Table 2 Controller parameters

Method	Parameters
Proposed	$k_{\rm p} = 1.3643, \tau_{\rm i} = 28.6500, \tau_{\rm d} = 5.4644$ $\tau_{\rm f} = 2.2050, b = 0.8, c = 1$ $T_{\rm s} = 1, P = 25, M = 19$ $\gamma = 0.01, \alpha = 0.3$
DMC	$T_{\rm s} = 1, P = 25, M = 19$ $\gamma = 0.01, \alpha = 0.3$
2DOF-PID	$k_{\rm p} = 1.3643, \tau_{\rm i} = 28.6500, \tau_{\rm d} = 5.4644$ $\tau_{\rm f} = 2.2050, b = 0.8, c = 1$
SP-PID	$k_{\rm p} = 10, \tau_{\rm i} = 21.3$

Fig.5 shows the disturbance responses under proposed P-PID, DMC, and PI control. At the time $t = 20$ s, the disturbance (its final value is -1) from the steam flow is input. Since the dead time of the disturbance transfer function $D(s)$ is 35 s, the output response will start at 55 s. We can find the responses under P-PID and DMC control suppress the disturbance earlier about at the time of $t = 71$ s than that of PI control about at the time of $t = 78$ s. And the response under P-PID control reaches the setpoint faster than that under DMC control. Fig.5 also gives the values of integral absolute error (IAE) for the three control strategies. It is obvious that the proposed P-PID scheme is superior to the DMC and PI control specially in the disturbance rejection property.



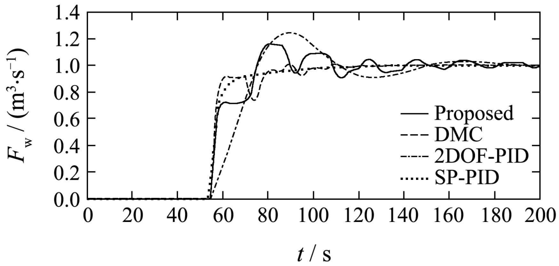


Fig. 5 Responses under proposed and other control schemes

5 Conclusions

A novel PID control algorithms with the predictive property is presented for the FOPDT model. The predictive output is based on the DMC scheme, which has the similar structure as that of the traditional Smith predictor. Moreover, the predictive property of the proposed scheme compensates the dead time of the process. Through giving a robust 2DOF PID parameter tuning method, better control performances can be easily attained. Simulation results show the effectiveness of the proposed predictive PID control structure compared with the DMC and PI control schemes.

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