Chemometrics and Intelligent Laboratory Systems 134 (2014) 110–117

Contents lists available at ScienceDirect

Chemometrics and Intelligent Laboratory Systems

journal homepage: www.elsevier.com/locate/chemolab

# Design of dynamic matrix control based PID for residual oil outlet temperature in a coke furnace

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ARTICLE INFO

*Article history:*
Received 6 March 2014
Received in revised form 24 March 2014
Accepted 26 March 2014
Available online 2 April 2014

*Keywords:*
PID control
Dynamic matrix control
Chemical processes
Industrial coke furnace

ABSTRACT

The application of proportional–integral–derivative (PID) controllers to chemical processes may not achieve the desired effect due to large time delay, model/plant mismatches, etc, which causes performance deterioration. In view of this, the paper first proposes a new PID controller design based on dynamic matrix control (DMC) optimization and then tests it on the residual oil outlet temperature in an industrial coke furnace. The resulting PID controller shows that it has the superior character of DMC algorithm and, at the same time, the simple structure as a traditional PID controller. Since model predictive control is effective in dealing with long time delays and model/plant mismatches, the control performance under the proposed PID is improved compared with typical PID controllers.



## 1. Introduction

Processes with large time delay are very common in the chemical industry. Due to the large time delay and model/plant mismatches, the application of traditional proportional–integral–derivative (PID) controller may not obtain the desired performance [1–3]. In view of these problems, many methods are proposed. One typical method may be the Smith predictor, which is also thought of as an advanced PID control algorithm for time delayed processes [4–7]. Although the Smith predictor can compensate for the time delay by first separating it and then designing a PID based on the time-delay free part of the process, results show that this kind of controller is sensitive to model/process mismatch and thus is less effective for industrial applications. Other advanced algorithms were also proposed to combine with the Smith predictor for better performance [8–10]. However, these methods obtain good performance in handling the long time delay processes by assuming that the process and its dynamic model match well, which is not the case for industrial engineering applications.

With the development of the computer control theory, model predictive control (MPC) has been proposed as an effective advanced algorithm in dealing with large time delayed processes [11,12]. Based on the obtained process model, MPC predicts the future trends of process behavior and then calculates the corresponding control input. Unlike the Smith predictor and other advanced PID controllers, MPC can predict and compensate for the error caused by model/plant mismatch such that exact process models are generally not very necessary and still, improved engineering application results can be obtained.

However, limited by the cost, hardware and so on, the implementation of MPC is more complex than PID control, which provides chances and challenges of finding a combination of both advantages of MPC and PID. Some representatives are as follows. Xu, et al. proposed a PID controller using generalized predictive control (GPC) framework and obtained the performance as that of GPC [13]; however, the controller derivation is based on linearization approximation. A multivariable predictive fuzzy-PID control system was developed by incorporating the fuzzy and PID control approaches into the predictive control framework by Savran [14]. Lee and Yeo developed a new PID controller on the basis of simplified GPC [15]. Many other advanced control algorithms were also introduced to improve the performance of the traditional PID controller in dealing with time delayed processes [16–21].

In this study, the dynamic matrix control (DMC) algorithm is combined with the PID control to obtain a new PID controller which bears the good performance of the DMC algorithm and also the same structure as traditional PID controllers. The detailed design of such DMC based PID is first illustrated and then compared with typical PID controllers. Specially, traditional PID controllers tuned by the Cohen–Coon method and IMC method are used for comparison, where results are illustrated through a case study of the outlet temperature regulation in an industrial coke furnace.

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http://dx.doi.org/10.1016/j.chemolab.2014.03.016
0169-7439/

## 2. Typical PID tuning methods

For simplicity, we choose the general first order plus dead time (FOPDT) model formulation that can be obtained by a step response test as the process model. Notice that extension to higher order process models is possible.

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

where $K$ is the steady process gain, $T$ is the time constant of the process and $\tau$ is the time delay.

The C–C method proposed by Cohen and Coon is an important engineering tuning method because it is developed on the basis of the Z–N method in order to compensate for its insufficiency in dealing with time delayed processes [22]. Note that the internal model control (IMC) based PID tuning method also shows its superiority because the process model is explicitly used and the controller design can be based on the "good" part of the process model [23]. The parameters of the above two traditional PID controllers are tuned as follows.

$$K_p = \frac{T}{K\tau}\left(\frac{16T+3\tau}{12T}\right), T_i = \frac{\tau\left(32+6\left(\frac{\tau}{T}\right)\right)}{13+8\left(\frac{\tau}{T}\right)}, T_d = \frac{4\tau}{11+2\left(\frac{\tau}{T}\right)} \tag{2}$$

$$K_p = \frac{(T+0.5\tau)}{K(\lambda+0.5\tau)}, T_i = T+0.5\tau, T_d = \frac{T\tau}{2T+\tau} \tag{3}$$

where Eq. (2) is the Cohen–Coon method and Eq. (3) is the IMC based method. $K_p$ is the proportional gain of the PID controller, $T_i$ is the integral time of the PID controller, $T_d$ is the derivative time of the PID controller, and $\lambda$ in Eq. (3) is the IMC filter factor which is usually chosen as $\lambda > 0.8\tau$.

## 3. DMC based PID controller design

In this section, the DMC algorithm is introduced to optimize the parameters of the PID controller. By doing so, the obtained PID controller has the performance as the DMC algorithm and the simple structure as the traditional PID controller simultaneously.

The model vector $\alpha = [\alpha_1, \alpha_2, \cdots, \alpha_N]^T$ is obtained from the step response test firstly, where $N$ is the model length, $\alpha, \alpha_2, \cdots, \alpha_N$ is the corresponding unit step response data sampled by sampling time $T_s$. The dynamic matrix of the model can be constructed as follows.

$$A = \begin{bmatrix} a_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ a_M & \cdots & a_1 \\ \vdots & \vdots & \vdots \\ a_P & \cdots & a_{P-M+1} \end{bmatrix} \tag{4}$$

where $A$ is the dynamic matrix whose dimension is $P \times M$, $P$ is the prediction horizon, and $M$ is the control horizon, and we usually require $N \geq P \geq M$.

The future output prediction of the model calculated by control increment $N$ at time instant $k-1$ is

$$y_{N1}(k-1) = y_{N0}(k-1) + \alpha\Delta u(k-1) \tag{5a}$$

where

$$y_{N1}(k-1) = \left[y_1(k|k-1), \quad \cdots, \quad y_1(k+N-1|k-1)\right]^T$$
$$y_{N0}(k-1) = \left[y_0(k|k-1), \quad \cdots, \quad y_0(k+N-1|k-1)\right]^T \tag{5b}$$

$y_{N1}(k-1)$ is the future prediction output at time instant $k-1$ under the effect of control increment $\Delta u(k-1)$, and $y_{N0}(k-1)$ is the initial prediction output at time instant $k-1$; here $k+i|k$ denotes the prediction for time instant $k+i$ made at time instant $k$.

In terms of the obtained future output prediction, we need to correct it because there are uncertainties that cause output prediction error; the correcting method is chosen as follows.

$$y_{cor}(k) = y_{N1}(k-1) + he(k) \tag{6a}$$

where

$$y_{cor}(k) = \left[y_{cor}(k|k), \quad \cdots, \quad y_{cor}(k+N-1|k)\right]^T \tag{6b}$$

$y_{cor}(k)$ is the corrected future prediction output at time instant $k$, $y(k)$ is the actual output of the process at time instant $k$, $e(k)$ is the error between the actual process output and model output prediction at time instant $k$, $h$ is the error correcting vector and $\alpha$ is the error correction coefficient.

For time instant $k$, the elements of $y_{cor}(k)$ need to be shifted to form the initial prediction output, and the shifting process is as follows.

$$y_{N0}(k) = Sy_{cor}(k) \tag{7a}$$

where $S$ is the shifting matrix.

$$S = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 1 \\ 0 & 0 & \cdots & \cdots & 1 \end{bmatrix} \tag{7b}$$

Note that $y_0(k+N|k)$, which is the last element of $y_{N0}(k)$, will be replaced by $y_{cor}(k+N-1|k)$ because of the model cutoff.

After obtaining the initial output prediction at time instant $k$, the future model output prediction under the control increment sequence $\Delta u_M(k) = [\Delta u(k), \cdots, \Delta u(k+M-1)]^T$ can be calculated as follows.

$$y_{PM}(k) = y_{P0}(k) + A\Delta u_M(k) \tag{8a}$$

where

$$y_{PM}(k) = \begin{bmatrix} y_M(k+1|k) \\ \vdots \\ y_M(k+P|k) \end{bmatrix}, y_{P0}(k) = \begin{bmatrix} y_0(k+1|k) \\ \vdots \\ y_0(k+P|k) \end{bmatrix} \tag{8b}$$

$y_{PM}(k)$ is the future output prediction under the effect of $\Delta u_M(k)$ at time instant $k$, and $y_{P0}(k)$ is the initial output prediction at time instant $k$.

In order to simplify the calculation, here the control horizon $M$ is chosen to be 1; then the cost function is

$$\min J(k) = (ref(k) - y_{P1}(k))^T Q(ref(k) - y_{P1}(k)) + r\Delta u^2(k) \tag{9a}$$

where

$$ref(k) = [ref_1(k), ref_2(k), \cdots, ref_P(k)]^T \tag{9b}$$

$$ref_i(k) = \beta^i y(k) + \left(1-\beta^i\right)c(k)$$
$$Q = diag(q_1, q_2, \cdots, q_P) \tag{9c}$$

Here $ref(k)$ is the reference trajectory, $Q$ is the error weighting matrix, $q_1, q_2, \cdots, q_P$ are the coefficients in $Q$, $r$ is the control weighting coefficient, $\beta$ is the smoothing factor of reference trajectory, and $y_{P1}(k)$ is the specific form of $y_{PM}(k)$ in which $M$ is 1.