Fast Predictive Control Algorithm and Its Application to Single-Loop Digital Regulator *

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Abstract: In this paper, a fast predictive control algorithm is presented. It decreases the computation complexity degree and saves the required memory space of predictive control law, and also has good adaptive ability and robustness. The single-loop digital regulator, which is based on the fast generalized predictive control algorithm, has been verified in its application to a industrial process. It has acquired good control performance, hence, it is worthy of being widely used in industrial processes.

Key words: self-tuning control; predictive control; computer control; fast predictive control; single-loop digital controller

快速预测控制算法及在单回路数字控制器中的应用

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摘要: 为使先进的预测控制算法在工业过程单回路数字控制器中方便有效地实现,本文设计了一种快速预测控制算法,降低了控制律在线运行的计算量,减少了算法实现所需的存储空间,且同时具有良好的适应性和鲁棒性.基于此算法的单回路数字控制仪表"广义预测自校正单回路调节器"在工业现场投入试运行,控制效果好,具有广泛的应用推广价值.

关键词: 自校正控制; 预测控制; 计算机控制; 快速预测控制算法; 单回路数字调节器

1 Introduction

In the industrial processes, there generally exist some factors , such as non-linearity, multivariable, coupling, time-varying, large time delay and stochastic disturbance, which make it difficult for the traditional control technology to achieve satisfactory closed loop control quality. With the development of modern control theory, many kinds of advanced control technology have been proposed in the field of controller design.

Among these methods, the model based predictive control (MPC)[1] has excellent performance and has been widely applied in the industrial processes. First of all, let us have a review of the achievements in the development of predictive control. Since Richalet[2] proposed model predictive heuristic control (MPHC), theoretically a lot of new MPC methods have been developed one by one, such as MAC, DMC, EHAC, EPSAC and GPC etc, and in practice, some famous predictive control products, such as IDCOM software and DMC software have been widely used in industrial processes. Because these MPC algorithm are based upon the advanced mechanism of long range prediction, horizon optimization and feedback tuning, the control system can obtain trustable performance. But due to the complex structure of these control algorithms, it requires comparatively large calculation quantity and memory space for the on-line running of these algorithms. Therefore, the successful application of predictive control relies heavily on the computer control system which is possessed of comparatively powerful computation ability, and as a result the application range of the methods is constrained.

Recently, it has become a developing tendency for the industrial process unit controller to realize intelligent digital instrumentation. If we want the predictive control method to be used in a wider range of fields, the methods ought to be modified to be fit for the digital control instrument, so the algorithms need to be simplified both in computing and in space complexity. For this purpose we design a fast predictive control algorithm (FGPC) whose calculation quantity only is $O(n^2)$.

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This paper is aimed at general industrial processes. In the single loop digital regulator hearted by Intel 8098 single chip microcomputer (SCM), FGPC based self-tuning control algorithm is incorporated. The fast calculation speed of FGPC can bring the predictive control technology into the use of fast sampling control system. Data and code occupy less space. Total algorithm only occupies 4.5K ROM. It will save comparatively large memory space for the basic monitoring, interface manipulation and communication function of the digital controller. The whole system has the features of agility and credibility. The digital controller has been plunged into use on the deoxidizing chamber control system of industrial boiler. And good effect has been acquired. This verifies the effectiveness of the fast predictive control algorithm and shows that the generalized predictive self-tuning single loop digital regulator has excellent applicable value.

2 Introduction of fast predictive control algorithm

Consider the following CARIMA model to represent an industrial plant:

$$A(q^{-1})y(t) = B(q^{-1})u(t-1)+\xi(t)/\Delta, \quad \Delta = 1-q^{-1}, \tag{1}$$

where $y(t)$, $u(t)$ and $\xi(t)$ are the output, input and disturbance of the system at current time t, q^{-1} is the backward shift operator, and

$$A(q^{-1}) = 1 + a_1 q^{-1} + \cdots + a_{na}q^{-na},$$

$$B(q^{-1}) = b_0 + b_1 q^{-1} + \cdots + b_{nb}q^{-nb}.$$

The predictive control law to design is based on the following cost function

$$J = E\{\sum_{j=1}^{N}[(y(t+j) - w(t+j))^2 + 2\lambda y_{\Delta u}(t+j)\Delta u(t+j-1) + \lambda^2(\Delta u(t+j-1))^2]\}, \tag{2}$$

where $y_{\Delta u}(t+j)$ represents the zero-state response at time t that refers to the future control increment sequence $\{\Delta u(t+i-1)\}_{i=1}^{j}$, $\lambda(\lambda > 0)$ is a control weighting factor, N is the predictive horizon, $\{w(t+j)\}$ is the smoothed sequence of the set-point, which can be available from the following dynamical equation:

$$w(t) = y(t),$$
$$w(t+j) = \alpha w(t+j-1) + (1-\alpha)y_r(t),$$
$$j = 1,\cdots,N, \tag{3}$$

where $\alpha(0 \leqslant \alpha < 1)$ is a smoothing factor, $y_r(t)$ is the current set point.

The future output of the plant (1) can be expressed as the sum of the zero-input response and two zero-state response, i.e.

$$y(t+j) = y_0(t+j) + y_{\Delta u}(t+j) + y_\xi(t+j), \tag{4}$$

where the zero-input response $y_0(t+j)$ can easily be solved at each sampling time:

$$\begin{cases} A\Delta y_0(t+j) = B\Delta u(t+j-1), \ \Delta u(t+j) = 0, & j > 0, \\ y_0(t+j) = y(t+j), & j \leqslant 0. \end{cases} \tag{5}$$

However, the zero-state response $y_{\Delta u}(t+j)$ and $y_\xi(t+j)$ are in conjunction with the future input increments

$$y_{\Delta u}(t+j) = \sum_{i=0}^{j-1} h_{j-i}^{\Delta u}\Delta u(t+i), \tag{6}$$

$$y_\xi(t+j) = \sum_{i=0}^{j-1} h_{j-i}^{\xi}\xi(t+i+1), \tag{7}$$

with

$$h_k^{\Delta u} = C_u A_m^{k-1} b_u, \quad h_k^\xi = C_\xi A_m^{k-1} b_\xi, \quad k = 1,\cdots,N, \tag{8}$$

$$C_u = [b_{n-1},\cdots,b_0], \quad C_\xi = [0,\cdots,0,1], \tag{9}$$

$$b_u = b_\xi = [0,\cdots,0,1]^{\mathrm{T}}, \tag{10}$$

$$A_m = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ \vdots & & \ddots & 1 \\ \vdots & & & 0 \\ -\bar{a}_n & \cdots & \cdots & -\bar{a}_1 \end{bmatrix}. \tag{11}$$

Alternatively $n = \max(na+1, nb+1)$, $\{\bar{a}_i\}$ and $\{\bar{b}_i\}$ are the coefficients of polynomials A and B, define

$$Y = [y(t+1,\cdots,y(t+N)]^{\mathrm{T}},$$
$$Y_0 = [y_0(t+1),\cdots,y_0(t+N)]^{\mathrm{T}},$$
$$U = [\Delta u(t),\cdots,\Delta u(t+N-1)]^{\mathrm{T}},$$
$$\xi = [\xi(t+1),\cdots,\xi(t+N)]^{\mathrm{T}},$$
$$W = [w(t+1),\cdots,w(t+N)]^{\mathrm{T}},$$

$$G = \begin{bmatrix} h_1^{\Delta u} & 0 & \cdots & 0 \\ h_2^{\Delta u} & h_1^{\Delta u} & \ddots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ h_N^{\Delta u} & h_{N-1}^{\Delta u} & \cdots & h_1^{\Delta u} \end{bmatrix},$$

$$H = \begin{bmatrix} h_1^{\xi} & 0 & \cdots & 0 \\ h_2^{\xi} & h_1^{\xi} & \ddots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ h_N^{\xi} & h_{N-1}^{\xi} & \cdots & h_1^{\xi} \end{bmatrix},$$

then Equation (4) can be rewritten as the vector form

$$Y = Y_0 + GU + H\xi. \qquad (12)$$

Make the assumption that $\{\xi(t)\}$ is a white disturbance sequence with which it can be suggested that $E\{\Delta u(t+i)\xi(t+i)\} = 0$, then the cost function (2) can be reformulated as

$$J = (Y_0 + GU - W)^{\mathrm{T}}(Y_0 + GU - W) + 2\lambda U^{\mathrm{T}}GU + \lambda^2 U^{\mathrm{T}}U + E\xi^{\mathrm{T}}H^{\mathrm{T}}H\xi, \qquad (13)$$

let $\partial J/\partial U = 0$, then the control law can be derived from the minimization of the above cost function

$$U = [(\lambda I + G^{\mathrm{T}})(\lambda I + G^{\mathrm{T}})]^{-1}G^{\mathrm{T}}(W - Y_0). \qquad (14)$$

Note that the first element of U is the current control increment:

$$\Delta u(t) = e_1^{\mathrm{T}}[(\lambda I + G^{\mathrm{T}})(\lambda I + G^{\mathrm{T}})]^{-1}G^{\mathrm{T}}(W - Y_0), \qquad (15)$$

where $e_1^{\mathrm{T}} = [1,0,\cdots,0]_N$.

Technically appreciate that $(\lambda I + G)$ is a lower-triangular Teoplitz matrix, so its inverse is provided with the simple form

$$(\lambda I + G^{\mathrm{T}})^{-1} = F = \begin{bmatrix} f_1 & 0 & \cdots & 0 \\ f_2 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ f_N & \cdots & f_2 & f_1 \end{bmatrix}, \qquad (16)$$

where $\{f_i\}$ is given by

$$\begin{cases} f_1 = (\lambda + h_1^{\Delta u})^{-1}, \\ f_{j+1} = -f_1 \sum_{i=1}^{j} f_i h_{j+2-i}^{\Delta u}, \quad j = 1\cdots N. \end{cases} \qquad (17)$$

At each sampling time, the output and input signals are sampled, and the parameters of plant are updated by an estimator, $\{h_i^{\Delta u}\}$ and $\{f_i\}$ can be calculated according to Equations (3), (5) and (8), yield the control signal $u(t)$ from Equation (15) and output it to the actuator.

3 The implementation of fast predictive self-tuning control algorithm

In view of the real controlled plant, there exist the phenomena of time-varying dynamic, nonlinear and dynamical characteristic moving with set-point. But the generalized predictive single loop regulator is a kind of digital control instrument which is devised for the commonly industrial processes, self-tuning scheme has to be joined to adapt to this complicated situation. An estimated model of plant (1) can be obtained by using time-variant forgetting recursive least square identification method.

$$\hat{A}(q^{-1})\Delta y(t) = \hat{B}(q^{-1}\Delta u(t-1) + \xi(t). \qquad (18)$$

The orders of polynomials $\hat{A}$ and $\hat{B}$ are chosen by field experiment adjustment. One step identification is on-line executed at each sample instant for the estimation of the coefficients of the two polynomials. Then based on the estimated model, the control signal could be calculated through fast predictive control algorithm to form closed loop control. The identification method is time-variant forgetting recursive least square. In order to improve the robustness of the estimator, some modifications, such as data filtering, data normalization and dead zone technology have to be taken account of.

4 Demand analysis for computing resource

In the section, we will make a comparison of the calculation quantity among the three kinds of algorithms. There are GPC[4], RGPC[5] and FGPC. Because the multiplication and division are the most complex basic calculating methods, hence the comparison of the calculation quantity is done in accordance with the required numbers of multiplication and division. The result can be seen in Table 1.

Table 1 The calculation quantity of algorithms

Algorithm	Multiply	Division
GPC	$\frac{3}{2}N_u(N_u+1)N + \frac{1}{2}N(N+1) + N_u + (na+nb+2)N$	$\frac{1}{2}N_u(N_u+1)N$
RGPC	$\frac{1}{2}N_u(NN_u + N_u^2 + 3N + 6N_u - 2) + 2\left(na + nb + \frac{3}{2}\right)N$	N_u
FGPC	$N(N + 2na + 4) + \frac{1}{2}nb(nb-1) - \frac{1}{2}na(na-1) - 1$	1

It is obvious that the calculation quantity of FGPC is decreased from $O(n^3)$ to $O(n^2)$, and thus superior to GPC and RGPC. It is propitious to correct the weakness of large calculation quantity for the inherent self-tuning GPC scheme. In addition, owing to the memory space required by the data and code of the algorithm, the structure of FGPC is concise, the programmed codes are brief. In the implemented digital controller, the codes about control algorithm part only occupy 4.5K ROM, and fewer RAM is used, and only needs to save the vectors of $\{y(t)\}$, $\{u(t)\}$, $\{h_j\}$, $\{f_j\}$, Y_0, W, the memory quantity is only $O(n)$. But the inherent GPC algorithm must save the polynomials of $\{F_j(q^{-1})\}$, $\{G_j(q^{-1})\}$, G and the matrix of $(\lambda I + G^T G)$, the memory quantity is $O(n^2)$. These advantages make for the system exploitation on other functions, such as handling interface and communication.

5 The brief introduction of the digital regulator

The generalized predictive self-tuning single loop regulator is hearted by Intel 8098 SCM. It provides with two 10 bit A/D inputs whose standard can be chosen, one 8 bit D/A output. It communicates with PC microcomputer by using RS485 interface. The least sampling interval could be set just at 0.1 second. The production for electricity turning-off and the function of watchdog can be provided. The information display on the faceplate is clear and particular. There is a small numeric keypad which can be inserted in and pulled out of the regulator under electrification, with which the adjustment of tuning-knobs, the modification of set-point and other manipulations can be accomplished. The standardization instrument shell is utilized. The installation and debugging for the system is brief and convenient. The running is safe and credible.

6 Application on industrial process

The digital control instrument has been plunged into use on a 20T/h industrial boiler plant in Tianjin Hebei pharmacy factory. This factory is a fermentation pharmacy enterprise. The steam plays a key role in ensuring the normal production. In the course of production, because the steam requirement of each workshop is largely waved, it often leads the whole boiler plant to fall in the state of large burden fluctuated, therefore the control on the water system of the boiler becomes an essential part to ensure safe production.

The digital controller has been used in the water height process of deoxidizing chamber of the boiler. The workflow of the system can be seen in Fig. 1. The controlled variable is the water height (denoted by H) of the deoxidizing chamber and the control variable is the location of the entering-water valve (denoted by EV). The backwater valve (denoted by BV) is used to adjust the water pressure P, and that the supplying-water valves of 1st boiler and 2st boiler, which are denoted by SV1 and SV2, are used to keep the water heights of the two boilers respectively. There are several kinds of disturbances to affect the water height of deoxidizing chamber. The change of BV, SV1 and SV2 would influence the dynamical characteristic of the plant. The valve EV have some nonlinear factors, such as dead zone and extraction characteristic, thus it is expected to achieve the better dynamic and static performance of the control system by utilizing adaptive predictive controller.

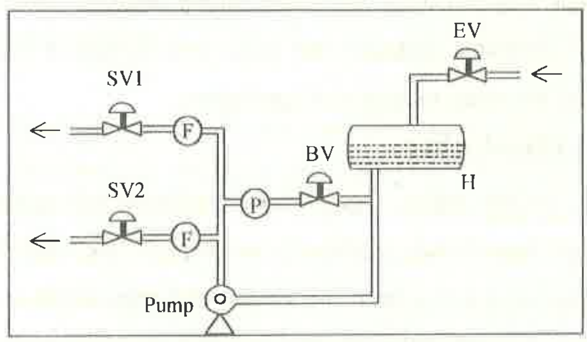

Fig. 1 The workflow of the deoxidizing chamber plant

The digital controller has been verified in the complicated and ever-changing working conditions of the industrial fields, and has proved to be good in performance. Fig. 2 and Fig. 3 are the real time curves of controlled variable y (water height of deoxidizing chamber) and control variable u (entering-water valve of the deoxidizing valve) at the 10% change of set point. Fig. 4 and Fig. 5 are the real time curves of y and u at a large disturbance work of situation in the 20-minute period of the load burden change caused by 1st boiler shutdown then restart. The sampling interval was selected as 2 seconds. The model orders are selected as $na = 2$, $nb = 3$, predictive horizon $N = 5$, $\lambda = 0.3$ and $\alpha = 0.5$.

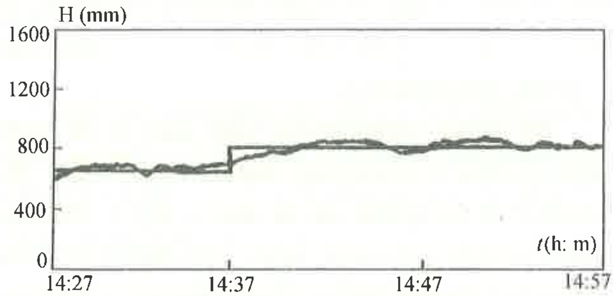

Fig. 2 The real-time curve of the water height of deoxidizing chamber (controlled variable y) in case of set point change

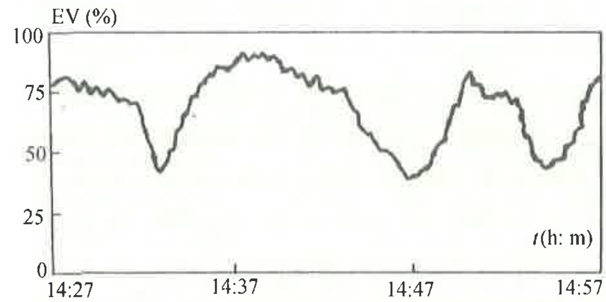

Fig. 3 The real-time curve of the entering-water valve of deoxidizing chamber (control variable u) in case of set-point change

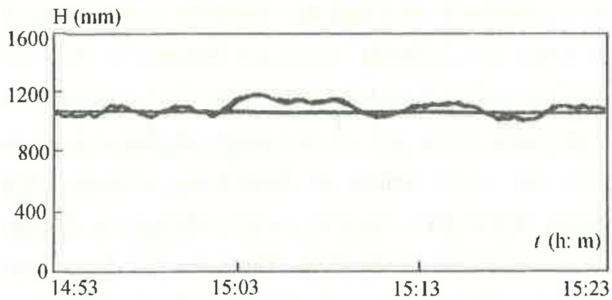

Fig. 4 The real-time curve of the water height of deoxidizing chamber (controlled variable y) in case of large disturbance

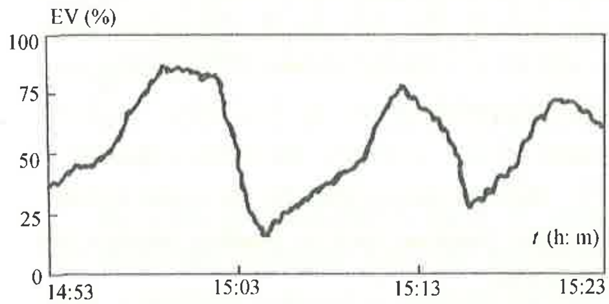

Fig. 5 The real-time curve of the entering-water valve of deoxidizing chamber (control variable u) in case of large disturbance

As is shown by the effect of practical running, the single loop regulator has rather strong adaptive ability and preferable dynamic and static performance, it can meet the needs of industrial application.

7 Conclusion

In this paper, a generalized predictive self-tuning single loop digital regulator is investigated. The control algorithm is a fast predictive control algorithm which requires less calculating quantity and memory space. It enables this kind of advanced control technology (generalized predictive) to be expediently implemented on the digital control instrument which is based upon Intel 8098 SCM. Undoubtedly, that will extend the applicable range of predictive control. The industrial application has demonstrated that the digital controller is not only able to overcome the burden load disturbance, but also can be adaptive to the characteristic of time-variant and nonlinear dynamics. Accordingly, it has the applicable value.

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