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An Improved PID controller Design based on Model Predictive Control for a Shell and Tube Heat Exchanger

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Abstract: In this paper an algorithm of PID controller based on model predictive control is designed for a shell and tube heat exchanger. PID controllers and model predictive controls are two control algorithm mostly used these types of process applications. The three parameters of PID controller must be tuned to the process to obtain a satisfactory closed loop process performance. The model of the heat exchanger is identified by using principles and empirical method. The proposed PID algorithm is used for controlling a temperature of a shell and tube heat exchanger. The results of the proposed controller are compared with conventional PID and model predictive control. The result shows that the PID controller based on model predictive control gives excellent performance.

Key words: Heat Exchanger, MPC, PID Control, Temperature Control, Tuning.

INTRODUCTION

In most of the industrial applications which make use of major power plants, chemical and nuclear reactor etc; accurate results and response of heat exchanger are necessary. The heat exchanger is a device which transfers the heat energy between a hot and cold fluid through a solid surface or material. There are various types of heat exchangers used in industries. Most commonly used and one among them is shell and tube heat exchanger. It consists of parallel tubes enclosed in a shell and it maintain appropriate temperature of the liquid which is possible by varying the outlet temperature of the liquid with respect to varying temperature and atmospheric conditions. The efficiency of the heat exchanger depends upon the load, basic characteristics of the fluid etc. The main aim of the heat exchanger is to maintain specific temperature which is achieved by controlling the exit temperature of one of the fluids in the response to variations of the operating conditions.

PID and MPC are two control algorithms widely used in industrial applications. PID control is simple in principle, easy to tune and implement in engineering, which is still widely used in industrial process control. Many advanced control method techniques are based on a PID control algorithm. But the conventional PID control algorithm cannot achieve ideal control effect in any practical production process with nonlinear and time varying uncertainty. There is strong evidence that PID controllers remain poorly understood and in particular, poorly tuned many applications. It is clear that the many tuning rules proposed in the literature are not having an impact on industrial practice. The ability of PID controllers to compensate most practical industrial process applications has led to their wide acceptance in industrial applications. Many tuning methods were proposed for PID controllers, one among them is Ziegler and Nichols tuning proposed in the year 1942. Using this Ziegler and Nichols tuning the parameters were obtained was used for temperature control for shell and tube heat exchanger. Simplicity and efficiency of this algorithm help to combine with commercial controllers, which have been proposed and successfully implemented to process applications. Using PID controllers for these applications, control algorithm cannot achieve the ideal control effect, in order to solve these problems, people explore the predictive PID controller, and introducing steady state error weighted items into predictive control performance index in a broad sense. The predictive control algorithm is reconstructed according to PID control algorithm. It means that the predictive control algorithm is decomposed as PID form and then the PID controller has a predictive function.

MATERIALS AND METHODS

Model Predictive Control:

Model predictive control (MPC) refers to a class of computer control algorithms that make the most of an explicit process model to predict the future response of a plant. At each control period an MPC algorithm efforts to optimize future plant behavior by computing a progression of future manipulated variable adjustments. The first input in the optimal sequence is then sent into the plant, and the entire calculation is repeated at subsequent control intervals. Originally developed to meet the specialized control needs of power plants and petroleum refineries, MPC technology can now be found in a wide variety of application areas including chemicals, food processing, automotive, and aerospace applications.

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Structure of MPC:

The term MPC describes a class of computer control algorithms that control the future behavior of the plant through the use of an explicit process model. At each control interval the MPC algorithm computes an open-loop sequence of manipulated variable adjustments in order to optimize future plant behavior. The first input in the optimal sequence is injected into the plant, and the entire optimization is repeated at subsequent control intervals (Henson, 1998). MPC technology was originally developed for power plants and petroleum refinery applications. However, at present MPC is used in a wide variety of manufacturing environments including chemicals, food processing, automotive, aerospace, metallurgy, and pulp and paper (Qin and Badgewell, 1998).

The success of MPC technology as a process control paradigm can be attributed to three important factors. First and foremost is the incorporation of an explicit process model into the control calculation. This allows the controller, in principle, to deal directly with all significant features of the process dynamics.

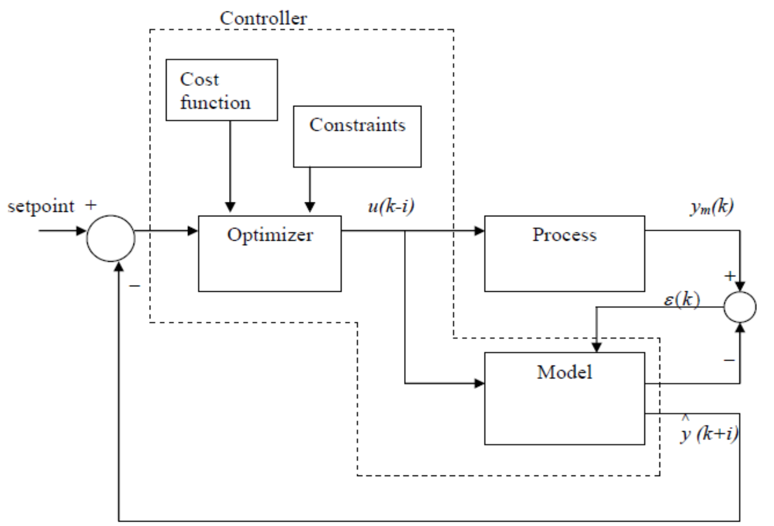

Fig. 1: Model Predictive Controller.

Secondly the MPC algorithm considers plant behavior over a future horizon in time. This means that the effects of feed forward and feedback disturbances can be anticipated and removed, allowing the controller to drive the plant more closely along a desired future trajectory. Finally the MPC controller considers process input, state and output constraints directly in the control calculation. This means that constraint violations are far less likely, resulting in tighter control at the optimal constrained steady-state in the process. It is the inclusion of constraints that most clearly distinguishes MPC from other process control techniques (Qin and Badgwell, 2003).

MPC is an advanced control algorithm based on model, which is divided into different types according to the different model it used, such as Dynamic Matrix control (DMC), Model Algorithmic Control (MAC), Generalized Predictive Control (GPC) and Internal Model Control (IMC) etc.

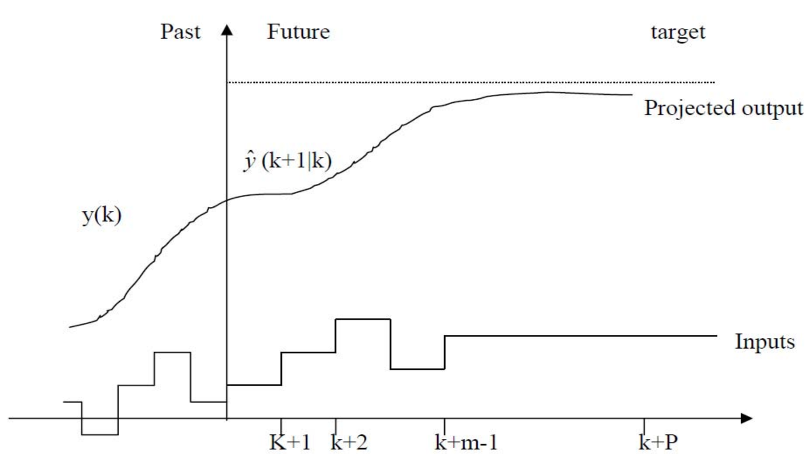

Fig. 2: Moving horizon approach of Model Predictive Controller.

MPC refers to a family of controllers that employ a distinctly identifiable model of the process to predict its future behavior over an extended prediction horizon. A performance objective to be minimized is defined over the prediction horizon, usually as a sum of quadratic set point tracking error and control effort terms. This cost function is minimized by evaluating a profile of the manipulated input moves to be implemented at successive sampling instants over the control horizon. Closed loop optimal feedback is achieved by implementing only the first manipulated input move and repeating the complete sequence of steps at the subsequent sample time. This “moving horizon” concept of MPC, where the controller looks a finite time into the future, is illustrated in Fig. 1: and Fig. 2:

PID And Predictive Control:

The PID controller is widely applied in industrial field. Apart from its simple structure and relatively easy tuning, one of the main reasons for its popularity is that it provides the ability to remove offset by using integral action. It improves the performance of the robustness in the steady state against noise and uncertainties. Moreover, since PID controllers are so widely used, one might expect that the structure should arise naturally given reasonable assumptions on system internal dynamics and control performance specifications. Model predictive control is a family of controllers that employ a distinctly identifiable model of the process to predict its future behavior over an extended prediction horizon. A performance objective to be minimized is defined over the prediction horizon, usually as a sum of quadratic set point tracking error and control effort terms. This cost function is minimized by evaluating a profile of the manipulated input moves to be implemented at successive instants over control horizon.

This idea behind predictive control is at each iteration to minimize a criterion of the following type,

$$J\left(t,\ u(t) \right) = [\sum_{t=N}^{P} r\left(t+i\right) - Y\left(t+i\right)]^2 + P\sum_{i}^{M} \Delta u\left(t+i-1\right)^2 \tag{1}$$

Where, Y= Prediction of output, u = Control input, Δ = Difference operator N = minimum cost horizon, P = Prediction horizon, M = Control horizon.

Model Algorthmic Control:

PID controller is still one of the most extensive applications of conventional control algorithm in industrial process control. It is combined proportional, integral and derivative of feedback system deviation. MAC control algorithm with the model of unit pulse response ($\{hi\}(i=1,2,...)$) optimizes control system by model predicting, rolling optimization online and feedback revising. The best excellence of MAC is that it puts the estate, hard control constraints and random disturbances into target function directly to optimize the control system. The algorithm deals with the constraints and disturbances systematically and distinctly. The MAC control algorithm is applicable in asymptotical stationary linear system for its simple model, less calculation and robustness in performance.

Consider the quadratic performance index:

$$J = \left\| Y_d(k+1) - \hat{Y}(k+1) \right\|^2 + \left\| U(k) \right\|_R^2 \tag{2}$$

Where, $Y_d(k+1)$ is desired output vector, $\hat{Y}(k+1)$ is output estimation value in the future P steps, $U(k) = [u(k),....,u(k+P-1)]^T$ is the control matrix, R is control weighted matrix.

Control system predictive state space model is:

$$X(k+1) = AX(k) + Bu(k) \tag{3}$$

$$y(k) = CX(k) \tag{4}$$

Where, $X(k) = [x_1(k),....,x_n(k)]^T$ is the state vector, $A = \begin{vmatrix} 0 & 1 & . & 0 \\ 0 & 0 & 1 & 0 \\ . & . & . & 1 \\ 0 & . & . & 0 \end{vmatrix}_{N*N}$,

$u(k) = K1[Y_d(k+1) - \hat{Y}_0(k+1)]$ $B = \begin{vmatrix} h_1 \\ h_2 \\ . \\ h_N \end{vmatrix}_{N*1}$ $, C = \begin{vmatrix} 1 & 0 & . & 0 \end{vmatrix}_N$ are coefficients matrixes.

Minimizing the performance index function, we get the instantaneous control input:

$$u(k) = K1[Y_d(k+1) - \hat{Y}_0(k+1)] \tag{5}$$

Model based Predictive PID Controller:

PID control is combined with MAC control for the sake of improving the control performance of the control system. By introducing proportion, integral and differential into the new objective function, the structure of the deduced controller is characterized by general proportion, integral and differential. The new performance index has generalized structure of proportion, integral and differential.

$$J = \sum^{P} \left(K_i[e(k+1)]^2 + K_P[\Delta e(k+1)]^2 + K_d[\Delta^2 e(k+1)]^2 \right) + \lambda u^2(k) \tag{6}$$

Where,

$$e(k+1) = Y_d(k+1) - \hat{Y}(k+1) \tag{7}$$

Then $e(k) = Y_d(k) - \hat{Y}_0(k) - A_2 U(k-1)$ (8)

According to the formula (7) and formula (8), we can get,

$$\Delta e(k+1) = e(k+1) - e(k) = \Delta Y_d(k+1) - \Delta \hat{Y}_0(k+1) - [A_2 U(k) - A_2 U(k-1)] \tag{9}$$

Then

$$\Delta e(k) = \Delta Y_d(k) - \Delta \hat{Y}_0(k) - [A_2 U(k-1) - A_2 U(k-2)] \tag{10}$$

From formula (9) and (10), we get as follows:

$$\Delta^2 e(k) = \Delta^2 Y_d(k+1) - \Delta^2 \hat{Y}_0(k+1) - [A_2 U(k) - 2A_2 U(k-1) + A_2 U(k-2)] \tag{11}$$

To facilitate the derivation, vectors and matrixes are introduced as follows:

$$Y_d = [y_d(k+1), ..., y_d(k+P)]^T \tag{12}$$

$$\Delta Y_d = [y_d(k+1), ..., y_d(k+P)]^T$$

$$\Delta^2 Y_d = [y_d(k+1), \Delta y_d(k+2) - y_d(k+1), \Delta^2 y_d(k+3), ..., \Delta^2 y_d(k+P)]^T$$

$$\hat{Y}_0 = [\hat{y}_0(k+1), ..., \hat{y}_0(k+P)]^T$$

$$\Delta \hat{Y}_0 = [\hat{y}_0(k+1), \Delta \hat{Y}_0(k+2) ...., \Delta \hat{y}_0(k+P)]^T$$

$$\Delta^2\hat{Y}_0 = [\hat{y}_0(k+1), \Delta\hat{Y}_0(k+2) - \hat{y}_0(k+1), \Delta^2\hat{y}_0(k+3)...., \Delta\hat{y}_0(k+P)]^T$$

$$e = [e(k+1),...., e(k+P)]^T$$

$$\Delta e = [e(k+1), \Delta e(k+2)...., \Delta e(k+P)]^T$$

$$\Delta^2 e = [e(k+1), \Delta e(k+2)...., \Delta^2 e(k+P)]^T$$

According to the vectors and matrixes above, we can derive modified performance index as below:

$$J = K_i e^T e + K_p \Delta e^T \Delta e + K_d \Delta^2 e^T \Delta^2 e + \lambda U^T U \quad (13)$$

Experimental Results and Discussions:

The shell and tube heat exchanger is made of mild steel and consists of outside shell diameter of 0.15m and 32 inner tubes of outer diameter 0.0125m with square pitch arrangement. Four baffles with 0.1m baffle spacing are used. The experiments are carried out with 1-1 pass with both parallel and counter flow patterns with cold fluid in shell side and hot fluid in tube side. The centrifugal pump of 0.5HP, water softener, and Rotameter and storage vessel of 100 liter capacity is installed for carrying out the experiment.

The temperature control experiment is conducted in the actual heat exchanger system following the principles simplified in Fig. 3: Before starting the experiment, the heat exchanger is washed with water. The stored cold fluid was pressurized to the tube side of the equipment using a centrifugal pump. The flow control was achieved by Rotameter connected between the pump and the heat exchanger . A control valve controls the fluid to the tube. The overhead tank was filled with water and the heater was switched on and heated till the temperature reaches 90°C. The inlet of cold fluid was noted and then the cold fluid was opened.

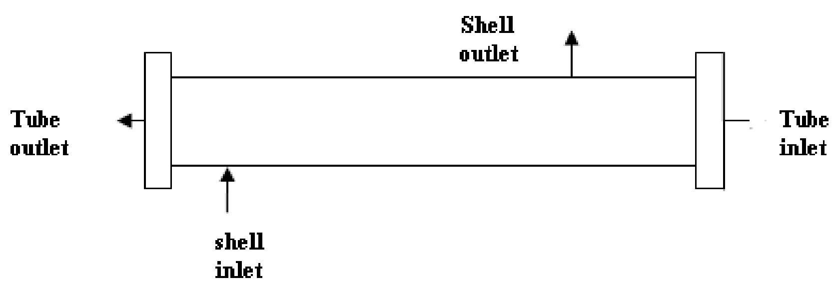

Fig. 3: Shell and Tube heat exchanger.

The pump was started and the required water flow rate of the cold fluid was fixed using Rotameter. The hot fluid inlet valve was opened and it waited until the steady state has been reached. At steady state, all four temperatures and flow rates of cold fluid and hot fluid do not change. Using this procedure we determined the model of the heat exchanger and it can fit to be a first order plus dead time (FOPDT). The experimental data were fitted and the transfer function is given in equation (14)

$$G(s) = \frac{1}{1+20s} e^{-0.26s} \quad (14)$$

For the identified transfer function, the PID parameters tuned by Ziegler's-Nichol (ZN), IMC and MPC are obtained and given in the Table 1:

Table 1: Tuning methods of PID controller parameters.

Tuning method of PID	K	TI	Td	Tf
Zieglers-Nichol	1.33	31	7.74	-
MPC	0.467	18.44	0.005	0.539

In this table we use predictive length and control length of the predictive control are *P=8* and *C=1*. The control effects of the 2 groups tuning method of PID are shown in the Fig. 4.

Fig. 4: shows that the PID parameters tuned by the predictive control algorithm is not superior to the other methods. On the contrary, a predictive control algorithm needs a large weight value of input increment; otherwise the system will be concussion or even divergent. The result is that the response speed of the PID controller is slow.

The manipulated variable and outputs are obtained, by setting Controller sampling interval as 0.3, prediction horizon as 48 and Control horizon as 12 and given in the Fig. 5: and Fig. 6:

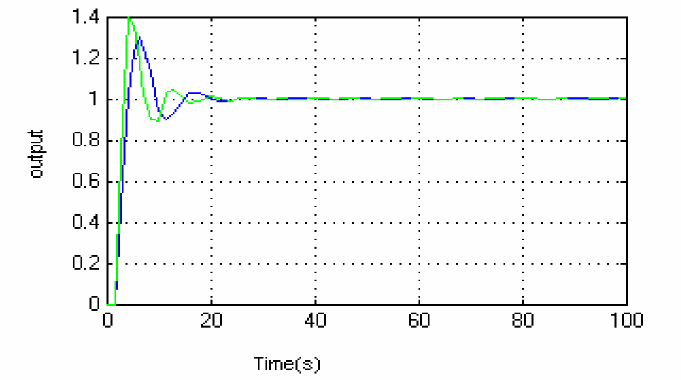

Fig. 4: Comparison control effects of PID controller with different parameters.

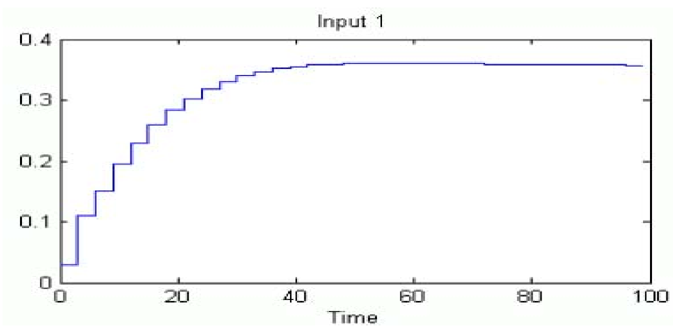

Fig. 5: Manipulated variable of the MPC.

From the output response of shell and tube heat exchange it was observed that MPC had almost eliminated the overshoot when compared to PI controller which shows a 10.2% overshoot. The settling time was observed to be very less for a MPC and the performance was much faster also.

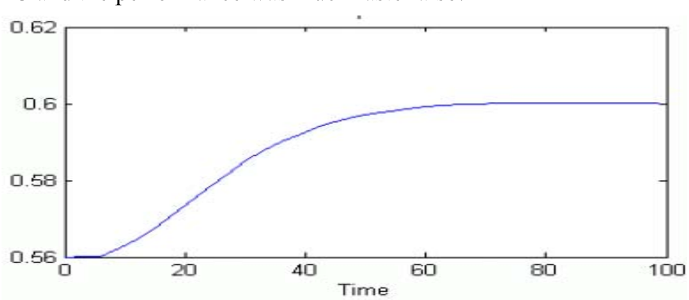

Fig. 6: Output of MPC.

Conclusions:

This paper emphasizes on the temperature control aspect of shell and tube heat exchanger. Using a model based predictive controller for temperature control, it reduces the computational complexities and softens the input signals by constraining the rolling optimization sequence of the controller. The experimental and simulation results show that the proposed system obtains a good control effect and can satisfy the requirements of temperature control of shell and tube heat exchanger. Through simulation, the approach has been shown to be very effective for first order plus dead time processes. Compared with conventional controllers the simplified predictive controller is more robust to the process variation.

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