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An IMC-DMC Control for Heat Exchanger Process

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ABSTRACT

In this paper, a novel method to eliminate the steady-state offset that is encountered when dealing with load change occurs in processes is proposed for identified heat exchanger process model. The algorithm proposed is based on the fact that DMC algorithm is equivalent to an IMC structure. Then we can improve conventional DMC using a modified IMC structure to remove the offset. A simulation result shows the effectiveness of modified control algorithm.

Categories and Subject Descriptors

MATLAB, SIMULINK and Model predictive toolbox

General Terms

Algorithms, Performance, Design, predictive control. Transfer function, controlller

Keywords

Dynamic matrix control (DMC), Internal model control (IMC).

1. INTRODUCTION

We know that DMC [l] has been one of the most popular advanced control strategy used in process industry because it is simple, intuitive and allows the formation of the predictive vector in a natural way. But conventional DMC [1] is only suitable for stable processes, not non-self-regulating processes because a steady-state offset occurs. for sustained load disturbance, which is not generally acceptable in practice, in [2] the authors indicate that the conventional DMC algorithm implies "the difference between the measured and the predicted output can be modeled as a step disturbance acting on the output".

This is why conventional DMC does have bad performance when a step input disturbance acts on a process. Therefore, A very direct idea to handle offset problem is using more suitable disturbance model, this is motivated by a modified Internal Model Control (IMC) structure for unstable system reported recently in [3]. As is well known, conventional DMC algorithm can be equivalent to an IMC structure [4]. Note that there is an offset when IMC structure is used for an integrating system. Then the offset of conventional DMC can be also regarded as a drawback of IMC structure. So a modified IMC structure can be used to improve the conventional DMC algorithm to attain good disturbance rejection. The rest of the paper arranged is as follows. The steady-state offset of conventional DMC for process is described, and then a modified IMC structure and corresponding DMC structure are presented. Subsequently a compensator (Proportional) and the modified DMC algorithm are proposed. Finally several simulations show that the technique is eflective and the designed compensator has a good robustness.

2. FORMULATION OF DMC

The step response coefficients of DMC used are $a\ 1 ,... ,a\ \ 2\ )..,.\ a\ \ m$ for a process, where m is truncated horizon, the predictive output of the process at time t can be described by the following step response model [5]

$$y(t/t)=\sum_{k=1}^{\infty} a(k)\Delta u(t-k) \qquad (1)$$

Where u is control input of the process. The predictive output $y(t+l/t)$ at time $t+1$ will be:

$$y(t+l/t)=\sum_{k=1}^{\infty} a(k)\Delta u(t+l-k)+d(t+l/t)$$

$$=\sum_{k=1}^{\infty} a(k)\Delta u(t+l-k)+\sum_{k=l+1}^{\infty} a(k)\Delta u(t+l-k)+d(t+l/t) \qquad (2)$$

Where $d\ \ t+l/t$ the predictive error at a time $t + l$.It is estimated by the predictive error at time t.

$$d(t+1/t)=d(t/t)=y_m(t)-y(t/t) \qquad (3)$$

Where $y_m\ \ t$ is the measurement of the output y at time t therefore,

$$y(t+l/t)=\sum_{k=1}^{l} a(k)\Delta u(t+l-k)+y_m(t)+\sum_{k=1}^{\infty}[a(k+l)-a(k)\Delta u(t-k) \qquad (4)$$

Let

$$y_0(t+l/t)=y_m(t)+\sum_{k=1}^{\infty}[a(k+l)-a(k)\Delta u(t-k) \qquad (5)$$

For the integrating process the step response is a straight line after truncated horizon that is to stay $a\ \ N+1\ -a\ \ N\ \ =a\ \ N+2\ \ -a\ \ N-1\ \ =\ldots\ldots h$

Where h is constant so we can get.

$$y_0(t+l/t)=y_m(t)+\sum_{k=1}^{N}[a(k+l)-a(k)]\Delta u(t-k)+lhu(t-N-1) \qquad (6)$$

And $y_0(t+l/t)$ is predicted value of the output at time $t+l$ due to past control moves which usually called the free response.

Consider control horizon M, prediction horizon p and move suppression λ let the control signal is given by,

$$C = (A^T A + \lambda \mathrm{A})^{-1} \mathrm{A}^T \quad (7)$$

Where A is dynamic matrix described by

$$A = \begin{bmatrix} a(1) & 0 & 0 \\ a(M) & 0 & \mathrm{a}(1) \\ .. .. .. & & \\ a(p) & 0.... & \mathrm{a(p\text{-}M+1)} \end{bmatrix} \quad (8)$$

And it is obtained from step response coefficient of process model. So we can calculate first control move of DMC algorithm

$$\Delta \mathrm{u(t)} = \sum_{i=1}^{p} C_i e_c(t+i) \quad (9)$$

$$e_c(t+i) = y_{sp} - y_0(t+i/t) \quad (10)$$

Where C_i represents the i[th] element in the first row of C ,$e_c(t+i)$ represents the error at the i[th] step that needs to be compensated and y_{sp} is desired constant value of output.
Combining (6). (9), (10) we get,

$$\Delta \mathrm{u(t)} = \sum_{i=1}^{p} c_i [\, y_{sp} - y_0(t+i/t)]$$

$$= \sum_{i=1}^{p} c_i [\, y_{sp} - y_0(t)] - \sum_{k=1}^{N} [\, a(k+i) - a(k) \Delta u(t-k) + ihu(t-N-1)$$

Where

$$= b_0 e(t) - \sum_{k=1}^{N} b_k \Delta u(t-k) - b_{N+1} u(t-N-1) \quad (11)$$

$$b_0 = \sum_{i=1}^{P} c_i$$

$$b_k = \sum_{k=1}^{P} c_i [\, a(i+k) - a(k)], k = 1,2,.....N$$

$$b_{N+1} = h \sum_{k=1}^{N} i c_i \quad (12)$$

And it is obvious

$\Delta u(t-k) = u(t-k) - u(t-k-1)$ Substituting this equation in (11) and taking z transform of both sides the transfer function of the DMC controller can be derived.

$$D(z) = \frac{b_0}{1 + (b_1 - 1) z^{-1} + \sum_{k=1}^{N} (b_{k+1} - b_k) z^{-k-1}} \quad (13)$$

Now consider load disturbance d_1 of the control closed loop system described in Fig. **1.** For process $G_p(s)$,

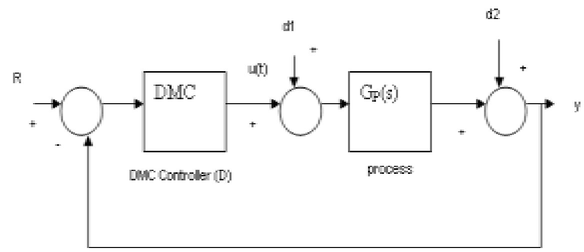

Fig1. DMC closed loop control system

2.1 Modified IMC Structure

The internal model control (IMC) with additional k1 is shown in fig. 2, which is modified IMC structure

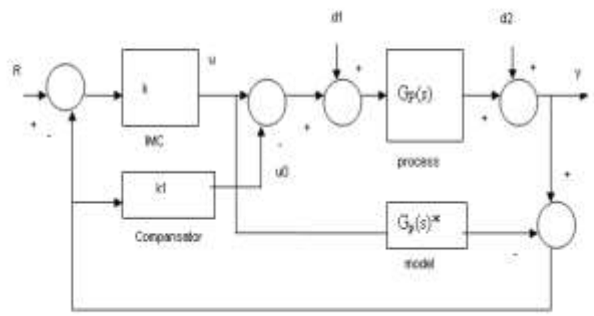

Fig. 2 Modfled IMC structure

To derive the transfer function considering that the plant model is perfect, i.e., $G_P(s) = G_p(s)^*$ we can derive the transfer function from R, $\boldsymbol{d_1}$, $\boldsymbol{d_2}$, to **y**

$$y = G_p(s) K R + (1 - G_p(s) K) \frac{G_p(s)}{1 + G_p(s) K_1} d_1 + (1 - G_p(s) K) \frac{1}{1 + G_p(s) K_1} d_2 \quad (14)$$

Where K is an IMC controller for $G_p(s)$ and the compensator K_1, is newly introduced. When k_1, =o, namely when the modified IMC structure reduces to conventional IMC structure, it is well known that the closed loop system can have good tracking performance and disturbance rejection for stable process.

2.2 Modified DMC Structure

Since conventional DMC algorithm is equivalent to an IMC structure, it is reasonable to use the previous modified IMC structure to improve DMC algorithm to eliminate the offset for processes On the basis of the modified IMC structure in the previous section, a modified DMC structure is shown in Fig. 3.

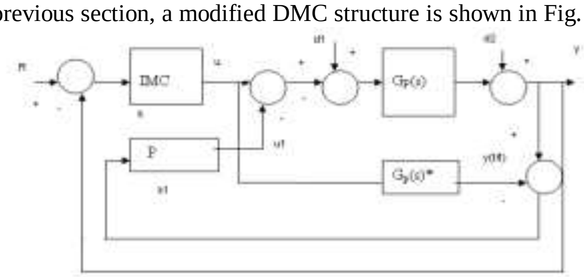

Fig.3 Modified DMC Structure

An internal model structure is introduced in new DMC Framework, which acts on the process through the compensator $K1$ the transfer function can he derived from r, d_1, d_2 to Y

$$y = \frac{GD}{1+G_p(s)D}R + \frac{G}{(1+G_p(s)D)(1+G_p(s)K_1)}d_1 + \frac{1}{(1+G_p(s)D)(1+G_p(s)K_1)}d_2 \quad (15)$$

From the equation (15), similar to the compensator K_1 the tracking performance in closed-loop system does not depend on K_1, and moreover a suitable design of K_1, will also eliminate the steady-state offset .In the modified DMC framework, the output response of the closed-loop system for a step disturbance d_1, can be given
as follows:

$$H(z) = \frac{1}{1-z^{-1}}\frac{1}{1+G(z)D(z)}\frac{G(z)}{1+G(z)K_1(z)} ----(16)$$

Comparing (16) with (15), it is not difficult to find that if the Compensator K_1, introduced can guarantee the last term in (16), to be stable the offset will become zero.
This is same as the compensator K_1 in the modified IMC structure

2.3 Calculation of K_1

It is observed from above modified IMC compensator K_1 has no influence on tracking performance of the closed loop system when the model is perfect, so their design can be independent of the DMC (IMC) controller and its main function is to reject disturbance. From transfer function (14), (16), we can sec that a suitable design should consider following two aspects.
1. It cannot affect the stability of the closed loop system, which requires guaranteeing $\frac{G_p(s)}{1+G_p(s)K_1}$ stable, and this is also the condition to remove the offset.
2. The rejection performance of output disturbance d_2, should he taken into account.

3 HEAT EXCHANGER PROCESS AND MODEL IDENTIFICTION

The identification of the heat exchanger model is carried out using following steps

3.1 Heat Exchanger Process

A chemical reactor called "stirring tank" is shown Fig.4. The top inlet delivers liquid to be mixed in the tank. The tank liquid must be maintained at a constant Temperature by varying the amount of steam supplied to the heat exchanger (bottom pipe) via its control valve. Variations in the temperature of the inlet flow are the main source of disturbances in this process.

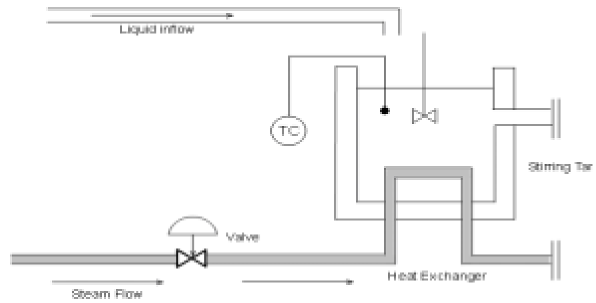

Fig. 4 Stirring Reactor with Heat Exchanger

3.2 Model Identification

Using Measured Data to Model the Heat Exchanger Dynamics and to derive a first-order-plus-dead time model of the heat exchanger characteristics inject a step disturbance in valve voltage V and record the effect on the tank temperature T over time. The measured response in normalized units is shown in fig.5.

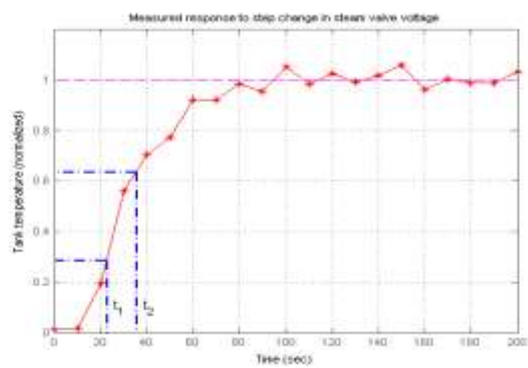

Fig. 5 Effect of step disturbance at valve and output temperature

The values t1 and t2 are the times where the response attains 28.3% and 63.2% of its final value. We have used these values to estimate the time constant τ and t_d, θ for the heat exchanger:

$$t_1 = 21.8; \; t2 = 36.0;$$
$$\tau = 3/2 * (t_2 - t_1)$$
$$\theta = t_2 - \tau$$
$$\tau = 21.3000, \theta = 14.7000$$

The above data calculated is used to build the transfer function of heat exchanger given by,

$$G_p(s) = \exp -\theta * s \; / \; 1 + \tau * s$$

$$G_p(s) = \frac{e^{-14.7s}}{21.3s+1} \quad (17)$$

A similar bump test experiment could be conducted to estimate the first-order response to a step disturbance in inflow temperature. The disturbance model obtained is given by,

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

Consider the mathematical model of heat exchanger given by (17) and using first order pade approximation it is converted into

$$G_p(s) = \frac{-s + 0.1361}{21.3\ s^2\ + 3.898\ s + 0.1361} \tag{18}$$

Then a simple IMC controller for such a process will be obtained by using following steps

1. Factorize the process model into good and bad part this factorization will be carried out for checking the resulting controller will be stable or not.
2. From idealized IMC controller the IMC is the inverse of good portion of process model.
3. to make the controller proper ad a filter having the transfer function

$$F(s) = \frac{1}{(\lambda s+1)^n} \tag{19}$$

Where n is chosen in such way that the controller will be proper. The IMC obtained using the above steps is given by,

$$k(s) = \frac{(21.3s+1)}{(\lambda s+1)} \tag{20}$$

Where λ is **a** tuning parameter of IMC controller. If λ is small the response is fast and if it is large the system will be more robust and insensitive to model errors.

4. DMC ALGORITHM

If compensator k_1 is constant the IMC structure will be easily converted into DMC controller. From step response model of DMC the output of the process at a time *t-1* can be described by

$$\text{y(t -1/t-1)}=\sum_{k=1}^{\infty} a(k)\Delta u(t-1-k) \tag{21}$$

From equation (1) and (19) we can find out IMC at time *t*

$$\text{y(t/t)=y(t-1/t-1)+a(1)}\Delta\text{u(t-1)}+\sum_{k=2}^{N}[a(k)-a(k-1)\Delta u(t-k)+hu(t-N-1) \tag{22}$$

Therefore the Following steps are used to carry out the simulation using DMC.

1. Obtain the response of process using DMC alone. Considering step response model of process. We have calculated different tuning parameters of DMC controller to eliminate the offset due to load disturbances d_1 and output disturbance d_2.

1. Obtain the response of process using IMC controller alone with tuning parameter **λ** for different values of *k1*.

2 use the modified IMC controller to eliminate the offset for change in load with compensator.

5. We applied the above combination for FOPD model for different time delay and time constant and it is observed that the above controller gives excellent results i.e. the offset is eliminated for load and output disturbance.

5 SIMULATIONS

In this section the Simulation of heat exchanger model is presented to illustrate the performance of the modified DMC algorithm.

5.1 Performance of DMC

Fig 6 shows the output response with DMC alone for process considering load disturbance and output disturbance. From figure it is observed that that offset is not removed completely.

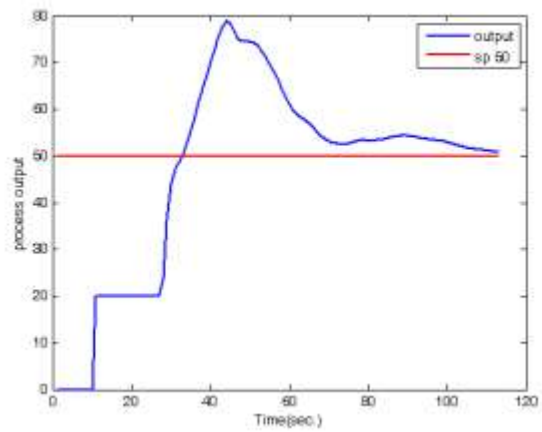

Fig.6 Output response for DMC controller for step input with load disturbance and output disturbance

5.2 Performance of IMC

Fig 7 shows the output response with IMC alone for process considering load disturbance and output disturbance

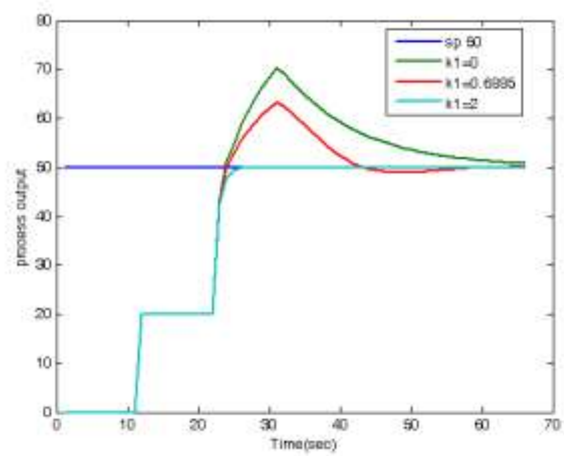

Fig.7 Output response for IMC controller for step input different k1 with load disturbance and output disturbance

5.3 Performance of Modified DMC

Fig 8 shows the output response with Modified DMC controller for process considering load disturbance and output disturbance To test the performance of the control system, suppose the set point *R* has a step change of magnitude *50* at *t = 1*, output disturbance $d2$ has a step change of magnitude 40 at $t = 0.5$ and load disturbance d_2 has a step change of magnitude 1 at $l = 20$, the time response is shown in Fig. 8.

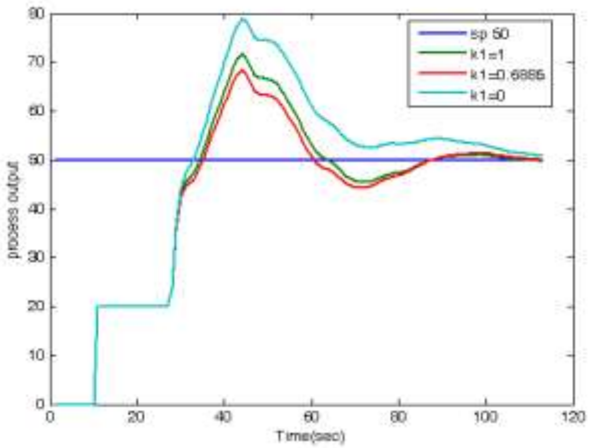

Fig.8 Output response for for modified DMC controller for different k1 for set point of 50 O_c with load disturbance and output disturbance

We **can also** obtain the response of conventional DMC controller that is K_1 = o and the responses in the case of $K_1 = 1$ and $K_1 = 0$. 0.6885. From Fig. 8, a larger K_1 can reject the disturbance d_1, better, but the performance to reject disturbance d_2, becomes worse. Likewise, a smaller K_1 will go against rejecting disturbance d_1 When $K_1 = 1$ we can obtain a good tradeoff between the performance to reject d_1 and d_2, the other parameters of DMC controller used are $N = 60$, $T = 1$, $P=60$, $\lambda=o.1$, $M = 6$.

Fig 9 shows the lactations of poles and zeros of modified DMC controllers for heat exchanger process and it is observer that the designed controller gives good stability for load disturbance and output disturbance

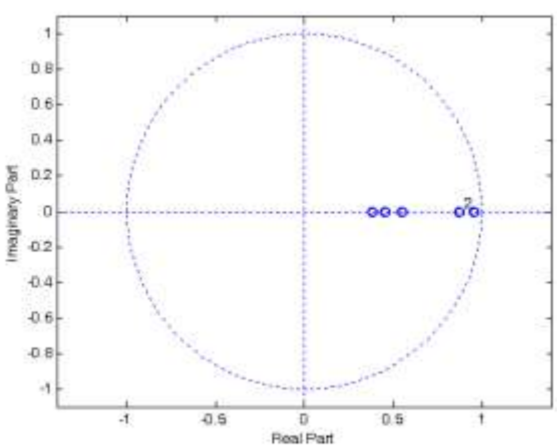

Fig.9 Response of DMC controller for poles and zeros

6 CONCLUSIONS

The modified DMC algorithm is presented in this paper and the main motivation is to eliminate the offset brought from load disturbance, by using conventional DMC controller for heat exchanger processes we can not eliminate the offset and hence using modified DMC algorithm we have performed a Simulation, which shows that the modified DMC algorithm can remove the offset, and has good control performance and robustness.

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