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Real Time Implementation of A New CDM-PI Control Scheme in A Conical Tank Liquid Level Maintaining System

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Abstract

The work focuses on the development and real time implementation of Coefficient Diagram Method (CDM) based PI (CDM–PI) controller for a Conical Tank Liquid Level Maintaining System (CTLLMS). The process exhibits severe static non- -linear characteristics. Based on the Polynomial approach (CDM), the elements of PI controller are designed and implemented in the conical tank liquid level maintaining control loop. Performance of the CDM-PI controller and its robustness are analyzed and reported.

Keywords: CDM-PI, CTLLMS, Real time implementation

1. Introduction

In most of the chemical plants, level control is extremely important because desired production rates and inventories are achieved through proper control of flow and level. The performance of some processes such as chemical reactors depends critically on the residence time in the vessel which in turn depends on the level. At this point it is clear that level control is an important control objective. Due to the pronounced non linear nature of several chemical processes, interest in non linear feed back control has been steadily increasing over the last several years [Bhaba,P.K et al,2007]. Linear controllers can yield a satisfactory performance if the process is operated close to a nominal steady state or is fairly linear. But the performance of the controller degrades with change in operating point and process parameters. Advance controllers such as adaptive or predictive controllers works well even with model mismatch, but the design and implementation require on-line identification of the model. A nonlinear gain scheduling controller works satisfactorily only when the gain is changing for different operating points and time delay is not significant. Further more the non linear gain scheduling controller has to be tuned at every sampling time, which is relatively complex [Chidambaram, M, 1997]. Thus, there is an incentive to develop and implement feed back control schemes that takes the process non linearity in control calculations.

In the present work, a new attempt is made to design a PI Controller for CTLLMS using CDM. The explicit tuning formula of CDM-PI controller is proposed. The important features of CDM are adaptation of the polynomial representation for the plant and the controller, nonexistence or existence of very small overshoot in the closed loop response, obtaining the characteristic polynomial of the closed loop system efficiently by taking a good balance of stability. This technique leads to good robustness of the control system with uncertainty in the plant parameters. The strength of CDM is simple and can be designed for any plant [Hamamci, S.E, 2002].

The paper is organized as follows. Section 2 gives the basics of CDM and the CDM controller design procedure. In section 3, the proposed CDM-PI tuning formula is presented. Experimental set up and experimental works are dealt in section 4. Results and discussions are described in section 5. Finally concluding remarks are given in section 6.

2. Coefficient Diagram Method

2.1 Basics of CDM

The polynomial algebraic method namely CDM was developed and introduced in control engineering in the year 1998 [Manabe, S, 1998]. The merits of the classical and modern control techniques are integrated with the basic principles of

CDM. CDM uses polynomial expressions for both the plant and the controller. In this representation, all equations are dealt with numerator and denominator polynomials independent from each other, better results can be achieved against pole-zero cancellations. In this approach, the type and degree of the controller polynomials and characteristic polynomial of the closed loop system are defined at the beginning. Considering the design specifications, coefficients of the controller polynomials are found later. CDM is an efficient and fertile control tool with which very good control systems can be designed. It is easy to realize a controller under the conditions of stability, time domain performance and robustness. The close relations between these conditions and coefficients of the characteristic polynomial can be easily found. That means CDM is not only effective for control system design but also for controller tuning.

2.2 CDM controller design procedure

The standard block diagram of the CDM control system is shown in Figure 1, where *y* is the output, *r* is the reference input, *u* is the controller signal and *d* is the external disturbance signal. *N*(*s*) and *D*(*s*) are numerator and denominator polynomials of the transfer function of the plant. *A*(*s*) is the forward denominator polynomial while *F*(*s*) and *B*(*s*) are the reference numerator and the feedback numerator polynomials of the controller transfer function. Since the transfer function of the controller has two numerators, it resembles to a 2DOF system structure. *A*(*s*) and *B*(*s*) are designed as to satisfy the desired transient behavior, while pre-filter *F*(*s*) is determined as zero order polynomial and used to provide the steady-state gain [Manabe, S. and Kim,Y.C, 2000].

From Figure 1, the output of the CDM control system is given by

$$y = \frac{N(s)F(s)}{P(s)}r + \frac{A(s)N(s)}{P(s)}d \tag{1}$$

where *P*(*s*) is the characteristic polynomial of the closed-loop system. This polynomial is a Hurwitz polynomial with real positive coefficients and defined by

$$P(s) = A(s)D(s) + B(s)N(s) = \sum_{i=0}^{n} a_i s^i \,, \qquad a_i > 0 \tag{2}$$

The polynomials, *A*(*s*) and *B*(*s*) appearing in the CDM control structure are given as

$$A(s) = \sum_{i=0}^{p} l_i s^i \text{ and } B(s) = \sum_{i=0}^{q} k_i s^i \tag{3}$$

where the condition p ≥ q must be satisfied for practical realization.

The CDM design parameters, namely equivalent time constant (τ) and stability indices (γ_i) are chosen as

$$\tau = t_s / (2.5 \approx 3), \tag{4a}$$

Where t_s is the user specified settling time.

$$\gamma_I = [2.5 \ 2 \ 2 \ \ldots] \tag{4b}$$

The above γ_i values are from the standard form [Manabe, S, 1998] and these values can be changed in order to satisfy the desired performance.

The controller polynomials defined in (3) are replaced in

$$P(s) = A(s)D(s) + B(s)N(s) = \sum_{i=0}^{n} a_i s^i \,, a_i > 0 \tag{5}$$

Hence the coefficients of this characteristic polynomial P(s) are expressed in terms of K_i and l_i (i.e.) P(s) is expressed in terms of the coefficients of the controller polynomials. Using the design parameters ($\tau$and γ_i), a target characteristic polynomial ($P_{target}(s)$) is determined as

$$P_{target}(s) = a_0 \left[\{ \sum_{i=2}^{n} (\prod_{j=1}^{i-1} \frac{1}{\gamma_{i-j}^{j}}) (\tau s)^i \} + \tau s + 1 \right] \tag{6}$$

Equating the two polynomials represented in (5) and (6), a Diophantine equation [Kucera, V, 1993] of

$$A(s)D(s) + B(s)N(s) = P_{target}(s) \tag{7}$$

is obtained. The controller parameters (K_i and l_i) are computed by solving this equation easily.

3. Proposed New CDM-PI Controller

The CDM –PI control structure is shown in Figure 2. Here *C(s)* is the main controller and *C$_f$(s)* is feed forward controller. It can be shown that the steady state error to unit step change and unit step disturbance become zero [Hamamci,S.E,et al.2007] if the conditions

$$\lim_{s\to 0} C(s) = 0 \qquad \text{and} \qquad \lim_{s\to 0} \frac{C_f(s)}{C(s)} = 0 \tag{8}$$

imposes on the controller. The most important result satisfied this condition is that C(s) must include an integrator. In this case, *C(s)* can be chosen as

$$C(s) = K_c \left(1 + \frac{1}{T_i s}\right) \tag{9}$$

in the type of the conventional PI element and *$C_f(s)$* is an appropriate element satisfying in (8).

When Figure 2 is connected with Figure 1, the polynomials of $C(s)$ and $C_f(s)$ in Figure 2 are expressed by $B(s)/A(s)$ and $F(s)/B(s)$ respectively. Here the CDM controller polynomials are chosen as follows:

$$A(s) = s, \tag{10a}$$

$$B(s) = k_1 s + k_0 \tag{10b}$$

The numerator polynomial *F(s)* which is defined as the set-point filter element is chosen to be

$$F(s) = P(s)/N(s)\big|_{s=0} = P(0)/N(0) = 1/K = k_0 \cdot \tag{11}$$

This way, the value of the error that may occur in the steady-state response of the closed-loop system is reduced to zero.

Now substituting the expression for C(s) in (9) we have

$$\frac{B(s)}{A(s)} = K_c \left(1 + \frac{1}{T_i s}\right) \tag{12}$$

Finally, equating the coefficients of the terms of equal power, the parameters of PI controller in terms of CDM controller polynomials are obtained as follows:

$$K_c = k_1 \quad \text{and} \quad \mathrm{T_i} = k_1/K_0 \tag{13}$$

Due to the structure of PI controller and approximation of the process dead time to be of first order by pade approximation, the parameters of PI controller designed by CDM can be obtained only by specifying the stability index γ_i because the equivalent time constant τ has been defined implicitly.

The parameters of feed forward controller is found to be

$$C_f(s) = \frac{F(s)}{B(s)} = \frac{k_0}{k_1 s + k_0} = \frac{1}{T_i s + 1} \tag{14}$$

Note that the parameters of $C_f(s)$ depend on PI parameters directly. Therefore, the designer does not need the extra calculation for the feed forward controller.

4. Experiments and Analysis

4.1 Experimental Set up

The schematic diagram of experimental set up is shown in Figure 3. The setup consists of a mild steel column of 34 cm diameter, height of 60 cm, opened to the atmosphere at the top. Flow rate is metered with Rota meter at the inlet. An RF capacitance level transmitter is used to measure the level in the tank (0-25cm). The output current signal (4-20 mA) from the sensor is processed using a VAD104, a multifunction, high-speed Analog and Digital Converter (ADC) interface board, to digital value. This digital value is read back as level and compared to the set point .The real time PI control algorithm written in "C" provides an appropriate control signal, which is again a digital value. This digital signal is converted to an analog

(4- 20 mA) signal in a digital to analog converter using VAD104.This current signal is converted to a pneumatic signal in an ABB make I/P converter. This pneumatic signal is employed for actuation of the final control element, an RK make control valve that is normally open with C_v of 2.0. Control algorithm is implemented using a P4 - PC, which is interfaced to the CTLLMS. In open loop scheme, after the level reaches a steady state, a step magnitude of +10% DAC output to control valve is given. The level in the tank varies and this variation in level (through RF capacitance Level transmitter) is recorded against time until a new steady state is reached. This recorded data are converted into fractional response and plotted against time to get process reaction curve. Using the results of S-K identification method [Sunderasan,K.R. and Krishnaswamy,P.R , 1978] the parameters for the model of CTLLMS are estimated from the reaction curve. Similarly at different steady state values and at different step magnitudes in DAC output the model parameters are identified and tabulated in Table 1.

4.2 Experimental Works

From Table 1, Worst case of the model parameters (larger process gain (K_p = 1.88), larger time delay (L = 4.66s) and smaller time constant of the process (τ_p = 56.95s)) are chosen, and the CDM-PI controller settings (Kc, Ti and $C_f(s)$) for the stability indices $\gamma_1 = 2.5$, $\gamma_2 = 2$are determined and tabulated in Table 2.

Experimental runs for set point tracking of ±5% and ±10% at the operating point of 40% in CTLLMS is carried out. The tracking responses are recorded in Figure 4.

5. Results and Discussion

5.1 Performance of CDM - PI controller in CTLLMS

The performance of the CDM - PI Controller is evaluated for various set points tracking at the operating point of 40% in CTLLMS. The performance measures (ISE and IAE) derived from Figure 4 is reported in Table 3.Total variation (TV) of the output (y) is also considered for evaluating the performance. By adopting the expression of TV = $\sum_{k=1}^{\infty}|y(k+1)-y(k)|$ the TV indices for CDM - PI controller is calculated and presented in Table 3. The minimum TV index clearly indicates the smoothness and more consistent output signal [Chen, D and Seborg, D.E, 2002]. In addition, Table 4 gives the time domain performance of the proposed controller. Together with the mentioned Figure, the tables indicate that CDM–PI controller gives minimum ISE, IAE, minimum total variation, fast settling time and minimum overshoot in all set point tracking cases.

To analyze the robustness of the proposed controller, an experimental run at other operating points of 60% and 72% level in CTLLMS are carried out. The results of set point tracking of ±5% and ±10% at these operating levels are recorded in Figures 5 and 6. The performance measures tabulated in Tables 3and 4 clearly indicate the supremacy of the CDM-PI controller.

6. Conclusions

In this work, a CDM - PI control schemes for a CTLLMS is designed. Real time implementation of this control scheme is carried out in a Conical Tank Liquid Level Maintaining System. The performance of the control schemes in set point tracking cases is analyzed. The results clearly favor CDM-PI control scheme. In addition, the Robustness of the controller is also investigated. It concludes that CDM - PI control techniques works well for non linear systems.

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Table 1. Identified model parameters at different steady state conditions

Step size	K_p	τ	L
36-46	1.88	85.76	16.41
38-48	1.51	76.38	12.39
42-52	1.66	111.89	33.89
46-56	1.00	80.94	34.66
50-60	1.42	56.95	23.32

Table 2. CDM - PI Controller Parameters

Tuning Rules	K_c	T_i	C_f (s)
CDM - PI	2.2	59.07	1/(59.07s + 1)

Table 3. Performance measures in terms of ISE, IAE and Total Variation at operating point of 40%, 60% and 72% for CDM – PI controller

Set Point Tracking cases	%ISE			%IAE			Total Variation (Output)		
	CDM - PI Controller- CTLLMS								
	Operating Points (%)								
	40	60	72	40	60	72	40	60	72
+05%	581.47	700.64	616.88	192.7	262.4	298	21.7	14.3	23.7
-05%	386.16	499.81	781.27	148.4	215.7	307.3	18.1	15.8	18.3
+10%	1979.56	2455.28	2499.7	311.8	441	531.8	24.2	24.7	31.3
-10%	1461.5	1828.78	2461.3	230.6	335.8	448.4	27.1	22	23

Table 4. Time domain Performance measures at operating point of 40%, 60% and 72% for CDM – PI controller

Set Point Tracking cases	Settling Time (Sec)			%Maximum overshoot			Rise Time (Sec)		
	CDM - PI Controller- CTLLMS								
	Operating Points (%)								
	40	60	72	40	60	72	40	60	72
+05%	480	321	744	1.3	1.5	1.8	123	174	147
-05%	459	273	690	1.7	2	2	84	99	135
+10%	411	492	768	1.6	2.5	3.1	138	153	159
-10%	474	639	678	1	2.5	3.1	102	108	132

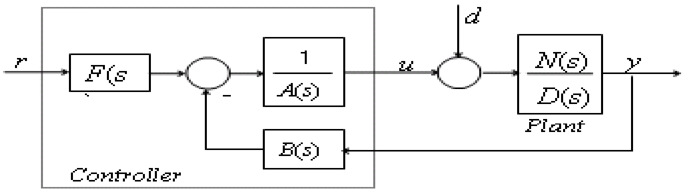

Figure 1. Block diagram of CDM control system

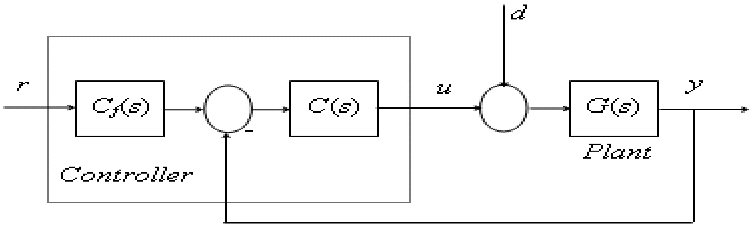

Figure 2. CDM based PI control system

Figure 3. Experimental set up of CTLLM

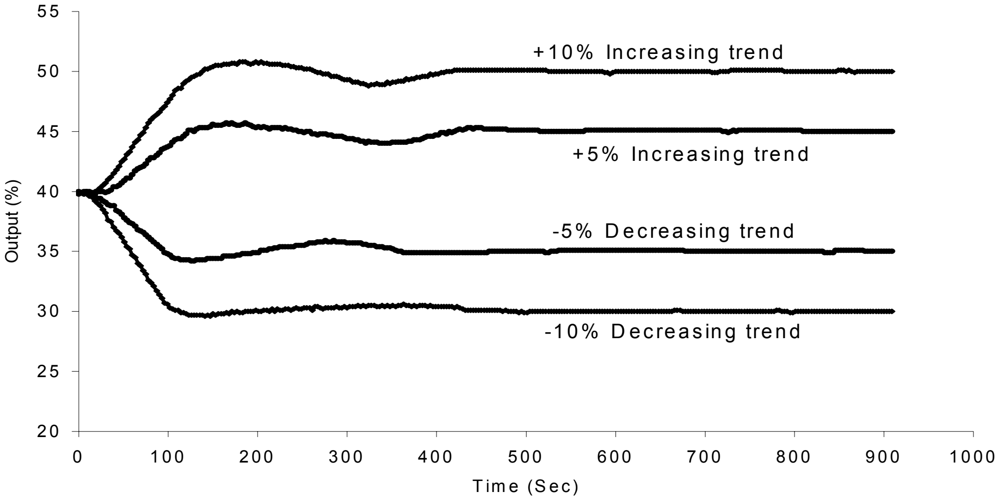

Figure 4. CDM-PI servo responses for step sizes of ±5% and ±10% at the operating point of 40%

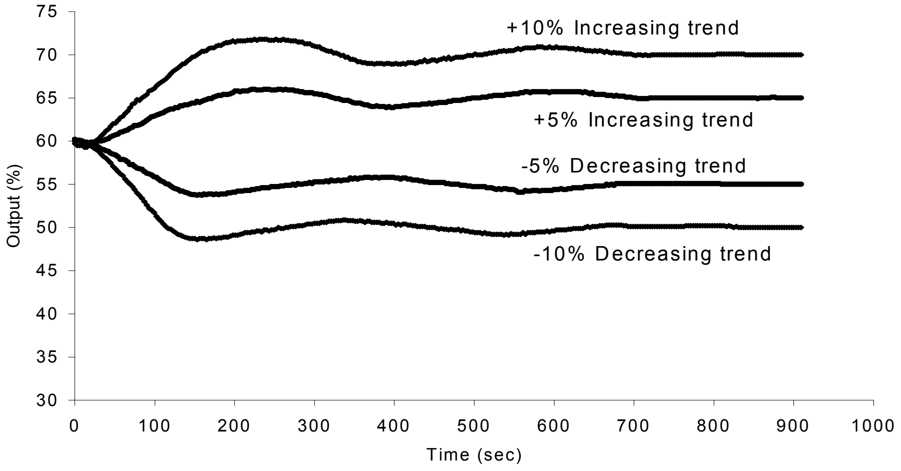

Figure 5. CDM-PI servo responses for step sizes of ±5% and ±10% at the operating point of 60%

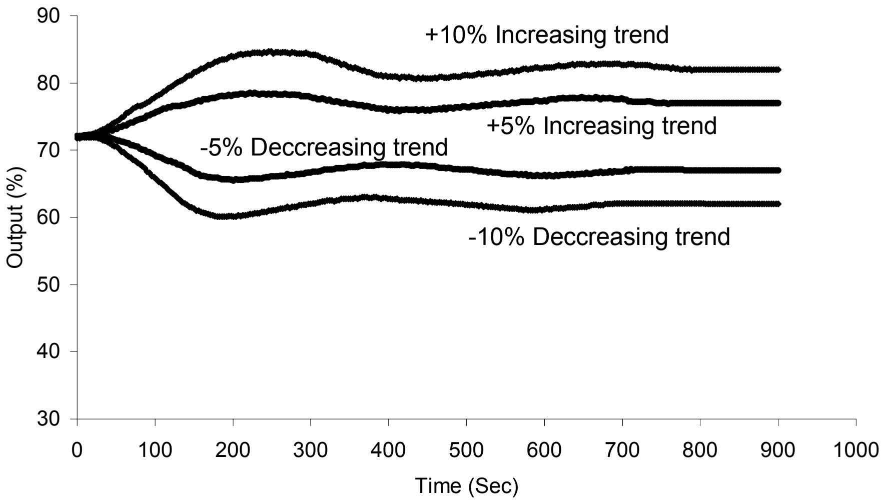

Figure 6. CDM-PI servo responses for step sizes of ±5% and ±10% at the operating point of 72%