Dahlin Deadbeat Internal Model Control for Discrete MIMO Systems

Original Scientific Paper

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Abstract *– Controlling Multiple Input Multiple Output (MIMO) systems present a considerable challenge, particularly when dealing with time delays, nonlinearities, and disturbances. While the Dahlin algorithm and deadbeat control can offer good performance for such systems especially for systems requiring aperiodic responses or those where overshoot and setteling time need to be minimized, their effectiveness can diminish if the model parameters are inaccurate or in the presence of disturbances which lead to steady-state errors. To address these limitations, we propose combining these approaches with Internal Model Control, known for its robustness in handling variations in process dynamics, ensuring accurate setpoint tracking and disturbance rejection. In this paper, we introduce the Dahlin Deadbeat Internal Model Control (DDIMC) for discrete MIMO systems. Initially designed for linear processes with multiple time delays, this control strategy addresses complex control challenges arising from coupling effects and time delays. For nonlinear processes, we extend this controller using a multimodal control strategy which involves describing the nonlinear system with multiple linear discrete models, each paired with a Dahlin Deadbeat controller. A fusion technique is then employed to select the most suitable controller for application. Simulation case studies performed using the MATLAB software validate the effectiveness of these strategies, demonstrating their ability to consistently ensure satisfactory dynamic and robust performance.*

***Keywords**: Dahlin Deadbeat control, Discrete Systems with Time Delays, Internal Model Control, Multimodal control, linear Multiple Input Multiple Output systems, nonlinear systems*

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1. INTRODUCTION

Controlling Multiple Input Multiple Output (MIMO) systems presents a significant challenge in control theory due to their inherent complexity arising from intricate variables interactions, time delays, and nonlinear characteristics [1, 2].

Various control laws have been developed to handle these difficulties and to achieve effective nominal performance. Conventional controllers like PID are commonly used due to their simplicity. However, they frequently yield inadequate performance leading to issues like instability, large overshoots, and slow responses [3]. With the advancement of intelligent control techniques, algorithms such as fuzzy control [4, 5], neural network control [6] and predictive control [7, 8] have been introduced for the control of MIMO systems with time delays. However, due to their complexity, these algorithms present challenges in practical applications [9]. In recent decades, the Deadbeat control stands out as an approach that aims to achieve the desired output behavior while minimizing settling time and eliminating steady-state error [10]. It is based on the use of a model to calculate the inputs that eliminate the current errors in finite time intervals. MIMO deadbeat control was proposed in [11] for linear continuous time systems with several constraints in time or frequency domain. In [12] the Deadbeat Algorithm was proposed to regulate the conical tank system. The nonlinear dynamics of this system were identified through mathematical modeling and approximated to a first-order system. The robustness of this control strategy becomes critical in the presence of non-linearities, parameter variation, or other mismatches [13]. To address these issues, the Deadbeat controller integrated with other strategies like PID, as presented in [14], was proposed to control a nonlinear higher-order system. The Dahlin Controller is an extension of the Deadbeat controller and well known especially for controlling deadbeat processes offering stability and nominal performance [15]. In [16], modulator based current control strategies (Deadbeat, PI and Dahlin controller) for permanent magnet synchronous motors were compared. Although all investigated control strategies exhibit stability, the Dahlin Controller stands out as offering better robustness properties for the closed-loop control system. For nonlinear systems. the operating-range scheduled robust Dahlin Algorithm was proposed in [9], for a class of SISO nonlinear systems represented by a nominal first-order inertia plus pure delay model. To eliminate steady state error, the integration control action is added when the output is close to the setting value. In [17], a modified Dahlin algorithm was proposed for level control in a nonlinear tank system, which was linearized around its equilibrium point. The proposed approach achieves better performance compared to conventional PID controllers.

While the Dahlin controller is known for its effectiveness, it faces challenges such as steady state errors and diminished robustness due to inaccuracies in model parameters or constraints on the control as discussed in [18]. To address these issues, Dahlin algorithm was combined to robust control methods or adaptive control algorithms [18].

The Dahlin Deadbeat algorithm can be combined to discrete internal model known for its nominal performance and robustness, while considering the model structure of the process [19, 20]. It was proposed to control the manipulator's positioning system in [21]. An IMC–Dahlin temperature control method based on relay feedback self-tuning identification was proposed and validated through real application on a thermostat in [22]. In this paper, the Dahlin Deadbeat based IMC, DDIMC, was initially proposed for MIMO linear discrete systems [23]. The promising outcomes achieved in controlling such systems prompted its broader application to multivariable nonlinear discrete-time systems by considering multimodeling strategy [24]. Multimodel methodologies have gained significant traction in both modeling and controlling nonlinear systems [25, 26]. This novel approach involves initially developing a model base to describe the MIMO nonlinear system. Each linear model is paired with its correspondent Dahlin deadbeat controller. The main key of the multi-model approach lies in the selection, at each sampling time, of the most fitting model that accurately approximates the current state of the process around an operational point. Subsequently, its corresponding controller is applied to the entire system.

This paper studies control challenges of MIMO systems. The DDIMC is initially proposed for linear systems with time delays and then extended to nonlinear systems using the DDIMMC control. The main objectives consist of ensuring good dynamic performance while maintaining robustness.

The remainder of this paper is organized as follows: the Dahlin Deadbeat Internal Model Control (DDIMC) is provided in Section 2. Dahlin Deadbeat Internal Multimodal Model Control (DDIMMC) is proposed in Section 3. Section 4 explores the results obtained from numerical simulations, while Section 5 presents some conclusions.

2. DAHLIN DEADBEAT INTERNAL MODEL CONTROL FOR LINEAR MIMO SYSTEMS

The DDIMC control is proposed for linear MIMO processes with time delays and particularly when there are requirements for fast response and robustness [2]. The proposed approach combines the advantages of the Dahlin Deadbeat control and the Internal model control within a unified structure. In a dead-beat controller, the system tracks a step input that is delayed by a few sampling times [10]. The Dahlin controller [13], which is built upon the dead-beat controller, generates a smoother exponential response in comparison to the standard dead-beat controller. As for the Internal Model Control (IMC), it is known for its robustness in handling both disturbances and uncertainties by incorporating a detailed model of the process [19].

2.1. THE DISCRETE IMC CONTROL FOR MIMO SYSTEMS

The discrete IMC structure, depicted in Fig. 1, incorporates a stable MIMO process $G(z)$, the internal model $M(z)$ and a controller $C_{CMI}(z)$ arranged to act as the model inverse. These components are described by transfer matrices of dimension $(n \times n)$. $u(z)$ and $y(z)$ represent respectively the input actions and the output vectors of dimension $(n \times 1)$. $r(z)$ and $d(z)$ are respectively the reference vector of dimension $(n \times 1)$ and the disturbance vector that may affect the system. The input actions are simultaneously applied to the process and its model. The outputs mismatch is considered to adjust the controller's input $e(z)$.

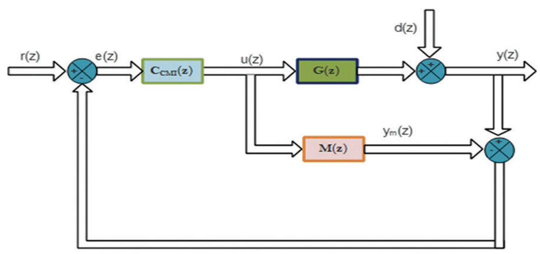

Fig. 1. The MIMO IMC structure [20]

From Fig. 1, we can deduce the following equation for the input action vector $u(z)$ [23]:

$$u(z) = (I_n + C_{CMI}(z)(G(z) - M(z)))^{-1} C_{CMI}(z)(r(z) - d(z)) \quad (1)$$

$$\begin{aligned} y(z) &= G(z)(I_n + C_{CMI}(z)(G(z) - M(z)))^{-1} C_{CMI}(z) r(z) \\ &+ (I_m - G(z)(I_n + C_{CMI}(z)(G(z) - M(z)))^{-1} C_{CMI}(z)) d(z) \end{aligned} \quad (2)$$

In conventional IMC theory, when the controller is chosen as the model inverse, perfect control is achieved. However, for many physical systems, the inversion task isn't feasible. An approximate inverse is then required [26, 27].

The IMC controller for non-minimum and delayed systems, depicted in Fig. 2, can be designed as proposed in [20, 23].

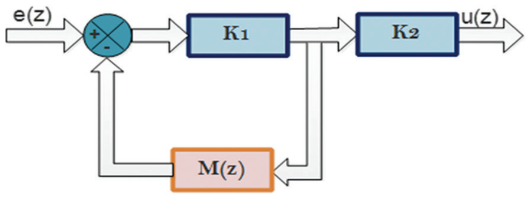

Fig. 2. Structure of the internal model controller [23]

The internal model controller $C_{CMI}(z)$ is then described as the following:

$$C_{CMI}(z) = K_1 K_2 (I_n + K_1 M(z))^{-1} \quad (3)$$

The gain matrix K_1 is crucial for ensuring the stability of the controller, while K_2 is considered to compensate for system's static errors.

K_2 is described below:

$$K_2 = (I_n + K_1 M(1))(K_1 M(1))^{-1} \quad (4)$$

where $M(1)$ represents the model's static matrix gain.

The proposed controller steady-state gain is equal to the inverse of the model steady-state gain. Offset-free control is then obtained for constant setpoints and output disturbances [28].

The IMC control structure illustrated in Fig. 1, can be modified to a classical feedforward control as presented in Fig. 3 below.

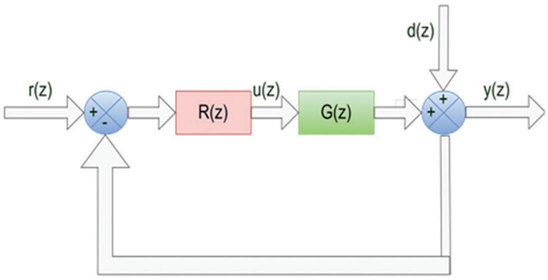

Fig. 3. Classical closed-loop control structure

where:

$$R(z) = \left(I_n - C_{CMI}(z)M(z)\right)^{-1} C_{CMI}(z) \quad (5)$$

$$H(z) = R(z)G(z) \times \left(I_n + R(z)G(z)\right)^{-1} \quad (6)$$

2.2. THE DAHLIN-DEADBEAT CONTROLLER

Deadbeat control is a control strategy aiming to drive the system outputs to the desired value within a few sampling times. Fast and accurate tracking of references signals are then ensured.

For MIMO systems that occur frequently in the processing industry, it's desirable to eliminate the coupling effects between the loops for MIMO systems. The proposed controller, in this paper, is chosen to handle both interactions and time delays, that may exist, within a single design [29]. For that reason, the desired closed-loop transfer matrix $H(z)$ is chosen to have a diagonal form and is defined as follows.

$$H(z) = \begin{bmatrix} z^{-k} & 0 & \cdots & 0 \\ 0 & z^{-k} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & z^{-k} \end{bmatrix}, \ k \geq 1 \quad (7)$$

The Dahlin algorithm is an extension of the deadbeat control that was proposed specifically for the system with pure time delay. The key idea of the Dahlin algorithm is to design an anticipant closed-loop transfer function. The system behaves similarly to a continuous first order process with time delay [13]. The transfer matrix H(s) is chosen as follows:

$$H(s) = \begin{bmatrix} h_{11}(s) & 0 & \cdots & 0 \\ 0 & h_{22}(s) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{nn}(s) \end{bmatrix} = \left(h_{ij}(s)\right)_{1\leq i,j\leq n} \quad (8)$$

where: $h_{ii}(s)=exp(-T_i s)/(\tau_i s+1), 1\leq i\leq n; T_i$ is the time delay selected as: $T_i=N\times T_s$, T_s is the sampling time and τ_i is the time constant.

The discrete form of the transfer functions $h_{ii}(s)$, $1\leq i\leq n$, obtained with a zero-order hold is then described below:

$$h_{ii}(z) = \left(\frac{1-exp\left(\frac{-T_s}{\tau_i}\right)}{\left(z-exp\left(\frac{-T_s}{\tau_i}\right)\right)}\right) z^{-N} \quad (9)$$

The Dahlin deadbeat controller R(z) is then described below:

$$R(z) = \left(I_n - H(z)\right)^{-1} H(z) G(z)^{-1} \quad (10)$$

2.3. THE DAHLIN DEADBEAT IMC CONTROL

The proposed DDIMC control strategy uses the Internal Model Control (IMC), as depicted in Fig. 4. Initially, the desired closed-loop dynamics are selected according to Eq. (8) and Eq. (9), followed by the design of the Dahlin controller described by Eq. (10).

The IMC controller considered in the DDIMC structure is then described as follows:

$$C_{CMI}(z) = R(z) \times \left(I_n + R(z)M(z)\right)^{-1} \quad (11)$$

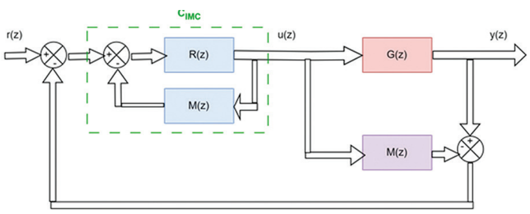

Fig. 4. The DDIMC structure

3. DAHLIN DEADBEAT INTERNAL MULTIMODEL CONTROL FOR NONLINEAR MIMO SYSTEMS

Modern industrial processes often exhibit nonlinearity. Linear models can't capture the dynamics of complex systems due to the presence of strong nonlinearities. The effects of these nonlinearities are mostly undesirable and can greatly affect the performance of controllers [26]. To tackle these challenges, multimodal approaches are emerging as promising alternatives to conventional linearization methods. These methods involve segmenting the system's operational range into distinct zones and considering localized linear models for each zone [17]. The Multimodal principle is depicted in Fig. 5.

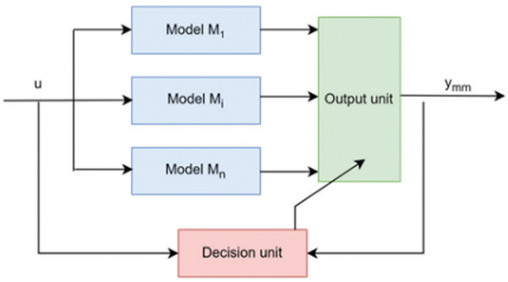

Fig. 5. Multimodel Control

The algorithm of the proposed method is given by:

Step 1: A base of several discrete MIMO linear models is defined to describe the nonlinear system across its entire operating ranges.

Step 2: The desired closed loop transfer matrix H(z) is specified based on Eq (9).

Step 3: For each linear MIMO model, a specific Dahlin Deadbeat controller is designed based on Eq10.

Step 4: At each sampling time, the model that closely matched the process dynamics is selected based on the switching technique illustrated in Fig. 6.

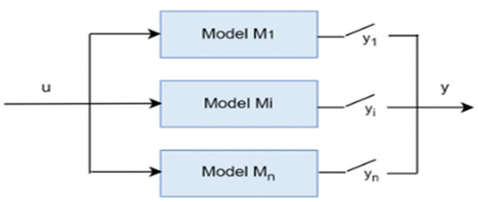

Fig. 6. Switching technique [26]

The errors between model outputs and the actual system responses should then be evaluated.

For each model M_i, a distance vector D_i, describing model outputs y_{M_i} and the system outputs y mismatch, is represented by the Eq. (12).

$$D_i = \sum_{j=1}^{m} \left\| y_j(k) - y_{M_{ij}}(k) \right\| \quad i = 1 \ldots n \qquad (12)$$

For each model M_i, i=1...n, a validity index v_i needs to be assessed. A validity index v_i of 1 is assigned to the model with the smallest distance vector, indicating its superior relevance in describing the nonlinear system. Conversely, for the other models in the set, v_i is set to 0. The multimodal vector of outputs aligns then with the vector of the chosen model's outputs (cf. Fig. 7).

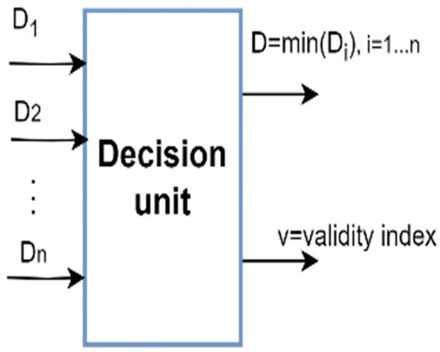

Fig. 7. Basic diagram of the model validation method [24]

Step 5. Once the model is validated, its corresponding DDIMC controller, is applied to control the entire nonlinear system.

The new DDIMMC, proposed for nonlinear discrete systems is depicted in Fig. 7.

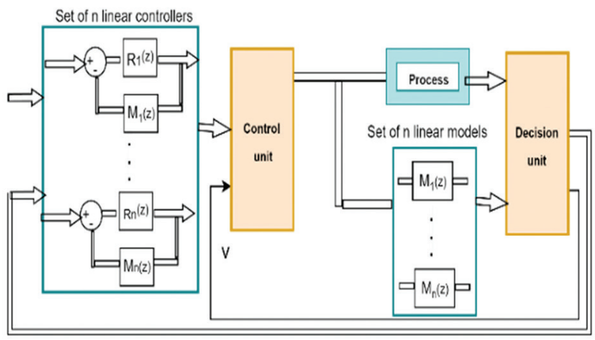

Fig. 8. The DDIMMC structure

4. SIMULATION CASE STUDIES

To demonstrate the effectiveness of the proposed control structures, two case studies were introduced. For the first case, a linear MIMO discrete system, specifically a neonatal incubator is proposed. As for the second case, it concerns a nonlinear discrete MIMO system: stirred tank reactor (CSTR) process.

4.1. DDIMC FOR A LINEAR MIMO DISCRETE SYSTEM: A NEONATAL INCUBATOR SYSTEM

- System description

Let's consider a linear MIMO neonatal incubator system described by the following transfer matrix [30]:

$$\begin{bmatrix} Y_H(s) \\ Y_T(s) \end{bmatrix} = \begin{bmatrix} \frac{0.3145}{1.753s+1} e^{-0.184s} & \frac{-0.01649}{0.3065s+1} e^{-0.496s} \\ \frac{-0.3483}{11.29s+1} e^{-1.31s} & \frac{0.2356}{26.07s+1} e^{-1.46s} \end{bmatrix} \begin{bmatrix} U_H(s) \\ U_T(s) \end{bmatrix} \qquad (13)$$

where $Y_H(s)$, $U_H(s)$, $Y_T(s)$, $U_T(s)$ are the outputs and control actions related respectively to the humidity and temperature inside the incubator.

The discrete transfer matrix is described as follows with a sampling time of Ts = 1.2 seconds.

$$\begin{bmatrix} Y_1(z) \\ Y_2(z) \end{bmatrix} = \begin{bmatrix} \frac{0.1383z+0.01755}{z-0.5043} z^{-1} & \frac{-0.01483z-0.00133}{z-0.01994} z^{-1} \\ \frac{-0.03205z-0.00366}{z-0.8992} z^{-2} & \frac{0.008344z+0.002255}{z-0.9924} z^{-2} \end{bmatrix} \begin{bmatrix} U_1(z) \\ U_2(z) \end{bmatrix} \quad (14)$$

Two scenarios are presented. The first one considers the nominal case without any disturbances, while the second one tests the robustness towards external disturbances.

- First scenario: Nominal case

Fig. 9 illustrates simulation results for this scenario. All the responses accurately settle the setpoints. The overall performance is better when applying the DDIMC compared to the discrete IMC [20]. The proposed approach has less overshoot and shorter settling time as presnted in Table 1 which illustrates a quantitative comparison of the obtained results, to validate the effectiveness of the proposed control approach compared to the IMC and its ability to ensure satisfactory performance.

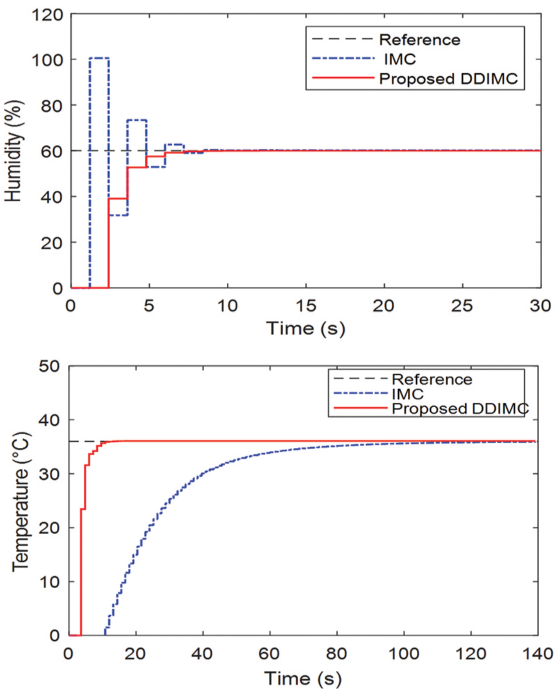

Fig. 9. Humidity and Temperature levels (Nominal case)

Table 1. Performance of the transient responses with the DDIMC and IMC [20]

	IMC		Proposed DDIMC	
	Humidity	**Temperature**	**Humidity**	**Temperature**
Rise Time (s)	0.57	36.52	2.53	2.72
Setting Time (s)	6.49	82.48	5.75	8.84
Overshoot (%)	67.46	0	$8.2.\ 10^{-5}$	0

- Second scenario: In the presence of disturbances

The robustness towards external disturbances of the proposed approach is presented in this scenario. Step type output disturbances of 10% occur at t=10s on the humidity level and 2°C occur at t=100s on the temperature level, respectively. Fig. 10 displays the responses for the DDIMC control. The system remains stable, and the disturbances are completely rejected after about 8 and 12 sampling times for the humidity and the temperature levels, respectively.

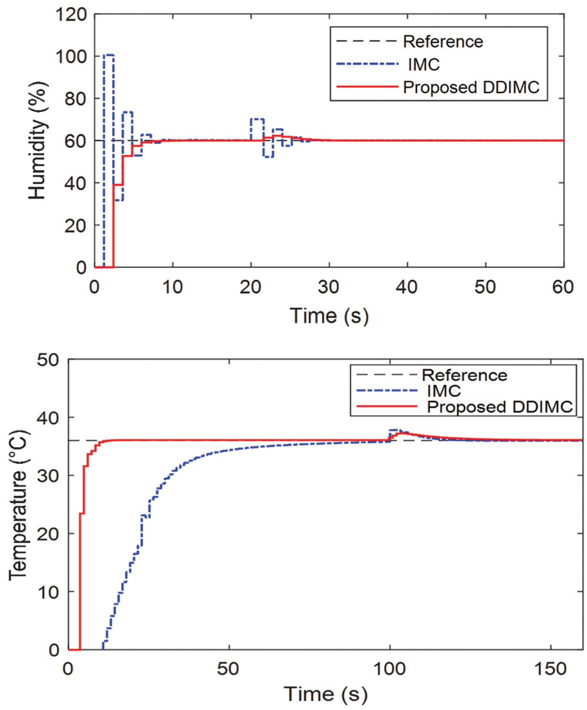

Fig. 10. Humidity and Temperature levels (robustness towards disturbances)

4.2. DDIMC FOR A NONLINEAR MIMO DISCRETE SYSTEM: STIRRED TANK REACTOR

- System description

Let's consider a MIMO stirred tank reactor (CSTR) process, which consists of an irreversible, exothermic reaction, A → B, in a constant volume reactor cooled by a single coolant stream. It can be modeled by the following nonlinear equations [31]:

$$\begin{cases} \dot{C}_A(t) = \frac{q}{V}[C_{A0} - C_A(t)] \\ \quad - k_0 C_A(t) e^{-(E/RT(t))} \\ \dot{T}(t) = \frac{q}{V}[T_0 - T(t)] + k_1 C_A(t) e^{-(E/RT(t))} \\ \quad + k_2 q_c(t)[1 - e^{-(k_3/q_c(t))}][T_{c0} - T(t)] \end{cases} \quad (15)$$

The system's inputs are the flow rate q and coolant flow rate q_c. The outputs are respectively the concentration C_A, and the temperature T. Table 2 displays the CSTR's parameter values.

Parmeter	Description	Value
C_{A0}	Feed concentration	1 mol/l
T_{C0}	Inlet coolant temperature	350 K
h_A	Heat transfer term	7×10^5 cal/minK
E/R	Activation energy term	10^4 K
ρ,ρ_c	Liquid densities	10^3 g/l
q	Process flow rate	100 l min^{-1}
T_0	Feed temperature	350K
V	CSTR volume	100 l
k_0	Reaction rate constant	7×10^{10} min^{-1}
ΔH	Heat of reaction	-2×10^5 cal/mol
C_p, C_{pc}	Specific heats	1 cal $g^{-1}K^{-1}$

$$k_1 = \frac{-\Delta H k_0}{\rho C_p} \qquad k_2 = \frac{-\rho_c C_{pc}}{\rho C_p V} \qquad k_3 = \frac{h_A}{\rho_c C_{pc}}$$

After linearization around three operating points, local linear models are obtained. In the discrete state-space representation with a sampling time of $T_s = 0.1$ seconds, these models are represented below [31]:

$$\begin{cases} x(k+1) = A_i x(k) + B_i u(k) \\ y(k) = Cx(k) + Du(k) \end{cases} \quad i = 1,2,3$$

where, $x(k)$, $u(k)$ and $y(k)$ represent respectively the states, inputs, and outputs vectors:

$$A_1 = \begin{bmatrix} 0.1552 & -0.004 \\ 143.4331 & 1.5794 \end{bmatrix}, B_1 = \begin{bmatrix} 0.0007 & 0.0002 \\ -0.0463 & -0.1122 \end{bmatrix}; \quad (16)$$

$$A_2 = \begin{bmatrix} -0.0225 & -0.0039 \\ 175.1096 & 1.5464 \end{bmatrix}, B_2 = \begin{bmatrix} 0.0006 & 0.0002 \\ -0.0343 & -0.1203 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 0.1801 & -0.0044 \\ 137.5519 & 1.6376 \end{bmatrix}, B_3 = \begin{bmatrix} 0.0007 & 0.0002 \\ -0.0509 & -0.1117 \end{bmatrix};$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ and } D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

Three discrete MIMO transfer matrices are obtained and described as follows:

$$M_1 = \begin{bmatrix} \frac{0.0007z - 0.0009}{z^2 - 1.735z + 0.8189} & \frac{0.0002z + 0.0001}{z^2 - 1.735z + 0.8189} \\ \frac{-0.0463z + 0.1076}{z^2 - 1.735z + 0.8189} & \frac{-0.1122z + 0.0461}{z^2 - 1.735z + 0.8189} \end{bmatrix};$$

$$M_2 = \begin{bmatrix} \frac{0.0006z - 0.0008}{z^2 - 1.524z + 0.6481} & \frac{0.0002z + 0.0002}{z^2 - 1.524z + 0.6481} \\ \frac{-0.0343z + 0.1043}{z^2 - 1.524z + 0.6481} & \frac{-0.1203z + 0.0323}{z^2 - 1.524z + 0.6481} \end{bmatrix}; \quad (17)$$

$$M_3 = \begin{bmatrix} \frac{0.0007z - 0.0009}{z^2 - 1.818z + 0.9002} & \frac{0.0002z + 0.0002}{z^2 - 1.818z + 0.9002} \\ \frac{-0.0509z + 0.1055}{z^2 - 1.818z + 0.9002} & \frac{-0.1117z + 0.0476}{z^2 - 1.818z + 0.9002} \end{bmatrix}$$

The desired closed loop transfer matrix is described below.

$$H(z) = \begin{bmatrix} \frac{0.09516}{z - 0.9048} z^{-1} & 0 \\ 0 & \frac{0.09516}{z - 0.9048} z^{-1} \end{bmatrix} \quad (18)$$

Two scenarios are presented. In the first one, the nominal case without any disturbances is considered, while the second one tests the robustness towards external disturbances.

- First scenario: Nominal case

Fig. 11 illustrates simulation results for this scenario. The setpoints are 0.09 mol/l and 450 K for the concentration and the temperature respectively. We can notice that the outputs of the CSTR system track the reference signals with zero steady state errors. Moreover, the system demonstrates better transient responses compared to the Discrete Internal Multimodel Control strategy [24]. The DDIMMC yields responses with minimized overshoot and undershoot, and shorter setting time as detailed in Table 3. In fact, the transient response performance is not explicitly considered in the IMMC controller design, whereas optimizing transient response is a primary concern for the proposed DDIMMC controller.

Table 3. Performance of the transient responses with the DDIMMC and IMMC [24]

	IMMC		Proposed DDIMMC	
	Concentration	Temperature	Concentration	Temperature
Setting Time (s)	0.96	1.03	0.22	0.21
Overshoot (%)	6.4	0.62	2.99	0.78
Peak	9.64×10-2	453	9.23×10^{-2}	452.3

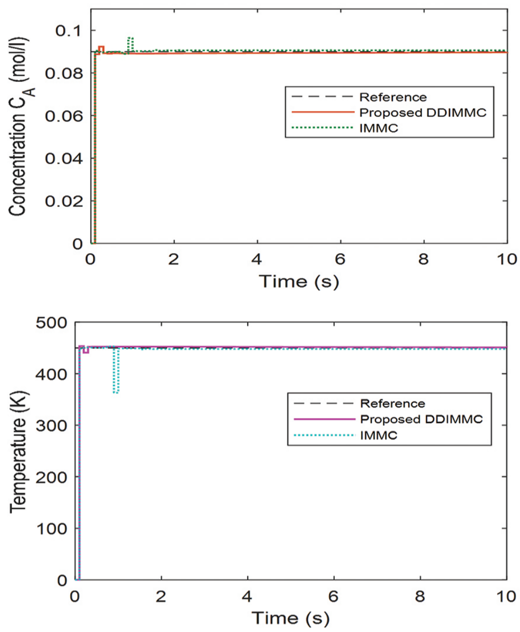

Fig. 11. Concentration and Temperature levels (Nominal case)

- Second scenario: In the presence of disturbances

The robustness towards external disturbances of the proposed approach is presented in this scenario. Persistent disturbances of 0.02 mol/l and 10 K occur at t=0.5 s on the concentration and the temperature levels respectively. Fig. 12 displays simulation results for this scenario. We can notice that despite the presence of persistent disturbances, the outputs remain able to follow the reference inputs. The DDIMMC controller has proven its ability to ensure good performance despite the disturbances.

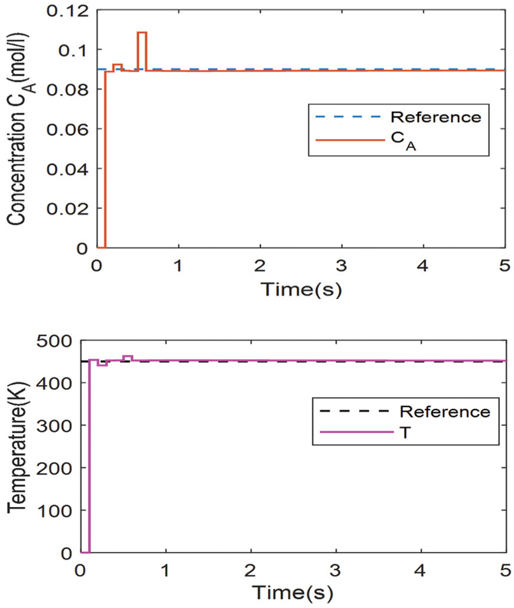

Fig. 12. Concentration and Temperature levels (Robustness towards disturbances)

5. CONCLUSION

The Dahlin deadbeat Internal Model Control was proposed in this paper for MIMO systems. It was designed on the principles of the Dahlin deadbeat control and the internal model control. The controller, proposed initially for linear systems, is easy to implement, robust and has good dynamic control performance. A simulation study on a linear MIMO neonatal incubator illustrates the effectiveness of this approach in ensuring good transient performance, accurate tracking, and robustness towards disturbances. Beyond linear systems, the DDIMC was extended to control MIMO nonlinear systems by incorporating a multi-modeling strategy based on describing the nonlinear system by a set of multiple linear models. At each sampling time, the most appropriate model is selected and its corresponding Dahlin deadbeat controller is applied to the entire system. This novel Dahlin deadbeat internal multimodal control method (DDIMMC) demonstrates its effectiveness through simulations on a stirred tank reactor (CSTR) process involving two inputs and outputs. The proposed control approach has proven its ability to ensure satisfactory nominal and robustness performances.

Future work may involve conducting experimental tests on real systems using DDIMC and DDIMMC methods aiming to prove the effectiveness of these approaches in real-world applications. Furthermore, extending these control strategies to address the complexities of non-square systems, which pose additional challenges in control, could be explored.

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