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Modelling and Control of a Dosing Pump for Water Treatment Plants

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ABSTRACT: This paper presents modelling and control of a dosing pump for effective production of high quality potable water for public consumption and utilisation. A mathematical model of a dosing pump is described in this study. Furthermore, the application of a model predictive control (MPC) algorithm to control the dosing pump in order to hold the output variable of the pump as close as possible to the set point without violating the constraints of pump input and output variables is examined. Simulations results of the servo-control and regulatory-control responses of MPC, Proportional Integral (PI) and Proportional Integral Derivative (PID) control algorithms show that MPC performs best when compared with the PI and PID controllers.

KEYWORDS: Coagulation; dosing pump; model predictive control; optimisation; water treatment plants

I. INTRODUCTION

Water treatment plants provide and supply safe and potable drinking water to public. The plant normally draws raw water from natural or artificial water source(s). A pumping station and transport system are available to lift water from the water source(s) and convey it to the water treatment plant. Raw water flows through the intake pipe into the chemical dosing unit. Raw water inlet valve is placed after the flowmeters to control the quantity of water flowing into the plants [1].

Raw water quality could have low turbidity with high algal content or high turbidity due to discharges from floods and rainfall. These changes in water turbidity often lead to difficulties in coagulation process. The amount of water abstracted is also used to determine the amount of chemicals that need to be dosed during the treatment process. The dosing unit might contain a mixing tank with inlet and outlet channels and dosing pumps for adding accurate quantities of coagulant and pH control chemical to the raw water. The chemically treated water flows out slowly and evenly through a series of baffled or flocculation channels, to grow the flocs [2-4].

The dosing of coagulant or coagulation chemicals into water treatment plants needs to be regulated to prevent the problem of feeding inadequate or excessive chemical dosages to the raw water by the pump. A dosing pump controlled by traditional on and off switch or controller may exhibit unsatisfactory performance due to the transport delay and nonlinearities associated with the coagulation process [3].

Therefore, there is a need to propose a control algorithm that will address these identified deficiencies of the traditional controllers. The application of a model predictive control (MPC) algorithm is investigated to control dosing pump by holding the output variable of the pump as close as possible to the set point without violating the constraints of the pump input and output variables.

Several studies have been carried out to compare the performances of MPC and PID controllers in the literature. For instance, authors of [5] studied the performance of MPC and optimised PID controller on first, second, third, fourth and fifth order systems. The results showed that MPC outperformed the PID controllers in all cases. In [6], the performances of MPC and PID controllers were investigated to control reverse osmosis desalination plant. It was found that PID controller indicated faster response and better disturbance rejection compared to the MPC. The performance of MPC and PID control strategies on milk pasteurization process was examined in [7]. It was found that MPC was more suitable to achieve effective pasteurization process control than PID control.

Furthermore, the authors of [8] investigated the robustness of MPC and PID controllers' performance on a hydro distillation system. The simulation results showed that MPC gave better performance than the PID controllers. In [9], the control of off-shore oiling processing using MPC and PID was analysed and compared. While in [10], the performance of MPC and PID controllers to control DC-DC converter was studied. The study observed that the step response of PID controller was slower than the step response of MPC. The time varying reference signal was tracked better by MPC than PID controller.

In our view, none of these previous studies have been carried to demonstrate and compare the controlling effect of MPC, PI and PID algorithms on dosing pumps. To the best of our knowledge this is the first study to apply MPC to control dosing pump for water treatment plants. It is envisaged that the proposed control strategy will improve the efficiency of the dosing pump and in directly lower the operational cost of water treatment plants. The paper is organised as follows. Section 2 presents mathematical modelling of the metering pump, PID and model predictive control and performance indices to evaluate the control system. The simulation results are discussed in section 3. The last section concludes the studies and suggests future research direction.

II. MATERIALS AND METHODS

A. Mathematical modelling of a dosing pump

Dosing pumps are oscillating positive displacement pumps that add a fluid stream to a process at accurate flow rate. They use reciprocating diaphragm to move the fluid into its chamber and disperse the fluid into another liquid substance or fluid inside a tank or pipe. The diaphragm is flexible and vibrates to create suction to move fluid into and out of the pump chamber. It is mostly powered by an electric motor [11].

Based on Newton's law of motion that states that the angular acceleration is proportional to the torque on the axis, the mechanical equation of motion for the motor-pump set is written as [12]:

$$J\frac{d\omega(t)}{dt}=T_M(t)-T_P(t) \tag{1}$$

$$T_M(t)=T_{IM}(t)+T_{\varsigma}(t) \tag{2}$$

$$J\frac{d\omega(t)}{dt}=T_{IM}(t)-T_P(t)+T_{\varsigma}(t) \tag{3}$$

where J is the moment of inertia, $T_{IM}(t)$ is the active torque from the induction motor, $T_P(t)$ is the resistive or passive motor torque and $T_{\varsigma}(t)$ is the viscous torque.

The viscous torque of the motor can be represented respectively by:

$$T_{\varsigma}(t)=k_{\varsigma}\omega(t) \tag{4}$$

The resistive torque of the pump is expressed as:

$$T_P(t)=k_p q_v\omega(t) \tag{5}$$

where k_{ς} is the viscous constant, k_p is the pump constant, q_v is the flow of the pump and $\omega(t)$ is the angular velocity.

Assuming that the induction motor operates at the steady-state, its speed-toque characteristic curve is approximately the same as the characteristic curve of a DC machine. Thus, the speed-torque equation can be given as:

$$\omega(t)=\frac{V(t)}{k_{\phi}}-\frac{RT_{IM}(t)}{k_{\phi}^2} \tag{6}$$

$$T_{IM}(t)=\frac{V(t)}{R}k_{\phi}-\frac{k_{\phi}^2}{R}\omega(t) \tag{7}$$

Manipulating (3) and (7),

$$J\frac{d\omega(t)}{dt}=\frac{V(t)}{R}k_{\phi}-\frac{k_{\phi}^2}{R}\omega(t)-k_p q_v\omega(t)+k_{\varsigma}\omega(t) \tag{8}$$

$$J\frac{d\omega(t)}{dt}+\frac{k_{\phi}^2}{R}\omega(t)+k_p q_v\omega(t)-k_{\varsigma}\omega(t)=\frac{V(t)}{R}k_{\phi} \tag{9}$$

Taking the Laplace transform of the expression, gives

$$sJ\omega(s)+\frac{k_{\phi}^2}{R}\omega(s)+k_p q_v\omega(s)-k_{\varsigma}\omega(s)=\frac{V(s)}{R}k_{\phi} \tag{10}$$

$$\omega(s)=\frac{k_{\phi}}{sJR+k_p q_v R+k_{\phi}^2-k_{\varsigma}R}V(s) \tag{11}$$

Where R is the resistance of the motor and k_{ϕ} is the torque constant.

B. Proportional Integral Derivative Control

PID controller is a widely used algorithm to automate many industrial processes [13]. It is easy and simple to implement. The PID controller can be represented in the continuous s-domain as:

$$G_{PID}(s)=K_p+\frac{K_i}{s}+K_d s \tag{12}$$

$$G_{PID}(s)=K_p\left(1+\frac{1}{T_i s}+T_d s\right) \tag{13}$$

where K_p is the proportional gain, K_i is the integral gain and K_d is the derivative gain, T_i is the integral action time or reset time and T_d is the derivative action time .

Alternatively, the output of the PID controller can be expressed in the time domain as:

$$u(t)=K_p e(t)+K_i\int_0^t e(\tau)d\tau+K_d\frac{de(t)}{dt} \tag{14}$$

Where $u(t)$ and $e(t)$ are the control input and tracking error signals respectively.

In a typical PID controller, the proportional part of it reduces error response to disturbances. The derivative term dampens the dynamic response and enhances the stability of the system while integral part eliminates steady-state error. The design and application of a PID controller involves systematic selection of the three gains (K_p, K_i, K_d) to produce the desired close loop response.

When K_d is 0, then PID controller becomes PI controller. Similarly, when K_i is 0, Proportional Derivative (PD) controller is created. The control objective is to ensure that the responses of the dosing pump controller in a close loop arrangement should exhibit very low settling time with little or no overshoot.

C. Model Predictive Control

Model predictive control (MPC) is an important advanced control that has attracted attention from both practitioners and researchers because of several advantages of this technology. MPC uses process model that captures both the dynamic and static interactions between the input, output and disturbance variables. It considers the constraints on inputs and output in a systematic manner. The computation of the optimum set points can be coordinated with the control calculations. It can control several process variables when a sensor or actuator is faulty or unavailable. The capability of MPC to handle complex control problems depends on the accuracy of the process model to predict the future response of the plant [14].

MPC has a process model that is used to predict the current values of the controlled variables. The error is the difference between the actual output and predicted output. It serves as the feedback signal to the prediction block. The responses of the prediction block are used in the optimiser at each sampling instant to solve the objective function and generate a sequence of input control increments. MPC computation thus determines a sequence of control moves that force the predicted response to follow the reference trajectory in an optimal manner [6,14].

The control strategy of the MPC is to find a sequence of control signals, that yield the predicted outputs, which is based on the system model to some desired reference signal vector. The span of the control sequence, M , is referred to as the control horizon, while that of the predicted output, P , is called the prediction horizon. Although the computed control values are based on P time steps, only the first move is implemented and a new sequence of control inputs is computed at the next sampling instance. The following cost function is to implement the proposed control strategy [15].

$$\min_{\Delta u(k)\ldots\Delta u(k+M-1)} \quad S_y(k)+S_{\Delta u}(k)+S_u(k) \tag{15}$$

where

$$S_y(k)=\sum_{i=1}^{P}\sum_{j=1}^{n_y}\left\{w_j^y\left[r_j(k+i)-y_j(k+1)\right]\right\}^2 \tag{16}$$

$$S_{\Delta u}(k)=\sum_{i=1}^{M}\sum_{j=1}^{n_u}\left\{w_j^{\Delta u}\Delta u(k+i-1)\right\}^2 \tag{17}$$

$$S_u(k)=\sum_{i=1}^{M}\sum_{j=1}^{n_u}\left\{w_j^{u}u(k+i-1)\right\}^2 \tag{18}$$

where $r(k)$ is the reference vector, $y(k+j\,|\,k)$ is the j-step ahead predicted output given the present output measurements, w_j^y is the positive definite output error weighting matrix, $w_j^{\Delta u}$ is the positive semi definite input increment weighting matrix, w_j^u is the positive semi definite input weighting matrix. The weighting matrices and the prediction horizon parameters, P , and the control horizon M are the tuning parameters which can be used to shape the closed-loop response of the system

D. Performance Indices

Performance indices are quantitative measures of the performance of a system. Root mean square error (RMSE) and mean absolute error (MAE) are used to evaluate the performances of the controllers in terms of set point tracking and disturbance rejection tests. These performance indices are defined as follows [16]:

$$\text{Root Mean Square Error (RMSE)} = \frac{1}{n}\sum_{i=1}^{n}|e_i| \tag{19}$$

$$\text{Mean Absolute Error (MAE)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}e_i^2} \tag{20}$$

Where n is the number of sampling interval, i , and e_i is the error between the reference and the output.

The controller with the minimum performance indices is considered to have the best performance among three controllers.

III. SIMULATION RESULTS

A. Simulation Set-up

The MPC, PI and PID controllers were applied to control the dosing pump model in the simulation experiments. Their performances were examined and compared using the parameters of the dosing pump stated in Table 1. The simulation experiments were set up using the MATLAB software package.

Table 1. Simulation Parameters

Parameters	**Values**
Motor torque constant	11.5
Pump torque constant	23.75
Viscous torque constant	0.0406
Total moment of inertia	3644 Nm
Flow rate of dosing pumps	90 L/h
Resistance	25
Operating voltage (single phase)	240

B. Servo-control response

Fig. 1 shows the comparison of servo-control of PI, PID and MPC of the dosing pump. At 2500s and 5000s, the angular velocity set-point has a step change of 0.05 rad/s. Also, at 5000s to 7500s, the angular velocity set point has a step change of 0.02 rad/s. From Fig 1, it can be observed that MPC has lowest overshoot and shortest settling time. From Table 2, the RMSE and MAE values of the MPC are the lowest when compared to the RMSE and MAE values of PID and PI. Thus, the servo-control or set point tracking of MPC is better than PI and PID controllers.

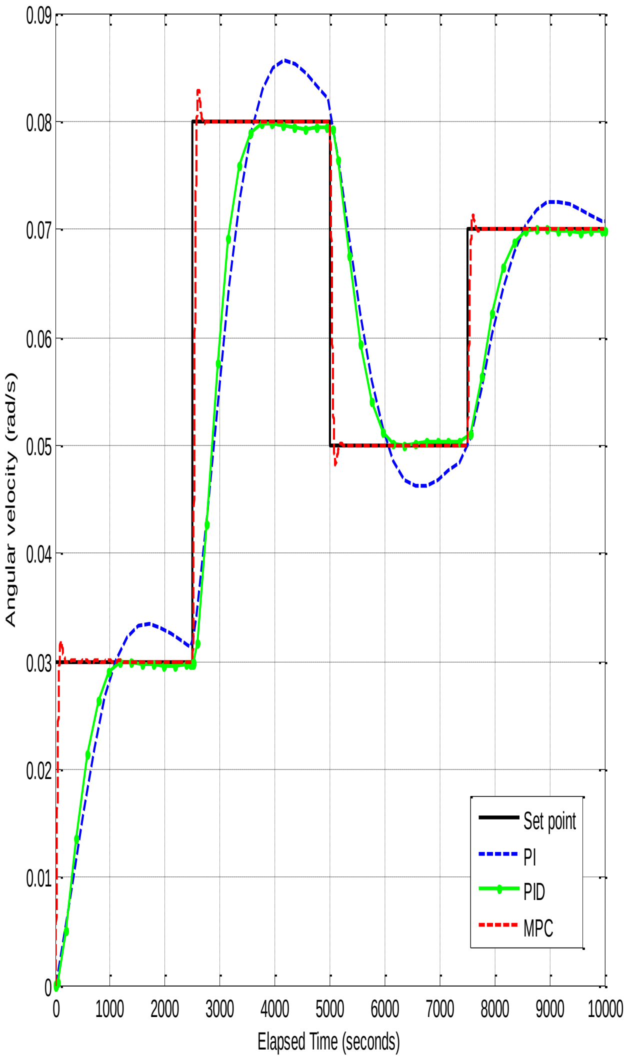

Fig. 1 Set point tracking response of the three controllers

C. Regulatory-control response

Fig 2 shows second simulation results of PI, PID and MPC under load disturbance test. The angular velocity was controlled to achieve target angular velocity at 0.05 rad/s in this instance. With the disturbance introduced to the dosing pump, the MPC performance is found to perform better than PI and PID controllers. The MPC maintained a level closer to the set point than PI and PID controllers. The MPC has an advantage of using the constraints to keep the level within the desired interval. The RMSE and MAE values of MPC were found to be the least and could be inferred to have best performance when compared with the remaining two controllers. The results of this study agreed with the findings in [5, 7-8].

Table 2 Performance Indices Of The Controllers

Controller	**RMSE**	**MAE**
PI	0.0024	0.0014
PID	0.0024	0.0013
MPC	4.37 x 10-4	8.38 x 10-5

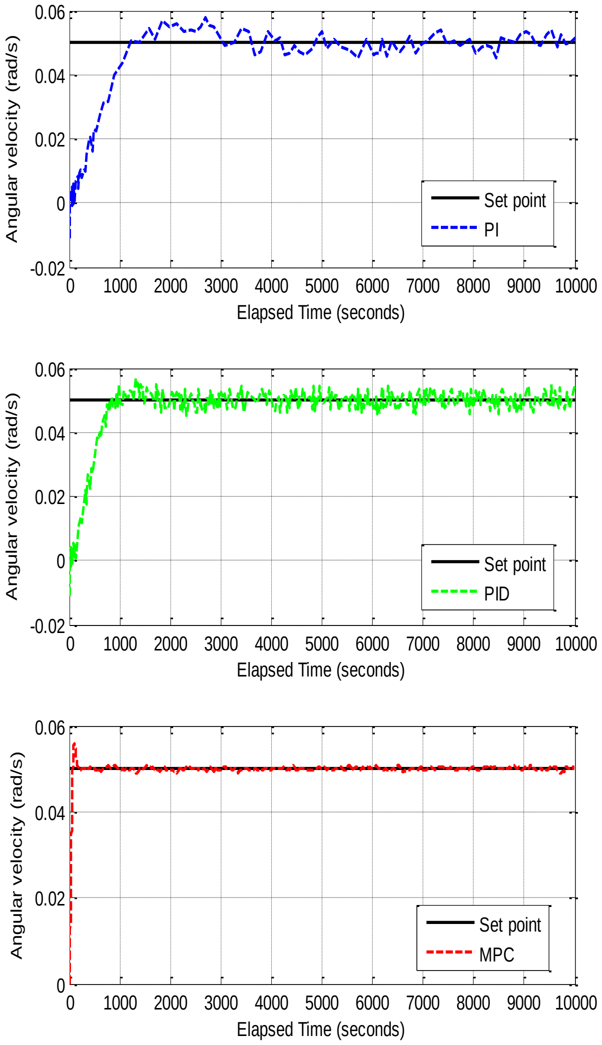

Fig. 2 Disturbance rejection response of the three controllers

Table 3. Performance Indices Of The Controllers

Controller	**RMSE**	**MAE**
PI	2.3 x 10^{-2}	1.41 x 10^{-2}
PID	0.13	5.8 x 10^{-2}
MPC	2.8x10^{-3}	2.47 x 10^{-4}

IV. CONCLUSION

The study examined and compared the performances of MPC, PI and PID controllers to control dosing pump for water treatment plants. The controllers were designed and implemented using MATLAB simulation software. The qualitative performances among MPC, PI and PID controllers is analysed in the time-domain plot of the step responses of the dosing pump. In addition, the comparison of the quantitative performances of the controlled system is done through two performance indices. The results of the simulation experiments showed that the MPC outperforms the PI and PID controllers for both servo-control and regulatory-control response. MPC demonstrated quick rise time, fast settling -time and zero overshoot compared to PID and PI controllers. MPC shows better set point tracking ability than PI and PID controllers. PI and PID suffers from overshoot but this was absent in the performance of MPC scheme. The settling time of MPC is lower than the settling time of PI and PID controllers. The findings of this study offer control system designers the capability of MPC as more preferred controller for dosing pumps to apply coagulation chemical to water under treatment. The future study will attempt to compare MPC with a variety of hybrid controllers and carry out validation using a pilot plant.

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