

A new technique to reduce overshoot in pneumatic positioning system

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Abstract

This paper presents a new approach for improving the performance of the pneumatic positioning system by incorporating a nonlinear gain function with observer system. System identification technique has been employed to represent the pneumatic system, while a model predictive control (MPC) with the observer system has been employed as the main controller to control the positioning of the system. The nonlinear gain function has been incorporated with the control strategy to compensate nonlinearities and uncertainties inherent in the parameters of the system. Unconstrained and constrained cases of control signals have been considered in this study. Simulation based on Matlab/Simulink indicated a reduction in overshoot of the system response for both cases due to additional nonlinear gain function in the strategy. Furthermore, remarkable enhancement was observed in effectiveness of this function while incorporated in constrained case, when this new strategy successfully improved the transient response in the pneumatic positioning system.

Keywords: model predictive control, nonlinear gain function, observer system, overshoot, pneumatic positioning control

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1. Introduction

Over the past decade, pneumatic actuator system has been widely used in numerous control applications, particularly in applications where control motion is required such as automotive, robotics and manufacturing [1]. However, the utilization of pneumatic system has been limited to certain applications due to difficulties associated to its performance, especially in terms of accuracy. A precise position control of the pneumatic system is known to be difficult to accomplish due to existence of nonlinearities and uncertainties in parameters of the system [2].

Various techniques have been reported to improve the performance of pneumatic positioning system. Extensive review of previously reported studies on the pneumatic system indicated the suitability of the predictive control to be utilized as a control strategy to control the positioning of the system [3-5]. This is due to the fact that this type of controller has the ability to predict the future outputs and take the control actions accordingly. A model predictive control (MPC) will be considered in this study. MPC is well known as a modern and effective control algorithm, owing to its successes in the process industries which deal with multivariable constrained control problems [6]. According to previous studies reported on control of the pneumatic positioning system, MPC is capable of reducing future tracking error at the end of prediction horizon, guarantees accurate tracking and can be implemented in a real-time experiment [7, 8]. Few studies [9, 10] suggested that the control strategy by utilizing MPC is able to consider input and output constraints presented in the particular system. Employment of MPC as a control strategy to control the pneumatic positioning system used in the present study has been evaluated in a study [11-14]. Constraint were applied to the input of the system in order to verify the effectiveness of the strategy in handling systems with constraints. Simulation results indicated the effectiveness of constrained MPC in comparison to unconstrained MPC in controlling the position of the system's cylinder stroke. Constrained MPC successfully produced better transient response and accurate tracking. However, overshoot is known as a major

concern, as the author expects generation of high overshoot as the system is being implemented in real-time environment. Recent study on the pneumatic utilized a combination of predictive control and the observer as a strategy for controlling the position of the cylinder stroke [5]. Results based on simulation and real-time experiment exhibited that the proposed method was sufficiently capable of controlling the pneumatic positioning system. However, overshoot remained as the main concern, especially when the method was implemented in a real-time experiment. This is due to the fact that in real-time environment the pneumatic system is highly nonlinear, due to the factors such as air compressibility and leakage, friction effect and uncertainties in parameters of the system [2].

Consequently, this study focuses on a technique to reduce overshoot in the response of pneumatic positioning system. Elimination or reduction of overshoot in the system response is of significance in order to achieve accurate and precise positioning control. Numerous methods has been reported regarding reduction of overshoot in the pneumatic positioning system. For instance, it was reported in few studies [15-18] that the overshoot in the pneumatic system was reduced by utilization of the nonlinear-proportional integral derivative (N-PID) controller as the control strategy. Furthermore in those studies, a nonlinear gain function was combined with PID controller as a strategy for controlling the cylinder stroke of pneumatic system. A payload with maximum weight up to 28 kg was attached to the end of the pneumatic cylinder stroke in order to investigate the capability of the proposed control method to perform as the load is implemented. Results based on simulation and real-time experiment indicated the capability of the proposed control method to control the pneumatic system by providing superior transient response and maintaining the performance under the variation of load up to 28 kg. Furthermore, reduction was observed in operation time of the cylinder stroke to reach the steady-state value. Moreover, this effectively reduce the overshoot in performance of the system, while this has been proven in various applications such as in robotics, milling systems, activated sludge and wastewater treatment process [19-22].

Due to stated considerations, this study proposes a new control technique to improve the pneumatic positioning system performance by incorporating a nonlinear gain function with the previous control strategy (predictive control with observer system). According to Syed Salim et al. [16-18], the overshoot in the system response can be significantly reduced by incorporating a nonlinear gain function with the control strategy, while enhancement can be observed in transient response of the pneumatic positioning system. To the author's knowledge, no study has been conducted with the proposed method of this study in order to control the pneumatic positioning system. It is believed that modification is highly necessary to ensure the efficiency of the control strategy, especially when implemented in the real-time experiment which involves nonlinearities and uncertainties in the system parameters. In this study, two cases of control signal (unconstrained and constrained) were evaluated, while the performance of this new strategy was compared with the strategy which does not employ a nonlinear gain function. In this present study, the simulation test was carried out in order to verify the effectiveness of the proposed strategy.

2. Research Method

Figure 1 depicts the pneumatic actuator system proposed in this study. The pneumatic actuator system in Figure 1 is equipped with optical sensor, laser stripe code, pressure sensor, on/off valves, and programmable system on chip (PSoC) control board. An optical sensor mounted at the top of the cylinder has been utilized to detect the smaller pitch of 0.01 mm on the stripe rod, while the pressure sensor has been employed to control the pressure inside the chamber (chamber 2). The PSoC control board integrated on the cylinder serves as a brain to control the whole operation of the system. As shown in Figure 1, two valves attached toward the end of the cylinder were employed to control the inlet and outlet air of the cylinder. Furthermore, the extension and retraction of the cylinder stroke are manipulated by the duty cycle of a pulse-width modulator (PWM) signal to drive the valves on the chamber (chamber 2). It must be mentioned that the pneumatic system utilized in this study is significantly different than any pneumatic actuator system available in the market. This is due to fact that the proposed system is mainly controlled by only one chamber (chamber 2), whereas the other chamber (chamber 1) is fixed at a constantly pressurized air (0.6 MPa). Hence, the proposed system in this study is considered to be unique.

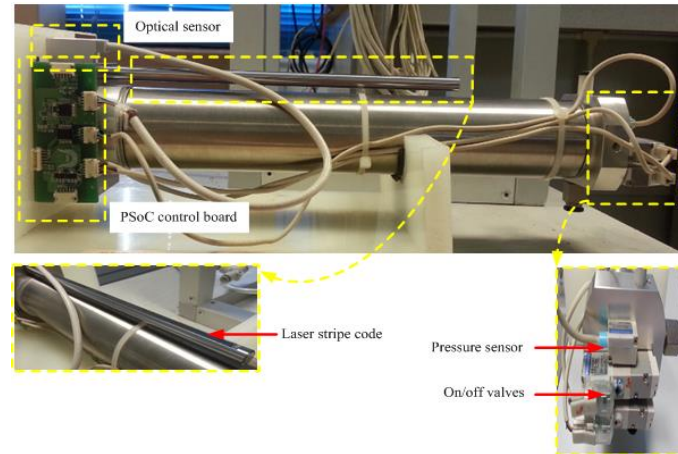


Figure 1. The pneumatic actuator system

2.1. Plant Mathematical Model

A mathematical model of the pneumatic actuator system utilized in this study was identified by means of an experimental approach, known as system identification. The techniques and procedures to generate a mathematical model of the pneumatic actuator system considered in this research are the same as described in the previous research [23]. 1500 measurements of input and output data were collected from a real-time experiment at sampling time (T_s) of 0.01 s. The input data contains 1500 data points of continuous step input signal applied to the valves, while the output is consist of 1500 measurements of the position signal. In this study, the auto-regressive with exogenous input (ARX) parametric model was chosen since it satisfies the criteria for system identification. The identified discrete state-space model based ARX model structure utilized throughout this study can be represented as (1).

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0.1284 & -0.9976 & 1.8690 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, C = [0.0016 \quad 0 \quad 0], D = [0] \quad (1)$$

The identified model fits the actual plant model at a value of approximately 91.09%. The loss of 8.91% may be caused by dead zone, friction, air leakage, etc. in the pneumatic system itself. The model is considered to be stable as it provides all the poles and zeros inside the unit circle. Thus, the identified model is sufficient to represents the pneumatic actuator system utilized in this study. In addition, the identified model is considered to be controllable and observable as it complies with the requirements of controllability and observability tests.

2.2. Controller Design

The main focuses of this study are to design a controller with the capability to provide a fast response with or without minimal overshoot and to achieve enhanced steady-state performance while maintaining the stroke of the pneumatic actuator system at the desired position. With these goals in mind, an additional function known as nonlinear gain function was incorporated with the observer system for the purpose of compensating the nonlinearities and uncertainties in the system parameters. Incorporation of this function to the observer system significantly reduced the system error while improving the transient response by reducing the overshoot in the system under control. Overall results indicated that this novel method was indeed highly accurate and efficient on improving the pneumatic positioning system that is subject to the constraint on its input signal.

2.2.1. Model Predictive Control (MPC)

The main strategy of this study is to maintain the position of the cylinder stroke at the desired level. The manipulated and controlled variables to be considered in this research are the signal to the valve and the position of the cylinder stroke, respectively. In this work, the MPC algorithm will be used to determine the future adjustments of the signal to the valve.

To do so, MPC will predict the future plant outputs and perform the control actions accordingly by solving the optimal future control actions (cost function and constraints). The cost function that reflects the control objective of the MPC algorithm can be expressed as in (2), while the optimal solution for the control signal can be defined as in (3) [24, 25].

$$J = (R_s - Y)^T (R_s - Y) + \Delta U^T \bar{R} \Delta U \quad (2)$$

where

$$R_s^T = \overbrace{[1 \quad 1 \quad \dots \quad 1]}^{n_p} r(k_i);$$

$$Y = Fx(k_i) + \Phi \Delta U;$$

$$F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ \vdots \\ CA^{n_p} \end{bmatrix}; \quad \Phi = \begin{bmatrix} CB & 0 & 0 & \dots & 0 \\ CAB & CB & 0 & \dots & 0 \\ CA^2B & CAB & CB & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & 0 \\ CA^{n_p-1}B & CA^{n_p-2}B & CA^{n_p-3}B & \dots & CA^{n_p-n_c}B \end{bmatrix}$$

$$\Delta U = (\Phi^T \Phi + \bar{R})^{-1} (R_s - Fx(k_i)) \quad (3)$$

where J is the cost function, R_s the set-point, Y the predicted output, ΔU the optimal control signal, \bar{R} the diagonal matrix ($=r_w I_{n_c \times n_c}$ ($r_w \geq 0$)), $x(k_i)$ the state variable at time k_i , $r(k_i)$ the set-point signal at time k_i , n_p the prediction horizon, and n_c the control horizon.

In this study, restrictions have been given to the control signal to determine to what extent does the signal influence the system response while evaluating the efficiency of the proposed control strategy in controlling the system with constraints on the input signal. A control signal in this study has been defined as a signal exported from the controller which will influence the system response (i.e. the position of the cylinder stroke). Thus, this signal should be controlled in order to ensure that it will always be in a range allowed by the system. Typically, overshoot will be generated in the system response as the signal exceeds the maximum allowable value. This phenomenon is known to occur frequently as the system is implemented in real-time environment. The maximum amplitude value allowed for the extension and retraction of the cylinder stroke during operation was set to +255 (for valve 1) and -255 (for valve 2), respectively. Thus, the signal from the MPC to the pneumatic actuator system (on/off valves) was constrained within the amplitude of ± 255 ($2^n - 1$; $n = 8$), as shown in (4):

$$u_{min} \leq u \leq u_{max} \quad (4)$$

where u is the control signal, u_{min} the minimum amplitude of the control signal and u_{max} the maximum amplitude of the control signal. MPC is well known as a model-based type controller. Based on the concept of MPC itself, the performance entirely depends on the model utilized to represent the process and the cost function to be minimized. However, the value of n_p , n_c , and r_w furthermore affects the cost function to be minimized while influencing the performance of MPC. Several studies have suggested denoting $n_p \gg n_c$ to avoid overshoot and oscillate response [26, 27]. In this study, the values designated for n_p and n_c are 20 and 3, respectively. Furthermore, the signal with an amplitude in range of ± 255 have been presented as constraints on the input signal in MPC algorithm.

2.2.2. Nonlinear Observer

To control the system by employing MPC in real-time environment, the design of state estimator/observer is essential. An observer system utilized in this study is basically a generalization of Luenberger observer and can be represented as in (5):

$$\begin{aligned} \hat{x} &= A\hat{x} + Bu + L(y - C\hat{x}) \\ y &= Cx \end{aligned} \quad (5)$$

where x is the system states, \hat{x} is the estimated states, u is the input variable, y is the actual output, and L is the gain of the observer. The term $L(y - C\hat{x})$ in the observer provides

the stability of the observer by generating a correction factor to the system. Based on (5), the stability of the system depends primarily on the value of gain (L). The pole-placement technique has been employed for this purpose while the poles are to be maintained in the unit circle to ensure the stability of the system. In this study, the nonlinear gain function will be employed to compensate the nonlinearities and uncertainties in the system parameters. This function will be utilized to control the error signal ($e(k)$) which will be subsequently used in the observer system. Controlling $e(k)$ is essential due to its influence on the formation of the control signal to the pneumatic actuator system. The key significance of utilization of this technique in this study is to adjust the observer gain (L) according to the output produced from this nonlinear function, known as the scaled error ($f(e)$), as described in (6):

$$f(e) = k_{nl}(e) \cdot e(k) \quad (6)$$

where

$$k_{nl}(e) = \frac{\exp^{\alpha e} + \exp^{-\alpha e}}{2};$$

$$e = \begin{cases} e & |e| \leq e_{max} \\ e_{max} \cdot \text{sign}(e) & |e| > e_{max} \end{cases}$$

the automatic gain adjustment ($k_{nl}(e)$) act as a nonlinear function of error ($e(k)$) and is bounded in the sector as described in (7).

$$1 \leq k_{nl}(e) \leq k_{nl}(e_{max}) \quad (7)$$

Incorporating the nonlinear gain function into observer system generates (8).

$$\dot{\hat{x}} = A\hat{x} + Bu + L[k_{nl}(e) \cdot e(k)] \quad (8)$$

Figure 2 illustrates the block diagram of the proposed nonlinear gain function connected in cascade with observer system. Based on the procedures and tests, the best value of the variation of nonlinear gain (α) and variation of error (e_{max}) are set to 10 and 0.1, respectively in order to ensure the stability in the system response. Generally, larger value of e_{max} will contribute to the largest overshoot, which will lead to instability in the system response. In addition, utilization of will lead to automatic adjustment of the value of the $k_{nl}(e)$ depending on the value of $e(k)$ that was generated at each time instant. In cases where error is not present, the system ($k_{nl}(e)$) will generate the value of 1, while the observer will react like any other conventional/linear observer since there is no participation of $k_{nl}(e)$ in the observer system. However, in instances where there is a presence of an error in the system, $k_{nl}(e)$ will participate and L will be adjusted accordingly to the value of $k_{nl}(e)$. Significant advantage regarding employment of this technique is the fact that the users are not required to tune the L value, but only the value of α is needed to be tuned.

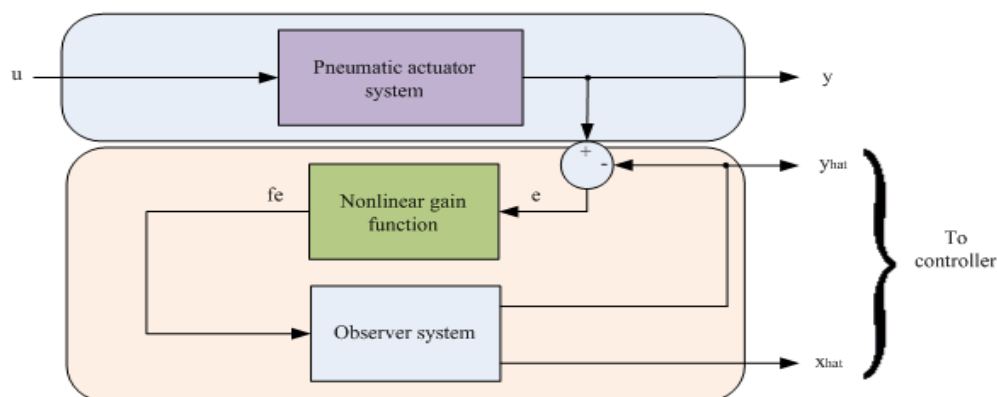


Figure 2. Block diagram of the proposed control strategy

3. Results and Analysis

This study was undertaken in order to improve the accuracy and precision of the pneumatic actuator's cylinder stroke in maintaining its position at the desired level. Thus, the proposed method is expected to improve the transient response as well as reducing the overshoot (OS), rise time (t_r) and settling time (t_s) of the system performance. A model predictive control with nonlinear observer (MPC-NO) was proposed in this study as the control strategy. Incorporation of the nonlinear gain function in the observer system to reduce overshoot in the system response is the key novelty of this study. The strategy has been performed in simulation test in order to evaluate its performance in controlling and maintaining the cylinder stroke of the pneumatic system at desired position. Two cases have been considered (unconstrained and constrained) and evaluated in conditions where the nonlinear gain function was either incorporated in its control strategy or was not. The signals to the on/off valves were limited to the maximum amplitude of ± 255 in constrained cases. Subsequently, these signals were incorporated into the MPC algorithm in order to provide a limitation to the on/off valves during operation. The performance of the proposed controller was compared in conditions where the nonlinear gain function for both unconstrained and constrained cases was included or not. The parameter values employed for the proposed strategy have been described and tabulated in Table 1. The values of the parameters employed for MPC have been obtained from the previous work [11].

Table 1. The Parameter Values Employed for the Proposed Controller

| Control strategies | Control parameters | | |
|--------------------|----------------------------------|--------------|---------------------------|
| | Name of parameter | Abbreviation | Value |
| MPC | Prediction horizon | n_p | 20 |
| | Control horizon | n_c | 3 |
| | Weight tuning | r_w | 0.01 |
| Observer | Observer poles | - | 0.0189, 0.0681, 0.0999 |
| | Observer gain | L | [0.8958 12.8045 21.5618]' |
| Nonlinear function | Rate variation of nonlinear gain | α | 10 |
| | Variation of error | e_{max} | 0.1 |

Figure 3 and Figure 4 both illustrate the corresponding responses of unconstrained and constrained MPC with and without possessing the nonlinear gain function in their observer system, respectively. A step input with final value of 100 mm was applied as a reference signal for both cases. This signal serves as a desired position to be achieved by a cylinder stroke of the pneumatic system during operation.

Figure 3 (a) shows the relation of control signal to the valve for unconstrained case. It can be seen that all of the controllers produced the signal exceeding the predetermined maximum value (+255, for the extension of the cylinder stroke), which surpasses the limits allowed. MPC without the observer system (MPC) was slower in reaching steady-state value in comparison to the controller with observer and nonlinear observer systems (MPC-O and MPC-NO). This finding indicates that MPC without the observer is less aggressive than MPC-O and MPC-NO in generating response toward the system. Performances of three different control strategies in controlling and maintaining the position of the cylinder stroke at 100 mm is illustrated in Figure 3 (b). Simulation results indicated that the transient response of the system improved by incorporation of the observer into the control strategy. Figure 3 (b) indicates that the overshoot in the system response reduced by 76% for MPC-O and 90% for MPC-NO. These results signify that the overshoot generated in the early process to achieve a position of 100 mm was significantly reduced due to incorporation of nonlinear gain function in the observer system. In terms of steady-state error (e_{ss}), MPC-NO showed lowest value of error in comparison to other strategies. Summary of the data obtained are tabulated in Table 2. Figure 4 (a) illustrates the response of the control signal to the valve for constrained case. The signal from the controller to the valve (valve 1) was limited to +255, contrary to the unconstrained case.

It can be seen in Figure 4 (a) that all the strategies successfully produced signals in an allowable range. Similar to the previous case, MPC without observer system is less aggressive than other strategies due to the fact that it took longer time to converge to steady-state value. Figure 4 (b) illustrates the responses of the cylinder stroke while maintaining its position at

100 mm in cases when the signal to the valve has a limitation. Results clearly indicated that incorporation of a nonlinear gain function with observer system enhances the cylinder stroke response while generating less overshoot in comparison to other control strategies. The percentage of overshoot ($\%OS$) reduced from 0.5236% to 0.0994% by addition of this nonlinear function into the strategy. Although reduction of overshoot among MPC-NO and MPC-O is not clearly obvious, however, the strategy of employing MPC-NO has proven that it can be utilized in the pneumatic system with constraint on the control signal. As expected, controlling the system by employing conventional MPC has contributed to the highest steady-state error (e_{ss}). Summary of the data obtained are tabulated in Table 2.

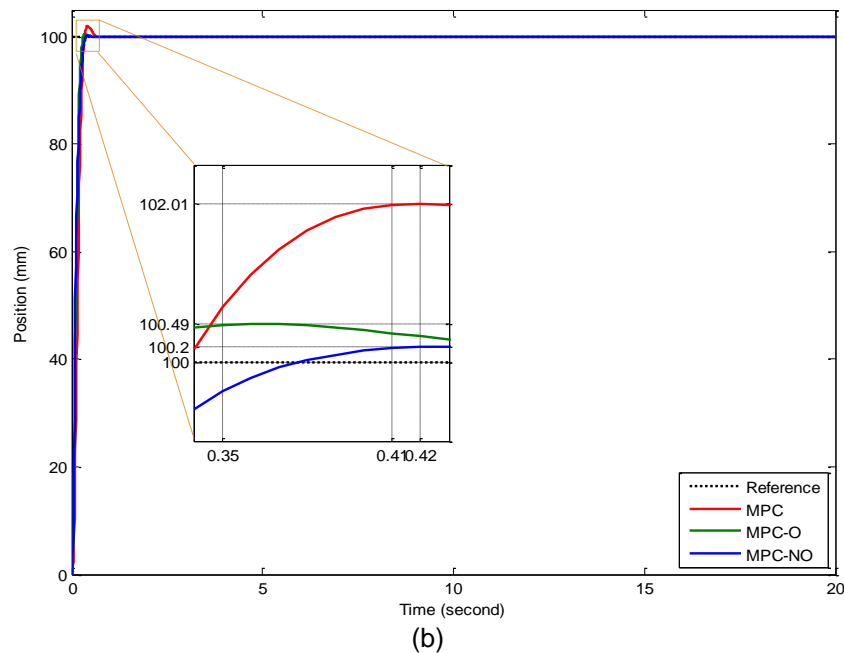
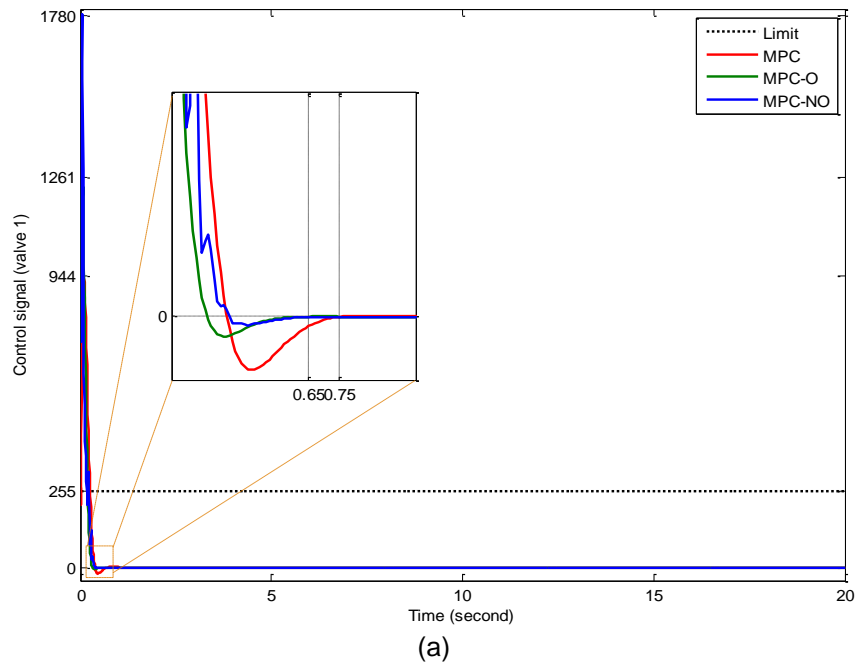


Figure 3. Simulation results for the unconstrained MPC: (a) control signal to the valve, (b) position of the cylinder stroke

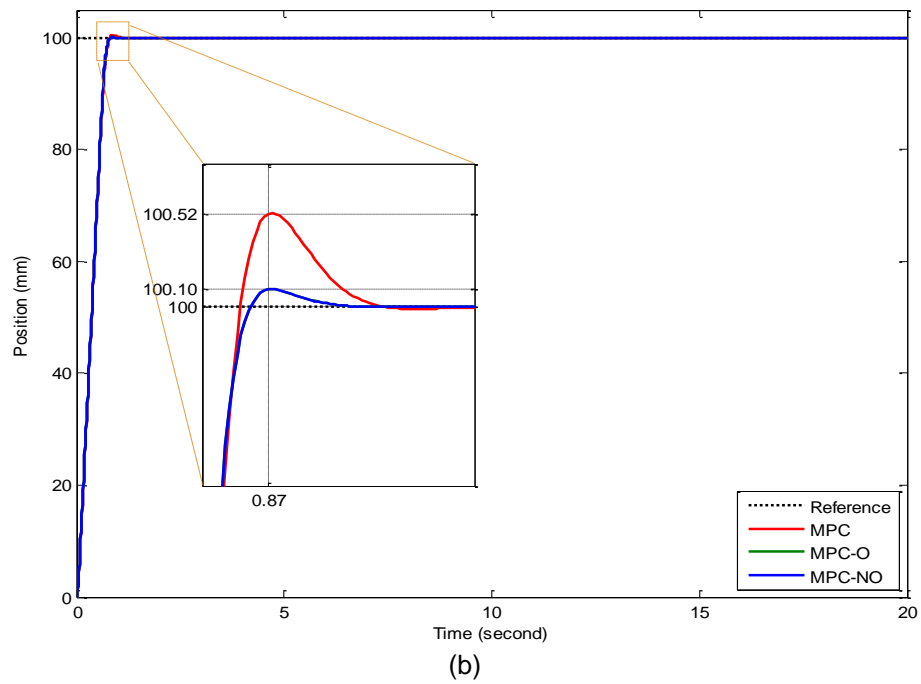
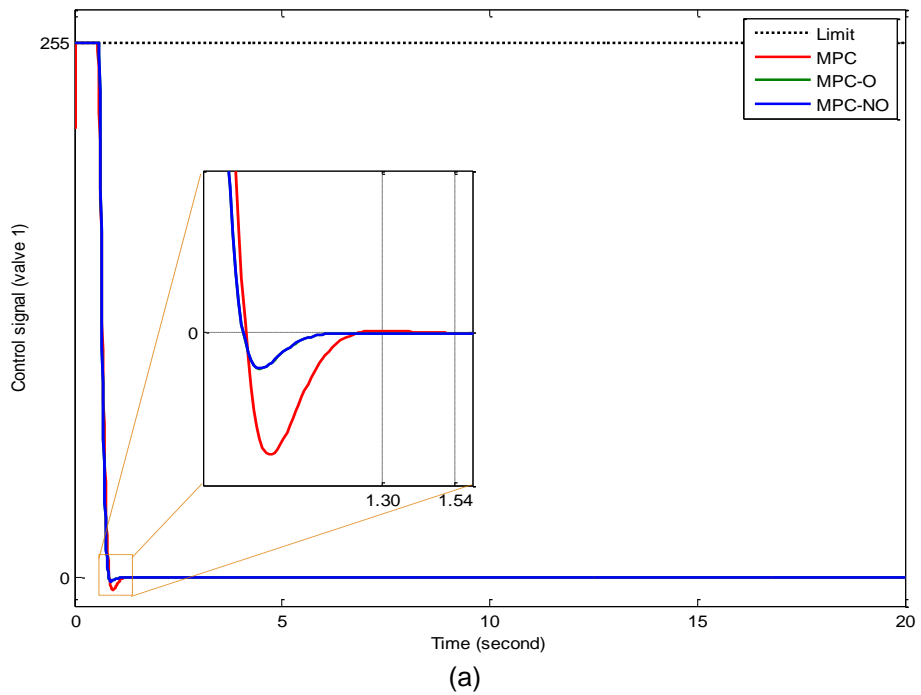


Figure 4. Simulation results for the constrained MPC: (a) control signal to the valve, (b) position of the cylinder stroke

Table 2. Comparison between Unconstrained and Constrained MPC

| | Unconstrained | | | Constrained | | |
|---------------------------------|---------------|----------|----------|-------------|----------|----------|
| | MPC-NO | MPC-O | MPC | MPC-NO | MPC-O | MPC |
| Percentage overshoot (%OS) | 0.1952% | 0.4863% | 2.0084% | 0.0994% | 0.0998% | 0.5236% |
| Rise time (t_r) | 0.1840 s | 0.1568 s | 0.1903 s | 0.5332 s | 0.5332 s | 0.5366 s |
| Settling time (t_s) | 0.2931 s | 0.2507 s | 0.4139 s | 0.7128 s | 0.7129 s | 0.7225 s |
| Peak time (t_p) | 0.4200 s | 0.3500 s | 0.4100 s | 0.8700 s | 0.8700 s | 0.8700 s |
| Steady-state error (e_{ss}) | ≈ 0 mm | ≈ 0 mm | ≈ 0 mm | 0 mm | ≈ 0 mm | ≈ 0 mm |

Based on the results obtained from the simulation test, it can be stated that the addition of nonlinear gain function into the observer system successfully managed to reduce the overshoot in the pneumatic positioning system response. The reduction was observed to be significant for the unconstrained case while values of t_r and t_s were effectively improved. Consequently, it can be stated that this study is in consistent with the previously reported studies [18-22] that indicated the effectiveness of incorporation of nonlinear gain function in significantly reducing the overshoot in the systems containing nonlinearities. This is due to the fact that the nonlinear gain function has the ability to minimize error and handle nonlinearities and uncertainties inherent in the system parameters, especially in real-time environment.

4. Conclusion

A new technique with the aim to reduce the overshoot and to ensure accurate and precise control of the pneumatic positioning system was proposed in this study. A nonlinear gain function was incorporated with observer system and the effect of incorporating this nonlinear gain function to the pneumatic positioning performance was evaluated. Simulation test was carried out in order to verify the performance of the proposed control strategy, while two cases (unconstrained and constrained) of control signals were considered. The performance of the observer system was remarkably enhanced by incorporation of the nonlinear gain function. Enhancement was observed to be superior in constrained case. Acquired results based on simulation test indicated the effectiveness of this novel control strategy in drastically reducing the overshoot in the system response by 90% in unconstrained case and 54% in constrained case. Furthermore, addition of the nonlinear gain function improved the rise time (t_r) and settling time (t_s) of the system response for constrained case. Incorporation of this nonlinear function has guaranteed the reduction of overshoot in the pneumatic system, providing more accurate and precise positioning control. Additionally, the proposed strategy in this study is able to implement constraints in the system, which signifies the potential of this method to be employed in the industries that involve control motion in their applications.

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