Constrained control of hot air blower system under output delay using globally stable performance-based anti-windup approach [†]

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Abstract

This paper describes the design and implementation of a linear controller with an Anti-Windup Compensator (AWC) for a hot air blower system having output delays, under actuator saturation constraint and noise. Traditional Anti-Windup (AW) schemes for time-delay systems are based on either local stability or global stability with performance restrictions. We modify an existing AWC architecture using a time-delay term in the compensator in order to ensure global stability and performance. It is also shown that the existing Linear Matrix Inequalities (LMIs) based optimization schemes for AWC, which are derived using the decoupled architecture and co-prime factorization, can be applied to the modified AWC architecture. This modified delay independent AWC scheme is applied to a hot air blower system and practical results are discussed. This paper aims to support the industrial application of the modified AWC ensuring global stability and performance, by applying it to a hot air blower system under actuator situation and output delay as well as electrical and thermal noises.

Keywords: System identification; PI controller; Anti-windup compensator; Air blower; Output delay

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1. Introduction

Temperature is an important control variable like flow rate and motor speed in thermal machines. For industrial applications, temperature needs to be finely controlled with consideration of equipment safety [1-4]. Saturation nonlinearity can lead to dangerous results when appropriate windup prevention is not provided. In the past, saturation has caused many accidents like the meltdown of the Chernobyl nuclear power plant [5]. Electrical furnaces used in industries operate at very high temperatures. At such high temperatures, lag, overshoot and instability of the plant due to saturation may cause dangerous results. In addition to saturation, delays can make such windup prevention difficult [6-9].

Anti-windup design and implementation has been studied extensively in the last decade. It is an additional controller (or collection of controllers) which are activated when the control signal or sensor output is under saturation and tries to recover the linear behavior of the closed-loop system. The main issues of anti-windup design and implementation are robustness, local and global stability, amplitude and rate saturation, per-

formance, computation reduction, architecture compactness and feasibility of solution [5]. Anti-windup techniques have also been implemented for experimental setups and practical applications (see [10-12]).

AWC designs for time-delay systems under actuator saturation are rare. Mostly, AWC design techniques [13, 14] achieved its local stability with consideration of enlarging the basin of attraction. Some techniques like [13] discussed global stability, but their performance was limited. Also, those techniques considering global stability were found to have infeasible results. On the other hand, the technique in [15] provides the global stability and robust performance and can be applied to both stable and marginally stable plants; but, one drawback is that it uses an open loop plant as anti-windup filter, which limits the system performance due to the presence of slow poles in the plant [16]. Moreover, a practical implementation of AWC techniques for time-delay systems is required to provide a solution that fulfills industrial needs and demands.

Decoupled architecture based AW techniques [16-19] using co-prime factors of the plant are very powerful in achieving global stability and performance. These techniques always give a feasible solution for linear stable plants without delays. In contrast to [15], these techniques have no limitation due to use of the open loop plant in the AWC architecture. But such techniques are not applicable to time-delay systems. In this
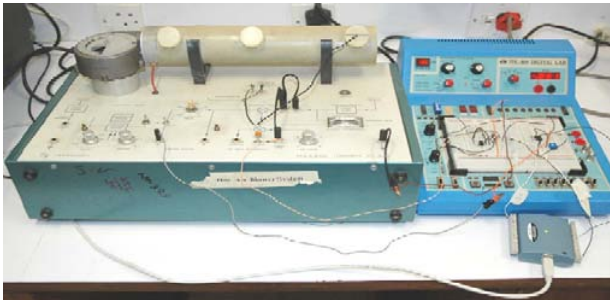
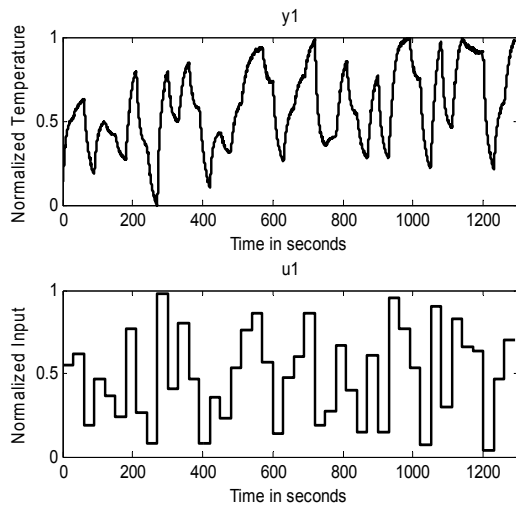Fig. 1. Hot air blower system PT326 interfaced with a computer.

Fig. 2. Input-output data for system identification (experimental results).
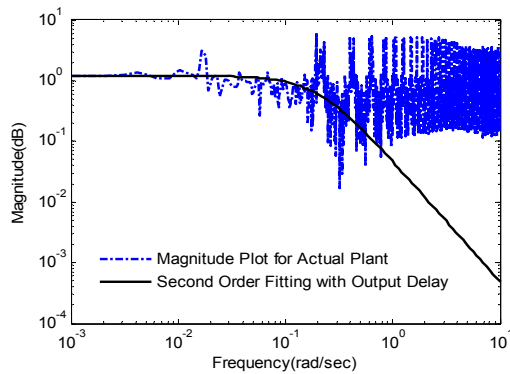

Fig. 3. Magnitude plots for actual and identified plants.

paper, we modify the architecture of [16] for systems with output delays to solve the problem of windup which ensure global stability and performance with feasibility. The modified architecture uses an existing linear matrix inequality [19] to find the anti-windup parameters. Hence, the modified AW design in our case is independent of the delay term present in the plant or AWC, unlike the traditional AWC designs. The proposed architecture has been successfully applied to a hot air blower system (PT326 [20] interfaced with a computer).

In this paper, we consider a constrained control of a hot air blower system with time-delays. The plant model is identified

using the uniform random number system identification technique. Signal conditioning is done by implementing a low pass filter. A PI controller is designed and implemented. It is found that the closed-loop system gives undesirable results due to windup caused by integral action. The proposed AWC is successfully applied to the hot air blower system. Implementation details and experimental results are also demonstrated at the end of the paper.

2. System description, identification and conditioning

The PT 326 system consists of a heater and a fan to blow hot air through a tunnel. A thermister is attached to the tunnel to sense the temperature of the hot air. The thermisters can be inserted at three different locations in the tunnel having different output delays. This system is interfaced with a computer through the 1208fs USB based module as shown in Fig. 1. To vary the operating power of the heater, 0~4 V input can be applied via the computer. The output of this system, in the form of voltage, is accessible to the computer. To convert the measured voltage signal V into temperature T, the following third order calibration equation is implemented:

$$T = 0.072V^3 - 0.3033V^2 + 2.2459V + 38.1792. \qquad (1)$$

The plant model is identified using an identification technique of uniformly distributed numbers similar to that in [11, 12]. For system identification, uniform random numbers (at every 30 sec) are applied at the plant input and output is recorded with a sampling time of 0.1 sec as shown in Fig. 2. This input-output plot can be used to obtain the magnitude plot for system identification in a similar way described in [11, 12]. Fig. 3 shows two magnitude plots: The dotted line is the actual magnitude plot of the plant obtained using MATLAB® command (etfe) and the solid one is an approximated magnitude plot by a second order transfer function. The second order transfer function is chosen in such a way that it can model the actual plant sufficiently close. A higher order model can be chosen, but it will be difficult to design a controller and an AWC with a higher order model (see [18]). The operation range of the plant is considered to 0.2 rad/sec. The identified plant is as follows:

$$G(s) = e^{-0.6s}G_p(s), G_p(s) = \frac{1.2}{25s^2 + 10s + 1}. \qquad (2)$$

An output delay in the plant is identified by finding a lag present in the step response. Note that the plant model (2) is identified with normalized input-output data. Hence, a proper input-output normalization is required for the practical implementation of a controller. In order to cancel the effects from noise, the following low pass filter is used:

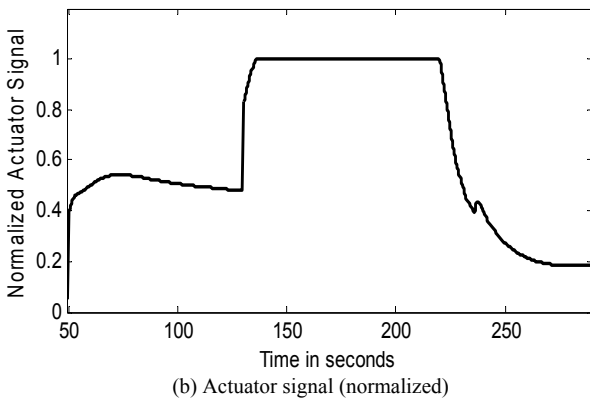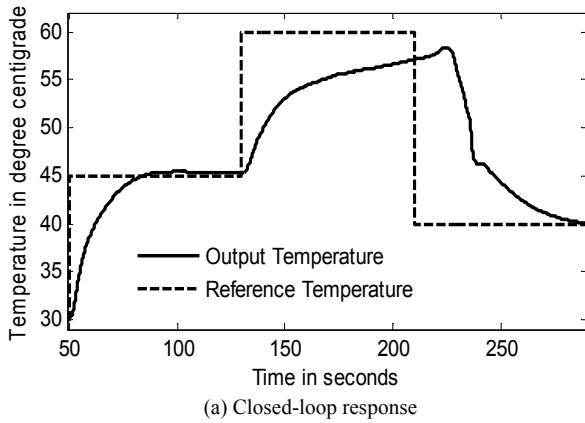$$H(s) = \frac{4}{s^2 + 4s + 4}. \qquad (3)$$

Fig. 4. Closed-loop response with a PI controller: A windup effect is shown due to actuator saturation (experimental results).

From Fig. 3, it is evident that the noise is present at higher frequencies, so the use of the low pass filter (Eq. (3)) is justified for noise removal. This filter is discretized using zero order hold (ZOH) of a sampling time 0.1 sec.

3. Linear controller design and implementation

An optimal PI controller is designed for the plant in Eq. (2) using the response optimization tool of MATLAB®, providing a rise time of 15.6 sec, settling time of 21 sec and overshoot less than 1 percent for the closed-loop system. The PI controller is given as follows:

$$K(s) = 0.6643 + \frac{0.0899}{s}. \tag{4}$$

The controller (Eq. (4)) is discretized using ZOH for a sampling time of 0.1 sec and implemented for the hot air blower system. Because the controller is designed for a normalized input, the error signal is divided by 30 (as temperature ranges from 30 °C to 60 °C). The normalized output of the controller is passed through a soft saturation of [0 1] implemented in the computer and then multiplied by 4 to feed it into the plant [21]. Fig. 4 (a) and (b) show the output response and the normalized actuator signal using this PI controller. The output response tracks the reference with some lag when the actuator signal is
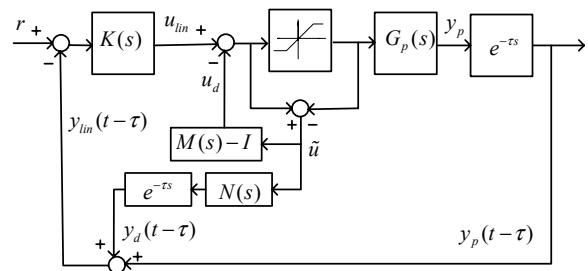

Fig. 5. Proposed AW architecture for the systems with input saturation and output delays.

saturated, which clearly indicates the windup. The lag is due to integral action of PI controller and causes windup effect (see details in [11, 12 and 18]).

4. AWC architecture and design

The proposed AWC architecture is shown in Fig. 5. Here $M(s)$ and $N(s)$ are parts of the co-prime factors of the plant as in [16-19]. The additional term included in the architecture is the lag term $e^{-\tau s}$ same as in the plant model. Because the plant output has a lag, it must be compensated with the same delay. The detailed functioning of the decoupled architecture for windup compensation using $M(s)$ and $N(s)$ can be explicitly found in [16, 19]. Our objective is to prove the stability and performance of the architecture of Fig. 5 by the addition of the delay term [22, 23] and to apply the architecture for the new scenario.

Remark 1: The addition of delay term $e^{-\tau s}$ in AWC is similar to what was done in [15], but the architecture of Fig. 5 gives better performance and less conservative results for stable plants because it uses the co-prime factorization of the plant for compensation rather than the plant model itself. The use of a plant model in AWC gives conservative results due to the slow poles in the plant.

Remark 2: An AWC will always exist for the architecture of Fig. 5 because, at least for $M(s) = I$, the architecture reduces to Internal Model Compensator (IMC) in similar fashion as for the architecture in [16].

The proposed architecture is valid for the system whose open loop is asymptotically stable, and satisfies the well-posedness and the asymptotic stability of the closed-loop system without considering saturation, as seen in [19]. Fig. 6 shows an equivalent decoupled architecture of Fig. 5. In order to obtain a linear performance, one has to minimize the L_2 gain from u_{lin} to $y_d(t - \tau)$. But the delays present in the non-linear part of the decoupled architecture complicate the design and create problems in developing Linear Matrix Inequalities (LMI), ensuring global stability and performance. So we further reshape the architecture of Fig. 6 to obtain the decoupled non-linear part independent of the delay term.

Fig. 7 shows an equivalent reshaped decoupled architecture of Fig. 6, in which the decoupled nonlinear part is independent of the delay term. In Fig. 6, $y_{lin}(t - \tau)$ minus $y_d(t - \tau)$ pro-
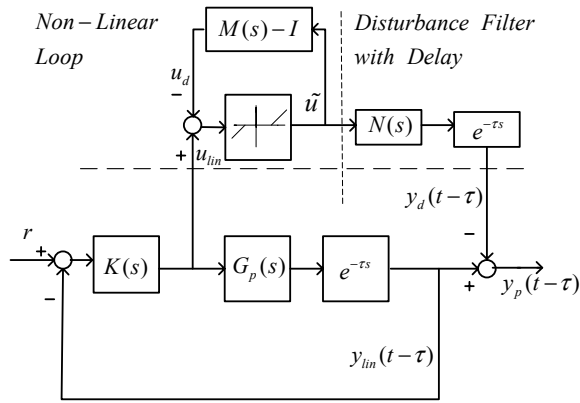
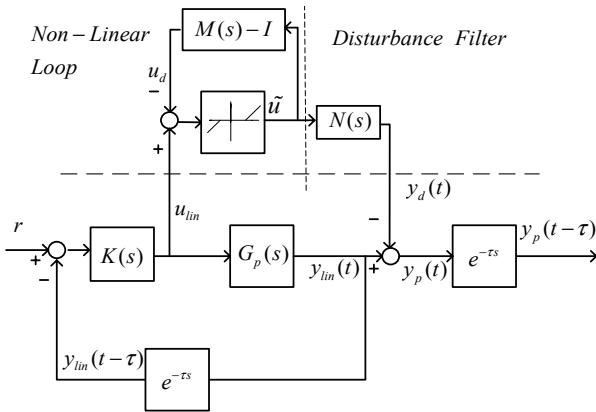Fig. 6. Equivalent architecture of Fig. 5 with decoupled linear and non-linear parts.

Fig. 7. Modified equivalent decoupled architecture with non-linear part independent of delay.

duces $y_p(t-\tau)$, whereas in Fig. 7, $y_{lin}(t)$ minus $y_d(t)$ produces $y_p(t)$ and then it is passed through the delay term $e^{-\tau s}$ to yield $y_p(t-\tau)$.

The only requirement for the stability of the architecture of Fig. 7 is to stabilize the system from u_{lin} to y_d (because the linear part is already stable). Hence in order to achieve stability and linear performance, one has to minimize L_2 gain γ, from u_{lin} to y_d as clear from Fig. 7. The advantage of this modified decoupled architecture is that the optimization of $M(s)-I$ and $N(s)$ becomes independent of the delay term. Hence, a globally stable AWC can be found for the proposed architecture by using the LMI based optimization for a full order AWC, derived in [19, 24] and given by

minimize γ
such that
$$\begin{bmatrix} X & B_pU-L^T & 0 & QC_p^T+L^TD_p^T \\ * & -2U & I & UD_p^T \\ * & * & -\gamma I & 0 \\ * & * & * & -\gamma I \end{bmatrix} < 0 , \qquad (5)$$

where $X = QA_p^T + A_pQ + L^TB_p^T + B_pL$, with $Q > 0$, $U > 0$

and diagonal, $\gamma > 0$ and L as LMI variables. Further F can be found from $F = LQ^{-1}$ and used to determine $M(s)-I$ and $N(s)$ with the following state space.

$$\begin{bmatrix} M(s)-I \\ N(s) \end{bmatrix} \sim \left[\begin{array}{c|c} A_p + B_pF & B_p \\ \hline F & 0 \\ C_p + D_pF & D_p \end{array} \right]. \qquad (6)$$

Here, (A_p, B_p, C_p, D_p) forms the state space of plant $G(s)$ as

$$G_p(s) \sim \left[\begin{array}{c|c} A_p & B_p \\ \hline C_p & D_p \end{array} \right]. \qquad (7)$$

Using the LMI based optimization of (5), the following values of F and γ are obtained for the hot air blower system.

$$F = \begin{bmatrix} -1.6358\times10^4 & -0.5206\times10^4 \end{bmatrix}, \gamma = 1.2. \qquad (8)$$

In Eq. (3), the filter $H(s)$ has poles at (-2, -2), whereas the plant (Eq. (2)) has poles at (-0.2, -0.2). Also, the filter is to have unity gain. Since the dynamics of the filter is very fast (ten times fast) and it has unity gain, it can be excluded in the AWC design. In this case, the filter can remove high frequency noises without affecting the plant output. Using the value of F in (6), we obtained the following AWC parameters for the present case:

$$\theta_1(s) = M(s) - I = \frac{-16360\,s - 5206}{s^2 + 16360\,s + 5206} , \qquad (9)$$

$$\theta_2(s) = e^{-\tau s}N(s) = e^{-0.6s}\frac{0.048}{s^2 + 16360\,s + 5206}. \qquad (10)$$

For implementation, $\theta_1(s)$ and $\theta_2(s)$ are discretized using first order hold (FOH) with a sampling time of 0.1 sec. In order to reduce the memory use due to the delay term in $\theta_2(s)$, one can also use the Pade approximation.

Remark 3: The proposed method uses the existing LMI based optimization of [19, 24] which is applicable for systems without delays. Hence our proposed architecture contains delays similar to [15] but, unlike that in [15], the optimization is independent from the delays. Therefore, the AWC design is simpler because the existing LMI based optimization approach is used.

5. Controller and AWC implementation

Fig. 8 shows the overall diagram of the closed-loop system [25-28] including the linear controller, calibration equation, filter and AWC parameters. The output of the plant is converted into temperature using a calibration equation. The noise present in the temperature output is filtered using $H(z)$. The difference between the reference and the measured temperature is normalized by using a gain k_I. This normalized error
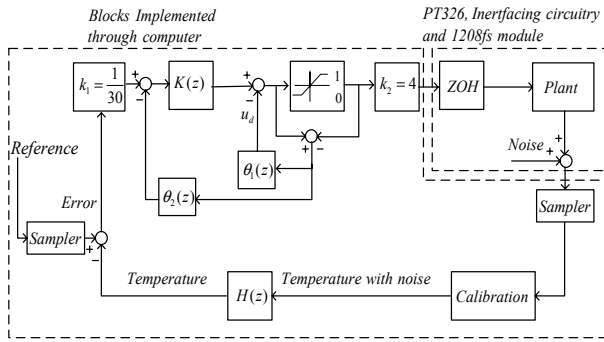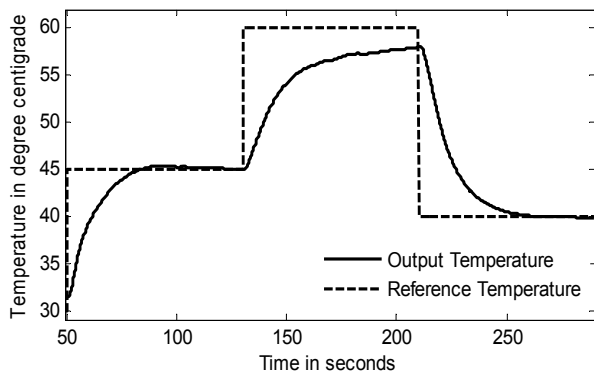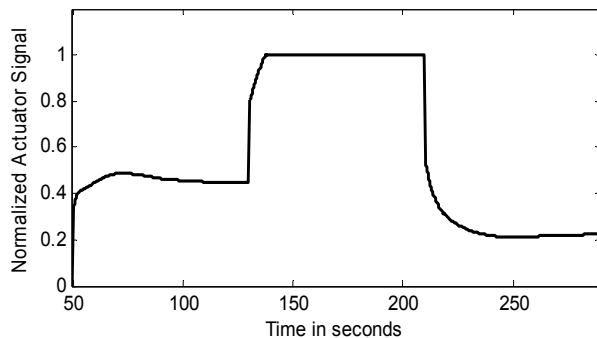
Fig. 8. Entire closed-loop system with the AWC proposed for a hot air blower system.

(a) Closed-loop response

(b) Actuator signal (normalized)

Fig. 9. Closed-loop response with the proposed AWC (experimental results).

is passed through the controller $K(z)$. Similarly a gain k_2 is used to convert the normalized actuator signal into the required plant input. Because anti-windup parameters θ_1 and θ_2 are designed using normalized plant $G(s)$, so their input is the difference of the normalized saturation block input and output. The output of θ_1 and θ_2 is used to compensate the controller input and output (which are also normalized signals). Normalized saturation of [0 1] is implemented in the computer, which also provides a saturated signal of [0 4] to the plant, by using the gain k.

It is important to note that the output of $\theta_2(z)$ is subtracted by the normalized error signal rather than added at the normalized plant output as shown in Fig. 8. Either way results in the

same effect on the overall closed-loop response but the former requires less computation. Fig. 9 (a) and (b) show the closed-loop response and normalized actuator signal with the proposed AWC. It can be seen that the closed-loop response has no lag due to saturation. It tracks the reference signal. Windup is prevented for the hot air blower system. The normalized actuator signal no longer remains under saturation, when reference changes from 60 $^{\circ}$C to 40 $^{\circ}$C at the time of 160s. To validate the proposed design, the simulations results for closed-loop response with AWC are also given in Appendix A. It can be seen that the simulation results are similar to experimental results.

Further, we used the first order Pade approximation of the delay term present in θ_2 and implemented it in the same way as shown in Fig. 8. The results of the closed-loop output and normalized actuator signal obtained with the Pade approximation are similar to Fig. 9 (a) and (b) and those shown in Appendix B.

6. Conclusions

In this paper, we addressed the constrained control of a hot air blower system under output delays, noise and actuator saturation. Different steps for control of the plant such as system identification, canceling of noise, PI control and AWC design and implementation were described. The existing globally stable AWC technique for linear systems without time-delays was modified for systems having an output lag by including a delay term in the compensator. This addition solved the problem of AWC design and ensured global stability and performance for stable processes with output delays and actuator saturation. The proposed AWC structure was successful for the hot air blower system, so it can be used for industrial processes. To reduce the memory consumption due to the output delay term, Pade approximation can also be a useful solution.

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Appendix

A. Simulation results

Fig. A.1(a) and (b) show the simulation results of the closed-loop responses and the normalized actuator signals using the proposed AWC, respectively. The response without AWC and with actuator saturation has a lag, similar to the experimental results of Fig. 4. The response with AWC and with actuator saturation has no lag, similar to the experimental results of Fig. 9. Hence, the simulation results are similar to the experimental results with same trends. Overall simulation behavior has some differences in terms of overshoot and rise time with experimental results because the actual plant is nonlinear.

B. AWC with Pade approximation of delay

The closed-loop response and the normalized actuator signal for the AWC with the first order Pade approximation of θ_2 are shown in Fig. A.2(a) and (b), respectively. These re-
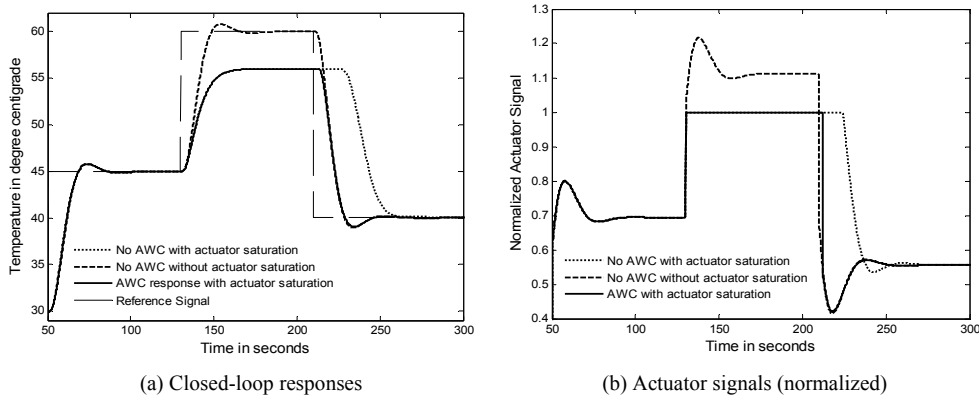
(a) Closed-loop responses

(b) Actuator signals (normalized)

Fig. A.1. Performance of the proposed AWC under actuator saturation (simulation results).

(a) Closed-loop response
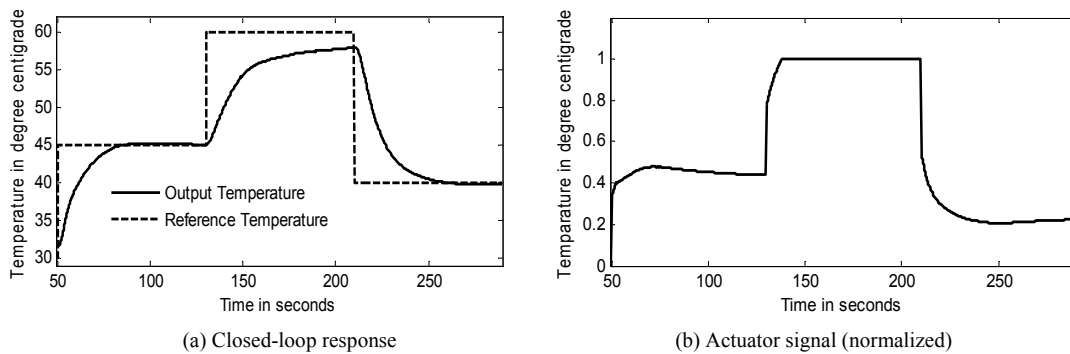

(b) Actuator signal (normalized)

Fig. A.2. Closed-loop output response with the first order Pade approximation of θ_2 (experimental results).

sponses are similar to the results of AWC without Pade approximation, see Fig. 9(a) and (b). As the order of Pade approximation increases, the performance of the AWC will get close to Fig. 9.

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