Improvement of Practical Control Method for Positioning Systems in the Presence of Actuator Saturation by Incorporating Takagi-Sugeno(TSK) Fuzzy Anti-reset Windup

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Abstract: Positioning system is widely used for many practical applications. This system requires a good controller to achieve high accuracy and fast response with simple and self-adjustable design. In order to satisfy the above requirements, a new practical controller for positioning systems, namely nominal characteristic trajectory following (NCTF) controller with PI compensator, has been proposed. However, the effect of actuator saturation can not be completely compensated for integrator windup when the object parameters vary. This paper presents a method to improve the NCTF controller by overcoming the problem of integrator windup by adopting a fuzzy system. The improvement of the NCTF controller is evaluated through simulation using a rotary positioning system. The simulation result has demonstrated the effectiveness of the compensated NCTF in overcoming the problem of integrator windup.

Keywords: Positioning system, NCTF controller, fuzzy system, anti-windup, robustness

1. INTRODUCTION

Motion control systems play important roles in industrial application such as machine tools, semiconductor manufacturing systems and robotic systems. One type of motion control systems is the point-to-point (PTP) positioning system, which is used to move an object from one point to another. The positioning systems generally need a good controller to satisfy some requirements such as high accuracy, fast response and robustness. Many types of controllers have been proposed and evaluated for positioning systems such as controllers with disturbance observer [1-4], time-optimal controllers [5-8] and sliding mode controllers [9,10]. These controllers will give good performance if the engineering designers are familiar with the motion control system. The designers also need to have a good knowledge regarding the design of the controller using the exact model and values of its parameters. In addition, advanced controllers tend to be complicated and require deep knowledge of controller theory and design. Moreover, exact modeling and parameter identifications are generally troublesome and time-consuming tasks. Consequently, the simplicity of controller design and its structure are very important in practical application.

In order to overcome these problems, nominal characteristic trajectory following (NCTF) controller has been proposed as a practical controller for point-to-point (PTP) positioning systems [11]. It has been shown that, the NCTF control system has a good positioning performance and robustness [12,13]. The NCTF controller is also effective to compensate the effect of the friction, which is the source of positioning inaccuracy [14]. However, the effect of actuator saturation cannot be completely compensated due to integrator windup when the object parameters vary [15]. The NCTF controller gives an excessive overshoot when both actuator saturation and parameter variations (especially inertia variation) occur in the positioning systems.

This paper describes one method to improve the NCTF controller for overcoming the degradation of the positioning performance due to integrator windup. In section 2 NCTF control concept and its controller design procedure are introduced while section 3 deals with the improvement of compensator with a fuzzy anti-windup. The experiment of setup and the simulation results are discussed in section 4 whereas the conclusion is given in section 5.

2. APPROACH AND METHODS

2.1 Basic Concept of NCTF Control

The structure of the NCTF control system is shown in Figure 1. The NCTF controller consists of a nominal characteristic trajectory (NCT) and a compensator. The NCTF controller works under the following two assumptions:

1. A DC or an AC servomotor is used as an actuator for the object.
2. PTP positioning systems are discussed in reference [11], so θ_r is constant.

Here, the objective of the NCTF controller is to make the object motion follow the NCT and end at the origin of the phase plane $(e, \dot{e})$.

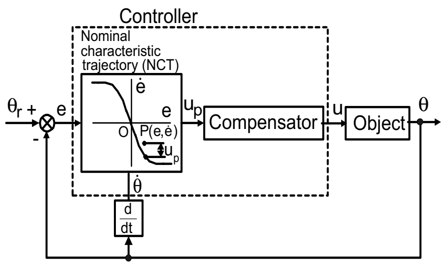


Fig. 1 NCTF control system

Figure 2 shows an example of object motion controlled with the NCTF controller. The motion comprises two phases. First phase is the reaching phase and the other one is the following phase. In the reaching phase, the compensator forces the object motion to reach the NCT as fast as possible. Then, in the following phase, the compensator controls the object motions to follow the NCT and end at the origin. The object movement stops at the origin, which represents the end of the positioning motion. Thus in the NCTF control system, the NCT governs the positioning response performance.

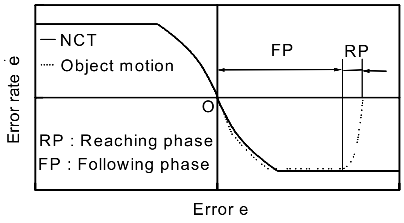


Fig. 2 NCT and object motion

The NCTF controller is designed based on a simple open-loop experiment of the object as follows:

1. Open-loop-drive the object with stepwise inputs and measure the displacement and velocity responses of the object. Figure 3(a) shows the stepwise inputs, the velocity and displacement responses due to the stepwise inputs. In this paper, the rated input to the actuator u_r is used as height of the stepwise inputs.
2. Construct the NCT by using the object responses.
   The velocity and displacement responses are used to determine the NCT. Since the main objective of PTP system is to stop an object at certain position, a deceleration process (curve in area A of Figure 3(a)) is used. Variable h in Figure 3 is the maximum motion velocity. From the curve in the area A and h in Figure 3(a), the NCT in Figure 3(b) is determined. Since the NCT is constructed based on the actual responses of the object, the NCT includes nonlinearity effects such as friction and saturation. The important NCT information, which will be used to design the compensator, are NCT inclination 'm' near the origin and maximum error rate 'h'. In this case, from the relationship between controlled-object dynamics of Eq. (1) and Figure 3(b), it is clear that the inclination near origin m and the maximum error rate h relate with parameters of the controlled-object as follows [12,15]:

$$K = -\frac{h}{u_r} \quad . \tag{1}$$

$$\alpha = -m \quad . \tag{2}$$

3. Design the compensator using the NCT information.
   Here, the following PI compensator is adopted due to its simplicity:

$$u = K_p u_p + K_i \int u_p dt \quad . \tag{3}$$

Here K_p and K_i are proportional and integral gains respectively. Using the PI compensator parameters K_p and K_i, and the NCT characteristic near the origin (see Figure 3(b)), the transfer function of the closed-loop positioning system controlled by the NCTF controller can be approximated as follows [11-15]:

$$\frac{\Theta(s)}{\Theta_r(s)} = G(s) = G_1(s)G_2(s) \tag{4}$$

where

$$G_1(s) = \frac{\alpha}{s+\alpha} \quad , \tag{5.a}$$

$$G_2(s) = \frac{2\zeta\omega_n + \omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \quad , \tag{5.b}$$

$$K_p = \frac{2\zeta\omega_n}{K\alpha} \quad , \tag{5.c}$$

$$K_i = \frac{\omega_n^2}{K\alpha} \quad . \tag{5.d}$$

When ζ and ω_n are large enough, G(s) becomes nearly equal to $G_1(s)$, which represent the condition when the object motion follows the NCT as the objective of the NCTF control system. Moreover, large ζ and ω_n also make the closed-loop system robust to friction or inertia variation of the object in the continuous systems [9]. Finally, by using ζ and ω_n as design parameters and considering Eq. (2) and (3), the PI compensator parameters are designed as follows:

$$K_p = \frac{2\zeta\omega_n u_r}{mh} \quad , \tag{6}$$

$$K_i = \frac{\omega_n^2 u_r}{mh} \quad . \tag{7}$$

Here, ω_n and ζ are design parameters which should be decided by the designer. Generally speaking, a higher ω and a larger ζ are preferable in the design of PI compensator parameters. However, digital implementation of the NCTF controller limits the design parameters to maintain the closed-loop stability. Detailed discussion on the theoretical background of the NCTF control system can be found in [12,15].

Due to the fact that the NCT and the compensator are constructed from a simple open-loop experiment of the object, the exact model including the friction characteristic and conscious identification task of the object parameters are not required to design the NCTF controller. Therefore, the controller design is simple and easy to implement in practical situation.

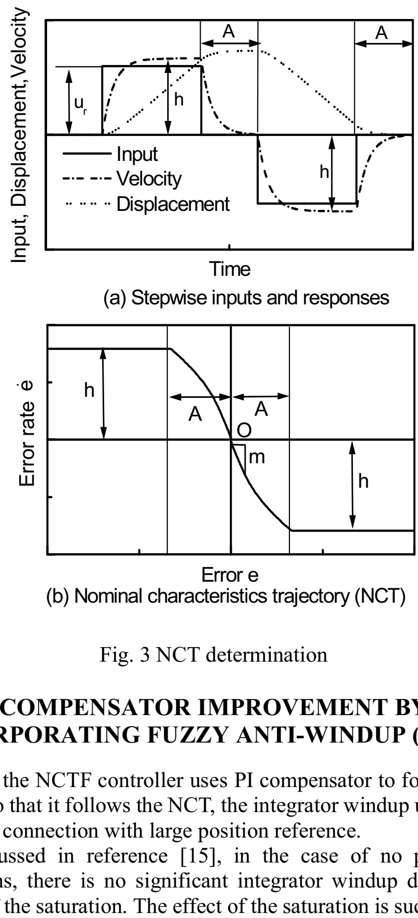


Fig. 3 NCT determination

3. COMPENSATOR IMPROVEMENT BY INCORPORATING FUZZY ANTI-WINDUP (TSK)

Since the NCTF controller uses PI compensator to force the object so that it follows the NCT, the integrator windup up may occur in connection with large position reference.

As discussed in reference [15], in the case of no parameter variations, there is no significant integrator windup due to the effect of the saturation. The effect of the saturation is successfully compensated by using NCTF controller. However, the integrator windup becomes a problem when the parameters vary.

To overcome this problem of integrator windup, the PI compensator is improved by adopting a fuzzy anti-windup scheme.

Hence, an anti-windup PI compensator is proposed to be use instead of a pure PI compensator. The fuzzy anti-windup is designed using Takagi-Sugeno fuzzy system.

The structure of the anti-windup PI compensator is illustrated in Figure 4 where FTS is the proposed fuzzy anti-windup.

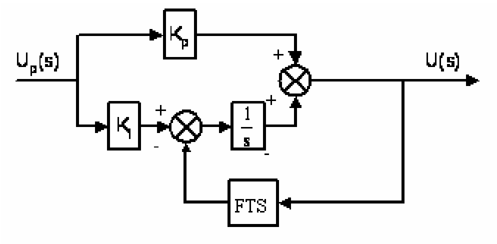


Fig. 4 Proposed anti-windup PI compensator

The assumption in designing the fuzzy anti windup Takagi-Sugeno (TSK) is that: when the input to the fuzzy system U(s) is not saturated (-6 until 6) the output from the fuzzy system is supposed to be zero. When the actuator is saturated negative value or positive value the out put from the fuzzy system will calculate the best value to reduce the integral part. It is not desirable to reset the integrator value immediately for that using the large output from fuzzy system to minimize the integrator value is desirable.

The fuzzy (TSK) system, which is use as the anti-windup (see Figure 5) consist of-

3.1 Fuzzification and membership function

The first step of the fuzzy (TSK) anti-windup is to convert the crisp input to the membership value of the fuzzy set. Membership function selected as triangular. As shown in figure 6, there are three partition of the membership function negative saturation, unsaturated and positive saturation. The range for the input is [-100 100].

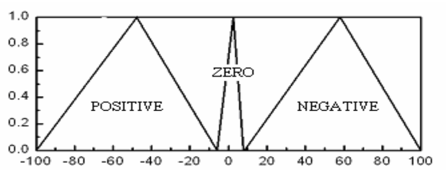


Fig. 6 - Membership Function of FLC (Takagi-Sugeno) Input

3.2 TSK Fuzzy rule base

TSK rule use function of the input variables as the rule consequent result. The main formula is

If x_1 is A AND x_2 is B THEN U(1) = f(x_1, x_2)

x1 and x2 are the antecedent ,u1 is consequent and f(x_1, x_2) is the liner equation depending on x_1 and x_2 .

Three rules are used to cover the entire situation, the rules are

If the U(s) is saturation negative THEN the output is U(1)

If the U(s) is nonstarter THEN the output is U(2)

If the U(s) is saturation positive THEN the output is U(3)

3.3 TSK Fuzzy inference

TSK Fuzzy inference or TSK fuzzy reasoning is used in the TSK fuzzy rule to determinate the rule outcome from the given rule input information. We are implementing Mamdani minimum inference. The combined membership for the consequent of the three rules is μ_3 (x,A) .where the *x* is the input and *A* is the situation . After that we multiply μ_3 (x,A) with the linear function in the rule consequent to get the TSK fuzzy inference result.

3.4 TSK fuzzy Defuzzification

Defuzzification is the mathematical approach used to convert a fuzzy set to the crisp number. The output from our fuzzy (TSK) anti-windup is calculated from the following equation.

$$U(n) = \frac{\sum_{j=1}^{\Omega} \mu_j(x, A)\left(a_j + \sum_{i=1}^{m} a_{ij}\left(x_i(n)\right)\right)}{\sum_{j=1}^{\Omega} \mu_j(x, A)} \quad . \quad (8)$$

Here a is the coefficients of the f(x1, x2) , the best values of a_0 = 4.9 and a_1 = 25 are found . (Ω) Is the number of the rules = three. (M) Is the input variable.

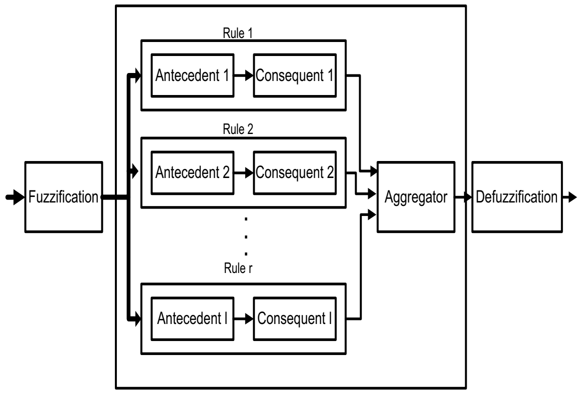


Fig. 5 Fuzzy anti-windup

4. RESULTS

4.1 Experimental Setup

The NCTF controller with anti-windup PI compensator is examined using a dynamic model of the experimental rotary positioning system as shown in Figure 7. The positioning system consists of an AC servomotor, a driver and an inertia mass (spindle). The examining the positioning performance, the detailed model of Figure 8 is used. Its parameters are shown in Table I. The positioning performance is examined under two conditions namely Normal Object and Increased Inertia Object. Normal Object has the nominal object parameters described in Table 1, while Increased Inertia Object has about 10 times spindle inertia than that of Normal Object.

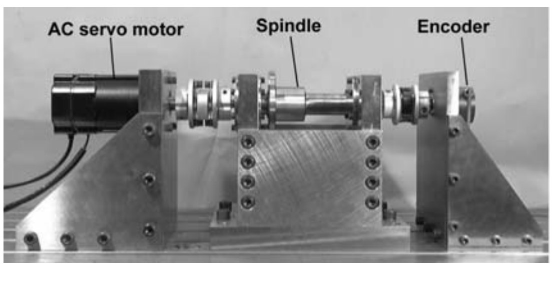


Fig. 7 Experimental rotary positioning system

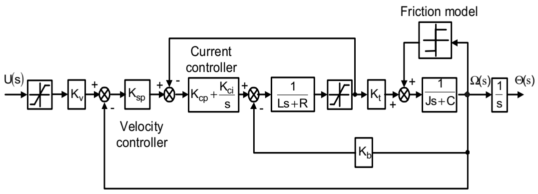


Fig. 8 Detailed model of rotary positioning system

Table 1 Parameters of the controlled object

Parameter	Value
Inertia load, J	1.17 x 10^{-3} kgm^2
Motor resistance, R	1.2 Ω
Motor inductance, L	8.7 mH
Motor torque constant, K_t	0.57 Nm/A
Back-Emf constant, K_b	0.57 Vs/rad
Viscous friction, C	1.67 x 10^{-3} Nms/rad
Frictional torque, τ_f	0.215 Nm
Proportional current gain, K_{cp}	26.2 V/A
Integral current gain, K_{ci}	3.62 x 10^3 V/As
Proportional velocity gain, K_{sp}	8.60 x 10^{-2} As/rad
Input voltage range	± 6 Volt

4.2 Controller Design

First, the NCTF controller design based on the Normal Object. Figure 9 shows the NCT as a result of a simulated experiment. According to Figure 9, the inclination m and maximum error rate h of the NCT are 67.4 and 40 respectively. The compensator parameters are designed by using h and m of the NCT. For designing the PI compensator, design parameters ζ and ω_n are chosen as 13 and 29 respectively [15]. Table 2 shows the value of the compensator parameters calculated with Eq(2).

The performance of the positioning system controlled by NCTF controller with fuzzy anti windup is compared with the PID anti windup controller and NCTF with conventional anti windup (dead zone) [21]. The PID controller is designed so that it has a similar bandwidth with the NCTF control system [15]. The anti-windup PID controller has the following transfer function [16]:

$$U(s)=\left[K_P+\frac{K_I}{s}+K_D s\right]U_p(s)-\frac{K_T}{s}\left[U(s)-U_s(s)\right] \quad (9)$$

Here K_T is tracking gain. Two tracking gain K_T are used. A tracking gain ratio K_T = 12 K_I is used The PID controller parameters are also shown in Table 2.

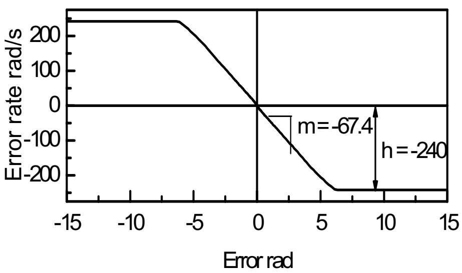


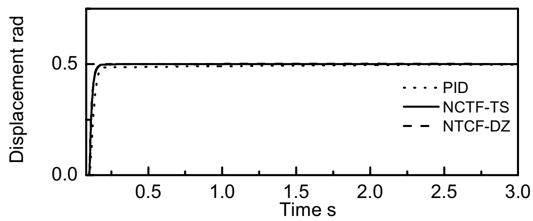
Fig. 9 Nominal characteristic trajectory (NCT*)*

Table 2 NCTF Compensator and PID controller Parameters

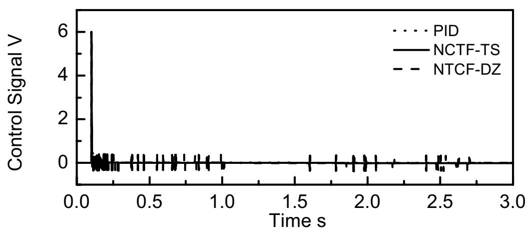
Controller	Kp	K_i	K_d
NCTF	0.28 Vs/rad	0.31 V/rad	-
PID	1.68 V/rad	0.17 V/srad	0.03 Vs/rad

4.3 Simulation Results

In this section, the performance of the positioning system controlled by the NCTF controller with Takagi-Sugeno fuzzy system (NCTF-TS) as anti-windup is compared with conventional NCTF (NCTF-DZ) basis on dead zone as anti windup and PID anti windup controllers. Figure 10 shows the step responses to a 0.5-rad step input when the controllers are used to control Normal Object and their positioning performances are summarized in Table 3. As shown in Figure 10(b), the 0.5-rad step input does not cause the saturation of the control signal. Hence, in terms of overshoot and settling time, all of the controller produce similar performance. Here, it is clear that all the controllers produce a similar response due to a similar bandwidth.



(a) Step responses to a 0.5-rad step input



(b) Control Signal

Fig. 10 Comparison of response to a 0.5-rad step input, normal object

Furthermore, in order to estimate the robustness of the control systems to inertia variation, all the controllers are implemented on Increased Inertia Object. Figure 11 shows the step responses to a 0.5-rad step input when all of the controllers are implemented for controlling Increased Inertia Object. Table 3 shows the positioning performance resulting from all them.

Table 3 – Performance Comparison, 0.5-rad Step Input

Object	Controller	Settling time	Overshoot%
Normal	NTCF-DZ	0.41	0
	NTCF- TS	0.35	0
	PID	0.40	0
Increased inertia	NTCF-DZ	0.23	14.4
	NTCF- TS	0.23	13.0
	PID	0.56	35.2

Figure 11 show that both of NCTF controllers give a better robustness to inertia Variation than the PID controller does. The remarkable thing that both the NCTF controllers give similar results since there is no significant saturation of the actuator as shown Figure 11(b). However, the result confirms that the use of anti-windup PI compensator does not affect the positioning performance when there is no saturation of the actuator.

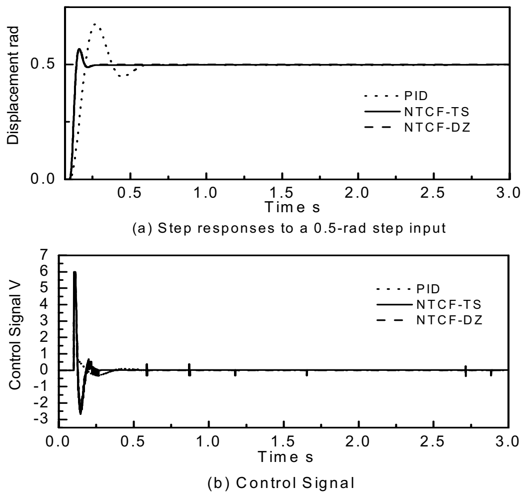


Fig. 11 Comparison of response to a 0.5-rad step input, increased inertia object

Next, simulation studies for a larger step input so that the saturation of the actuator occurs as shown in Figure 12(b) are carried out. Figure 12 shows the step responses to a 5-rad step input when the controllers are implemented for controlling Increased Inertia Object. However, as it is shown Figure 12(a) and Table 4 the positioning performance of the positioning system with NCTF-TS has less overshoot than the rest. In addition, in terms of the settling time both of NCTF have the same time but better than PID controller.

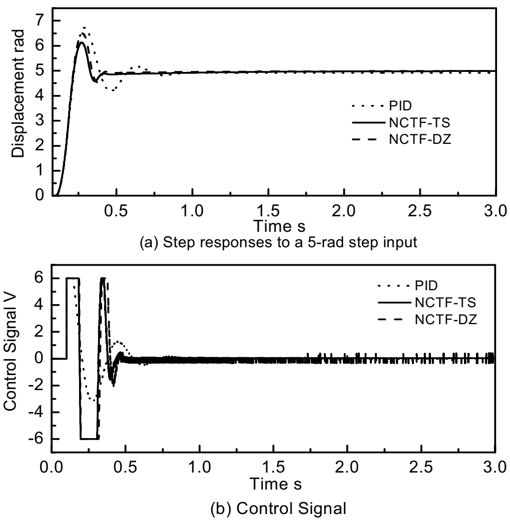


Fig. 12 Comparison of response to a 5-rad step input, increased inertia object

Table 4 Performance Comparison,5-Rad Step Input and 50-Rad Step Input

Reference	Controller	Settling time	Overshoot%
5-Rad	NTCF- DZ	0.41	29.8
	NTCF- TS	0.37	22.6
	PID	0.91	34.4
50-Rad	NTCF- DZ	1.23	31.4
	NTCF- TS	1.04	26.5
	PID	3.10	3.26

The last simulation studies are done when 50-rad step input is applied. However, the saturation of the actuator occurs as shown in Figure 13(b). Therefore, as shown in figure in Figure 13 and table 4 the overshoot of the PID system is less than both of the NCTF controllers. On the other hand , in term of the steady state error the PID has 7.79 and both of the NCTF is almost zero .consequently, if the whole performance of the system is considered ,the result confirm that still NCTF-TS has better performance than the rest when 50-rad step input is applied.

It is obvious that in all cases when NCTF uses the anti-windup PI compensator, the integrator windup due to actuator saturation is successfully compensated. Consequently, it is clear that the improvement of NCTF controller which uses anti-windup PI compensator, especially NCTF-TS can attain the robustness to parameter variation with the present of the saturation

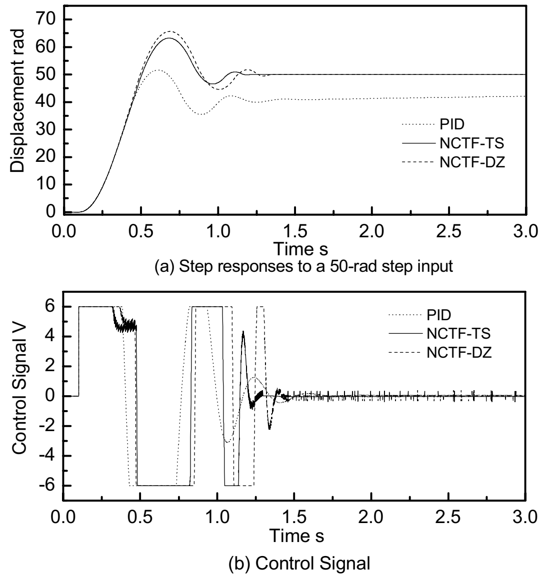


Fig. 13 Comparison of response to a 50-rad step input, increased inertia object

5. CONCLUSIONS

In this paper the effectiveness of using fuzzy anti-windup PI compensator to treat the anti windup problem in the NCTF by comparing with the conventional methods is demonstrated .The design of the NTCF and the design of the anti windup bias on Takagi-Sugeno fuzzy system is also demonstrated. The rotary position system is used to evaluate the differences between the conventional anti windup system, PID anti windup and fuzzy system as the anti windup. Moreover in term of changing variable we estimate how fuzzy anti windup (special fuzzy Takagi-Sugeno) are more robust than the rest. The methodology has verified through the numerical solution. The simulation is done by SIMULINK IN MATLAB 6.5

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