Hybrid Input Shaping and Non-collocated PID Control of a Gantry Crane System: Comparative Assessment

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Abstract - **This paper presents investigations into the development of hybrid control schemes for anti-swaying and input tracking control of a gantry crane system. A nonlinear overhead gantry crane system is considered and the dynamic model of the system is derived using the Euler-Lagrange formulation. To study the effectiveness of the controllers, initially a collocated PD-type Fuzzy Logic control is developed for cart position control of gantry crane. This is then extended to incorporate a non-collocated PID and an input shaper control schemes for anti-swaying control of the system. The positive input shapers with the derivative effects are designed based on the properties of the system. Simulation results of the response of the gantry crane with the controllers are presented in time and frequency domains. The performances of the control schemes are examined in terms of level of input tracking capability, sway angle reduction and time response specifications in comparison to the PD-type Fuzzy Logic control. Finally, a comparative assessment of the control techniques is presented and discussed.**

Index Terms – Gantry crane, non-collocated PID, input shaping.

I. INTRODUCTION

The main purpose of controlling a gantry crane is transporting the load as fast as possible without causing any excessive sway at the final position. However, most of the common gantry crane results in a sway motion when payload is suddenly stopped after a fast motion [1]. The sway motion can be reduced but will be time consuming. Moreover, the gantry crane needs a skilful operator to control manually based on his or her experiences to stop the sway immediately at the right position. The failure of controlling crane also might cause accident and may harm people and the surrounding.

Various attempts in controlling gantry cranes system based on open loop system were proposed. For example, open loop time optimal strategies were applied to the crane by many researchers such as discussed in [2,3]. They came out with poor results because open loop strategy is sensitive to the system parameters (e.g. rope length) and could not compensate for wind disturbances. Another open loop control strategies is input shaping [4,5,6]. Input shaping is implemented in real time by convolving the command signal with an impulse sequence. The process has the effect of placing zeros at the locations of the flexible poles of the original system. An IIR filtering technique related to input shaping has been proposed for controlling suspended payloads [7]. Input shaping has been shown to be effective for controlling oscillation of gantry cranes when the load does not undergo hoisting [8, 9]. Experimental results also indicate that shaped commands can be of benefit when the load is hoisted during the motion [10].

On the other hand, feedback control which is well known to be less sensitive to disturbances and parameter variations [11] is also adopted for controlling the gantry crane system. Recent work on gantry crane control system was presented by Omar [1]. The author had proposed proportional-derivative PD controllers for both position and anti-sway controls. Furthermore, a fuzzy-based intelligent gantry crane system has been proposed [12]. The proposed fuzzy logic controllers consist of position as well as anti-sway controllers. However, most of the feedback control system proposed needs sensors for measuring the cart position as well as the load sway angle. In addition, designing the sway angle measurement of the real gantry crane system, in particular, is not an easy task since there is a hoisting mechanism.

This paper presents investigations into the development of techniques for anti-swaying and input tracking of a gantry crane system. Control strategies based on input shaper with PD-type Fuzzy Logic controller and with combined non-collocated PID and PD-type Fuzzy Logic controllers are investigated. For non-collocated control, sway angle feedback through a PID control configuration whereas positive input shaper is utilised as a feedforward scheme for reducing a sway effect. A simulation environment is developed within Simulink and Matlab for evaluation of performance of the control schemes. Simulation results of the response of the gantry crane with the controllers are presented in time and frequency domains. The performances of the control schemes are examined in terms of level of input tracking capability, sway angle reduction and time response specifications in comparison to the PD-type Fuzzy Logic control. Finally, a comparative assessment of the control techniques is presented and discussed.

II. THE GANTRY CRANE SYSTEM

The two-dimensional gantry crane system with its payload considered in this work is shown in Figure 1, where x is the horizontal position of the cart, l is the length of the rope, θ is the sway angle of the rope, M and m is the mass of the cart and payload respectively. In this simulation, the cart and payload can be considered as point masses and are assumed to move in two-dimensional, x-y plane. The tension force that may cause the hoisting rope elongate is also ignored. In this study the length of the cart, $l = 1.00$ m, $M = 2.49$ kg, $m = 1.00$ kg and $g = 9.81$ m/s^2 is considered.

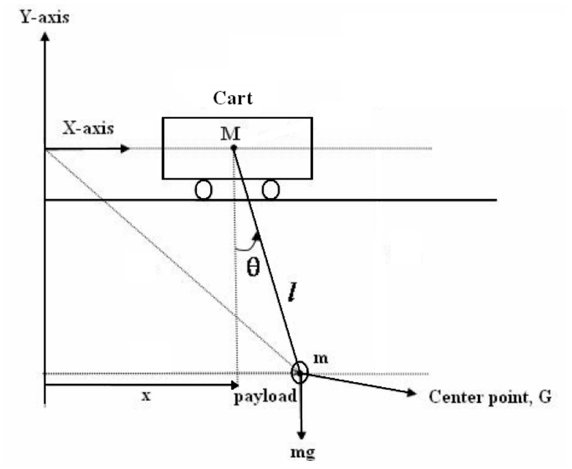

Fig. 1 Description of the gantry crane system.

III. DYNAMIC MODELLING OF THE GANTRY CRANE

This section provides a brief description on the modelling of the gantry crane system, as a basis of a simulation environment for development and assessment of the input shaping control techniques. The Euler-Lagrange formulation is considered in characterizing the dynamic behaviour of the crane system incorporating payload.

Considering the motion of the gantry crane system on a two-dimensional plane, the kinetic energy of the system can thus be formulated as

$$T = \frac{1}{2}M\dot{x}^2 + \frac{1}{2}m(\dot{x}^2 + \dot{l}^2 + l^2\dot{\theta}^2 + 2\dot{x}\dot{l}\sin\theta + 2\dot{x}l\dot{\theta}\cos\theta) \quad (1)$$

The potential energy of the beam can be formulated as

$$U = -mgl\cos\theta \quad (2)$$

To obtain a closed-form dynamic model of the gantry crane, the energy expressions in (1) and (2) are used to formulate the Lagrangian $L = T - U$. Let the generalized forces corresponding to the generalized displacements $\overline{q} = \{x, \theta\}$ be $\overline{F} = \{F_x, 0\}$. Using Lagrangian's equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = F_j \qquad j = 1,2 \quad (3)$$

the equation of motion is obtained as below,

$$F_x = (M+m)\ddot{x} + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) + 2m\dot{l}\dot{\theta}\cos\theta + m\ddot{l}\sin\theta \quad (4)$$

$$l\ddot{\theta} + 2\dot{l}\dot{\theta} + \ddot{x}\cos\theta + g\sin\theta = 0 \quad (5)$$

IV. CONTROL SCHEMES

In this section, control schemes for rigid body motion control of the cart and swaying angle reduction of hoisting rope are proposed. Initially, a PD-type Fuzzy Logic controller is designed. Then a non-collocated PID control and input shaper control are incorporated in the closed-loop system for control of swaying angle of the hoisting rope.

A. PD-type Fuzzy Logic Controller

A common strategy in the control of manipulator systems involves the utilization of PD-type Fuzzy Logic feedback of collocated sensor signals. In this work, such a strategy is adopted at this stage. A block diagram of the PD-type Fuzzy Logic controller is shown in Fig. 2, where R_f is the reference horizontal position, x and $\dot{x}$ represent horizontal position and velocity of the cart, respectively, θ and $\dot{\theta}$ represent sway angle and sway velocity, respectively, whereas k_1, k_2 and k_3 are scaling factors for two inputs and one output of the fuzzy logic controller used with the normalised universe of discourse for the fuzzy membership functions.

In this paper, triangular membership functions are chosen for cart position error, derivative of cart position error, and force input with 50% overlap. Normalized universes of discourse are used for both cart position error and its derivative and output force. Scaling factors k_1 and k_2 are chosen in such a way as to convert the two inputs within the universe of discourse and activate the rule base effectively, whereas k_3 is selected such that it activates the system to generate the desired output. Initially all these scaling factors are chosen based on trial and error. To construct a rule base, the cart position error, cart position error derivative, and force input are partitioned into five primary fuzzy sets as

Cart position error E = {NM NS ZE PS PM},
Cart position error derivative V = {NM NS ZE PS PM},
Force U = {NM NS ZE PS PM},

where E, V, and U are the universes of discourse for cart position, cart velocity and force input, respectively. The *n*th rule of the rule base for the FLC, with cart position error and derivative of cart position error as inputs, is given by
R_n: IF(e is E_i) AND ($\dot{e}$ is V_j) THEN (u is U_k),
where , R_n, n=1, 2,…N_{max}, is the *n*th fuzzy rule, E_i, V_j, and U_k, for i, j, k = 1,2,…,5, are the primary fuzzy sets.

A PD-type fuzzy logic controller was designed with 11 rules as a closed loop component of the control strategy for maintaining the cart position of gantry crane system while suppressing the swaying effect. The rule base was extracted based on underdamped system response and is shown in Table 1. The three scaling factors, k_1, k_2 and k_3 were chosen heuristically to achieve a satisfactory set of time domain parameters. These values were recorded as, $k_1 = 0.0684$, $k_2 = 0.0099$ and $k_3 = -350$.

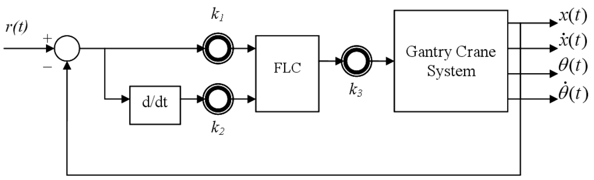

Fig. 2 PD-type fuzzy logic control structure.

TABLE I
LINGUISTIC RULES OF THE FUZZY LOGIC CONTROLLER

No.	Rules
1.	If (e is NM) and ($\dot{e}$ is ZE) then (u is PM)
2.	If (e is NS) and ($\dot{e}$ is ZE) then (u is PS)
3.	If (e is NS) and ($\dot{e}$ is PS) then (u is ZE)
4.	If (e is ZE) and ($\dot{e}$ is NM) then (u is PM)
5.	If (e is ZE) and ($\dot{e}$ is NS) then (u is PS)
6.	If (e is ZE) and ($\dot{e}$ is ZE) then (u is ZE)
7.	If (e is ZE) and ($\dot{e}$ is PS) then (u is NS)
8.	If (e is ZE) and ($\dot{e}$ is PM) then (u is NM)
9.	If (e is PS) and ($\dot{e}$ is NS) then (u is ZE)
10.	If (e is PS) and ($\dot{e}$ is ZE) then (u is NS)
11.	If (e is PM) and ($\dot{e}$ is ZE) then (u is NM)

B. *PD-type FLC with non-collocated PID controller*

A combination of PD-type FLC and non-collocated PID control scheme for control of rigid body motion of the cart and swaying angle reduction of the system is presented in this section. The use of a non-collocated control system, where the sway angle of the hoisting rope is controlled, can be applied to improve the overall performance, as more reliable output measurement is obtained. The control structure comprises two feedback loops: (1) The cart position feedback as input to compensate the control gain for rigid body motion control. (2) The sway angle of hoisting rope as input to a separate non-collocated control law for swaying angle suppression. A block diagram of the control scheme is shown in Fig. 3 where θ represents the sway angle of the hoisting rope. r_θ represents sway angle reference input, which is set to zero as the control objective is to have zero sway angle during movement of the gantry crane.

For rigid body motion control, the PD-type FLC strategy developed in the previous section is adopted whereas for the sway angle control loop, the sway angle of the hoisting rope feedback through a PID control scheme is utilized. The PID controller parameters were tuned using the Ziegler-Nichols method using a closed-loop technique, where the proportional gain K_p was initially tuned and the integral gain K_i and derivative gain K_d were then calculated [13]. Accordingly, the PID parameters K_p, K_i and K_d were deduced as 3.0, 3.0 and 0.7 respectively. To decouple the sway angle measurement from the rigid body motion of the gantry crane's cart, a third-order infinite impulse response (IIR) Butterworth high-pass filter was utilised. In this investigation, a high-pass filter with cut-off frequency of 1.5 Hz was designed.

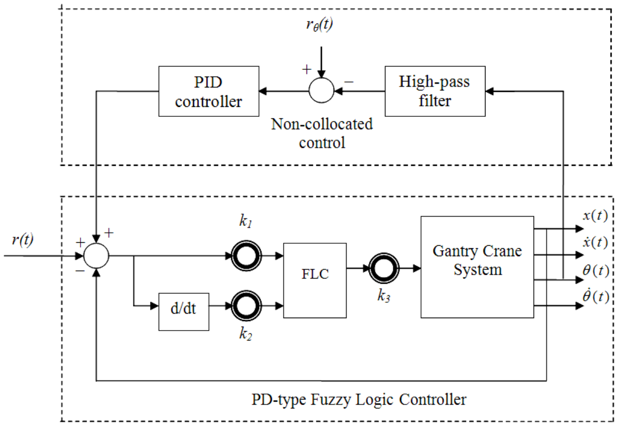

Fig. 3 The PD-type FLC and non-collocated PID control structure.

C. *PD-type FLC with input shaping control*

A control structure for control of rigid body motion and sway angle reduction of the gantry crane system based on PD-type FLC and input shaping control is proposed in this section. The positive input shapers are proposed and designed based on the properties of the system. In this study, the input shaping control scheme is developed using a Zero-Vibration-Derivative-Derivative (ZVDD) input shaping technique [14]. Previous experimental study with a flexible manipulator has shown that significant vibration reduction and robustness is achieved using a ZVDD technique [15]. A block diagram of the PD-type FLC with input shaping control technique is shown in Fig. 4.

The input shaping method involves convolving a desired command with a sequence of impulses known as input shaper. The design objectives are to determine the amplitude and time location of the impulses based on the natural frequencies and damping ratios of the system. The positive input shapers have been used in most input shaping schemes. The requirement of positive amplitude for the impulses is to avoid the problem of large amplitude impulses. In this case, each individual impulse must be less than one to satisfy the unity magnitude constraint. In addition, the robustness of the input shaper to errors in natural frequencies of the system can be increased by solving the derivatives of the system vibration equation. This yields a positive ZVDD shaper with parameter as

$$t_1 = 0,\ t_2 = \frac{\pi}{\omega_d},\ t_3 = \frac{2\pi}{\omega_d},\ t_4 = \frac{3\pi}{\omega_d}$$

$$A_1 = \frac{1}{1+3H+3H^2+H^3},\ A_2 = \frac{3H}{1+3H+3H^2+H^3}$$

$$A_3 = \frac{3H^2}{1+3H+3H^2+H^3},\ A_4 = \frac{H^3}{1+3H+3H^2+H^3} \quad (6)$$

where

$$H = e^{-\zeta\pi/\sqrt{1-\zeta^2}},\quad \omega_d = \omega_n\sqrt{1-\zeta^2}$$

ω_n and ζ representing the natural frequency and damping ratio respectively. For the impulses, t_j and A_j are the time location and amplitude of impulse j respectively.

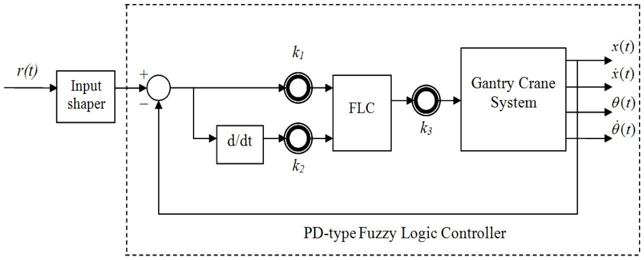

Fig. 4 The PD-type FLC and input shaping control structure.

V. IMPLEMENTATION AND RESULTS

In this section, the proposed control schemes are implemented and tested within the simulation environment of the gantry crane system and the corresponding results are presented. The cart of the gantry crane is required to follow a trajectory position of 4 m. System responses namely the horizontal position of the cart and sway angle of the hoisting rope are observed. To investigate the sway angle effect in the frequency domain, power spectral density (PSD) of the sway angle response is obtained. The performances of the control schemes are assessed in terms of sway angle suppression, input tracking and time response specifications. Finally, a comparative assessment of the performance of the control schemes is presented and discussed.

Figs. 5-7 show the responses of the gantry crane system to the reference input trajectory using PD-type FLC in time-domain and frequency domain (PSD). These results were considered as the system response under rigid body motion control and will be used to evaluate the performance of the non-collocated PID and input shaping control. The steady-state cart position trajectory of 4 m for the gantry crane was achieved within the rise and settling times and overshoot of 1.207 s, 6.813 s and 9.175 % respectively. It shows that the PD-type FLC is capable in tracking the trajectory input. However, a noticeable amount of sway angle occurs during movement of the cart. It is noted from the sway angle response with a maximum residual of ±0.8 rad. Moreover, from the PSD of the sway angle response the swaying frequencies are dominated by the first three modes, which are obtained as 0.2943 Hz, 0.9812 Hz and 1.57 Hz with magnitude of 25.12 dB, -14.10 dB and -29.87 dB respectively.

The horizontal cart position trajectory, sway angle of the hoisting rope and power spectral density responses of the gantry crane system using PD-type FLC with non-collocated PID (PD-FLC-PID) and input shaping (PD-FLC-IS) control are shown in Figs. 5-7 respectively. It is noted that the proposed control schemes are capable of reducing the system sway effect while maintaining the input tracking performance of the gantry crane. Similar cart position trajectory, sway angle and power spectral density of sway angle responses were observed as compared to the PD-FLC controller.

Table 2 summarizes the levels of sway effect reduction of the system responses at the first three modes in comparison to the PD-type Fuzzy Logic control. In overall, higher levels of sway effect reduction for the first three modes were obtained using PD-FLC-IS as compared to PD-FLC-PID. However, the system response using PD-FLC-PID is faster than the case of PD-FLC-IS. It is noted with the input shaping controller, the impulses sequence in input shaper increase the delay in the system response. The corresponding rise time, setting time and overshoot of the cart position trajectory response using PD-FLC-IS and PD-FLC-PID is depicted in Table 1. Moreover, as demonstrated in the cart position trajectory response with PD-FLC-PID control, the minimum phase behaviour of the gantry crane is unaffected. A significant amount of sway angle amplitude suppression was demonstrated with both control schemes. With the PD-FLC-PID control, the maximum sway angle is ±0.5 rad while with the PD-FLC-IS control is ±0.05 rad. Hence, it is noted that the magnitude of oscillation was significantly reduced by using PD-FLC with input shaping control as compared to the case of PD-FLC with non-collocated PID control. In overall, the performance of the control schemes at input tracking capability is maintained as the PD-FLC.

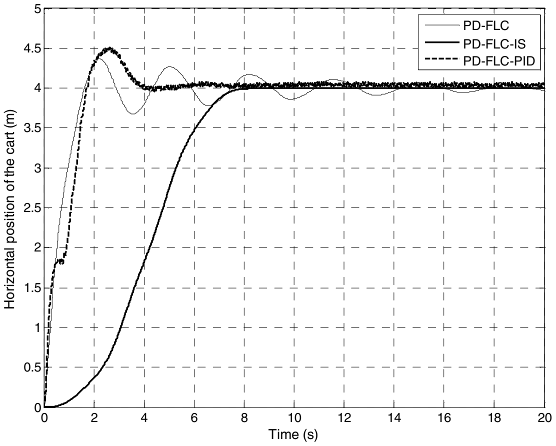

Fig. 5 Horizontal position of the cart using PD-FLC, PD-FLC-PID and PD-FLC-IS.

TABLE II

LEVEL OF SWAY ANGLE REDUCTION OF THE ROPE AND SPECIFICATIONS OF THE CART TRAJECTORY RESPONSE FOR PD-FLC-PID AND PD-FLC-IS CONTROL SCHEMES

Controller	Attenuation (dB) of sway angle of the rope			Specifications of cart trajectory response		
	Mode 1	Mode 2	Mode 3	Rise time (s)	Settling time (s)	Overshoot (%)
PD-FLC-PID	18.89	2.73	5.44	1.392	3.368	12.7
PD-FLC-IS	35.11	40.30	35.92	4.182	6.806	0.0

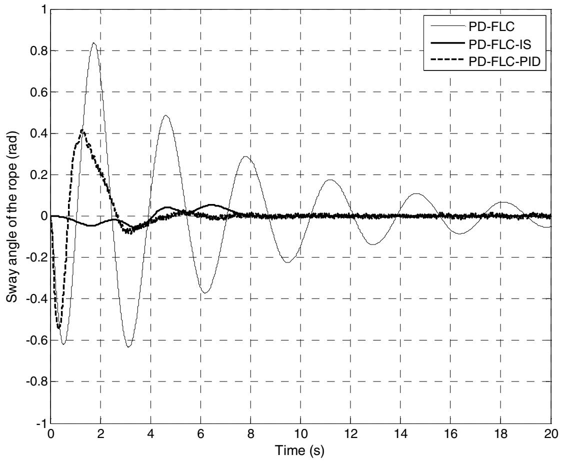

Fig. 6 Sway angle of the rope using PD-FLC, PD-FLC-PID and PD-FLC-IS

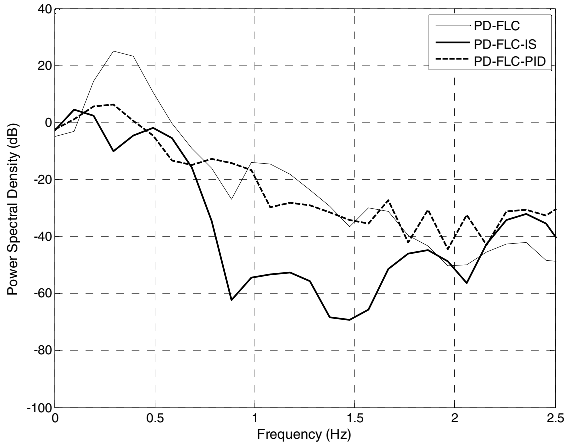

Fig. 7 PSD response using PD-FLC, PD-FLC-PID and PD-FLC-IS.

The simulation results show that the performance of PD-FLC-IS control scheme is better than PD-FLC-PID schemes in sway angle suppression of the gantry crane. This is further evidenced in Fig. 8 that demonstrates the level of sway effect reduction at the resonance modes of the PD-FLC with non-collocated and input shaping control respectively as compared to the PD-FLC. It is noted that higher sway angle reduction is achieved with PD-FLC-IS at the first three modes of sway effect. Almost twofold, twelvefold and sevenfold improvement in the sway effect reduction at the first, second and three resonance mode respectively were observed with PD-FLC-IS as compared to PD-FLC-PID. Moreover, implementation of PD-FLC with input shaping control is easier than PD-FLC with non-collocated PID control as a large amount of design effort is required to determine the best PID parameters. Note that a properly tuned PID could produce better results. However, as demonstrated in the cart position trajectory response, slightly slower response is obtained using PD-FLC with input shaping control as compared to the PD-FLC with non-collocated control.

Further comparisons of the specifications of the cart position trajectory responses are summarized in Fig. 9 for the rise and settling times. The work thus developed and reported in this paper forms the basis of design and development of hybrid control schemes for input tracking and sway effect suppression of three-dimensional gantry crane systems and can be extended to and adopted in practical applications.

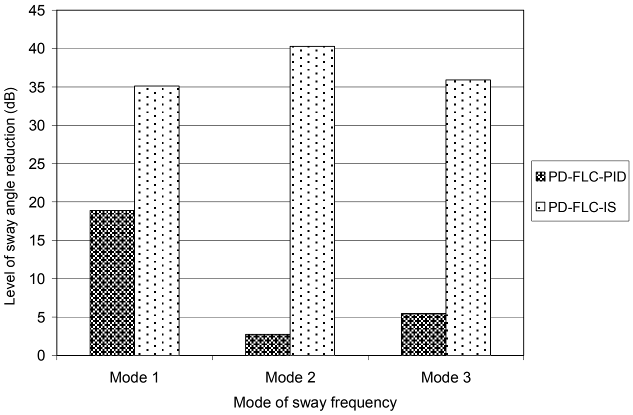

Fig. 8 Level of sway angle reduction using PD-FLC-PID and PD-FLC-IS.

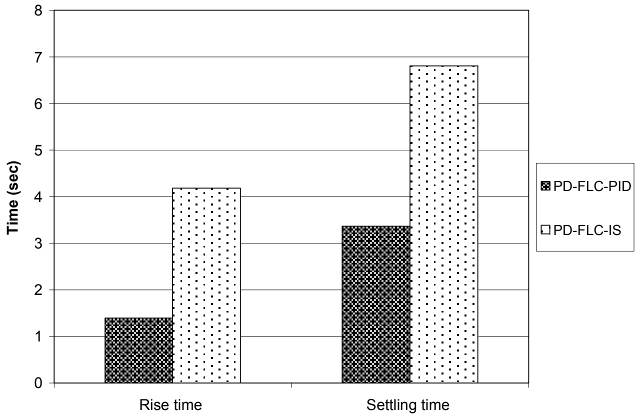

Fig. 9 Rise and settling time of the cart trajectory using PD-FLC-PID and PD-FLC-IS.

VI. CONCLUSION

The development of techniques for anti-sway and input tracking of the gantry crane system has been presented. The control schemes have been developed based on PD-type FLC with non-collocated PID control and PD-type FLC with input shaper technique. The proposed control schemes have been implemented and tested within simulation environment of a non-linear gantry crane. The performances of the control schemes have been evaluated in terms of residual sway angle suppression and input tracking capability at the resonance modes of the gantry crane. Acceptable performance in sway angle suppression and input tracking control has been achieved with proposed control strategies. A comparative assessment of the control schemes has shown that the PD-type FLC with input shaping performs better than the PD-type FLC with non-collocated PID control in respect of sway angle reduction of the hoisting rope. However, the speed of the response is slightly improved at the expenses of decrease in the level of sway angle reduction by using the PD-type FLC with non-collocated PID control. It is concluded that the proposed controllers are capable of reducing the system sway effect while maintaining the input tracking performance of the gantry crane.

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