The investigations of PD-type Fuzzy Logic with different polarities input shaping for anti-sway control of a gantry crane system

M.A. Ahmad, *Member, IEEE*, M.S. Ramli, R.M.T. Raja Ismail, A.N.K. Nasir and M.A. Zawawi

***Abstract*—This paper presents investigations into the development of PD-type Fuzzy Logic Control with different polarities input shaping for anti-sway 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 PD-type Fuzzy Logic Control is developed for cart position control of gantry crane. This is then extended to incorporate input shaper control schemes for anti-sway control of the system. The positive and modified specified negative amplitude (SNA) input shapers with the derivative effects respectively are designed based on the properties of the system. Simulation results of the response of the system 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, swing angle reduction, time response specifications and robustness to parameters uncertainty in comparison to the PD-type Fuzzy Logic control. Finally, a comparative assessment of the amplitude polarities of the input shapers to the system performance is presented and discussed.**

I. INTRODUCTION

The main purpose of controlling a gantry crane is transporting the load as fast as possible without causing any excessive swing at the final position. However, most of the common gantry crane results in a swing motion when payload is suddenly stopped after a fast motion [1]. The swing 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 swing 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]. To reduce the delay in the system response, negative amplitude input shapers have been introduced and investigated in sway control. By allowing the shaper contain negative impulses, the shaper duration can be shortened, while satisfying the same robustness constraint. [11, 12, 13]

On the other hand, feedback control which is well known to be less sensitive to disturbances and parameter variations [14] 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-swing controls. Furthermore, a fuzzy-based intelligent gantry crane system has been proposed [15]. 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 swing angle. In addition, designing the swing 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 input shaping with different amplitude polarities for anti-sway control of a gantry crane system. To demonstrate the effectiveness of the proposed control schemes, initially a PD-type Fuzzy Logic controller is developed for cart position control of gantry crane system. This is then extended to incorporate the proposed input shapers for swing control of the gantry crane. In terms of robustness, the control schemes are assessed with up to 30% error tolerance in sway frequencies. This paper provides a comparative assessment of the performance of proposed control schemes with different polarities of input shapers.

Manuscript submitted March 17, 2009. This work was supported in part by the Universiti Malaysia Pahang.

M. A. Ahmad is with the Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300, Kuantan, Pahang, Malaysia. (Phone: 6095492366; Fax: 6095492377; Email: mashraf@ump.edu.my)

M. S. Ramli is with the Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300, Kuantan, Pahang, Malaysia. (Email: syakirin@ump.edu.my)

R. M. T. Raja Ismail is with the Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300, Kuantan, Pahang, Malaysia. (Email: rajamohd@ump.edu.my)

A.N.K. Nasir is with the Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300, Kuantan, Pahang, Malaysia. (Email: kasruddin@ump.edu.my)

M. A. Zawawi is with the Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300, Kuantan, Pahang, Malaysia. (Email: mohdanwar@ump.edu.my)

II. GANTRY CRANE SYSTEM

The two-dimensional gantry crane system with its payload considered in this work is shown in Fig. 1, where *x* is the horizontal position of the cart, *l* is the length of the rope, *θ* is the swing 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.

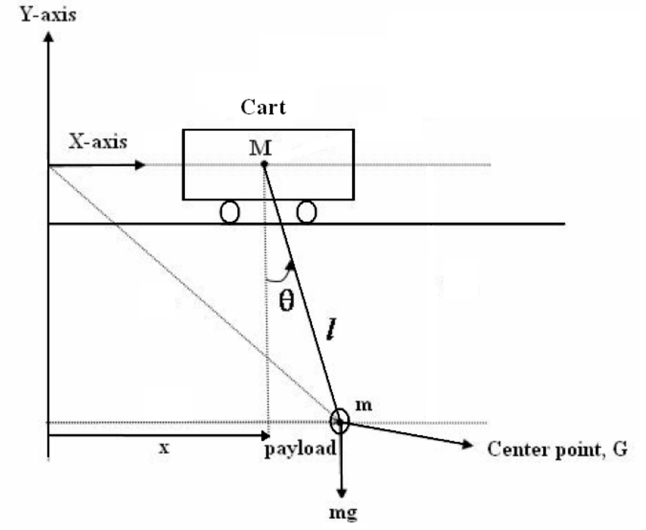


Fig. 1. Description of the gantry crane system.

III. MODELLING OF THE GANTRY CRANE SYSTEM

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

$$\begin{aligned} T = &\frac{1}{2}M\dot{x}^2 + \\ &\frac{1}{2}m(\dot{x}^2 + \dot{l}^2 + l^2\dot{\theta}^2 + 2\dot{x}\dot{l}\sin\theta + 2\dot{x}l\dot{\theta}\cos\theta) \end{aligned} \tag{1}$$

The potential energy of the beam can be formulated as

$$U = -mgl\cos\theta \tag{2}$$

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

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

the equation of motion is obtained as below,

$$\begin{aligned} F_x = &(M+m)\ddot{x} + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) \\ &+ 2m\dot{l}\dot{\theta}\cos\theta + m\ddot{l}\sin\theta \end{aligned} \tag{4}$$

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

IV. CONTROL SCHEMES

The control schemes for rigid body motion control and vibration suppression of a flexible robot manipulator are proposed in this study. Initially, a collocated PD controller is designed for rigid body motion control. Then a non-collocated PID control and feedforward control based on input shaping are incorporated in the closed-loop system for control of vibration of the system.

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 swing angle and swing 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 nth 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 nth fuzzy rule, E_i, V_j, and U_k, for i, j, k = 1,2,…,5, are the primary fuzzy sets.

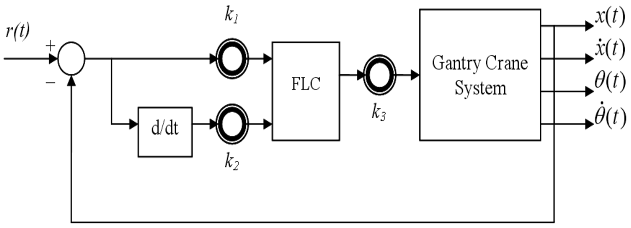


Fig. 2. PD-type Fuzzy Logic Control Structure.

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, $k_1 = 0.013$ $k_2 = 0.0028$ and $k_3 = -150$.

TABLE I

LINGUISTIC RULES OF 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)

The design objectives of input shaping are to determine the amplitude and time locations of the impulses in order to reduce the detrimental effects of system flexibility. These parameters are obtained from the natural frequencies and damping ratios of the system. The requirement of positive amplitudes for the input shapers has been used in most input shaping schemes. The requirement of positive amplitude for the impulses is to avoid the problem of large amplitude impulses. For the case of positive amplitudes, each individual impulse must be less than one to satisfy the unity magnitude constraint. In order to increase the robustness of the input shaper to errors in natural frequencies, the positive Zero-Sway-Derivative-Derivative (ZSDD) input shaper, is designed by solving the derivatives of the system vibration equation. This yields a four-impulse sequence with parameter as

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

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

$$A_3 = \frac{3K^2}{1+3K+3K^2+K^3},\ A_4 = \frac{K^3}{1+3K+3K^2+K^3} \tag{6}$$

where

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

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

In order to achieve higher robustness for positive input shaper, the duration of the shaper is increased and thus, increases the delay in the system response. By allowing the shaper to contain negative impulses, the shaper duration can be shortened, while satisfying the same robustness constraint. To include negative impulses in a shaper requires the impulse amplitudes to switch between 1 and -1 as

$$A_i = (-1)^{i+1};\quad i = 1, \dots\dots, n \tag{7}$$

The constraint in (7) yields useful shapers as they can be used with a wide variety of inputs. However, the increase in the speed of system response achieved using the SNA input shapers is at the expense of some tradeoffs and penalties. The shapers containing negative impulses have tendency to excite unmodeled high modes and they are slightly less robust as compared to the positive shapers. Besides, negative input shapers require more actuator effort than the positive shapers due to high changes in the set-point command at each new impulse time location.

To overcome the disadvantages, the modified SNA input shaper is introduced, whose negative amplitudes can be set to any value at the centre between each normal impulse sequences. In this technique, the previous SNA input shaper [11] has been modified by locating the negative amplitudes at the centre between each positive impulse sequences with even number of total impulses. This will result the shaper duration to one-fourth of the sway period of an undamped system as shown in Fig. 4. The modified SNA ZSDD shaper is applied in this work by adding more negative impulses in order to enhance the robustness capability of the controller while increasing the speed of the system response. Moreover, by considering the form of modified SNA ZSDD shaper shown in Fig. 4, the amplitude summation constraints equation can be obtained as

$$2a + 2c - 2b - 2d = 1 \tag{8}$$

The values of a, b, c and d can be set to any value that satisfy the constraint in (8). However, the suggested values of a, b, c and d are less than |1| to avoid the increase of the actuator effort

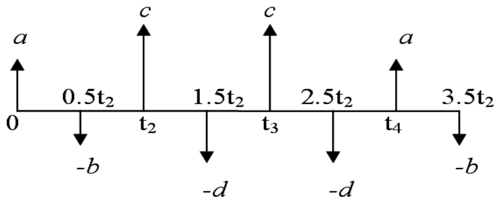


Fig. 3. Modified SNA ZSDD shaper.

V. IMPLEMENTATION AND RESULTS

In this investigation, positive and modified SNA input shaping for swing angle reduction of the gantry crane is examined. Initially, a PD-type Fuzzy Logic controller is designed to control the position of the cart. This is then extended to incorporate both positive ZSDD and modified SNA ZSDD input shaping schemes for control of swing angle of the system. The natural frequencies were obtained by exciting the gantry crane system with an unshaped reference input under PD-type Fuzzy Logic controller. The input shapers were designed for pre-processing the trajectory reference input and applied to the system in a closed-loop configuration, as shown in Fig. 4. In this work, the input is applied at the cart of the gantry crane. The cart position of the gantry crane is required to follow a trajectory within the range of ±4 m. The first three modes of swing angle frequencies of the system are considered, as these dominate the dynamic of the system.

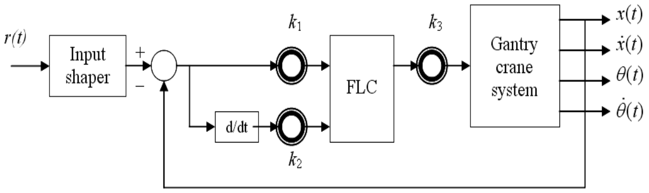


Fig. 4. Block diagram of the control schemes configuration.

The responses of the gantry crane system to the unshaped trajectory reference input were analyzed in time-domain and frequency domain (spectral density). These results were considered as the system response to the unshaped input under tracking capability and will be used to evaluate the performance of the input shaping techniques. Simulation results with PD-type Fuzzy Logic controller have shown that the steady-state cart position trajectory of +4 m for the gantry crane was achieved within the rise and settling times and overshoot of 1.168 s, 3.728 s and 12.40 % respectively. It is noted that the cart reaches the required position from +4 m to -4 m within 6 s, with high overshoot. In addition, a noticeable amount of swing angle occurs during movement of the cart. It is noted from the swing angle response with a maximum residual of ±1.5 rad. Moreover, from the PSD of the swing angle response the sway frequencies are dominated by the first three modes, which are obtained as 0.3925 Hz, 1.177 Hz and 1.962 Hz with magnitude of 27.27 dB, -10.73 dB and -29.55 dB respectively.

In the case of input shaping control schemes, positive and modified SNA ZSDD shapers were designed for three modes utilising the properties of the system. With the exact natural frequencies of 0.3925 Hz, 1.177 Hz and 1.962 Hz, the time locations and amplitudes of the impulses for positive ZSDD shaper were obtained by solving (6). However, the amplitudes of the modified SNA ZSDD shaper were deduced as [0.3 -0.1 0.5 -0.2 0.5 -0.2 0.3 -0.1] while the time locations of the impulses were located at the half of the time locations of positive ZSDD shaper as shown in Fig. 4. For evaluation of robustness, input shapers with error in natural frequencies were also evaluated. With the 30% error in natural frequency, the system sways were considered at 0.5103 Hz, 1.5301 Hz and 2.5506 Hz for the three modes of sway frequencies. Similarly, the amplitudes and time locations of the input shapers with 30% erroneous natural frequencies for both positive and modified SNA ZSDD were calculated.

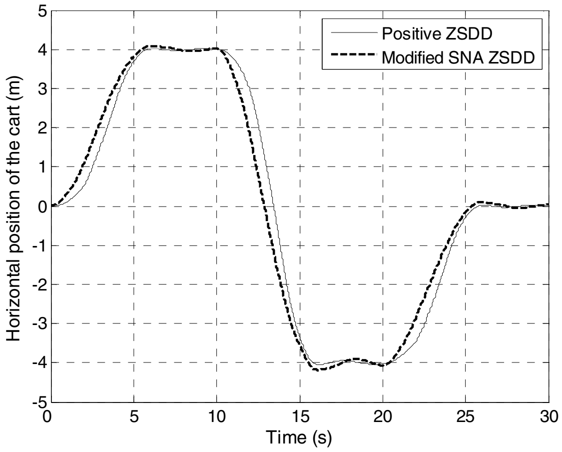
The system responses of the gantry crane to the shaped trajectory input with exact natural frequencies using PD-type Fuzzy Logic controller with positive and modified SNA shapers are shown in Fig. 5. Table 2 summarises the levels of sway reduction of the system responses at the first three modes in comparison to the PD-type Fuzzy Logic control. Higher levels of sway reduction were obtained using PD-type Fuzzy Logic control with positive ZSDD shaper as compared to the case with modified SNA ZSDD shaper. However, with modified SNA ZSDD shaper, the system response is faster. The corresponding rise time, setting time and overshoot of the cart response using PD-type Fuzzy Logic control with positive and modified SNA ZSDD shapers with exact natural frequencies is depicted in Table 2. It is noted that a slower cart response for PD-type Fuzzy Logic control with input shaping control schemes, as compared to the PD-type Fuzzy Logic control, was achieved.

To examine the robustness of the shapers, the shapers with 30% error in sway frequencies were designed and implemented to the gantry crane system. Fig. 6 shows that the sways of the system were considerable reduced as compared to the system with PD-type Fuzzy Logic control. However, the level of sway reduction is slightly less than the case with exact natural frequencies. Table 2 summarises the levels of sway reduction with erroneous natural frequencies in comparison to the PD-type Fuzzy Logic control. The time response specifications of the cart position with error in natural frequencies are summarised in Table 2. It is noted that the response is slightly faster for the shaped input with error in natural frequencies than the case with exact frequencies.

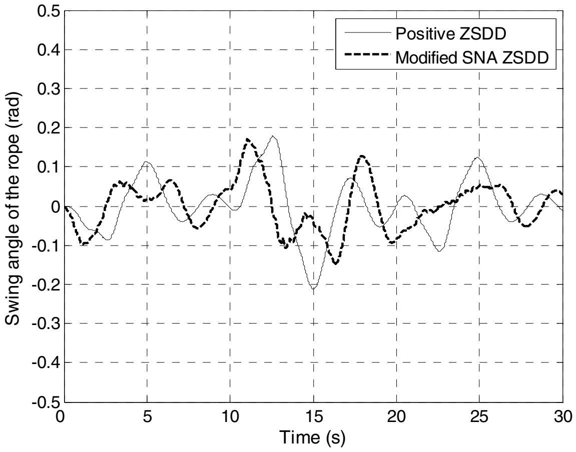
TABLE II

LEVEL OF SWING ANGLE REDUCTION OF THE ROPE AND SPECIFICATIONS OF THE CART TRAJECTORY RESPONSE

Frequency	Types of shaper (ZSDD)	Attenuation (dB) of swing angle of the rope			Specifications of cart trajectory response		
		Mode 1	Mode 2	Mode 3	Rise time (s)	Settling time (s)	Overshoot (%)
Exact	Positive	36.16	39.20	39.10	3.071	4.866	0.63
	Modified SNA	22.99	34.11	32.01	3.492	4.607	2.15
Error	Positive	19.93	26.56	24.21	2.431	3.901	3.30
	Modified SNA	26.86	14.22	12.23	2.661	3.615	2.90

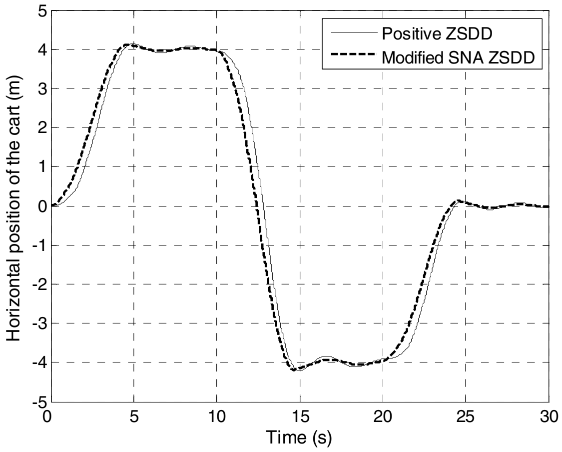


(a) Cart position

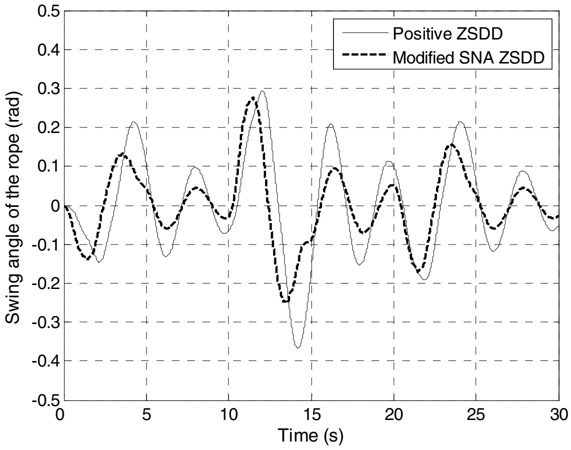


(b) Sway angle

Fig. 5. Response of the gantry crane with exact natural frequencies.



(a) Cart position



(b) Sway angle

Fig. 6. Response of the gantry crane with erroneous natural frequencies.

VI. CONCLUSIONS

The development of PD-type Fuzzy logic control with positive and negative input shapers for input tracking and sway suppression of gantry crane system has been presented. Acceptable performance in input tracking control and sway suppression has been achieved with both control strategies. Moreover, a significant reduction in the system sway has been achieved with the hybrid controllers regardless of the polarities of the shapers. For exact natural frequency case, a comparative assessment of the control schemes has shown that the PD-type Fuzzy logic controller with positive ZSDD shaper provides higher level of sway reduction of the gantry crane system as compared to the PD-type Fuzzy logic controller with modified SNA-ZSDD shaper. However, the speed of the response is slightly improved at the expenses of decrease in the level of vibration reduction by using the modified SNA-ZSDD shaper. The study also shows that input shapers are very robust with the error in natural frequencies.

ACKNOWLEDGMENT

This work was supported by Faculty of Electrical & Electronics Engineering, Universiti Malaysia Pahang, especially Control & Instrumentation (COINS) Research Group.

REFERENCES

[1] Omar, H.M, Control of gantry and tower cranes. Ph.D. Thesis, M.S. Virginia Tech, 2003.

[2] Manson, G.A., Time-optimal control of and overhead crane model, Optimal Control Applications & Methods, Vol. 3, No. 2, 1992, pp. 115-120.

[3] Auernig, J. and Troger, H. Time optimal control of overhead cranes with hoisting of the load, Automatica, Vol. 23, No. 4, 1987, pp. 437-447.

[4] Karnopp, B H., Fisher, F.E., and Yoon, B.O., "A strategy for moving mass from one point to another", Journal of the Franklin Institute, Vol. 329, 1992, pp. 881-892.

[5] Teo, C.L., Ong, C. J. and Xu, M. Pulse input sequences for residual vibration reduction. Journal of Sound and Vibration, Vol. 211, No. 2, 1998, pp. 157-177.

[6] Singhose, W.E., Porter L.J. and Seering, W., "Input shaped of a planar gantry crane with hoisting", Proc. of the American Control Conference, 1997, pp. 97-100.

[7] Feddema, J.T., "Digital Filter Control of Remotely Operated Flexible Robotic Structures," *American Control Conference*, San Francisco, CA, Vol. 3, pp. 2710-2715, 1993.

[8] Noakes, M.W. and J.F. Jansen, "Generalized Inputs for Damped-Vibration Control of Suspended Payloads," *Robotics and Autonomous Systems*, 10(2): p. 199-205, 1992.

[9] Singer, N., W. Singhose, and E. Kriikku, "An Input Shaping Controller Enabling Cranes to Move Without Sway," *ANS 7th Topical Meeting on Robotics and Remote Systems,* Augusta, GA, 1997.

[10] Kress, R.L., J.F. Jansen, and M.W. Noakes, "Experimental Implementation of a Robust Damped-Oscillation Control Algorithm on a Full Sized, Two-DOF, AC Induction Motor- Driven Crane," *5th ISRAM*, Maui, HA, pp. 585-92, 1994.

[11] Mohamed Z., Chee A.K., Mohd Hashim A. W. I., Tokhi M. O., Amin S. H. M. and Mamat R., "Techniques for vibration control of a flexible manipulator", Robotica, 24, 499-511, 2006.

[12] Mohamed, Z. and Ahmad, M.A., "Hybrid Input Shaping and Feedback Control Schemes of a Flexible Robot Manipulator", *Proceedings of the 17th World Congress The International Federation of Automatic Control*, Seoul, Korea, pp. 11714-11719, 2008.

[13] Ahmad M.A., Nasir A.N.K., Raja Ismail, R.M.T., and Ramli, M.S., "Comparison of Hybrid Control Schemes for Vibration Suppression of Flexible Robot Manipulator", *Proceedings of International Conference on Computer Modelling and Simulation*, Macau, 20-22 February 2009, pg. 356-360.

[14] Belanger, N.M., Control Engineering: A Modern Approach, Saunders College Publishing, 1995.

[15] Wahyudi and Jalani, J., Design and implementation of fuzzy logic controller for an intelligent gantry crane system, *Proceedings of the 2nd International Conference on Mechatronics*, pp. 345- 351, 2005.