



## **PRACTICAL SWAY MOTION CONTROL FOR DOUBLE PENDULUM-TYPE OVERHEAD CRANE SYSTEM**

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*Abstract- The sway motion of crane can be successfully suppressed by properly shaping the reference command. Input shaping is a one type of feed-forward shaping method that is based on linear superposition. In this paper, we present the impact of double pendulum type overhead crane (DPTOC) system on the effectiveness of input shaping. An unshaped bang-bang input force is used to determine the characteristic parameters of the system for design and evaluation of the input shaping control techniques. The input shapers with the derivative effects are designed based on the properties of the system. The response DPTOC system to shaped input is experimentally verified in time and frequency domain. The performance of the input shaper is examined in terms of sway angle reduction and time response specification. Experimental results demonstrate the effectiveness of the proposed approach in reducing the sway motion of crane system.*

**Index terms:** Input shaping, double pendulum, and sway motion.



Figure 1. Illustration of input shaping technique.

The earliest form of input shaping was developed by Smith. However, his posicast control method was extremely sensitive to modeling errors [11]. This sensitivity to modeling errors prohibited the input shaper from practical use on many systems. Singer and Seering were the first to develop an input-shaping technique robust enough to be used in most practical applications. To reduce the sensitivity of the input shaper to errors in natural frequency, they set the derivative of the vibration with respect to the natural frequency to zero at the modeling frequency.

However, the rise-time penalty incurred for the added robustness of this shaper. To solve this drawback, Singhose and his co-workers [12] have proposed the extra-insensitive (EI) shaper. In order to increase the robustness of input shapers without adding additional time delays, the requirement of having exactly zero vibration at the natural frequency need to be relaxed. Instead of forcing the vibration to exactly zero value, it is allowed to equal some small nonzero value. As a consequence, the shaper can be more robust without incurring an additional rise-time penalty.

Input shaping was first implemented on a gantry crane at the Savannah River Technology Center [13]. Fixed-duration (FD) shapers were implemented on this crane, in which the shaper duration was held fixed while the robustness to modeling errors was maximized. This process creates a set of shapers for different payload suspension lengths with identical rise times. Constant rise times are desirable from an operator standpoint, as they do not have to adjust for variable deceleration times. In previous research, input shaping schemes has been proposed for sway angle suppression of various types of crane system [14,15,16]. Hong and Hong [17] showed simulation results for point-to-point motions of container cranes using a deflection-limiting input shaping technique and nonlinear vibration stabilization control.

This paper presents investigations into the development of input shaping schemes for anti-swaying control of a double- pendulum-type overhead crane (DPTOC) system. An experimental rig of DPTOC system is considered in this work. An unshaped bang-bang force



In order to verify the effectiveness of the proposed input shaping techniques, experimental research was conducted on a double pendulum type overhead crane system as shown in Figure 3. The pendulum system used in this study transmits the rotational power of the motor that is generated as the motor rotates through the ball screw and the rotation is changed into the straight line motion through the ball screw. The straight line motion of the ball screw moves the trolley that is connected to it and the pendulum angle that is connected to the trolley is controlled.



Figure 3. Double pendulum type overhead crane system at Control and Instrumentation Lab, UMP.

Since the overhead crane system using two pendulums, it requires two encoder sensors to sense the sway motion at hook and load of the pendulum. The location of the trolley is recognized by the encoder that is connected to the motor. The detail specification of the lab-scale overhead crane system is shown in Table 1. The input shaping schemes is designed and implemented using CEMTool and SIMTool software with the sampling period selected at 1 ms. The encoder sensor's signals from the angle and trolley motion are connected to analogue I/O Port of RG-DSPIO01 with a voltage range of -10V to +10V. The output of the controller is also sending to the analogue I/O Port of RGDSPIO01 using 25P connector.



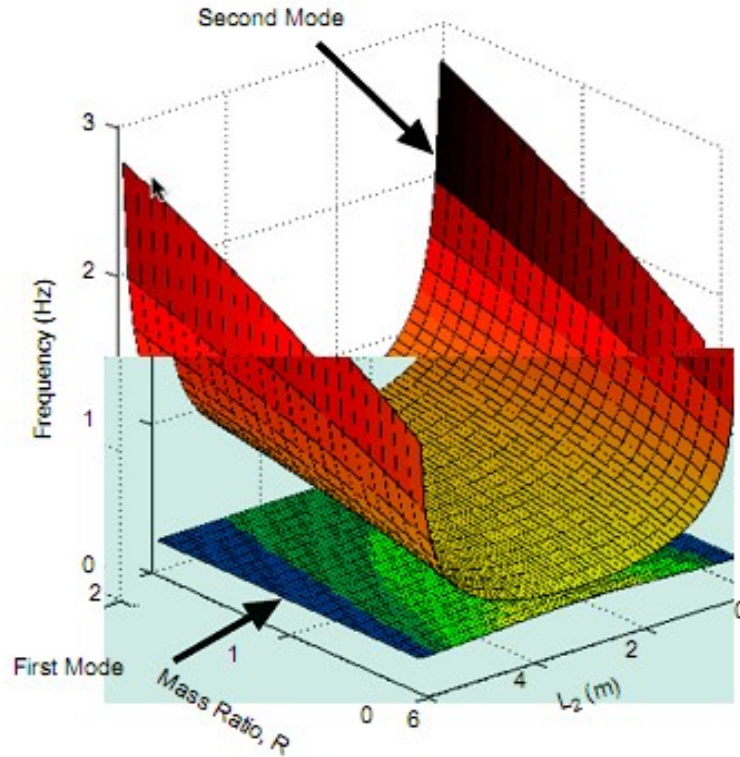


Figure 4: Variation of low and high frequencies [17].

However, their investigations only limited to two mode of sway frequency only. This study can be more practical if three modes of sway frequencies are considered to design the input shapers. Since the ratio of the payload mass to the hook mass is very significant in this study, the higher mode should be taken into account when designing the input shaper. The corresponding design relations for achieving a zero residual of the first three modes sway of a system and to ensure that the shaped command input produces the same rigid body motion as the unshaped command. Generally, a vibratory system of any order can be modelled as a superposition of second order systems each with a transfer function

$$G(s) = \frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2} \quad (1)$$

where  $\omega$  is the natural frequency of the vibratory system and  $\zeta$  is the damping ratio of the system. Thus, the response of the system in time domain can be obtained as





To achieve zero vibration after the last impulse, it is required that both  $V_1$  and  $V_2$  in Equation (4) are independently zero. This is known as the zero residual vibration constraints. In order to ensure that the shaped command input produces the same rigid body motion as the unshaped reference command, it is required that the sum of amplitudes of the impulses is unity. This yields the unity amplitude summation constraint as

$$\sum_{i=1}^N A_i = 1 \quad (5)$$

In order to avoid response delay, time optimality constraint is utilised. The first impulse is selected at time  $t_1 = 0$  and the last impulse must be at the minimum, i.e.  $\min(t_N)$ . The robustness of the input shaper to errors in natural frequencies of the system can be increased by taking the derivatives of  $V_1$  and  $V_2$  to zero. Setting the derivatives to zero is equivalent to producing small changes in vibration corresponding to the frequency changes. The level of robustness can further be increased by increasing the order of derivatives of  $V_1$  and  $V_2$  and set them to zero. Thus, the robustness constraints can be obtained as

$$\frac{d^i V_1}{d\omega_n^i} = 0; \quad \frac{d^i V_2}{d\omega_n^i} = 0 \quad (6)$$

The positive ZS input shaper, i.e. two-impulse sequence is designed by taking into consideration the zero residual sway constraints, time optimality constraints and unity magnitude constraints. Hence, by setting  $V_1$  and  $V_2$  in Equation (4) to zero,  $\sum_{i=1}^N A_i = 1$ ,  $t_1 = 0$  to avoid response delay and solving yields a two-impulses sequence with parameters as

$$t_1 = 0, \quad t_2 = \frac{\pi}{\omega_d},$$

$$A_1 = \frac{1}{1+K}, \quad A_2 = \frac{K}{1+K} \quad (7)$$



The positive ZSDD input shaper, i.e. four-impulse sequence is obtained by setting Equations (4) and (9) to zero and solving with the other constraint equations. Hence, a four-impulse sequence can be obtained with the parameters as

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

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

$$A_3 = \frac{3K^2}{1+3K+3K^2+K^3}, A_4 = \frac{K^3}{1+3K+3K^2+K^3} \quad (10)$$

where  $K$  as is equation (1).

## V. IMPLEMENTATION AND RESULTS

In this investigation, input shaping control schemes are implemented and tested within the experimental environment of the DPTOC system and the corresponding results are presented. The bang-bang input force of  $\pm 1$  N is applied to the trolley of the DPTOC. The bang-bang input is required to have positive and negative period to allow the DPTOC to, initially, accelerate and then decelerate and eventually, stop at the target position. For the sway suppression schemes, positive zero-sway (PZS), positive zero-sway-derivative (PZSD) and positive zero-sway-derivative-derivative (PZSDD) are designed based on the sway frequencies and damping ratios of the DPTOC system. The first three modes of sway of the system are considered, as these dominate the dynamic of the system. The responses of the DPTOC system to the unshaped input were analyzed in time-domain and frequency domain (spectral density). These results were considered as the system response to the unshaped input and will be used to evaluate the performance of the input shaping techniques. The sway frequencies for both hook cable and load cable were obtained as 0.977 Hz, 1.953 Hz and 2.686 Hz for the first three modes of sway.



Load swing angle, $\theta_2$	15.73	42.86	23.55		
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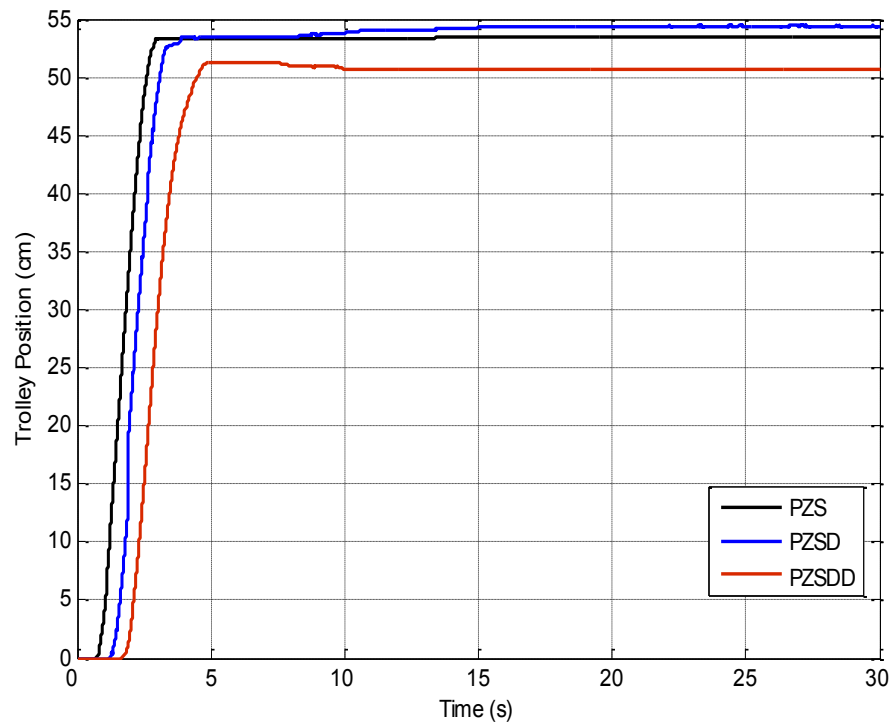


Figure 5. Response of the trolley position.

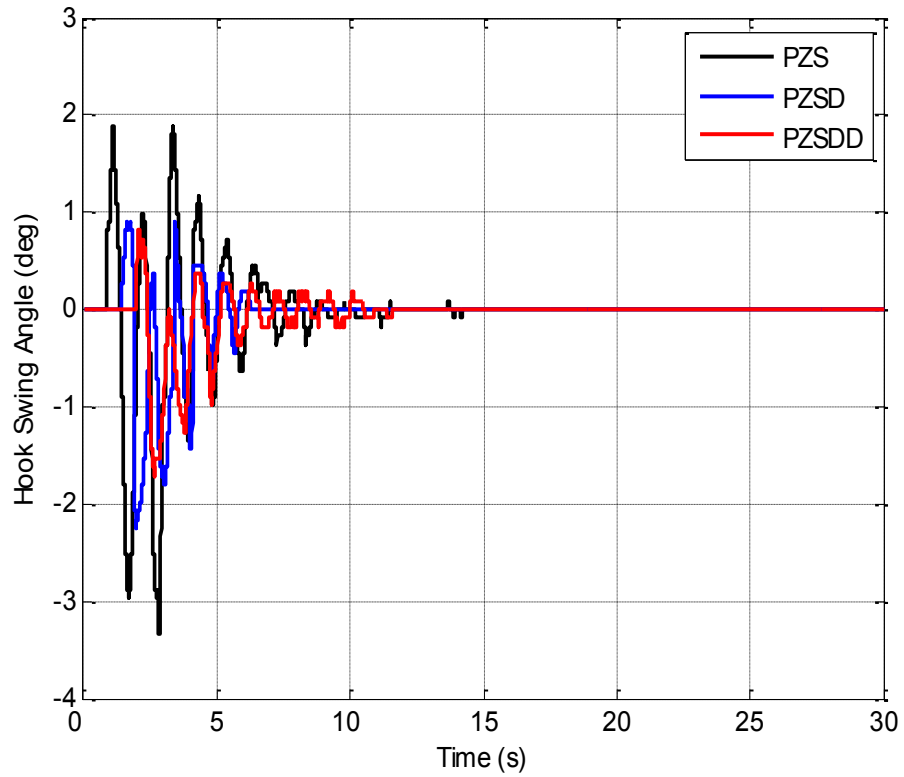


Figure 6. Response of the hook swing angle.

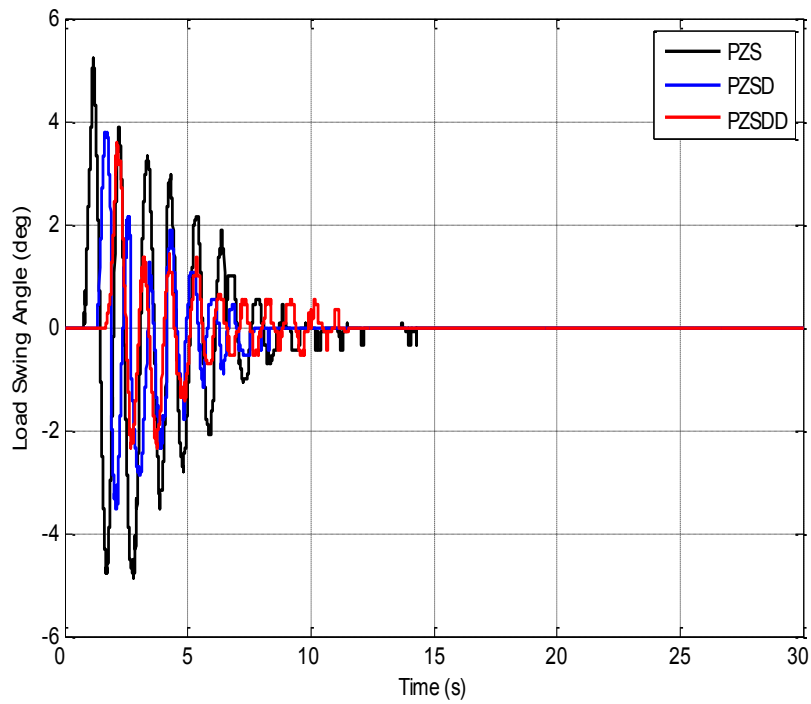


Figure 7. Response of the load swing angle.

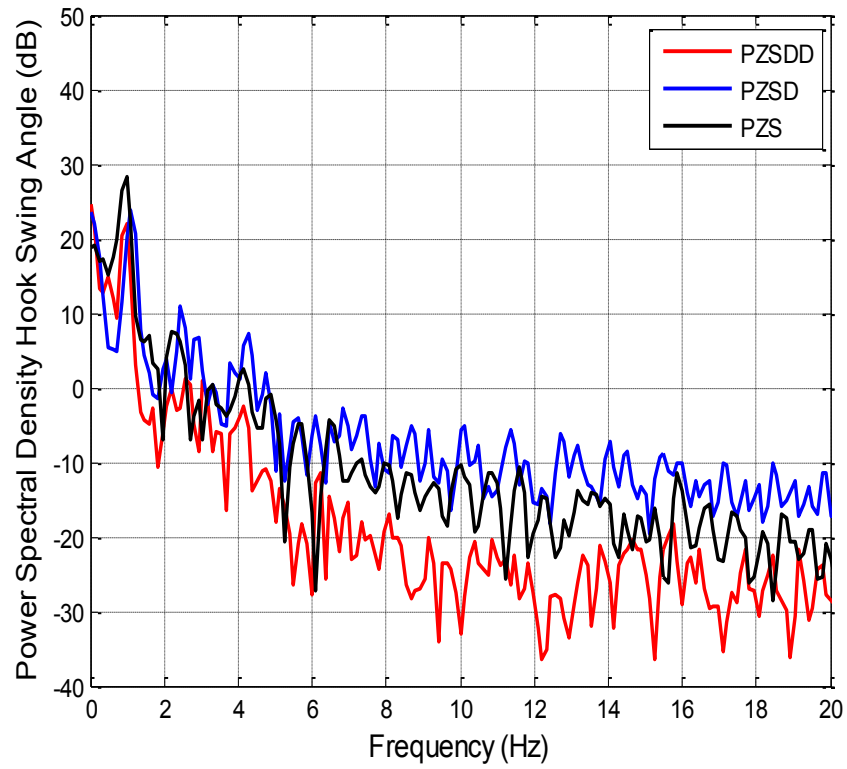


Figure 8. Power spectral density of the hook swing angle.

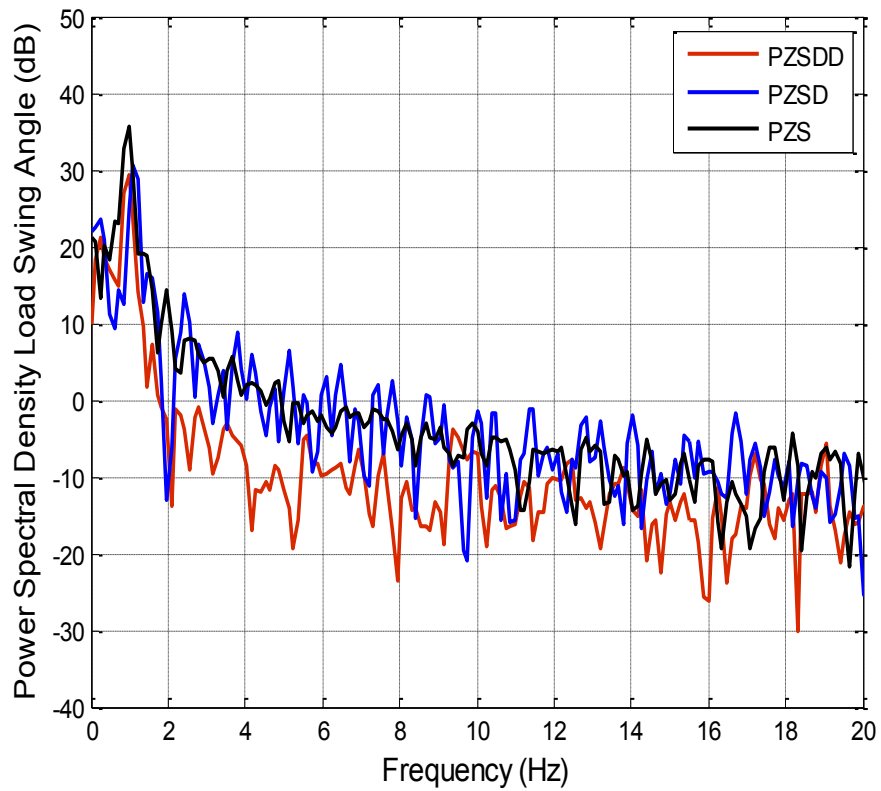


Figure 9. Power spectral density of the load swing angle.

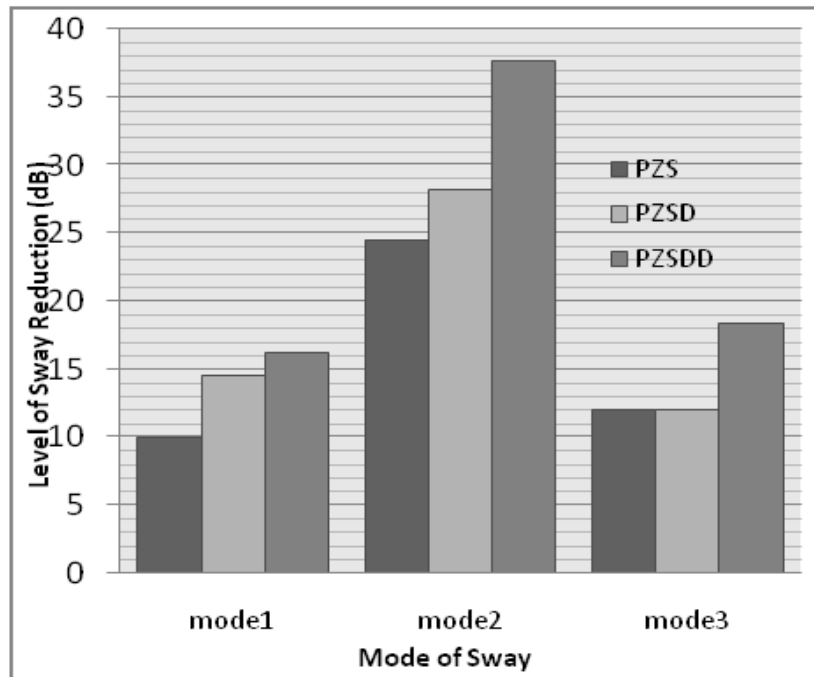


Figure 10. Level of sway reduction for hook swing angle.

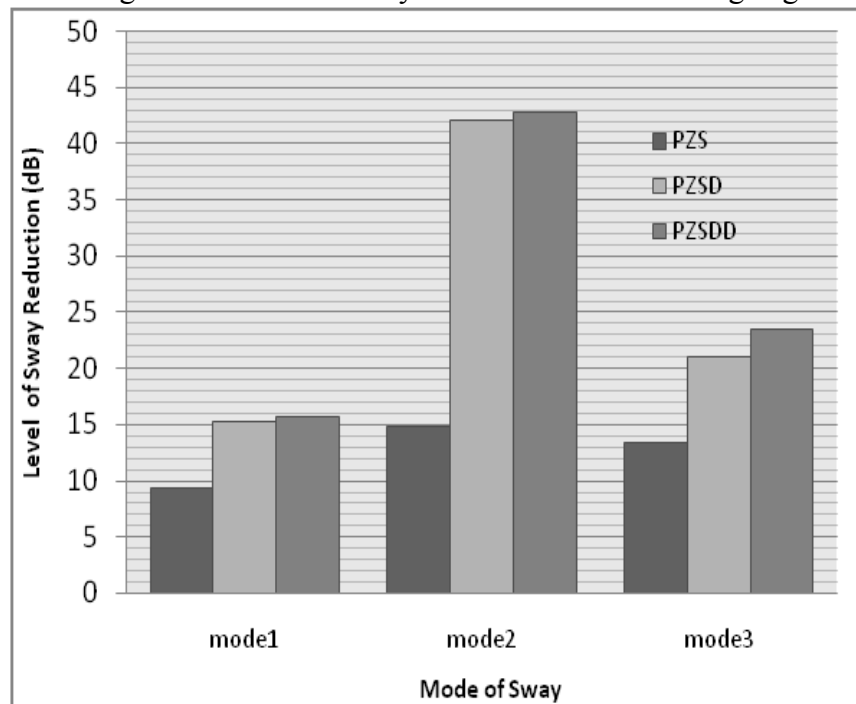


Figure 11. Level of sway reduction for load swing angle.



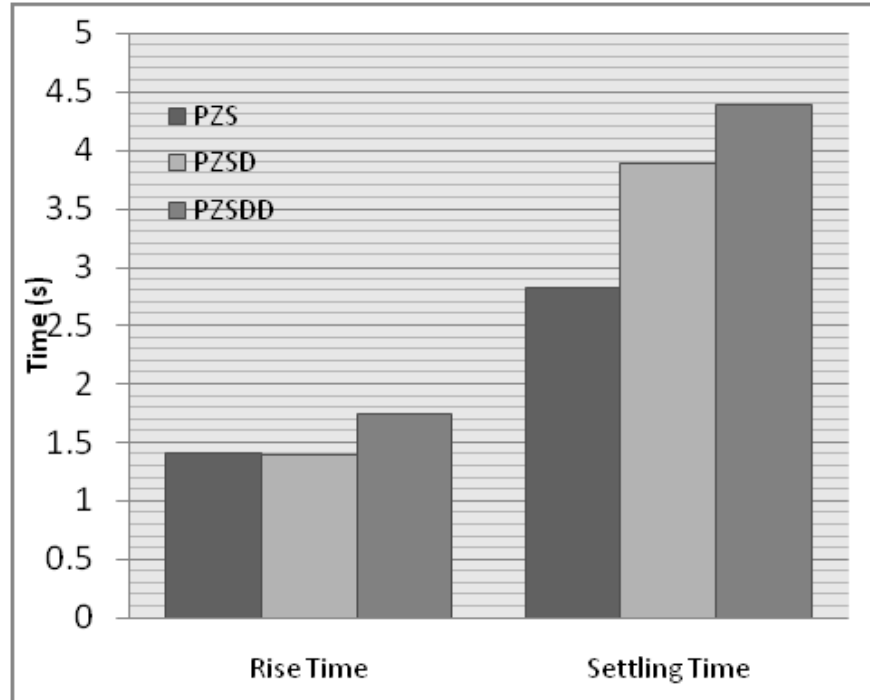


Figure 12. Rise and settling times of trolley position with PZS, PZSD and PZSDD shaper.

## VI. CONCLUSIONS

The development of input shaping control schemes for anti-sway of a DPTOC system has been presented. The performances of the control schemes have been evaluated in terms of level of sway reduction and time response specifications. A comparison of the results has demonstrated that the positive ZSDD shapers provide higher level of sway reduction as compared to the cases using positive ZSD and ZS shapers. By using the positive ZS shapers, the speed of the response is slightly improved in term of settling time at the expenses of decrease in the level of sway reduction. It is concluded that the experiment results on DPTOC system has demonstrated the effectiveness and practicality of the proposed approach.

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