A Novel Approach in S-Shaped Input Design for Higher Vibration Reduction

Mohammad Javad Maghsoudi[1*], Hadidi Nacer[2], M. O. Tokhi[3] and Z. Mohamed[4]

[1]Shahid Bahanor Copper Industries Co., Kerman, Iran.
[2]Département de Génie Mécanique, Ecole Nationale Polytechnique, El Harrach, Algeria.
[2]School of Engineering, London South Bank University, London, UK.
[4]School Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia.

[*]Corresponding author: maghsoudiab@yahoo.com

Abstract: This paper presents development and implementation of a novel approach to produce an s-shaped command with higher residual vibration. In this work, a three dimensional gantry crane is considered where a complete nonlinear mathematical model of a laboratory crane with variable cable length is simulated. A distributed delay zero vibration shaper based approach is proposed to produce an s-curved command. The effectiveness of the shaped command is examined through simulations using the nonlinear model and experiments on the laboratory crane. Simulation and experimental results show that the proposed scheme resulted in lower overall sways for rail and trolley of the crane when compared to a conventional s-shaped signal.

Keywords: Gantry crane; Input shaping; S-shaped input; Sway reduction; Vibration control.

1. INTRODUCTION

Vast applications of overhead cranes have encouraged many researchers to reduce the motion-induced sway of these structures. Several control schemes for control of cranes have been reviewed in [1], and one of the best approaches to reduce the motion-induced sway of oscillatory systems is input shaping. The well-known input shaping technique was firstly introduced by Singer and Seering [2]. Since then, researchers have studied different types of input shapers including, Zero Vibration (ZV) and Zero Vibration Derivative (ZVD) [3-6], negative shapers [7], multi-hump extra intensive shapers [8], adaptive shaper [9], two mode shapers [10] and unity magnitude shapers [11]. Input shapers based on a model reference [12] and neural network [13] have also been proposed recently. Besides, an input shaping scheme based on a distributed delay known as Distributed Zero Vibration (DZV) shaper has been designed and implemented on a laboratory overhead crane [14]. This is on contrast to a common shaper developed based on a lump type delay.

Due to the effect of the inrush current, considerable input jerks similar to shaped commands, cause harmful effects on actuators of flexible systems [15,16]. Transient over-current has harmful effects on motors and sudden changes in input current and/or voltage cause severe damages to motor windings insulation. Some researchers attempted to tackle the problem of jerks in a shaped command profiles by a semi-smooth shaped command profile and a continuous smooth profile [17, 18]. Several studies were conducted to compare the performances of various input shaping techniques in terms of amplitude of transient oscillations, maneuver speed, ease of implementation, robustness to modeling errors and smoothness. Results have shown that input shaping schemes are more effective than input smoothing schemes. Moreover, the command smoothing techniques usually have a more considerable delay as compared to input shaping schemes [19, 20].

In this paper, a novel DZV shaping based technique to produce an s-shaped signal is proposed. Although the proposed scheme produces apparently an s-shaped input, the input is as fast as a normal DZV shaper. A complete mathematical model of the system is obtained based on Newtonian techniques and thus, the natural frequency and damping ratio of the system are obtained. DZV shapers are designed for movement of rail and trolley of the 3D gantry crane. Simulation and experimental results are carried out to investigate performance of the proposed scheme in reducing payload sway of the crane. Maximum magnitudes of residual and transient sways are obtained as well as Integrated Absolute Error (IAE) of the response that indicates overall sway. A conventional s-shaped scheme is also implemented for performance comparisons.

2. A 3D GANTRY CRANE SYSTEM

Figure 1 shows a laboratory 3D gantry crane used in this research. The gantry crane is capable of transferring a load from any location to a desired place in a restricted three dimensional space. The system hardware consists of three main components: a cart, a rail and a pendulum. The mathematical model is obtained based on the given characteristics of the crane by the manufacturer and the study by Pauluk et al. [21]. The obtained model is simulated using Simulink to investigate the dynamic behaviour of system. Control objective is to achieve low sway output during and after motions and hoisting. A schematic diagram of the 3D gantry crane system is shown in Figure 2 with *XYZ* as the coordinate system. m_p, m_t and m_r are the payload mass, trolley mass (including gear box, encoders and DC motor) and moving rail respectively. l represents the length of the lift-line, α represents the angle of lift-line with *Y* axis and β represents the angle between negative part of *Z* axis and projection of the payload cable onto the *XZ* plane. Table 1 shows the parameters used for simulation and experiment in this study. T represents a reaction force in the payload cable acting on the trolley. F_x , F_y and F_z represent forces driving the moving rail, trolley and lifting the payload respectively. f_x, f_y and f_z are the corresponding friction forces.

Figure 1. The laboratory 3D gantry crane

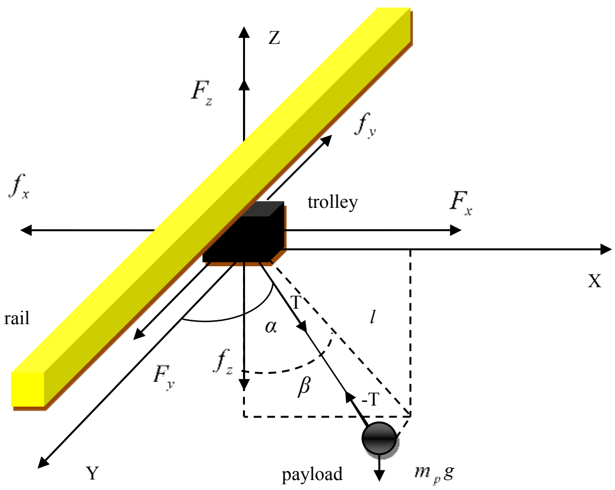

Figure 2. The schematic diagram and forces

Table 1. System parameters

Variables	Values
Mass of payload, m_p	1 kg
Mass of trolley, m_t	1.155 kg
Mass of moving rail, m_r	2.2 kg
Gravitational constant, g	9.8 m/s
Corresponding friction forces, f_x, f_y, f_z	100, 82, 75 Ns/m

Defining

$$\mu_1 = \frac{m_p}{m_t}, \mu_2 = \frac{m_p}{m_t + m_r}; u_1 = \frac{F_x}{m_t}, u_2 = \frac{F_y}{m_t + m_r}, u_3 = \frac{F_z}{m_p}; \; f_1 = \frac{f_x}{m_t}, f_2 = \frac{f_y}{m_t + m_r}, f_3 = \frac{f_z}{m_p}; K_1 = u_1 - f_1, K_2 = u_2 - f_2, K_3 = u_3 - f_3$$

The dynamic equations of motion of the crane can be obtained as [21]

$$\ddot{x}_t = K_2 + \mu_2 K_3 \sin\alpha \sin\beta \tag{1}$$

$$\ddot{y}_t = K_1 + \mu_1 K_3 \cos\alpha \tag{2}$$

$$\ddot{x}_p = \ddot{x}_t + (\ddot{l} - l\dot{\alpha}^2 - l\dot{\beta}^2)\sin\alpha \sin\beta + 2l\dot{\alpha}\dot{\beta}\cos\alpha\cos\beta + (2\dot{l}\dot{\alpha} + l\ddot{\alpha})\cos\alpha\sin\beta + (2\dot{l}\dot{\beta} + l\ddot{\beta})\sin\alpha\cos\beta \tag{3}$$

$$\ddot{y}_p = \ddot{y}_t + (\ddot{l} - l\dot{\alpha}^2)\cos\alpha - (2\dot{l}\dot{\alpha} + l\ddot{\alpha})\sin\alpha \tag{4}$$

$$\begin{aligned}\ddot{z}_p &= (-\ddot{l} + l\dot{\alpha}^2 + l\dot{\beta}^2)\sin\alpha\cos\beta + 2l\dot{\alpha}\dot{\beta}\cos\alpha\sin\beta - \\ &(2\dot{l}\dot{\alpha} + l\ddot{\alpha})\cos\alpha\cos\beta + (2\dot{l}\dot{\beta} + l\dot{\beta})\sin\alpha\sin\beta\end{aligned} \tag{5}$$

where x_p, y_p and z_p are position of payload in X, Y and Z axes respectively. x_t and y_t are position of trolley in X and Y axes.

3. SWAY CONTROL SCHEME

Open loop control scheme is utilised in several industrial applications to transfer loads using gantry cranes. Therefore, it is desirable to study the performance of input shapers based on DZV shaping scheme and s-curved shaping scheme in reducing the payload sway in an open loop configuration. Figure 3 shows the feed-forward input shaping technique used for sway control of the trolley where x and θ represents trolley position and payload sway angle respectively.

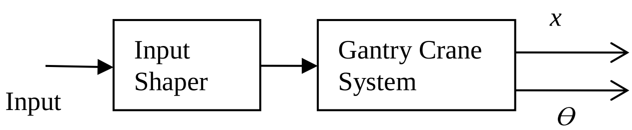

Figure 3. Open loop control scheme with input shaping

3.1 DZV Shaper

The input shaping needs dividing the input signal into some different signals with a specific delay. In the ZV and ZVD shapers, the delay is a lumped type delay. However, in the DZV shaper [14], the delay is distributed. Both types of delay can be described as

$$y(t) = \int_0^\beta x(t-\varepsilon)\,dw(\varepsilon) \tag{6}$$

where y and x are the delay output and input respectively, and the delay distribution over the interval $[0, \beta]$ is described by $\omega(\varepsilon)$. The equally distributed delay as shown in Figure 4 can be formulated as

$$w(\varepsilon) = \begin{cases} 0, & \varepsilon < 0 \\ \frac{1}{\beta}\varepsilon, & \varepsilon \in [0,\beta] \\ 1, & \varepsilon > \beta \end{cases} \tag{7}$$

As $dw(\varepsilon) = \frac{1}{\beta}d\varepsilon$ for $\varepsilon \in [0,\beta]$, Equation (6) can be written as

$$y(t) = \frac{1}{\beta}\int_0^\beta x(t-\varepsilon)\,d\varepsilon \tag{8}$$

Using Laplace transform with zero initial conditions, the DZV transfer function can be described as

$$D(s,\beta) = \frac{1 - e^{-s\beta}}{s\beta} \tag{9}$$

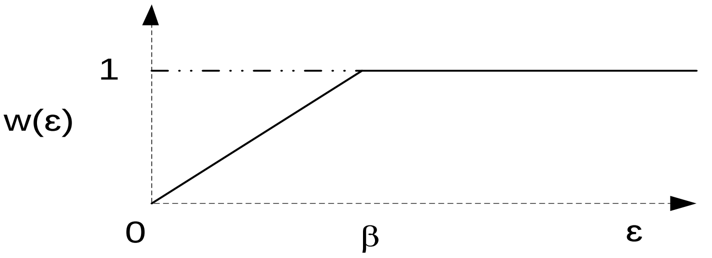

Figure 4. The equally distributed delay

The DZV shaping process is illustrated in Figure 5 and a new shaped input is obtained which is different from the conventional ZV and ZVD type shaped inputs. For a second order oscillatory system, the values of D and β can be obtained as [14]

$$\omega_n e^{-\xi\beta} + \xi \sin(\omega_n \beta) - \omega_n \cos(\omega_n \beta) = 0 \tag{10}$$

$$D = \frac{\sin(\omega_n \beta)}{\sin(\omega_n \beta) - \beta \omega_n e^{-\xi\beta}} \tag{11}$$

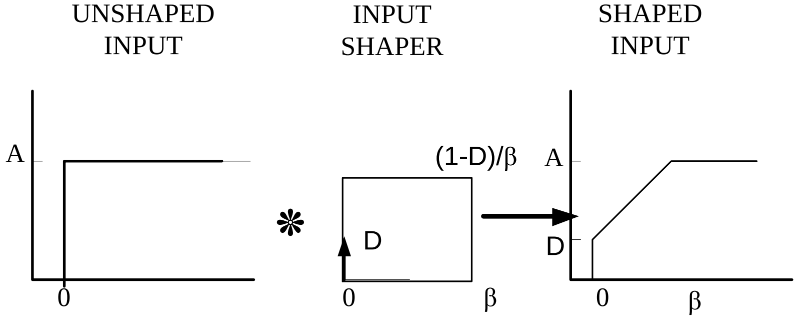

Figure 5. DZV Shaper

3.2 The Proposed Scheme

In the proposed scheme a limited ramp input is applied to a pre-designed DZV shaper (Figure 5) to provide an s-shaped input as shown in Figure 6. Initially, DZV shaper is designed based on natural frequency and damping ratio of the system. Then, a ramp input is applied to a limiter and the output is convolved with the DZV shaper. As the model is nonlinear, DZV shaper is implemented based on the previous study to shape the signal in a symmetric pattern for both falling and rising edge [22]. The result is an s-shaped signal without any sudden changes that is able to eliminate the motion induced sway of the crane without any additional delay.

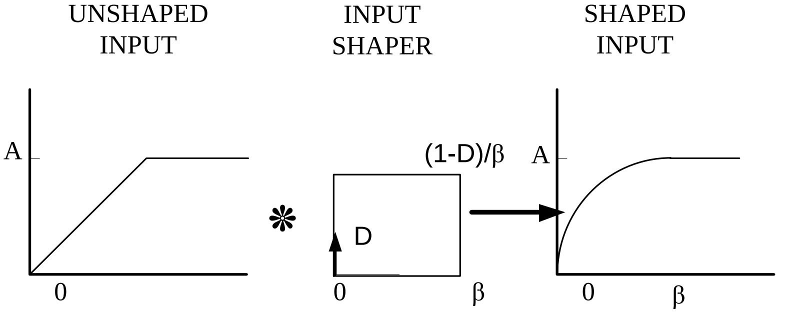

Figure 6. DZV based S-Shaped producing procedure

4. SIMULATION RESULTS

In this section, the control schemes are implemented and tested within the simulation environment of the 3D gantry crane system and the corresponding results are presented. To solve the mathematical equations related to the input shaping, natural frequency and damping ratio of 3D gantry crane were obtained using curve fitting toolbox of Matlab [23]. Table 2 shows natural frequency and damping ratio of 3D gantry crane for both rail and trolley movements. The DZV shapers were designed by solving Equations (10) and (11). The calculated DZV parameters for both rail (X) and trolley (Y) are shown in Table 3. The DZV-based s-shaped input was then designed and implemented for both directions of the 3D gantry crane. Figure 7 shows torque input applied for X (rail) and Y (trolley) directions of the 3D gantry crane with shaped patterns for both conventional s-shaped and proposed implementation schemes. The conventional s-shaped signal was produced by Matlab Simulink and adjusted to have similar start and rest time as compared to proposed shaped input signal. The sway responses of both control schemes for rail and trolley are shown in Figures 8 and 9 respectively.

Considering zero as desired sway, IAE values for rail and trolley were calculated for both controllers. The results show that proposed implementation scheme provided better transient sway for both rail and trolley. With the proposed scheme (DZV-based s-shaped), maximum transient sways were 3.21 degrees and 2.43 degrees for rail and trolley respectively whereas maximum transient sways of 4.45 degrees and 3.32 degrees using s-shaped scheme were obtained. It was noted that the conventional s-shaped scheme yields higher residual sway when compared to the proposed scheme which has nearly half value of s-shaped signal's oscillation. The results were reflected with the IAE values shown in Table 4 where the proposed scheme provided almost half of IAE value when compared to s-shaped signal for trolley and rail. It can be shown that for both rail and trolley, the proposed control scheme provided better sway response performance as compared to conventional s-shaped input.

Table 2. Natural frequencies and damping ratios for rail and trolley

	ω_n(rad/s)	ζ
X	4.538	0.095
Y	4.57	0.09

Table 3. DZV shaper parameters

	D	β
X	0.056	1.31
Y	0.051	1.3

Table 4. Simulated IAE values and maximum transient and residual sway of system responses

	S-Curved Input			DZV-Shaped Input		
	IAE	Residual sway (degree)	Transient sway (degree)	IAE	Residual sway (degree)	Transient sway (degree)
X	917	1.15	4.45	566	0.35	3.21
Y	740	1.01	3.32	462	0.42	2.43

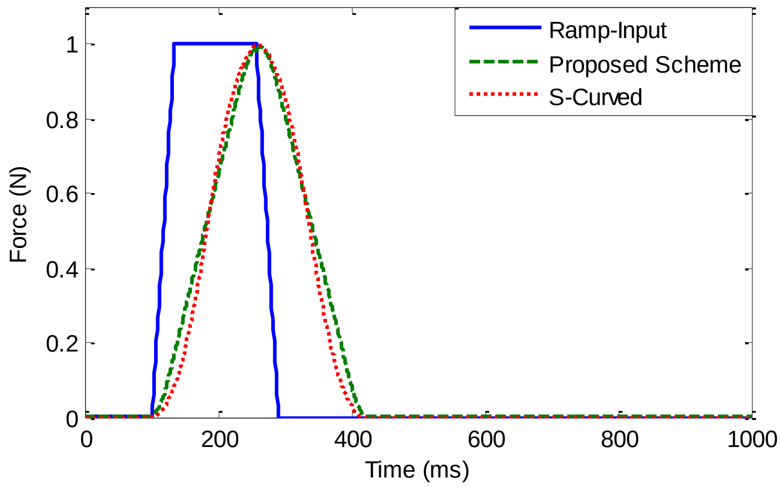

Figure 7. Ramp input, gain-delay shaped and proposed shaped signal (UM-ZV)

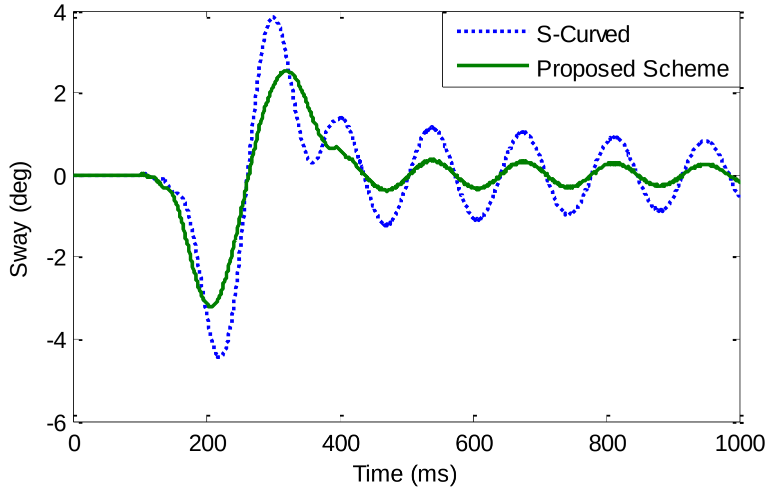

Figure 8. Simulated sway response of payload in *X* direction (rail)

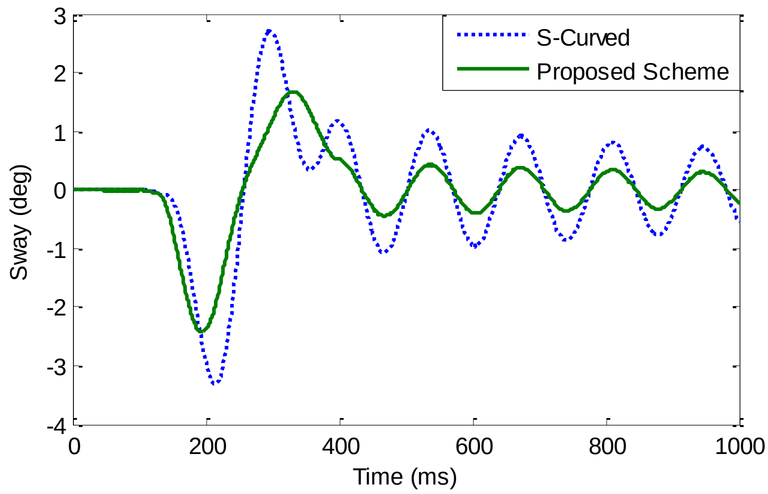

Figure 9. Simulated sway response of payload in *Y* direction (trolley)

4. EXPERIMENTAL RESULTS

Experiments were performed on a laboratory gantry crane shown in Figure 1 to validate the simulation results. The crane is equipped with 5 incremental encoders to measure the position of trolley in *X* and *Y* directions and position of payload in *Z* direction and the payload sway in *X* and *Y* directions. All the data are transmitted on-line to a PC by an interface card. The motors are also actuated by specific DC drives. Similar input as used for simulation is applied to the real gantry crane.

Figures 10 and 11 show the sway response of the payload to similar inputs as in the simulation (Figure 7). The results verified the simulation results where the proposed shaping scheme has reduced significantly the motion induced sway of the payload. The results were reflected with the IAE values shown in Table 5. The residual sway of the payload has been reduced from 4.1 degrees and 3.8 degrees to about 3.1 degrees and 3 degrees for rail and trolley respectively. The IAE values for s-shaped and DZV-shaped signals were 1372 and 769 for rail and 1346 and 832 for trolley respectively. This verified the simulation results where IAE values for proposed scheme input were nearly half of the IAE of s-shaped input. Similar to the simulation results, sway response of payload utilizing DZV shaper has lower transient sway when compared to the s-shaped signal. Experiments verify the simulation results and for both rail and trolley, the proposed control scheme provided better sway response performance.

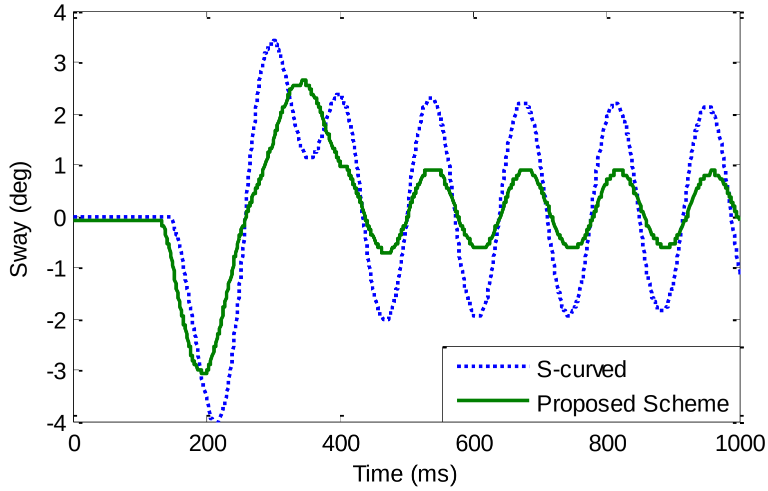

Figure 10. Experimental sway response of payload in *X* direction (rail)

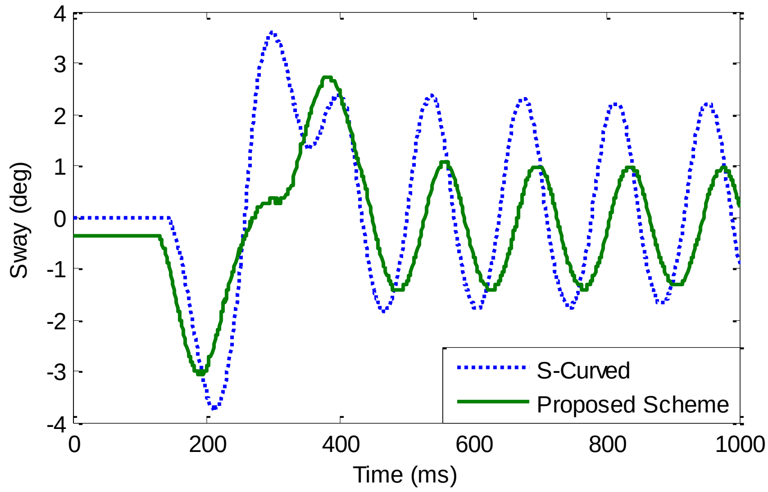

Figure 11. Experimental sway response of payload in *Y* direction (trolley)

Table 5. Experimental IAE Values and maximum transient and residual sways

	S-curved Input			DZV-Shaped Input		
	IAE	Residual sway (degree)	Transient sway (degree)	IAE	Residual sway (degree)	Transient sway (degree)
X	1372	2.3	4.1	769	0.9	3.1
Y	1346	2.4	3.8	832	1	3

5. CONCLUSION

A novel technique for producing a DZV-based s-shaped input has been presented. The shaped inputs have been designed for both rail and trolley. A limited ramp input was applied to the DZV shaper to produce an s-shaped signal and implemented for sway control of a 3D gantry crane. The nonlinear model of the gantry crane has been obtained and used for evaluation of the proposed technique. Simulation and experimental results have demonstrated that the proposed shaper was able to reduce significantly the motion-induced payload sway of the nonlinear gantry cranes. Lower IAE, transient and residual sways were achieved as compared to conventional s-shaped input signal.

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