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Tóm tắt

Trong bài báo này, vấn đề phát triển bộ điều khiển vòng hở input shaping của hệ thống cầu trục sẽ được trình bày. Ba bộ điều khiển input shaping gồm: zero vibration (ZV), zero vibration derivative (ZVD) và zero vibration derivative-derivative (ZVDD) sẽ được áp dụng để khử dao động lắc của tải. Việc thiết kế các input shapers được dựa trên mô hình đã được tuyến tính hóa của cầu trục. Tính hiệu quả của bộ điều khiển input shaping sẽ được làm rõ thông qua các kết quả thực nghiệm.

Abstract: In this paper, three input shaping control schemes of an overhead crane are investigated. Three input shaping controllers, which are zero vibration (ZV), zero vibration derivative (ZVD) and zero vibration derivative-derivative (ZVDD), are applied to suppress sway motions of the overhead crane. The linear dynamic model of the overhead crane is employed to design the input shapers. The effectiveness of the proposed control controllers is verified by experiment results.

1. Introduction

Overhead crane systems are widely used to move heavy cargo from one place to another place in factories and harbors. A crane is naturally an under actuated mechanical system, in which the number of actuators is less than the degree of freedom of the system. For an overhead crane, the degree of freedom is five (i.e., trolley and rail positions, rope length, and two sway angles), but the number of actuators is three (i.e., trolley, rails, and hoisting motors). To improve the transferring efficiency, the trolley and rails should travel as fast as possible.

However, fast trolley/rail movement will cause sway of the load, which is dangerous for the operator and the crane system. Therefore, the research field of crane control (i.e., sway vibration control, trolley motion control, and hoisting motion control) is focused by many researchers.

Models of overhead crane systems were developed by number of researches. The development of modeling and control method for a 3D crane has been reported in Lee et al. [1]. Nonlinear dynamic modeling and analysis of a 3D overhead gantry crane system with system parameters variation was introduced Ismail et al. [2]. These researches developed 3D models of overhead cranes with four degrees of freedom (DOF), i.e., trolley and rail positions and two sway angles. However, the two factors, hoisting motion and effects of friction were not considered. In practice, it should be noted that the variation of the length of cable affects significantly to the crane dynamic. Moreover, it is well known that the consideration of the friction forces is very important in many mechanical systems, especially, in crane systems, the effects of friction forces are considerable under heavy payload.

In crane control, there are two approaches, semi-automated and automated approaches. In the first approach, operator is kept in the loop and dynamics of the load are modified to make his job easier. A number of researchers developed damping controllers employing feedback signals of the load sway angles and their rate (Henry et al. [3]; Masoud et al. [4]). Robinett et al., 1999 developed a filter to remove noise of the input to avoid exciting the load near its natural frequency. Balachandran et al. [5] used a mechanical absorber to suppress the vibration of the payload. Implementation of these methods requires considerable energy consumption, which is not cost effective.

In the second approach, the operator is removed from the loop and the operation is completely automated. Many various techniques can be applied for this. The first technique is based on generating trajectories to transfer the load to its destination with minimum swing (Sakawa and Shindo et al. [6]), in which optimal-velocity profiles of the trolley that minimize the sway angle and its derivative were proposed. In their work, the trolley motion was split into five different sections. Another important method of generating trajectories is input shaping, which consists of a sequence of acceleration and deceleration pulses. These sequences are generated such that there is no residual swing at the end of the transfer operation (Singhose et al. [7]; Singhose, Porter, Kenison, & Kriikku et al. [8]; Hong, Huh, & Hong et al. [9]; Sorensen, Singhose, & Dickerson et al. [10]; Ngo & Hong et al. [11]; Kim & Singhose et al. [12]).

The control objectives are to drive the trolley to the desired position and to suppress the sway angle of the payload simultaneously. Two tasks can be achieved by using two feedback controllers: a controller for prompt sway suppression, which is implemented by a proper feedback of the swing angle and its rate, and a controller for tracking trolley's position and velocity. The tracking controller can be either a classical proportional-derivative (PD) controller (Henry [3]; Masoud [4]) or a fuzzy logic controller (FLC) (Yang et al. [13]; Nalley and Trabia et al. [14]; Lee et al. [15]; Ito et al., 1994; Al-Moussa et al. [16]). These techniques also are employed to design the anti-swing controller. For example, Henry [3] and Masoud [4] used delayed-position feedback, whereas Yang [13], Nalley & Trabia [14], and Al-Moussa [16] used FLC.

The cable length is considered in the design of the anti-swing controller to improve the control performance. Lee, Liang, & Segura et al. [17] proposed a sliding-mode anti-swing control for overhead cranes to realize an anti-swing trajectory control with high-speed load hoisting. A feedback linearization control of container cranes with varying rope length proposed by Park, Chwa, & Hong et al. [18]; these studies were used for 2D model overhead crane.

Recently, the input-shaping method (or command-shaping method) was applied to control cranes [7-12]. The input shaping is constructed by convolving an input shaper with a reference command. Instead of the reference input, the input shaping is applied to the plant. In vibration control, the input shaper is designed based on the natural frequency and damping ratio of the system. Since the input shaping shows two advantages, sensorless and significant effectiveness to linear systems, it has been a promising method to suppress the sway motions of crane systems.

The contributions of this paper are the following. Three input shaping schemes for container cranes are developed. Second, the experiment results show that the proposed control schemes shows good control performance.

2. Dynamics of an overhead crane

This section provides brief description on the model of an overhead crane. Detail of modeling can be found in [19-20]. Figure 1 shows the sway motion of the payload resulted from the trolley movement in *XY* plane is the inertial coordinate system. The definition of the parameter used in the overhead crane system is given in Table 1.

Table 1 Parameters of 2D overhead crane system.

Symbol	Description
$x(t)$	Trolley position over time along *X*-axis (m)
$\theta(t)$	Sway angle over time (rad)
l	Length of rope (m)
M	Mass of trolley (kg)
m	Mass of payload (kg)
g	Acceleration of gravity (m/s^2)
B_{eq}	Equivalent viscous damping of crane along *X*-axis (Ns/m)
B_p	Equivalent viscous damping of crane seen from rope axis (Ns/rad)

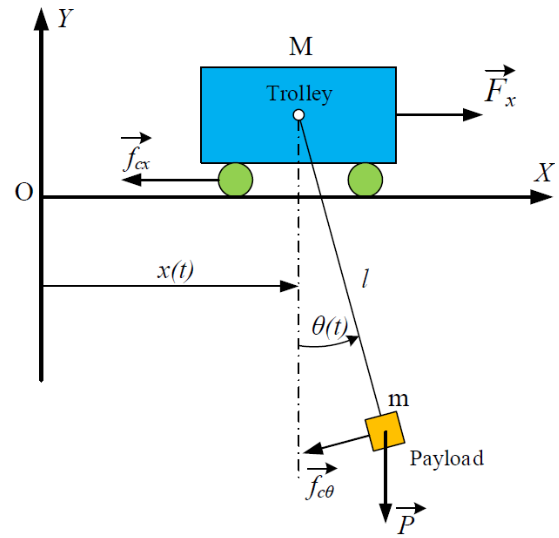

Fig 1. *Overhead crane system*

In this research, the following assumptions are made:

- The payload and trolley are connected by a massless and rigid link.
- Trolley move along *X*-axis only.
- The rope length can be measured.
- The position of trolley $x(t)$ and sway angle $\theta(t)$ of payload are measureable.
- Trolley and payload are considered as point masses and are known.
- All viscous damping (B_{eq}, B_p) are given.
- The effects of disturbances are neglected.

The nonlinear dynamic model of the overhead crane is given as follows:

$$F_x - B_{eq}\dot{x} = (M+m)\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta \quad (1)$$

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

Assuming the sway angle $\theta(t)$ is sufficient small such that the following assumptions hold.

$$\cos\theta \approx 1;\ \sin\theta \approx \theta;\ \dot{\theta}^2 \approx 0. \quad (3)$$

The equations of motion of the overhead crane are then derived as [19]

$$\ddot{x} = \frac{mg}{M}\theta - \frac{B_{eq}}{M}\dot{x} - \frac{mB_p}{M}\dot{\theta} + \frac{1}{M}F_x \quad (4)$$

$$\ddot{\theta} = -\frac{(M+m)g}{Ml}\theta + \frac{B_{eq}}{Ml}\dot{x} - \frac{(M+m)B_p}{Ml}\dot{\theta} - \frac{1}{Ml}F_x \quad (5)$$

By neglect of the viscous damping B_p and B_{eq}, and using Eq. (4), the natural frequency of the vibration of the payload can be obtained as follows

$$\omega_n = \sqrt{\frac{(M+m)g}{Ml}} \quad (6)$$

It should be noted that Eq. (6) is used to determine the natural frequency of payload in the experiment. The dynamics of the overhead crane can be rewritten by the following state space representation

$$\begin{cases} \dot{\mathbf{x}}(\mathbf{t}) = \mathbf{A}\mathbf{x}(\mathbf{t}) + \mathbf{B}u(t), \\ \mathbf{y}(\mathbf{t}) = \mathbf{C}\mathbf{x}(\mathbf{t}), \end{cases} \tag{7}$$

where:

$$\mathbf{x}(\mathbf{t}) = [x \ \dot{x} \ \theta \ \dot{\theta}]$$

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{mg}{M} & \dfrac{-B_{eq}}{M} & \dfrac{-mB_p}{M} \\ 0 & \dfrac{-(M+m)g}{Ml} & \dfrac{B_{eq}}{Ml} & \dfrac{-(M+m)B_p}{Ml} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 1/M & -1/Ml \end{bmatrix}^T \tag{8}$$

$$\mathbf{C} = [1 \ 0 \ 1 \ 0]$$

$$u(t) = F_x.$$

3. Design of input shaping

Basic technical point of input shaping is described in Fig.2. When first impulse is applied, it results in vibration to a system (solid line). Then, if we continue to apply second impulse with appropriate amplitude and time location, this impulse generate vibration (dash line), which can suppress the vibration caused by first impulse. This effect results in zero vibration of the system.

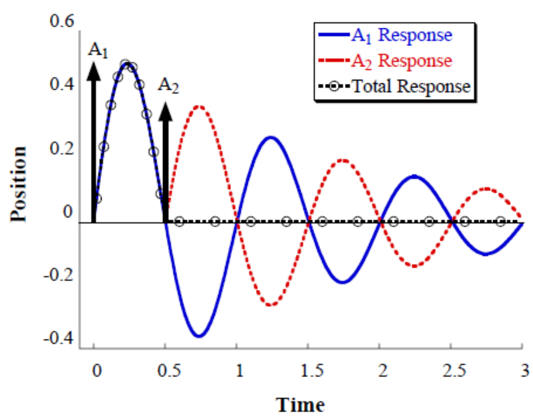

Fig 2. *Basic concept of input shaping* [21]

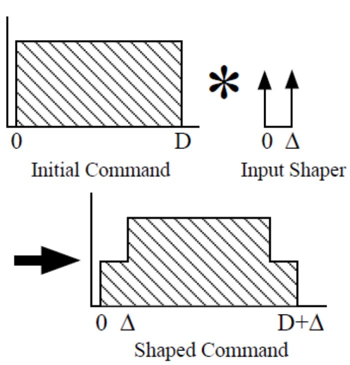

Fig 3. *Input shaping Process* [21]

In input shaping algorithm, next portion of vibration will suppress the vibration caused by previous command. It is a vibration self-canceling process. A sequence of impulses that caused no vibration when apply to system is called input shaper.

William Singhose was the first person who introduced the calculation of input shapers. As his result [22], the percentage residual vibration between the sequence of impulses and single, unity-magnitude impulse is demonstrated in Eq. (9):

$$V(\omega_n,\xi) = e^{-\xi\omega_n t_n}\sqrt{C(\omega_n,\xi)^2 + S(\omega_n,\xi)^2}, \tag{9}$$

where

$$\begin{aligned} C(\omega_n,\xi) &= \sum_{i=1}^{n} A_i e^{\xi\omega_n t_i}\cos(\omega_d t_i) \\ S(\omega_n,\xi) &= \sum_{i=1}^{n} A_i e^{\xi\omega_n t_i}\sin(\omega_d t_i) \end{aligned} \tag{10}$$

A_i and t_i is the amplitude and time location of the i-th impulse, n is the number of impulses in the impulse sequence, ω_n is natural frequency, ξ is damping ratio, and $\omega_d = \omega_n\sqrt{1-\xi^2}$ is defined as damped natural frequency.

ZV is the simplest and earliest input shaper, it can be obtained by solving following constraints [22]:

$$\begin{aligned} &1)\ V(\omega,\zeta) = 0 \\ &2)\ \sum A_i = 1 \\ &3)\ A_i > 0 \\ &4)\ t_1 = 0 \\ &5)\ \min(t_n). \end{aligned} \tag{11}$$

Defining $K = \exp\left(-\dfrac{\xi\pi}{\sqrt{1-\xi^2}}\right)$, ZV input shaper is solved and summarized as following matrix [22], with $T_d = 2\pi/\omega_d$ is the damped period of vibration:

$$\begin{bmatrix} A_j \\ t_j \end{bmatrix} = \begin{bmatrix} \dfrac{1}{1+K} & \dfrac{K}{1+K} \\ 0 & 0.5T_d \end{bmatrix} \tag{12}$$

Real crane system cannot move around with impulses, so that we cannot use input shapers to drive crane directly. Input shapers need to be converted to usable signal. A simple way to achieve this is that the input shapers will be convolved with any desired command signal (velocity, position of trolley …). If input shaper causes no vibration then the convolution product will cause no vibration. This process is called input shaping. Figure 3 demonstrated input shaping process.

4. Robust input shapers

In real system, we cannot exactly estimate crane parameters, or in case that the natural frequency of crane varied over time due to change of the rope length (hoisting) and the mass of container… That leads to the modeling errors when we design ZV shaper thus; there is still an amount of residual vibration after last impulse occur even if ZV input shaper is applied. To demonstrate this effect, Figure 4 will show the amplitude of residual vibration as a function of normalized frequency (normalized frequency is the ratio between actual natural frequency and modeling natural frequency). Notice that the residual vibration tolerance (V_{tol}) line cross the sensitivity curve at two point, width of the curve between them is called Shaper Insensitivity (I) at that V_{tol} and it is a non-dimensional value. The width of the curve that remains below an acceptable level of vibration can be used as a quantitative measure of the insensitivity to modeling errors. In case of ZV, this input shaper has I = 0.064 and such a low value of insensitivity makes ZV input shaper highly sensitive to modeling error, (in this case is natural frequency modeling error). According to figure 3, the residual vibration increase rapidly as the change of normalized frequency. Percentage of residual vibration increases 31% when normalized frequency changes from 1 to 0.8 and up to 59% at 0.6 of normalized frequency. This is major stumbling block of ZV input shaper when apply to real crane system. To solve this problem, we must place more constraint on impulses to increase the robustness of input shaper.

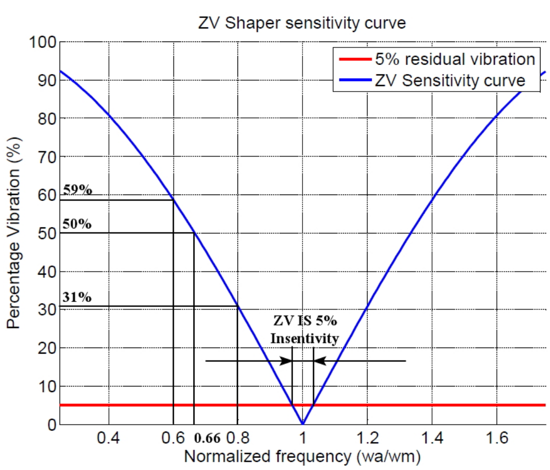

Fig 4. *ZV input shaper sensitivity curve*

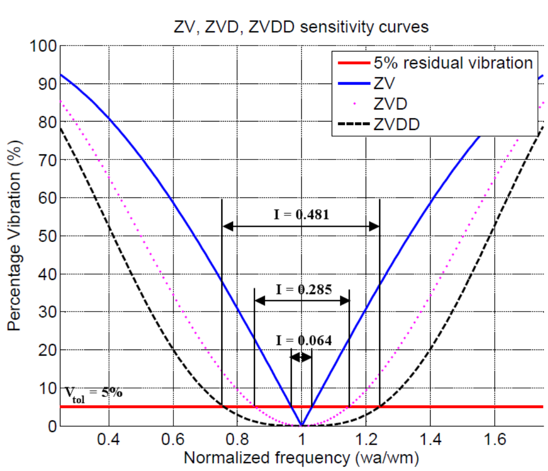

Fig 5. *Comparison of Insensitivity of ZV/ZVD/ZVDD IS*

The earliest robust input shaper is ZVD which is first proposed by Singer and Seering in [24]. The following first derivative constraint is made:

$$\frac{dV(\omega_n,\xi)}{d\omega_n}=0 \tag{13}$$

By adding the constraint (27) to (11), we have the amplitudes and time locations of ZVD input shaper as following matrix [22]:

$$\begin{bmatrix} A_j \\ t_j \end{bmatrix}=\begin{bmatrix} \frac{1}{1+2K+K^2} & \frac{2K}{1+2K+K^2} & \frac{K^2}{1+2K+K^2} \\ 0 & 0.5T_d & T_d \end{bmatrix} \tag{14}$$

To achieve more robustness than ZVD, we replace the first derivative equation (24) by the second derivative of $V(\omega,\xi)$; this leads to the formation of ZVDD input shaper. ZVDD input shaper is determined as following matrix [22]:

$$\begin{bmatrix} A_j \\ t_j \end{bmatrix}=\begin{bmatrix} \frac{1}{J} & \frac{3K}{J} & \frac{3K^2}{J} & \frac{K^3}{J} \\ 0 & 0.5T_d & T_d & 1.5T_d \end{bmatrix} \tag{15}$$

where $J = K^3 + 3K^2 + 3K + 1$.

In order to compare the insensitivity of ZV, ZVD and ZVDD input shaper, figure 5 is plotted. Figure 5 shows that ZVDD has the highest value of insensitivity (I = 0.481), approximately 1.68 times as high as ZVD (which has I = 0.285) and 4.45 times when compare with ZV (I = 0.064). Hence, we have a conclusion that the ZVDD is the most robust in three types of input shapers. But the more robust to modeling errors, the longer duration of shapers is. This leads to the increase of rise time. There is always a tradeoff between the robustness and rise time. ZVDD has the slowest rise time, next is ZVD and ZV is the fastest input shaper (otherwise is the most sensitive one). This effect will be clearly indicated in following experiments.

5. Experiment results

Experiments were conducted at HCMUT mechatronics lab and shown in Fig. 6. The payload is hung at the end of a flexible rope and driven by an AC servo motor (hoist motion). The gantry motion is handled by an AC servo motor through a synchronous belt and a belt connector. The trolley motion uses the similar mechanism with gantry motion. Three AC servo motors are controlled by SMC-4DF-PCI board, which is attached to computer through PCI bus. The control board transmits the reference signals to motors through three MR-J2S-A servo amplifiers. There are two 2048 ppr incremental encoders to measure the swing angles around X-axis and Y-axis. Phase signals of encoders are directly read by control board. The necessary parameters of crane are:

M = 20 kg, m = 0.8 kg, l = 1 m, g = 9.81 m/s², ξ = 0.00358.

According to crane parameters, we compute input shapers and the results are described as (16). Notice that A_j are non-dimensional values and the dimension of t_j are second.

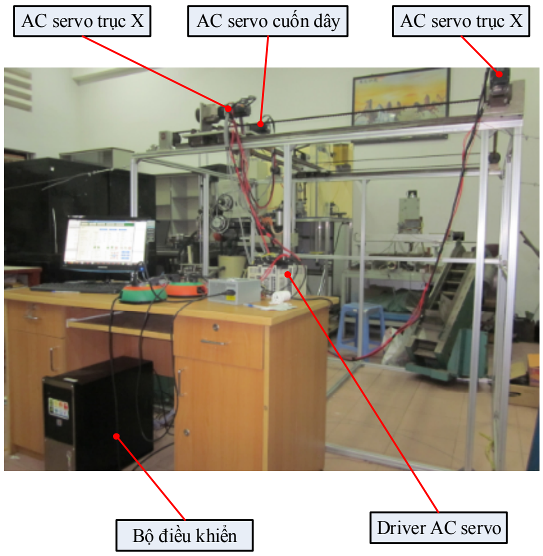

Fig 6. *Overhead crane system at HCMUT Mech. lab*

$$
\begin{aligned}
&ZV: \begin{bmatrix} A_j \\ t_j \end{bmatrix} = \begin{bmatrix} 0.503 & 0.497 \\ 0 & 0.98 \end{bmatrix} \\
&ZVD: \begin{bmatrix} A_j \\ t_j \end{bmatrix} = \begin{bmatrix} 0.253 & 0.5 & 0.247 \\ 0 & 0.98 & 1.97 \end{bmatrix} \\
&ZVDD: \begin{bmatrix} A_j \\ t_j \end{bmatrix} = \begin{bmatrix} 0.127 & 0.377 & 0.373 & 0.123 \\ 0 & 0.98 & 1.97 & 2.95 \end{bmatrix}
\end{aligned} \tag{16}
$$

As mentioned above, input shapers must be convolved with desired command. In our experiments, the trolley velocity is 0.5 m/s and travel distance is 0.5 m. The trolley velocity profile is shown in Figure 7. Figure 8 shows the peak of sway angle $\theta(t)$ (in case of no control) is 16 degrees and remain about 14 degrees after 20 seconds because of the low damping ratio (ξ = 0.00358, which is estimated by using experiments).

In order to prove the effectiveness of input shaping algorithm, ZV input shaper is first convolve with trolley velocity and applied to system. Figure 9 demonstrates the result in this case. As shown in Fig. 9, ZV input shaper significantly reduces the sway angle of payload. Peak of sway angle is reduced to 4.6 degrees and almost to zero degree after 20 s. Because ZV input shaper is highly sensitive with natural frequency error, there exists still very small residual vibration after the trolley reaches the desired position. The effects of the natural frequency were decreased when ZVD and ZVDD input shapers were applied.

Figure 10 shown the experiment result when ZVD input shaper applied to system. The peak of payload's sway angle is reduced to 2.6 degrees (less than 3.8 degrees of ZV shaper and 16 degrees of none-controller). Moreover, ZVD input shaper totally suppresses the residual vibration after trolley reach the destination (at $t = 4.22$ s).

ZVDD input shaper is then applied to crane system and the sway angle after run time is plotted in Fig. 11. Similar to ZVD, ZVDD is a robust input shaper; at the time when trolley arrives the desired distance, the sway angle of payload is totally eliminated. Besides, peak of sway angle is just 1.4 degrees and it is the smallest in comparison with ZV or ZVD.

In order to compare with another algorithm, a closed-loop controller designed based on linear quadratic regulator technique is applied to the crane system. Four coefficients of K matrix are tuned manually until get the best control performance:

$$\mathbf{K} = \begin{bmatrix} 3.5 & 0.5 & -130 & -30 \end{bmatrix}$$

Then, the controlled signal $u = -\mathbf{Kx}$ (with $\mathbf{x} = \begin{bmatrix} x & \dot{x} & \theta & \dot{\theta} \end{bmatrix}$ is the state variables of crane system) is used to drive the trolley. Figure 12 shows the result when LQR controller is applied. Peak payload's sway angle when use LQR controller is 4 degrees, just a little smaller than ZV input shaper – which has the largest peak sway angle in three types of input shaper. However, time for totally cancel the sway angle of payload is up to 7.5s, longer than ZVDD – which is the slowest input shaper. However, LQR can eliminate disturbances effectively unlike input shaping is open loop control so it can do nothing with position or angle disturbances.

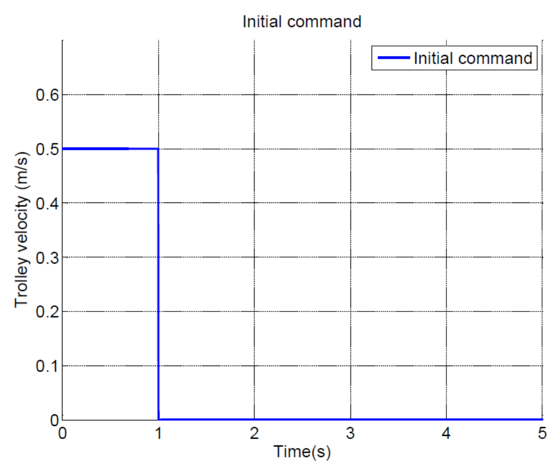

Fig 7. *Initial command*

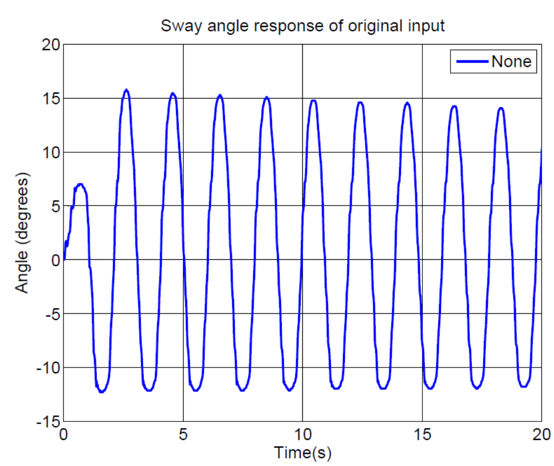

Fig 8. *Sway angle of payload without any controllers*

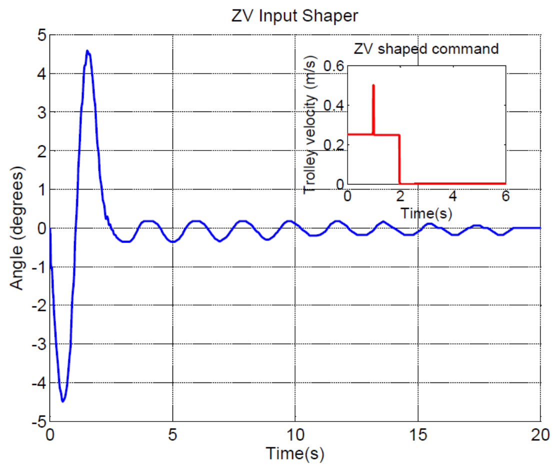

Fig 9. *Sway angle of payload with ZV input shaper*

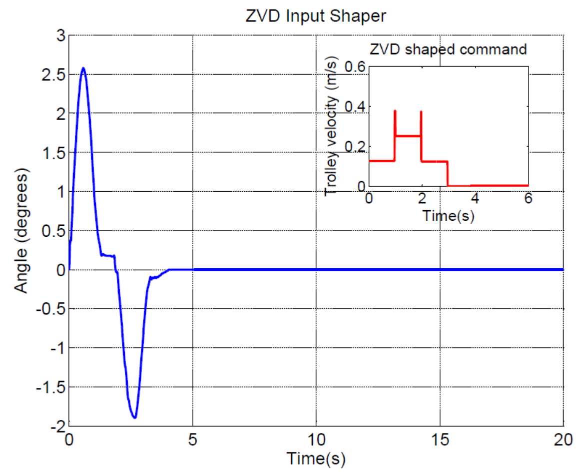

Fig 10. *Sway angle of payload with ZVD input shaper*

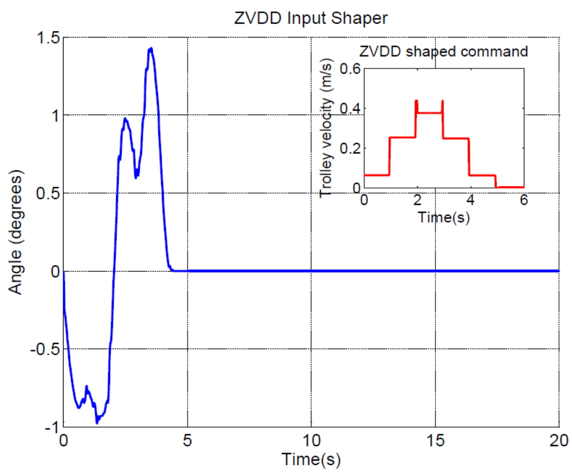

Fig 11. *Sway angle of payload with ZVDD input shaper*

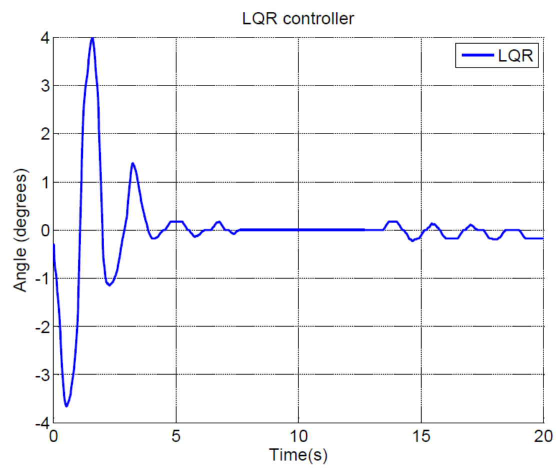

Fig 12. *Sway angle of payload with LQR controller*

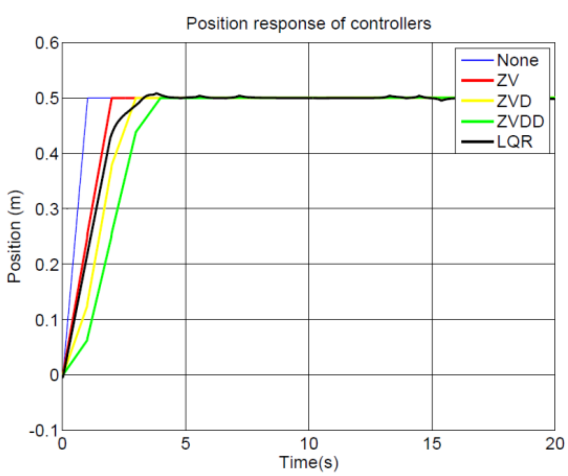

Fig 13. *Position response of controllers*

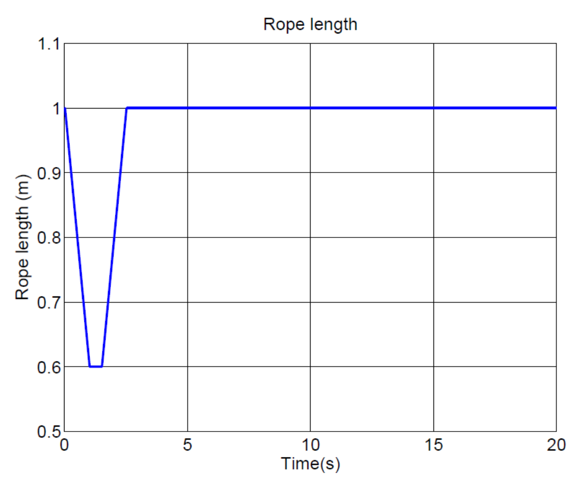

Fig 14. *Rope length profile*

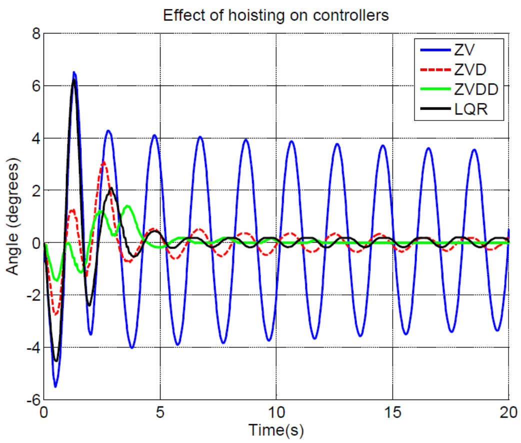

Fig 15. *Effect of hoist motion on sway angle*

Table 2 Sway angle of payload with hoist motion

	Sway angle after trolley stop (degrees)	$V(\omega,\xi)$ (%)
No-controller	16	x
ZV	4.3	26.88
ZVD	1.2	7.5
ZVDD	0.7	4.38

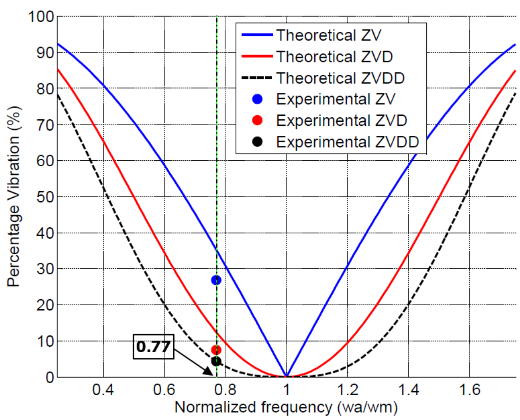

Fig 16. *Comparison between experimental results and theoretical sensitivity curves*

As mentioned above, there is always a tradeoff between the robustness and rise time. This effect is described in Figure 13 and Table 3 summarize the rise time and robustness ranking of three input shapers. Moreover, Fig.13 shown that LQR controller takes 3.3 s to reach 0.5 m of desired distance, faster than ZVDD input shaper but slower than ZV and ZVD input shapers. In addition, LQR performs a small position overshoot which is a typical characteristic of every closed-loop controller.

Table 3 Rise time and robustness ranking

Input shaper	Rise time	Rise time rank	Robustness rank
ZV	2 s	1st	3rd
ZVD	2.98 s	2nd	2nd
ZVDD	3.98 s	3rd	1st

In reality, crane must perform the hoist motion to load/unload the containers. This means the rope length will vary in a wide range thus the natural frequency of crane system has a large change. To illustrate this effect, the rope length of crane model changes as shown in Figure 14. Firstly, the payload is moved up to 0.6 m rope length in 1 second. Secondly, then during next 0.5 second, the rope length velocity is zero. Finally, the payload is moved down to 1 m rope length in 1 second. Trolley velocity and desired distance are kept to be constant. Figure 15 compares the robustness between ZV, ZVD, ZVDD shaper and LQR controller. This experiment proves the robustness of input shapers, which are theoretically plotted in previous section. After reach the desired position, ZV performs the largest residual vibration (3.5 degrees of sway angle at the time trolley reach 0.5m, t = 2s). The following is ZVD, it performs 1.2 degrees of sway angle (smaller than ZV shaper) at t_{last} = 2.98 s and the last is ZVDD, this input shaper achieve the sway angle 0.38 degrees at the time the trolley reaches the desired position. Among three input shaping applied to the crane system, it is concluded that the ZVDD input shaping is the best control algorithm for the overhead crane.

On the other hand, LQR is least sensitive to the change of natural frequency when compares with ZV or ZVD input shaper because of the benefit of closed-loop controller type. However, there is some effect of hoisting on LQR controller. First is the peak of sway angle in transient period increases to 6 degrees, larger than 4 degrees when no hoisting. Second is the sway angle is not completely suppress to zero degree, there is still very small angle exist (smaller than ZV & ZVD shapers but larger than ZVDD). The reason for all mentioned problem is: the coefficients of LQR controller is tuned with specified crane parameters, when hoisting is performed, the rope length change to new value thus the previous coefficients is not correct anymore, so the performance of LQR controller is affected. To overcome these problems, an appropriate adaptive controller must be applied. Adaptive controller can predict the change of system parameters and auto-tuned the coefficients of controller. This work is implemented by Quoc Toan Truong, Anh Huy Vo and Quoc Chi Nguyen with a nonlinear adaptive controller in [34].

In order to compare the theoretical sensitivity curves in Figure 5 with experiment results, Fig. 16 is plotted. Table 2 summarize the payload's sway angle of each input shaping controller after trolley reach to desired position. Figure 16 shown that the real residual vibration is remained below the theoretical values. This is obvious because when crane perform the hoist motion, the change of normalized frequency $\sqrt{\frac{l_{\min}}{l_{\max}}}=\sqrt{\frac{0.6}{1}}\approx 0.77$ is the maximum value of whole duration while Fig.5 is plotted with the 0.77 constant value of normalized frequency.

6. Conclusions

In this paper, input shaping controllers (ZV, ZVD and ZVDD) were proposed. The experiments illustrated the significant effectiveness of the three input shaping methods. The sensitivity of input shapers to natural frequency error (through hoisting motion) was investigated. A closed-loop controller LQR was also applied to overhead crane system in order to compare with input shaping algorithms. LQR is more effective than input shaping when there is hoisting motion or sway angle disturbances. However, input shaping is a sensorless control while LQR requires a complicated measure system, this leads the increase of costs. Moreover, it is hard to find appropriate coefficients of K matrix in real crane system.

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