Improved Three-Step Input Shaping Control of Crane System

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Abstract: Shaping command input is performed for reducing residual vibrations in motion control of dynamical structures. System inputs are changed so that the structure reaches to planned motion in minimum duration without residual oscillation. Shaping input is obtained by convolving desired input with an impulse sequence. Main goal of the input shaper design is to define impulse amplitudes and their instants from the dynamical behavior of uncontrolled response. Zero Vibration (ZV), Zero Vibration and Derivative (ZVD) and Extra Insensitive (EI) are the most common shaper types. Improving the robustness respect to modeling errors requires more impulses. These increase control duration and make difficult to solve constraint equations directly. Required parameters can be determined from the derivation of constraint equations.

This paper presents Three-Step (TS) input shaping technique. A solution space for three-impulse shaping is given including both positive and negative shapers. It is shown here that ZVD and EI shapers are the special solution points in TS shaping space. The duration of the shaper less or more than ZVD's can be obtained in the defined space. Some of the new shapers give better robustness than ZVD. Experimental results from a prototype planar crane system are used to support the numerical results.

Keywords: Vibration, Input shaping, Three-step shaper, Planar crane, Robustness, Command generation

1 Introduction

The vibration is a significant problem in dynamical systems that are required to perform precise motion in presence of structural flexibility. Step motors, robotic arms, flexible manipulators and crane systems are some examples for this category. Oscillatory behavior is seen not only system itself but also in its load or together. Examples of such loads range from sheets to long pipes and other elastic materials.

The performance of precision motion depends on damping capacity of the system. The damping capability of a dynamical system can be enhanced by passive or active damping methods. In the passive approach, oscillation damping is increased by deploying external dampers such as dashpots or viscous dampers [1]. Feedback control can also be used as an active approach in a wide band of insensitivity. Another approach is feedforward control techniques. For example, residual vibration of the system is successfully reduced by shaping the input command. The earliest incarnation of this self-canceling command generation was developed in the 1950's by O.J.M. Smith [2]. His posicast control method involved breaking a command of certain magnitude into two smaller magnitude commands, one of which is delayed one-half period of vibration. Unfortunately, his technique was extremely sensitive to modeling errors [3]. Singer and Seering developed reference commands that were robust enough to be effective on a wide range of systems [4]. This new robust technique is named as input shaping.

Input shaping is implemented by convolving a sequence of impulses, an input shaper, with a desired system command to produce a shaped input that produces self-canceling command signal [5]. Input shaper is designed by generating a set of constraint equations which limit the residual vibration, maintain actuator limitations, and ensure some level of robustness to modeling errors [6]. The process has the effect of placing zeros near the locations of the flexible poles of the oscillatory system. In the input shaper, the amplitudes and time locations of the impulses are determined by solving the set of constraints [6-10].

Most existing crane control systems are designed to maximize speed, in an attempt to minimize system vibration and achieve good positional accuracy in a minimum duration [11-14]. High stiffness can be achieved by using short rope or heavy carrier head. As a result, such cranes are usually heavy with respect to its payload. This limits the speed of operation of transportation, increases size of driving motor and energy consumption [15-17]. The payload to carrier weight ratio is also low under this condition. In contrast, a tall crane system with a light carrier head provides many returns. It requires less material, is lighter in weight, has higher conveyance speed, lower power consumption, requires smaller motors, is more maneuverable, is safer to operate, has less total cost and has higher payload to carrier weight ratio. Conversely, the control of such systems with accurate positioning is not easy. Troubles begin due to precise positioning requirements in many application areas. Some difficulties occur to obtain accurate model of the system [17].

This paper presents experimental investigations into the development of control schemes for vibration control of a light and very oscillatory crane system driving in high speeds. It is preferred in this study a feedforward control technique, input shaping. Feedback anti-sway control schemes can not be used crane systems, generally. Main problem in the feedback control systems. Optical, laser or proximity sensor measurements are not easy to setup in most systems. The rope length and high vibration amplitudes make difficult to define precision measurement.

Classical and new input shaping methods are compared respect to their performance. The input shaper is designed on the basis of the dynamic characteristics of the crane system and used for pre-processing the reference input. Performances of the developed control schemes are evaluated in terms of level of vibration reduction, tracking capability in high speeds and robustness to the modeling errors. Experimental results of the trolley travel and payload acceleration with the control schemes are presented.

If the constraints are minimum duration and zero residual vibration, then the solution shaper is ZV shaper. However, ZV shaper is not well on most systems because it is sensitive to modeling errors. Robustness can be improved by adding more impulse to the shaper. The resulting shaper is a three step shaper. Direct solution of amplitudes and their duration is not possible due to the inadequate number of constraint equations. ZVD shaper, as a special solution, can be obtained by setting the derivation of constraint equations with respect to the frequency of the residual vibration equal to zero. ZVD scheme is less sensitive to timing error and hence generally is more robust in real applications than the ZV scheme. However, it requires a time penalty. ZVD shaper has duration of one period of unshaped vibration, while ZV has only a half period [7, 8, 11-15].

There are infinite numbers of solution for TS shaping including ZVD shaper. Duration of obtained shapers for the selected space is between ZV and ZVD. This paper demonstrates that TS shaping can be improved to damp the residual vibration when the length of the command is not allowed to be increased. Some new shapers produce more robustness than ZVD somewhat. In Section II, the derivation of expressions for TS shaping is given. Section III displays response and robustness comparisons for the new and classical shapers. Finally, concluding remarks are emphasized in Section IV.

2 Modeling of Input Shaping

Linear dynamical systems are generally modeled by second order differential equations. A damped oscillatory dynamic system model can be given as:

$$m\frac{d^2x}{dt} + c\frac{dx}{dt} + kx = Fu(t) \qquad (1)$$

The transfer function of this second-order dynamical model is

$$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{2}$$

where, ω_n is the undamped natural frequency and ξ is the damping ratio. Relationship between the coefficients of transfer function and differential equation is given as:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{3}$$

$$\xi = \frac{c}{2\sqrt{km}} \tag{4}$$

Step or impulse response of the system yields generally damped oscillatory behavior [9, 16, 17]. Impulse response of a second order system at time t is:

$$x(t) = A\frac{\omega_n}{\sqrt{1-\xi^2}} e^{-\xi\omega_n(t-t_0)} \sin(\omega_n\sqrt{1-\xi^2}(t-t_0)) \tag{5}$$

Where A and t_0 are the impulse amplitude and instant of the impulse, respectively. For n impulses, the impulse response can be expressed as

$$x(t) = M\sin(\omega_d t + \phi) \tag{6}$$

where

$\omega_d = \omega_0\sqrt{1-\xi^2}$ is damped frequency,

$$M = \sqrt{(\sum_{j=1}^{n} B_j\cos(\omega_d t_j))^2 + (\sum_{j=1}^{n} B_j\sin(\omega_d t_j))^2}$$

and

$$B_j = \frac{A_j\omega_n}{\sqrt{1-\xi^2}} e^{-\xi\omega_n(t-t_i)}$$

$$\phi = \cos^{-1}(\xi)$$

A_j and t_j are the magnitudes and times at which the impulses occur [17].

The residual vibration amplitude is obtained at the time of the last impulse, t_n as

$$V_{(\xi,\omega)} = e^{-\xi\omega_n t_n}\sqrt{C_{(\xi,\omega)}^2 + S_{(\xi,\omega)}^2} \tag{7}$$

where

$$C_{(\xi,\omega)} = \sum_{j=1}^{n} A_j e^{\xi\omega_n t_j} Cos(\omega_d t_j) \tag{8}$$

$$S_{(\xi,\omega)} = \sum_{j=1}^{n} A_j e^{\xi\omega_n t_j} Sin(\omega_d t_j) \tag{9}$$

Input shaping limits residual vibration by generating a command profile that tends to cancel its vibration [16]. The vibration occurs due to the first part of the command input is compensate by vibration occur due to the next part of the command input. These sequences of impulses are convolved with the desired system command. Then, the convolution is used to drive the system. The desired command is a step input theoretically. Several types of input shapers have been proposed [4, 17]. The shaper contains impulses; all of them have positive amplitudes for positive input shaping.

Input shaping requires constraints to produce a solution. Eq.(8) and Eq.(9) should be independently zero to achieve vibration free response after the last impulse [10, 18]. The sum of amplitudes of the impulses is required unity to ensure that the shaped command produces the same set point as unshaped motion, $\sum_{j=1}^{n} A_j = 1$. The first impulse is applied at time zero, t_1=0. Impulse amplitudes are selected between 0 and 1 to obtain a positive shaper.

If the system is solved for two impulse sequence, ZV shaper is obtained. Amplitudes and time locations of the ZV shaper is shown in Eq.(10) as first and second rows respectively.

$$ZV = \begin{bmatrix} A_1 & A_2 \\ 0 & t_2 \end{bmatrix} \tag{10}$$

Exact solution of Eq.(10) for a given system is

$$ZV = \begin{bmatrix} \dfrac{1}{1+K} & \dfrac{K}{1+K} \\ 0 & \dfrac{\pi}{\omega_d} \end{bmatrix} \tag{11}$$

where $K = e^{-\xi\pi/\sqrt{1-\xi^2}}$.

Fig.1 shows the ZV shaper implementation by convolving sequence of two impulses with the desired system command.

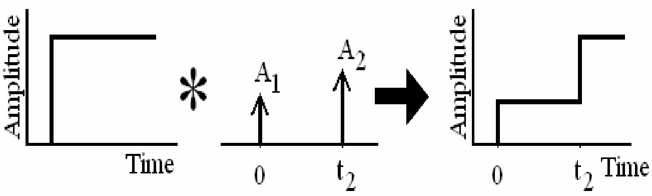


Fig.1 ZV shaper

Robustness can be improved by increasing the number of impulses. Adding an impulse to ZV produces TS shaper. Direct solution is impossible owing to the insufficient constraint equations. Although we have only three equations, three-impulse amplitudes and their time locations require solving five unknown parameters, A_1, A_2, A_3, t_2 and t_3. A specific analytical solution can be obtained by making the derivative of the constraint equations (8) and (9) respect to natural frequency of the system equal to zero,

$$\frac{dC}{d\omega_n} = \sum_{j=1}^{n} - A_j t_j e^{\xi\omega_n t_j} \sin(\omega_d t_j) = 0 \qquad (12)$$

and

$$\frac{dS}{d\omega_n} = \sum_{j=1}^{n} A_j t_j e^{\xi\omega_n t_j} \cos(\omega_d t_j) = 0 \qquad (13)$$

However, increase the impulse number results a delay in response time. Resulting shaper is named ZVD.

$$ZVD = \begin{bmatrix} \frac{1}{1+2K+K^2} & \frac{2K}{1+2K+K^2} & \frac{K^2}{1+2K+K^2} \\ 0 & \frac{\pi}{\omega_d} & \frac{2\pi}{\omega_d} \end{bmatrix} \qquad (14)$$

Implementation of the ZVD shaper is shown in fig.2.

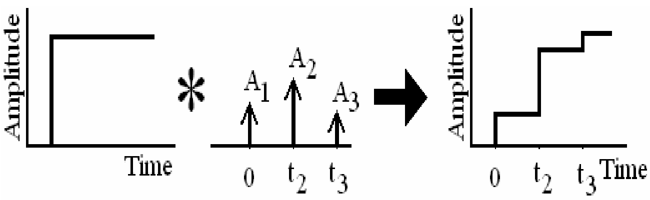


Fig.2 ZVD shaper

2 TS Input Shaping

This paper evaluates TS input shapers. The proposed shapers are derived from constraints that require zero residual vibration of the oscillatory payload. The searched shaper contains only positive amplitudes. TS shaper is selected because it is less sensitive to modeling errors.

In the case of TS input shaping, the control system designer wants to avoid derivation process. Then it is required to write the constraint equations in matrix form. Three constraint equations for five unknown parameters can be expressed depend on them as:

$$\begin{bmatrix} 1 & e^{\xi\omega_n t_2} Cos(\omega_d t_2) & e^{\xi\omega_n t_3} Cos(\omega_d t_3) \\ 0 & e^{\xi\omega_n t_2} Sin(\omega_d t_2) & e^{\xi\omega_n t_3} Sin(\omega_d t_3) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad (15)$$

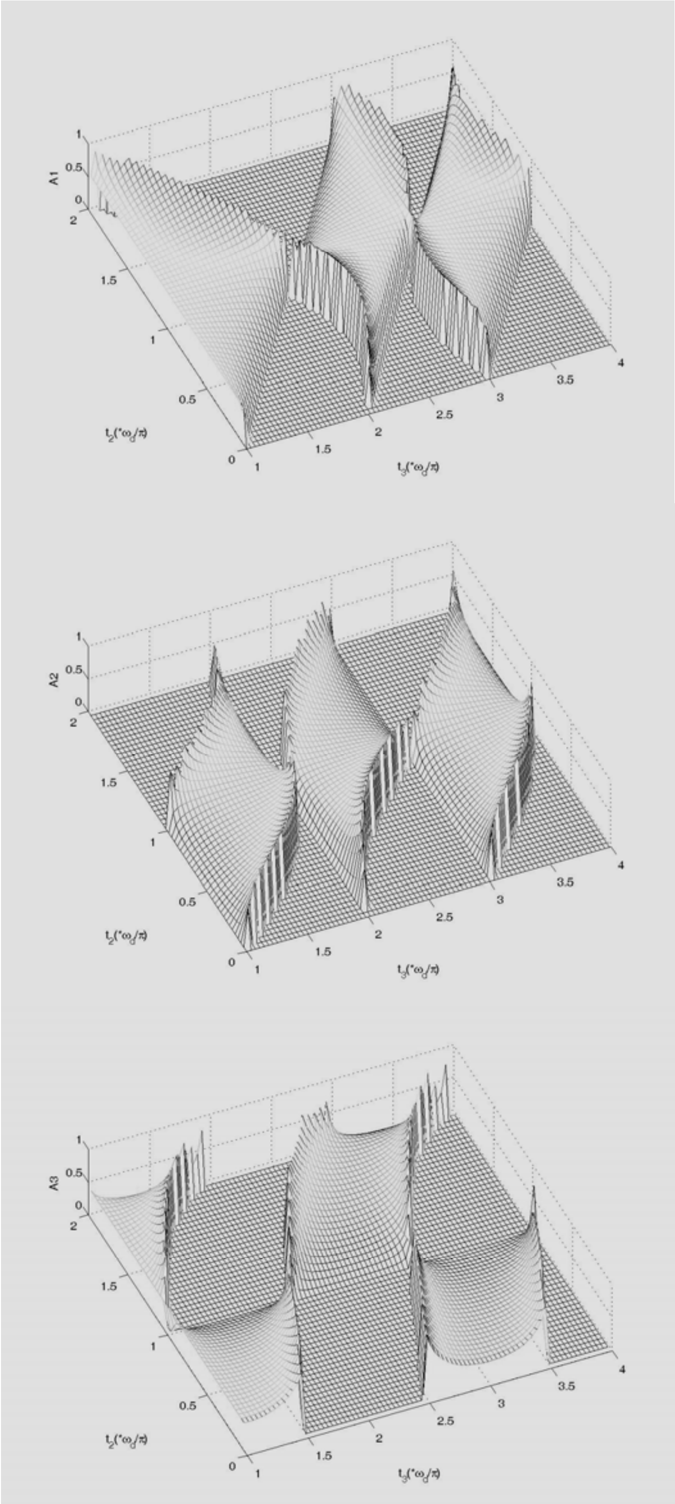
The matrix form can be rewritten for impulse amplitudes that each depends on t_2 and t_3 [11].

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} \frac{e^{\xi\omega_n (t_2+t_3)} \left(Cos(\omega_d t_2) Sin(\omega_d t_3) - Sin(\omega_d t_2) Cos(\omega_d t_3)\right)}{K_1 - K_2} \\ \frac{-e^{\xi\omega_n t_3} Sin(\omega_d t_3)}{K_1 - K_2} \\ \frac{e^{\xi\omega_n t_2} Sin(\omega_d t_2)}{K_1 - K_2} \end{bmatrix} \qquad (16)$$

Where

$$K_1 = e^{\xi\omega_n t_2} Sin(\omega_d t_2)\left(1 - e^{\xi\omega_n t_3} Cos(\omega_d t_3)\right)$$
$$K_2 = e^{\xi\omega_n t_3} Sin(\omega_d t_3)\left(1 - e^{\xi\omega_n t_2} Cos(\omega_d t_2)\right)$$

Fig.3 shows mesh plot of amplitudes respect to scaled time locations by π/ω_d .



(a) Mesh plot for A_1
(b) Mesh plot for A_2
(c) Mesh plot for A_3
Fig.3 A_1, A_2 and A_3 amplitudes respect to normalized time locations

The usable regions for all positive impulse amplitudes can be shown in fig.4. A_1, A_2 and A_3 produce positive value in these regions [12].

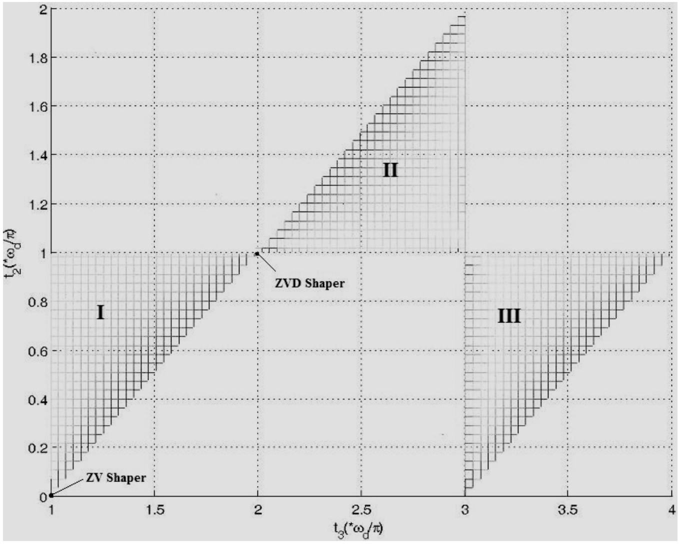
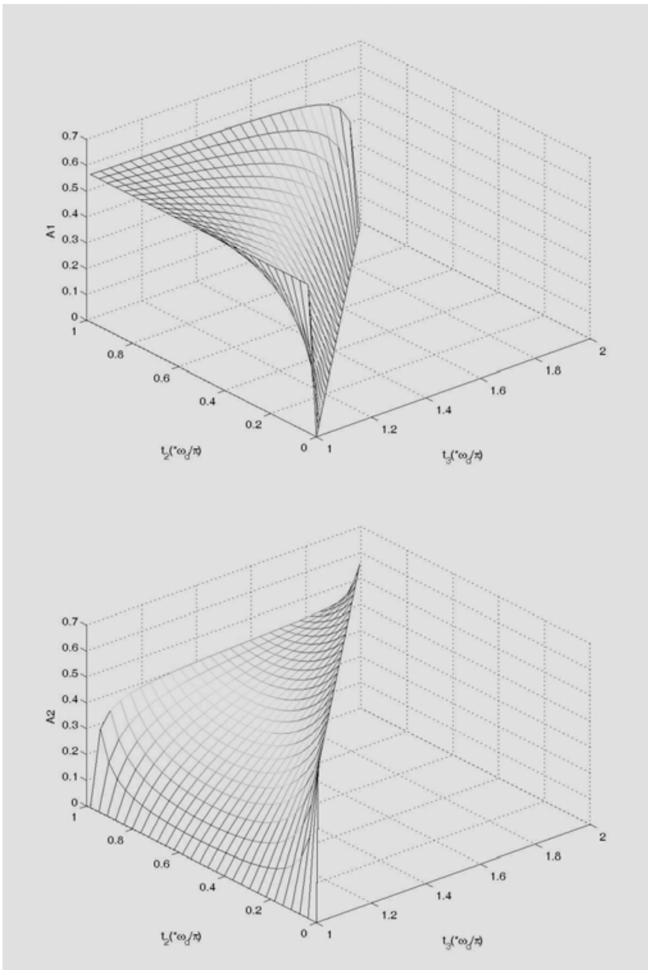
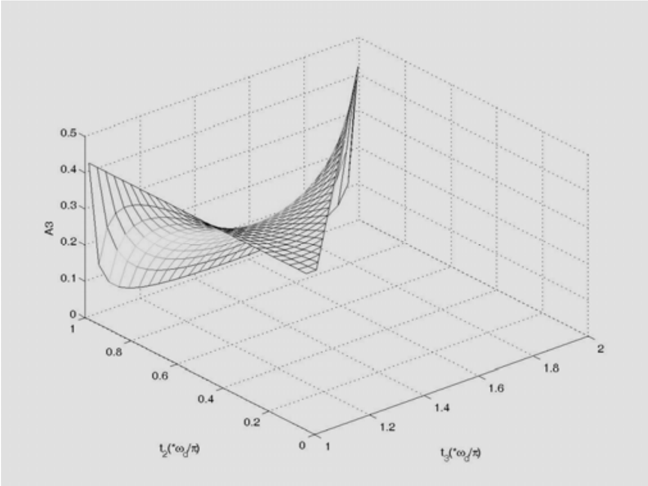


Fig.4 Positive TS shaper region

ZV and ZVD are pointed out as special locations in this figure. For the minimum shaping duration, the Region-I is selected as search space in this study. All of the shapers in this area have less duration than ZVD. Impulse amplitudes variations in the selected area are meshed as:





(a) Mesh plot for A_1 for selected space
(b) Mesh plot for A_2 for selected space
(c) Mesh plot for A_3 for selected space
Fig.5 A_1, A_2 and A_3 amplitudes mesh plot for selected space

Our search focuses on some optimal results for different performance measures. Minimum control time and insensitiveness to modeling errors are main optimization parameters. The fastest is ZV and the most robust is ZVD. These are the extreme points in the search area. The search area produces infinite number of new shapers. Durations of these shapers are shorter than ZVD shaper. Thus, the first performance measure is provided. Other measure is robustness. It requires that the value of the percent residual vibration to modeling errors should be as small as possible. In the other words, residual vibration amplitude should be stay under the defined level as wide as possible for more robustness while oscillation frequency changes. Fig.6 shows the sensitivity curve along the selected impulse time variation area. Some shapers in this area satisfy the robustness criteria partly. These are more robust than ZVD under the defined level of residual vibration for higher frequencies.

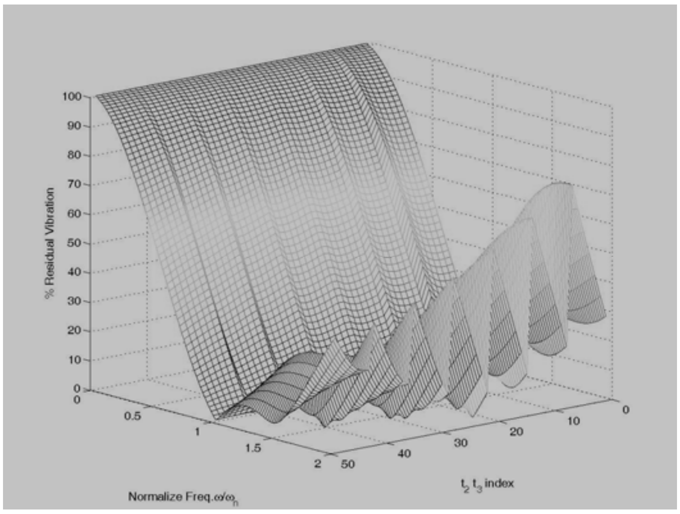


Fig.6 Residual vibration mesh respect to impulse time index

3 Results

Fig.7 shows the three-step input shaper control of the experimental planar crane system setup. This is a prototype experimental system. Some specifications are given in Table.1.

Table.1 Crane system specifications

Drive System	Geared DC Motor
Motor Controller	A3953SB H-Bridge
Controller	PIC16F877A
Programming Language	PIC-C Compiler
Starting Point Set Method	Optical Sensor
Supply Voltage	30V
Rope Length	466mm
Total Travel Length	136mm
Travel Speed	0.162m/s
Payload Weight	18.8g

The payload is controlled using predetermined three steps at defined time intervals. Starting time t_1 is selected zero, state-I. Then crane is moved along the A_1 displacement. System is braked at the end of motion, state-II. Crane is waited during the t_2 delay. Payload reaches its maximum level. Crane is moved again to A_2 distance at this time, state-III. The command of the final step, A_3, is given after the last delay t_3, state-IV.

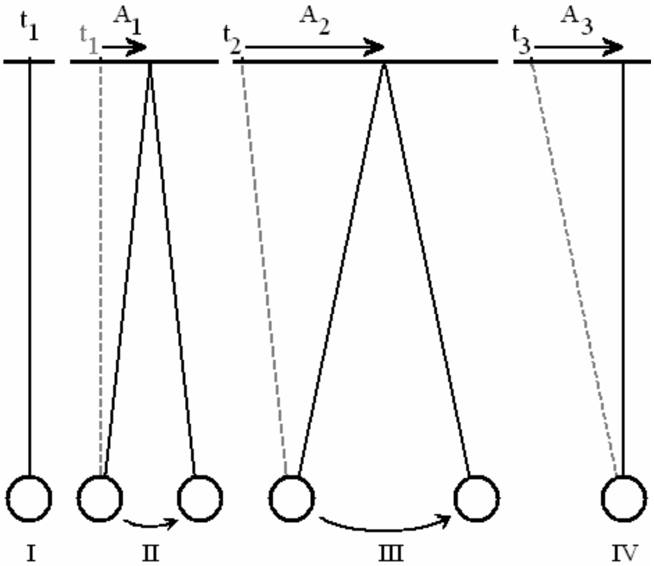


Fig.7 Three-step shaped crane motion system

Fig.8 shows the experimental crane system. In the system, starting position is set by using the fixed optical sensor as limit switch and moving cover attached to belt-pulley system, at the right bottom. The geared DC motor is shown at the left bottom. The rope and payload is at the middle bottom. Small circuit in the figure is H-bridge driver, Allegro Micro Systems A3953SB. The motion length of trolley is entered by using pad-keyboard to PIC controller circuit. Payload is selected as a 626z bearing.

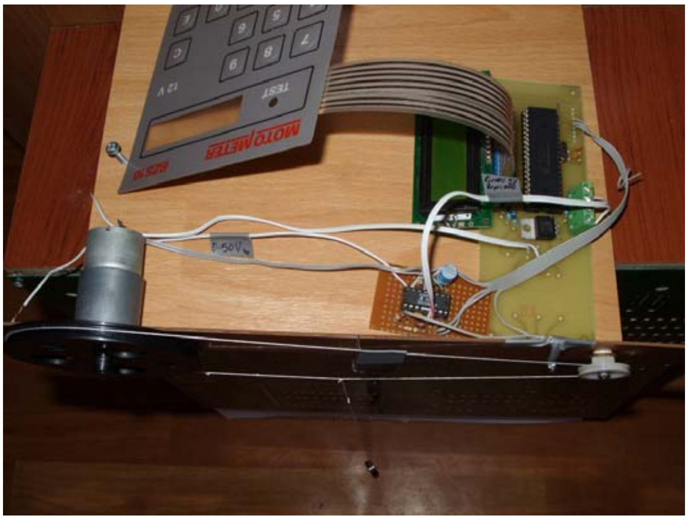


Fig.8 Experimental setup

ZVD shaper is designed as step functions in vertical ladder form, normally. However, it is impossible to finish the motion at the time of zero. Acceleration of the motor and the rigid body motion of the crane carrier add a delay to the total journey. Therefore, the motion is a ramp function while motor voltage is the step functions. Fig. 9 shows the motor input and motion respect to time.

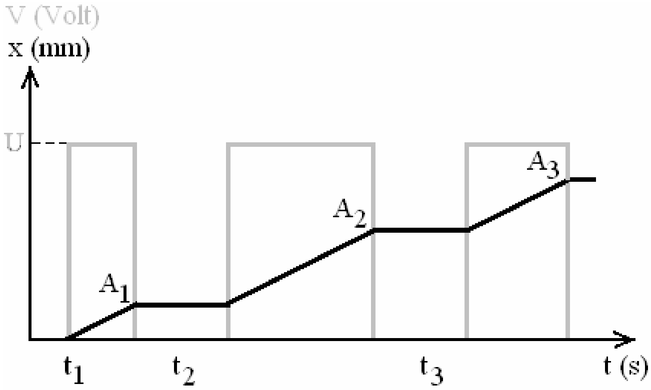


Fig.9 Motor input and motion variation

Our search is focused on some measures as [21]

1. Residual Vibration: The chosen control technique should not produce any vibration during the controlled motion. This must be valid for all different length of journey for trolley.
2. Sensitivity: Sensitivity curve is a plot of percentage residual vibration versus the normalized frequency. Percentage residual vibration is defined as the vibration with shaping divided by vibration without shaping. Normalized frequency is found as the actual frequency divided by modeling frequency.
3. Robustness: Robustness is defined as the width of sensitivity curve at a specific level of acceptable vibration. It is also known as insensitivity range.
4. Time Penalty: More robustness requirement increases the length of the input shaper. It results an increasing in duration of control. Duration of the ZVD shaper is greater a half period than ZV shaper. Transcendental nature of constraint equations (8) and (9) results multiple solution for three step input shaping control technique. To make the solution time optimal subject to the residual vibration and robustness constraints, the shaper must be made as short as possible.
5. Time Efficiency: It is equivalent to time optimality in the sense of satisfying all additional constraints.
6. Other measures: Input shapers are designed based on some additional set of desired performance specifications. These specifications include constraints on quantities such as rise time, braking mechanism characteristic, etc. Another idea that comes into view in this paper is the thought that these specifications should be acceptable in practice. For example, real systems always exhibit some level of residual vibration. Therefore, when a constraint is placed on the residual vibration amplitude, it is better to limit the vibration to some low level rather than

require the vibration to be identically zero. To achieve the theoretical possibility of zero residual vibration, some other performance criteria must be sacrificed [22].

Some assumptions are taken to account for applying input shaping control to the crane system.

1. All initial conditions are zero: Model of the control system requires all of the initial conditions should be zero. If the initial conditions are not zero then it is hard to form a model for dynamical behavior of the crane system.
2. External disturbances should be omitted: If the system has any external disturbances, they should not affect the modeled dynamics of the system.
3. Impossibility of measurement for feedback control: If the crane oscillation can not be measured easily, only feedforward control system can be applied to the crane system.

Responses of the unshaped, some new shapers, ZV and ZVD shapers are shown together in fig.10. The length of ZVD shaper is T_{ZVD}=0.2749 s. ZV shaper duration is half of ZVD shaper.

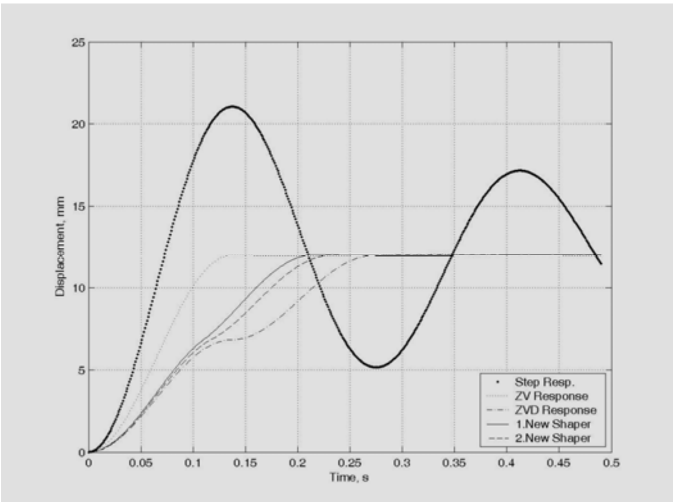


Fig.10 Response of the shapers

The robustness curves for them are given in fig.11. The new shapers can be named as skewed shapers due to their shapes. The skewed shaper concept is introduced from vector diagram. The insensitivity of the classical shapers can be widened by displacing the vectors from the frequency axis. When the vectors are located off the horizontal axis, the sensitivity curve is skewed. It is not symmetrical depending on the modeled natural frequency. In this case, main goal is to find the maximum insensitivity range of the skewed. Durations of the proposed shapers are less than ZVD shaper in the entire searched region, Region-I in the fig.4. Skewing disappear when the proposed shapers approaches to the ZVD shaper.

The selected new shapers are not better than ZVD shapers in decreasing frequency. The residual vibration stays under a specified level along a wide range for increasing frequency. For example, maximum level of residual vibration in 1.New Shaper is under 8.66% while frequency rises 1.653 time of natural frequency. The duration of this shaper is only $0.8494_{*}T_{ZVD}$. 2.New Shaper stays 4.343% along the rising frequency of 1.434 and its duration is only $0.7912_{*}T_{ZVD}$. These are only two example point in the Region-I of fig.4. This region gives lots of new shapers which are more robust and shorter in duration than ZVD shaper.

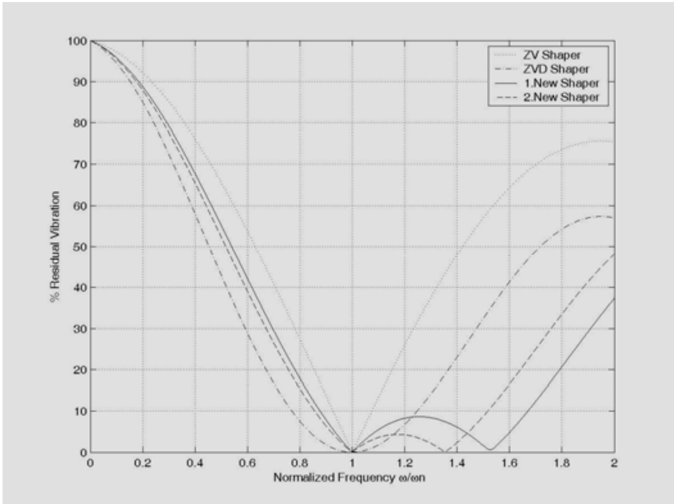


Fig.11 Sensitivity curve of the shapers

The experimental tests show that the presented methods are extremely robust to the variation of load mass. We added three times of weight to the modeled weight. There is no significant oscillation using these techniques.

4 Conclusion

This study proposes a TS input shaping technique. We have presented a new approach to the input shaping generation technique. The new shaper extends ZVD shaping technique into a generalized TS shaper method that is easily applicable for any dynamical system model. It is demonstrated here that small length shaped TS shaper, though having higher amplitudes, result in less vibration than ZVD shaper especially over ranges of natural frequencies somewhat. It is demonstrated in this study that important amount of reduction in settling time can be obtained by using TS shaping.

In this study, we specifically search the Region-I in fig.4. This space provides wide sensitivity curve if the vibration frequency rises. The Region-II can give more robust results in decreasing vibration frequency though its duration longer than ZVD shaper. Region-III can also be search for some advantages as future works.

The major advantages of the proposed technique are:

- To show the ZVD shaper is not unique solution for positive three-step input shaper.
- More robust three step shaper can be selected.
- The duration of the shaper can be decreased by using the proposed search region.
- Both faster and more robust TS input shaper can be generated in some increased modeling frequencies.
- Unsearched regions in fig.4 can be investigated for robustness although the duration of the shaper increases in future works.

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