The Acceleration Limit in Input-Shaped System to Reduce Residual Vibration of a Flexible Link Robot

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Abstract

Vibration control of flexible systems is the most important problem in both control theory and control applications. Especially, the vibration occurs in the systems with highly flexible. In general, there are three causes that make the controlled system vibrate. First, the elastic property of plants (or structures) represent by its natural frequencies. Second, the external perturbations from surrounding. Third, the reference command exciting to plants. The control technique known as Input Shaping can be used for eliminate these vibrations by using the convolution of the reference command and the impulse signals at certain times and amplitudes. As a result, the response has zero vibration at the desired position. In practical, we have some constraints (or called limitations) on command references of the systems, such as maximum values of acceleration, velocity and displacement. These limitations are similar with saturation in control effort. The mainly effect of these limitations is it can be causes to reduce the efficiency of suppressing residual vibration. In this paper, the velocity command was designed the ramp-step operation to eliminate acceleration limits of the system. The experimental results, the input shaping techniques under acceleration limits can be reduced the residual vibration more than the baseline command in desired positions.

***Keywords**:* Mechanic vibration, Input shaping technique, Acceleration limit, Velocity command

1. Introduction

The vibration control of flexible systems is an interesting research topic in several reasons, such as, vibration control in the system with uncertainty, the vibratory system in infinite dimensions, the combination design of closed-loop (ex. PID controller) and opened-loop control (ex. input shaping), how can we design the command reference so that the response of the controlled outputs has minimum (or zero) vibration. What is the shape of command references that suitable for plant's control effort, and etc. In the present, several control techniques were developed to reduce the residual vibration by using advanced controls or intelligent controls and so on. Moreover, a famous technique is implemented by convolving a sequence of impulses with the system's command reference is called "Input Shaping (IS) technique. The IS technique was implemented in many highly flexible systems, such as crane system, robot arm, hard disk drive etc. In order that, reference commands does not excite with resonance frequencies of the system, which can be calculated from natural frequencies and damping ratios. so that, the residual vibration will be zero magnitude.

In the practical, acceleration limit exists in most actuators. The shaped command can be distorted by the acceleration limits. As a result, the efficiency of input shaping technique has decreased for eliminating residual vibration. Existing researches on input shaping under acceleration limit are very few. [1] and [2] studied input shapers under velocity command and acceleration upper limit. They proposed an additional constraint during the design of the unity-magnitude (UM) input shaping system in [3]. This additional constraint ensures that the resulting shaped velocity command will not violate the acceleration limit. The additional constraint is given by

$$v_f = a\left[(t_2 - t_1) + (t_4 - t_3)\right],$$

Where v_f, a and t_i represents the desired final velocity, the acceleration limits and time location, respectively.

Moreover, most input shaping technique can be controlled with multiple input and output (MIMO) system, Vaughan et al. [3]. And Y. Pao [4] used to the s-plane pole placement method for controlling to reduce residual vibration in MIMO systems also.

In section 2 denotes a flexible link robot such as actuator, sensors for measuring the responses. Moreover, block diagram explains about a manipulated method to control of movement. Section 3 shows the dynamic model of a flexible link robot about related parameters with this researched problem. And then, represents the procedure and equations of finding the natural frequencies and damping ratios of system. Section 4 describes about advantages and principle of the input shaping technique. In section 5 presents an interested method of development the baseline commands to avoid violating the acceleration limits by using ramp-step command and in last section 6 concludes the experimental results.

2. Experimental Setup

In figure 1, a flexible link robot made from a flexible steel ruler and assembles with a 12 volts servo motor. A potentiometer was applied to measure the actual positions, which the voltages value must be calibrated to become the actual positions. In tip of the flexible link robot was installed an accelerometer sensor of pololu MMA7341L3 for measuring the vibration signals.

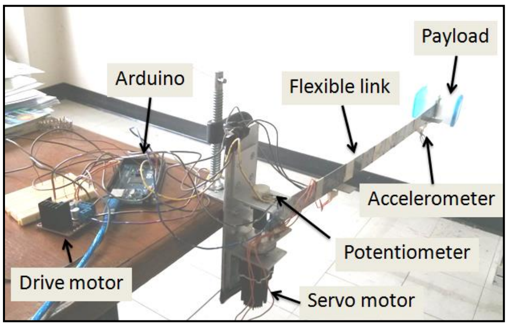

Fig. 1 a flexible link robot

In this paper, a control board used an Arduino Mega 2560, which can program the logics to control and measure by using the Matlab and Simulink programs. A drive motor L298N model was utilized to drive the servo motor. The Arduino board, which can operate on real-time systems, shows the actual positions and vibration responses. The block diagram can be shown in Figure 2.

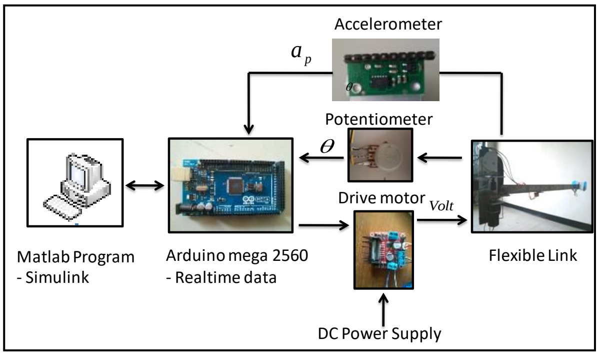

Fig. 2 block diagram of the control system

3. The flexible link robot dynamic

Figure 3 shows the dynamic of flexible link robot which presents about a main problem of controlling the flexible link robot. This problem is the error between the desired position angle (θ) and the tip position angle (θ_p). Because of, flexible link systems have many vibration modes. An acceleration sensor was applied to measure these vibrations a_p in operating times.

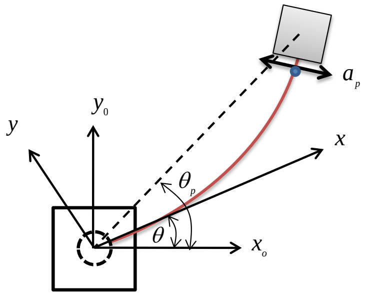

Fig. 3 the dynamic of flexible link robot

The solution, the system was excited between the natural frequencies and reference command frequencies. A famous method is the input shaping (IS) technique. Zero vibration (ZV) and zero vibration derivative (ZVD) were utilized to design the new reference commands. The main principle is to design the amplitudes and time locations of impulses in order to reduce residual vibration.

The main parameters of IS calculation are the natural frequencies and damping ratios in bandwidth of the control operation. In this paper, we interested in first-third modes only, these parameter was obtained by exciting of chirp signal from 0.1 to 8 Hz. Meanwhile, vibration signal was recorded from the acceleration sensor. Afterward, these values was analyzed on Fast Fourier Transform (FFT) method. In figure 4 noticed the peak magnitudes which are natural frequencies of this system. These values were ω_1 = 41.07, ω_2 = 121.5 and ω_3 =366.5 rad/sec respectively. [5]

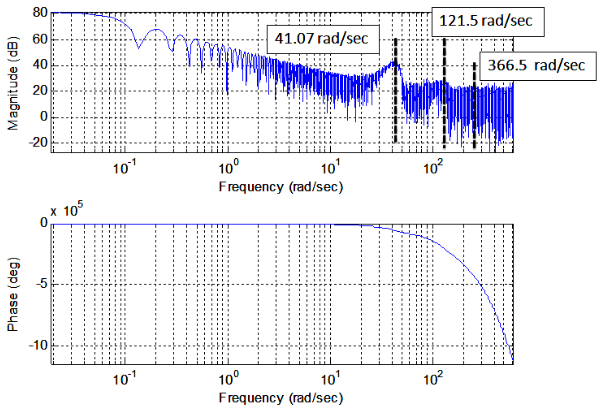

Fig. 4 natural frequencies of the system

In figure 5, damping ratios can be determined from acceleration signals of the free vibration response. Afterward, their signals were analyzed by using the logarithmic decrements equation (1). In calculation procedure, the fifth periodic oscillation in the positive

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amplitudes was the first amplitudes x_n = 1.964 volts and fifty amplitudes x_{n+m} = 1.523 volts.

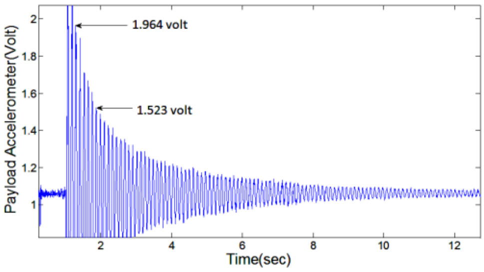

Fig. 5 damping ratio of the system

$$\delta = \frac{1}{m}\ln\frac{x_n}{x_{n+m}} = \frac{1}{5}\ln\frac{1.964}{1.523} = 0.0508 \quad (1)$$

where m is any integer number of successive positive peaks.

x_n is the amplitude at time t.

x_{n+m} is the amplitude of the peak *n* periods away.

From calculation result of equation (1) was utilized by substitution in equation (2). Therefore, the damping ratio of this system was ζ = 0.0081.

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}} \quad (2)$$

4. Input Shaping Technique

Input shaping is a feed-forward technique. An advantage is able to reduce the residual vibration in flexible systems. Input shaping is implemented by convolving a sequence of impulses. Their use only requires evaluating the equations using estimates of the natural frequencies and damping ratios to obtain the amplitudes and time locations to appropriate with reference commands of the system [6].

In figure 6, response of base line command (solid line) has highly vibration at steady state time (dash line). But when, this base line command convoluted with input shaper. As a result, shaper command looks a same staircase function. The vibration response can be reduced at desired positions.

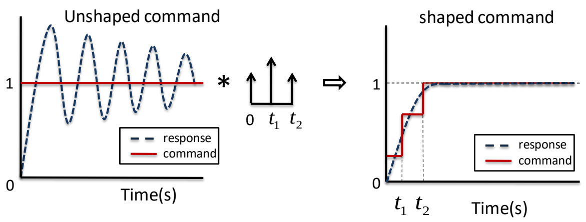

Fig. 6 process of input shaping technique

From equation (3) is the vibration percentage $V(\omega_n,\zeta)$, which is the ratio between the n-impulse response amplitude at time $t \ge t_n$ and the single-impulse response amplitude at time $t \ge t_1$ is given by

$$V(\omega_n,\zeta) = e^{-\zeta\omega_n t_n}\sqrt{\left[C(\omega_n,\zeta)\right]^2 + \left[S(\omega_n,\zeta)\right]^2}, \quad (3)$$

Where

$$C(\omega_n,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega_n t_i}\cos\left(\omega_n\sqrt{1-\zeta^2}\,t_i\right),$$

$$S(\omega_n,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega_n t_i}\sin\left(\omega_n\sqrt{1-\zeta^2}\,t_i\right),$$

The amplitudes A_i and time locations t_i of the impulse sequence are computed from the knowledge of ω_n and ζ by solving the following equations:

$$V(\omega_n,\zeta) = 0, \quad (4)$$

$$\frac{\partial V(\omega_n,\zeta)}{\partial\omega_n} = 0, \quad (5)$$

$$\sum_{i=1}^{n} A_i = 1, \quad (6)$$

$$t_1 = 0, \quad (7)$$

Equations (4) - (7) are used to solve four unknowns, which are the amplitudes and time locations of three impulses. The three-impulse shaper is known in the zero-vibration derivative (ZVD) shaper. Closed forms of ZVD shaper are equations (8):

$$A_1 = 1/\left(1+2K+K^2\right),$$
$$A_2 = 2K/\left(1+2K+K^2\right),$$
$$A_3 = K^2/\left(1+2K+K^2\right), \quad (8)$$

where

$$K = e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}},\ t_2 = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}},\ t_3 = \frac{2\pi}{\omega_n\sqrt{1-\zeta^2}},$$

which ζ is the damping ratio

ω_n is the natural frequency (rad/sec)

t_s is the sampling time (ms)

t_2, t_3 are the time location (ms)

In figure 8 shows the block diagram for open - loop control systems. In this paper, velocity command was to be input command for controlling the flexible link robot.

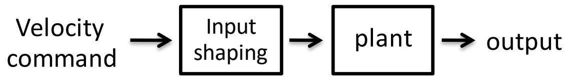

Fig. 7 open-loop control with input shaping technique

In first time, baseline command has the desired final velocity was v_f = 17.53 rad/sec. And when, these command convoluted with ZVD shaper by using a natural frequency was ω_1 = 41.07 rad/sec and damping ratio was ζ = 0.0081. From calculation results, the amplitudes were A_1 = 0.2564, A_2 = 0.4999 and A_3 = 0.2437. Moreover, the time locations were t_2 = 0.0765 and t_1 = 0.1530. In figure 8 shows a baseline command and step command (baseline command convoluted with ZVD shaper).

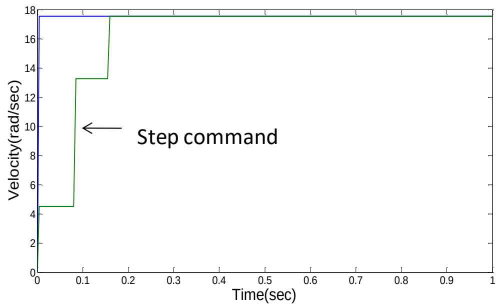

Fig. 8 the baseline and step command

5. Baseline Velocity Command That Avoids Violating the Acceleration Limits

On the other hand, the most actuators in practice have the acceleration limits. In figure 9 shows a block diagram to operate the input shaping under acceleration limit. The parameter v_b is the baseline command, which is a step function of a magnitude v_f. v_s is the step command, a staircase function and v_a is the ramped-step command.

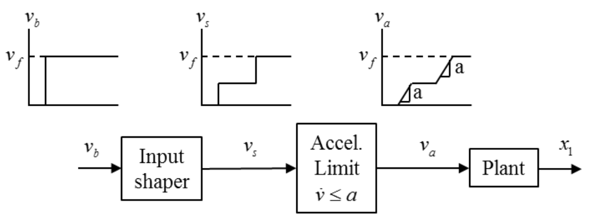

Fig. 9 Input shaping under acceleration limits.

The step command v_s is designed to suppress residual vibration of the plant output x_1. However, because of the acceleration limit $\dot{v} \le a$, where a is a constant, v_a is given to the plant instead of v_s. As a result, the vibration suppression performance of the input shaper is degraded as can be shown in equation (9)

$$v_a(s)=\frac{1}{c}\frac{a}{s^2}(1-e^{-(v_f/a)s})\sum_{i=1}^{n}A_i e^{-t_i s} \qquad (9)$$

Where $\frac{1}{c}\frac{a}{s^2}(1-e^{-(v_f/a)s})$ is the Laplace Transform of a ramped-step command with slope a, v_f is a steady-state value and $\sum_{i=1}^{n}A_i e^{-t_i s}$ is an input shaper.

An experimental problem, the maximum-rotated position of this flexible link robot can be rotated between 0 to 4.5 rad only. The on-off control is unsuitable commands to be the input commands. Therefore, the velocity command was intergraded to be the position command for controlling the system. Velocity commands must be simulated the final positions before. In this paper, there are the PI controller by using Kp = 7 and Ki = 3. In figure 10 shows block diagram for manipulation the system in this research.

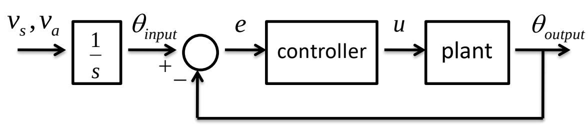

Fig. 10 block diagram of feedback control

. In figure 11 shows the baseline command, v_b, step command, v_s. From the simulation result, the ramped-step command v_a obtained by using a maximum acceleration value was a = 226.8 rad/sec², which this value was found from the experimental result.

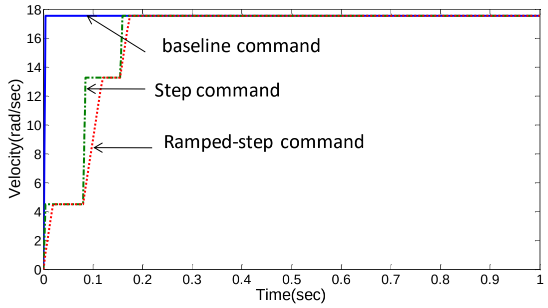

Fig. 11 step and ramp-step commands by using the single-mode shaper

In figure 12 shows the vibration signals of step command (Solid line) and ramped-step command (dash line). From a result, the residual vibration is suppressed even under acceleration limits. This is because the modified command is designed that the modified shaping command is not distorted by acceleration limit. In figure 13 represents the displacement of step command and ramped-step

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command. From the displacement results, the position of both commands does not equal. Because, the ramped- step command has delayed more than the other commands. On the other hand, the vibration magnitudes can be reduced from the step command at steady state time.

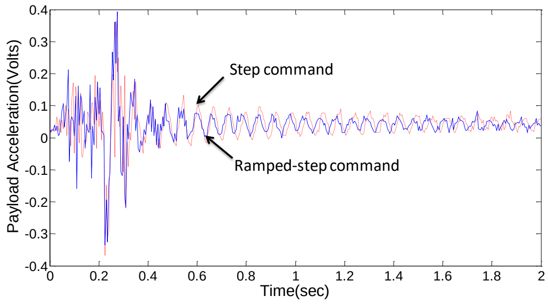

Fig. 12 vibration results of step and ramped-step command

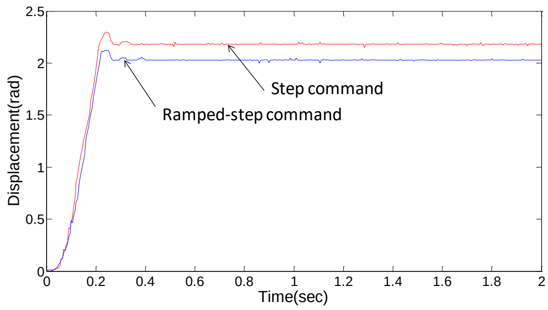

Fig. 13 displacement results of step and ramped-step command

The multi-mode shaper has all the 9 sequence of impulses. In figure 14 is the ramped-step command to compare with step command. The natural frequencies of the first mode was ω_1 = 41.07 rad/sec and the second mode was ω_2 = 121.5 rad/sec. Damping ratio was ζ = 0.0081. The desired final position was θ = 2.1 rad. which can be shown in figure 15.

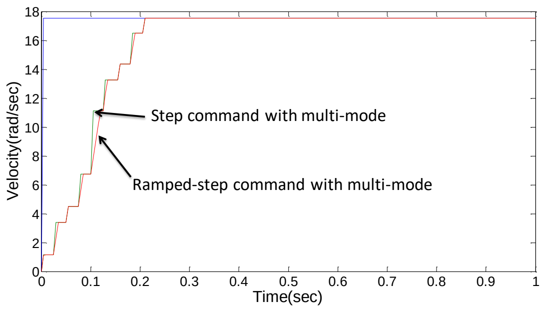

Fig. 14 velocity commands by using the multi-mode shaper under acceleration limit

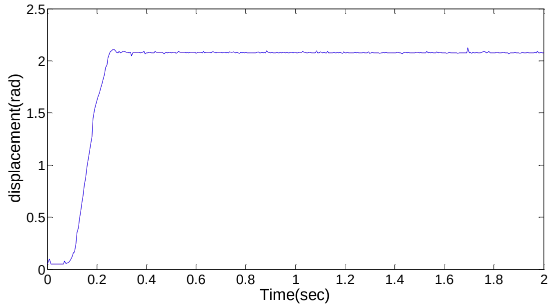

Fig. 15 Displacement result of a multi-mode ramped-step command

Vibration results of the single-mode and multi-mode of ramped-step command can be shown in figure 16. The multi-mode system can be reduced the vibration magnitude more than single-mode system at steady state time.

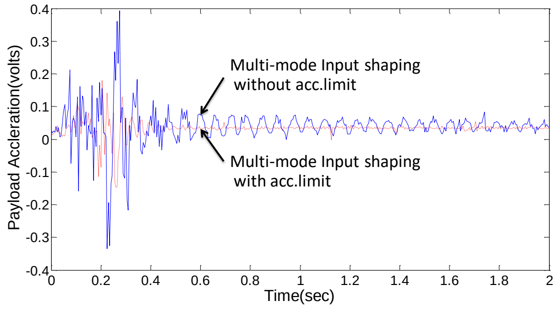

Fig. 16 vibration results of single-mode and multi-mode of ramped-step command

6. Conclusions

Input shaping technique is a highly-efficiency technique for reducing the vibration of the flexible systems by using the convolution of a sequence of impulses and the command reference. The response of the controlled flexible system is well behave i.e., the output is to be zero residual vibration. However, in practice, the actuators have acceleration limits. As a result, the efficiency was reduced to suppress the vibration of the system.

This research used a ramped-step command to propose a modification to the baseline command so that the shaped command will not violate the acceleration limit. In the experiment result, ramped-step command can be reduced the residual vibration more than the baseline command.

The ramped-step command of single-mode was applied to be reference command for controlling the system. From an experimental result, Vibration can be reduced by comparing with the baseline command. Moreover, multi-mode was used to design the multi-mode of ramped-step command. From the modified command result, vibration magnitude of multi-mode method can be increased the efficiency of input shaping technique for controlling the highly flexible systems

7. Acknowledgement

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8. References

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