

Experimental Investigation of Feedforward Control Schemes of a Flexible Robot Manipulator System

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Abstract: This paper presents experimental investigations into the applications of feedforward control schemes for vibration control of a flexible manipulator system. Feedforward control schemes based on input shaping and filtering techniques are to be examined. A constrained planar single-link flexible manipulator is considered in this experimental work. An unshaped bang-bang torque input is used to determine the characteristic parameters of the system for design and evaluation of the input shaping control techniques. The input shapers and filtering techniques are designed based on the properties of the system. Simulation results of the response of the manipulator to the shaped and filtered inputs are presented in time and frequency domains. Performances of the shapers are examined in terms of level of vibration reduction and time response specifications. The effects of derivative order of the input shaper on the performance of the system are investigated. Finally, a comparative assessment of the control strategies is presented and discussed.

Keywords: Flexible manipulator, input shaping, vibration control.

1. INTRODUCTION

Flexible-link robotic manipulators are known by its advantages over conventional rigid robotic arms; use cheaper and lighter material, lower power consumption, higher manipulation speed, and more safer to operate. Nevertheless, due to highly non-linear and complexity of the system, it is much more challenging to achieve and maintain the accurate positioning. Several problems arise as to attain the precise positioning requirement, vibration due to system flexibility, the difficulty in obtaining accurate model of the system and non minimum phase characteristics of the system. Therefore, flexible manipulators have not been favoured in production industries, because of un-attained end-point positional accuracy requirements in response to input commands. In this respect, a control mechanism that accounts for both the rigid body and flexural motions of the system are required [1]. The vibration control for flexible manipulator systems can be classified as feedforward and feedback control schemes [2]. The fundamental problem with systems that vibrate is that the motion transient excites the vibration. Feedforward control techniques are based on the fact that the vibrations exhibited by most systems can be characterized by measuring one or more frequencies that are excited by the motion transient. Using this information, it is possible to generate a modified command signal that will move the system at the maximum rate possible, without exciting vibrations. This control techniques has been successfully used to reduce residual vibrations in numerous mechanical systems, such as coordinate measuring machines, experiments on board of the space shuttle Endeavor,

long-reach manipulators, cranes, and two-link flexible manipulator [3]. This method also does not require any additional sensors or actuators and does not account for changes in the system once the input is developed. The feedforward control scheme is considered based on input shaping and low-pass filtering techniques [1].

A number of techniques have been proposed as feedforward control strategies for control of vibration. These include utilisation of Fourier expansion as the forcing function to reduce peaks of the frequency spectrum at discrete points [4], derivation of a shaped torque that minimises vibration and the effect of parameter variations [5], development of computed torque based on a dynamic model of the system [6], utilisation of single and multiple-switch bang-bang control functions [7], construction of input functions from ramped sinusoids or versine functions [8]. Moreover, feedforward control schemes with command shaping techniques have also been investigated in reducing system vibration. These include filtering techniques based on low-pass, band-stop and notch filters [9,10,11] and input shaping [12,13]. In filtering techniques, a filtered torque input is developed on the basis of extracting the input energy around the natural frequencies of the system. Previous experimental studies on a single-link flexible manipulator have shown that higher level of vibration reduction and robustness can be achieved with input shaping technique than with filtering techniques. However, the major drawback of the feedforward control schemes is their limitation in coping with parameter changes and disturbances to the system [14]. Moreover, this technique requires relatively precise knowledge of the dynamics of the system.

This paper presents experimental investigations into

the applications of feedforward control schemes using input shapers and filtering techniques for vibration control of a single-link flexible manipulator. This paper provides a comparative assessment of the performance of these schemes. The results of this work will be helpful in designing efficient algorithms for vibration control of various systems. In this work, input shaping with positive input shapers using Zero-Vibration (ZV) and Zero-Vibration-Derivative-Derivative (ZVDD) and filtering techniques using low-pass and band-stop filter are considered. Experimental work of flexible manipulator system is performed in Matlab/Simulink environment using Matlab/Real Time Windows Target. Initially, the flexible manipulator is excited with a single-switch bang-bang torque input in order to obtain the characteristic parameters of the system. Then the input shapers are designed based on the properties of the manipulator and used for pre-processing the input, so that no energy is fed into the system at the natural frequencies. The performances of the controllers are assessed in terms of the vibration reduction and time response specifications. Moreover, a comparative assessment of the effectiveness of the input shapers and filtering techniques in suppressing vibration of the flexible manipulator is discussed.

2. FLEXIBLE MANIPULATOR SYSTEM

A description of the single-link flexible manipulator system considered in this work is shown in Figure 1, where $\{O X_o Y_o\}$ and $\{O X Y\}$ represent the stationary and moving coordinates frames respectively, s represents the applied torque at the hub. E , I , ρ , A , I_h , r , and M_p represent the Young modulus, area moment of inertia, mass density per unit volume, cross-sectional area, hub inertia, radius and payload mass of the manipulator respectively. In this work, the motion of the manipulator is confined to the $\{O X_o Y_o\}$ plane. The rotation of $\{O X Y\}$ relative to frame $\{O X_o Y_o\}$ is described by the angle θ . The displacement of the link from the axis OX at a distance x is designated as $v(x, t)$. Since the manipulator is long and slender, transverse shear and rotary inertia effects are neglected. This allows the use of the Bernoulli–Euler beam theory to model the elastic behaviour of the manipulator. The manipulator is assumed to be stiff in vertical bending and torsion, allowing it to vibrate dominantly in the horizontal direction and thus, the gravity effects are neglected. Moreover, the manipulator is considered to have constant cross-section and uniform material properties throughout.

2.1 The Flexible Manipulator

The experimental work of this study has been implemented at the University of Technology Malaysia robotic laboratory. Figure 2 shows a single-link flexible manipulator system consists of a flexible aluminium beam and a KollMorgern Servo Disk DC motor JR12M4CH with a built-in optical encoder used to measure the load shaft angular position. The encoder has the high resolution up to 3000 counts in quadrature and signal from encoder is sent directly to computer through data acquisition board PCL 818. The light-weight flexible

beam is clamped to the shaft of the motor through a coupling and is confined to turn only in the horizontal plane, thus the gravity effect is neglected. The tip deflection of the link is computed by an accelerometer ADXL202JQC which is located at the tip of the flexible link. This accelerometer is capable to trace deflection within the amount of 0.2 angstroms or $1/10^{\text{th}}$ of an atomic diameter. The control voltage for driving the motor is sent to the servo amplifier through a similar PCL 818 board. The control algorithms are coded in Matlab/Simulink, compiled with the Matlab/Real Time Windows Target. Real-Time Windows Target includes an analog input and analog output that provide connections between the physical I/O board (PCL 818) and the real-time model.

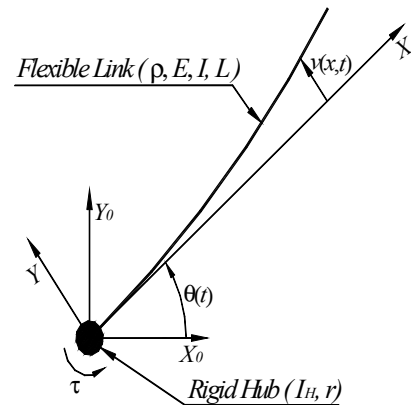


Figure 1. Description of the flexible manipulator system.

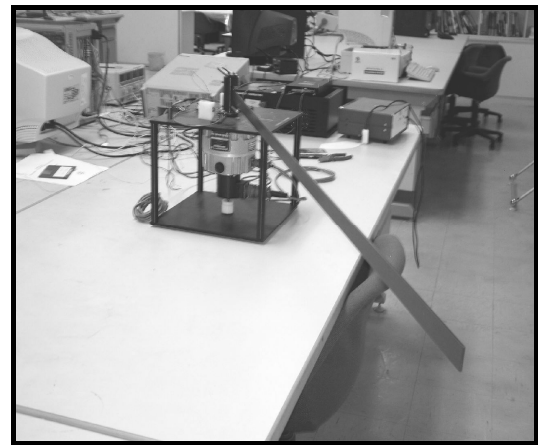


Figure 2. Experimental rig of the flexible manipulator system.

3. FEEDFORWARD CONTROL SCHEMES

In this section, the proposed control schemes for vibration control of the flexible manipulator are designed. These include input shaping using ZV and ZVDD shapers and filtering techniques using low-pass and band-stop filter. The feedforward control techniques were designed on the basis of vibration frequencies and damping ratios of the flexible manipulator system. In this experiment, the first two natural frequencies are considered as these dominantly characterize the dynamic behaviour of the single-link flexible manipulator system. The input

shapers and filters thus designed were used for pre-processing the bang-bang torque input. The shaped and filtered torque inputs were then applied to the system in an open-loop configuration to reduce the vibrations of the manipulator.

3.1 Input Shaping Techniques

The input shaping method involves convolving a desired command with a sequence of impulses known as input shaper. The design objectives are to determine the amplitude and time location of the impulses based on the natural frequencies and damping ratios of the system. This yields a shaped input that drives the system to a desired location with reduced vibration.

A vibratory system can be modelled as a superposition of second-order systems each with a transfer function.

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

where ω_n is the natural frequency and ζ is the damping ratio of the system. Thus, the impulse response of the system at time t is

$$y(t) = \frac{A\omega_n}{\sqrt{(1-\zeta^2)}} e^{-\zeta\omega_n(t-t_0)} \sin(\omega_n\sqrt{(1-\zeta^2)}(t-t_0)) \quad (2)$$

where A and t_0 are the amplitude and time of the impulse, respectively. Further, the response to a sequence of impulses can be obtained using the superposition principle. Thus, for N impulses, with $\omega_d = \omega_n\sqrt{(1-\zeta^2)}$, the impulse response can be expressed as

$$y(t) = M \sin(\omega_d t + \alpha) \quad (3)$$

where

$$M = \sqrt{\left(\sum_{i=1}^N B_i \cos \varphi_i\right)^2 + \left(\sum_{i=1}^N B_i \sin \varphi_i\right)^2}$$

$$B_i = \frac{A_i \omega_n}{\sqrt{(1-\zeta^2)}} e^{-\zeta\omega_n(t-t_i)}, \quad \varphi_i = \omega_d t_i$$

and

$$\alpha = \tan^{-1} \left(\frac{\sum_{i=1}^N B_i \cos \varphi_i}{\sum_{i=1}^N B_i \sin \varphi_i} \right)$$

A_i and t_i are the magnitudes and times at which the impulses occur.

The residual single mode vibration amplitude of the impulse response is obtained at the time of the last impulse, t_N as

$$V = \sqrt{(V_1^2 + V_2^2)} \quad (4)$$

where

$$V_1 = \sum_{i=1}^N \left\{ \frac{A_i \omega_n}{\sqrt{(1-\zeta^2)}} e^{-\zeta\omega_n(t_N-t_i)} \cos(\omega_d t_i) \right\},$$

$$V_2 = \sum_{i=1}^N \left\{ \frac{A_i \omega_n}{\sqrt{(1-\zeta^2)}} e^{-\zeta\omega_n(t_N-t_i)} \sin(\omega_d t_i) \right\}$$

To achieve zero vibration after the last impulse, it is required that both V_1 and V_2 in equation (4) are independently zero. Furthermore, to ensure that the shaped command input produces the same rigid body motion as the unshaped command, it is required that the sum of amplitudes of the impulses is unity. To avoid response delay, the first impulse is selected at time $t_1 = 0$. Hence by setting V_1 and V_2 in equation (4) to zero, $\sum_{i=1}^N A_i = 1$ and solving yields a two-impulse sequence with parameters as

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

$$A_1 = \frac{1}{1+K}, \quad A_2 = \frac{K}{1+K} \quad (5)$$

where $K = e^{-\zeta\pi/\sqrt{(1-\zeta^2)}}$

The robustness of the input shaper can further be increased by taking and solving the second derivative of the vibration in equation (4). Similarly, this yields a four-impulse sequence with parameters as

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

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

$$A_3 = \frac{3K^2}{1+3K+3K^2+K^3}, A_4 = \frac{K^3}{1+3K+3K^2+K^3} \quad (6)$$

where K is as in equation (5). In handling other vibration modes, an input shaper for each vibration mode can be designed independently. Then the impulse sequences can be convoluted together to form a sequence of impulses that attenuate vibration at required modes. In this manner, for a vibratory system, the vibration reduction can be accomplished by convolving a desired system input with the impulse sequence. This yields a shaped input that drives the system to a desired location with reduced vibration.

3.2 Filtering Techniques

The filters designs are thus used for pre-processing the input signal so that no energy is put into the system at frequencies corresponding to the vibration modes of the system. In the former, the filter is designed with a cut-off frequency lower than the first resonance mode of the system. Then, band-stop filters with centre frequencies at the resonance modes of the system are designed. Using the low-pass filter, the input energy at all frequencies above the cut-off frequency can be attenuated. In this

study, a low-pass filter with cut-off frequency at 20% of the first vibration mode was designed. On the other hand, using the band-stop filter, the input energy at selected (dominant) resonance modes of the system can be attenuated. In this study, band-stop filters with bandwidth of 60 rad/s were designed for the first two resonance modes.

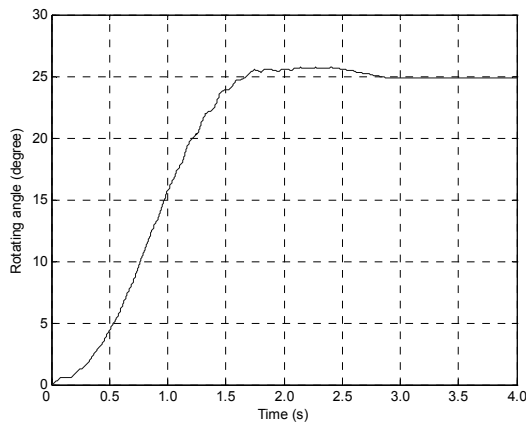
4. SYSTEM CHARACTERISTICS

In this work, the characteristics of flexible manipulator system are identified by applying a bang-bang torque input to the experimental-rig as described in section 2. The hub-angle and end-point acceleration responses of the flexible manipulator are measured using quadrature encoder and accelerometer respectively. Furthermore, to obtain the system characteristics in the frequency domain, Fast Fourier Transform (FFT) analysis of the end-point acceleration is obtained. Figure 3 shows the hub angle

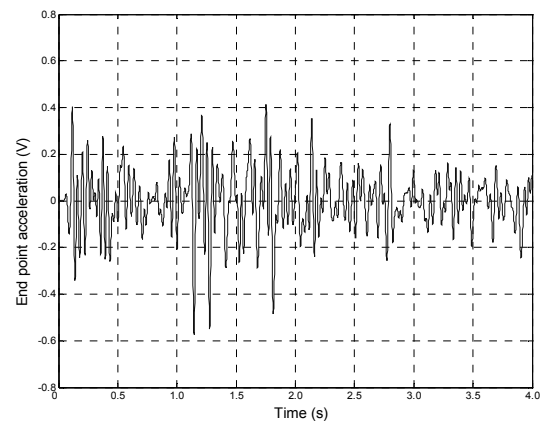
response, measured end-point acceleration and the corresponding result of FFT of the system. The result show that significant end-point vibration occurs during the system movement. It can be seen that the first two modes characterize the system vibration. In this work, the damping ratio is calculated on the basis of decay characteristic of the measured vibration signal. The mode parameters of the experimental flexible manipulator are listed in Table 1.

Table 1. Mode parameters of the flexible manipulator

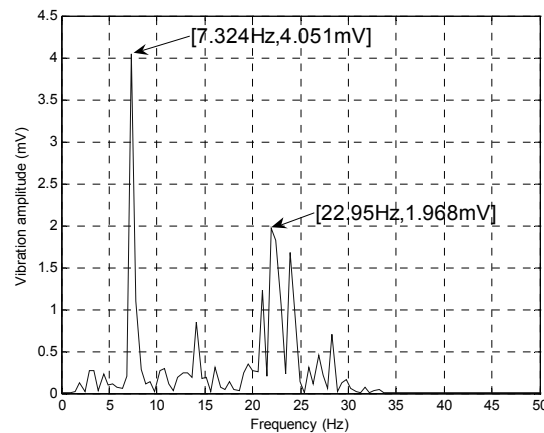
Parameter	First mode	Second mode
Frequency (Hz)	7.32	22.95
Damping ratio	0.03	0.01



(a) Hub angle.



(b) End point acceleration.



(c) FFT result

Figure 3. Dynamic characteristic of the flexible manipulator.

5. EXPERIMENTAL RESULTS

This section presents experimental results of the applications of feedforward controllers with input shaper and filtering techniques on the flexible manipulator. System responses are presented in time and frequency domains. Performance comparisons of the controllers are

studied in term of time domain specification and level of vibration reduction.

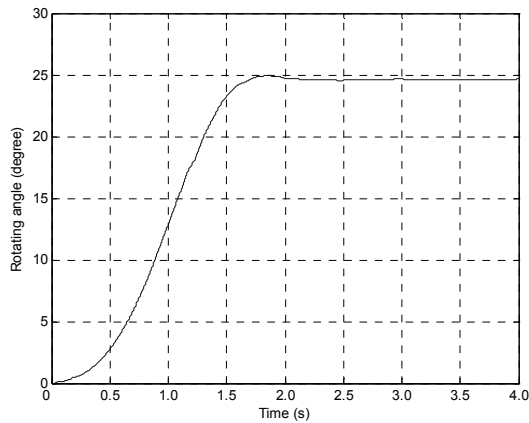
The feedforward control techniques were designed on the basis of vibration frequencies and damping ratios of the flexible manipulator system. As demonstrated from the previous chapter, the natural frequencies of the system were obtained as 7.32 Hz and 22.95 Hz and the

damping ratios were deduced as 0.03 and 0.01 for the first two modes of vibration respectively. The input shapers and filters thus designed were used for pre-processing the bang–bang torque input. The shaped and filtered torque inputs were then applied to the system in an open-loop configuration to reduce the vibrations of the manipulator. Experimental results of the response of the flexible manipulator to the shaped and filtered inputs are presented in this section in time and frequency domains. To verify the performance of the control techniques, the results are examined in comparison to the unshaped bang–bang torque input for a similar input level in each case. Similarly, three system responses are investigated namely the hub angle, end point acceleration and power spectral density of the end-point acceleration.

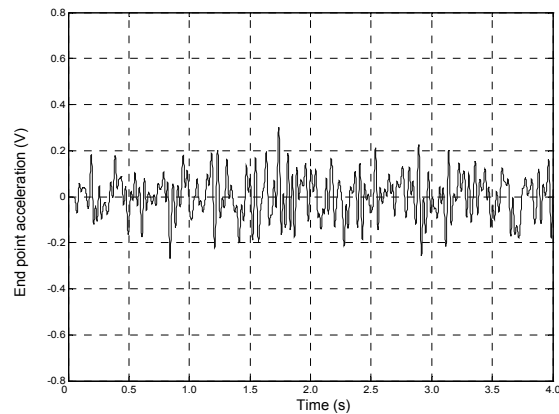
5.1 Input Shaping Techniques

Using the parameters of the system, input shapers with two and four-impulse sequences for the first two modes of vibration were designed. The amplitude and time locations of the impulses were obtained by solving equations (3) and (4) respectively. Figures 4 and 5 show

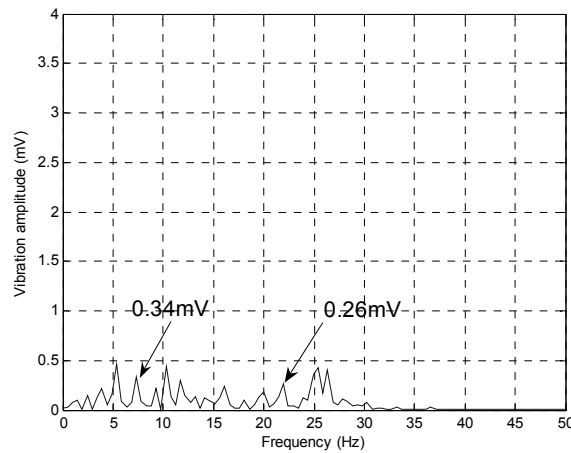
the hub angle, end point acceleration and power spectral density for two and four impulses sequence for the first two modes of vibration respectively. It is noted that the amplitude of vibration at the resonance modes of the system, with the rotation of hub angle, end point acceleration responses and power spectral density, have significantly been reduced. Lower amplitudes of the power spectral density as compared to the unshaped input were achieved. The settling times of the rotation angle response were obtained as 1.602 s and 1.655 s and the percentage overshoot as 1.13% and 0.94% with the two and four-impulse sequences respectively. Besides, the percentages of vibration amplitude reduction (power spectral density) for the first resonance mode were obtained as 91.6% and 93.3% with the two and four-impulse sequences respectively. These results show that the hub-angle response is slower than the response to the unshaped input. It is noted that the level of vibration reduction increases with higher number of impulses, at the expense of increase in the delay in the response of the system.



(a) Hub angle.

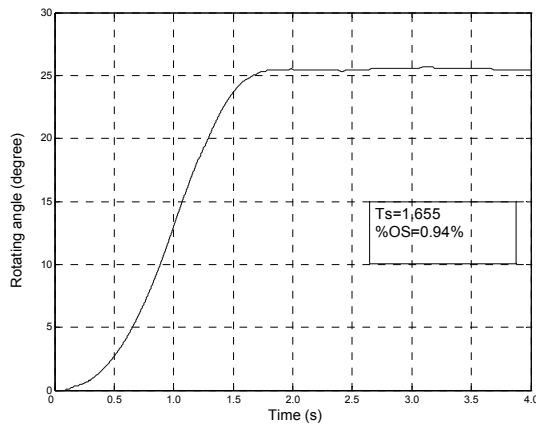


(b) End point acceleration.

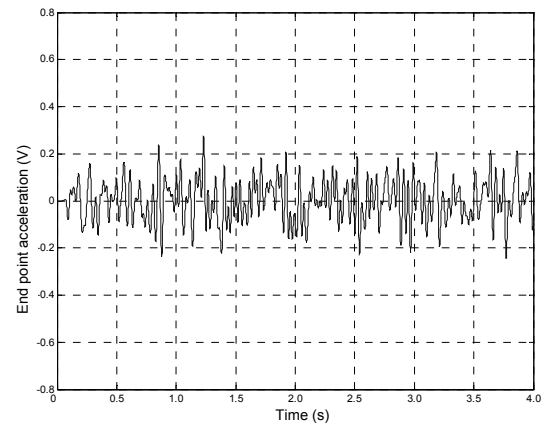


(c) Power spectral density.

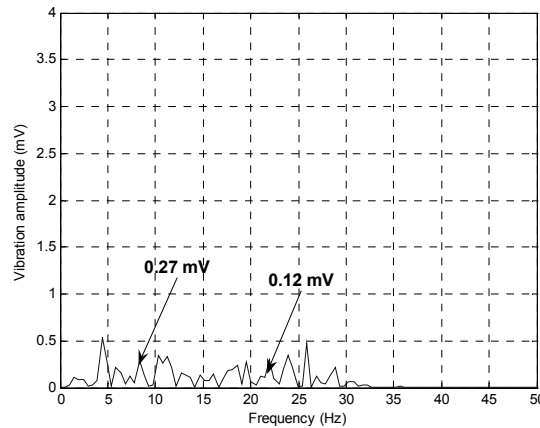
Figure 4. Experimental results using two-impulse input shaping.



(a) Hub-angle.



(b) End point acceleration.



(c) Power spectral density.

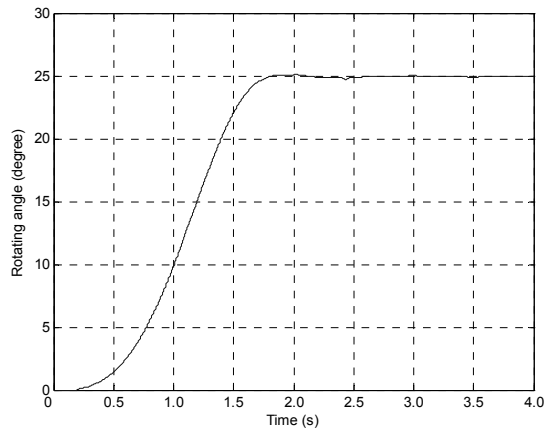
Figure 5. Experimental results using four-impulse input shaping.

5.2 Filtering Techniques

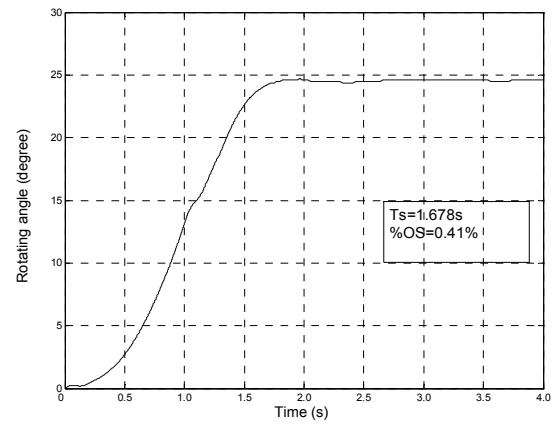
In this research, a low-pass filter with cut-off frequency at 20% of the first vibration mode was designed to attenuate the input energy at all frequencies above the cut-off frequency. Thus, for the flexible manipulator, the cut-off frequencies of the filters were selected as 10 rad/s. On the other hand, using the band-stop filter with bandwidth of 60 rad/s, the input energy at dominant resonance modes of the system also can be attenuated. Figures 6 and 7 show the hub angle, end point acceleration and power spectral density for both third orders Butterworth low pass filter and band stop filter. Using these control techniques, the settling times of the rotation angle response were obtained as 1.699 s and 1.678 s and the percentage overshoot as 0.80 % and 0.41 % with the low pass filter and band stop filter respectively. The percentages of vibration amplitude reduction (power spectral density) for the first resonance mode were obtained as 91.6% and 84.7% with the low pass filter and band stop filter respectively. It is noted that the amplitude of vibration at the resonance modes of the system, with the rotation of hub angle, end point acceleration responses and power spectral density, have significantly been reduced for both filtering techniques.

5.3 Comparative Performance Assessments

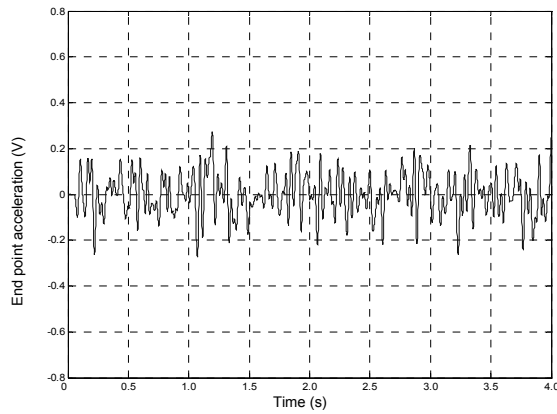
Table 2 summarizes the experimental results using input shaping and filtering techniques in time response specifications. The level of vibration reduction using both of the techniques with the end-point residual at the resonance modes in comparison to the bang-bang torque input is shown in Figure 8. The result reveals that the highest performance in reduction of vibration of the flexible manipulator is achieved with the input shaping technique. This is observed as compared to the low-pass and band-stop filtered inputs at the first two modes of vibration. It is noted that better performance in vibration reduction of the system is achieved with the low-pass filtered input as compared to the band-stop filtered input. This is mainly due to the higher level of input energy reduction achieved with the low-pass filter, especially at the second vibration modes. As expected, system responses were slower with the shaped and filtered inputs as compared to the system response to the unshaped input. It is also noted that the delay in the system response increases with the number of impulses. Comparisons of specifications of rotating angle responses for input shaping and filtering techniques noted that the differences in rise and settling times are negligibly small.



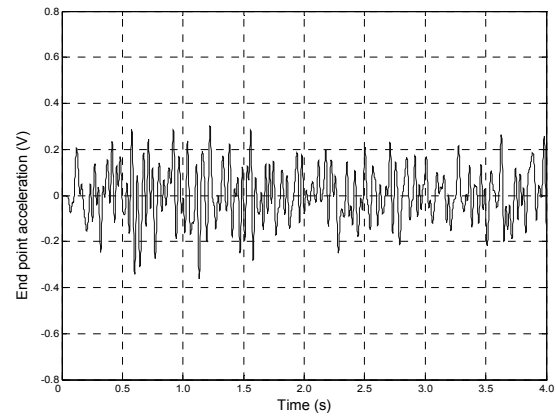
(a) Hub-angle.



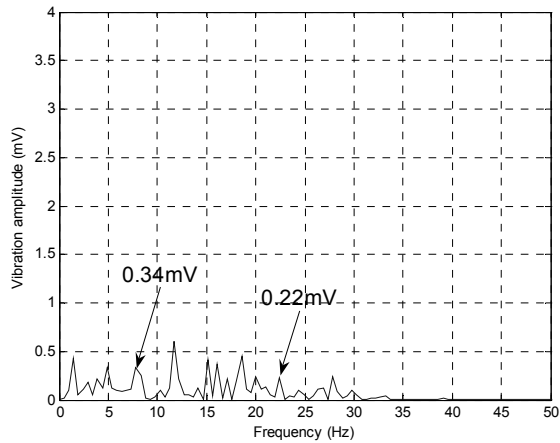
(a) Hub-angle.



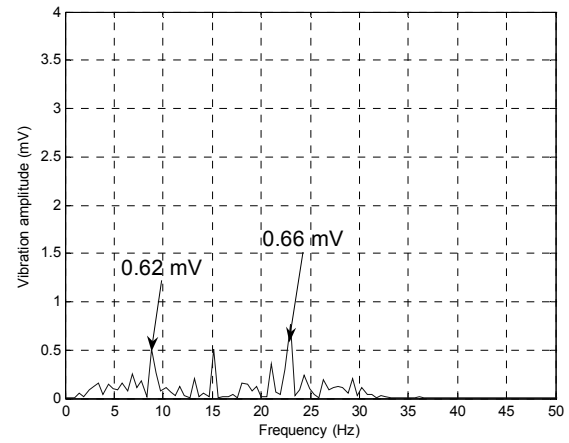
(b) End-point acceleration



(b) End-point acceleration



(c) Power spectral density



(c) Power spectral density

Figure 6. Experimental results using third order Butterworth Low Pass filter.

Figure 7. Experimental results using third order Butterworth Band Stop filter.

Table 2. Experimental results for input shaping and filtering techniques in time response specifications

Feedforward Controller		Hub angle		Acceleration
		Settling time (s)	Overshoot (%)	Maximum range (V)
Input Shaping	2 impulse	1.602	1.13	-0.27 to 0.30
	4 impulse	1.655	0.94	-0.25 to 0.27
Filtering Techniques	Low-pass filter	1.699	0.80	-0.27 to 0.27
	Band-stop filter	1.678	0.41	-0.36 to 0.30

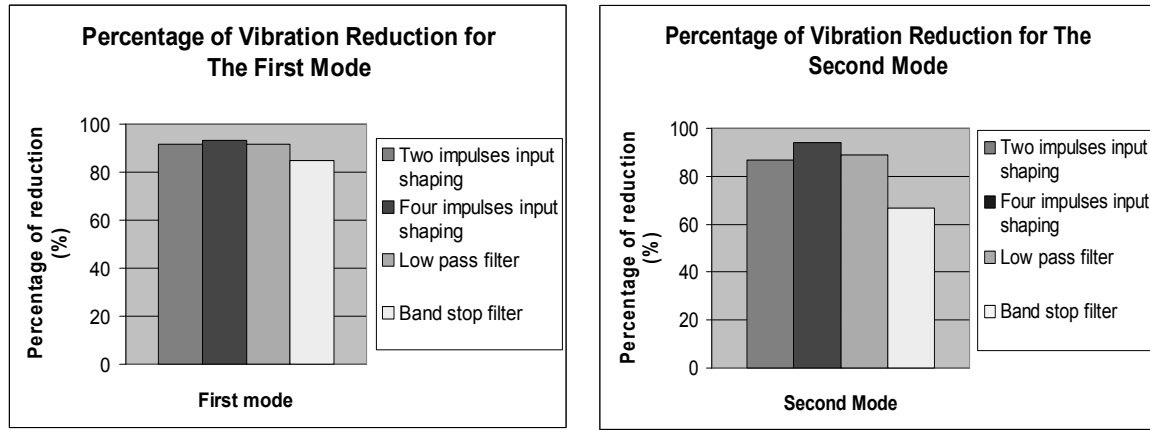


Figure 8. Percentage of vibration reduction using two and four impulses of input shaping, low pass filter and band stop filter.

6. CONCLUSION

Experimental investigations into the development of feedforward control schemes for vibration control of a flexible manipulator system have been presented. A feedforward control strategies for vibration control of a flexible robot manipulator has, initially, been developed using input shaping, low-pass and band-stop filtered input techniques. The system response to the unshaped bang-bang torque input has been used to determine the parameters of the system for evaluation of the control strategies. Significant reduction in the system vibrations has been achieved with these control strategies. Performances of the techniques have been evaluated in terms of level of vibration reduction and speed of response. In overall, a significant reduction in the system vibrations has been achieved with the input shaper and filtering techniques. A comparison of the results has demonstrated that the input shaping provide the best performance in vibration reduction as compared to filtering techniques. However, the delay in the system response increases with the number of impulses.

REFERENCES

- [1] Z. Mohamed, M.O. Tokhi, "Vibration control of a single link flexible manipulator using command shaping techniques," *Proceedings of IMechE-I: Journal of Systems and Control Engineering*, vol. 216(2), 2002, pp. 191-210.
- [2] Z. Mohamed, J.M. Martins, M.O. Tokhi, J. Sa da Costa, M.A. Botto, "Vibration control of a very flexible manipulator system," *Journal of Systems and Control Engineering*, vol. 13, 2003, pp. 267-277.
- [3] Jinjun Shan, Hong-Tao Liu, Dong Sun, "Modified input shaping for a rotating single link flexible manipulator," *Journal of Sound and Vibration*, vol. 285, 2004, pp. 187-207.
- [4] D.M. Aspinwall, "Acceleration profiles for minimising residual response," *Transactions of ASME: Journal of Dynamic Systems, Measurement and Control*, vol. 102 (1), 1980, pp. 3-6.
- [5] J.C. Swigert, "Shaped torque techniques," *Journal of Guidance and Control*, vol. 3(5), 1980, pp. 460-467.
- [6] H. Moulin and E. Bayo, "On the accuracy of end-point trajectory tracking for flexible arms by non-causal inverse dynamic solution," *Transactions of ASME: Journal of Dynamic Systems, Measurement and Control*, vol. 113, 1991, pp. 320-324.
- [7] T. Onsay and A. Akay, "Vibration reduction of a flexible arm by time optimal open-loop control," *Journal of Sound and Vibration*, vol. 147(2), 1991, pp. 283-300.
- [8] P.H. Meckl and W.P. Seering, "Experimental evaluation of shaped inputs to reduce vibration of a cartesian robot," *Transactions of ASME: Journal of Dynamic Systems, Measurement and Control*, vol. 112(6), 1990, pp. 159-165.
- [9] W.E. Singhose, N.C. Singer and W.P. Seering, "Comparison of command shaping methods for reducing residual vibration," *Proceedings of European Control Conference*, Rome, 1995, pp. 1126-1131.
- [10] M.O. Tokhi, and H. Poerwanto, "Control of vibration of flexible manipulators using filtered command inputs," *Proceedings of international congress on sound and vibration*, St. Petersburg, Russia, 1996, pp. 1019-1026.
- [11] M.O. Tokhi and A.K.M. Azad, "Control of flexible manipulator systems," *Proceedings of IMechE-I: Journal of Systems and Control Engineering*, vol. 210, 1996, pp. 283-292.
- [12] N.C. Singer and W.P. Seering, "Preshaping command inputs to reduce system vibration," *Transactions of ASME: Journal of Dynamic Systems, Measurement and Control*, vol. 112(1), 1990, pp. 76-82.
- [13] Z. Mohamed, and M.O. Tokhi, "Vibration control of a single-link flexible manipulator using command shaping techniques," *Proceedings of IMechE-I: Journal of Systems and Control Engineering*, vol. 216(2), 2002, pp. 191-210.
- [14] F. Khorrami, S. Jain, and A. Tzes, "Experiments on rigid body-based controllers with input preshaping for a two-link flexible manipulator," *IEEE Transactions on Robotics and Automation*, vol. 10(1), 1994, pp. 55-65.