HYBRID INPUT SHAPING AND PID CONTROL OF A FLEXIBLE ROBOT MANIPULATOR

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ABSTRACT

This paper presents experimental investigations into the development of hybrid input shaping and PID control for vibration suppression and input tracking of a flexible robot manipulator. Initially, a PID controller is developed for control of rigid-body motion of the system. This is then extended to incorporate a feedforward controller based on input shaping techniques for vibration control. Experimental results of the response of the manipulator with the controllers are presented in time and frequency domain. The effects of derivative order of the input shaper on the performance of the system are also investigated. The performances of the hybrid control schemes are assessed in terms of input tracking capability and level of vibration reduction in comparison to the PID control. Finally, a comparative assessment of the hybrid control schemes is presented.

Keywords: *Flexible Manipulator, Input Shaping, PID control, Vibration Control*

1.0 INTRODUCTION

Flexible robot manipulators exhibit many advantages over their rigid counterparts: they require less material, are lighter in weight, have higher manipulation speed, lower power consumption, require smaller actuators, are more manoeuvrable and transportable, are safer to operate due to reduced inertia, have less overall cost and higher payload to robot weight ratio. However, the control of flexible manipulators to maintain accurate positioning is challenging. Due to the flexible nature and distributed characteristics of the system, the dynamics are highly non-linear and complex. Problems arise due to precise positioning requirements, system flexibility leading to vibration, the difficulty in obtaining accurate model of the system and non-minimum phase characteristics of the system [1].

The control strategies for flexible manipulator systems can be classified as feedforward (open-loop) and feedback (closed-loop) control. Feedforward control techniques are mainly developed for vibration suppression and involve developing the control input through consideration of the physical and vibrational properties of the system, so that system vibrations at response modes are reduced. This method does not require any additional sensors or actuators and does not account for changes in the system once the input is developed. A number of techniques have been proposed as feedforward control schemes for control of vibration in flexible structures. These include utilisation of Fourier expansion [2], development of computed torque [3], utilisation of single and multiple-switch bang-bang control functions [4] and construction of input functions from ramped sinusoids or versine functions [5]. Moreover, command shaping techniques have also been investigated in reducing system vibration in flexible manipulators. These include filtering techniques based on low-pass, band-stop and notch filters [6,7] and input shaping [8,9]. Previous experimental studies on a single-link flexible manipulator have shown that input shaping gives higher level of vibration reduction and robustness than filtering techniques. However, the major drawback of feedforward control schemes is their limitation in coping with parameter changes and disturbances to the system [10]. Moreover, the technique requires relatively precise knowledge of the dynamics of the system.

Feedback control techniques use measurement and estimate of the system states for control of rigid body motion and vibration suppression. Feedback controllers can be designed to be robust to parameter uncertainty. In general, control of flexible manipulators can be made easier by locating every sensor exactly at the location of the actuator, as collocation of sensors and actuators guarantees stable servo control [11]. In the case of flexible manipulator systems, the end-point position is controlled by obtaining the parameters at the rotating and end-point of the manipulator and using the measurements as a basis for applying control torque at the rotating. Thus, the feedback control can be divided into collocated and non-collocated control. By applying control torque based on non-collocated sensors, the problem of non-minimum phase and of achieving stability is of concern. Several approaches utilising closed-loop control strategies have been reported for control of flexible manipulators. These include linear state feedback control [12,13], adaptive control [14,15], robust control techniques based on H-infinity [16] and variable structure control [17] and intelligent control based on neural networks [18] and fuzzy logic control schemes [19].

This paper presents experimental investigations into the development of hybrid input shaping and PID control for vibration suppression and input tracking of a flexible robot manipulator. To demonstrate the effectiveness of the control schemes, initially a PID controller as a feedback control is developed for control of rotating angle motion of flexible manipulator system. This is then extended to incorporate a feedforward controller based on input shaping techniques for vibration suppression of the manipulator. The performances of the controllers are assessed in terms of the input tracking capability and vibration reduction as compared to the response with PID control. The effects of derivative order of the input shaper on the performance of the system are also investigated. Finally, a comparative assessment and further analysis of the control strategies is discussed.

2.0 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, IH, 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 $\upsilon(x, t)$. Since the manipulator is long and slender, transverse shear and rotary inertia effects are neglected [20]. This allows the use of the Bernoulli–Euler beam theory to model the elastic behavior 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.

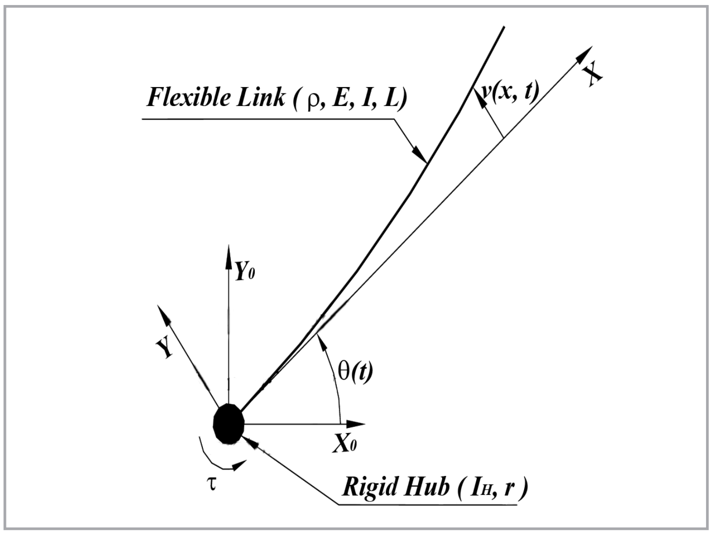


Figure 1: Mechanical model of the flexible manipulator

2.1 Lab-Scale Experimental of Flexible Manipulator

The experimental work for this research was carried out at the University of Technology Malaysia robotic laboratory. Figure 2 shows a single-link flexible manipulator system consists of a flexible aluminum beam and a KollMorgern Servo Disk DC motor JR12M4CH with a built-in optical encoder used to measure the load shaft angular position. The system parameters of flexible robot manipulator are described precisely in [21]. 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 installed at the tip of the flexible link. This accelerometer is capable of tracing deflection within the amount of 0.2 angstroms or 1/10th of an atomic diameter. The control voltage for driving the motor is sent to the servo amplifier through a similar PCL 818 board.

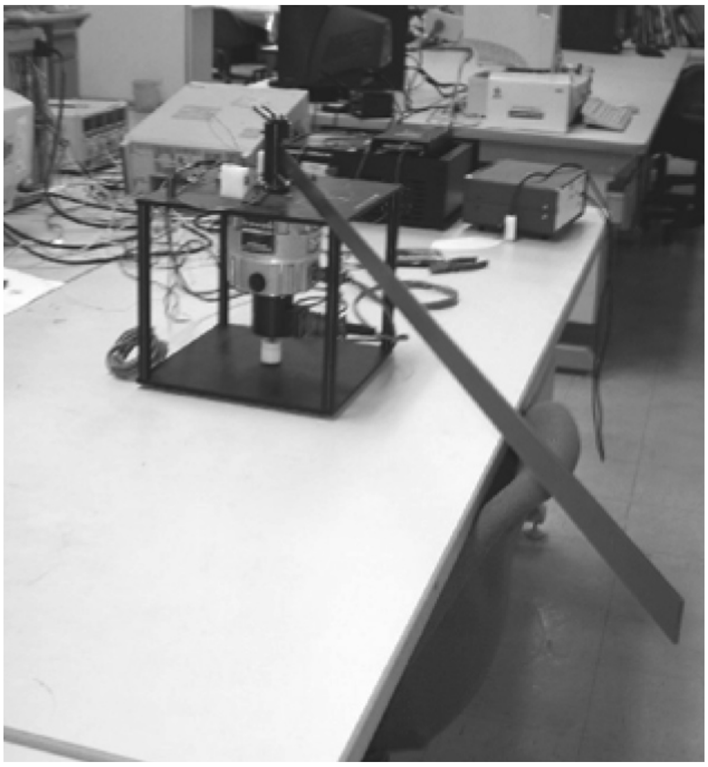


Figure 2: Actual flexible-link test bed in UTM

The setup of the control system is schematically shown in Figure 3. 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. Rotating-angle and acceleration measurements are fed back and use to derive the actuator command. From these two signals, a closed loop system with PID controller can be built to control the rotation of the flexible link.

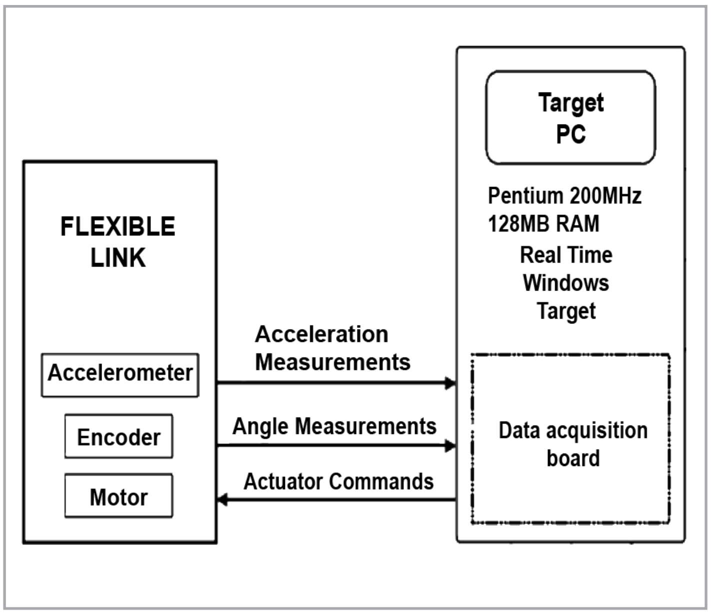


Figure 3: Flow diagram of the system

3.0 CONTROL SCHEMES

In this section, the proposed control schemes for rigid body-motion and vibration control of a flexible manipulator are designed. Initially, a PID control is developed. Then input shaping techniques are incorporated in the closed-loop system for control of vibration of the system.

3.1 PID controller

To demonstrate the performance of the hybrid control schemes, a PID control strategy is adopted for control of rigid-body motion of the manipulator. A block diagram of the PID controller is shown in Figure 4, where K_p, K_d and K_i are the proportional, derivative and integral gains respectively, θ represents rotating angle, r is the reference rotating angle. Essentially, the task of this controller is to position the flexible robot arm to the specified angle of demand. The rotating angle signal is fed back and used to control the rotating angle of the manipulator. The control signal $U(s)$ in Figure 4 can thus be obtained as

$$U(s) = \left(K_p + K_d s + \frac{K_i}{s}\right)[R(s) - \theta(s)] \tag{1}$$

where s is the Laplace variable. Hence the closed-loop transfer function is obtained as

$$\frac{\theta(s)}{R(s)} = \frac{\left(K_p + K_d s + \frac{K_i}{s}\right)G(s)}{1 + \left(K_p + K_d s + \frac{K_i}{s}\right)G(s)} \tag{2}$$

where $G(s)$ is the open-loop plant from the input torque to the rotating angle. In this study, the Ziegler-Nichols approach is utilized to tune the controller parameter of K_p, K_d and K_i.

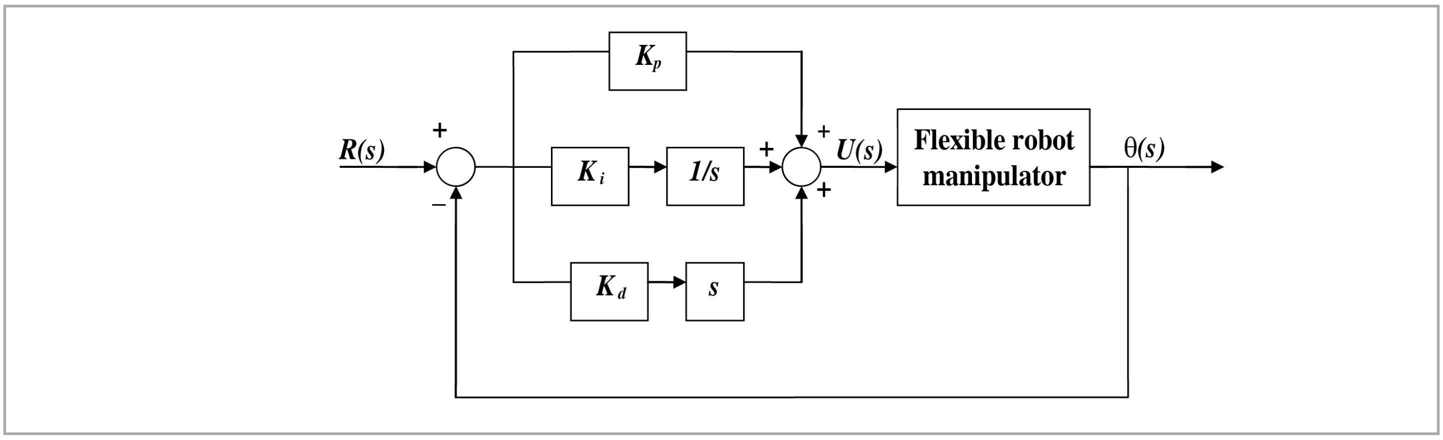


Figure 4: The PID control structure

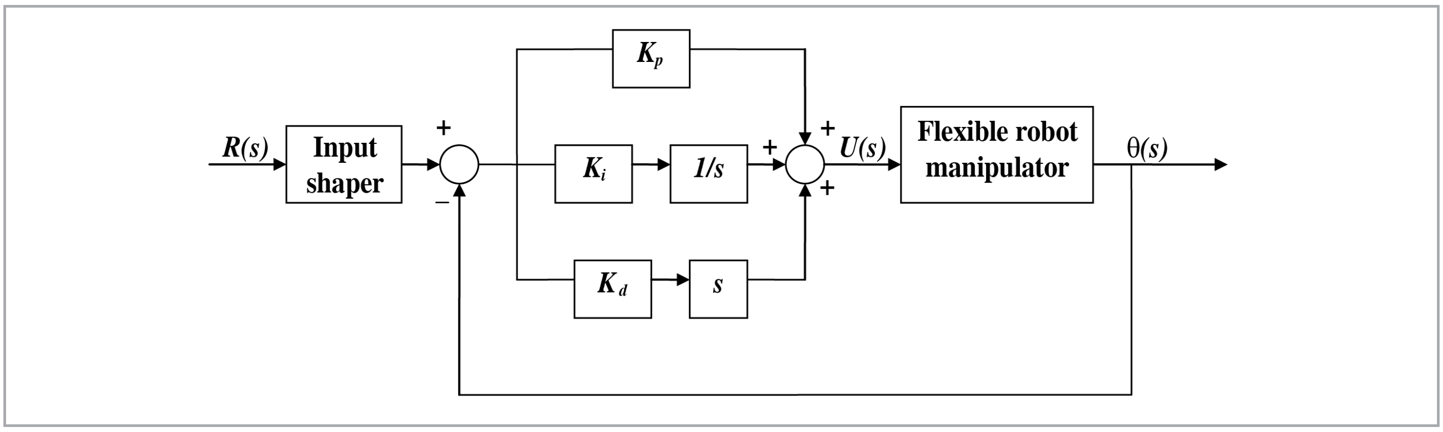


Figure 5: The PID and input shaper control structure

3.2 Hybrid PID and Input Shaping control

A hybrid control structure for control of rigid body motion and vibration suppression of the flexible manipulator based on a PID and input shaping control is proposed in this section. The input shaping 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 behavior of the single-link flexible manipulator system. The input shapers thus designed were used for pre-processing the reference input. The shaped inputs were then applied to the system in the closed-loop configuration with PID controller to reduce the vibrations of the manipulator. In this study, the input shaping control schemes is designed using a two-impulse sequence (ZV) and four-impulse sequence (ZVDD). A block diagram of the hybrid control schemes is shown in Figure 5.

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. The corresponding design relations for achieving a zero residual single mode vibration of a system and to ensure that the shaped command input produces the same rigid body motion as the unshaped command yields a two-impulse sequence with parameters as

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

$$A_1 = \frac{1}{1+H},\ A_2 = \frac{H}{1+H}. \tag{3}$$

where ω_n and ζ represent the natural frequency and damping ratio respectively, $H = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}}$, $\omega_d = \omega_n\sqrt{1-\zeta^2}$, t_j and A_j are the time location and amplitude of impulse j respectively. The robustness of the input shaper to errors in natural frequencies of the system can be increased by solving the derivatives of the system vibration equation. This yields a four-impulse sequence with parameters as

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

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

$$A_3 = \frac{3H^2}{1+3H+3H^2+H^3},\ A_4 = \frac{H^3}{1+3H+3H^2+H^3} \tag{4}$$

where H is as in equation (3).

To handle higher vibration modes, an impulse sequence 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 higher modes. In this manner, the vibration reduction can be accomplished by convolving a desired input reference with the input shaper. This yields a shaped input that drives the system to a desired location with reduced vibration.

4.0 EXPERIMENTAL RESULTS

This section presents experimental results of the applications of hybrid control schemes on the flexible robot manipulator. The corresponding results are presented in time and frequency domain. The manipulator is required to follow a unit step trajectory of 45 degree as shown in Figure 6. System responses, namely the rotating angle, end-point acceleration and power spectral density, are observed. To investigate the vibration of the system in the frequency domain, power spectral density (PSD) of the response at the end-point is obtained. The performances of the hybrid controllers are assessed in terms of input tracking and vibration suppression in comparison to the PID control.

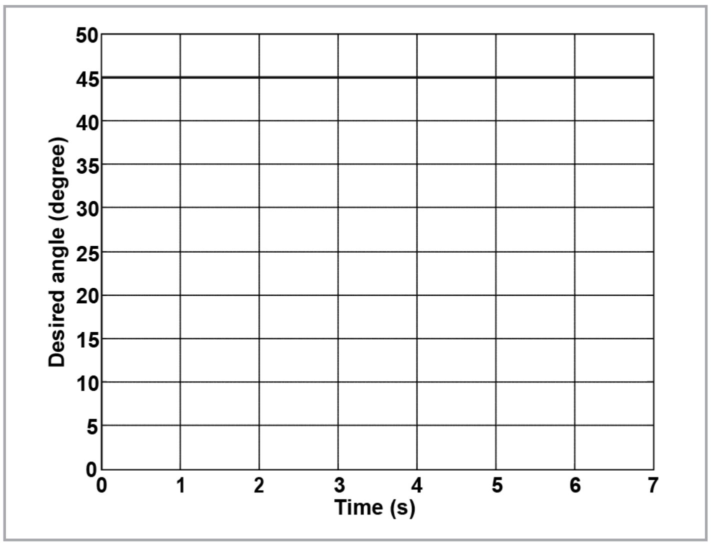


Figure 6: The reference rotation angle

4.1 PID controller

In this experiment, the unshaped reference input of the motor is a 45 degree step command. The feedback parameters of the PID controller are chosen experimentally to realize a good-compromise rotating-angle response in terms of overshoot and settling time. The sampling frequency is set to 1 ms. Utilizing the Ziegler Nichols method with several adjustments, the final gains are chosen as

$$K_p = 0.0145,\ K_i = 0.0015 \text{ and } K_d = 0.0155.$$

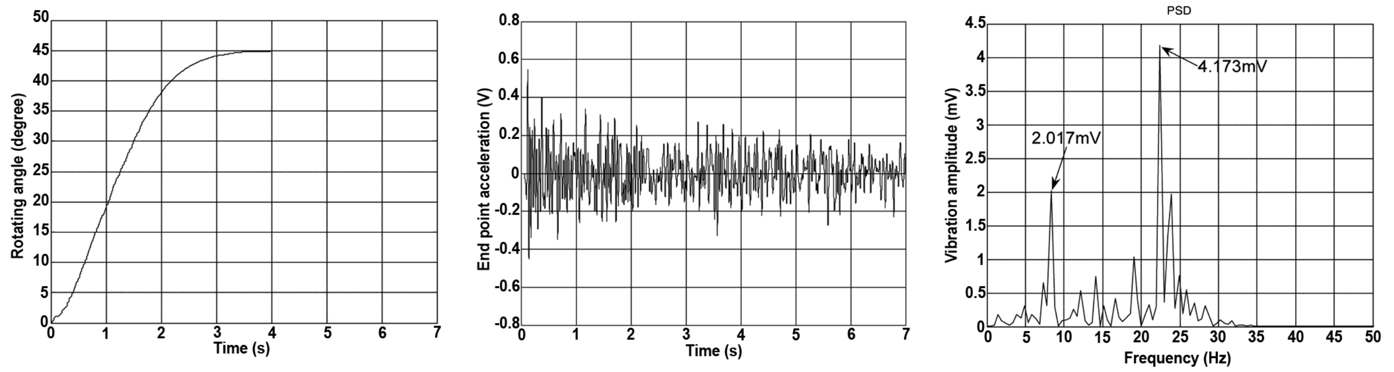
Figure 7 shows the response of the system and power spectral density with the PID controller. The experimental results show that, with the PID controller, the magnitudes of the first two vibration modes are 2.02 *mV* and 4.17 *mV*, respectively from the power spectral density measurement. It is also noted that the vibration modes at the end point is dominated by the first two vibrational modes, which are obtained as 7.813 *Hz* and 22.95 *Hz*, respectively. These results were considered as the system response without vibration control and will subsequently be used to design and evaluate the performance of the hybrid control strategies. The steady-state rotation angle of 45 degree for the flexible manipulator system was achieved within the settling times and overshoot of 3.013 *s* and 0.00% respectively, while for the end point acceleration response; the maximum acceleration range is ±0.50 *V*.

4.2 Hybrid control

In the case of hybrid PID and input shaping control schemes, an input shaper was designed based on the dynamic behaviour of the closed loop system obtained using only the PID control. In designing the hybrid PID with two impulses (PID-ZV) and four impulses (PID-ZVDD) sequence, the magnitudes and time locations of the impulses were obtained by solving equations (3) and (4). For digital implementation of the input shaping, locations of the impulses were selected at the nearest sampling time. Figures 8 and 9 show the rotating angle, end point acceleration and power spectral density response with PID-ZV and PID-ZVDD respectively for the first two modes of vibration. It is noted that the hybrid controller is capable of reducing the system vibration while maintaining the input tracking capability of the manipulator. The vibration magnitudes of the hybrid control have significantly been reduced as compared to the response with PID control. With PID-ZV control, the magnitudes of the first two vibration modes were obtained at 0.51 *mV* and 0.71 *mV* respectively, while with PID-ZVDD control, the magnitudes were obtained at 0.49 *mV* for both vibration modes. It is noted that, higher levels of vibration reduction were obtained using PID-ZVDD as compared to the PID-ZV control schemes. This is also evidenced in end-point acceleration response, where the maximum acceleration ranges of PID-ZVDD is lower than PID-ZV control schemes. Table 1 summarises the levels of vibration magnitude reduction of the system responses at the first two modes in comparison to the PID control. In overall, the hybrid control schemes results a slower rotation angle response as compared to the PID control. The steady-state rotation angle of 45 degree for PID-ZV and PID-ZVDD control were achieved within the settling times of 3.255 *s* and 3.339 *s*. It shows that, with PID-ZVDD, the system response is slightly slower as compared to PID-ZV control. Hence, it is shown that the speed of the system response reduces with the increase in number of impulse sequence. The corresponding setting time and overshoot of the rotation angle response using PID-ZV and PID-ZVDD control schemes is depicted in Table 1.

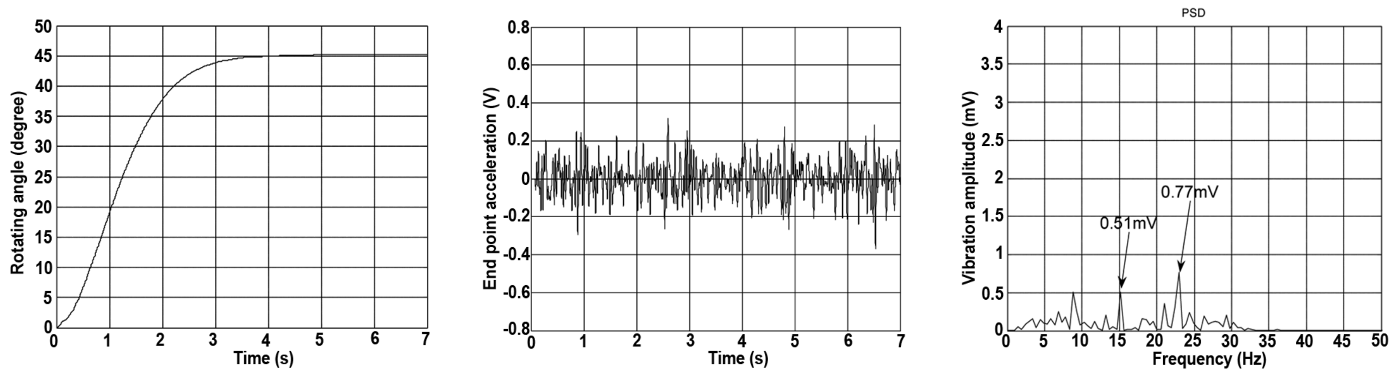
Table 1: Experimental results using PID, PID-ZV and PID-ZVDD controller

Controller	Time domain			Frequency domain	
	Rotating angle		Acceleration	First mode	Second mode
	Settling time (*s*)	Overshoot (%)	Maximum range (*V*)	Vibration magnitude (*mV*)	Vibration magnitude (*mV*)
PID-ZV	3.255	0.00	±0.37	0.51	0.77
PID-ZVDD	3.339	0.00	±0.29	0.49	0.49
PID	3.013	0.00	±0.50	2.02	4.17



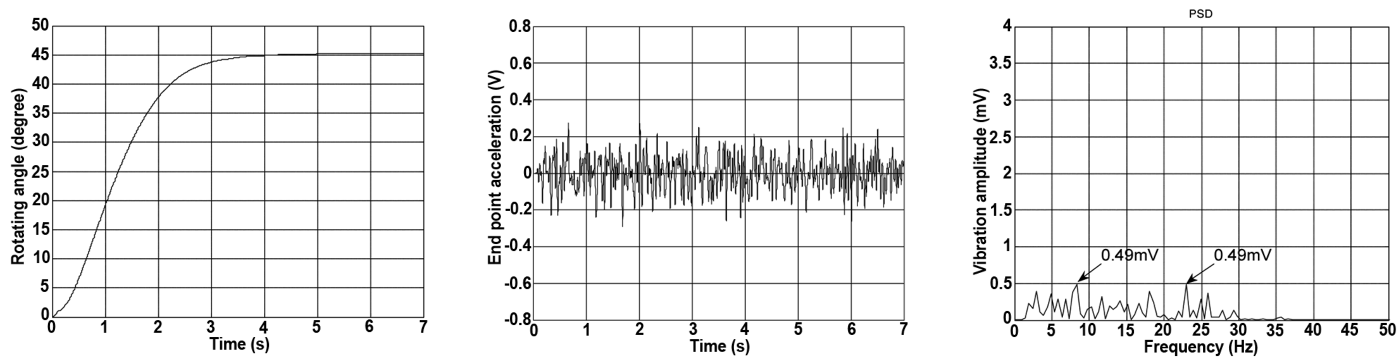
(a) Rotating angle (b) End point acceleration (c) Power spectral density

Figure 7: Response of the manipulator with PID Controller



(a) Rotating angle (b) End point acceleration (c) Power spectral density

Figure 8: Response of the manipulator with PID-ZV controller



(a) Rotating angle (b) End point acceleration (c) Power spectral density

Figure 9: Response of the manipulator with PID-ZVDD controller

6.0 CONCLUSION

Experimental investigations into the development of hybrid input shaping and PID control for vibration suppression and input tracking of a flexible robot manipulator have been presented. The hybrid control schemes have been developed based on PID with ZV shaper (PID-ZV) and PID with ZVDD shaper (PID-ZVDD). The proposed control schemes have been implemented and tested within the experimental environment of a single-link flexible robot manipulator. The performances of the control schemes have been evaluated in terms of input tracking capability and vibration suppression at the resonance modes of the manipulator. Acceptable performance in input tracking control and vibration suppression has been achieved with both control strategies. A comparison of the results has demonstrated that the PID-ZVDD control provides higher level of vibration reduction as compared to the PID-ZV control. In term of speed of the responses, PID-ZVDD control results in a slower tracking response as compared to PID-ZV control. It is noted that the proposed hybrid controllers are capable of reducing the system vibration while maintaining the input tracking performance of the manipulator. ■

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PROFILES

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