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Vibration control of a very flexible manipulator system

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Abstract

This paper presents experimental investigations into the development of feedforward and feedback control schemes for vibration control of a very flexible and high-friction manipulator system. A feedforward control scheme based on input shaping and low-pass filtering techniques and a strain feedback control scheme are examined. To study the effectiveness of the controllers, initially a collocated PD control is developed for control of rigid body motion. The performances of the controllers are assessed in terms of the input tracking capability and vibration reduction as compared to the response with PD control. Moreover, the robustness of the feedforward control schemes is discussed. Finally, a comparative assessment of the control strategies is presented.

Keywords: Command shaping; Flexible manipulator; PD control; Strain feedback; Vibration control

1. Introduction

Most existing robotic manipulators are designed to maximise stiffness, in an attempt to minimise system vibration and achieve good positional accuracy. High stiffness is achieved by using heavy material. As a consequence, such robots are usually heavy with respect to the operating payload. This, in turn, limits the speed of operation of the robot manipulation, increases the size of actuators and energy consumption. Moreover, the payload to robot weight ratio, under such situations, is low. In contrast, 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, have less overall cost and higher payload to robot weight ratio (Azad, 1994). However, the control of flexible manipulators to achieve and maintain accurate positioning is challenging. Problems arise due to precise positioning requirements, system flexibility which leads to vibration, the difficulty in obtaining accurate model of the system and non-minimum phase characteristics of the system (Yurkovich, 1992). To attain end-point positional accuracy, a control mechanism that accounts for both the rigid body and flexural motions of the system is required.

The control strategies for flexible manipulator systems can be classified as feedforward and feedback control schemes. 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. These include utilisation of Fourier expansion as the forcing function to reduce peaks of the frequency spectrum at discrete points (Aspinwall, 1980), development of computed torque based on a dynamic model of the system (Moulin & Bayo, 1991), utilisation of single and multiple-switch bang–bang control functions (Onsay & Akay, 1991), construction of input functions from ramped sinusoids or versine functions (Meckl & Seering, 1990). Moreover,

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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 (Singhose, Singer, & Seering, 1995; Tokhi & Poerwanto, 1996) and input shaping (Mohamed & Tokhi, 2002; Singer & Seering, 1990). 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 (Khorrami, Jain, & Tzes, 1994). Moreover, this technique requires relatively precise knowledge of the dynamics of the system.

Feedback control techniques use measurements and estimates of the system states and changes the actuator input accordingly for control of rigid body motion and vibration suppression of the system. 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 (Gevarter, 1970). In the case of flexible manipulator systems, the end-point position can be controlled using the measurement obtained from the hub and end-point of the manipulator. The measurement is then used as a basis for applying control torque at the hub. Thus, feedback control strategies can be divided into collocated and non-collocated control techniques. Sensors that can be utilised are strain gauge and accelerometer. An appreciable amount of work utilising strain gauges to design a compensator for vibration suppression of flexible manipulators has been carried out (Hasting & Ravishankar, 1988; Sangveraphunsiri, 1984). A direct strain feedback control, where a damping term is introduced into the differential equation governing the vibration of flexible manipulators has also been proposed (Luo, 1994). The theoretical and experimental results show an improvement in vibration behaviour but without any information about the end-point behaviour of the manipulator. Strain gauges have the disadvantage of not giving a direct measurement of manipulator displacement, as they can only provide local information. Thus, displacement measurement by using strain gauges requires more complex and possibly time consuming computations which can lead to inaccuracies (Hasting & Ravishankar, 1988). Alternatively, several control approaches utilising end-point measurements have been studied for control of vibration (Cannon & Schmitz, 1984; Kotnik, Yurkovich, & Ozguner, 1988). It has been demonstrated that using the end-point sensor, more accurate end-point positioning can be accomplished. However, the resulting controller is less robust to plant uncertainties than the corresponding collocated design. Moreover, by applying control torque based on non-collocated sensors, the problems of non-minimum phase and of achieving stability will be of concern.

This paper presents experimental investigations into the development of control schemes for vibration control of a very flexible and high-friction robot manipulator clamped to a high-ratio reduction gear actuation mechanism. The control strategies are developed based on feedforward and feedback control techniques. In the former, input shaping with a four-impulse sequence and third-order Butterworth low-pass filter are considered. In the latter case, direct strain feedback utilising a strain gauge is designed for control of vibration of the manipulator. The strain gauge is located close to the hub of the manipulator so as to avoid problems associated with non-collocated control. Moreover, this paper provides a comparative assessment of the performance of these techniques. A two-link flexible manipulator is considered, and experimental investigations are confined to the movement of the second link alone, with the first link fixed. To demonstrate the effectiveness of the controllers in reducing vibration of the manipulator, initially a joint-based collocated PD controller utilising the hub angle and hub velocity is developed for control of rigid body motion. This is then extended to incorporate the proposed feedforward and strain feedback controllers for control of vibration of the manipulator. The input shaper and filter are designed on the basis of the dynamic characteristics of the closed-loop system and used for pre-processing the reference input. Performances of the developed control schemes are assessed in terms of the level of vibration reduction, input tracking capability and robustness. These are accomplished by comparing the system responses with the response of PD control. Experimental results of the hub angle and end-point acceleration with the control schemes are presented. For evaluation of robustness, the control schemes are assessed with up to 30% error tolerance in the natural frequencies. Finally, a comparative assessment of the performance of the control strategies in vibration control of the flexible manipulator is presented. The rest of the paper is structured as follows: Section 2 provides a brief description of the flexible manipulator considered in this study. Section 3 describes the feedforward and feedback control techniques used in this investigation. Implementation, experimental results and performance assessment of the controllers are presented in Section 4. Finally, the paper is concluded in Section 5.

2. The flexible manipulator system

Fig. 1 shows the two-link flexible manipulator used in this investigation. The manipulator has been designed for the purpose of test and verification of position and force control algorithms (Martins, Ventura, & Sá da Costa, 1998). It consists of a modular structure where the joints and links can be easily exchanged. To transform it into a single-link flexible manipulator, the respective joint of the first link, which is a very stiff steal beam, is blocked. Only the second joint of the manipulator is allowed to rotate and the respective link is made of a very flexible spring–steal beam. The flexible-link is clamped to a high-ratio reduction gear actuation mechanism. As shown in Fig. 1, a reduction gear of 50:1 is used. Thus, the joint friction of the flexible manipulator is high and consequently the hub of the manipulator will not rotate in free-vibration. The actuation mechanism is a Harmonic Drive RH-14-6002 servo system, current driven by a 12A8 servo amplifier from Advanced Motion Controls. The mechanical model of the flexible manipulator system is shown in Fig. 2 where $\{O\ X_o\ Y_o\}$ and $\{O\ X\ Y\}$ represent the stationary and moving frames, respectively. The link is clamped to a rigid hub of moment of inertia, I_H and radius, r. τ is the torque applied at the hub of the manipulator. The rotation of frame $\{O\ X\ Y\}$ 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 $v(x,t)$.

The relevant characteristics of the manipulator are as follows: length of the beam $L = 0.5$ m, width of the beam $w = 0.001$ m, height of the beam $h = 0.02$ m, mass density $\rho = 7850\ \mathrm{kg/m^3}$, Young modulus $E = 209 \times 10^9$ Pa and hub radius $r = 0.075$ m. Two sensors namely encoder and tachogenerator are mounted at the joint of the manipulator for measurements of the hub angle and hub velocity of the system, respectively. In this work, the first three natural frequencies are considered as these dominantly characterise the dynamic behaviour of the system. In order to capture the first three modes of vibration with low interference of higher modes, the strain gauge bridges mounted on the beam were placed at the zeros of the curvature function of the fourth mode. These distances are 4.5, 18 and 32 cm from the clamping point of the beam. Furthermore, in order to

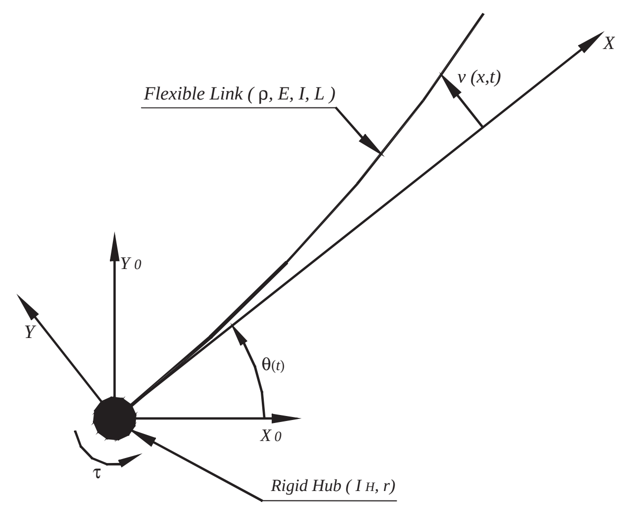

Fig. 2. Mechanical model of the flexible manipulator.

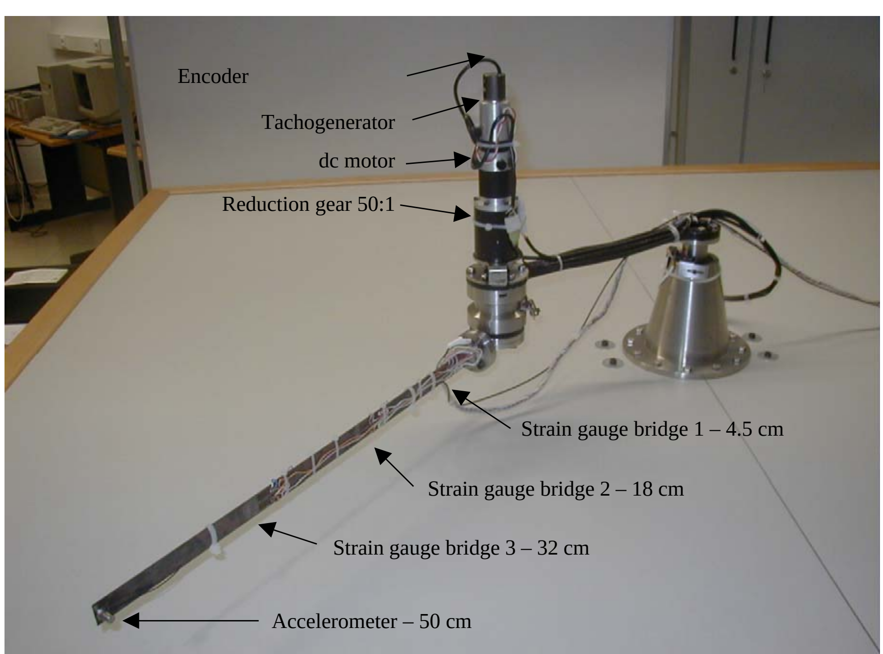

Fig. 1. The flexible manipulator system.

have a direct measurement of the behaviour of the end-point of the beam, a piezoelectric accelerometer was placed at its end-point. Considering linear beam theory, the sensor measurements are related to physical quantities in a simple form. The strain gauge bridges measure the beam curvature;

$$V_s = K_s \frac{\partial^2 v(x,t)}{\partial x^2} \tag{1}$$

and the accelerometer measures the end-point acceleration;

$$V_a = K_a\{\ddot{\theta}(t)(r+L) + \ddot{v}(r+L,t)\}, \tag{2}$$

where V_s and V_a are considered as the output voltage signals from the signal conditioning circuitry for the strain gauge bridges and the accelerometer, respectively. The beam curvature is the second derivative of the displacement variable $v(x,t)$, and can be evaluated at any point along the beam. K_s is a constant that depends on the input voltage to the strain gauge bridge, the strain gauge factor, the width of the beam and amplification gains. K_a is also a constant and depends on amplification gains of the accelerometer.

3. Control schemes

In this section, the proposed control schemes for vibration control of the flexible manipulator are introduced. These include feedforward control based on input shaping and low-pass filtering techniques and feedback control using direct strain feedback. Initially, a collocated PD control is developed for control of rigid body motion of the system.

3.1. Collocated PD control

To demonstrate the performance of the vibration control schemes, a PD feedback control of collocated sensor signals is adopted for control of rigid body motion of the manipulator. A block diagram of the PD controller is shown in Fig. 3, where K_p and K_v are the proportional and derivative gains, respectively, θ represents hub angle, $\dot{\theta}$ represents hub velocity and r is the reference hub angle. Essentially, the task of this controller is to position the flexible arm to the specified angle of demand. The hub angle and hub velocity signals are fed back and used to control the hub angle of the manipulator. The control signal $U(s)$ in Fig. 3 can thus be obtained as

$$U(s) = [K_p\{R(s) - \theta(s)\} - K_v\dot{\theta}], \tag{3}$$

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

$$\frac{\theta(s)}{R(s)} = \frac{K_p G(s)}{1 + K_v(s + (K_p/K_v))G(s)}, \tag{4}$$

where $G(s)$ is the open-loop transfer function from the input torque to the hub angle of the system (Martins, Botto, & Sá da Costa, 2002). Thus, the closed-loop poles of the system are given by the characteristic equation as

$$1 + K_v(s + Z)G(s) = 0, \tag{5}$$

where $Z = K_p/K_v$ represents the compensator zero which determines the control performance of the closed-loop system. In this study, a root locus approach is utilised to design the PD controller.

3.2. Feedforward control techniques

A hybrid control structure for control of rigid body motion and vibration suppression of the flexible manipulator based on the collocated PD and feedforward control schemes is presented here. As indicated earlier, the feedforward control scheme based on input shaping and low-pass filtering techniques is considered. A block diagram of the hybrid control scheme is shown in Fig. 4. In this manner, the reference input is shaped or filtered before feeding into the closed-loop system with the PD controller.

3.2.1. Input shaping

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 method is briefly described in this section (Singer & Seering, 1990).

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

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \tag{6}$$

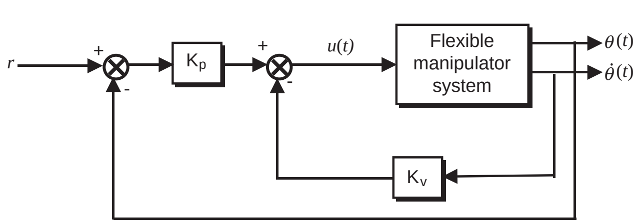

Fig. 3. The PD control structure.

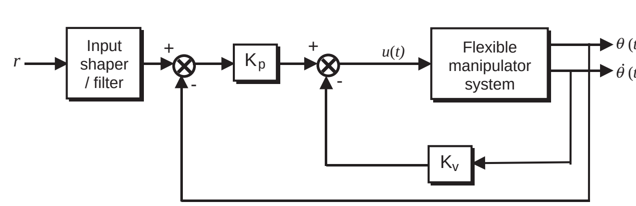

Fig. 4. The PD with feedforward control structure.

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

$$y(t) = \frac{A\omega_n}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n(t-t_o)} \sin\left(\omega_n\sqrt{1-\zeta^2}(t-t_o)\right), \quad (7)$$

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

$$y(t) = M \sin(\omega_d t + \alpha), \quad (8)$$

where

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

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

and

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

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

$$V = \sqrt{V_1^2 + V_2^2}, \quad (9)$$

where

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

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

To achieve zero vibration after the last impulse, it is required that both V_1 and V_2 in Eq. (9) 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 Eq. (9) to zero, $\sum_{i=1}^{N} A_i = 1$ and solving yields a two-impulse sequence with parameters as

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

$$A_1 = \frac{1}{1+K}, \quad A_2 = \frac{K}{1+K}, \quad (10)$$

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

The robustness of the input shaper to errors in natural frequencies of the system can be increased by setting $dV/d\omega_n = 0$. Setting the derivative to zero is equivalent of producing small changes in vibration corresponding to natural frequency changes. By obtaining the first derivatives of V_1 and V_2 in Eq. (9) and simplifying yields

$$\frac{dV_1}{d\omega_n} = \sum_{i=1}^{N} A_i t_i e^{-\zeta\omega_n(t_N-t_i)} \sin(\omega_d t_i),$$

$$\frac{dV_2}{d\omega_n} = \sum_{i=1}^{N} A_i t_i e^{-\zeta\omega_n(t_N-t_i)} \cos(\omega_d t_i). \quad (11)$$

Hence by setting Eqs. (9) and (11) to zero and solving yields a three-impulse sequence with parameters as

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

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

$$A_3 = \frac{K^2}{1+2K+K^2}, \quad (12)$$

where K is as in Eq. (10). The robustness of the input shaper can further be increased by taking and solving the second derivative of the vibration in Eq. (9). Similarly, this yields a four-impulse sequence with parameters as

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

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

$$A_3 = \frac{3K^2}{1+3K+3K^2+K^3},$$

$$A_4 = \frac{K^3}{1+3K+3K^2+K^3}, \quad (13)$$

where K is as in Eq. (10).

To handle 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.

3.2.2. Filtering techniques

Command shaping based on filtering techniques is developed on the basis of extracting input energy around natural frequencies of the system using filtering techniques. The filters are thus used for pre-processing the input signal so that no energy is fed into the system at the natural frequencies. In this manner, the flexural modes of the system are not excited, leading to a vibration-free motion. This can be realised by employing either low-pass or band-stop filters. In the former, the filter is designed with a cut-off frequency lower than the first natural frequency of the system. In the latter case, band-stop filters with centre frequencies at the natural frequencies of the system are designed. This will require one filter for each mode of the system. The band-stop filters thus designed are then implemented in cascade to pre-process the input signal. There are various filter types such as Butterworth, Chebyshev and Elliptic that can be designed and employed. In this investigation, an infinite impulse response (IIR) Butterworth low-pass filter is examined.

3.3. Strain feedback

The strain feedback approach adopted in this investigation follows the main route found in works such as Bremer and Pfeiffer (1992), Luo (1994) and Luo and Feng (1999). The underlying idea is that vibration damping cannot be achieved with collocated control because of the Coulomb friction present at the joint. Basically, an observability problem occurs when the torque at the clamping point of the beam on the hub is smaller than the Coulomb friction torque at the joint. An approach to overcome this problem is to place a strain gauge close to the hub of the manipulator.

In this work, a direct strain feedback is proposed for control of vibration of the flexible manipulator. The control structure comprises two feedback loops: (1) The hub angle and hub velocity as inputs to a collocated PD control for rigid body motion control. (2) A direct strain feedback signal from a strain gauge for vibration control. These two loops are then combined to give a torque input to drive the system. A block diagram of the control scheme is shown in Fig. 5 where $\alpha = \partial^2 v/\partial x^2$ represents the signal from the strain gauge. In order to avoid problems associated with non-collocated control and Coulomb friction, the signal from the strain gauge located at 4.5 cm from the hub is utilised. Thus, the control law is given by

$$U(s) = K_p\{R(s) - \theta(s)\} - K_v\dot{\theta} - K_s\frac{\partial^2 v}{\partial x^2}. \tag{14}$$

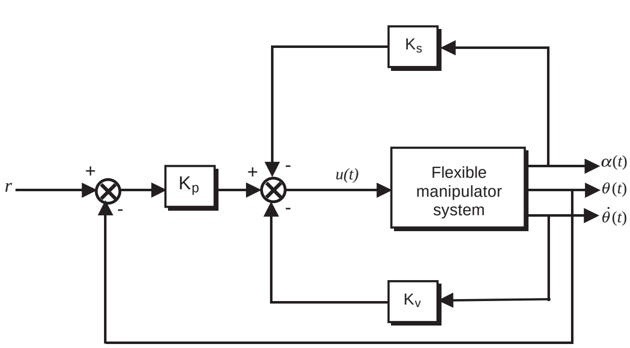

Fig. 5. The PD with strain feedback control structure.

4. Experimentation and results

In this section, real-time implementation of the proposed control schemes for vibration control of the flexible manipulator is presented. Experimental results of the response of the manipulator with PD control, PD with feedforward controllers and PD with strain feedback control are presented. The second link of the manipulator is required to follow a step input of 45°. Hub angle and end-point acceleration responses of the system were measured and analysed to study the performance of the controllers. The performances are assessed in terms of input tracking and vibration suppression achieved with the controllers. This is examined by comparing the results with the PD control for a similar input level. Experiments were performed with a sampling frequency of 1 kHz. Finally, a comparative assessment of the performance of the control schemes is presented.

4.1. Collocated PD control

The controller parameters K_p and K_v were deduced as 0.22 and 0.001, respectively using the root locus analysis. The required torque input driving the manipulator with the controller action is shown in Fig. 6. The corresponding hub angle and end-point acceleration responses of the manipulator using the PD control are shown in Fig. 7. It is noted that an acceptable hub angle response was achieved. The manipulator reached the demanded angle with a rise and settling times and overshoot of 0.098, 0.143 s and 2.2%, respectively. However, a significant amount of vibration occurred during movement of the manipulator as demonstrated in the end-point acceleration response. Moreover, the oscillation does not settle within 4 s with magnitude of acceleration of $\pm 50\,\mathrm{m/s^2}$. Fig. 8 shows the power spectral density of the end-point acceleration response.

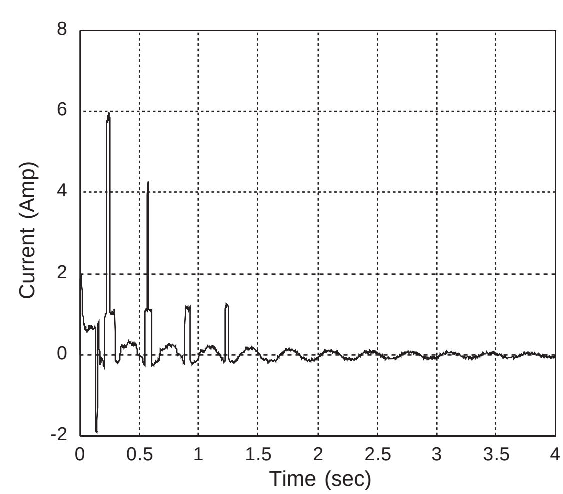

Fig. 6. The torque input with the PD controller.

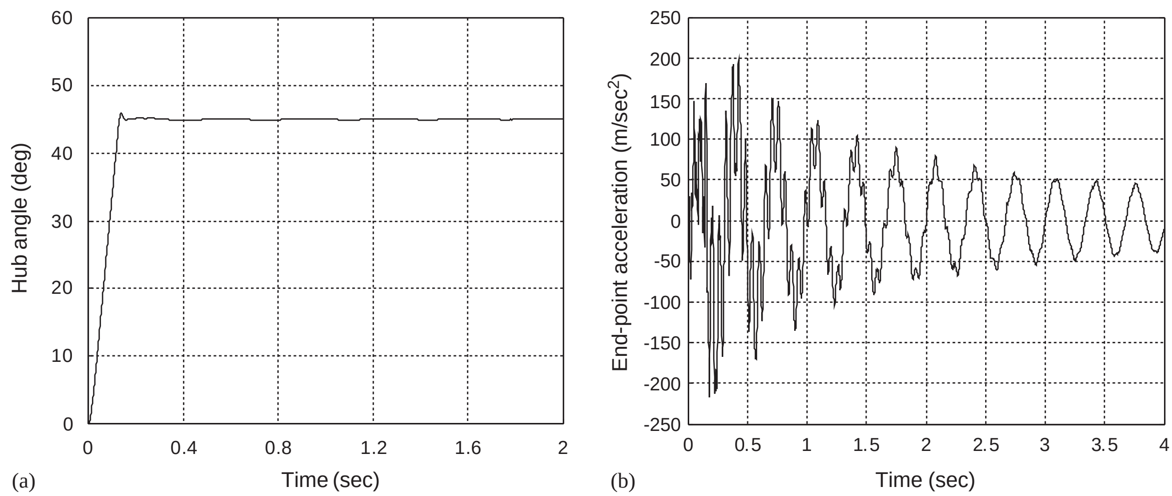

Fig. 7. Response of the manipulator with PD control: (a) hub angle; (b) end-point acceleration.

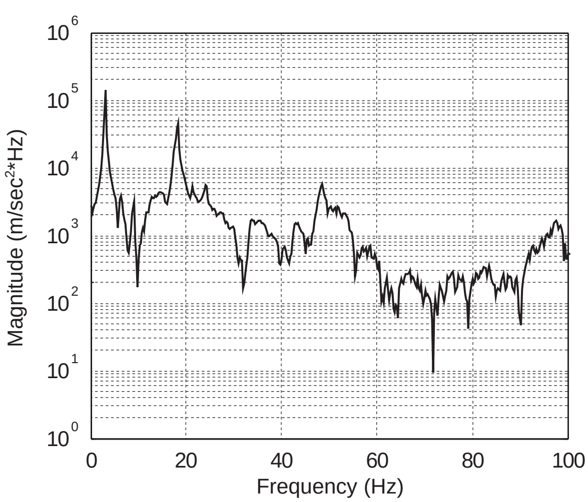

Fig. 8. Power spectral density of end-point acceleration.

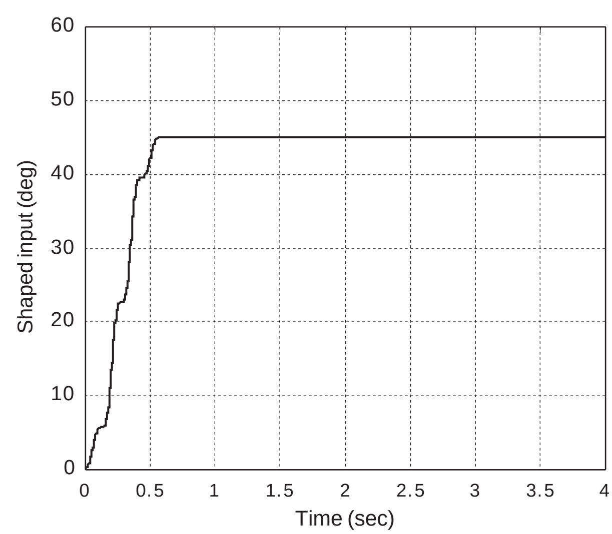

Fig. 9. The shaped input with a four-impulse sequence.

It is noted that the vibration at the end-point is dominated by the first three vibrational modes, which are obtained as 3.3, 19 and 48 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 feedforward and feedback control strategies in reducing the system vibration.

4.2. Command shaping techniques

The feedforward controllers based on input shaping and low-pass filtering techniques were designed on the basis of the dynamic behaviour of the closed-loop system obtained using the PD control. Previous experimental study has shown that the damping ratios of the flexible manipulator for the first three modes are 0.005, 0.0036 and 0.003, respectively (Martins et al., 2002). The input shapers and filters thus designed were used for preprocessing the reference input and used in the closed-loop configuration with PD control as shown in Fig. 4.

In designing the input shapers with a four-impulse sequence, the magnitudes and time locations of the impulses were obtained by solving Eq. (13). For evaluation of robustness, the system vibration with 30% error in the actual natural frequencies was considered. Thus, the vibration frequencies of the system were assumed as 4.3, 24.7 and 62.4 Hz. Accordingly, an input shaper was designed based on these new frequencies and used in the system in a similar configuration. For digital implementation of the input shaping, locations of the impulses were selected at the nearest sampling time. Fig. 9 shows the shaped input with a four-impulse sequence.

Fig. 10 shows the hub angle and end-point acceleration responses of the manipulator to the exact and erroneous shaped inputs. It is noted that the hybrid controller is capable of reducing the system vibration while maintaining the input tracking capability of the

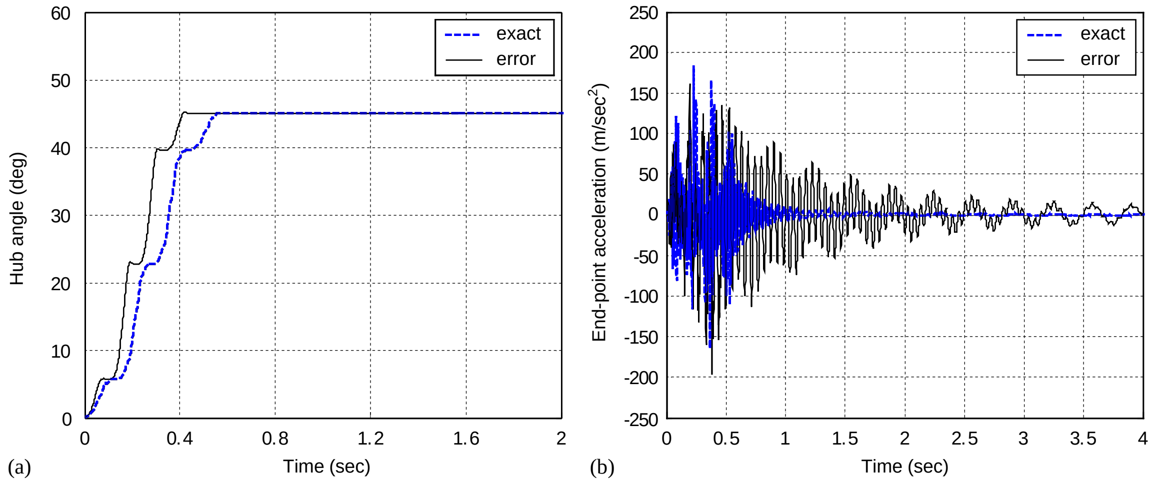

Fig. 10. Response of the manipulator with combined PD control and input shaping: (a) hub angle; (b) end-point acceleration.

manipulator. With the exact frequency, the magnitudes of vibration of the system have significantly been reduced as compared to the response with PD control. Moreover, the end-point response was found to have almost zero acceleration within 2 s. However, as demonstrated in the end-point acceleration, initially a noticeable amount of vibration was observed. The hub angle response reaches the demanded angle with the rise and settling times and overshoot of 0.407, 0.532 s and 0.04%, respectively. As expected with the erroneous frequencies, the level of vibration reduction of the manipulator is slightly less than the case without error. The magnitude of vibration of the end-point acceleration at 4 s was achieved as $\pm 10\ \mathrm{m/s^2}$. Despite that, significant improvement in vibration reduction as compared to the PD control was observed. In this case, the hub angle reached the demanded angle with the rise and settling times and overshoot of 0.316, 0.404 s and 0.25%, respectively. A faster response is noted with the erroneous natural frequencies, as the length of the input shaper is shorter.

Using the low-pass filter, the input energy at all frequencies above the cut-off frequency can be attenuated. In this study, third-order low-pass filters with cut-off frequency at 50% of the first vibration mode were designed. Thus, for the flexible manipulator, the cut-off frequencies of the filters were selected at 1.6 and 2.2 Hz for the two cases of exact and 30% error in the natural frequencies, respectively. Fig. 11 shows the low-pass filtered input obtained with the specifications.

Fig. 12 shows the hub angle and end-point acceleration response of the flexible manipulator to the exact and erroneous filtered inputs. It is noted with exact frequency that the system vibrations have significantly been reduced in comparison to the PD control. The end-point acceleration was found to be reduced immediately, but required more than 4 s to settle to zero. In this case, at 4 s the magnitude of acceleration was $\pm 5\ \mathrm{m/s^2}$.

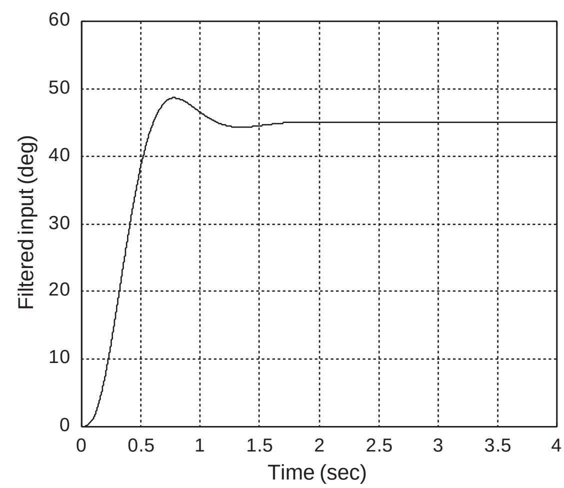

Fig. 11. The filtered input with third-order low-pass filter.

However, as demonstrated in the hub angle response, an unacceptable overshoot occurs during movement of the manipulator. This is due to the effect of the low-pass filtering technique as shown with the filtered input. The corresponding rise and settling times and overshoot were obtained as 0.364 s, 1.061 s and 8.1%, respectively. The robustness of this technique is demonstrated with the erroneous filtered input. As evidenced in the end-point acceleration response, relatively small reduction in system vibration was achieved. At 4 s, the end-point acceleration reduced to $\pm 40\ \mathrm{m/s^2}$, which is only 20% improvement as compared to the response with PD control. The rise and settling times and overshoot of the hub angle response were obtained as 0.145, 0.424 s and 8.3%, respectively. It is noted that a faster hub angle response than the case without error is achieved. This is due to the utilisation of a higher cut-off frequency which increases the input energy into the system.

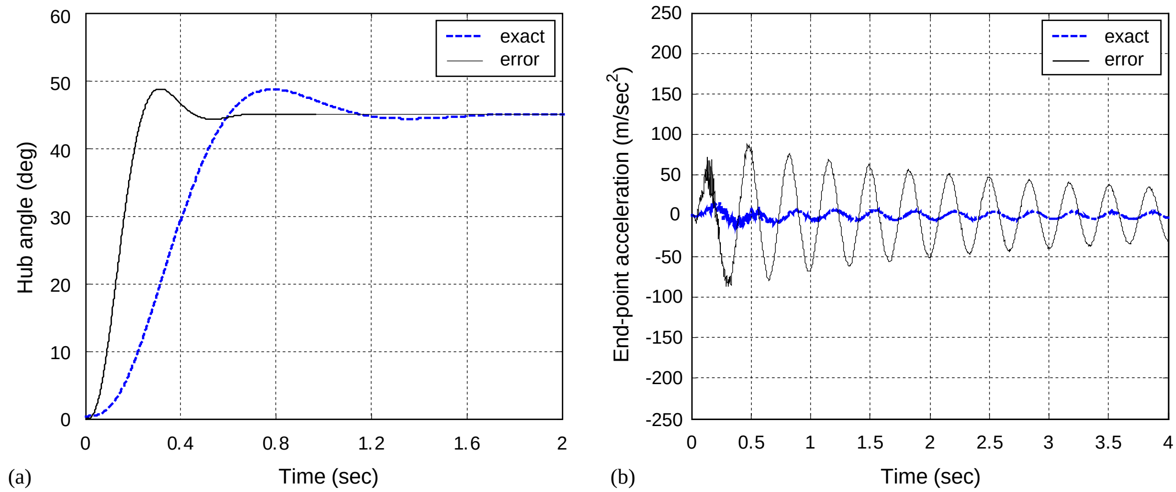

Fig. 12. Response of the manipulator with combined PD control and low-pass filtered input: (a) hub angle; (b) end-point acceleration.

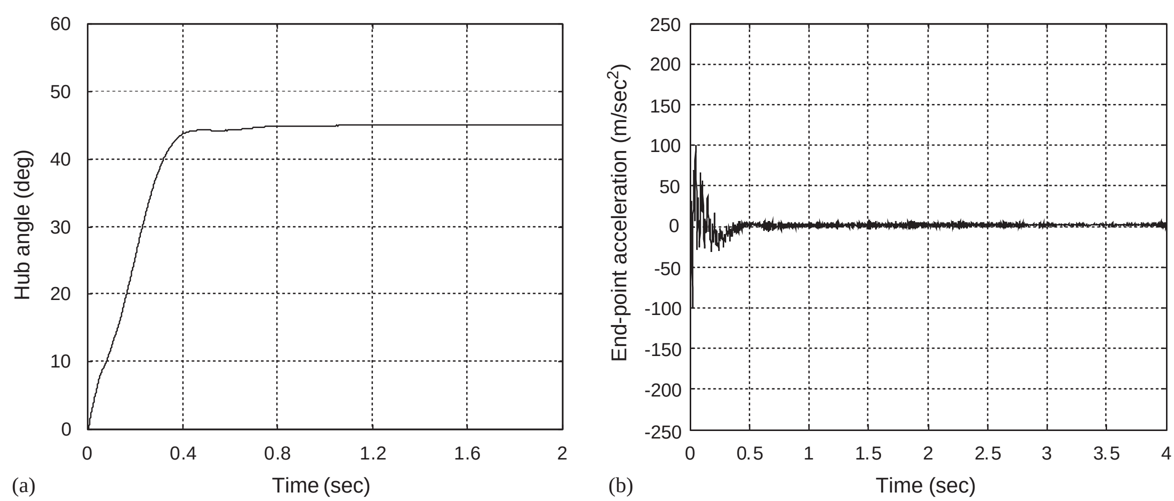

Fig. 13. Response of the manipulator with combined PD control and strain feedback: (a) hub angle; (b) end-point acceleration.

4.3. Strain feedback

Fig. 13 shows the hub angle and end-point acceleration responses of the manipulator with the collocated PD and strain feedback control. It is noted that the system vibrations have significantly been reduced in comparison to the PD control. Moreover, the end-point acceleration was found to be almost zero within 2 s. The required angle was achieved with rise and settling times and overshoot of 0.3, 0.44 s and 0.008%, respectively. For the case of strain feedback, the issue of robustness was not investigated as the control strategy is expected to be more robust as compared to the feedforward control schemes.

4.4. Comparative performance assessment

A comparison of the system responses using the control schemes reveals that the highest performance in reduction of vibration is achieved using input shaping and strain feedback control techniques. This is further evidenced in Fig. 14 that demonstrates the level of vibration reduction achieved using the techniques at 3 s as compared to the PD control. Both techniques produce almost 100% reduction at this period whereas vibration reduction of 90% was achieved using the low-pass filter.

Comparisons of the specifications of the hub angle responses with the techniques reveal that by incorporating a controller for vibration suppression resulted in a slower response. It is noted that the fastest settling time of the response is achieved using the strain feedback control whereas the slowest was achieved with the low-pass filter of 1 Hz cut-off frequency. It is also revealed that the lowest overshoot was achieved using input shaping and strain feedback, which are almost zero. Moreover, with the low-pass filter, an unacceptable overshoot in the hub angle response was achieved.

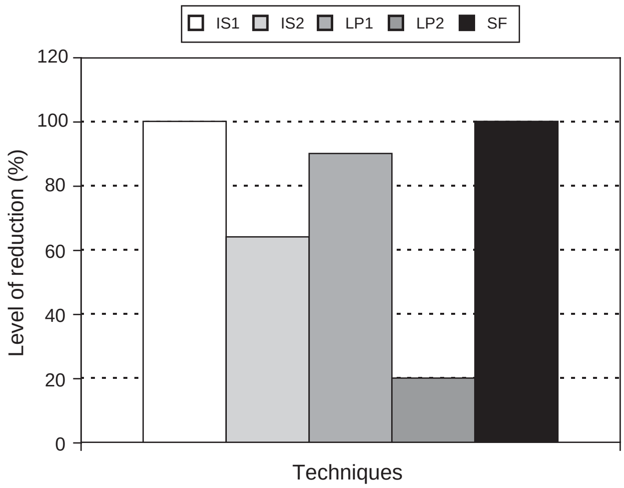

Fig. 14. Level of vibration reduction at the end-point of the manipulator with combined PD control and (IS1—exact input shaping, IS2—erroneous input shaping, LP1—exact filter, LP2—erroneous filter, SF—strain feedback) as compared to the PD control only.

However, the hub angle response of the manipulator with input shaping was not as smooth as with other techniques. Although strain feedback has shown to be the best in controlling the system vibration and at input tracking, it requires an additional sensor. On the other hand, input shaping technique produces an acceptable level of vibration reduction and input tracking without any additional sensor.

A comparison of the results with error in vibration frequencies shows that input shaping gives higher robustness than the low-pass filter. With 30% error tolerance in the natural frequencies, vibration reduction of 64% is achieved with input shaping whereas only 20% with low-pass filtered input. Moreover, using this technique, as demonstrated in Fig. 10, the hub angle response of the manipulator was not affected by the error. It is revealed with the results that although utilisation of a very low cut-off frequency of the filter can give better vibration reduction, it results in a slower hub angle response with higher overshoot.

5. Conclusion

Experimental investigations into the development of feedforward and feedback control schemes for vibration control of a very flexible and high-friction flexible manipulator system have been presented. A collocated PD controller has, initially, been developed for control of rigid body motion. A feedforward control scheme based on input shaping and low-pass filtering techniques and strain feedback control technique have been combined with the PD control for vibration control of the manipulator. Performances of the control schemes have been evaluated in terms of the input tracking capability and level of vibration reduction as compared to the response with PD control. It has been demonstrated that significant reduction in the system vibration is achieved with the hybrid control schemes incorporating input shaping and strain feedback control. In term of input tracking, strain feedback has been shown to be the most effective technique. With the low-pass filter, an acceptable level of vibration reduction has been achieved. It has also been demonstrated that input shaping is more robust than low-pass filtering to errors in natural frequencies.

Future work will consider the implementation of the controllers on a multi-link flexible manipulator incorporating a payload. The effects of friction and other non-linear elements of the system will also be investigated. The performances of the controllers will be more apparent as the system is complicated with higher degrees of freedom and the dynamic behaviour of the system is affected by various factors. Moreover, with a payload, the behaviour of the flexible manipulator changes and the vibration frequencies shift to lower frequencies.

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