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Hybrid Input Shaping and Feedback Control Schemes of a Flexible Robot Manipulator

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Abstract: This paper presents investigations into the development of hybrid control schemes for input tracking and vibration control of a flexible robot manipulator. A constrained planar single-link flexible manipulator is considered and the dynamic model of the system is derived using the assume mode method. To study the effectiveness of the controllers, initially a collocated PD control is developed for control of rigid body motion. This is then extended to incorporate input shaper control schemes for vibration control of the system. The positive and modified specified negative amplitude input shapers are designed based on the properties of the system. Simulation results of the response of the manipulator with the controllers are presented in time and frequency domains. The performances of the hybrid control schemes are examined in terms of level of input tracking capability, vibration reduction, time response specifications and robustness to parameters uncertainty in comparison to the PD control. Finally, a comparative assessment of the amplitude polarities of the input shapers to the system performance is presented and discussed.

1. INTRODUCTION

The control strategies for flexible manipulator systems can be classified as feedforward and feedback control. A number of techniques have been proposed as feed-forward control strategies for control of vibration. These include the development of computed torque based on a dynamic model of the system (Moulin and Bayo, 1991), utilisation of single and multiple-switch bang–bang control functions (Onsay and Okay, 1991), construction of input functions from ramped sinusoids or versine functions (Meckl and Seering, 1990). 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 (Singhose *et al*, 1995; Tokhi and Azad, 1996) and input shaping (Mohamed and Tokhi, 2002; Singer and Seering, 1990). To reduce the delay in the system response, negative amplitude input shapers have been introduced and investigated in vibration control. By allowing the shaper to contain negative impulses, the shaper duration can be shortened, while satisfying the same robustness constraint. A significant number of negative shapers for vibration control have also been proposed. These include negative unity-magnitude (UM) shaper, specified-negative-amplitude (SNA) shaper, negative zero-vibration (ZV) shaper, negative zero-vibration-derivative (ZVD) shaper, negative zero-vibration-derivative-derivative (ZVDD) shaper and time-optimal negative shaper (Mohamed *et al*, 2006; Rappole *et al*, 1993).

On the other hand, 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. Several approaches utilizing closed-loop control strategies have been reported for control of flexible manipulators. These include linear state feedback control (Hasting and Book, 1990), adaptive control (Yang *et al*, 1992), robust control techniques based on *H*-infinity (Moser, 1993), variable structure control (Moallem *et al*, 1998) and intelligent control based on neural networks (Gutierrez *et al*, 1998) and fuzzy logic control schemes (Moudgal *et al*, 1994).

This paper presents investigations into the development of hybrid control schemes for input tracking and vibration control of a single-link flexible manipulator. A constrained planar single-link flexible manipulator is considered. Hybrid control schemes based on feedforward with PD controllers are investigated. In this work, feedforward controls based on ZVDD input shapers with positive and modified SNA shapers are considered. To demonstrate the effectiveness of the proposed control schemes, initially a PD controller is developed for control of rigid body motion of the manipulator. This is then extended to incorporate the proposed input shapers for control of vibration of the manipulator. In terms of robustness, the hybrid control schemes are assessed with up to 30% error tolerance in vibration frequencies. This paper provides a comparative assessment of the performance of hybrid control schemes with different polarities of input shapers.

2. THE FLEXIBLE MANIPULATOR SYSTEM

The single-link flexible manipulator system considered in this work is shown in Fig. 1, where X_oOY_o and XOY represent the stationary and moving coordinates frames respectively, τ represents the applied torque at the hub. *E, I,*

ρ, A, I_h, $v(x,t)$ and $\theta(t)$ represent the Young modulus, area moment of inertia, mass density per unit volume, cross-sectional area, hub inertia, displacement and hub angle of the manipulator respectively. In this study, an aluminium type flexible manipulator of dimensions 900 × 19.008 × 3.2004 mm³, E = 71 × 10^9 N/m², I = 5.1924 × 10^{11} m^4 , ρ = 2710 kg/m^3 and I_H = 5.8598 × 10^{-4} kgm^2 is considered.

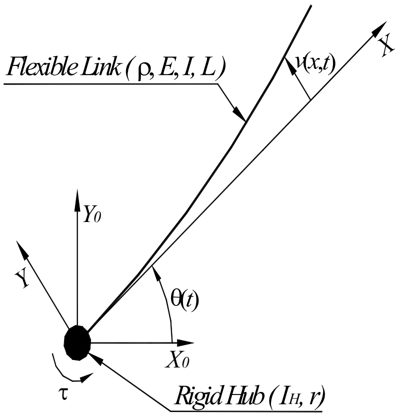


Fig. 1. Description of the flexible manipulator system

3. MODELLING OF THE FLEXIBLE MANIPULATOR

This section provides a brief description on the modelling of the flexible robot manipulator system, as a basis of a simulation environment for development and assessment of the input shaping control techniques. The assume mode method with two modal displacement is considered in characterising the dynamic behaviour of the manipulator incorporating structural damping. The dynamic model has been validated with experimental exercises where a close agreement between both theoretical and experimental results has been achieved (Martin et al, 2003).

Considering revolute joints and motion of the manipulator on a two-dimensional plane, the kinetic energy of the system can thus be formulated as

$$T=\frac{1}{2}(I_H+I_b)\dot{\theta}^2+\frac{1}{2}\rho\int_0^L(\dot{v}^2+2\dot{v}x\dot{\theta})dx \tag{1}$$

where I_b is the beam rotation inertia about the origin O_0 as if it were rigid. The potential energy of the beam can be formulated as

$$U=\frac{1}{2}\int_0^L EI\left(\frac{\partial^2 v}{\partial x^2}\right)^2 dx \tag{2}$$

This expression states the internal energy due to the elastic deformation of the link as it bends. The potential energy due to gravity is not accounted for since only motion in the plane perpendicular to the gravitational field is considered.

To obtain a closed-form dynamic model of the manipulator, the energy expressions in (1) and (2) are used to formulate the Lagrangian $L=T-U$. Assembling the mass and stiffness matrices and utilising the Euler-Lagrange equation of motion, the dynamic equation of motion of the flexible manipulator system can be obtained as

$$M\ddot{Q}(t)+D\dot{Q}(t)+KQ(t)=F(t) \tag{3}$$

where M, D and K are mass, damping and stiffness matrices of the manipulator respectively. The damping matrix is obtained by assuming the manipulator exhibit the characteristic of Rayleigh damping. $F(t)$ is a vector of external forces and $Q(t)$ is a modal displacement vector given as

$$Q(t)=\begin{bmatrix}\theta & q_1 & q_2 & \dots & q_n\end{bmatrix}^T=\begin{bmatrix}\theta & q^T\end{bmatrix}^T \tag{4}$$

$$F(t)=\begin{bmatrix}\tau & 0 & 0 & \dots & 0\end{bmatrix}^T \tag{5}$$

Here, q_n is the modal amplitude of the i th clamped-free mode considered in the assumed modes method procedure and n represents the total number of assumed modes.

4. COLLOCATED PD CONTROL SCHEME

A common strategy in the control of manipulator systems involves the utilization of PD feedback of collocated sensor signals. In this work, such a strategy is adopted at this stage. A sub-block diagram of the PD controller is shown in Fig. 2, where K_p and K_v are proportional and derivative gains, respectively, θ and $\dot{\theta}$ represent hub angle and hub velocity, respectively, R_f is the reference hub angle and A_c is the gain of the motor amplifier. Here the motor/amplifier gain set is considered as a linear gain. To design the PD controller, a linear state-space model of the flexible manipulator was obtained by linearising the equations of motion of the system.

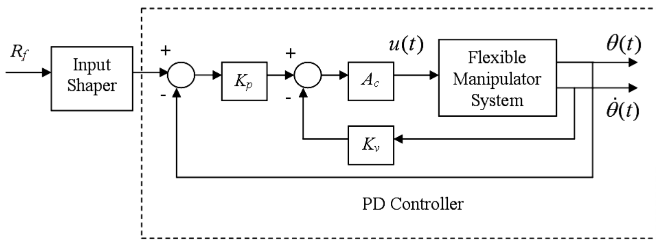


Fig. 2. Block diagram of hybrid control scheme configuration

The control signal $u(s)$ in Fig. 2 can be written as

$$u(s)=A_c[K_p\{R_f(s)-\theta(s)\}-K_v s\theta(s)] \tag{6}$$

where s is the Laplace variable. The closed-loop transfer function is, therefore, obtained as

$$\frac{\theta(s)}{R_f(s)} = \frac{K_p H(s) A_c}{1 + A_c K_v (s + K_p / K_v) H(s)} \tag{7}$$

where $H(s)$ is the open-loop transfer function from the input torque to hub angle, given by

$$H(s) = C(sI - A)^{-1} B \tag{8}$$

where A, B, and C are the characteristic matrix, input matrix and output matrix of the system, respectively, and I is the identity matrix. The closed-loop poles of the system are, thus, given by the closed-loop characteristics equation as

$$1 + A_c K_v (s + K_p / K_v) H(s) \tag{9}$$

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

5. INPUT SHAPING CONTROL SCHEME

The design objectives of input shaping are to determine the amplitude and time locations of the impulses in order to reduce the detrimental effects of system flexibility. These parameters are obtained from the natural frequencies and damping ratios of the system.

5.1 Positive Input Shaper

The requirement of positive amplitudes for the input shapers has been used in most input shaping schemes. The requirement of positive amplitude for the impulses is to avoid the problem of large amplitude impulses. For the case of positive amplitudes, each individual impulse must be less than one to satisfy the unity magnitude constraint. In order to increase the robustness of the input shaper to errors in natural frequencies, the positive ZVDD input shaper, is designed by solving the derivatives of the system vibration equation. This yields a four-impulse sequence with parameter as

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

$$A_1 = \frac{1}{1+3K+3K^2+K^3},\ A_2 = \frac{3K}{1+3K+3K^2+K^3} \tag{10}$$

$$A_3 = \frac{3K^2}{1+3K+3K^2+K^3},\ A_4 = \frac{K^3}{1+3K+3K^2+K^3}$$

where $K = e^{-\zeta\pi / \sqrt{1-\zeta^2}}$ and $\omega_d = \omega_n \sqrt{1-\zeta^2}$. ω_n and ζ represent the natural frequency and damping ratio respectively. For the impulses, t_j and A_j are the time location and amplitude of impulse j respectively.

5.2 Modified SNA Input Shaper

In order to achieve higher robustness for positive input shaper, the duration of the shaper is increased and thus, increases the delay in the system response. By allowing the shaper to contain negative impulses, the shaper duration can be shortened, while satisfying the same robustness constraint. To include negative impulses in a shaper requires the impulse amplitudes to switch between 1 and -1 as

$$A_i = (-1)^{i+1};\ \ i = 1, \dots\dots, \mathrm{n} \tag{11}$$

The constraint in (11) yields useful shapers as they can be used with a wide variety of inputs. However, the increase in the speed of system response achieved using the SNA input shapers is at the expense of some tradeoffs and penalties. The shapers containing negative impulses have tendency to excite unmodeled high modes and they are slightly less robust as compared to the positive shapers. Besides, negative input shapers require more actuator effort than the positive shapers due to high changes in the set-point command at each new impulse time location.

To overcome the disadvantages, the modified SNA input shaper is introduced, whose negative amplitudes can be set to any value at the centre between each normal impulse sequences. In this work, the previous SNA input shaper (Mohamed *et al*, 2006) has been modified by locating the negative amplitudes at the centre between each positive impulse sequences with even number of total impulses. This will result the shaper duration to one-fourth of the vibration period of an undamped system as shown in Fig. 3. The modified SNA ZVDD shaper is applied in this work by adding more negative impulses in order to enhance the robustness capability of the controller while increasing the speed of the system response. Moreover, by considering the form of modified SNA ZVDD shaper shown in Fig. 3, the amplitude summation constraints equation can be obtained as

$$2a + 2c - 2b - 2d = 1 \tag{12}$$

The values of a, b, c and d can be set to any value that satisfy the constraint in (12). However, the suggested values of a, b, c and d are less than |1| to avoid the increase of the actuator effort.

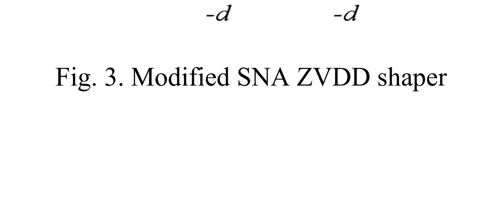


Fig. 3. Modified SNA ZVDD shaper

6. IMPLEMENTATION AND RESULT

In this investigation, hybrid control schemes for tracking capability and vibration suppression of the flexible manipulator are examined. Initially, a collocated PD control is designed. This is then extended to incorporate both positive and modified SNA input shaping schemes for control of vibration of the system. The tracking performance of the collocated PD control applied to the flexible manipulator systems was investigated based on the root locus analysis, from which K_p, K_v and A_c were deduced as 60, 19, and 0.02 respectively. The closed loop parameters with the PD control will subsequently be used to design and evaluate the performance of hybrid control schemes in terms of input tracking capability and level of vibration reduction. For the vibration suppression schemes, the positive and modified SNA input shapers are designed based on the vibration frequencies and damping ratios of the flexible manipulator system. The natural frequencies were obtained by exciting the flexible manipulator with an unshaped unit step reference input under a collocated PD controller. The input shapers were designed for pre-processing the unit step reference input and applied to the system in a closed-loop configuration, as shown in Fig. 2.

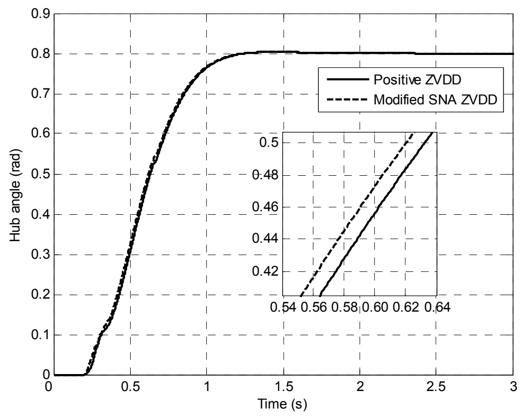
6.1 Collocated PD Control

In this work, the input is applied at the hub of the flexible manipulator and the manipulator is required to follow a trajectory of 0.8 rad. The first two modes of vibration of the system are considered, as these dominate the dynamic of the system. The responses of the flexible manipulator system to the unshaped unit step reference input were analysed in time-domain and frequency domain (spectral density). These results were considered as the system response to the unshaped input under tracking capability and will be used to evaluate the performance of the input shaping techniques. Simulation results with the PD controller have shown that the steady-state end-point trajectory of 0.8 radian for the flexible manipulator system was achieved within the rise and settling times and overshoot of 0.504 s, 0.993 s and 0.5% respectively. However a significant vibration occurs at the end-point during the movement of the manipulator. In this case, the end-point acceleration response was found to oscillate between ±600 m/s^2. The vibration frequencies of the flexible manipulator system were obtained as 15 and 55 Hz for the first two modes of vibration.

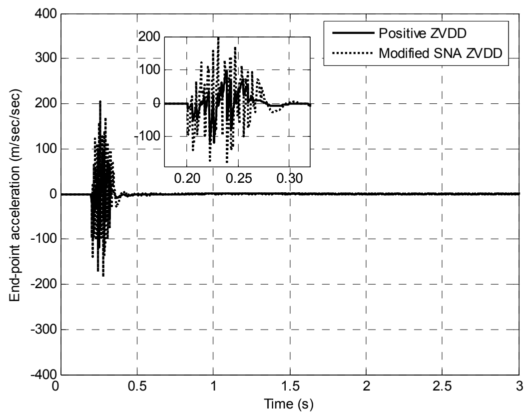
6.2 Hybrid Control

In the case of hybrid control schemes, positive and modified SNA ZVDD shapers were designed for two modes utilising the properties of the system. With the exact natural frequencies of 15 and 55 Hz, the time locations and amplitudes of the impulses for positive ZVDD shaper were obtained by solving (10). However, the amplitudes of the modified SNA ZVDD shaper were deduced as [0.3 -0.1 0.5 -0.2 0.5 -0.2 0.3 -0.1] while the time locations of the impulses were located at the half of the time locations of positive ZVDD shaper as shown in Fig. 3. For evaluation of robustness, input shapers with error in natural frequencies were also evaluated. With the 30% error in natural frequency, the system vibrations were considered at 19.5 and 71.5 Hz for the two modes of vibration. Similarly, the amplitudes and time locations of the input shapers with 30% erroneous natural frequencies for both the positive and modified SNA ZVDD shapers were calculated.

The system responses of the flexible manipulator to the shaped unit step input with exact natural frequencies using collocated PD control with positive and modified SNA shapers are shown in Fig. 4. Table 1 summarises the levels of vibration reduction of the system responses at the first two modes in comparison to the PD control. Higher levels of vibration reduction were obtained using PD control with positive ZVDD shaper as compared to the case with modified SNA ZVDD shaper. However, with modified SNA ZVDD shaper, the system response is faster. The corresponding rise time, setting time and overshoot of the hub angle response using PD control with positive and modified SNA ZVDD shapers with exact natural frequencies is depicted in Table 1. It is noted that a slower hub angle response for hybrid control schemes, as compared to the PD control, was achieved.



(a) Hub angle



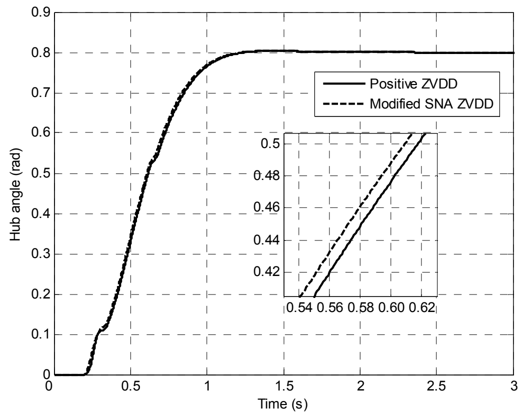
(b) End-point acceleration

Fig. 4. Response of the flexible manipulator with exact natural frequencies.

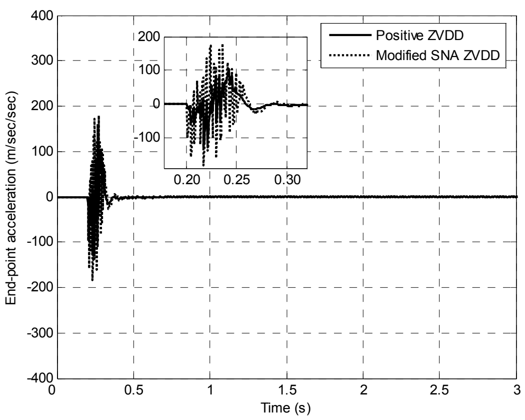
Table 1. Level of vibration reduction of the end-point acceleration and specifications of hub angle response.

Frequency	Types of shaper (ZVDD)	Attenuation (dB) of vibration end-point acceleration		Specifications of hub angle response		
		Mode 1	Mode 2	Rise time (s)	Settling time (s)	Overshoot (%)
Exact	Positive	64.56	146.52	0.513	1.064	0.49
	Modified SNA	32.80	75.75	0.516	1.053	0.49
Error	Positive	35.73	87.44	0.522	1.059	0.49
	Modified SNA	33.83	72.00	0.517	1.045	0.49

To examine the robustness of the shapers, the shapers with 30% error in vibration frequencies were designed and implemented to the flexible manipulator system. Fig. 5 shows that the vibrations of the system were considerable reduced as compared to the system with PD control. However, the level of vibration reduction is slightly less than the case with exact natural frequencies. Table 1 summarises the levels of vibration reduction with erroneous natural frequencies in comparison to the PD control. The time response specifications of the hub angle with error in natural frequencies are summarised in Table 1. It is noted that the response is slightly faster for the shaped input with error in natural frequencies than the case with exact frequencies.



(a) Hub angle



(b) End-point acceleration

Fig. 5. Response of the flexible manipulator with erroneous natural frequencies

6.3 Comparative Performance Assessment

By comparing the results presented in Table 1, it is noted that the higher performance in the reduction of vibration of the system is achieved using PD control with positive ZVDD shaper. This is observed and compared to the PD control with modified SNA ZVDD shaper at the first two modes of vibration. For comparative assessment, the levels of vibration reduction of the end-point acceleration using PD control with both positive and modified SNA ZVDD shapers are shown with the bar graphs in Fig. 6. The result shows that, highest level of vibration reduction is achieved in hybrid control schemes using the positive ZVDD shaper, followed by the modified SNA ZVDD shaper for both modes of vibration. Therefore, it can be concluded that the PD control with positive ZVDD shapers provide better performance in vibration reduction as compared to the PD control with modified SNA ZVDD shapers in overall.

Comparisons of the specifications of the hub angle responses of hybrid control schemes using both positive and modified SNA ZVDD shapers are summarised in Fig. 7 for the rise times and settling times. It is noted that the differences in rise times of the hub angle response for the hybrid control schemes are negligibly small. However, the settling time of the hub angle response using the PD control with modified SNA ZVDD shaper is faster than the case using the positive ZVDD shaper. It shows that the speed of the system response can be improved by using a negative impulse input shapers.

The results showed in Table 1 for the shaping techniques with error in natural frequencies reveals that the higher robustness to parameter uncertainty is achieved with the PD control with positive ZVDD shaper. In both cases, errors in natural frequencies can successfully be handled. This is revealed by comparing the magnitude of vibration of the system in Fig. 6. Comparisons of the hub angle response using PD control with both positive and negative input shapers with erroneous natural frequencies are summarised in Fig. 7. The results show a similar pattern as the case with exact natural frequencies. The system response with modified SNA shaper provides slightly faster responses than the positive input shaper.

7. CONCLUSION

The development of hybrid control schemes based on PD with feedforward control for input tracking and vibration suppression of a flexible manipulator has been presented. The performances of the control schemes have been evaluated in terms of level of input tracking capability, vibration reduction, time response specifications and robustness. Acceptable input tracking capability and vibration suppression have been achieved with both control strategies. A comparison of the results has demonstrated that the PD control with input shaping using positive shapers provide higher level of vibration reduction as compared to the cases using modified negative (SNA) shapers. By using the PD control with modified negative input shapers (SNA-ZVDD), the speed of the response is slightly improved at the expenses of decrease in the level of vibration reduction. It is concluded that the proposed hybrid controllers are capable of reducing the system vibration while maintaining the input tracking performance of the manipulator.

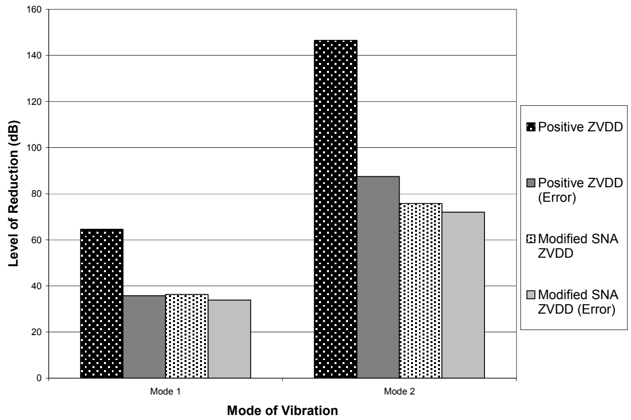


Fig. 6. Level of vibration reduction with exact and erroneous natural frequencies using positive and negative shapers.

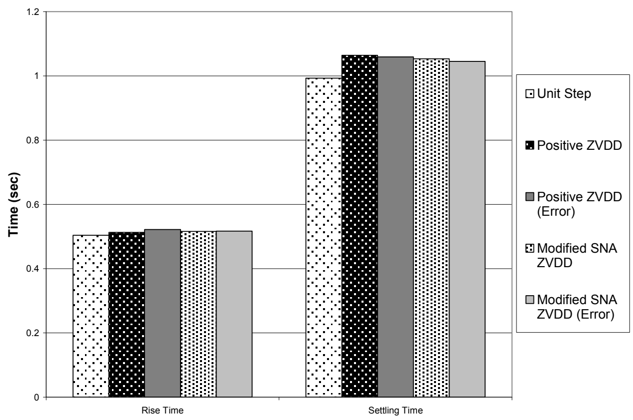


Fig. 7. Rise and settling times of the hub angle with exact and erroneous natural frequencies using positive and negative shapers.

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