Vibration Suppression Techniques in Feedback Control of a Very Flexible Robot Manipulator

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Abstract

This paper presents the use of angular position control approaches for a flexible robot manipulator with disturbances effect in the dynamic system. Delayed Feedback Signal (DFS) and Proportional-Derivative (PD) controller are the techniques proposed in this investigation to actively control the vibrations of flexible structure. A constrained planar single-link flexible manipulator is considered and the dynamic model of the system is derived using the assume mode method. A complete analysis of simulation results for each technique is presented in time domain and frequency domain respectively. Performances of the controller are examined in terms of vibration suppression and disturbances cancellation. Finally, a comparative assessment of the impact of each controller on the system performance is presented and discussed.

1. Introduction

Research on the control methods that will eliminate vibration from wide range of physical systems has found a great deal of interest for many years. The methods used to solve the problems arising due to unwanted structural vibrations include passive and active control. The passive control method consists of mounting passive material on the structure in order to change its dynamic characteristics such as stiffness and damping coefficient. This method is efficient at high frequencies but expensive and bulky at low frequencies [1]. Active vibration control consists of artificially generating sources that absorb the energy caused by the unwanted vibrations in order to cancel or reduce their effect on the overall system. Lueg in 1930 [2], is among the first who used active vibration control in order to cancel noise vibration.

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 [3], utilization of single and multiple-switch bang–bang control functions [4], construction of input functions from ramped sinusoids or versine functions [5]. 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 [6] and input shaping [7]. On the other hand, several approaches utilizing closed-loop control strategies have been reported for control of flexible manipulators. These include linear state feedback control [8], adaptive control [9], robust control techniques based on H-infinity [10] and intelligent control based on neural networks [11] and fuzzy logic control schemes [12].

This paper presents investigations of angular position control approach in order to eliminate the effect of disturbances applied to the single-link flexible robot manipulator. A simulation environment is developed within Simulink and Matlab for evaluation of the control strategies. In this work, the dynamic model of the flexible manipulator is derived using the assume mode method (AMM). To demonstrate the effectiveness of the proposed control strategy, the disturbances effect is applied at the tip of the flexible link. This is then extended to develop a feedback control strategy for vibration reduction and disturbances rejection. Two feedback control strategies which are DFS and PD controller are developed in this simulation work. Performances of each controller are

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examined in terms of vibration suppression and disturbances rejection. Finally, a comparative assessment of the impact of each controller on the system performance is presented and discussed.

2. The flexible manipulator system

The single-link flexible manipulator system considered in this work is shown in Figure 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, $E = 71 \times 10^9$ N/m², $I = 5.1924 \times 10^{11}$ m^4, ρ = 2710 kg/m^3 and I_H = 5.8598 × 10^{-4} kgm^2 is considered.

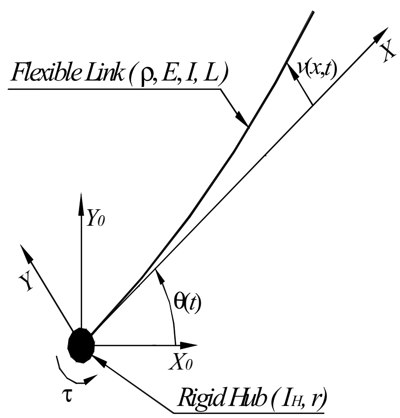

Figure 1. Description of the flexible manipulator system

3. Modeling of the flexible manipulator

This section provides a brief description on the modeling 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 characterizing the dynamic behavior 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 [13].

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 utilizing 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 global 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

$$Q(t) = [\theta \quad q_1 \quad q_2 \quad \ldots \quad q_n]^T = [\theta \quad q^T]^T \tag{4}$$

$$F(t) = [\tau \quad 0 \quad 0 \quad \ldots \quad 0]^T \tag{5}$$

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. The model of the uncontrolled system can be represented in a state-space form as

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{6}$$

with the vector $x = [\theta \ \dot{\theta} \ q_1 \ q_2 \ \dot{q}_1 \ \dot{q}_2]^T$ and the matrices A and B are given by

$$\mathbf{A} = \left[\begin{array}{c|c} 0_{3\times3} & I_{3\times3} \\ \hline -M^{-1}K & -M^{-1}D \end{array}\right], \quad \mathbf{B} = \left[\begin{array}{c} 0_{3\times1} \\ \hline M^{-1} \end{array}\right]$$
$$\mathbf{C} = [I_{1\times3} \mid 0_{1\times3}], \qquad \mathbf{D} = [0] \tag{7}$$

4. Controller design

In this section, two feedback control strategies (DFS and PD controller) are proposed and described in detail. The main objective of the feedback controller in this study is to maintain the angular position of flexible manipulator while suppressing the vibration due to disturbances effect. All the feedback control strategies are incorporated in the closed-loop system in order to eliminate the effect of disturbances.

4.1. Delayed feedback signal controller

In this section, the control signal is calculated based on the delayed position feedback approach described in (8) and illustrated by the block diagram shown in Figure 2.

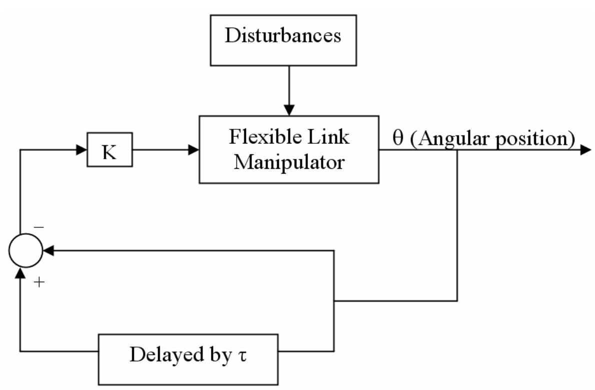

Figure 2. The delayed feedback signal (DFS) controller structure

$$u(t) = k(y(t) - y(t-\tau)) \tag{8}$$

Substituting Equation (8) into Equation (6) and taking the Laplace transform gives

$$sIx(s) = Ax(s) - kBC(1-e^{-s\tau})x(s) \tag{9}$$

The stability of the system given in (9) depends on the roots of the characteristic equation

$$\Delta(s,\tau) = |\, sI - A + kBC(1-e^{-s\tau})\,| = 0 \tag{10}$$

Equation (10) is transcendental and results in an infinite number of characteristic roots. Several approaches dealing with solving retarded differential equations have been widely explored. In this study, the approach described in [14] will be used on determining the critical values of the time delay τ that result in characteristic roots of crossing the imaginary axes. This approach suggests that Equation (10) can be written in the form

$$\Delta(s,\tau) = P(s) + Q(s)e^{-s\tau} \tag{11}$$

P(s) and *Q(s)* are polynomials in s with real coefficients and deg(*P(s)*=n>deg(*Q(s)*) where n is the order of the system. In order to find the critical time delay τ that leads to marginal stability, the characteristic equation is evaluated at $s=j\omega$. Separating the polynomials *P(s)* and *Q(s)* into real and imaginary parts and replacing $e^{-j\omega\tau}$ by $\cos(\omega\tau)-j\sin(\omega\tau)$, Equation (11) can be written as

$$\begin{aligned}\Delta(j\omega,\tau) &= P_R(\omega) + jP_I(\omega) \\ &\quad + (Q_R(\omega) + jQ_I(\omega))(\cos(\omega\tau) - j\sin(\omega\tau))\end{aligned} \tag{12}$$

The characteristic equation $\Delta(s,\tau) = 0$ has roots on the imaginary axis for some values of $\tau \geq 0$ if Equation (12) has positive real roots. A solution of $\Delta(j\omega,\tau) = 0$ exists if the magnitude $|\Delta(j\omega,\tau)| = 0$. Taking the square of the magnitude of $\Delta(j\omega,\tau)$ and setting it to zero lead to the following equation

$$P_R^{\,2} + P_I^{\,2} - (Q_R^{\,2} + Q_I^{\,2}) = 0 \tag{13}$$

By setting the real and imaginary parts of Equation (13) to zero, the equation is rearranged as below

$$\begin{bmatrix} Q_R & Q_I \\ Q_I & -Q_R \end{bmatrix} \begin{bmatrix} \cos\beta \\ \sin\beta \end{bmatrix} = \begin{bmatrix} -P_R \\ -P_I \end{bmatrix}, \tag{14}$$

where $\beta=\omega\tau$.
Solving for $\sin\beta$ and $\cos\beta$ gives

$$\sin(\beta) = \frac{(-P_R Q_I + P_I Q_R)}{(Q_R^{\,2} + Q_I^{\,2})} \text{ and}$$
$$\cos(\beta) = \frac{(-P_R Q_R - P_I Q_I)}{(Q_R^{\,2} + Q_I^{\,2})}$$

The critical values of time delay can be determined as follows: if a positive root of Equation (13) exists, the corresponding time delay τ can be found by

$$\tau_k = \frac{\beta}{\omega} + \frac{2k\pi}{\omega} \qquad (15)$$

where $\beta \in [0\ 2\pi]$. At these time delays, the root loci of the closed-loop system are crossing the imaginary axis of the s-plane. This crossing can be from stable to unstable or from unstable to stable. In order to investigate the above method further, the time-delayed feedback controller is applied to the single-link flexible manipulator. Practically, the control signal for the DFS controller requires only one position sensor and uses only the current output of this sensor and the output τ second in past. There is only two control parameter: k and τ that needs to be set. Using the stability analysis described in [15], the gain and time-delayed of the system is set at $k=55$ and $\tau=0.005$. The control signal of DFS controller can be written as below

$$u_{DFS}(t) = -55(\theta(t) - \theta(t-0.005))$$

4.2. PD controller

To demonstrate the performance of the PD controller in dealing with vibration and disturbances, a PD feedback of collocated sensor signals is adopted for control the angular position of the flexible manipulator. A block diagram of the PD controller is shown in Figure 3, where K_P and K_D are the proportional and derivative gains respectively, θ and $\dot{\theta}$ represent hub angle and hub velocity, respectively. 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.

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. The control signal $u(s)$ in Figure 3 can be written as

$$u_{PD}(s) = -[K_P\theta(s) + K_D\dot{\theta}(s)]$$

where s is the Laplace variable. In this study, the Ziegler-Nichols approach is utilized to design the PD controller. Analyses the tuning process of the proportional and derivative gains using Ziegler-Nichols technique shows that the optimum response of PD controller is achieved by setting $K_P = 1.2$ and $K_D = 0.8$.

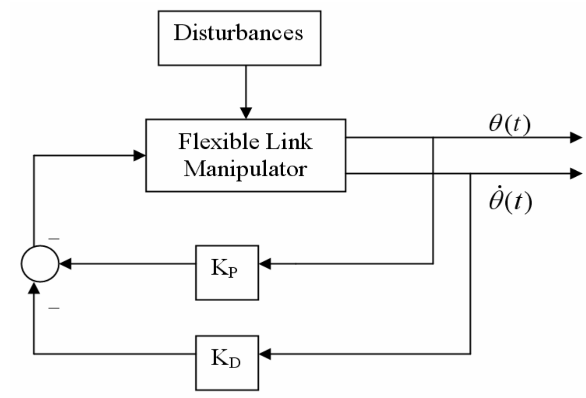

Figure 3. The proportional-derivative (PD) controller structure

5. Simulation results

In this section, the proposed control schemes are implemented and tested within the simulation environment of the flexible manipulator and the corresponding results are presented. The control strategies were designed by undertaking a computer simulation using the fourth-order Runge-Kutta integration method at a sampling frequency of 1 kHz. The system responses namely modal displacement and its corresponding power spectral density (PSD) are obtained. In all simulations, the initial condition $x_o = [0\ \ 0\ \ 1\times10^{-3}\ \ 0\ \ 1\times10^{-5}\ \ 0]^T$ was used. This initial condition is considered as the disturbances applied to the flexible manipulator system. The first two modes of vibration of the system are considered, as these dominate the dynamic of the system.

The open loop responses of the free end of the flexible arm were considered as the system response with disturbances effect and will be used to evaluate the performance of feedback control strategies. It is noted that, in open loop configuration, the modal displacement oscillate between ±0.03 m and the vibration frequencies of the flexible manipulator system under disturbances effect were obtained as 16 and 55 Hz for the first two modes of vibration.

The system responses of the flexible manipulator with the delayed feedback signal controller (DFS) are shown in Figure 4 and 5. It shows that, with the gain and time delay of 55 and 0.005s respectively, the effect of the disturbances has been successfully eliminated. This is evidenced in modal displacement response as shown in Figure 4 whereas the amplitudes of vibration were reduced in a very fast response as compared to the open loop response. This can be clearly demonstrated in frequency domain results as the magnitudes of the PSD at the natural frequencies were significantly reduced.

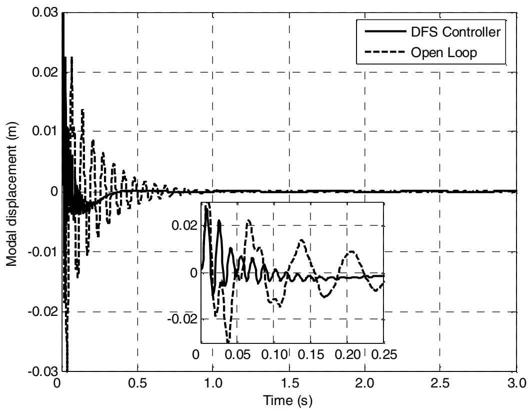

Figure 4. Modal displacement response with DFS controller

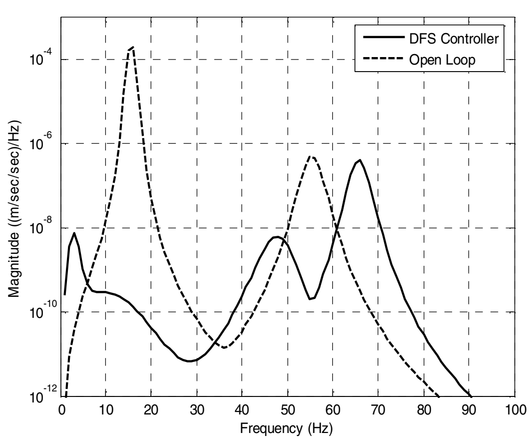

Figure 5. PSD of modal displacement response with DFS controller

Figure 6 and 7 show the closed loop system responses of the flexible manipulator under proportional-derivative controller (PD) for the modal displacement and its PSD results respectively. The modal displacement response shows a similar pattern as the case DFS controller. The results also demonstrated that the conventional PD controller can eliminate the effect of disturbances in the system. The vibration amplitude in the modal displacement responses were reduced as compared to the open loop response. The PSD result shows that the magnitudes of vibration were significantly reduced especially for the first two modes of vibration.

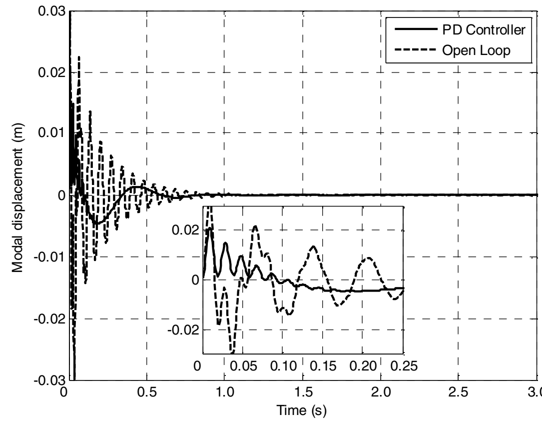

Figure 6. Modal displacement response with PD controller

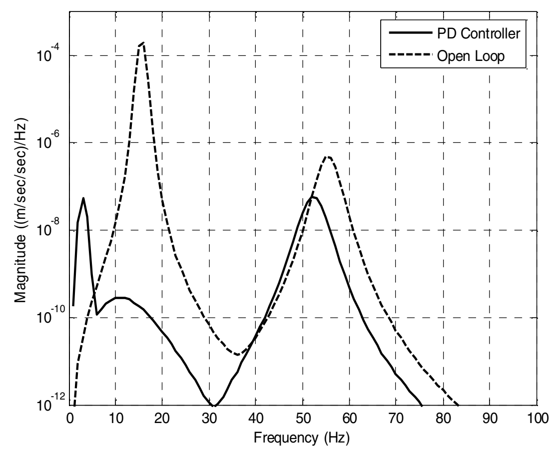

Figure 7. PSD of modal displacement response with PD controller

For comparative assessment, the levels of vibration reduction with the modal displacement using DFS and PD controller are shown with the bar graphs in Figure 8. The result shows that the DFS controller achieved highest level of vibration reduction with the value of 123.36 dB and 66.94 dB for the first two modes of vibration respectively. While for PD controller, the level of vibration reduction was obtained at 122.36 dB and 27.74 dB for the first two modes of vibration respectively. Therefore, it can be concluded that overall the delayed feedback signal (DFS) provide better performance in vibration reduction as compared to the PD controller.

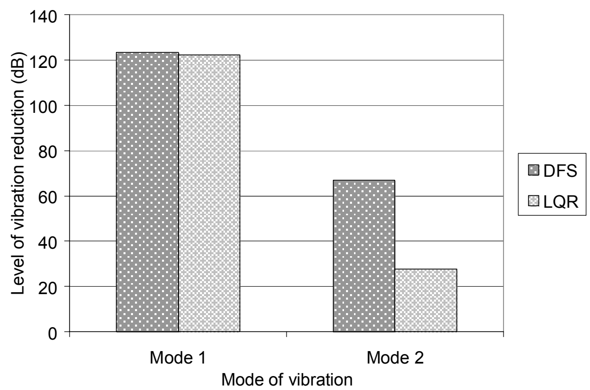

Figure 8. Level of vibration reduction using DFS and PD controller

6. Conclusions

Investigations into vibration suppression of a flexible robot manipulator with disturbances effect using the DFS and PD controller have been presented. Performances of the controller are examined in terms of vibration suppression and disturbances cancellation. The results demonstrated that the effect of the disturbances in the system can successfully be handled by DFS and PD controller. A significant reduction in the system vibration has been achieved with the DFS controller as compared to the PD controller.

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