Vibration Reduction of the Flexible Manipulator using Sliding Mode Controller

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Abstract-

For the purpose of vibration reduction of a two-link flexible manipulator (TLFM) a popular robust controller Sliding mode controller (SMC) has been developed in this study. Very traditional approach has been adopted for the design of SMC. Utilizing the lumped parameter method, the mathematical equation for the two-link flexible manipulator has been developed. Closed loop stability of system has been established using Lyapunov approach. The efficiency of the suggested controller has been demonstrated in the simulation section.

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1. Introduction-

Today, flexible manipulators are used often in place of rigid link manipulators. because flexible link manipulators are affordable, light, and low power consumers, and they can operate at high operational speeds. It's still challenging to put joints in the right places. Since, it affects the accurate placement of the flexible link. Dynamics of the TLFM are highly nonlinear, complex and coupled. Under such condition obtaining an accurate mathematical model is very difficult. Robust controllers can perform satisfactorily in the absence of accurate mathematical model, coupled and complex nonlinear system.Researchers have created a wide range of controllers to address this issue.For tracking the chaotic trajectory and minimizing vibration, sliding mode controllers (SMCs) have been created in [1]. Variables associated to payloads are thought to be uncertain, according to the author in [2]. The author of [2] suggested a variable structure control strategy with payload as the uncertainty to lessen vibration. The smooth trajectory was produced by the author using a virtual control force. Variations in payload have also been made in [3], and their effects have been noted. In [4], the payload was altered to enable performance analysis while vibration was reduced using a state feedback control approach. In [5], the author develops a hybrid position/force controller for tracking that considers the connection between contact forces and elastic deformation.In [6], the author presents a PID controller self-tuning approach. A neural network controller has been used in [7] to reduce TLFM vibration. To reduce vibration, the authors in [8, 9] used a boundary controller. The flexible manipulator system was divided into two subsystems by the inventor in [10]: a rapid subsystem and a slow subsystem. The dynamics of angular motion are dealt with by the slow system, whereas deflection dynamics are dealt with by the quick system. For the fast and slow systems, respectively, SMC and LQR controllers have been created. From most of the articles mentioned above Robust controllers have beenpreferred by most of the researches.In this paper in section 2: the mathematical model of the two-link flexible manipulator has been derived using Lumped Parameter Method. The detailed design of the SMC has been presented in the Section 3. Simulation results and conclusions have been presented in Section 4 and section 5, respectively.

2. Mathematical Modeling

In this work, the mathematical models were created using the Lumped Parameter Method [1].

$$\begin{aligned}\ddot{\theta}_1 &= -\frac{b_{eq}}{j_{eq1}}\dot{\theta}_1 + \frac{k_{stiff}}{j_{eq1}}\phi_1 + \frac{1}{j_{eq1}}u_1 \\ \ddot{\theta}_2 &= -\frac{b_{eq}}{j_{eq2}}\dot{\theta}_2 + \frac{k_{stiff}}{j_{eq2}}\phi_2 + \frac{1}{j_{eq2}}u_2\end{aligned} \tag{1}$$

$$\begin{aligned}\ddot{\phi}_1 &= \frac{b_{eq}}{j_{eq1}}\dot{\theta}_1 - k_{stiff}\left(\frac{1}{j_{eq1}} + \frac{1}{j_{link1}}\right)\phi_1 - \frac{1}{j_{eq1}}u_1 \\ \ddot{\phi}_2 &= \frac{b_{eq}}{j_{eq2}}\dot{\theta}_2 - k_{stiff}\left(\frac{1}{j_{eq2}} + \frac{1}{j_{link2}}\right)\phi_2 - \frac{1}{j_{eq2}}u_2\end{aligned} \tag{2}$$

In the following equation, θ denotes the joint angle, b_{eq} the equivalent viscous damping coefficient, k_{stiff} the link stiffness, ϕ the link deflection, u the joint torque, j_{eq} the equivalent moment of inertia, and j_{link} the link moment of inertia.

3. Controller design

In this work a very popular robust controller i.e., Sliding mode controller (SMC) has been designed using a very traditional approach. The purpose of designing this controller is to reduce the flexible link vibrations. Design of the sliding surface plays a major role in SMC. Here, a traditional sliding surface as mentioned in (3) has been used.

$$\begin{aligned}S_1 &= \theta_1 + \Im\dot{\theta}_1 \\ S_2 &= \theta_2 + \Im\dot{\theta}_2\end{aligned} \tag{3}$$

Where, $\Im$ is a positive quantity. Differentiating (3) and putting the values of $\ddot{\theta}_1$ and $\ddot{\theta}_2$,

$$\begin{aligned}\dot{S}_1 &= \ddot{\theta}_1 + \Im\dot{\theta}_1 \\ &= -\frac{b_{eq}}{j_{eq1}}\dot{\theta}_1 + \frac{k_{stiff}}{j_{eq1}}\phi_1 + \frac{1}{j_{eq1}}u_1 + \Im\dot{\theta}_1 \\ \dot{S}_2 &= \ddot{\theta}_2 + \Im\dot{\theta}_2 \\ &= -\frac{b_{eq}}{j_{eq2}}\dot{\theta}_2 + \frac{k_{stiff}}{j_{eq2}}\phi_2 + \frac{1}{j_{eq2}}u_2 + \Im\dot{\theta}_2\end{aligned} \tag{4}$$

The closest thing to a continuous control law that would result in $\dot{S}_1 = 0$ and $\dot{S}_2 = 0$ is$\hat{u}$. $\hat{u}$ is the equivalent control law, whose expression has been given by,

$$\begin{aligned}&-\frac{b_{eq}}{j_{eq1}}\dot{\theta}_1 + \frac{k_{stiff}}{j_{eq1}}\phi_1 + \frac{1}{j_{eq1}}\hat{u}_1 + \Im\dot{\theta}_1 = 0 \\ &\hat{u}_1 = j_{eq1}\left(\frac{b_{eq}}{j_{eq1}}\dot{\theta}_1 - \frac{k_{stiff}}{j_{eq1}}\phi_1 - \Im\dot{\theta}_1\right)\end{aligned} \tag{5}$$

And,

$$-\frac{b_{eq}}{j_{eq2}}\dot{\theta}_2+\frac{k_{stiff}}{j_{eq2}}\phi_2+\frac{1}{j_{eq2}}\hat{u}_2+\Im\dot{\theta}_2=0$$

$$\hat{u}_2=j_{eq2}\left(\frac{b_{eq}}{j_{eq2}}\dot{\theta}_2-\frac{k_{stiff}}{j_{eq2}}\phi_2-\Im\dot{\theta}_2\right) \tag{6}$$

Therefore, the final control law can be given as

$$\begin{aligned} u_1&=\hat{u}_1-K\,\text{sgn}(S_1)\\ &=j_{eq1}\left(\frac{b_{eq}}{j_{eq1}}\dot{\theta}_1-\frac{k_{stiff}}{j_{eq1}}\phi_1-\Im\dot{\theta}_1\right)-K\,\text{sgn}(S_1)\end{aligned} \tag{7}$$

And,

$$\begin{aligned} u_2&=\hat{u}_2-K\,\text{sgn}(S_2)\\ &=j_{eq2}\left(\frac{b_{eq}}{j_{eq2}}\dot{\theta}_2-\frac{k_{stiff}}{j_{eq2}}\phi_2-\Im\dot{\theta}_2\right)-K\,\text{sgn}(S_2)\end{aligned} \tag{8}$$

Where K is a positive quantity.

Proof of Stability-

Here, Lyapunov candidate function has been obtained with the help of sliding surface.

Table1 – Parameters of TLFM [1]

Parameters	Values
K_{stiff}	6.4π Hz
J_{eq1}	0.099 kg m^2
J_{eq2}	0.092 kg m^2
J_{link1}	0.00195 kg m^2
J_{link2}	0.00933 kg m^2
B_{eq}	1.99

$$V=\frac{1}{2}S_1^2+\frac{1}{2}S_2^2 \tag{9}$$

Differentiating (9) and putting all the respective values,

$$\begin{aligned}\dot{V}&=S_1\dot{S}_1+S_2\dot{S}_2\\ &=S_1\left(\ddot{\theta}_1+\Im\dot{\theta}_1\right)+S_2\left(\ddot{\theta}_2+\Im\dot{\theta}_2\right)\\ &=S_1\left(\Im\dot{\theta}_1-\frac{b_{eq}}{j_{eq1}}\dot{\theta}_1+\frac{k_{stiff}}{j_{eq1}}\phi_1+\frac{1}{j_{eq1}}u_1\right)+S_2\left(\Im\dot{\theta}_2-\frac{b_{eq}}{j_{eq2}}\dot{\theta}_2+\frac{k_{stiff}}{j_{eq2}}\phi_2+\frac{1}{j_{eq2}}u_2\right)\end{aligned} \tag{10}$$

Putting the values of the control laws u_1 and u_2 from (7) and (8) in the equation (10),

$$\dot{V}=-\frac{K}{j_{eq1}}S_1\,\text{sgn}(S_1)-\frac{K}{j_{eq2}}S_2\,\text{sgn}(S_2) \tag{11}$$

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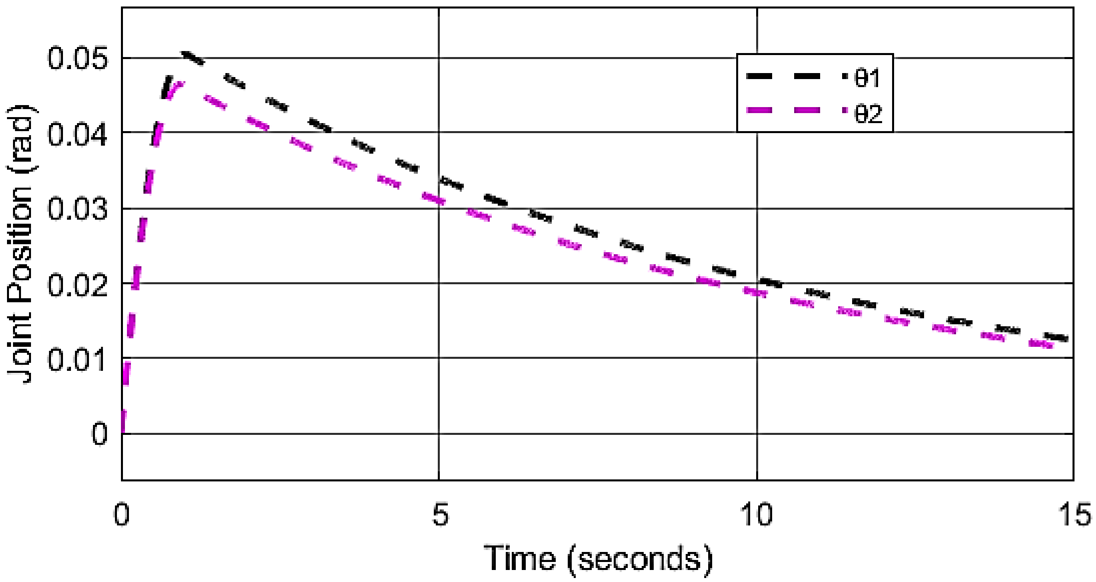


Figure 1. Angular position response of the first flexible link and second flexible link.

From (11), it can be concluded that, $\dot{V} \le 0$. Therefore, the Lyapunov condition has been satisfied.

4. Simulation Results-

In this section, the simulation results have been presented to show the effectiveness of the proposed controller. The simulation has been performed in the MATLAB environment. The simulation has been run for 15 seconds and RK4 method has been used with the time step of 0.001. The initial value of the states has been considered as $\left(\theta_1, \dot{\theta}_1, \theta_2, \dot{\theta}_2\right) = \left(0, 0.1, 0, 0.1\right)$, initial value of the others has been considered

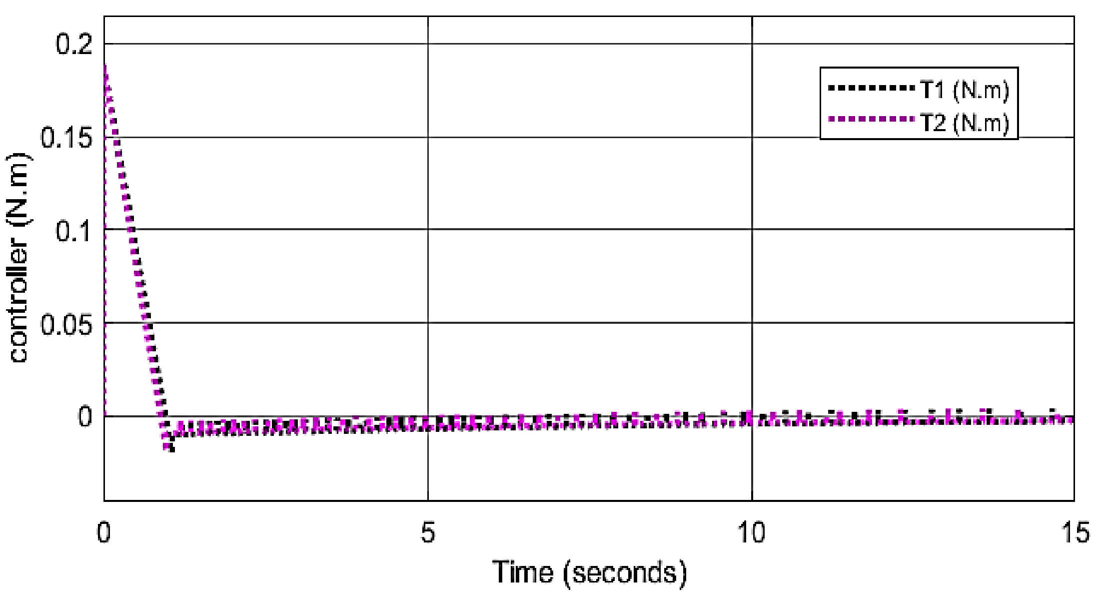


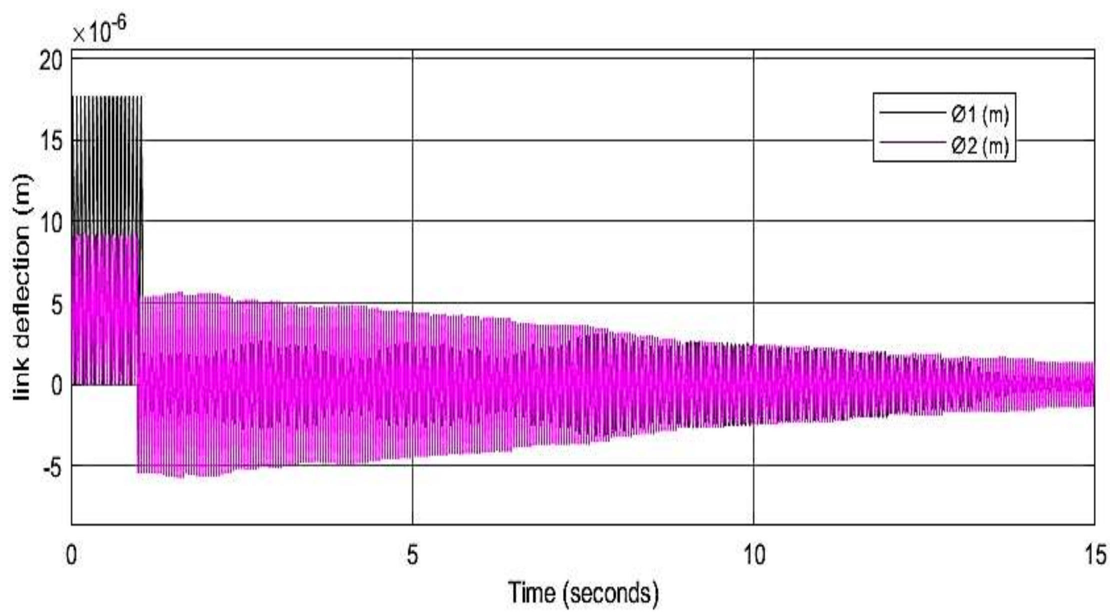
Figure 2. Controller Response obtained with the help of deigned Sliding mode controller.

zero (“0”).To satisfy the sliding condition $\frac{1}{2}\frac{d}{dt}S^2 \leq -K|S|$ [11], the value of the parameters used in the design of SMC has been considered as $\Im = 0.1$ and $K = 0.01$. The value of the parameters of TLFM has been obtained from Table 1.

Figure 1 represents the angular position response of both the flexible links. The mean value of angular position response of flexible link1 is $\theta_1 = 2.764\times10^{-2}rad$ on the other hand mean value angular position response of link2 is $\theta_2 = 2.532\times10^{-2}rad$. Figure 2 is the sliding mode controller response. This figure represents the amount of torque required by the actuators to settled down the flexible links and to reduce vibrations of the flexible links. From the simulation results, it has been observed that the torque requirement is very less i.e, the average torque required by the actuator of first joint is $9.675\times10^{-4}N.m$ and the torque required by the actuator of the second joint is $8.765\times10^{-4}N.m$. Hence the torque requirement is very less. Figure 2 represents the deflection of the links. It has been observed that the deflection of the flexible links is reduced significantly. The average value of ϕ_1 has been obtained as $5984.\times10^{-7}m$ and the average value of the deflection of the second link is $\phi_2 = 2.843\times10^{-7}m$
.

4. Conclusion-

Vibration reduction of flexible links ofTLFM is the major objective of this work. To achieve that sliding mode controller has been developed with the help of traditional procedure. The designed controller is able to reduce the link vibration significantly. From the simulation results it has been observed that the vibration is reduced in the order of $10^{-7}m$ which is very less. The actuators of the joints need torque in the order of $10^{-4}N.m$. Therefore, it can be concluded that, the torque requirement of the actuators is very less. Therefore, high rating actuators are not required. Hence, low power consumption.Therefore, the overall design cost and the power consumptions reduced. Utilizing the Lumped Parameter Method, the mathematical model of the two-link flexible manipulator was developed. Utilizing the Lyapunov approach, the system's closed loop stability has been confirmed. The suggested methodology is straightforward, original, and extremely efficient. Other complex problems can also be solved using this methodology. Future iterations of this work will include real-time validation.



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