Nonlinear Dynamics of Robotic Manipulator with Flexible Tendons

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ABSTRACT

The paper deals with a mathematical model of a one degree of freedom robotic manipulator which has two rotary actuators located on the remote base to drive the manipulator via a pair of flexible tendons. With a recursive Newton-Euler approach dynamic equation of the manipulator is derived. Unlike earlier work in this field, the present work deals with tendons nonlinear stiffness and linear damping. Positions of the manipulator and torque requirement have been investigated for certain rotation of the actuators. Effects of various system parameters on the end-effactor position have also been investigated. A PD feedback controller is used for controlling the end-effactor positioning of manipulator.

Keywords: tendon, transmission, modeling, dynamics, control

1. Introduction

The development of lightweight, small volume, versatile and low cost manipulators have been grown in the field of robotics. Therefore, the development and design of tendon-driven robotics mechanism has been enthusiastically carried out. The term tendon is widely used to imply belts, cable, ropes, tapes or similar type transmission device. The major advantage of using tendon transmission lies in that it permits actuators to be installed remotely from the end-effectors, thus reduction in bulk and the inertia of the manipulator system. However, using of tendon transmission may introduce other problems such as friction and compliance in tendons and or increasing extra components in the system. Introduction of tendon transmission in robotic manipulators is more compliant than the transmission by geared mechanism and direct-driven robotic manipulators because of flexibility of tendon than those components. Tendon-driven robotics manipulator can be efficiently used in both serial and parallel robotic manipulators and they are generally classified in two ways i.e., open-ended and endless type. One end of the tendon is fixed to the moving link while other end is attached to a driving actuator. A transmission line is formed from the moving link to the driving actuator. For fast and desired motion control of the manipulator, the study of the compliance of the tendon and dynamics of the system are very important.

A number of analytical modeling methods for tendon-driven systems have been studied by several researchers which are briefly described here. Chang et al. [1] carried out the kinematic and compliance analysis of the tendon-driven robotic mechanisms with flexible tendons and also developed the dynamic model of the manipulator. The modeled the flexible tendons as linear springs. Lee and Lee [2] controlled the tendon-driven one-DOF robotic manipulator considering the flexible tendons as linear spring and damper in parallel. Using a PD controller, Hiller et al. [3] studied the kinematics and trajectory planning of the tendon-driven parallel manipulators. Lee et al. [4] developed a tendon-driven robot hand with stiffness control capability. Jacobsen et al. [5] studied the control of a tendon driven manipulator where the link inertia, the elasticity of the tendon and actuator dynamics are included in the dynamic model. They developed two-control algorithm for the accurate positioning and the active stiffness control of the manipulator. Kino et al [6] developed dynamic model for single and two-link tendon driven manipulators using basic characteristics of belt pulleys.

In this paper a realistic model of the flexible tendon driven single-link manipulator is considered by taking a nonlinear model of the tendon forces. The tendons are modeled as a nonlinear spring and a linear dashpot in parallel. It transmits the motion to one end to the other end of the tendon without friction and slippage in idle pulley. Frictionless idle pulleys are used only for changing the direction of the tendon. Due to the compliance property of the tendon, output of the manipulator will be deferred from the input. Among various system parameters, values of the stiffness (K) and damping coefficient (C) of the tendon have a great impact on the end-effector position. Slackness of the tendon causes error in output and this can be reduced by introducing the pretension value. Finally, a control strategy is employed to make a desired end-effector position.

2. Dynamic model of the manipulator

Figure 1 shows a single-link manipulator driven by two flexible tendons spooled to the two actuators remotely situated on the base. Two frictionless idle pulleys are used to change the direction of the tendon. Manipulator is capable of moving in both directions by using of two actuators. Figure 2 shows an equivalent model of the tendon driven manipulator where it's shown the flexible tendons are model as nonlinear spring and linear damper in parallel.

In the present works some assumptions mainly are considered :(i) all tendons are under tension (ii) No slippage occurs between pulleys and tendons (iii) tendons are lightweight such that weight /inertia, flexural bending, and shear effects of tendons are not to be considered (iv) For the sake of simplicity, the friction in the pulley bearings and other moving parts of transmission are not included and also no friction and (v) no slippage occurs in idle pulley (vi) The gyroscopic effects associated to the rotation of the pulleys are neglected. Using the recursive Newton-Euler formulation equation of motion of the mechanism is derived. In order to write in a compact form the dynamic equation, it is useful to define the quantities, related to the tension in the tendon.

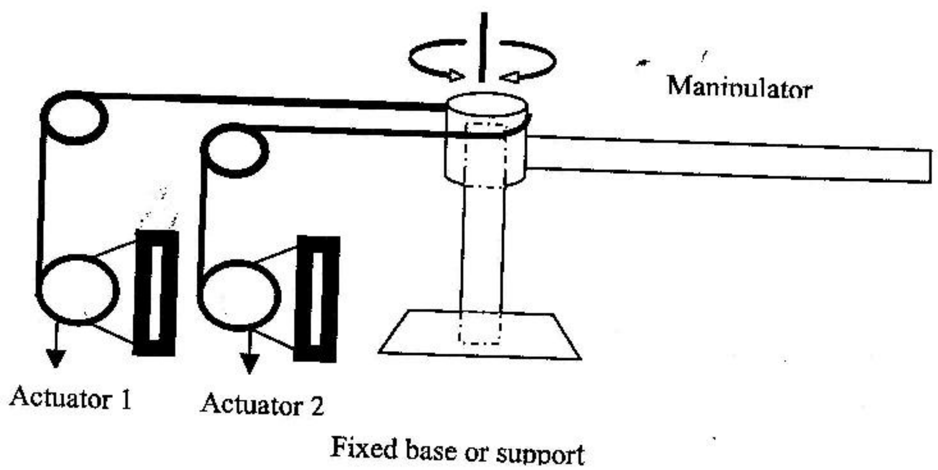


Figure: 1: One degree freedom manipulator

Equivalent mechanism:

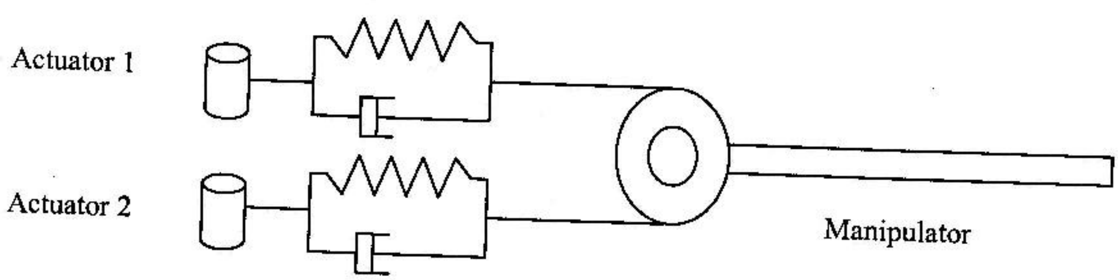


Figure: 2: -Equivalent model of the tendon driven manipulator

Modeling of the flexible tendon

A simple flexible tendon model is described with a pulley pair where m identifies the pulley in manipulator end and i specify the actuator end. Pulley i and m are coupled by a flexible tendon having nonlinear spring and linear co-efficient damping. For the unidirectional characteristic of the tendon, tendon transmits the force to manipulator end one way. Therefore, tendon force can be transmitted from the actuator end to the manipulator only when the relative displacement is occurred in between pulley pair.

So the tendon force equation can be written as

$$t_{i,m} = [t_0 \pm K_1(r_m\theta_m - r_i\theta_i) \pm K_j(r^j{}_m\theta^j{}_m - r^j{}_i\theta^j{}_i) \pm C_1(r_m\dot{\theta}_m - r_i\dot{\theta}_i)] \qquad (1)$$

Where ($\pm$) Sign of each term in tendon equation use for the different configuration of the tendon $t_{i,m}$ is tendon force equation of the manipulator, t_0 is pretension of the tendon initially set, $\theta_i, \dot{\theta}_i$ and $\theta_m, \dot{\theta}_m$ are rotation and angular velocity of the pulley in actuator end i and manipulator end, r_i and r_m are corresponding radius of the pulley in actuator end and manipulator end, C_1 is for linear damping coefficient and K_i and K_j are linear and nonlinear stiffness of the flexible tendon

Dynamic equation of manipulator

From equation (1) equation of motion the manipulator can be written as

$$\frac{M}{3}L^2\dot{\theta}_m = -r_m[t_0 + K_1(r_m\theta_m - r_i\theta_i) + K_j(r^j{}_m\theta^j{}_m - r^j{}_i\theta^j{}_i) + C_1(r_m\dot{\theta}_m - r_i\dot{\theta}_i)]$$

$$+ r_m[t_0 - K_1(r_m\theta_m - r_i\theta_i) - K_j(r^j{}_m\theta^j{}_m - r^j{}_i\theta^j{}_i) - C_1(r_m\dot{\theta}_m - r_i\dot{\theta}_i)] \qquad (2)$$

Where j is 2 stand for quadratic and 3 stand for cubic nonlinearities of tendon and i is 1 for actuator 1 and 2 for actuator 2, M is mass of the manipulator and L is length of the manipulator

With introducing a PD controller to the system, the equation of motion of the system is related with joint variables and gains. Figure 3 shows the block diagram of the PD control system. Actuators input can be written as

$$\theta_1 = K_p(\theta_d - \theta_m) + K_d(\dot{\theta}_d - \dot{\theta}_m) \text{ and } \theta_2 = K_p(\theta_d - \theta_m) + K_d(\dot{\theta}_d - \dot{\theta}_m) \qquad (3)$$

Where K_p the proportional is gain and K_d is the derivative gain θ_d is desired value

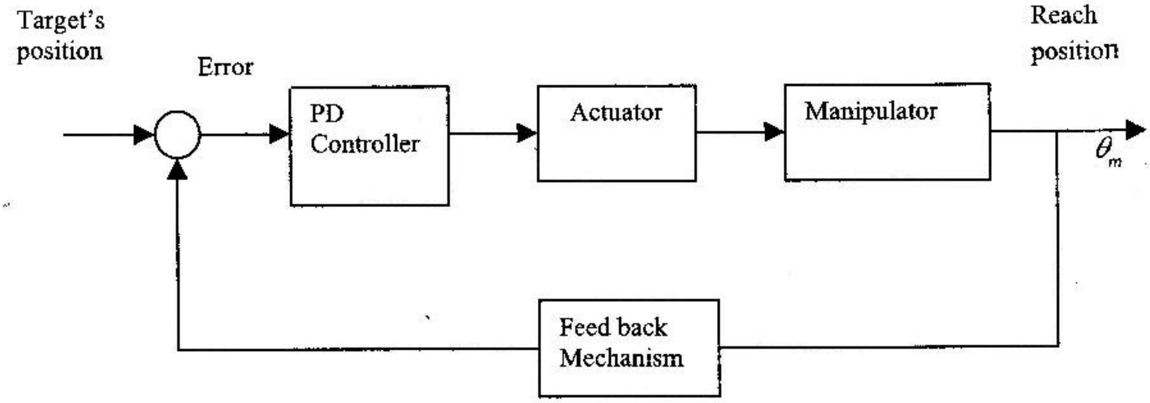


Figure 3: Block diagram of the PD control system

From equations (1- 3), equation of motion of the system can be written in terms of gain as follows

$$\frac{M}{3}L^2\dot{\theta}_m =$$

$$-r_m[t_0 + K_1(r_m\theta_m - r_i(K_p(\theta_d - \theta_m) + K_d(\dot{\theta}_d - \dot{\theta}_m)) + K_j(r^j{}_m\theta^j{}_m - r_i{}^j(K_p(\theta_d - \theta_m)$$
$$+ K_d(\dot{\theta}_d - \dot{\theta}_m))^j + C_1(r_m\dot{\theta}_m - r_i(K_p(\dot{\theta}_d - \dot{\theta}_m) + K_d(\ddot{\theta}_d - \ddot{\theta}_m))]$$

$$+ r_m[t_0 - K_1(r_m\theta_m - r_i(K_p(\theta_d - \theta_m) + K_d(\dot{\theta}_d - \dot{\theta}_m)) - K_j(r^j{}_m\theta^j{}_m - r_i{}^j(K_p(\theta_d - \theta_m)$$
$$+ K_d(\dot{\theta}_d - \dot{\theta}_m))^j - C_1(r_m\dot{\theta}_m - r_i(K_p(\dot{\theta}_d - \dot{\theta}_m) + K_d(\ddot{\theta}_d - \ddot{\theta}_m))] - - - -(4)$$

3. Numerical results and discussion

In this work, effect of flexible tendon on end- effactor position of the manipulator is represented in terms of joint variables. In all simulation, mass of the beam M= 15 kg, length of the beam L= 1.5 m, radius of the pulleys $r_m=r_i$ = 0.3 m, linear stiffness K_1 =15000 N/m² and damping co-efficient C=20 N-s/m² are taken. The nonlinear stiffness (K_2, K_3,) and pretension parameters (t_0) are taken as variable for all observations. Figures 4 (a) and (b) show the end-effactor position of the manipulator for different values of cubic nonlinearities of tendon where the pretension value are set as10 N and 50 N. Manipulator response is almost same when nonlinear stiffness value of tendon is 0.1 and 0.01 times the linear stiffness value (K_1). Figures 5(a) and (b) display the end-effactor position of the manipulator for different value of quadratic nonlinearities for the same pretension values and it is observed that there is slightly difference in the manipulator response when nonlinear stiffness values are 0.1 and 0.01 times the linear stiffness (K_1). Figures 4 depict that increase of pretension for highly nonlinear stiffness gives the desired end-effactor position. From figures 4 and 5 it is clearly seen that end-effactor position is much deviated from the desired position in case of cubic nonlinearity. Figures 6 (a) and (b) show the end-effector position considering both cubic and quadratic nonlinearities simultaneously and one may observe that the combined effect is only slightly higher than the effect considered individually. Figures 7 and 8 show the required torque as a function of the rotation of the manipulator considering different nonlinear stiffness in the tendon and it is observed that torque requirement for quadratic nonlinearities is more than that of the cubic nonlinearities for same value of nonlinear stiffness. It seems that end-effactor position is marginally affected when the nonlinear stiffness values is 0.1 and 0.01times the linear stiffness value (K_1) and give the appreciable difference when the nonlinear stiffness is same order as the linear value. Therefore a PD feedback type controller is implemented to reach the desired position of the end-effactor of the manipulator. End-effactor position of the manipulator depends on the gain values. From figures 9, it is concluded that the end-effactor position of the manipulator is close to the desired one when the gain values are more

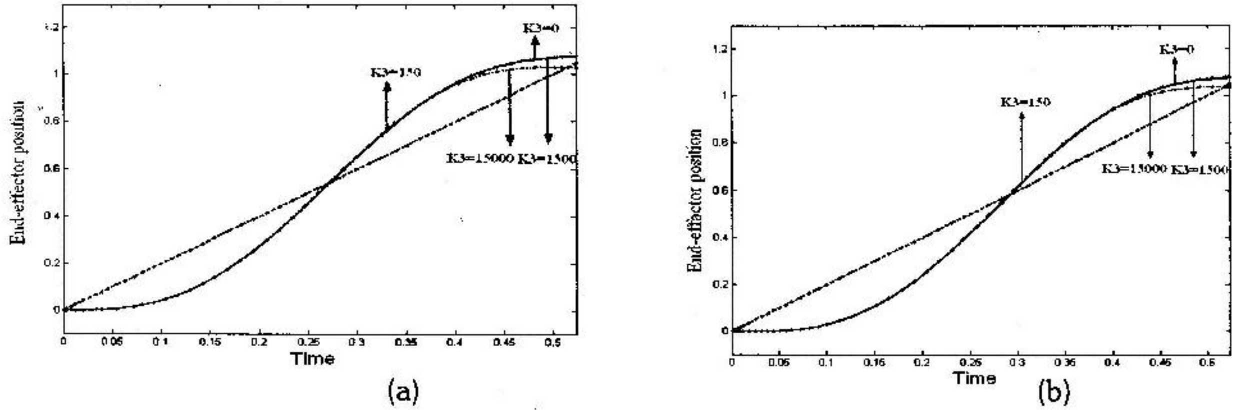
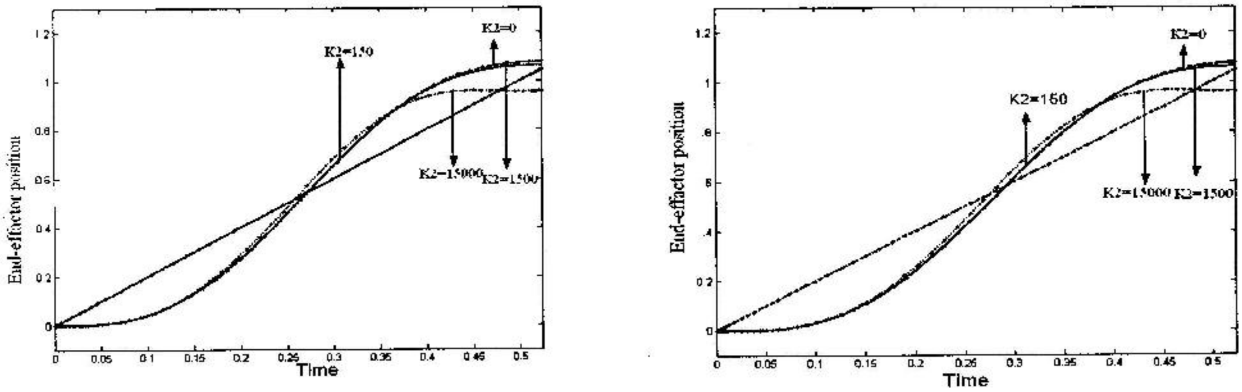
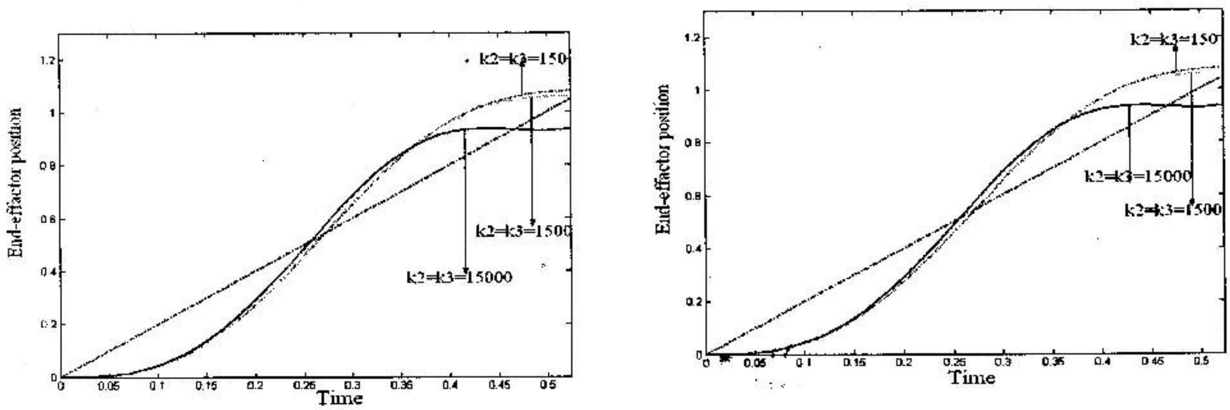


Figure 4: Effect of cubic nonlinearities of tendon for C_1=20 N-s/m², and K_1=15000N/m² (a) for pretension (t_0) =10 N and (b) for pretension (t_0) =50 N



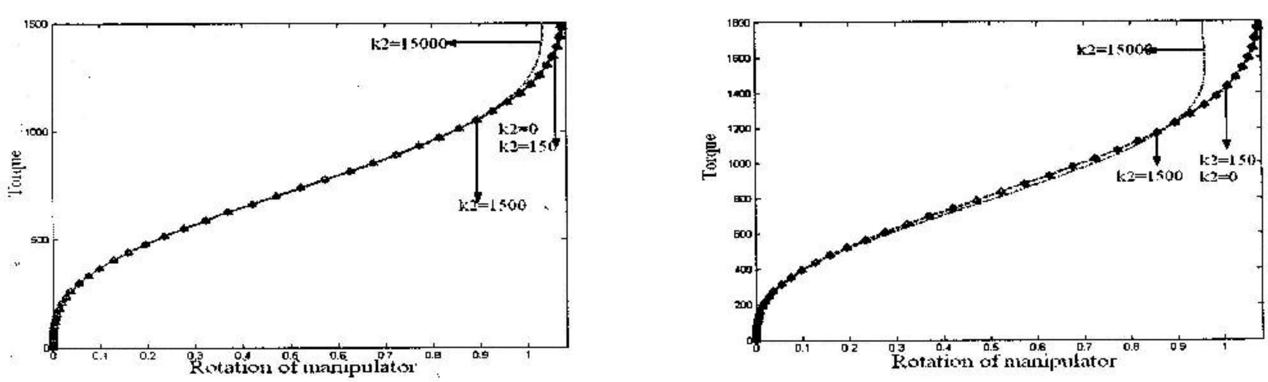
(a) (b)

Figure 5: Effect of quadratic nonlinearities of tendon for C_1=20 N-s/m², and K_1=15000N/m² (a) for pretension (t_0) =10 N and (b) for pretension (t_0) =50 N



(a) (b)

Fig 6: Effect of both cubic and quadratic nonlinearities of tendon for C_1=20 N-s/m², and K_1=15000N/m² (a) for pretension (t_0) =10 N and (b) for pretension (t_0) =50 N



(a) (b)

Figure 7: Effect of nonlinearities of tendon on tendon force for C_1=20 N-s/m², K_1=15000N/m², and t_0=10 N (a) for cubic nonlinearities of tendon and (b) for quadratic nonlinearities of tendon

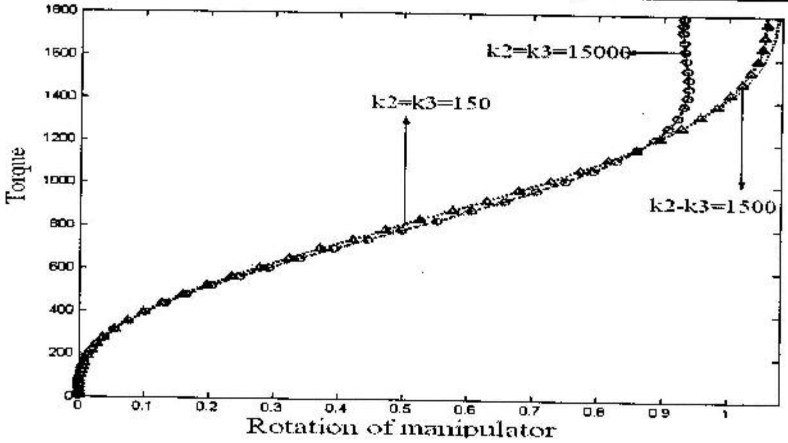


Figure 8: Effect of both cubic and quadratic nonlinearities of tendon on tendon force for C_1=20 N-s/m², K_1=15000 N/m², and t_0= 10 N

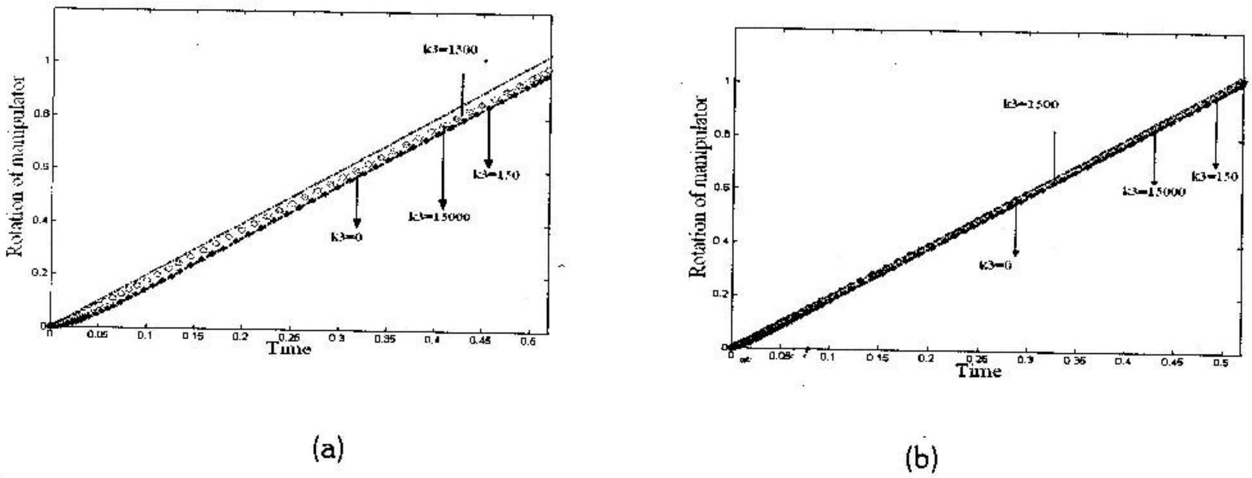


Figure : 9 response of the manipulator for C=20 N-s/m², k1=15000 N/m², and t_0=10 N (a) for gain value K_p=K_d=10 and (b) for gain value K_p=K_d= 50 different value of the gains

4. Conclusion

A dynamic model of a flexible tendon driven single-degree of freedom manipulator is investigated. The flexibility of the tendon is taken into account by modeling this as a combination of linear, quadratic and cubic springs and linear damper. Dynamic equation of motion of the system has been derived through recursive Newton-Euler formulation. Influence of the pretension and nonlinear stiffness of the tendon on the dynamic motion of the manipulator has been investigated. It is observed that pretension has little effect on the rotation of the manipulator and with increase in nonlinear stiffness the manipulator will not reach to the desired position. Hence a PD controller is also incorporated to move it to the desired position.

REFERENCES

[1] S. L. Chang., J. J. Lee., H. C. Yen: "Kinematic and compliance analysis for tendon-driven robotic mechanisms with flexible tendons", Mechanism and Machine Theory, 40 (2005) 728-739

[2] Y. H. Lee., J. J. Lee, "Modeling of the dynamics of tendon-driven robotic mechanisms with flexible tendons", Mechanism and Machine Theory 38 (2003) 1431-1447

[3] M. Hiller., S. Fang., S. Mielczarek., R. Verhoeven and D. Franitza: "Design, analysis and realization of tendon-based parallel manipulators", Mechanism and Machine Theory 40 (2005) 429-445

[4] Y. Y. Lee., J. H. Kim., W. K. Chung and Y. Youm; "Stiffness Control of the Coupled Tendon-Driven

Robot Hand", IEEE, proceeding of International conference as system , Man and Cybernetics, Vol 3, 710-715, 1993

[5] Jacobsen, S. C., K. H., Iversen., E. K., Davis C.C., "Antagonistic Control of a tendon Driven Manipulator", IEEE , Proceeding of International Conference on Robotics and Automation, vol.3, 1334 - 1339, 1989

[6] H. Kino., N. Okamura and S. Yabe. "Bacis Characteristics of tendon-Driven Manipulator Using Belt Pulleys, proceeding of 2004 IEEE/RSJ international Conference on Intelligent Robots and System 2004