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Vibration Control of Flexible Manipulators by Active Cable Tension

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Abstract

The end point vibrations of the serial manipulator should be controlled during motion or working process. In this study the residual vibrations of the flexible manipulator were controlled with cable tensions. The finite element model was established in ANSYS Mechanical APDL. The open loop and closed loop control simulations were performed under the trapezoidal velocity motion profiles. Zero and three different initial strain values were assigned to the cables. As a result, the end point vibration amplitudes, axial forces of the cables and the bending strain values of the one element near the fixed end were observed in order to define the limitations of the sensors and actuators which will be selected for experimental setup.

Keywords: Vibration Control, Flexible Manipulator, Finite Element Analysis

1. Introduction

The serial manipulators are commonly used in industry for many applications as path following motions, pick and place operations etc. The end effector vibrations must be controlled during the operations. There are two ways to suppress the end point vibrations as passive and active control. The passive vibration control can be achieved by using appropriate velocity motion profiles to actuate the manipulator.

Trapezoidal velocity motion profile is the basic velocity motion profile in order to actuate a serial manipulator. Trapezoidal velocity profiles consist of three-time parameters as acceleration time, deceleration time and constant velocity time. Selection of these time parameters are crucial for elimination of end point vibrations of a flexible manipulator or to keep them at a certain level. Some studies (Malgaca et al., 2016; Yavuz et al., 2016) proved that selection of the trapezoidal motion profile time parameters which are related with the natural period of the one degree of freedom flexible manipulator, reduces the residual vibrations. The same approach was also applied on two degrees of freedom flexible manipulator and the reduced residual vibrations were obtained in the study (Karagülle et al., 2017). In these studies, (Karagülle et al., 2017; Malgaca et al., 2016; Yavuz et al., 2016) when the deceleration time of trapezoidal motion profile was selected as integer multiples of first natural period of the manipulator, the residual vibrations were suppressed.

In the literature, different velocity profiles that have smoother acceleration changes than trapezoidal velocity motion profiles were suggested and used to drive a motor or dynamic system. The firstly proposed the 3rd order S-curve motion profile which has seven-time segment by Castain and Paul (Castain and Paul, 1984) was used also in practice (Liu and Chen, 2018; Liu, 2002; Lu and Chen, 2016).

The effect of the time parameters of 3rd order polynomial S-curve and trapezoidal motion profiles on transient and residual vibrations of a flexible manipulator were investigated (Akdağ and Şen, 2021). Finite element model of manipulator was established, and numerical calculations were done by using Newmark method.

Active vibration control of the flexible manipulators can be performed by using another actuator such as piezoelectric actuators or input shaping methods (Malgaca et al., 2017; Tzes and Yurkovich, 1993).

Vibration control was achieved by using active cable tension for many different cases such as vibration control of large trusses (Preumont and Achkire, 1997; Preumont et al., 2000), cable stayed bridges (Warnitchai et al., 1993) or even membrane antenna structure vibrations (Liu et al., 2018).

In this study, the finite element model of the flexible beam with cables was established Ansys Mechanical APDL instead of Ansys Workbench in order to perform the closed loop control simulations. The open loop and closed loop control simulations were performed under the trapezoidal motion profiles. Zero initial strain and three different initial strain values were assigned to the cables for performed simulations. As a result, the end point vibration amplitudes, axial forces of the cables and the bending strain values of the one element near the fixed end were observed in order to define the limitations of the sensors and actuators which will be selected.

2. Methodology

The finite element model of the flexible beam with cables was established in ANSYS APDL in order to perform the closed loop control simulations by writing scripts. Flexible beam was modeled by using BEAM188 element and the cables were modeled by using LINK180 element. LINK180 elements were modeled as members that carry only axial tension forces to model the cables. Detailed schematic view of the model is shown in Figure 1. The model parameters were given in Table 1 and established model in Ansys APDL was shown in Figure 2.

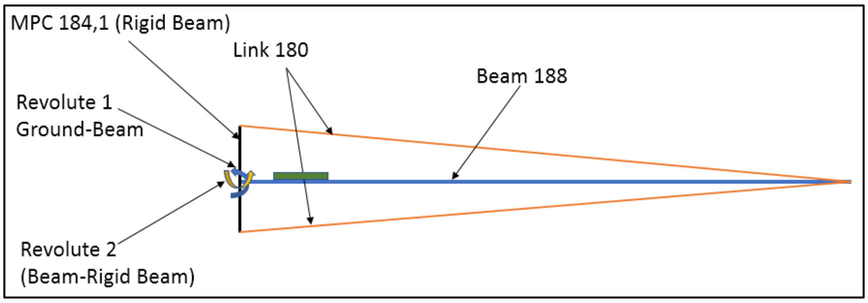

Figure 1. Schematic FE model of the tendon controlled flexible beam

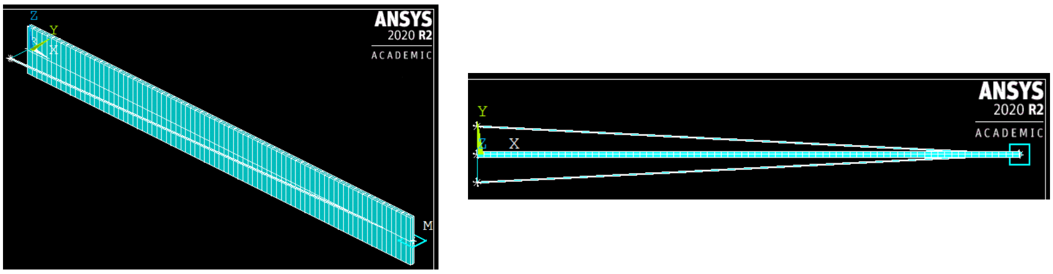

Figure 2. Established M-model in ANSYS APDL

Table 1. Model parameters

Elastic modulus	$2x10^{11}$ Pa
Poisson ratio	0.3
Density	7850 kg/m^3
Payload mass	1.25 kg
Inertia of payload	$633.445x10^{-6}$ kgm^2
Cable Diameter	Ø1 mm
Cross section	3.8x40 mm^2
Beam length (L2)	400 mm
Rayleigh damping coefficients	η=0 and $\beta=3.75x10^{-5}$
Motor rotational spring constant	Km2=16000 Nm/rad
Number of finite elements	ne2=80
Time step	Δt=0.005 s

Symmetric trapezoidal velocity motion profiles were used to actuate the manipulator. The manipulator was rotated 90˚ in 1 sec. The motion vector of trapezoidal motion profiles was defined as qm=[Tacc-Tdec-Tm]. Used symmetric trapezoidal motion profile parameters were defined acceleration and deceleration times as percentage of the motion time. Tacc and Tdec values were defined in Tables and Figures as %Tm. The used velocity motion profile is shown Figure 3.

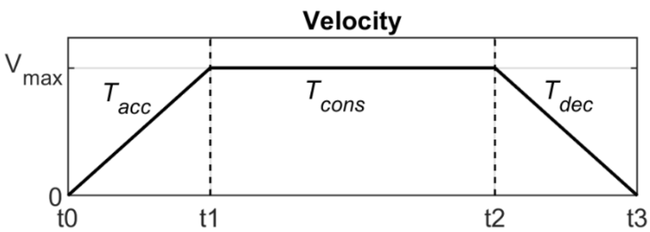

Figure 3. Trapezoidal Velocity Motion Profile

The effect of the pretension amount of the cables on the natural frequency of flexible manipulator was also observed. The closed loop control algorithm which includes proportional control (Kp) was established in ANSYS APDL. Bending strain values on an element which is away 15 mm from fix end was used as a feedback for closed loop control.

3. Results and Discussions

Obtained natural frequencies from both modal analyses and fast Fourier transform by using free vibration responses of residual vibrations were shown in Table 2. The reason the differences between the modal analyses and fast Fourier transform frequency result, both cables are not effective at the same time on the stiffness matrix. The axial load on one of the cables becomes zero during motion and that cable cannot make any contribution to the stiffness. The duration of this noncontributing region changes according to the actuation velocity profile. This situation was understood from the observation of the axial forces on the cables during the motion as shown in Figure 4.

Table 2. Obtained first natural frequencies

		Trapezoidal Motion Cases				
Pretension	**Modal Analyses**	**[0.1-0.1-1]**	**[0.2-0.2-1]**	**[0.3-0.3-1]**	**[0.4-0.4-1]**	**[0.5-0.5-1]**
No cable	5.5786 Hz	5.5786 Hz	5.5786 Hz	5.5786 Hz	5.5786 Hz	5.5786 Hz
0	7.9992 Hz	6.9316 Hz	6.8777 Hz	6.9794 Hz	6.9628 Hz	6.9134 Hz
5N	8.0279 Hz	6.9128 Hz	6.9466 Hz	7.7108 Hz	7.1592 Hz	6.9994 Hz
10N	8.0564 Hz	6.9319 Hz	7.0433 Hz	7.4993 Hz	7.3843 Hz	7.0978 Hz
15N	8.0848Hz	6.9504 Hz	7.1987 Hz	7.4894 Hz	7.9754 Hz	7.2699 Hz

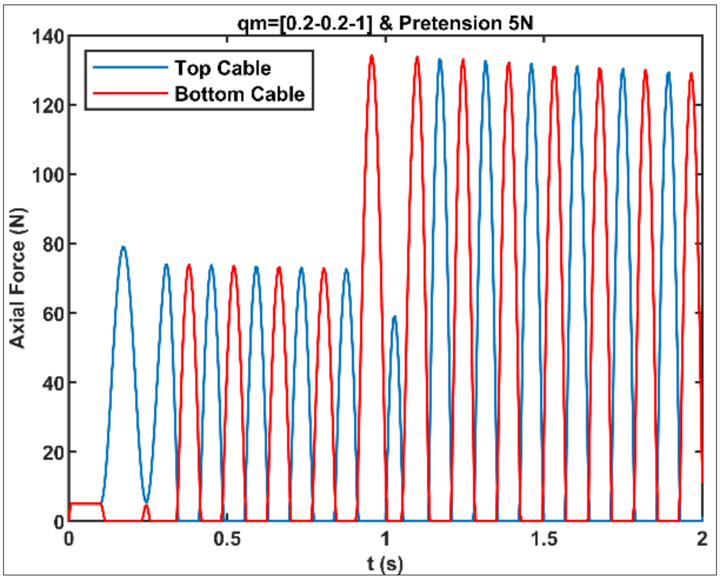

Figure 4. Axial forces on the cables during the qm=[0.2-0.2-1] with 5N pretension

The observation of the pretension amount effect on the vibration results for both qm=[0.3-0.3-1] and qm=[0.4-0.4-1] for all pretension values and without cable model were shown in Figure 5 (a) and (b). It was obtained that the vibration amplitudes are not directly affected by the pretension amount on cables. It is related with the natural period and given motion profile parameters. It was known that the coinciding or close values of the first natural period of the manipulator and the acceleration time of the motion profile reduce the vibration amplitudes. These effects were explained in detail in (Akdağ and Şen, 2021; Akdağ and Şen, 2023).

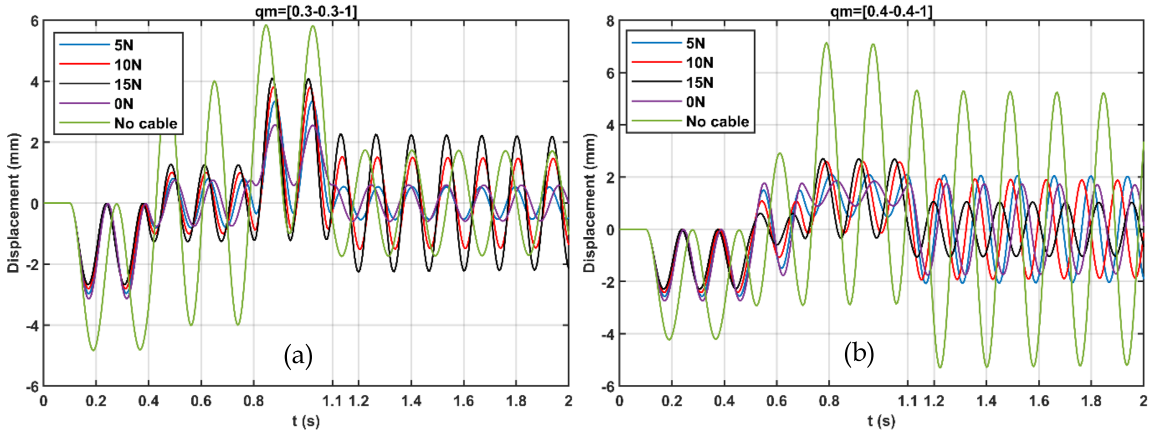

Figure 5. The effect of the pretension values on the vibration amplitudes

There should be a limitation for initial pretension amount. Two parameters should be taken into consideration. During the motion axial force on the cables should not reach up to yield force. And the axial force of the cable should not cause the buckling failure of the beam. For this reason, axial yield force (Fax_{yield}) and maximum axial load (P_{crt}) that the beam can carry can be calculated from Eq. (1) and Eq. (2), respectively. During the motion, these values should be observed. The obtained max Fax_{yield} on cables will also be used for calculation of the needed torque amount of control motor. According to the obtained result from Table 2 and Table 3 reached max Fax load 208.9676 N for 15N pretension and for qm=[0.1-0.1-1]. However, this value is higher than Fax_{yield}. Therefore, if the 15N pretension are going to be used motion case qm=[0.1-0.1-1] should not be chosen. If the diameter of cable increased, then it can be safe for use. The reached maximum holding torque value was obtained as 4.179352Nm. This can be taken as a reference for selection of the control motor. However, the real torque value of the motor should be selected after performing the closed loop control simulations.

$$Fax_{yield} = \sigma_{yield} A_{cable} \rightarrow \sigma_{yield} = 250MPa, A_{cable} = \pi(0.5x10^{-3})^2$$
$$Fax_{yield} = 196.35\ N \quad (1)$$

$$P_{crt} = \frac{\pi^2 EI}{L_e^2} \rightarrow L_e = 2L \rightarrow P_{crt} = 564N \quad (2)$$

Table 3. Axial forces on cable 1 for open loop control

	Trapezoidal Motion Cases/CableTension1 (N)				
Pretension	**[0.1-0.1-1]**	**[0.2-0.2-1]**	**[0.3-0.3-1]**	**[0.4-0.4-1]**	**[0.5-0.5-1]**
5N	161.5214	133.1011	60.7261	53.3922	97.4236
10N	186.3857	119.3072	62.7435	55.4848	94.5357
15N	205.5897	98.3538	65.0928	57.945	83.83
	Needed Holding Torque (Nm)				
5N	3.230428	2.662022	1.214522	1.067844	1.948472
10N	3.727714	2.386144	1.25487	1.109696	1.890714
15N	4.111794	1.967076	1.301856	1.1589	1.6766

Table 4. Axial forces on cable 1 for open loop control

	Trapezoidal Motion Cases/CableTension2 (N)				
Pretension	**[0.1-0.1-1]**	**[0.2-0.2-1]**	**[0.3-0.3-1]**	**[0.4-0.4-1]**	**[0.5-0.5-1]**
5N	162.0161	134.2044	67.7446	44.6053	98.7319
10N	187.1463	122.4846	81.1568	58.7313	98.3083
15N	208.9676	109.608	91.2579	65.5933	94.4689
	Needed Holding Torque (Nm)				
5N	3.240322	2.684088	1.354892	0.892106	1.974638
10N	3.742926	2.449692	1.623136	1.174626	1.966166
15N	4.179352	2.19216	1.825158	1.311866	1.889378

In Ansys APDL closed loop control algorithm includes proportional control (Kp) was established by written a script. Bending strain value on the element which is away 15 mm from the fix-end was read from the simulation and used as a feedback for closed loop control. Obtained closed loop results for different Kp values and different motion profiles were shown in Figure 6 (a), (b) and (c).

The closed loop simulations were also studied for different motion profiles. The end point vibrations were suppressed significantly only using proportional controller and vibration control has been successfully performed.

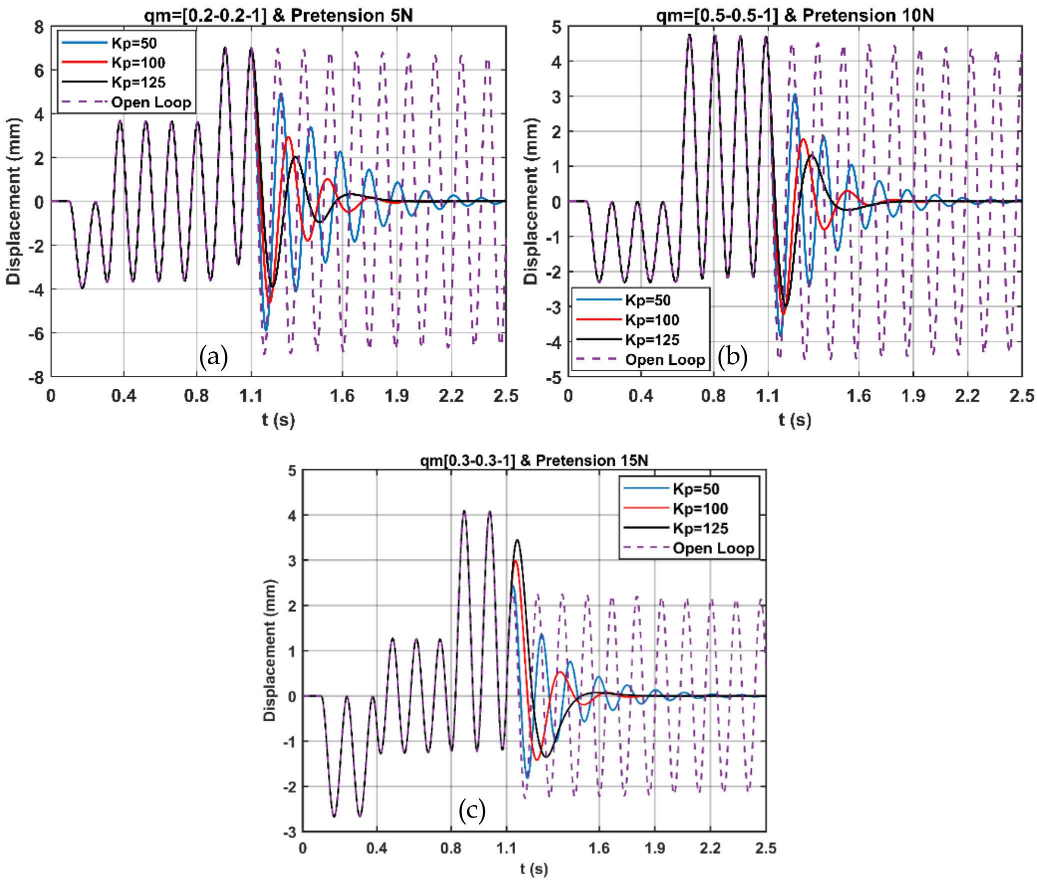

Figure 6. Closed loop control for different Kp values for same pretension axial load

4. Conclusions

The finite element model of the flexible beam with cables was established using Ansys Mechanical APDL instead of Ansys Workbench in order to perform the closed loop control simulations. The open loop and closed loop control simulations were performed under the trapezoidal motion profiles. Zero initial strain and three different initial strain values were assigned to the cables for performed simulations. As a result, the end point vibration amplitudes, axial forces of the cables and the bending strain values of the one element near the fixed end were observed in order to define the limitations of the sensors and actuators which will be selected. According to the obtained results the outcome will be as follows.

- For this system for control motor torque should be at least 4.2 Nm and strain gauge max limit value at least 3x10-4 m/m. These values should multiply minimum 1.5 as a safety factor.
- And for the setting of the initial pretension values a force measuring sensor is needed. That can carry up to 200N because the max Fax on the cables reaches approximately this value.
- According to obtained results the closed loop vibration control of flexible manipulator can be achieved by active cable tension.

Author Statement

All authors reviewed the results and approved the final version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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