VIBRATION ANALYSIS OF FLEXIBLE COMPOSITE MANIPULATOR

A THESIS SUBMITTED

IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE

OF

Dual Degree B. Tech and M. Tech

In

Mechanical Engineering

(Specialization: Mechatronics and Automation)

By

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CERTIFICATE

This is to certify that thesis entitled "**Vibration Analysis of Flexible Composite Manipulator"** by **Rocky Vinay Kujur**, submitted to National Institute of Technology, Rourkela in partial fulfillment of requirement for the award of **Dual Degree** in Mechanical Engineering with specialization in "**Mechatronics and Automation**", is a record of research work carried out by him in the Department of Mechanical Engineering, under our supervision and guidance.
I believe that this thesis fulfills the partial requirement for the award of Dual Degree in Mechanical Engineering. The results shown in this thesis has not been used in any other thesis for award of any other degree elsewhere.

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A C K N O W L E D G E M E N T

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ABSTRACT

Flexible Manipulators are promising in field of robotics, it provide a prominent replacement for rigid manipulators which consume more power, response time is slower and due to mass moment inertia difficult to maneuver. On the other hand Flexible Manipulators being light in weight consume less power, response time is also fast, and being light weight there is no problem of mass moment inertia so safe in operations. However in using flexible manipulators in operations some difficulties are faced. The main drawback while using flexible manipulator is its residual vibration produced due to its light weight. By choosing appropriate material as manipulator and using proper control techniques the effect of vibration such as vibration amplitude and vibration settling time can be decreased. Flexible materials are being used in many fields such as space, underwater as well as high speed energy efficient manipulation. Here vibration analysis is done on three types of single link flexible manipulators i.e. aluminum, Kevlar epoxy composite and graphite epoxy composite. Many researches have been done on modelling of the flexible manipulator using finite element procedures and thus this thesis is done to analyze vibrational property of manipulator for different materials and finally concluded which type of flexible manipulator gives best result.

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Chapter-1

INTRODUCTION

1.1 Flexible Manipulator

A robotic manipulator is generally used for pick and place operations and some of the complex operations such as assembling. But the structure of these robots are made up of heavy materials in order to maximize the stiffness of material. Stiffness is directly associated with vibration, increase in stiffness decreases system's vibration and thus increases accuracy. So by increasing stiffness of manipulator weight also increases making it difficult to operate, consumes more energy as bulkier motors are used for its maneuver and cost also increases. So flexible manipulators are designed to be lightweight and so they have certain amount of flexibility. These light weight manipulators can be used that have higher speed and less response time, these consumes less power due to use of smaller actuators, due to lower mass inertia they can be safely maneuvered. But these advantages comes with some demerits. Due to light weight of manipulators these produces residual vibrations, lack sensing and doesn't have precise positioning as well as due to their complex modelling friction and damping factors are affected. So to utilize the advantages of flexible manipulator and reducing the problems an efficient modeling and control techniques have to be used.

1.2 Composite Beam

Sandwich beam is a type of composite beam in which core layer which is viscoelastic layer is sandwiched between two bottom and top face sheets which are elastic layers. So it describes the behavior of three of three layer beam according to beam theory. The most commonly sandwich theory that is applied is linear also it is an extension of first order beam theory. Viscoelastic materials are those materials that can store energy when they deform, these exhibit characteristics of both viscous fluid and elastic solid. These properties of viscoelastic materials make them suitable for damping of vibration. Viscoelastic property is shown by various materials such as polymers ranging from synthetic rubbers or natural rubbers to thermostat or thermoset materials.

1.3 Problem Statement

Robotic manipulators especially if they are used in accurate positioning applications in which high precise positions are necessary undergo vibration problems. Residual vibration and transient deflection in manipulators can affect the positioning application of the system. The source of the vibration is the weight of the flexible manipulators. Being light in weight make them easy to move but another problem we face are unwanted vibration. To overcome this vibration problem and without compromising the light weight of flexible manipulators an appropriate control technique is to be developed.

1.4 Problem Background

The system's vibration is affected by speed and accuracy. Machines are designed to efficiently work in maximum speed and lightness of the machine contribute crucial role. Due to this, the control of such machines so that possess flexibility becomes important factor. A lot of research has been carried out on different control strategies.

Chapter-2

LITERATURE REVIEW

Two types of manipulators are being studied here in this thesis i.e. conventional manipulator and advanced composite manipulators. Conventional manipulators are that manipulators in which it is formed from single material used as replacement for rigid manipulators in which in order to increase stiffness of system to compensate for the vibration of the system weight of manipulator is increased but flexible manipulators are light in weight and it is easy and safe to maneuver it. In case of flexible composite manipulators the manipulators are made of laminated materials one layer on another to which manipulators possess flexibility characteristics.

2.1 Conventional Manipulator

Chen and Chan [1] used Euler-Bernoulli beam theory to model cantilever beam to derive equation of motion of the system. The resonant frequency of the cantilever beam is analyzed by applying mass at the free end of the beam. As well as loss of factor was analyzed on applying mass at free end of beam. It is shown that the resonant frequency and loss of factor is dependent on physical characteristics and geometrical constraints of layer.

Wang and Welt [2] have studied the analysis of flexible arm that is moved by moving slender prismatic beam. In their investigation extending and contracting motion produces stabilizing and destabilizing effect on the vibration of arm. Only rectilinear motion is considered in their investigation considering both rotational and vertical motion. And finally an experiment is done to damp the vibration at present time .

2.2 Advanced Composite Manipulator

Ahmad et al. [3] have studied the effect of length of the flexible manipulator on dynamic behavior of flexible manipulator. In their study dynamic model is done on single link manipulator using finite element method and bang-bang torque is used as input to simulate the model using MATLAB. Effect of length has been studied in time and frequency domain. With increase in length it was noted that end-point residual acceleration and hub velocity decreases and response mode of the system's vibration moved to lower frequency but it is also shown that with increase in beam's length response time decreases. However the overshoot of hub angle increases gradually with length.

Choi et al. [4] have investigated the modeling and control of single-link manipulator that is fabricated using advanced composite laminates. In this paper it is shown that performance of composite manipulators are superior in comparison with manipulators fabricated from aluminum material. In their experiment it is observed that less input torque is required for composite manipulators as compared to aluminum manipulator, so composite manipulators require less power. By applying same torque it is shown that maximum overshoot of composite arm is less in comparison to aluminum arm.

2.3 Control Methodology

Two types of control technique are discussed here that can be implement to be used in control of flexible manipulator, those are feed forward control system and feedback control system. Recently, intelligent control methods are been used in control of flexible-link manipulators. Intelligent control is the discipline in which control algorithms are developed by emulating certain characteristics of intelligent biological systems. However, an unbiased and accurate comparison of intelligent and classical control strategies is not yet available in the literature. However optimization of control is being done with the help of fuzzy logic, genetic algorithm and neural network by many researchers.

The feed-forward technique or command shaping technique includes the development of the control input by considering the physical and vibrational properties of the system. This technique uses the physical and vibrational properties of the system to reduce system vibrations. Unlike the feedback technique, use of extra sensors or actuators are not needed because this technique does not depend on the modification of the system once the input is created. And since use of sensors or actuators are not needed the cost of the system is reduced.

Fig.1 Block Diagram of Feedforward Control

In the figure given above designed input shapers and filters were used for pre-processing of the bang–bang torque input. The shaped and filtered torque inputs were then applied to the system in an open-loop configuration to reduce the vibrations of the manipulator. Mohamed and Tokhi [5], investigated the development of feed forward control technique for vibration control of a flexible manipulator using command shaping techniques based on input shaping, low-pass and band-stop filtering. In their research an aluminum type flexible manipulator is used and single switch bang-bang input used as an input signal. The dynamic model of the flexible manipulator is done using the Finite Element method. Significant reduction in the vibration of the system has been observed with these control technique. Performances of these techniques have been observed and compared in terms of amount of vibration reduction, response speed, robustness and computational complexity. The low-pass filter input has been shown to have better performance than the band-stop filter input. The input used i.e. bang–bang torque has a positive (maximum value) and negative (minimum value) for a certain period, causing the manipulator to accelerate and then suddenly decelerate for a time period and ten stop at a time.

Singer and Seering [6] have proposed the use of input shaping to improve response time and positioning accuracy by reducing residual vibration in a system this approach involves convolving of a shaped input called input shapers with a series of impulses. Input shapers are designed in such a way that the system becomes insensitive towards changes in uncertain environmental parameters. As the insensitivity of the system increases robustness also increases. The system's insensitivity can be increases by adding more constraints when producing an impulse input series for the system. By doing that, the number of impulses in the sequence will also increase. But the downside is, by increasing the insensitivity of the system, the response time of the system also increases and control of unwanted residual vibration due to flexibility of system becomes more difficult due to which there is difficulty in obtaining accurate model of the flexible manipulator system. These are the reason that industry doesn't favor use of flexible manipulators. For that a control mechanism has to be developed for completely utilizing the advantages of flexible manipulator.

To reduce the vibration the feedback technique uses measurement and approximation of the system. It is also called as closed-loop system. This technique usually requires additional sensors or actuators.

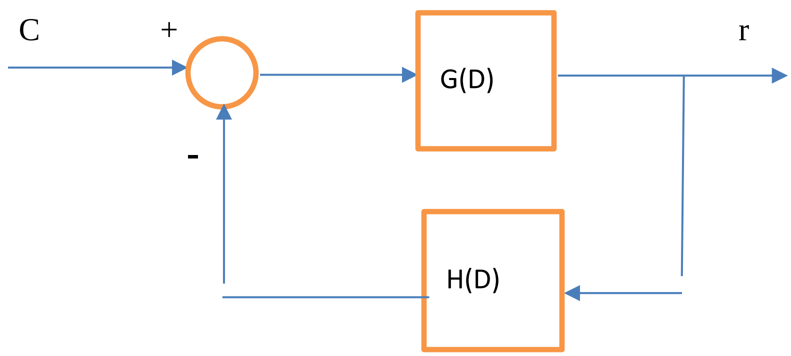

Fig.2 Block Diagram of Feedback Control

In the above figure a simple negative feedback control configuration is shown where C is reference signal which is required and r is actual output and a feedback signal is send back to the input and compared with the reference signal. Having main goal is that error that is difference of reference and feedback signal reaches zero.

Kotnik et al. [7] have examined compensation for the closed loop system using endpoint acceleration feedback. The endpoint acceleration is used as the non-collocated feedback signal. This is done by slewing a robotic arm as fast as possible through a pre-determined angle with a step input command and the mission is to sustain stability of the endpoint through hub motor actuation.

This controller exploits the endpoint acceleration through a static feedback gain for endpoint position.

Akyuz et al. [8] have implemented positioning and trajectory tracking control of a single-link flexible-joint robot arm with a cascade FLC structure. Step-response experiments were conducted to see the effect of different feedback signals on the response of the system. When the number of feedback signals in these experiments was increased, the vibrations of the end-point in the flexible joint decreased, as expected. In the position control experiments, no steadystate error was found in the end-point of the link. In order to compare the performance of the cascade FLC with the PID controller, step inputs were applied to the system. Based on the comparison, the proposed FLC yields better results than the PID controller. In the disturbance experiments, the cascade FLC structure was able to suppress link vibrations in a short time. When a longer link was used, more overshoot and oscillations occurred in θ andα, respectively, and the performance of the trajectory tracking was reduced. Results of the robustness experiments show that the cascade FLCs are robust to external disturbances and system parameter changes. Considering the results of all of the experiments, fast trajectory tracking and precise position control were obtained with cascade FLCs in the flexible-joint robot manipulators.

Choi et al. [4] showed that the performances of the overall closed-loop system for both aluminum and composite arm are satisfactory, and composite arm imparts some superior performance characteristics as compared to the aluminum manipulator, such as fast settling time, requirement of small input torque and smaller maximum overshoot. An output feedback controller is designed with collocated angular position and velocity sensors based on the reduced order model and they have experimentally applied it in order to observe the performance of flexible manipulator in terms of control that are fabricated from aluminum and composite laminates. The experimental results clearly shows the significant results associated with implementing the composite materials featuring superior strength and stiffness-to-weight ratios to the conventional metals on the flexible manipulators.

Cannon and Schmitz [9], has presented another approach in the feedback technique for control of end point vibration. The end point feedback is the direct measurement of the end's position which serves as a basis for giving torque at the other end. With a good dynamic model of the system and proper control technique, an acceptable tip-control response can be achieved. But stability problem arises because actuator and sensor are not collocated.

Some of the researchers have done research on the effect of vibration on the behavior of a laminated aluminum beam and a fiber reinforced composite beam with a piezoelectric actuators using the interactive MATLAB code, using piezoelectric actuators for isotropic and/or anisotropic beam materials. A finite element model has been proposed using Euler-Bernoulli beam theory to predict the static and the free dynamic characteristics of laminated aluminum and fiber reinforced composite beams with distributed piezoelectric actuators.

Manjunath and Bandyopadhyay [10] have done research work on smart flexible cantilever beam using periodic feedback output control technique and modelled it in state space form using finite element method and Euler-Bernoulli beam theory. They designed the control technique such that it would give satisfactory result for multivariable, multiple input multiple output flexible beam by bonding numerous pairs of actuators and sensors at different location of beam along length of the beam. The beam has been divided into eight finite elements and sensor/actuator pairs bonded to the master structure at even elements.

2.4 Motivation and Objective

Flexible manipulators provides a solution as an alternate for rigid manipulators and problems faced in industries due to the lack of alternative for rigid manipulators. This field has attracted for some of the reasons like its use in space programs because the use of light weight designs are required to attain the escape velocity and for better fuel efficiency. But also some rigidity is needed for space robots. But flexible nature of manipulator benefits in area such as cleaning of delicate surfaces, high speed manipulation, prevents manipulator from being damaged due to collision and also increase in productivity. Conventional robots which are used to carry load have limitation of load carrying capacity of 5 to 10 percent of their own weight. Achieving of high speed of the manipulator with light weight of structure is always desirable. In energy consumption point of view this field is attractive since smaller actuators are needed for lighter loads. Precise positioning and stable control of manipulator becomes necessary when flexibility becomes essential.

Objective of the work:

i. To analyze the dynamic behavior of flexible manipulator and advanced composite manipulator for vibration

ii. To compare the performance of manipulator and identifying which produces better result.

Chapter-3

MATHEMATICAL FORMULATION FOR FLEXIBLE COMPOSITE MANIPULATOR

3.1 Finite Element modeling for flexible manipulator

The total displacement of the end effector of a flexible manipulator (as shown in Fig. 3) can be written as

$$y(x,t) = x\theta_1(t) + w(x,t) \tag{1}$$

Where $w(x, t)$ is the elastic deflection. The system kinetic energy can be obtained as follows

$$E_k = E_h + E_l + E_{MP} \tag{2}$$

Where E_h, E_l, and E_{mp} are the kinetic energies associated with rigid hub, flexible link (i.e. beam), and the payload respectively. The kinetic energies E_h and E_{mp} can be determined as follows

$$E_h = \frac{1}{2} I_h \dot{\theta}_1^2(t), E_{MP} = \frac{1}{2} M_p \left\{ \left[\left(\frac{\partial w(x,t)}{\partial t} + x\dot{\theta}_1(t) \right)_{x=l} \right]^2 + [\dot{\theta}_1(t)\omega(l,t)]^2 \right\} + \frac{1}{2} I_p \left\{ \left[\dot{\theta}_1(t) + \frac{\partial}{\partial t} \left(\left. \frac{\partial \omega(x,t)}{\partial x} \right|_{x=l} \right) \right]^2 \right\} \tag{3}$$

Where I_h, I_p and l are the hub inertia, inertia associated with payload and length of the manipulator.

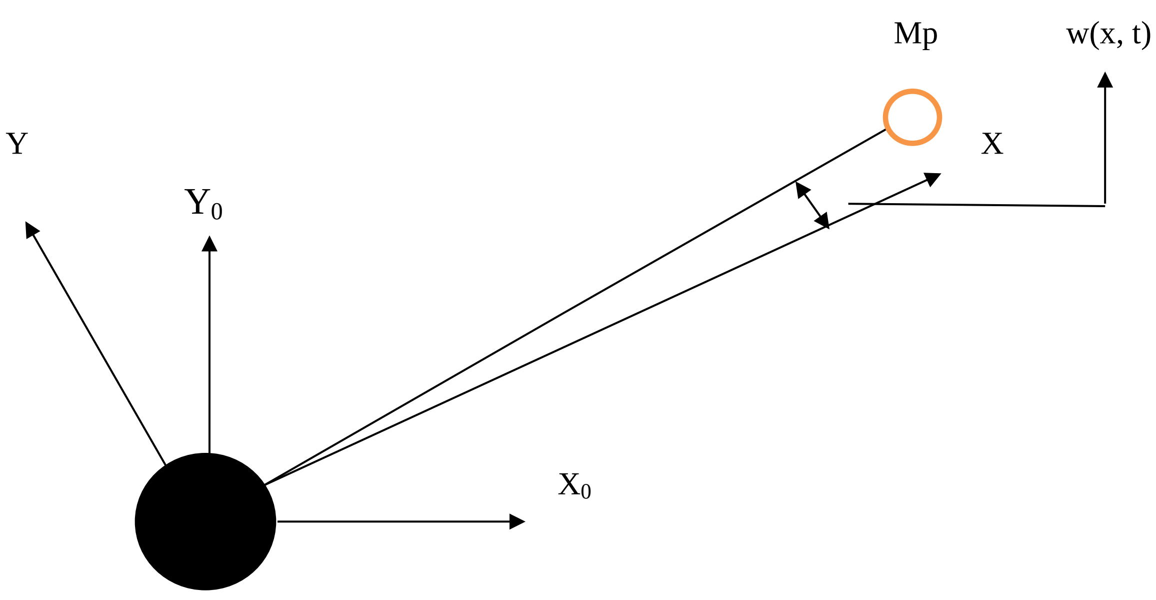

Fig. 3. Single Link Flexible Manipulator

The dynamic equations of motion of the manipulator system can be derived using extended Hamilton's principle as follows

$$\int_{t_2}^{t_1} \delta\left(E_K - E_p + W\right) dt = 0 \tag{4}$$

Where E_P and W are potential energy of the system and external work done.

3.2 Formulation of Composite beam

The equation of motion of the composite beam can be derived using the Hamilton's principle as follows

$$\int_{t_1}^{t_2} (\delta T - \delta U) dt = 0$$

$$\delta w : I_m \frac{\partial^2 w}{\partial t^2} + k_s \left(A_{55} + A_{66}\right)\left(\frac{\partial \beta_x}{\partial x} - \frac{\partial w}{\partial x}\right) = 0$$

$$\delta \beta_x : I_d \frac{\partial^2 \beta_x}{\partial t^2} - D_{11} \frac{\partial^2 \beta_x}{\partial x^2} - k_s \left(A_{55} + A_{66}\right)\left(\frac{\partial w}{\partial x} - \beta_x\right) = 0$$

The terms A_{55}, A_{66}, D_{11} , I_m and I_d of above equation for *n* number of composite plies are given as follows

$$A_{55} = \frac{\pi}{2}\sum_{i=1}^{n} \bar{Q}_{55i}(r_{i+1}^2 - r_i^2) \ , A_{66} = \frac{\pi}{2}\sum_{i=1}^{n} \bar{Q}_{66i}(r_{i+1}^2 - r_i^2) \ , D_{11} = \frac{\pi}{4}\sum_{i=1}^{n} \bar{Q}_{11i}(r_{i+1}^4 - r_i^4),$$

$$I_m = \pi \sum_{i=1}^{n} \rho\left(r_{i+1}^2 - r_i^2\right), I_d = \frac{\pi}{4}\sum_{i=1}^{n} \rho\left(r_o^4 - r_i^4\right)$$

where, $\delta =$ ply orientation

Utilizing all energy of the system in equation 4, the governing equation of the single link composite manipulator can be obtained as

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F\} \tag{5}$$

3.3 State Space Representation

The second order matrix differential equation i.e. equation (11) can be converted in a state-space form as

$$\dot{X} = AX + Bu \ ;$$

$$y = CX$$

Where $A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}$; $B = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}$

$u = [\tau \quad 0 \quad ... \quad 0]$ and the state vector $X = [\theta \quad w \quad ... \quad \beta... \quad \dot{\theta} \quad \dot{w} \quad ... \quad \dot{\beta}...]^T$ One of the simple type of control technique used is Linear Quadratic Regulator Technique, in which all states are considered as measurable and control input can be defined as

u = -kx

where k is the closed loop gain and can be obtain by using Matlab function

[K, S, e] = lqr (A, B, Q, R)

S is the solution of ricatti equation and e is Eigen value of closed loop system the further left Eigen we get the faster he decay of system occurs and it can be said that system is stable.

Chapter-4

RESULT AND DISCUSSION

4.1 Detail of flexible manipulator

The manipulator used in this work is simulated using MATLAB program and output response is given in the following figures. Beam is divided into 10 equal finite elements along length of manipulator. And finite element used here is three noded line element.

Table 1

Parameters of Composite shaft

Parameter	Manipulator
Length	1.2 m
Outer Diameter	0.019 m
Inner Diameter	0.0126 m
Thickness of laminate	4e-04
Shear Correction Factor	0.56
End point Payload	.09 kg
Hub Inertia	5.8598e-4

4.2 Comparison of two Flexible Manipulators

There are two types of flexible manipulator used to observe the dynamic behavior for vibration in terms of end point displacement, hub angle, hub velocity, end point residual.

Aluminum fabricated manipulator in which the material used is only of single metal is isotropic in nature. Flexible Composite manipulator which is made of combination of two materials Kevlar epoxy and Graphite Epoxy. The output response of the manipulator is simulated using bang-bang torque as input which maximum value is 0.3 Nm simulated for 4 sec using Matlab program. The output response of both aluminum based manipulator and advanced composite manipulators are compared.

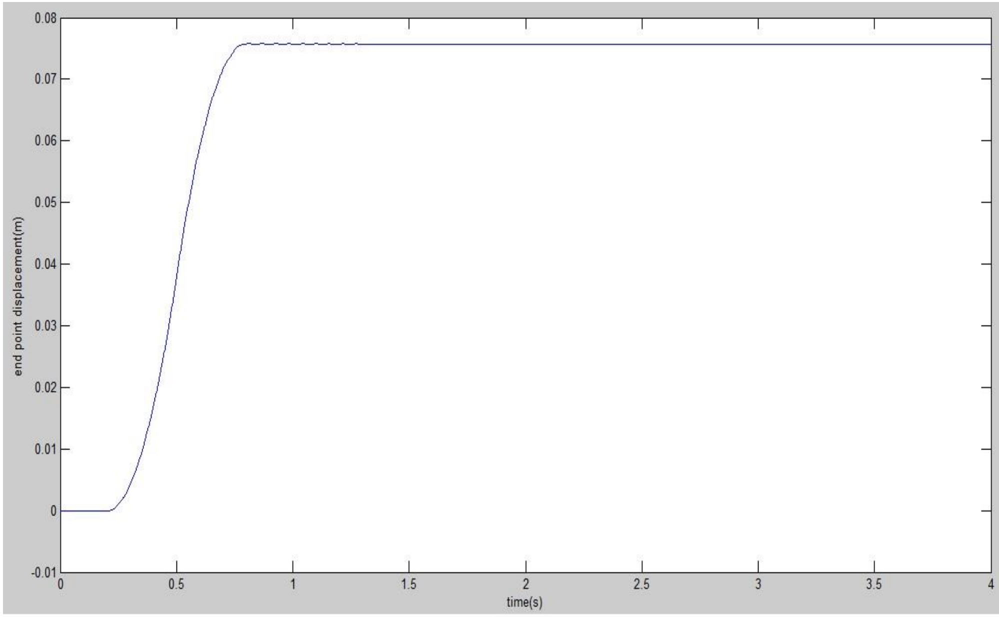

Fig. 4. End Point Displacement Response of Aluminum based Flexible manipulator

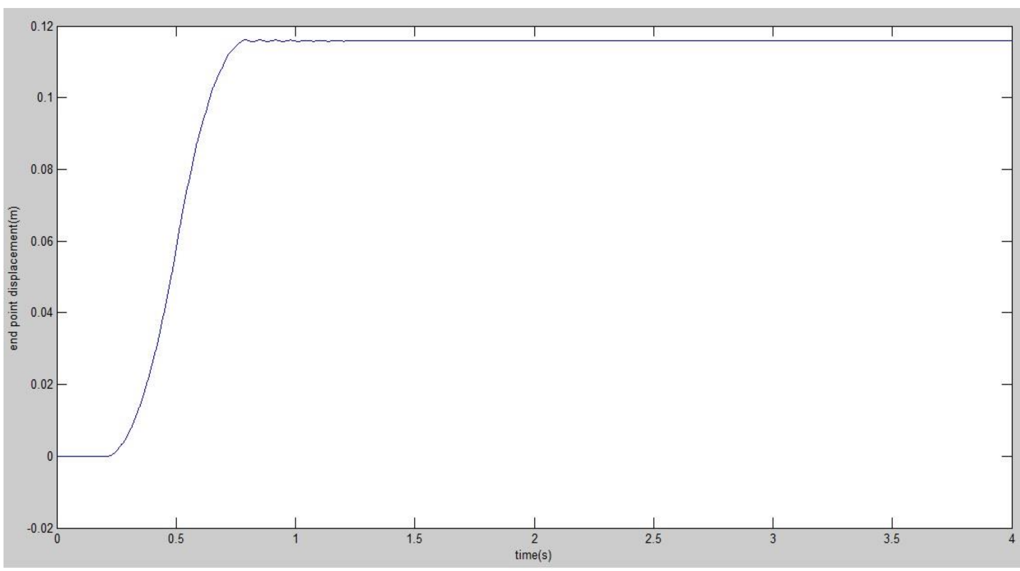

Fig. 5. End Point Displacement Response of Composite Manipulator

From the above plotted Fig. 4 and 5, it is observed that aluminum based manipulator gives end point displacement of 0.075 m whereas for composite manipulator end point displacement produced is 0.12 m and settling of vibration takes place at 1.25 sec for aluminum based manipulator whereas for composite manipulator settling of vibration takes place at 1.15 sec.

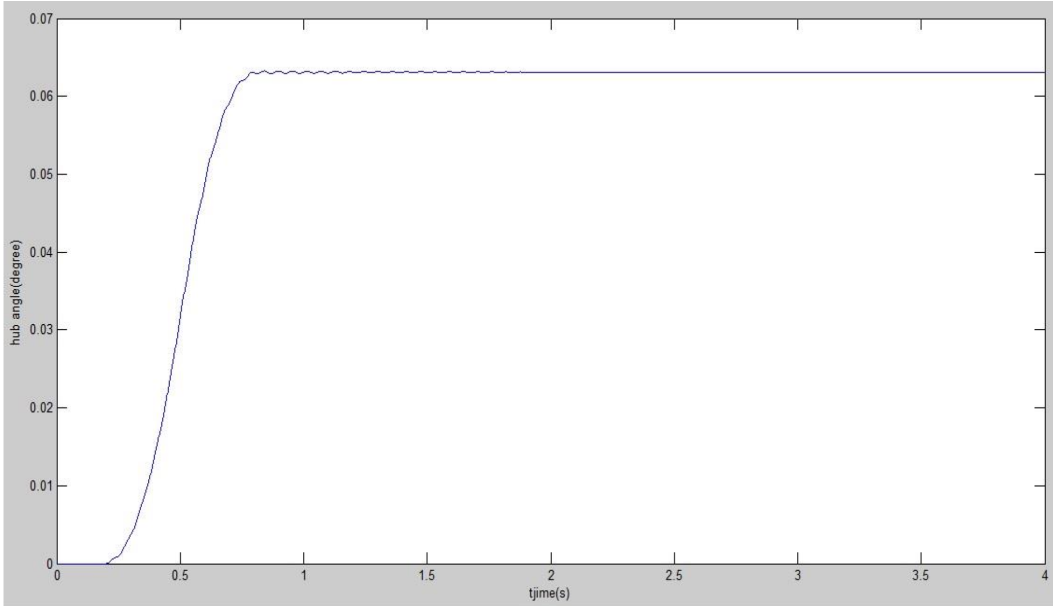

Fig. 6. Hub Angle Response for Aluminum based Flexible Manipulator

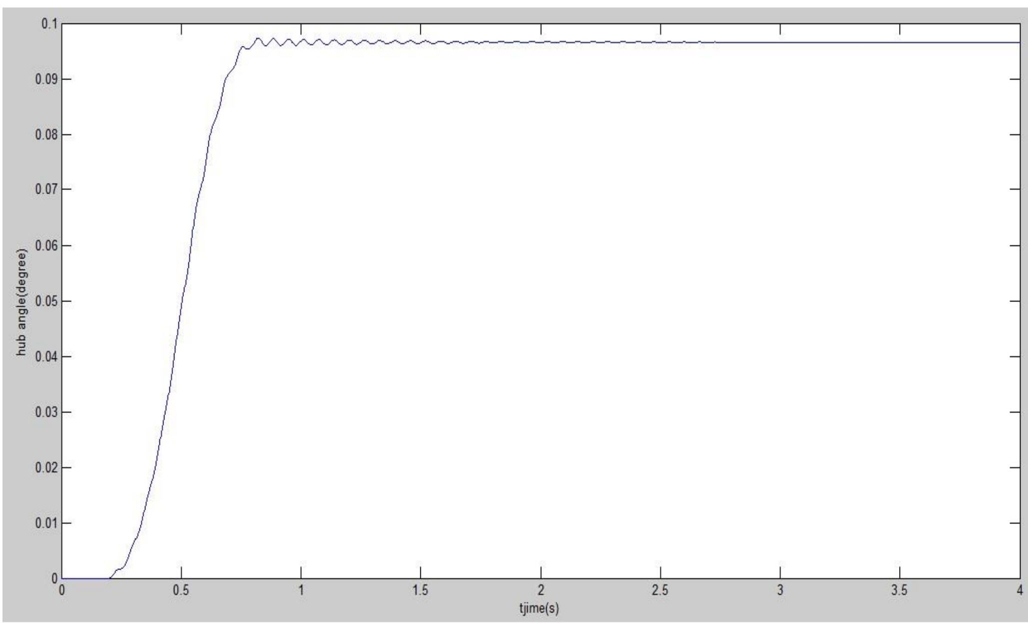

Fig. 7. Hub Angle Response for Composite Manipulator

From above Fig. 6 and 7, it is clearly observed that Hub Angle response for Aluminum based flexible Manipulator is 0.063 degree rotation of hub and settling of vibration takes place at 1.375 sec.

Hub Angle Response for Composite Manipulator gives 0.096 degree of rotation of hub whereas settling time is 2.51 sec.

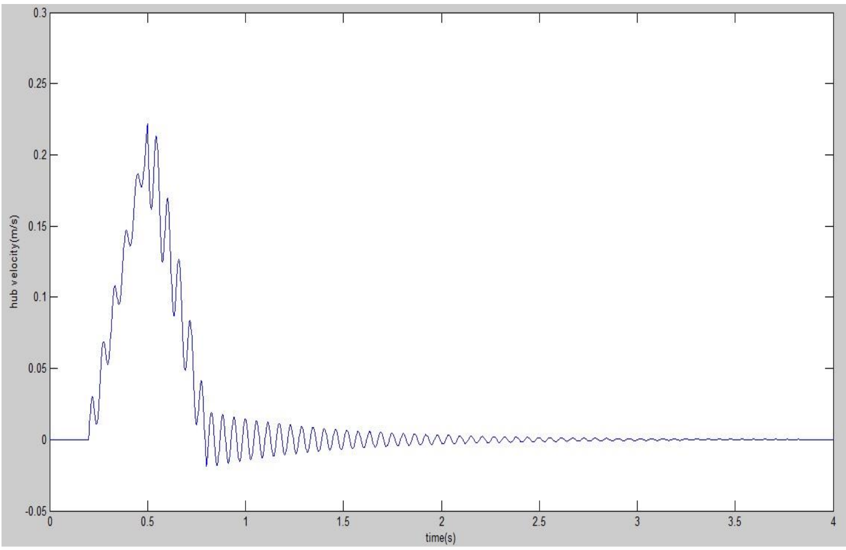

Fig. 8. Hub Velocity Response of Aluminum Based Flexible Manipulator

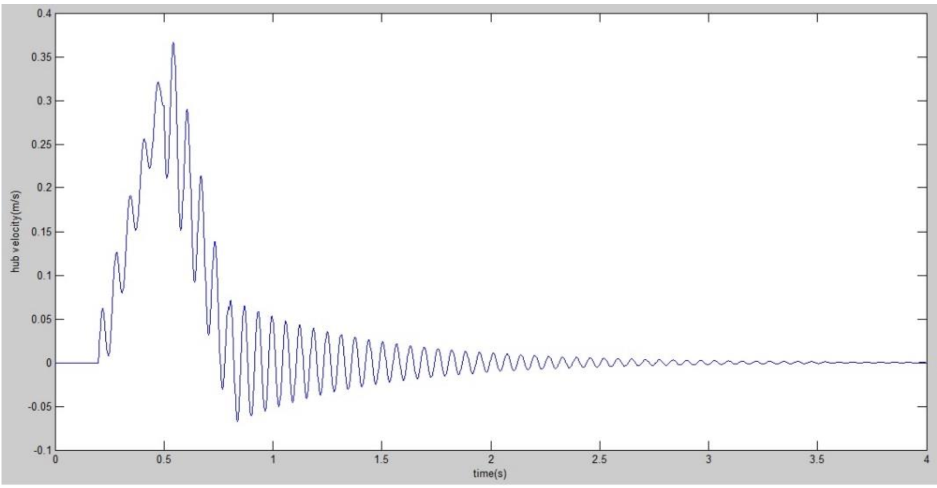

Fig. 9. Hub Velocity Response of Composite Flexible Manipulator

From above Fig. 8 and 9 of Hub Velocity Response it is observed that maximum velocity of hub for Aluminum Based Flexible Manipulator achieved of 0.225 degree/s and settling time is 3.528 sec.

For Composite Flexible Manipulator maximum velocity achieved is 0.3525 degree/s and settling time is 3.95 sec.

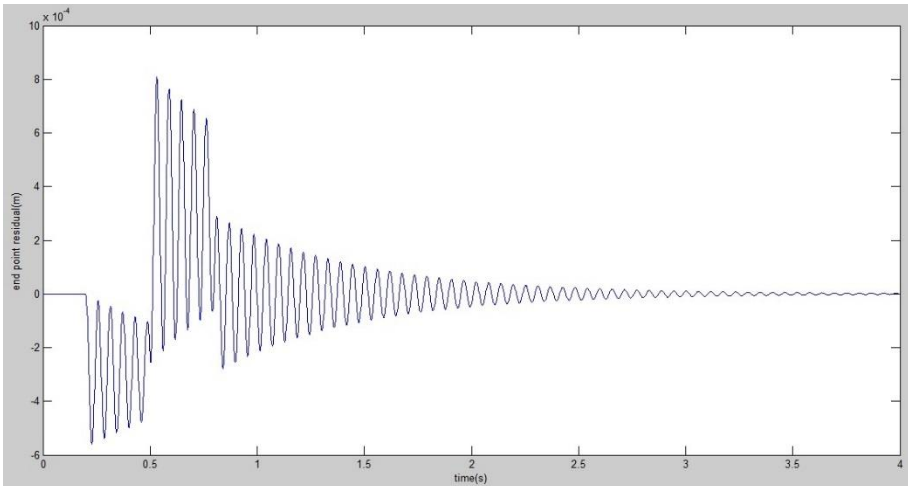

Fig. 10. End Point Residual Response for Aluminum Based Flexible Manipulator

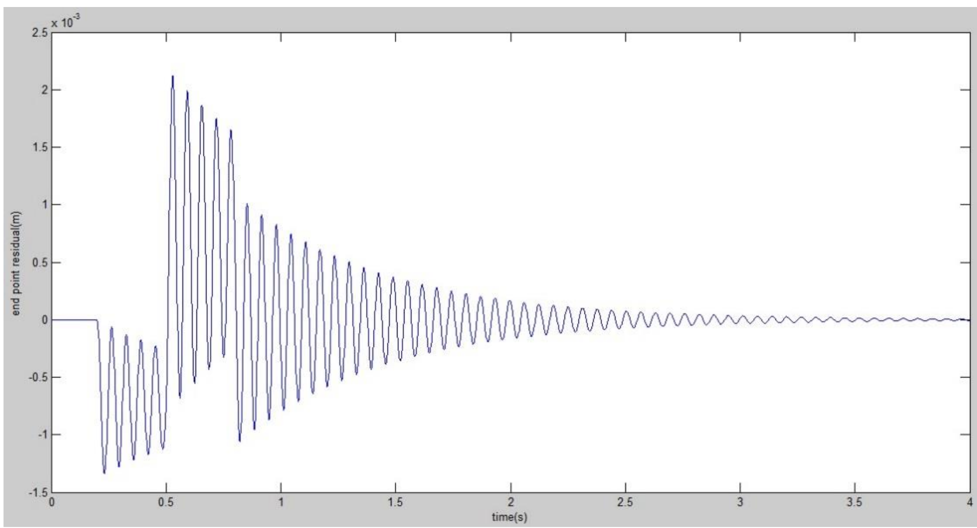

Figure 11. End Point Residual Response for Composite Flexible Manipulator

It is observed from the above Fig. 10 and 11 of End Point Residual Response for Aluminum based Flexible Manipulator that maximum acceleration of end point is $8x10^{-4}m/sec^2$ and deceleration at $-5.9x^{-4}$ m/sec^2.

For Composite Flexible Manipulator maximum acceleration of end point produced is $2.1x10^{-3}$ m/sec^2 and deceleration at $-1.4x10^{-3}$ m/sec^2.

Chapter-5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

From the above result from plotted graph using Matlab code it is observed that performance of composite flexible manipulator is better as compared to aluminum based flexible manipulator. In terms of end point displacement composite manipulator gives more output for the given same input of bang-bang torque than in aluminum based flexible manipulator. Implying need of less power for composite manipulator than aluminum based, consecutively smaller actuator is needed. Settling time for end point is also less in case of composite manipulator than aluminum based manipulator. Hub angle for composite manipulator is more as compared to aluminum based manipulator but settling time of aluminum based manipulator at hub takes less time as compared to composite manipulator. In terms of Hub velocity of composite manipulator attains higher velocity than aluminum based manipulator, whereas settling time for composite manipulator takes longer than aluminum based. In terms of end point residual no significant change observed from both the manipulators.

Better performance of composite manipulator than aluminum based manipulator in terms end point displacement, hub velocity.

5.2 FUTURE SCOPE

i. Modeling of flexible manipulator can be extended to use in two-link flexible manipulator.

ii. Control of vibration of flexible manipulator can be done to further reduce the effect of residual vibration in manipulator.

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