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HUB ANGLE REGULATION AND END EFFECTER VIBRATION CONTROL OF SINGLE LINK FLEXIBLE MANIPULATOR

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Abstract:- Accurate trajectory regulation of flexible link manipulators is a challenging task. In the present work, a single link flexible manipulator with attached piezoelectric patches has been considered for the study. Model free controllers like Proportional-Integral-Derivative (PID) type of compensators provide better hub angle regulation as compared with H∞ optimization based controllers. However, the tip (end - effecter) vibrations can be better compensated using the later. PID controller has been applied for hub angle regulation and H∞ controller is applied at the piezoelectric actuator to reduce the tip vibrations. Different robust control algorithms have been applied. A comparative performance study of the closed loop system showing the relative merits and demerits of each control technique is presented.

***KEYWORDS*:-** Flexible link manipulator, H_∞ controller, μ-synthesis controller, H_∞ loop shaping controller

I.INTRODUCTION

Robotic manipulators are widely used to help in dangerous, monotonous, and tedious jobs. Most of the existing robotic manipulators are designed and build in a manner to maximize stiffness in an attempt to minimize the vibration of the end-effector to achieve good position accuracy. This high stiffness is achieved by using heavy material and a bulky design. Hence, the existing heavy rigid manipulators are shown to be inefficient in terms of power consumption or speed with respect to the operating payload. For these purposes it is very desirable to build flexible robotic manipulators. These conflicting requirements between high speed and high positioning accuracy have rendered the robotic assembly task a challenging research problem. In order to improve industrial productivity, it is required to reduce the weight of the arms and/or to increase their speed of operation. Due to the importance and usefulness of these topics, researchers worldwide are now a day's engaged in the investigation of dynamics and control of flexible manipulator [1-5].

In order to achieve high precision in tip positioning, the use of tip position measurement is essential. In [6], Canon and Schmitz initiated the experiment to control the tip positioning of flexible manipulator by using measurement from a tip positioning sensor as a feedback input. They designed a linear quadratic Gaussian (LQG) controller and the obtained results suggested a satisfactory step response with accurate tip positioning. However, the LQG controller was not robust with respect to modeling errors. If the modeling error has to be considered, robust controllers based on H∞ optimization, are the best option.

To enhance the flexible link's vibration damping property, additional sensors and actuators can be applied [7]. When modeling the flexible links, assumed mode method or finite element method is most often used to obtain the discrete dynamic model for the flexible link. On the parallel lines, researchers have been intensifying over the past two decades regarding active vibration control methods for structures using smart materials. The widely used smart materials

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for vibration control in structures are piezoelectric materials since they have desirable characteristics. Based on these characteristics, piezoelectric materials are being used as sensors and actuators. By using piezoceramic actuators (i.e. lead zirconate titnate or PZT patches) bonded to the flexible link, the link vibrations can be suppressed through a combination of hub motion control and control of PZT actuators. In the context of PZT patch control design, Sun et al [8] studied the active vibration control of flexible link damping problem using a combined scheme of hub PD (proportional derivative) feedback and linear velocity (so called 'L-type') feedback of PZT actuators. In ref. [9] Shaw et al showed that the L-type control of the distributed PZT patches was only conditionally stable and that to ensure stability, the PZT patches had to be placed in spots where the curvature of the link would not inflect across the domain of the patch. To be safe, it was recommended that the PZT patches be placed only at the hub or the tip of the beam to ensure satisfaction of this condition. This work was extended to rotating cantilever beams in references [10-11]. Only recently, Gurses et al [12] investigated on a new shape sensor, ShapeTape™ from Measurand Inc. It was used as an effective feedback sensor for active vibration damping of the flexible link. ShapeTape™ is an array of fiber optic curvature sensors laminated on a thin flexible ribbon substrate/tape, arranged to sense its bends and twist. This resulted in a more effective vibration damping controller. Many control strategies has been applied such as velocity feedback [8], neural networks [13], genetic algorithms [14],adaptive control [15], fuzzy control [16] and so on. Positive position feedback (PPF) was introduced by Goh and Caughey in 1985 [17] for the control of flexible structures. An autonomous control technique was developed using online pole zero identification to design optimal feedback compensator [18]. Normally, PPF control is not optimal for all the modes. Its tuning for optimality for any particular mode reduces the damping effect for other modes of interest. In reference [19], the condition for optimality is provided. It has been observed in the present work that model free control like PID can provide better hub angle regulation as compared with H_∞ optimization based controllers.
However , the tip (end- effecter) vibrations can be better compensated using the later. PID controller has been applied at hub for hub angle regulation and H_∞ controller is applied at the piezoelectric actuator to reduce the tip vibrations. Different robust control algorithms (H_∞ , μ - synthesis based controller and H_∞ based loop shaping controller) have been applied at the piezoelectric actuator. A comparative performance study of the closed loop system shows the relative merits and demerits of each control technique

II.THE FLEXIBLE LINK MANIPULATOR

A. THE MATHEMATICAL MODEL

The flexible link is modeled using the finite element method, as a flexible beam rigidly attached to a rotating hub as shown in the fig.1(a). Euler – Bernoulli beam theory is applied and axial deformation is neglected. The flexible link is assembled using n elements, the hub is node 0 and tip is node n. We first consider the ith beam element, extending between nodes i-1 and i,which has two surface bonded with PZT patches and therefore referred to as piezo-beam element as shown in the fig.1(b). The transverse deflection of the ith element is defined as

$$w_i(x) = a_1 x^3 + a_2 x^2 + a_3 x + a_4 \qquad (1)$$

Where the x axis originates at node i-1 and is aligned with the deformed piezo-beam element. Applying boundary conditions on the deflection and factoring the nodal degree of freedom produces the hermitian shape function,N_1 through N_4 [20]

$$w_i(x,t) = N(x)\, d_i(t) \qquad (2)$$

Where

$$N(x) = [N_1\ N_2\ N_3\ N_4]$$
$$d_i(t) = \{d_y{}^{(i-1)}\ \phi^{(i-1)}\ d_y{}^{(i)}\ \phi^{(i)}\}$$
$$N_1 = \frac{1}{L^3}(2x^3 - 3x^2L + L^3),$$
$$N_2 = \frac{1}{L^3}(x^3L - 2x^2L^2 + xL^3)$$

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$$N_3 = \frac{1}{L^3}(-2x^3 + 3x^2 L)$$
$$N_4 = \frac{1}{L^3}(x^3 L - x^2 L^2)$$

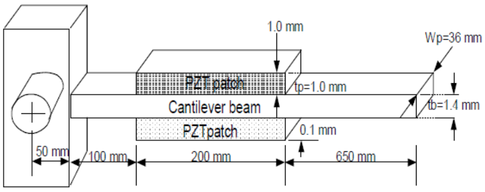

Fig. 1(a) Flexible beam with PZT actuator and PVDF sensor

Where L denotes the length of the ith element. N(x) is matrix of shape functions and $d_i(t)$ is the vector containing the nodal DOF – two translational ($d_y^{(i-1)}$ at node i-1 and $d_y^{(i)}$ at node i) and two rotational($\varphi^{(i-1)}$ at node i-1 and $\varphi^{(i)}$ at node i). The kinetic and strain energy equations for the ith element are given by

$$T_i = \frac{1}{2}\int_0^L (\rho_b A_b + \rho_p A_p)\{(\dot{N} d_i)(\dot{N} d_i) + [x^2 + (N d_i)(N d_i)]\dot{\theta}^2 + 2(\dot{N} d_i)x\dot{\theta}\}dx \quad (3)$$

$$U_i = \frac{1}{2}\int_0^L (\overline{EI})(\ddot{N} d_i)(\ddot{N} d_i)dx \quad (4)$$

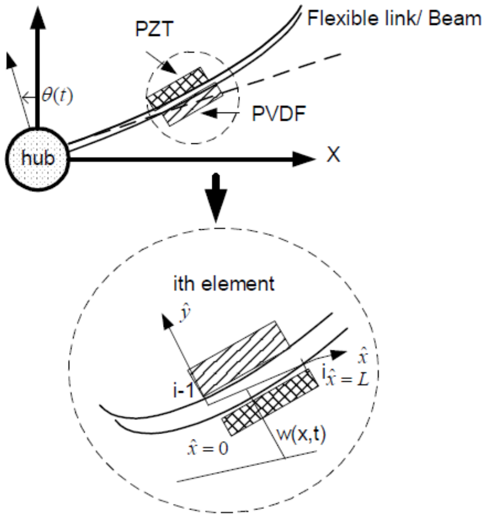

Fig. 1(b) Piezo Beam element

Lagranges equations for the ith element are given by

$$\frac{d}{dt}\left[\frac{\partial T_i}{\partial \dot{d}_i}\right] - \frac{\partial T_i}{\partial d_i} + \frac{\partial U_i}{\partial d_i} = Q_{d,i} \quad (5a)$$

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$$\frac{d}{dt}\left[\frac{\partial T_i}{\partial \theta}\right] - \frac{\partial T_i}{\partial \theta} + \frac{\partial U_i}{\partial \theta} = Q_{\theta,i} \qquad (5b)$$

Where $Q_{d,I}$ and $Q_{\theta,I}$ are the generalized forces associated with the beam deformation and hub rotation.
Expressing these equation in a matrix form produces state space model for the ith element.

$$\begin{bmatrix} M & A \\ A^T & {d_i}^T M d_i + D \end{bmatrix}\begin{bmatrix} \ddot{d}_i \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} 0 & -M\theta d_i \\ \dot{\theta}{d_i}^T M & {d_i}^T M d_i \end{bmatrix}\begin{bmatrix} \dot{d}_i \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} K \\ 0 \end{bmatrix}\begin{bmatrix} d_i \\ \theta \end{bmatrix} = \begin{bmatrix} Q_{d,i} \\ Q_{\theta,i} \end{bmatrix} \qquad (6)$$

where

$$M = (\rho_b A_b + \rho_p A_p)\left[\int_0^L N^T N dx\right], A = \rho_b A_b + \rho_p A_p \left[\int_0^L N^T x dx\right] \quad ,$$

$$K = \overline{EI}\int_0^L \ddot{N}^T \ddot{N} dx$$

The model for the entire flexible beam is formed by assembling a series of the element equations. The assembled equation of motion are given by

$$\begin{bmatrix} M_G & A_G \\ A_G^T & J_0 \end{bmatrix}\begin{bmatrix} \ddot{d}_G \\ \ddot{\theta} \end{bmatrix} + \begin{bmatrix} 0 & -M_G\theta d_G \\ \dot{\theta}{d_G}^T M_G & {d_G}^T M_G d_g \end{bmatrix}\begin{bmatrix} \dot{d}_G \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} K_G \\ 0 \end{bmatrix}\begin{bmatrix} d_G \\ \theta \end{bmatrix} = \begin{bmatrix} F_G \\ u(t) \end{bmatrix} \qquad (7)$$

The resultant flexible link system is a two input and three output system. The inputs are applied torque and PZT actuation. Outputs are hub angle, tip displacement and PVDF sensor output. The frequency response function of multi input and multi output system is shown in the fig2

B. *LINEAR FRACTIONAL TRANSFORMATION MODELING*

It is common practice to represent the system uncertainties in LFT form. Every single mode of a structural system is represented in transfer function form by equation.

$$\frac{y}{u} = \frac{\phi_{12}}{s^2 + 2\xi\omega s + \omega^2} \qquad (8)$$

Where φ_{12} ,ξ and ω represent the product of mode shapes at actuator and sensor locations, damping ratio and natural frequency of the structural system. All the parameters are subjected to change around some nominal values like

$$\phi_{12} = \bar{\phi}_{12}(1 + p_{\phi_{12}}\delta_{\phi_{12}}) \qquad (9)$$

$$2\xi = 2\bar{\xi}(1 + p_{2\xi}\delta_{2\xi}) \qquad (10)$$

$$\omega = \bar{\omega}(1 + p_{\omega}\delta_{\omega}) \qquad (11)$$

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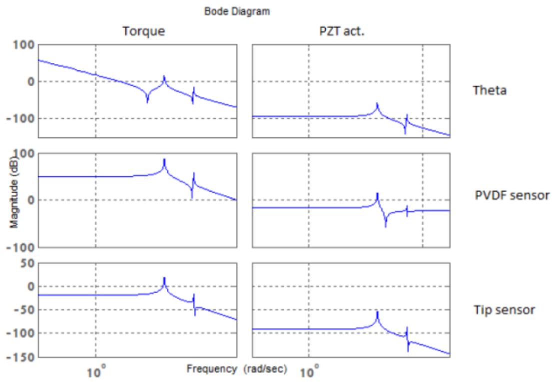

Fig. 2 Frquency Response function of Multi-Input Multi output Single link flexible manipulator

$$\omega^2 = \bar{\omega}^2(1 + p_{\omega^2}\delta_{\omega^2}) \qquad (12)$$

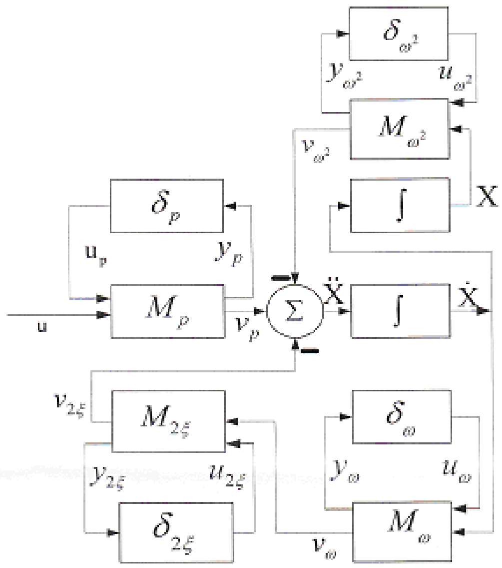

Fig. 3 LFT representation for a single mode

Where$\bar{\phi}_{12}$ $2\bar{\xi}, \bar{\omega}$ and $\bar{\omega}^2$ are the nominal values of φ_{12}, 2ξ, ω and ω^2 respectively. δ_φ , $\delta_{2\xi}$,δ_ω , δ are corresponding perturbations around the nominal values.The values of the parameters $p_{\phi_{12}}$, $p_{2\xi}$,p_ω , p_{ω^2} ranges from 0 to1. These are structured uncertainties and variations in low frequency dynamics can be represented by these type of uncertainties as shown in the fig. 3.

In the present work, the effect of high frequency dynamics has been taken into consideration by using feed through term. Unstructured uncertainties have not been considered. perturbed parameters can be written in the form given as

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forming the standard configuration to represent the system.

$$\begin{bmatrix} y_{\phi_{12}} \\ V_{\phi_{12}} \end{bmatrix} = \begin{bmatrix} 0 & \bar{\Phi}_{12} \\ p_{\phi_{12}} & \bar{\Phi}_{12} \end{bmatrix} \begin{bmatrix} u_{\phi_{12}} \\ u \end{bmatrix} \qquad (13)$$

$$\begin{bmatrix} y_{2\xi} \\ V_{2\xi} \end{bmatrix} = \begin{bmatrix} 0 & 2\bar{\xi} \\ p_{2\xi} & 2\bar{\xi} \end{bmatrix} \begin{bmatrix} u_{2\xi} \\ V_{\omega} \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} y_{\omega} \\ V_{\omega} \end{bmatrix} = \begin{bmatrix} 0 & \bar{\omega} \\ p_{\omega} & \bar{\omega} \end{bmatrix} \begin{bmatrix} u_{\omega} \\ X \end{bmatrix} \qquad (15)$$

$$\begin{bmatrix} y_{\omega^2} \\ V_{\omega^2} \end{bmatrix} = \begin{bmatrix} 0 & \bar{\omega}^2 \\ p_{\omega^2} & \bar{\omega}^2 \end{bmatrix} \begin{bmatrix} u_{\omega^2} \\ X \end{bmatrix} \qquad (16)$$

$$u_{\phi_{12}} = \delta_{\phi_{12}} y_{\phi_{12}} \qquad (17)$$

$$u_{2\xi} = \delta_{2\xi} y_{2\xi} \qquad (18)$$

$$u_{\omega} = \delta_{\omega} y_{\omega} \qquad (19)$$

$$u_{\omega^2} = \delta_{\omega^2} y_{\omega^2} \qquad (20)$$

The uncertainty matrix Δ, corresponding to parameter variations is a diagonal matrix.

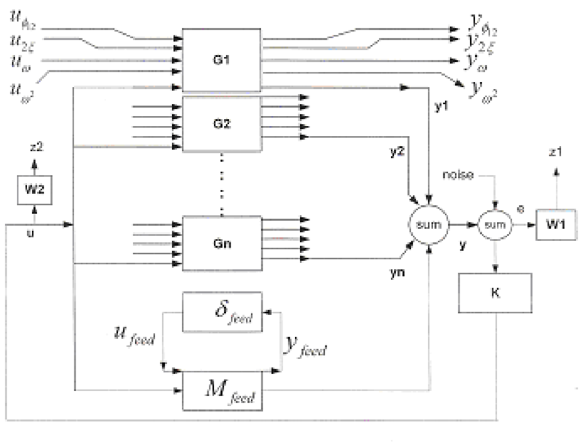

Fig. 4 Input Output block diagram of the multiple mode flexible manipulator along with a controller

$$\Delta = \begin{bmatrix} \Delta_1 & 0 & 0 & 0 \\ 0 & \Delta_2 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \Delta_9 \end{bmatrix} \qquad (21)$$

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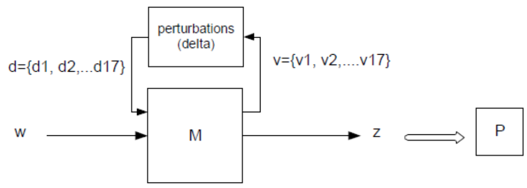

Fig. 5 Standard M- Δ Configuration

It contains nine perturbed parameters. The model contains two modes. There are four perturbed parameters in each mode. The 9th parameter corresponds to feed through term. In this manner, the real and complex uncertainties can be separated easily[22].The system uncertainties can be represented in the form of real parameter uncertainties as compared to complex uncertainties which are normally available from FEM based models. The controller designed by considering first type of uncertainties only, are better in terms of robust stability and performance as compared to later. By combining different modes, the model can be generated for multiple modes as shown in fig.4 .Fig. 5shows the standard M-Δ configuration. Fig.6 shows the standard H_∞ configuration. Where W_1 and W_2 are weighting functions used for controller design. W_1 is the performance weighting function and W_2 is the control weighting function as shown in the fig 7.

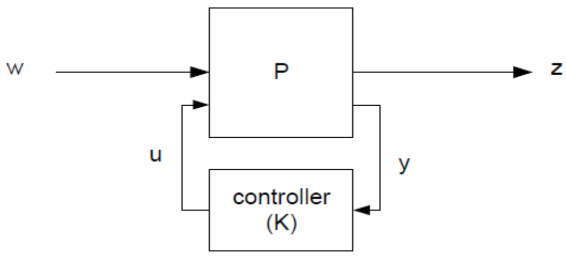

Fig. 6 Standard $\mathbf{H_\infty}$ configuration

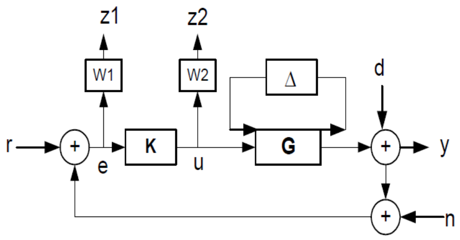

Fig. 7 Mixed sensitivity configuration

C. *THE EXPERIMENTAL SETUP*

The flexible manipulator used here consists of a steel beam (950 mm x 36 mm x 1.4 mm) clamped directly to the shaft of a Glentic GM 4040-41 dc brush servo motor. An illustration of the experimental set up is shown in fig.8.

The motor was driven by a Glentek GA 377 pulse width modulation servo amplifier. The motor has a continuous stall torque of 3.54 Nm and a maximum bandwidth of 58 Hz. The shaft encoder of the motor was used to measure the hub angle rotation. It has a least count of 0.072. MA-17 high voltage amplifier was used to amplify the signal to be given *to PZT* actuator. An infrared light - emitting diode (LED) and a Hamamatsu S 1352 position sensitive detector was used

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to measure the tip deflection of the beam. The LED was fixed on the top of the hub. A Hamamatsu C 5923 signal processing unit was used to drive the infrared LED. A dSPACE DS 1103 controller board was used for real time control application. A sampling frequency of 30 kHz was used in order to avoid aliasing.

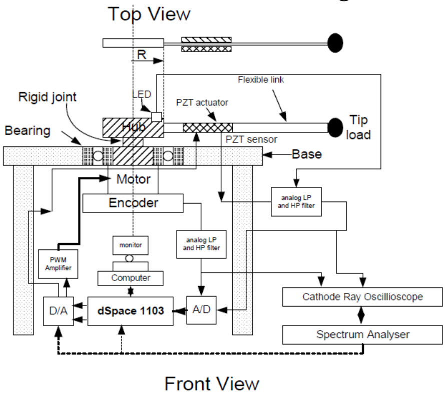

Fig. 8 Experimental Setup of the single link manipulator

III. CONTROLLER DESIGN

A. *HUB ANGLE REGULATION*

Hub angle regulation is obtained using PID controller designed on pattern search technique. The parameters of the PID controller are designed using Simulink Response Optimisation tool box of the MATLAB. Pattern search algorithm is used. Pattern search algorithm computes a sequence of point that closer and closer to the optimal point. At each step, the algorithm searches a set of points called Mesh, around the current point, the point computed at the previous step of the algorithm. The algorithm forms the mesh by adding the current point to a scalar multiple of a fixed set of vector called a pattern. If the algorithm finds a point in the mesh that improves the objective function at the current point, the new point becomes the current point at the next step of the algorithm. The timer intervals t_1 (lower) to t_4 (lower) and t_1(upper) to t_4 (upper) are chosen based on the actual trajectory to be followed as show in Fig. 9.

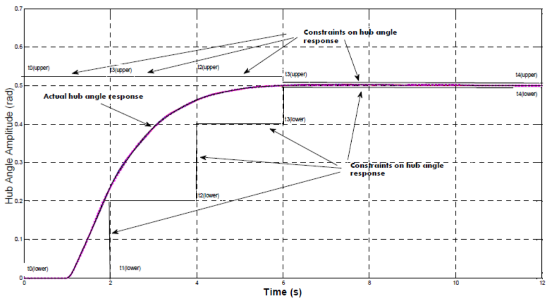

Fig. 9 Constraints on the Hub Angle

B. *H$_\infty$ CONTROLLER DESIGN*

The **H$_\infty$** solution Formulas uses solutions of two Algebraic Riccati Equation (ARE). An ARE is:

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$$E^TX + XE - XWX + Q = 0 \qquad (22)$$

Where $W=W^T$ and $Q=Q^T$, uniquely correspond to a Hamiltonian matrix $\begin{bmatrix} E & -W \\ -Q & -E^T \end{bmatrix}$. The stabilizing solution X, if it exists, is a matrix which solves the ARE and is such that **E-WX** is a stable matrix. Similarly the second ARE gives solution of Y. Then, the central controller K can be designed by using X and Y[22]. The MATLAB command 'hinfyn' can be used to design $\mathbf{H}_\infty$ controller in continuous time domain.

C. *H_∞ LOOP SHAPING CONTROLLER DESIGN*

The $\mathbf{H}_\infty$ robust stabilization against such perturbations and the consequently developed design method, the $\mathbf{H}_\infty$ LSDP[22], could relax the restrictions on the number of right-half plane poles and produce no pole-zero cancellations between the nominal model and controller designed. This method does not require an iterative procedure to obtain an optimal solution and thus raises the computational efficiency. Using a pre-compensator, W_1 , and/or a post compensator, W_2, the singular values of the nominal system G are modified to give a desired loop shape. The nominal system and weighting functions W_1 and W_2 are combined to form the shaped system, G_S, where $G_S = W_2GW_1$. It is assumed that W_1 and $W_2$are such that G_S contains no hidden unstable modes. A feedback controller, K_S, is synthesized which robustly stabilizes the normalized left co-prime factorization of G_S, with a stability margin ε. It can be shown [22] that if ε is not less than 0.2, the frequency response of $K_SW_2GW_1$ will be similar to that of W_2GW_1. On the other hand, if the achievable ε is too big, that would probably indicate an over-designed case in respect of the robustness, which means that the performance of the system may possibly be improved by using a lager γ in computing K_S. The final feedback controller, K_{final}, is then constructed by combining the $\mathbf{H}_\infty$ controller K_S, with the weighting functions W_1 and W_2

$$K_{final}=W_1K_SW_2 \qquad (23)$$

MATLAB Command 'ncfsyn' can be used to design the loop shaping design procedure based controller. This command synthesizes a controller to robustly stabilize a family of systems given by a ball of uncertainty in the normalized co prime factor of the system description.

D. *μ-SYNTHESIS CONTROLLER*

For robust stability and robust performance, it is required to find a stabilizing controller K such that

$$\underset{\omega \epsilon R}{sub}\, \mu[M(P,K)(j\omega)] < 1 \qquad (24)$$

An iterative method was proposed to solve (24) in ref [22]. The method is called D-K iterative method and is based on solving the following optimization method, for the

stabilizing controller K and a diagonal constant scaling matrix D

$$\underset{K(s)}{inf}\ \underset{\omega \epsilon R}{sup}\ \underset{D \epsilon D}{inf}\, \bar{\sigma}[DM(P,K)D^{-1}(j\omega)] \qquad (25)$$

Where the scaling matrix D is defined [22]. InShort μ-synthesis algorithm is given as

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1. Start with an initial guess for D, Usually D=I.
2. Fix D and solve **H**$_\infty$ optimization of K,

$$K = arg \inf_{K} \|F_l(P, K)\|_\infty$$

3. Fix K and solve convex optimization problem D at each frequency over a selected frequency range,

$$D(j\omega) = arg \inf_{D \epsilon D} \bar{\sigma}[DF_l(P,K)D^{-1}(j\omega)]$$

4. Curve fit D(jω)to get a stable, minimum phase D(s).
5. Go to step 2 and repeat until a pre-specified convergence is achieved

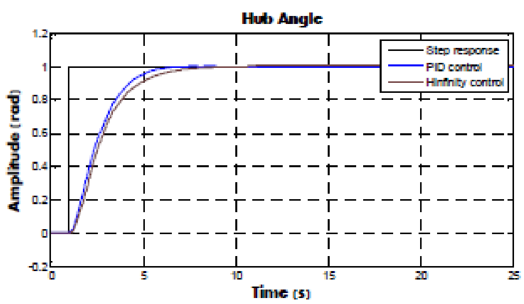
MATLAB Command 'dkit' can be used to design the μ synthesis based controller.

IV. EXPERMENTAL RESULTS

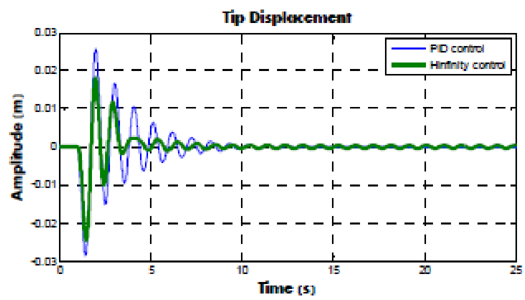
PID and H$_\infty$ controller both are first applied at the hub alternatively. For a step change in hub angle position, with a tip load of 0.1 Kg,it is found that the hub angle trajectory following is better with PID control and tip vibration reduction is better with H$_\infty$ controller as shown in the fig.10 Similarly, for the perturbed system with 0.4kg tip load, better follow up of hub angle trajectory can be made by using PID controller as compared to H$_\infty$ controller at the hub as shown in the fig11. Therefore it is decided to apply PID controller at the hub and three different robust controller (H$_\infty$ controller , μ- synthesis based controller and H$_\infty$ based loop shaping controller) were applied at the piezoelectric actuator attached to the flexible link.

Fig. 12shows the hub angle regulation obtained by using PID controller at the hub and different robust controllers at the piezoelectric actuator with 0.1Kg tip load. End effecter vibration response with different robust controllers with 0.1Kg tip load is shown in the fig.13 and control voltage applied at the piezoelectric patch using various robust controllers are shown in the fig.14.

These controllers are then tested for the perturbed system with 0.4Kg tip load. Fig. 15 shows the hub angle responses. Fig.16 and fig.17 shows the tip response and control voltage applied at the piezoelectric patch.



(a)



(b)

Fig. 10(a) & (b) Comparison of PID and H$_\infty$ Control for 0.1 Kg tip load

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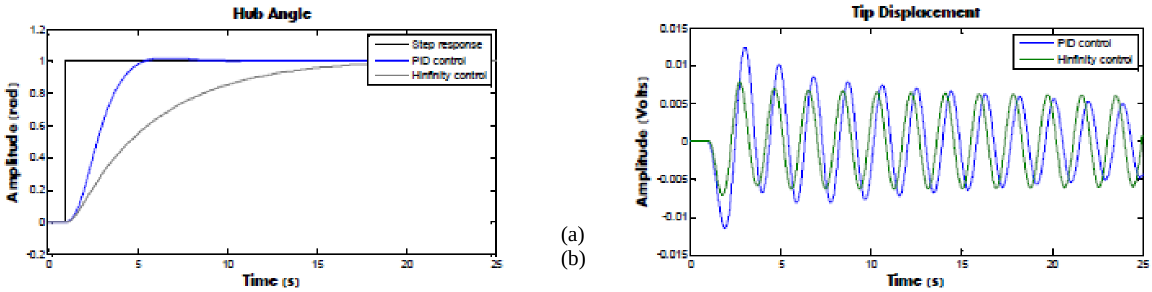

Fig. 11(a) & (b) Comparison of PID and H_∞ Control for 0.4 Kg tip load

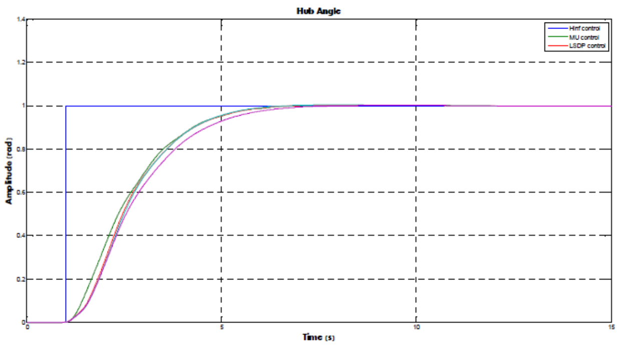

Fig.12 Hub Angle regulation Using Various Robust Control Techniques at 0.1 Kg Tip Load

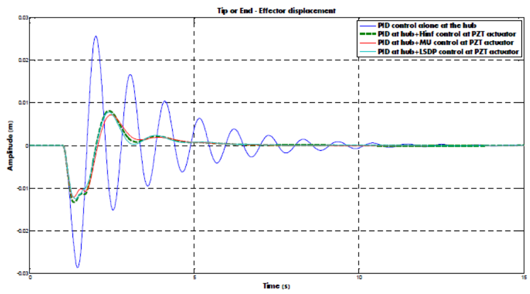

Fig.13 Tip Displacement Using Various Robust Control Techniques at 0.1 Kg Tip Load

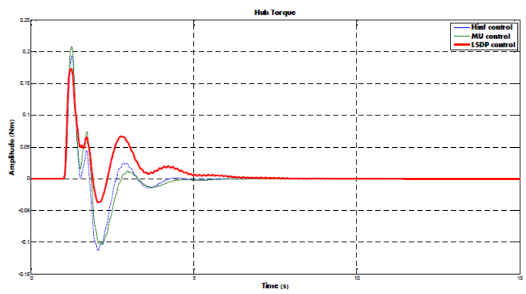

Fig.14 Control Voltage applied at the PZT patch Using Various Robust Control Techniques at 0.1 Kg Tip Load

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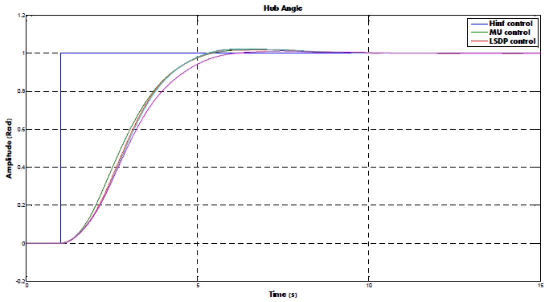

Fig.15Hub Angle regulation Using Various Robust Control Techniques at 0.4 Kg Tip Load

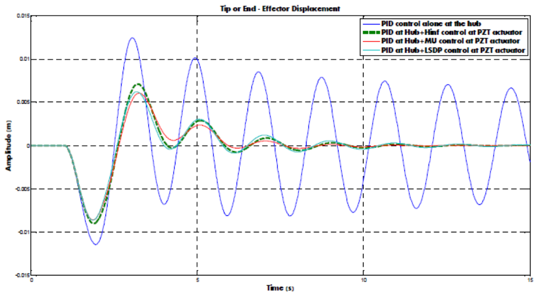

Fig.16 Tip Displacement Using Various Robust Control Techniques at 0.4 Kg Tip Load

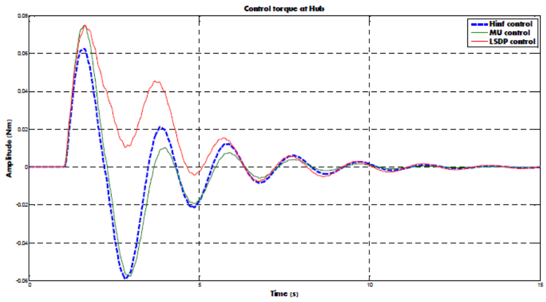

Fig.17 Control Voltage applied at the PZT patch Using Various Robust Control Techniques at 0.4 Kg Tip Load

V. CONCLUSION

To study the performance of the system with different robust control techniques applied at the piezoelectric actuator , it is found that better end effecter vibration suppression is obtained with PID controller at the hub and with any one of the robust controller at the PZT actuator with 0.1Kg and 0.4Kg tip loads. But in perturbed system, the settling time is more as compared to nominal system As far as comparison of control effort required to suppress vibration using different control methods as shown in the table 1.It is found that for the nominal system with 0.1Kg tip load LSDP based controller requires minimum control effort and however for the perturbed system H_∞ controller requires the minimum control effort for the same effectiveness for vibration reduction. Therefore the manipulator which is being used for pick and place purpose, H_∞ controller best serves the purpose.

Table 1:- Comparison of Control Effort using different control strategies

Tip Load	H_{inf}	% Saving	μ-Synthesis	% Saving	LSDP	% Saving
0.1 Kg	2.3	13.86	2.58	27.72	2.02	0
0.4 Kg	0.7	0	0.83	18.57	0.92	31.43

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