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Experimental Verification on Vibration Suppression of a Flexible Manipulator Using MPID Controller

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***Abstract*— This paper presents a MPID (Modified Proportional-Integral-Derivative) controller used to suppress vibration of flexible manipulator moving vertically. To attain the vibration suppression a vibration variable should play role in the control signal which drives the flexible manipulator. The proposed controller is based on the conventional PID control but the integral term is replaced with another one which mainly depends on the vibration of the end effector. Camera becomes an inherent part of space manipulator, using the MPID controller with the visual information recorded by the camera makes the strain measuring circuits and amplifiers unnecessary. This means reducing the hardware used in the control of flexible manipulator. The novelty of the results lies in the fact that the measurement of the rate of change in deflection, which is used as a vibration variable, has been done without the need of numerical differentiation. Experiments successfully demonstrate that using the visual data with an observer based on Kalman filer can achieve a noticeable damping of the end effector vibration of the flexible manipulator.**

***Index Terms*— Flexible manipulator, Kalman filter, Modified PID, Vibration suppression.**

I. Introduction

Interest has been focused in the study of control flexible link manipulators in the last decades. Flexible-link manipulators are especially feasible for applications in space, such as in orbit or on other planets because the cost for launching is proportional to the weight of the object to be launched. Not only the benefits of the lower energy consumption compared with rigid link robots but also those robots can work in a faster speed than the normal massive rigid robots. A safer operation can be granted due to reduced inertia. The suppressing of vibration of the end effector is considered as one of the great challenges facing the spreading of using flexible manipulators in wide applications. In space applications, the vibrations of the end effector have undesirable effects on the precision of the executed tasks. Beside that, it increases the execution time of the manipulator task since vibrations of the end effector have to be attenuated before any other task takes place.

Since Cannon et al. [1] performed initial experiments using linear quadratic approach, various control methods have been used to control flexible link manipulators. Cetinkunt and Book [2] started by studying the performance limitations of flexible manipulators under joint variable-feedback control only. They made a finite-dimensional time-domain dynamic model of a two-link, two-joint planar manipulator and emphasized on the limitations of control algorithms that use only joint variable-feedback information in calculations of control decisions since most motion control systems in practice are of this kind.

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Many researchers try to use the traditional controller with a kind of modification to increase the ability of suppressing the vibration due to the flexibility of the manipulators. The most widely way used for enhancement of the traditional PD controller is done by adding a term related to the vibration to controller. Lee et al. proposed PDS (proportional-derivative strain) control for vibration suppression of multi-flexible-link manipulators and analysed the Lyapunov stability of the PDS control [3]. Matsuno and Hayashi, applied the PDS control to a cooperative task of two one-link flexible arms [4]. They aimed to accomplish the desired grasping force for a common rigid object and the vibration absorption of the flexible arms. Sun et al. [5] tried to suppress the flexible beams vibration using a control law combining two controllers. They used enhanced PD feedback with a non-linear differentiator to derive a high-quality velocity signal to control the gross motion of the beam and a vibration control by piezoelectric actuators bonded on the surface of the beam.

A two-step for design of flexible link manipulator control is presented by Cheong et al. [6]. After investigating the relationship between macro joint tracking performance and vibration suppression capability using the bandwidth parameter, they made a composite control, which is the second step, consisting of rigid and flexible sub-controllers by using a direct modal feedback. Mohamed et al. developed a collocated PD controller for control of rigid body motion by using feed forward control scheme based on input shaping, low-pass filtering techniques. A strain feedback control technique have been combined with the PD control for vibration control of the manipulator [7]. Economoua et al. [8] proposed a preconditioning approach based on designing a conventional low-pass IIR digital filters. After establishing the requirements for a preconditioned guidance function that moves the flexible system to a desired end position without exciting residual vibration effects, they achieved these requirements by the proper design of a digital IIR filter.

Other researchers give attention to the use of visual information aiming to enhance the vibration of the flexible manipulators. Yoshikawa et al. focused on using visual sensor to measure distributed state variables of flexible manipulators [9] and Bascetta and Rocco [10] utilized the visual servoing of eye-in-hand flexible manipulators to control the tip position.

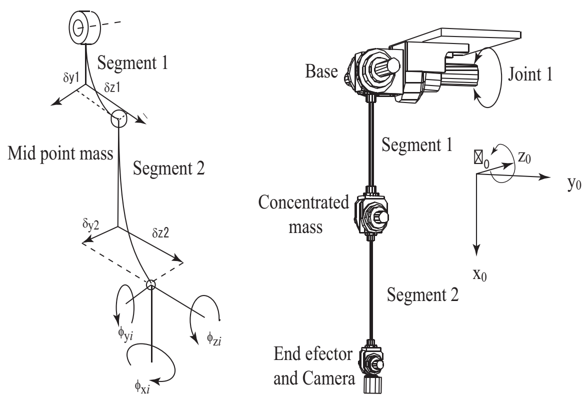

Fig. 1. Schematic of the flexible manipulator.

In this research, a MPID (Modified Proportional-Integral-Derivative) controller will be proposed. The MPID is characterized by using the rate of change in deflection of the end effector as a vibration feedback variable. The vibration variable is estimated using the visual information collected from a camera at the end effector. The controller is used for suppressing the vibration of flexible manipulator moving vertically to exercise the ability of the MPID to deal with the effect of gravity.

The paper is organized as follows. Section I gives a brief introduction about the control of flexible manipulators. In section II the mathematical modelling of the experimental system is driven. The proposed controller for vibration suppression is explained in section III. The method used in evaluating the vibration variable and the merits of using visual measurement in finding the rate of change of deflection is highlighted in section IV. In section V, the proposed method for measuring the vibration variable is applied to a flexible manipulator and the experimental verification for the controller is done. The conclusion of the paper is finally presented in section VI.

II. Modelling

The real flexible-link manipulator shown in Fig. 1 is a 3D flexible manipulator. To verify the proposed controller (i.e. MPID) experimentally, the flexible-link manipulator is intentionally used as 2D flexible manipulator moving vertically. A previous research has been done for the usage of this controller with a single-link flexible manipulator moving horizontally [11]. The flexible manipulator is modelled by lumped masses and massless springs. The masses are assumed to be concentrated on the base, mid-point, and end-effector. They are considered to be connected with massless flexible link segments. In the analysis, it is considered that the flexible link is divided into two segments with a concentrated mass between them. The first segment lies between base joint and the mid-point mass and the second segment connects the mid-point to the end effector. A camera is attached to the end effector. The dynamics equation can be expressed as:

$$\begin{bmatrix}\tau\\0\end{bmatrix}=\begin{bmatrix}M_{11}(\theta,e) & M_{12}(\theta,e)\\M_{21}(\theta,e) & M_{22}(\theta,e)\end{bmatrix}\begin{bmatrix}\ddot{\theta}\\\ddot{e}\end{bmatrix}+\begin{bmatrix}h_1(\theta,\dot{\theta},e,\dot{e})\\h_2(\theta,\dot{\theta},e,\dot{e})\end{bmatrix} + \begin{bmatrix}0 & 0\\0 & K_{22}\end{bmatrix}\begin{bmatrix}\theta\\e\end{bmatrix}+\begin{bmatrix}g_1(\theta,e)\\g_2(\theta,e)\end{bmatrix}, \quad (1)$$

where θ is the joint angle and $e=[e_1,\ \cdots e_m]^T$ is the deflection variable vector, τ stands for the input joint torque vector, M_{11}, M_{12}, M_{21} and M_{22} are inertia matrices, h_1 , h_2 are the centrifugal and Coriolis force vectors, K_{22} represents the stiffness matrix and g_1 , g_2 are gravity vectors. A velocity controlled actuator is used in the system to drive the base joint, joint 1, and thus the actual inputs to the system is formed as an angular velocity reference for the joint.

In the research, the analysis deals with relatively slow motions, so it is acceptable to assume that the centrifugal and Coriolis terms can be neglected. The elastic vibration is excited around the equilibrium state of the joint configuration, where the bending of link segments take balance with gravity effect. Referring to (1), the following equilibrium conditions can be derived:

$$\begin{bmatrix}0 & 0\\0 & K_{22}\end{bmatrix}\begin{bmatrix}\theta_0\\e_0\end{bmatrix}+\begin{bmatrix}g_1(\theta_0)\\g_2(\theta_0)\end{bmatrix}=\begin{bmatrix}\tau_0\\0\end{bmatrix}, \quad (2)$$

where θ_0 is a given joint configuration, e_0 is the static deflection, and τ_0 is the torque to maintain balance. The influence of deflection on gravity terms is ignored. Δe and $\Delta\tau$ are defined to represent the deviation of corresponding variables from their static values as follows:

$$\Delta e \quad = \quad e-e_0=e+K_{22}^{-1}g_2(\theta_0), \quad (3)$$
$$\Delta\tau \quad = \quad \tau-g_1(\theta_0). \quad (4)$$

With these variables, a linearized model is derived as:

$$\begin{bmatrix}M_{11} & M_{12}\\M_{21} & M_{22}\end{bmatrix}\begin{bmatrix}\ddot{\theta}\\\Delta\ddot{e}\end{bmatrix}+\begin{bmatrix}0 & 0\\0 & K_{22}\end{bmatrix}\begin{bmatrix}\theta\\\Delta e\end{bmatrix}=\begin{bmatrix}\Delta\tau\\0\end{bmatrix}, \quad (5)$$

where Δe is computed from (3). It should be noticed that the lower part of (5) can be thought to dominate the behaviour of vibration. For motions in free space, it can be proved that the deflection variables are not independent. The independent variables are chosen to be the bending deflection of $e=\begin{bmatrix}\delta_{y1} & \delta_{z1} & \delta_{y2} & \delta_{z2}\end{bmatrix}^T$ as shown in Fig. 1. As the flexible manipulator is constrained to move only in vertical plane, the values of δ_{y1} and δ_{y2} can be neglected and the bending deflection parameters become only δ_{z1} and δ_{z2}. The first and second modes of vibration is taken into consideration during evaluating the bending deflection values.

III. Controller

An enhancement based on the classical PID controller defined as a Modified PID controller (MPID) is proposed for controlling the tip position of the flexible manipulator. Taking into consideration the effect of the vibration of the flexible manipulator, and selecting an effective vibration variable can suppress the vibration of the end effector of the flexible manipulator. To execute a correct task motion with the flexible manipulator two error components have to be removed. The first component is related to the joint and the second one is related to the end effector. The first one, θ_{error} is the error in joint motion and is defined is follows:

$$\theta_{error}(t) = \theta_{ref} - \theta(t), \tag{6}$$

where θ_{ref} is the input reference angle of the joint and $\theta(t)$ is the joint angle at time t. This part of error is identical with the rigid manipulator error. The second error component, $\delta(t)$, is the end effector deflection. This component is due to the flexibility of the link and it is much more important specially in the field of vibration suppression. These two error components are coupled to each other. Since only single actuator is used to drive the flexible manipulator, the control signal must have the ability to suppress the vibration of the end effector while reaching its reference base joint value. The controller which is used here is the Modified PID control (MPID) which is a modification to the classical PID controller by replacing the classical integral term with a vibration feedback term to include the effect of flexible modes of the beam in the generated control signal.

The MPID controller is formed as follows:

$$\begin{aligned} \dot{\theta}_c &= K_{jp}\theta_{error}(t) + K_{jd}\dot{\theta}_{error}(t) \\ &\quad + K_m\alpha(t)\ \mathrm{sgn}(\dot{\theta}_{error}(t)) \int_0^t |\dot{\theta}_{error}(t)|\alpha(t)dt, \end{aligned} \tag{7}$$

where $\dot{\theta}_c$ is the velocity command signal, K_{jp}, K_{jd} are the proportional and derivative gains for the joint, K_m is the vibration feedback gain, $\theta_{error}(t)$ is the error in the joint angle represented by (6) and $\alpha(t)$ is a vibration variable such as strain, deflection, shear force or acceleration under a single condition that the vibration variable value equal zero when the flexible robot is static.

The control signal is formed from two components, one of them related to the base of flexible manipulator and the other related mainly to the end effector. For the one related to the joint, it is joint PD consists of the first two terms of (7). In the vibration component, it first contain a vibration term, $\alpha(t)$, envelops the value generated from the integral. The second part of the vibration component is a signum function, which change the polarity of the term according to the velocity of the joint. The last part, integral part, generates a signal, which couples the velocity of the joint to the vibration parameter.

Some previous researches have tried many variables for the vibration feedback. For example Ge et al. [12] suggest the strain at the base as a vibration variable. If the length of the flexible manipulator is L, then a vibration variable $\alpha(t)$, for instance, is represented by $\alpha(0,t)$ at the base and $\alpha(L,t)$ at the end effector. Herein the rate of change of the deflection at the tip, $\dot{\delta}(L,t)$, is chosen as the vibration variable $\alpha(t)$. The use of $\dot{\delta}(L,t)$ has an advantage over the use of $\delta''(0,t)$, which represents the strain at the base, when the flexible-links have quasi-static strains due to gravity or initial strains due to material problems, because $\dot{\delta}(L,t)$ is not affected by such static deformations. When $\delta''(0,t)$ is used for $\alpha(t)$, the static components in $\delta''(0,t)$ must be removed by some means. Ge et al. did not consider the static deformations, however such static deformations are generally seen in a real manipulator system.

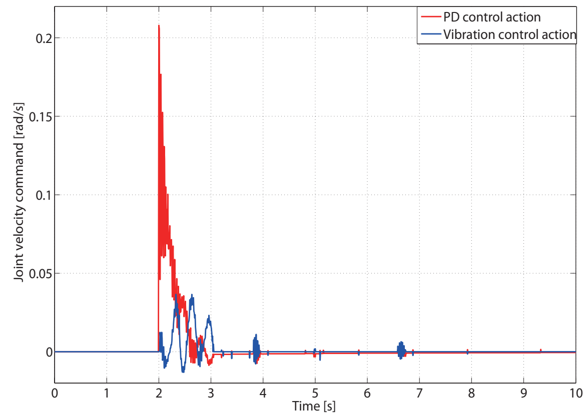

Fig. 2. Control action using MPID.

The rate of change of deflection is evaluated with the help of visual data captured with camera at the end point of the flexible manipulator. The behaviour of the vibration suppression controller represented by (7) is illustrated in Fig. 2. A step input is given after two seconds for the base joint and the corresponding generated control signal is recorded. On the control loop, $\alpha(t)$ is evaluated by the first mode of vibration. By this way both the two effects are taken into consideration in generating the control action. At the beginning of the motion, the effect of PD control is the dominant in the control action, which is indicated by the red curve in Fig. 2. When the system becomes closer to the reference position, the vibration term becomes to be dominant, which is indicated by the blue curve in Fig. 2.

IV. ESTIMATION OF VIBRATION VARIABLE USING VISUAL DATA

A new method is proposed for evaluating the value of the vibration feedback variable which is used in the controller. As mentioned in the controller section the vibration variable is selected to be the rate of change in deflection in order to avoid the effect of gravity or initial strains due to material problems. Instead of getting the deflection through the strain as in [13] and differentiate it to get the rate of deflection, an observer based on Kalman filter is designed. Using the observer accompanied with the camera is aimed to achieve two points. First, the value of the rate of change in deflection is directly evaluated instead of using numerical differentiation. Secondly, the noise in the measurements can be reduced. The observer uses the data from a camera mounted at the tip of the end effector to estimate the rate of deflection directly. The lower part of (5) can be rewritten as:

$$M_{22}\Delta\ddot{e} + K_{22}\Delta e = -M_{21}\ddot{\theta}. \tag{8}$$

This equation describes the elastic motion of the flexible manipulator. From (8), the state space model of vibration can be written as :

$$\begin{bmatrix}\Delta\dot{e}\\ \Delta\ddot{e}\end{bmatrix} = \begin{bmatrix}0 & I\\ M_{22}^{-1}K_{22} & 0\end{bmatrix}\begin{bmatrix}\Delta e\\ \Delta\dot{e}\end{bmatrix} + \begin{bmatrix}0\\ -M_{22}^{-1}M_{21}\end{bmatrix}\ddot{\theta}$$
$$\dot{x} = Ax + Bu, \tag{9}$$

where $x = [\Delta e, \Delta\dot{e}]^T$.

The measurement for the observer comes from the reading of the endpoint camera. For simplicity, it is assumed that the feature points are stationary. In the experiment presented in Section V, four marks are attached to a fixed location as feature points, as shown in Fig. 3. Both the movement of the joints and vibration affect the velocity of the feature points in the image plane. Therefore, the velocity of the feature points expressed in difference formula, $\Delta\xi$, is divided into two components: low frequency component $\Delta\xi_{low}$ and high frequency component $\Delta\xi_{high}$. It is assumed that the movement of the joint mainly affects $\Delta\xi_{low}$, while the vibration affects $\Delta\xi_{high}$. Hence $\Delta\xi_{high}$ is fed to the observer. The high frequency component is expressed as follows:

$$\Delta\xi_{high} = \begin{bmatrix}J_{image}J_e & 0\end{bmatrix}\begin{bmatrix}\Delta e\\ \Delta\dot{e}\end{bmatrix}$$
$$z = Cx, \tag{10}$$

where J_e refers to end-effector Jacobian with respect to link deflection, while J_{image} refers to the Image Jacobian matrix, which relates the velocity of the end-effector with the velocity of the feature points in the image plane.

Based on (9) and (10) a Kalman filter is designed. In this filter state variable x can be estimated from visual information, the rate of deflection which is expressed as $\Delta\dot{e}$ in x can be estimated directly as follow:

$$\Delta\dot{e} = \begin{bmatrix}\dot{\delta}_{z1}\\ \dot{\delta}_{z2}\end{bmatrix}, \tag{11}$$

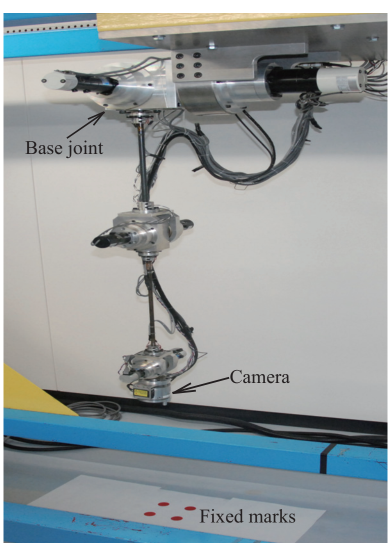

Fig. 3. Experimental setup with fixed marks.

then a mode decomposition is done. By constraining the motion of the robot in vertical space, a simplified model can be derived. Equation (8) can be rewritten as:

$$\Delta\ddot{e} + M_{22}^{-1}K_{22}\Delta e = -M_{22}^{-1}M_{21}\ddot{\theta}. \tag{12}$$

If the modal transformation $\Delta e = \Phi\Delta e^*$ is applied to (12) where Φ is the modal matrix and Δe^* is the modal coordinate, then (12) becomes as follows:

$$\Delta\ddot{e}^* + \Phi^{-1}M_{22}^{-1}K_{22}\Phi\Delta e^* = -M_{22}^{-1}M_{21}\ddot{\theta}, \tag{13}$$

where $\Omega = \Phi^{-1}M_{22}^{-1}K_{22}\Phi$ is a diagonal matrix whose diagonal elements indicate the frequency of the corresponding mode. In the controller, the rate of the first mode after the decomposition is used as $\alpha(t)$.

The visual system proposed early has the ability to be used in a three dimension applications. This means that it can be used with flexible space manipulator for measuring the rate of change in deflection of manipulator links. For simplicity and for the verification of the ability of the proposed controller to achieve good vibration suppression, the motion of the robot is constrained in vertical plane to take the effect of gravity into consideration in this research.

Two technical difficulties appears when applying the discrete Kalman filter to the system expressed by (9) and (10). The first problem is the difference between the update rate of measurements of both the image and the servo.Since a NTSC standard camera is employed in this experiment, z in (10) is updated at the NTSC camera frame rate (30 Hz). On the other hand, in order to guarantee the stability and control performance, the servo rate in the experiments is set at 128 Hz, which is approximately four times faster than the camera frame rate. This difference brings a difficulty in the implementation of the discrete Kalman filter. The second one is the delay in the output measurement expressed by (10). It takes approximately one video frame to capture a camera image in a frame memory, and takes approximately $10 \sim 20$ ms. An instability may be brought into the vibration suppression control system due to the phase-lag. To overcome the above two problems in the implementation of the standard discrete Kalman filter, the Kalman filter is modified and a delay compensation is introduced [14]. The method used to compensate the delay on Kalman filter is similar to the one proposed by Larsen et al. [15]. To confirm the performance of the modified Kalman filter, an experiment have been done. In this experiment the rate of deflection $\dot{\delta}_{z1}$ and $\dot{\delta}_{z2}$ at the end of segment 1 and segment 2 respectively is recorded with two different way of measurements. The rate of deflection for the two segments $\dot{\delta}_{z1}$ and $\dot{\delta}_{z2}$ estimated using the Kalman filter is compared with the deflections calculated from the strain gauge signal using numerical differentiation as shown in Fig. 4. The deflection data is high-pass filtered to eliminate the gravitational deflection with a cut-off frequency of 1.0 Hz. It is clear from Fig. 4 that the estimation using the Kalman filter shows satisfactory accuracy in addition to the ability for noise removing. Note that the natural frequency at the experimented configuration of the arm is about 3 Hz for the first mode and 18 Hz for the

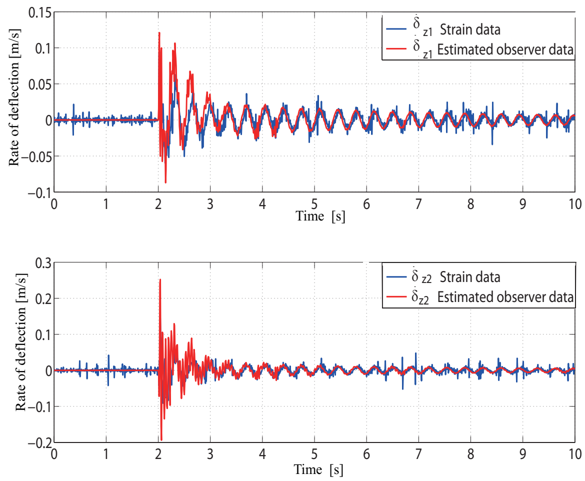

Fig. 4. Comparison between using Kalman filter and strain to evaluate the rate of change in deflection.

second mode. That is to say the sampling speed of camera as 30 Hz is fast enough according to sampling theory. The vibration suppression controller (7) is experimented using the endpoint camera image and Kalman filer instead of using a strain gauge. The experimental verification results for MPID controller using the visual data to estimate the rate of change of deflection are presented in section V.

V. Experimental verification

In this section, an experimental verification for the effectiveness of the proposed controller in vibration suppression of the flexible link manipulator is shown. The experiment setup is shown in Fig. 3. The experimental setup consists of a flexible link manipulator fixed from the top to a fixed base and a camera is attached to the other end. The base joint has the ability to rotate the link vertically. The flexible link is divided into two segments with a concentrated mass between them.

Combining the vibration suppression control described in section III with the estimated rate of change of deflection using visual information explained in section IV, an experimental verification is carried out. Before the experiment starts the flexible manipulator end effector is brought to a stable state while ensuring that it does not suffer pre-deflection. Due to the narrow view range of the camera, a small step input for the base joint is given. As shown in Fig. 5 the deflection of both segments of the flexible manipulator have been suppressed when using the rate of change of deflection as a vibration feedback compared with the case of not using it (K_m =0). Feeding back the vibration variable to the controller with appropriate gain in the controller gives noticeable damping for the vibration of the first and second modes of oscillation as illustrated in Fig. 6. Also it damps the deflection velocity of the both modes. To analyse the results obtained after using the vibration feedback term in the controller, a comparison between the response for both

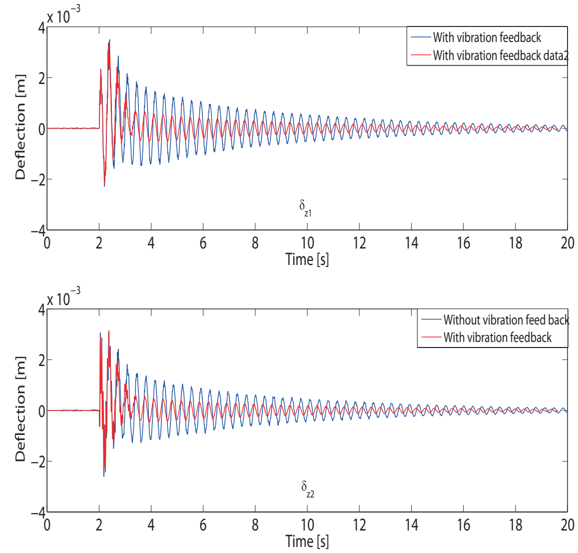

Fig. 5. Comparison between the deflection with and without vibration feedback.

the first and second mode of deflection is done. When we use only PD controller in the MPID (i.e. $K_m = 0$) the root mean square (RMS) of the first mode of deflection equals 0.801×10^{-3} m. After activation of the vibration term by setting the value of modified gain K_m to 350 s/m^2 the value of the RMS of the first mode of deflection is reduced to 0.5×10^{-3} m. For the second mode of vibration of the end effector, the values of root mean square error are 0.131×10^{-3} m and 0.121×10^{-3} m for the MPID with $K_m = 0$ and $K_m = 350$ respectively. For the vibration variable, the rate of change in deflection, a value of 0.0178 m/s for the root mean square is obtained for the first mode of vibration when only PD controller is used. A reduction with about 35 % of the amplitude of the RMS is achieved if the vibration variable is used in the controller. The value of the RMS when using the MPID with K_m equals 350 s/m^2 is 0.0117 m/s. While for the second mode of vibration, the values of the RMS is reduced by 13 % when using the MPID with the vibration variable. The value of the RMS becomes 0.0151 m/s when imposing the vibration variable while it was 0.0169 m/s while using only PD controller.

VI. Conclusions

In this paper an experimental verification on vibration suppression control of a flexible manipulator is proposed. The MPID controller is used to control the end effector of a flexible manipulator moving vertically. The velocity control signal drive the base joint of the flexible manipulator through a servo motor.

The camera which is attached at the end effector of the flexible manipulator is used for collecting visual data. The dynamic model of the flexible manipulator is fed jointly with the visual data to an observer. A discrete Kalman filter is used to estimate the rate of change in deflection of the link.

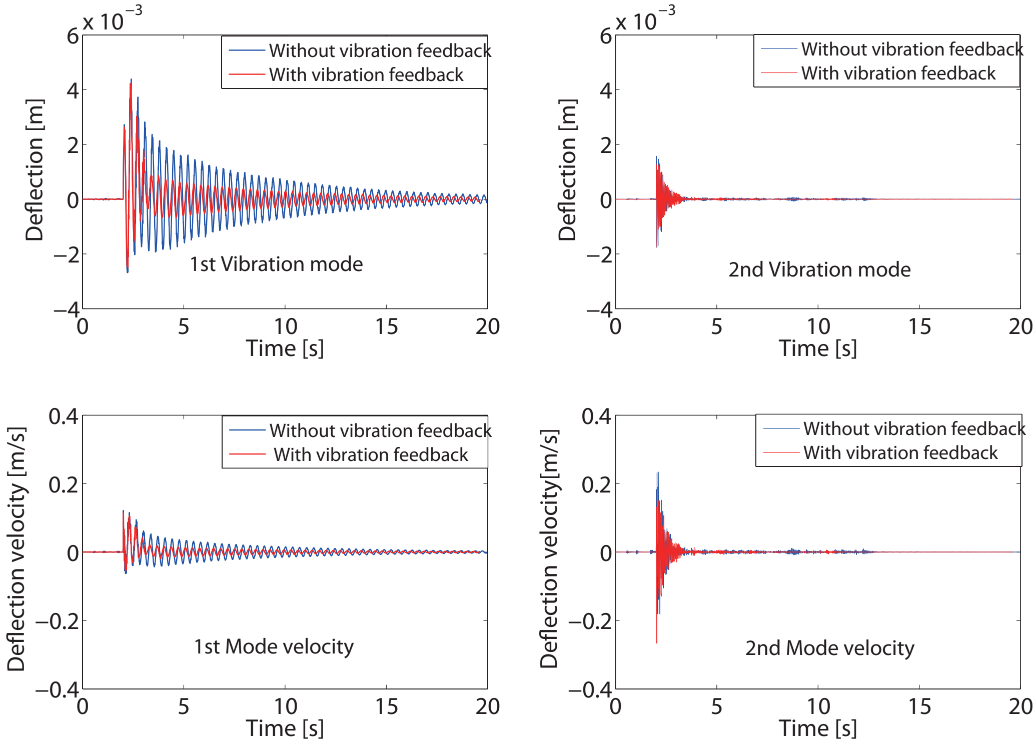

Fig. 6. Effect of vibration feedback on vibration modes.

Delay compensation is used in the Kalman filter in order to overcome the problem of time delay. To beat the huge deference in frequencies between the video frame rate of the camera (30 Hz) and the sampling rate of the servo system (128 Hz), a two-time-scale algorithm is developed .

The proposed system utilizes the visual data to evaluate the vibration variable directly. The MPID control accompanied with the visual measurement succeeded to achieve good vibration suppression to the end effector of the flexible manipulator.

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