A Simple Active Damping Control for Compliant Base Manipulators

Jae Young Lew, *Member, IEEE*, and Suk-Min Moon

***Abstract*—When a robotic manipulator is mounted to a crane, boom or mobile platform, it loses its accuracy and speed due to the compliance of the base. This paper presents a simple robust control strategy that will reduce mechanical vibrations and enable better tip positioning. The control algorithm will use the sensory feedback of the base oscillation to modulate the manipulator actuator input to induce the inertial damping forces. Previous work by the author has demonstrated the feasibility of the proposed concept using linear analysis. This work extends to a more general case of a nonlinear multiple link manipulator using acceleration feedback and one sample delayed torque. A simulation and an experimental study show very promising results for a test bed consisting of a two-link manipulator and a compliant base.**

***Index Terms*—Acceleration feedback, active damping, flexible base, one sample delayed torque.**

I. Introduction

THE ultimate goal of the research is to develop an outdoor robotic system which can help people work outside and enhance their safety. An outdoor robotic system generally implies an unstructured environment, larger and stronger robots, manipulators with a moving base, and conjunction with autonomous and tele-robotic control. The proposed research focuses on the issue of controlling a manipulator attached to a deployment system which typically exhibits compliance due to its mechanical nature. The problem is generalized as a motion control of a robotic manipulator attached to a compliant base. For example, a robotic manipulator is attached to a crane to cover a large work space in an outside field. Once the crane has approached a target position and has parked itself, the manipulator can then perform its tasks as shown in Fig. 1. Considering the crane with a long reach as a passive structure, the system can be simplified as a manipulator attached to a complaint base.

The proposed controller is based on the measurement and feedback of the joint acceleration and base oscillation. First, the controller computes unmodeled friction and nonlinear terms from the acceleration and from one-sample previously computed torque to cancel out undesired nonlinear and time-varying dynamics. This approach has been demonstrated previously for a rigid manipulator in [1]. Then a composite (fast and slow) controller is added using two-time scale theory. The fast controller, as positioning control, actuates the link to move to the desired position and, at the same time, the slow controller, as damping control, generates the inertial force to compensate for the oscillation.

Several researchers have worked on the vibration active damping by a micro for its base structure. Tilly [2] introduced wrist reaction control for a flexible, one-link manipulator using an LQR algorithm. Sharon [3] presented a damping controller based on a simple linear model, but it required the tip position measurement, which is not trivial in real world application. Lee [4] developed a robust controller based on a two-time scale model of micro/macro manipulators. However, damping effect was limited to one configuration. Yoshikawa [5] showed a tip dynamic tracking control for a micro/macro manipulator. However, the stability of its internal dynamics was ignored for the nonminimum system. Sharf [6] simulated a damping algorithm for a space station long-reach arm, but it was computationally complex. Torres [7] proposed a damping algorithm, but it was not an active feedback approach. Lew [8] demonstrated an inertial force damping control using an industrial manipulator test bed and later extended it to contact task control, but his design was based on a linear model. Nenchev [9] used the internal motion of a redundant micro to suppress its base oscillation, which required extra degrees of freedom.

The contribution of the proposed method can be summarized as follows. First, a simple robust decoupling method, which does not require the exact information of the model, is applied to a flexible structure. Second, the method is applicable to a nonlinear multiple link manipulator with multiple dimensional oscillation. Third, the controller has two separate feedback loops for positioning and damping, and the damping control is independent of manipulator positioning control. Therefore, the proposed damping control strategy can be easily added to existing position controlled industrial manipulators.

II. Modeling

In this section, a mathematical model of the manipulator is obtained from independently known dynamics. The oscillatory dynamics of the base may be simplified as a lumped mass with a spring, as shown in Fig. 2(a). The dynamic equation of the motion is represented as

$$\mathbf{M}_b \ddot{X}_b + \mathbf{C}_b \dot{X}_b + \mathbf{K}_b X_b = 0 \tag{1}$$

where X_b is a 6×1 vector describing the translational and rotational oscillatory motion of the base, $\mathbf{M}_b$ and $\mathbf{K}_b$ are the inertia matrix and stiffness matrix, respectively, and $\mathbf{C}_b$ is the damping matrix, which is assumed to be very small.

Manuscript received October 5, 1999; February 28, 2001. Recommended by Guest Editor N. Xi.

J. Y. Lew is with the Mechanical Engineering, Ohio University, Athens, OH 45701 USA (e-mail: lew@ohio.edu).

S.-M. Moon is with the Mechanical Engineering, Duke University, Durham, NC 27706 USA.

Publisher Item Identifier S 1083-4435(01)08151-0.

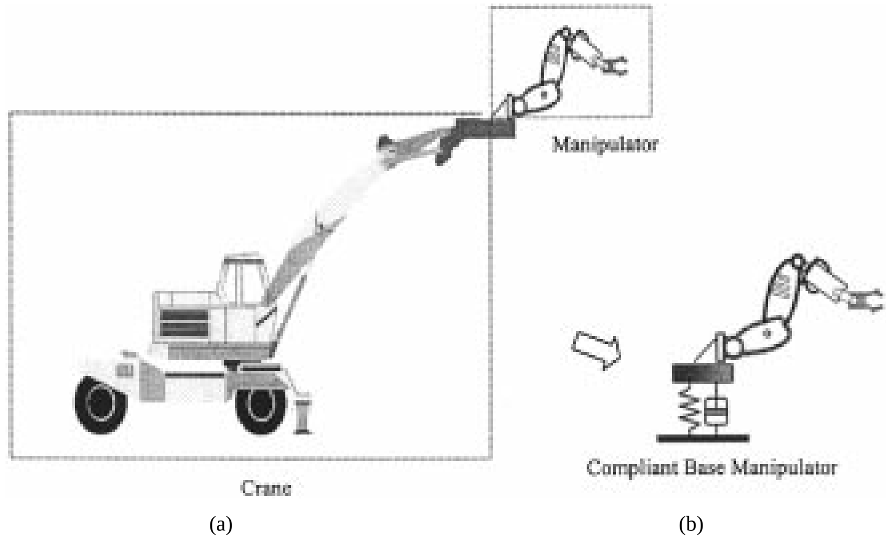


Fig. 1. Conceptual model of compliant manipulators.

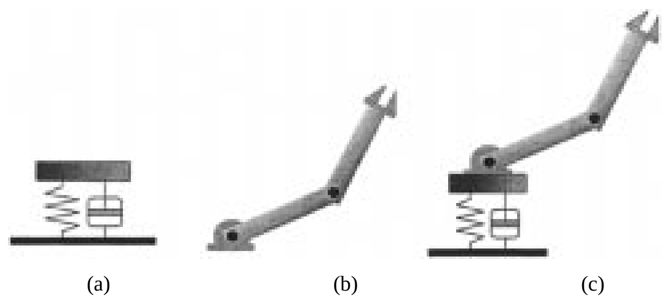


Fig. 2. (a) Lumped mass model of compliant base, (b) robotic manipulator with fixed base; and (c) robotic manipulator with compliant base.

On the other hand, the dynamics of the robotic manipulator fixed to the ground are represented in Fig. 1(b) and can be expressed as

$$\mathbf{M}_r(q)\ddot{q} + C_r(\dot{q}, q) = \tau \tag{2}$$

where q is the joint coordinate vector, $\mathbf{M}_r$ is the inertia matrix which varies with the system configuration, and $\mathbf{C}_r$ is a nonlinear term including centrifugal, Coriolis, joint friction and gravitational force.

When the two systems are serially combined, as shown Fig. 1(c), detailed analysis shows that the overall system can be represented as

$$\begin{bmatrix} \mathbf{M}_b + \mathbf{M}_{b/r}(X) & \mathbf{M}_{br}(X) \\ \mathbf{M}_{br}^{\mathrm{T}}(X) & \mathbf{M}_r(q) \end{bmatrix} \begin{Bmatrix} \ddot{X}_b \\ \ddot{q} \end{Bmatrix} + \begin{Bmatrix} \mathbf{C}_b \dot{X}_b + C_{br}(\dot{X}, X) \\ \mathbf{C}_r(\dot{q}, q) + C_{b/r}(\dot{X}, X) \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_b & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} X_b \\ q \end{Bmatrix} = \begin{Bmatrix} 0 \\ \tau \end{Bmatrix} \tag{3}$$

where $\mathbf{M}_{br}(X)$ and $\mathbf{M}_{b/r}(X)$ are the coupling inertia matrices, $C_{br}(\dot{X}, X)$ and $C_{b/r}(\dot{X}, X)$ are the nonlinear coupling terms, and $X = \left[X_b^{\mathrm{T}}, q^{\mathrm{T}}\right]^{\mathrm{T}}$. Details of the coupling terms and their physical meaning can be found in [10]. However, if only the translational motion of base and the revolute joints of manipulator are considered, then the coupling dynamics can be simplified. The overall dynamics can be rewritten as

$$\begin{bmatrix} \mathbf{M}_b + \mathbf{M}_{b/r} & \mathbf{M}_{br}(q) \\ \mathbf{M}_{br}^{\mathrm{T}}(q) & \mathbf{M}_r(q) \end{bmatrix} \begin{Bmatrix} \ddot{X}_b \\ \ddot{q} \end{Bmatrix} + \begin{Bmatrix} \mathbf{C}_b \dot{X}_b + C_{br}(\dot{q}, q) \\ C_r(\dot{q}, q) \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_b & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} X_b \\ q \end{Bmatrix} = \begin{Bmatrix} 0 \\ \tau \end{Bmatrix}. \tag{4}$$

In this paper, the control algorithm is developed for only the simplified model described by (4). Further control theory needs to be developed for the full model including both translational and rotational base oscillation. From the practical application point of view, often one mode (which is coupled with translation and rotation) is dominant in structural oscillation. Controlling translation implies controlling rotation too. Therefore, the paper focuses on translational oscillation only as an initial study.

III. Control Scheme

The control objective is to determine the input control τ such that the base oscillation X_b damps out as quickly as possible while the joint angle q follows the desired path. This is a difficult control problem because: (1) one control input, τ has to control two variables q and X_b and (2) an exact model of an inertia matrix and nonlinear terms is not available, and they vary as the configuration changes. A special damping controller is necessary to meet such a goal.

The derivation of the controller is as follows: first, the rigid body motion is decoupled from the flexible mode under the assumption that we know only an estimation of $\mathbf{M}_r(q)$, $\hat{\mathbf{M}}_r$ and that no information on nonlinear term C_r is provided. The second equation of (4) is rewritten as

$$\hat{\mathbf{M}}_r \ddot{q} + (\mathbf{M}_r(q) - \hat{\mathbf{M}}_r)\ddot{q} + \mathbf{M}_{br}^{\mathrm{T}}(q)\ddot{X}_b + C_r(\dot{q}, q) = \tau. \tag{5}$$

The inertia matrix error term, nonlinear term, and coupling term with base oscillation can be combined as uncertainty, $N(\ddot{X}, \dot{X}, X)$. N is obtainable from (5) as

$$\begin{aligned} N(\ddot{X}, \dot{X}, X) =& (\mathbf{M}_r(q) - \hat{\mathbf{M}}_r)\ddot{q} + \mathbf{M}_{br}^{\mathrm{T}}(q)\ddot{X}_b + C_r(\dot{q}, q) \\ =& \tau_p - \hat{\mathbf{M}}_r\ddot{q}. \end{aligned} \tag{6}$$

τ_p is the one-sample previous actuator torque assuming $\tau_p \approx \tau$ at high sampling rate, and the estimation of manipulator's inertia term $\hat{\mathbf{M}}_r$ is known, and joint acceleration $\ddot{q}$ is assumed to be measurable from the optical encoders by differentiating twice with respect to time. However, numerical noise in the differentiation could be a problem. To reduce the numerical noise without significant phase lag, a careful design of a digital filter is recommended. In summary, using (6) the uncertainty term can be computed from the acceleration measurement and one-sample delayed torque, and it is used as a feedforward term to linearize the system dynamics. Thus, the acceleration feedback will be implemented to the control system in the form of

$$\tau = \tau_p - \hat{\mathbf{M}}_r\ddot{q} + u. \tag{7}$$

By applying the controller specified in (7), the system equation from (4) becomes

$$\begin{aligned} &\begin{bmatrix} \mathbf{M}_b + \mathbf{M}_{b/r} & \mathbf{M}_{br}(q) \\ 0 & \hat{\mathbf{M}}_r \end{bmatrix} \begin{Bmatrix} \ddot{X}_b \\ \ddot{q} \end{Bmatrix} + \begin{Bmatrix} \mathbf{C}_b\dot{X}_b + C_{br}(\dot{q}, q) \\ 0 \end{Bmatrix} \\ &\quad + \begin{bmatrix} \mathbf{K}_b & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} X_b \\ q \end{Bmatrix} = \begin{Bmatrix} 0 \\ u \end{Bmatrix} \end{aligned} \tag{8}$$

where u is the new input for the feedback control. By taking the inverse of the inertia matrix of (8), it may be rewritten as

$$\begin{aligned} &\begin{Bmatrix} \ddot{X}_b \\ \ddot{q} \end{Bmatrix} + \begin{bmatrix} \mathbf{H}_{11}\mathbf{K}_b & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} X_b \\ q \end{Bmatrix} \\ &\quad + \begin{Bmatrix} \mathbf{H}_{11}(\mathbf{C}_b\dot{X}_b + C_{br}(\dot{q}, q)) \\ 0 \end{Bmatrix} = \begin{bmatrix} \mathbf{H}_{11} & \mathbf{H}_{12}(q) \\ 0 & \hat{\mathbf{M}}_r^{-1} \end{bmatrix} \begin{Bmatrix} 0 \\ u \end{Bmatrix} \end{aligned} \tag{9}$$

where

$$\begin{aligned} \mathbf{H}_{11} =& (\mathbf{M}_b + \mathbf{M}_{b/r})^{-1} \\ \mathbf{H}_{12}(q) =& (\mathbf{M}_b + \mathbf{M}_{b/r})^{-1}\mathbf{M}_{br}(q)\hat{\mathbf{M}}_r^{-1} \\ =& \mathbf{H}_{11}\mathbf{M}_{br}(q)\hat{\mathbf{M}}_r^{-1}. \end{aligned}$$

As shown in the second row of (9), the manipulator rigid motion is mostly decoupled from the base oscillation. The base motion has no effect on the joint motion. They are coupled only through the control input, u. Rewrite (9) into two equations with compliant base and rigid body motion equation as

$$\left\{\ddot{X}_b + \mathbf{H}_{11}\mathbf{C}_b\dot{X}_b\right\} + \mathbf{H}_{11}\mathbf{K}_bX_b + \mathbf{H}_{11}C_{br}(\dot{q}, q) = \mathbf{H}_{12}(q)u \tag{10}$$

$$\hat{\mathbf{M}}_r\ddot{q} = u. \tag{11}$$

Second, a composite (fast and slow) controller is designed based on the partially decoupled model in (10) and (11). Recall that the control objective is to determine the control input u that stabilizes both (10) and (11). Define the control input u to have two parts

$$u = u_{\mathrm{fast}}(q) + u_{\mathrm{slow}}(X_b). \tag{12}$$

Using two-time scale theory, u_{fast} and u_{slow} are chosen in two different time scales. It is intended that u_{slow} affects mainly on (10), slow base motion and u_{fast} mainly on (11), fast decoupled joint angle dynamics. For u_{fast}, a typical linear tracking controller is proposed with high gains such that the control bandwidth is much higher than the natural frequency of the base motion, X_b. For example, u_{fast} can be chosen as

$$u_{\mathrm{fast}} = \mathbf{K}_p\tilde{q} + \mathbf{K}_d\dot{\tilde{q}} + \hat{\mathbf{M}}_r\ddot{q}_d \tag{13}$$

where $\tilde{q}$ is the joint angle error between the desired and measured, $q_d - q$; $\dot{\tilde{q}}$ is the joint velocity error between the desired and measured, $\dot{q}_d - \dot{q}$; $\ddot{q}_d$ is the desired joint acceleration; and $\mathbf{K}_p$ and $\mathbf{K}_d$ are the proportional and derivative gain matrix, respectively. The control bandwidth of $\tilde{q}$ and time scale separation of $\tilde{q}$ and X_b can be checked easily by applying u_{fast}, (13) only while $u_{\mathrm{slow}} = 0$ for the system. It can be shown that the base motion X_b, (10) remains stable as long as gain $\mathbf{K}_p$ and $\mathbf{K}_d$ are positive definite matrix. However, X_b, still possesses oscillatory response, often not desired in real world application.

When the composite controller (12) is applied to (11), the closed loop error dynamics for the joint angle becomes

$$\hat{\mathbf{M}}_r\ddot{\tilde{q}} + \mathbf{K}_d\dot{\tilde{q}} + \mathbf{K}_p\tilde{q} = -u_{\mathrm{slow}}. \tag{14}$$

If u_{slow} changes slowly compared to the fast error dynamics, it can be treated as more like a constant. Then the error dynamics of (14) converge to be very small with positive definite matrices $\mathbf{K}_p$ and $\mathbf{K}_d$. Furthermore, if $\hat{\mathbf{M}}_r$ is estimated as a diagonal matrix, gain $\mathbf{K}_p$ and $\mathbf{K}_d$ also can be chosen as diagonal matrices related to the natural frequency and damping of the decoupled joint angle motion. This simplifies the gain selection of the controller.

Now, the slow control input, u_{slow}, is defined for the flexible base coordinates in (10) as

$$u_{\mathrm{slow}} = -\mathbf{H}_{12}^{-1}(q_d)\mathbf{K}_{bd}\dot{X}_b \tag{15}$$

assuming H_{12} is nonsingular, i.e., its determinant is nonzero. Only the derivative feedback of the base oscillation with gain $\mathbf{K}_{bd}$ is added to increase the structural damping. As (11) converges quickly with high gain $\mathbf{K}_p$, it is true that $\tilde{q} \approx 0$ and $\dot{\tilde{q}} \approx 0$, i.e., $q \approx q_d$ and $\dot{q} \approx \dot{q}_d$ for the slow dynamics, where q_d is the desired joint angle. Then, after applying the composite controller, (10) becomes

$$\begin{aligned} &\ddot{X}_b + (\mathbf{K}_{bd} + \mathbf{H}_{11}\mathbf{C}_b)\dot{X}_b + \mathbf{H}_{11}\mathbf{K}_bX_b \\ &\quad = -\mathbf{H}_{11}C_{br}(\dot{q}_d, q_d) + \mathbf{H}_{12}\hat{\mathbf{M}}_r\ddot{q}_d. \end{aligned} \tag{16}$$

It can be easily shown that $\mathbf{H}_{11}\mathbf{K}_b$ and $\mathbf{H}_{11}\mathbf{C}_b$ are positive definite and the right-hand side is of (16) bounded since q_d, $\dot{q}_d$ and $\ddot{q}_d$ are bounded. Therefore, as long as $\mathbf{K}_{bd}$ is chosen as a positive definite matrix, (16) remains stable. We may adjust the damping of the base oscillation by increasing gain $\mathbf{K}_{bd}$.

According to (16), the infinite amount of damping could be obtained by simply increasing gain K_{bd} very high. However, in reality, this is not true. The stability proof of the proposed damping controller is derived on the assumptions that two-time scale separation exists in the closed loop system and that the base oscillation X_b changes slowly. It can be shown that these assumptions hold while $u_{\text{slow}} = 0$ in (14). On the other hand, when the damping controller u_{slow} with very high gain $\mathbf{K}_{bd}$ is added to the feedback controller, the assumptions may not hold, and the closed loop system may become unstable. For that reason, damping gain $\mathbf{K}_{bd}$ should be chosen carefully. In the actual implementation, the damping gain was increased gradually until maximum damping is obtained without violating the assumption.

Finally, combining acceleration feedback, u_{fast} and u_{slow}, the overall proposed damping controller is

$$\tau = \tau_p - \hat{\mathbf{M}}_r \ddot{q} + \mathbf{K}_p \tilde{q} + \mathbf{K}_d \dot{\tilde{q}} + \hat{\mathbf{M}}_r \ddot{q}_d - \mathbf{H}_{12}^{-1}(q) \mathbf{K}_{bd} \dot{X}_b.$$

The physical meaning of matrix $\mathbf{H}_{12}(q)$ is the coupling dynamic relationship effect between the joint torque and base oscillation. If $\mathbf{H}_{12}(q)$ is singular, it implies a special geometrical configuration where the joint motion does not affect dynamically on the base oscillation in Cartesian space similar to kinematic singularity. This dynamic singularity could occur for any compliant base manipulators in a given workspace. Therefore, the desired trajectory of the manipulator should be chosen carefully to avoid the dynamic singularity as well as kinematic singularity.

IV. Simulation/Experimental Study

First, a simulation study is performed based on a mathematical model. Then, an experimental study is carried out to demonstrate the effectiveness of the proposed active damping control scheme in a physical system. The test bed at Ohio University consists of a two-link rigid manipulator and a compliant base, as shown in Fig. 3. The rotational joint with linear springs emulates the compliance of various supporting structures. The base compliance can be adjusted by adding a different set of linear springs. Since the manipulator is attached at other than the pivot point, its base goes through two types of oscillation: translation and rotation as each link moves. However, these two motions are not independent. Thus, just controlling translational oscillation implies controlling rotational motion at the same time in this case. For the feedback controller design, only the translation of the base is considered in this experiment.

The manipulator consists of two 0.285-m long metal links and two dc motors. Each dc motor is a PITTMAN GM9000 Series with 19.7:1 gear ratio and equipped with an optical encoder at the motor side to measure joint angle. The encoder is an Integrated Hewlett-Packard® optical encoder with 500 CPR (Cycles/Rev). Base vibration in the y_b direction (Fig. 3) is measured by a US DIGITAL Optical Encoder E2 Series, which is an optical incremental shaft encoder with 250 CPR, and is attached on the shaft of the pin joint. The test bed is controlled by a MultiQ™ board with Pentium 233 Computer. The sampling rate is selected at 500 Hz.

The input torque to the manipulator system is calculated by the computer based on the joint displacement and base displacement, and is sent through a D/A board to the amplifiers which drive currents to the motors in the joints. MATLAB™/SIMULINK™ are used to write the program, and

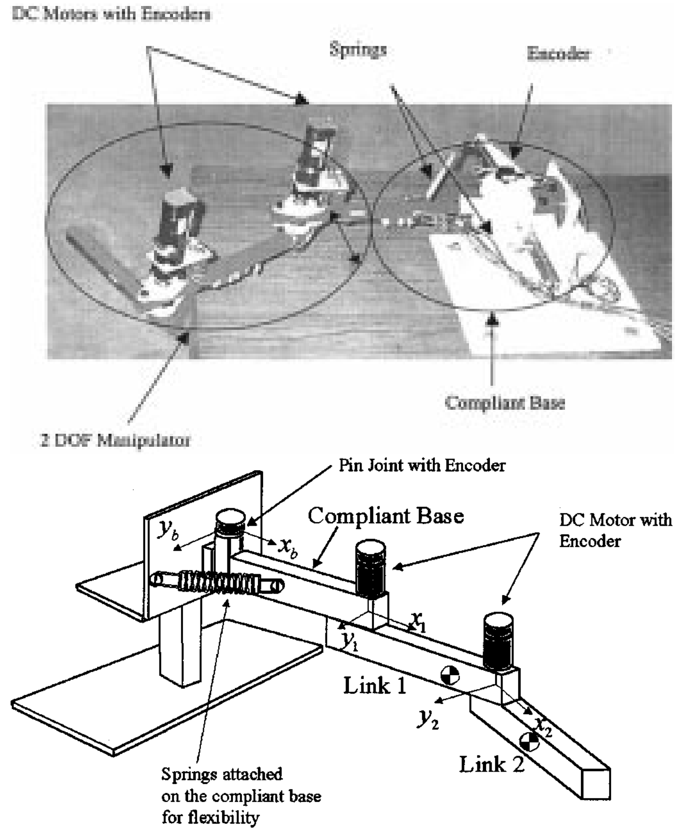


Fig. 3. Ohio University test bed.

Real-Time Workshop™ converts the program to C language and WinCon™ is used as a real-time control system.

During all the experiments, the following values were used for the estimation of the inertia matrix, $\hat{\mathbf{M}}$ the proportional gain matrix $\mathbf{K}_p$, and the derivative gain matrix $\mathbf{K}_d$, for joint motion

$$\hat{\mathbf{M}} = \begin{bmatrix} 0.028 & 0 \\ 0 & 0.005 \end{bmatrix}$$
$$\mathbf{K}_p = \begin{bmatrix} 30 & 0 \\ 0 & 30 \end{bmatrix}$$
$$\mathbf{K}_d = \begin{bmatrix} 0.8 & 0 \\ 0 & 0.6 \end{bmatrix}.$$

$\hat{\mathbf{M}}$ is obtained based on physical measurement of the link while neglecting off-diagonal terms. The feedback controller gain matrices were selected according to second order system performance specifications, which correspond to the desired pole locations at $-14 \pm i29.45$ and $-60 \pm i48.99$ rad/s for two decoupled systems. This is just an independent joint proportional and derivative (PD) control with acceleration feedback. With the selected gains, base oscillation during the motion is observed with a damped natural frequency of 2.85 rad/s. Later, the damping controller was added, and its gain was gradually increased until it showed significant damping improvement. The damping gain was tuned as $\mathbf{K}_{bd} = 300$.

A third order polynomial trajectory from 0.0 to 1.0 rad in 1.0 s for both joints was applied as a desired trajectory. Figs. 4 and 5 show the responses of the base and joint 1 under PD control

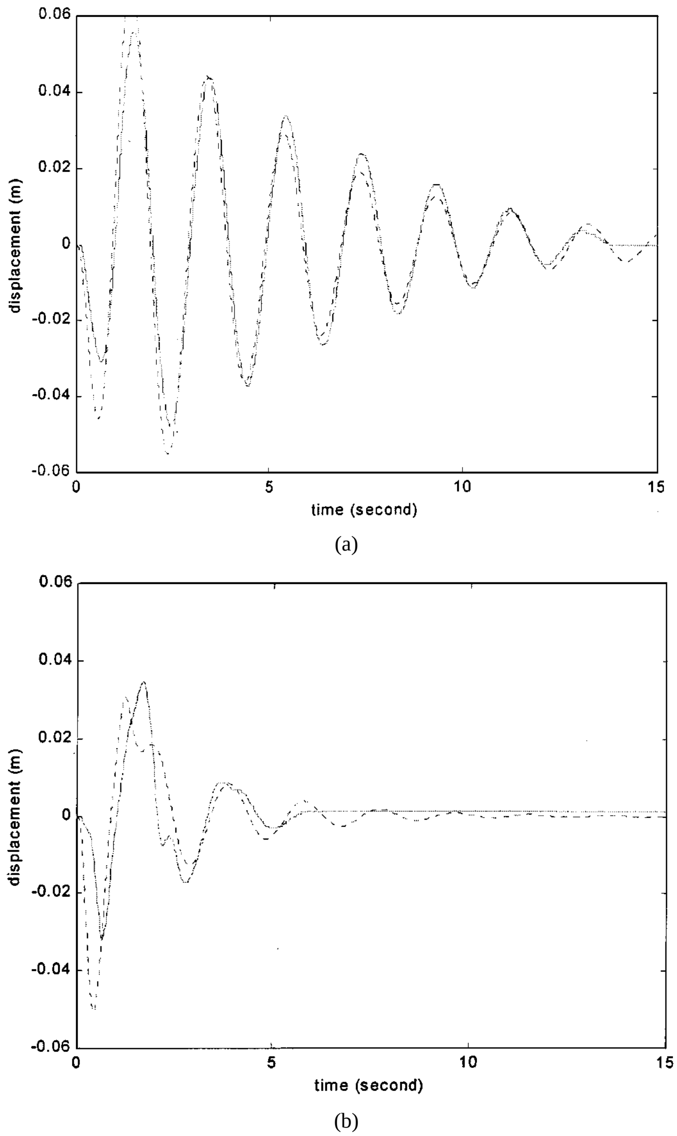


Fig. 4. Base motion for third order polynomial desired path (solid line: experiment result, dashed line: simulation result).(a) With PD control. (b) With active damping control.

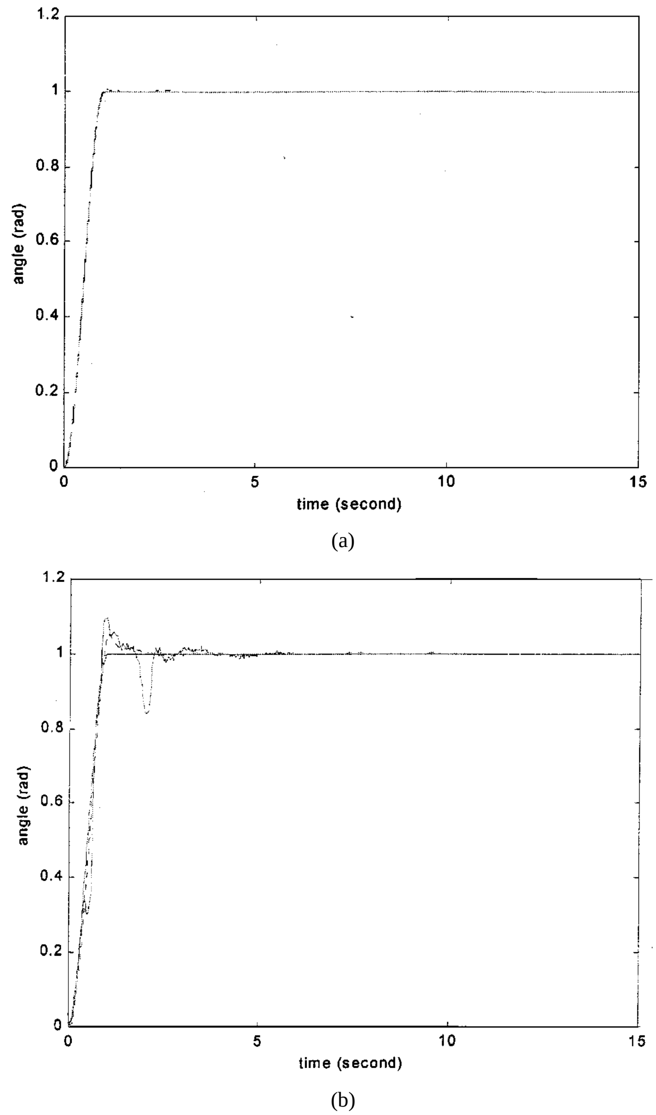


Fig. 5. Joint 2 motion for third order polynomial desired path (solid line: experiment result, dashed line: simulation result).(a) With PD control. (b) With active damping control.

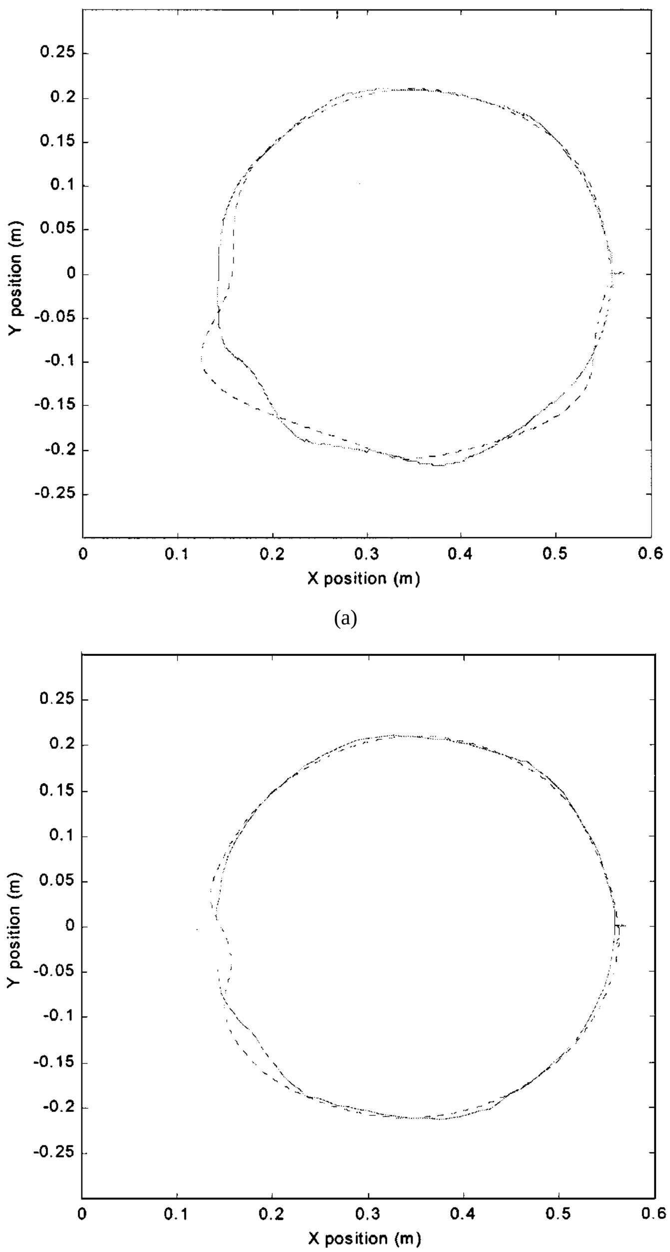
and the proposed damping control for both simulation and experiment result. The dotted line is the simulation result, and the solid line is the experiment result. Fig. 4(a) and (b) indicates that the damping controller reduced the base oscillation by 40% in settling time. Fig. 5(a) and (b) shows that joints followed the desired angles. One solid line is a desired and actual third order polynomial path. The dotted line is the simulated joint motion. You may notice that in Fig. 5 the joint angle actually oscillated during the transient responses to generate the inertial force for damping.

Next, a circular motion with radius 0.2 m was given as a desired trajectory with 5-s traveling time. The circular path yielded a significant configuration change of the manipulator. For example, joint 1 moved from -0.50 to -1.95 rad and joint 2 moved from 1.0 to asmuchas 2.80 rad. Fig. 6(a) shows the simulated/actual tip path with PD control, and Fig. 6(b) shows when the damping controller was activated. Again, the dotted line is the simulation result, and the solid line is the experiment result. Comparing the two results, the damping controller drew a more perfect circle since the base did not oscillate as much as the case without the damping controller. It may be concluded that the damping controller was effective in various configurations.

Throughout the experiment, the acceleration was measured from the joint encoders by differentiating twice with respect to time. As expected, numerical noise was significant and a digital filer had to be added to obtain reasonable signals. A third-order Butterworth filter with 4-Hz cutoff frequency was chosen for the experiment. It is observed that the cutoff frequency and order of the filter had some effect on overall system response occasionally. Therefore, filter design should be done carefully upon the characteristics of systems.

V. Conclusion

An active damping controller for a manipulator mounted on a compliant base is proposed in this paper. Under the assumption of two-time scale, its stability and design procedures are presented for a multiple link manipulator with multiple dimensional oscillation. The proposed controller is simple but robust.



(a)

(b)

Fig. 6. Tip position for circular desired path (solid line: experiment result, dashed line: simulation result). (a) With PD control. (b) With active damping control.

It does not require the exact information of the model. The controller cancels out nonlinear and uncertain dynamics by acceleration feedback and adds more damping by base motion feedback. The simulation and experimental study demonstrated the improvement of the overall system performance over large configuration change.

REFERENCES

[1] G. Bonitz and T. C. Hsia, "Robust internal force based impedance control for coordinating manipulators—theory and experiments," presented at the IEEE Int. Conf. Robotics and Automation, Minneapolis, MN, Apr. 1996.

[2] S. Tilley and R. Cannon, "End-point control of a very flexible manipulator with a fast end-effector," *ASME J. Dynamic Syst., Meas. Control*, vol. 3, pp. 1–9, 1986.

[3] A. Sharon, "The Macro/Micro Manipulator: An Improved Architecture for Robot Control," Ph.D. dissertation, MIT, Cambridge, MA, 1988.

[4] S. Lee and W. J. Book, "Robot vibration control using inertial damping forces," presented at the VIII CISM-IFTOMM Symp. Theory and Practice of Robots and Manipulators, Cracow, Poland, July 1990.

[5] T. Yoshikawa, H. Kensuke, and A. Matsunomo, "Hybrid position/force control of flexible-macro/rigid-micro manipulator systems," *IEEE Trans. Robot. Automat.*, pp. 633–640, 1996.

[6] I. Sharf, "Active damping of a large flexible manipulator with a short reach robot," in *Proc. 1995 American Control Conf.*, Seattle, WA, pp. 3329–3333.

[7] M. A. Torres, S. Dubouwsky, and A. Pisoni, "Path-planning for elastically-mounted space manipulators: experimental evaluation of the coupling map," presented at the IEEE Int. Conf. Robotics and Automation, San Diego, CA, May 1994.

[8] J. Y. Lew, "Contact control of flexible micro/macro-manipulators," presented at the IEEE Int. Conf. Robotics and Automation, Albuquerque, NM, Apr. 1997.

[9] D. Nechev *et al.*, "Experiments on reaction null-space based decoupled control of a flexible structure mounted manipulator system," presented at the IEEE Int. Conf. Robotics and Automation, Albuquerque, NM, Apr. 1997.

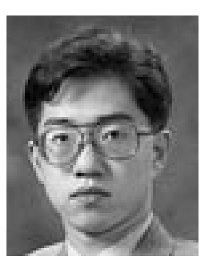
[10] J. Y. Lew and S. M. Moon, "Coupling dynamics analysis for micro/macro manipulator," presented at the IFTOMM, Oulu, Finland, June 20–24, 1998.

[11] ——, "Acceleration feedback control of compliant base manipulators," in *Proc. 1999 American Control Conf.*, San Diego, CA, pp. 1955–1959.

Jae Young Lew (M'94) received the M.Eng. degree from Carnegie-Mellon University, Pittsburgh, PA, and the Ph.D. degree from the Georgia Institute of Technology, Atlanta, in 1987 and 1993, respectively, both in mechanical engineering.

From 1993 to 1997, he worked as a research scientist at Pacific Northwest National Laboratory, Richland, WA, developing robotics technology related to nuclear waste handling. Currently, he is an assistant professor, in the Department of Mechanical Engineering, Ohio University, Athens. His research interests include linear/nonlinear large structure control, human-robot interactive control, force/impedance control, and dynamic path planning.

Dr. Lew is a member of the American Society of Mechanical Engineers.



Suk-Min Moon received the B.S. degree in from Yonsi University, Seoul Korea in 1995 and the M.S. degree from Boston University, Boston, MA, and Ohio University, Athens, in 1997 and 1999, respectively, both in mechanical engineering. At present, he is a doctoral candidate in mechanical engineering and materials science at Duke University, Durham, NC.

His research interests include adaptive system, structures, and control.