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FLEXIBLE OBJECTS VIBRATION CONTROL AND HANDLING USING DD ROBOT ARMS

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ABSTRACT

This paper addresses issue of flexible object manipulation by using robot arms. The main objective is to establish a suitable control system of the robot for performing flexible object manipulation tasks. A force sensor equipped at the wrist of the robot arm is used to measure the vibration of the flexible object. A vibration control scheme is designed based on linear feedback of vibration measured by the force sensor. The control system is established by adding the vibration control scheme into the joint trajectory tracking controller. A 2-link DD (Direct Drive) robot arm with a six axes force/torque sensor equipped at the end is used as experimental test bed. Both simulation and experiment are carried out based on joint trajectory tracking and link flexible object manipulation experiments are carried out. The results demonstrate the effectiveness of the proposed manipulating strategy based on vibration control and trajectory tracking.

1. INTRODUCTION

In space development and industrial applications, we often deal with handling and manipulation of light-weight elastic trusses and flexible materials. To meet the needs in this area, recently study on robotic manipulation of flexible objects has been an increasingly popular research filed in robotics. Literature shows that the main research activities on this issue have been focused on flexible object modeling, sensing, task planning, dual-arm co-operation, and control design[1]-[9].

To perform such the robotic manipulation task, vibration of the flexible object needs to be suppressed by the robot arm, and the measurement of vibration using some suitable and practical sensors is a key issue for the design and implementation of the control system. As a usual method for vibration measurement of an elastic body, strain gauges are widely used. However, it is not feasible to paste a strain gauge on a flexible object before performing its manipulation task. Using of vision system is a good choice for identification and estimation of deformation of the flexible objects. The fast mode and fine vibrations, however, may be difficult to measure in real time because the speed of response of recent CCD camera systems is still not fast enough. A method using force sensors to detect the contact location and surface of external objects has been proposed, but this method is difficult to be used for vibration measurement of a flexible object being handled by the robot. On the other hand, for the vibration suppressing, extensive related research activities have been focused on control of flexible robots, however, only few reports have been published on the issue of flexible object manipulation.

In this paper, we deal with the issues of vibration measurement and control design in order to establish flexible objects manipulating system using robot arms. First, a method for vibration measurement of the flexible object using a force/torque sensor equipped at the end of the robot is presented. Second, based on this method a control strategy for the flexible object manipulating is proposed. This control strategy is mainly consisted of two parts: one is to track the trajectories designed in order for performing a desirable manipulation task; another one is to suppress vibration of the flexible object during the manipulation. In detail of the control design, we divide the control system of the robot into two subsystems functionally, and design each of them separately. One is the control subsystem for the wrist joints, hand and flexible object, which is designed on the basis of a force sensor signal feedback approach for vibration suppressing. Another one is the control subsystem of the joints of the arm, which is designed for trajectory tracking. We used a 2-link DD robot arm with a force/torque sensor equipped at the tip of second link as the experimental setup facility. Several very flexible beams made of copper alloy are selected as the flexible objects. We carry out flexible object manipulation simulations and experiments. The results demonstrate the effectiveness of the proposed control strategy.

This paper is organized as follows. In Section 2, we describe the dynamic model of robot system with the flexible object manipulated by the robot, and analyze the relationship between vibration of the flexible object and the force sensor responses. In Section 3, we discuss the issues of control design and stability of the system. Section 4 gives the simulation and experimental results on flexural object vibration control and manipulation. Finally, conclusions are in Section 5.

2. DYNAMIC ANALYSIS

Consider an n-link robot arm carrying a flexible object as its payload, shown in Fig.1. It is assumed that the robot associates with a force/torque sensor equipped on the tip of the last link, and the force/torque sensor has enough axes to measure external forces acting on the end-effector.

The dynamic equations of the robot-flexible payload system can be derived using Lagrange approach and FEM (Finite Element Method). The results are given as follows

$$M_{11}(q,e)\ddot{q} + M_{12}(q,e)\ddot{e} + h_1(q,e,\dot{q},\dot{e}) = \tau \qquad (1)$$

$$M_{21}(q,e)\ddot{q} + M_{22}(q,e)\ddot{e} + Ke + h_2(q,e,\dot{q},\dot{e}) = 0 \qquad (2)$$

where, (1) and (2) are the motion equations of the robot and the flexible object respectively; $q \in R^n$, $\tau \in R^n$, and $e \in R^m$ denote the joint variable and torque of the robot, and flexural displacements of the flexible object; $M_{11}(q,e)$, $M_{12}(q,e)$, $M_{21}(q,e)$, and

$M_{22}(q,e)$ are inertia matrices; $h_1(q,e,\dot{q},\dot{e})$, $h_2(q,e,\dot{q},\dot{e})$ contain the Coriolis, centrifugal forces and gravity; K denotes the rigid matrix.

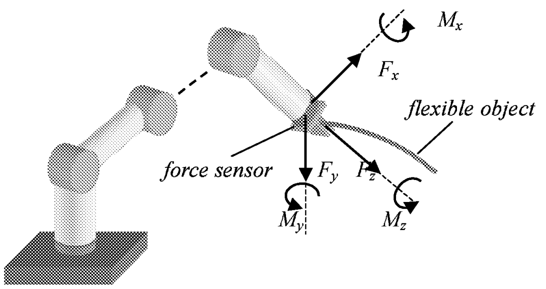

Fig. 1. An n-link robot arm for manipulation of a flexible object.

When the flexible object is being manipulated by the robot the reaction force resulting from vibration of the object acts at the hand of the robot, and eventually acts on every link and joint through the force/torque sensor equipped at the end of the robot. If the force sensor associates with enough axes, the reaction force and torque can be measured so that the dynamic relationship between motions of the robot and the flexible object can be completely described by the force/torque sensor output. We accordingly analyze the force/torque sensor information dynamically using the dynamics of the system, further confirm if force/torque sensor information can be used for measurement of the vibration of the flexible object.

As described in the following equation, we divide the dynamic equation of the robot (1) into two parts: one consists of the terms regarding to the dynamic equation of the robot arm without carrying the flexible object, another one is the terms that describe the reaction forces from the flexible object.

$$M(q)\ddot{q} + v(q,\dot{q}) + h(q,\dot{q},\ddot{q},e,\dot{e},\ddot{e}) = \tau \quad (3)$$

where, $M(q)$, $v(q,\dot{q})$ are the inertia matrix, Colioris and centrifugal forces, and gravity of the robot arm, $h(q,\dot{q},\ddot{q},e,\dot{e},\ddot{e})$ is such a term contains the reaction forces transformed from the hand to each joint through the force/torque sensor. In detail, it is given as follows

$$h(q,\dot{q},\ddot{q},e,\dot{e},\ddot{e}) = M_e\ddot{q} + M_{12}\ddot{e} + h_1(q,\dot{q},e,\dot{e}) \quad (4)$$

where M_e is a matrix separated from M_{11} and contains masses and moments of inertia of the flexible object; h involves dynamics of the hand and also Colioris, centrifugal, and gravity forces related to the flexible object.

Let us consider how the dynamics changes when there is an external force acting at the hand of the robot arm and being measured by the force sensor as $F_s \in R^n$, without noting how the external force generated. As well-known in force control issues, the dynamics of the robot arm with an external force can be written as

$$M(q)\ddot{q} + v(q,\dot{q})\dot{q} + J_s^T T_s F_s = \tau \quad (5)$$

where $J_s \in R^{n \times n}$ is the Jacobian of the origin of the force sensor coordinate frame with respect to the joint variables of the robot, $T_s \in R^{n \times n}$ is the transformation matrix from the force sensor coordinate system to the base coordinate system.

If F_s is such a reaction force caused by the motion of the flexible object, comparing with (3) and (5) we obtain

$$J_s^T T_s F_s = h(q,\dot{q},\ddot{q},e,\dot{e},\ddot{e}) \quad (6)$$

Noting that M_{22} is invertible, from (2) we solve $\ddot{e}$ as below

$$\ddot{e} = -M_{22}(M_{21}\ddot{q} + Ke + h_2(q,e,\dot{q},\dot{e})) \quad (7)$$

Noting (4) and substituting (7) to (4) yields

$$J_s^T T_s F_s = M_e \ddot{q} - M_{12} M_{22}^{-1} (M_{21} \ddot{q} + Ke + h_2(q, e, \dot{q}, \dot{e})) + h \quad (8)$$

For non-singular configurations of the robot, from (8) we solve F_s as follows

$$F_s = W_e e + W_\theta \ddot{\theta} + w \quad (9)$$

where, $W_e = -(J_s^T T_s)^{-1} M_{12} M_{22}^{-1} K$,

$W_\theta = (J_s^T T_s)^{-1} (M_e - M_{21} M_{22}^{-1} M_{21})$,

$w = (J_s^T T_s)^{-1} (h - M_{12} M_{22}^{-1} h_1)$.

In equation (9), the first term on the right side describes the part of the force sensor output which caused by vibration of the flexible object. It is the linear function of deflections of the flexible object. By some meanings, W_e can be considered as a gain matrix, and it mainly depends on configuration of the robot. The second and third terms are the reactions against the forces that drive the flexible object moving together with the robot arm.

From the above analysis and discussion, we make some remarks summarized as: (a) flexural displacements of the flexible object can be described as a linear function in the force/torque sensor output; (b) when the robot moves slowly, dynamics of the hand can be ignored, and the forces/torques caused by vibration of the flexible object become the main part of the force sensor output; (c) force sensor output contains enough information for measurement of vibration of the flexible object.

3. CONTROL SYSTEM DESIGN

We consider a class of manipulation tasks such as the robot arm moves the flexible object from a location to another location. This kind of the manipulation tasks can be simply performed with end-effector/joint trajectory control. The control system can be formulated with control framework either provided by the controllers of usual industrial robots or designed by the users.

One of the common natures robot arms have is that the payload carrying capacity is relatively low in comparing with their weights. It tells us that only the lightweight flexible objects can be considered as the payloads of the industrial robot arms. To manipulate such the lightweight flexible object, controlling of its vibration is the key point for the design of the control system, whereas trajectory tracking control is needed for performing planned manipulation tasks. Thus, we divide the control system of the robot into two subsystems functionally to design each of them separately. One is the control subsystem for the control of the flexible object, which is designed on the basis of adding a force sensor signal feedback approach to the controllers of the last joint for vibration suppressing of the flexible object. Another one is the control subsystem of the joints of the arm, which is designed for positioning of the joints or for tracking the trajectories planned for the manipulation task. Under the assumption that the masses and moments of inertia of the robot links and joints are big enough comparing with their flexible object counterparts, forces generated from dynamic coupling from the object to each link and joint of the arm are small enough and can be ignored. Thus, the control design for each joint from the base to the wrist can be done without considering the flexible object.

The control system is designed based on PID control technology and the force sensor signal feedback is added into the PID controller for the vibration suppressing. The control scheme can be designed in two ways: associating with force feedback, and associating with torque feedback. As the results, the former is given as follows,

$$\tau = M(q)u + h(q,\dot{q})\dot{q} + K_d sig(\dot{q}) \quad (10)$$

where $h(q,\dot{q})\dot{q}$ is the term to compensate Coriolis and centrifugal forces and gravity, and $K_d sig(\dot{q})$ is such a term that compensates the Coulomb's friction. This nonlinear control scheme contains a linear control input given as below

$$u = \ddot{q}_d - K_v(\dot{q} - \dot{q}_d) - K_p(q - q_d) + u_f \quad (11)$$

where K_v and K_p are joint feedback gain matrices needs to be chosen as that it has positive non-zero singular values; q_d, $\dot{q}_d$, and $\ddot{q}_d$ are desired trajectories of joint angle, velocity and acceleration. u_f is the vibration control input designed as below

$$u_f = -k_f f_f \quad (12)$$

where f_f is the flexible object reaction force measured by the force sensor, and k_f is a scalar feedback gain.

On the other hand, the control scheme using torque feedback can be designed by substituting the linear control input in (10) with the following expression.

$$u = \ddot{q}_d - K_v(\dot{q} - \dot{q}_d) - K_p(q - q_d) + u_m \quad (13)$$

and

$$u_m = -K_m f_m \quad (14)$$

moment measured by the force sensor and a scalar feedback gain respectively.

4. EXPERIMENTS

4.1 CONTROL SIMULATION

In order to conform the effectiveness of the proposed force feedback based control method, a 2-link DD arm equipped with a six axes force sensor at the end is used as an experimental test bed, and a very flexible beam made by alloy of copper and zinc is used as the flexible object to be manipulated by the arm.

The system is shown in Figure 2. The specifications of the robot arm are given as Table 1. The parameters of the flexible beam are given as follows, length: l=0.5m, cross section: A=0.036x0.001m^2, mass: m=155g, bending stiffness: EI=0.367Nm^2.

Simulations are carried out with the robot dynamics formulated using the Lagrange approach, and the flexible beam modeled using FEM for dimension truncation. The dynamic models are given by (1) and (2). The output of the force/torque sensor is calculated using (9). The approximation of the flexible displacements of the flexible beam and the shape functions are given as below.

$$e_i(x,t) = H_{0i}(x)\delta_i(t) + H_{1i}(x)\phi_i(t) + H_{0i+1}(x)\delta_{i+1}(t) + H_{1i+1}(x)\phi_{i+1}(t)$$

$$H_{0i} = 1 - 3(x/l_i)^2 + 2(x/l_i)^3$$

$$H_{1i} = x(x/l_i - 1)^2$$

$$H_{0i+1} = (x/l_i)^2(3 - 2x/l_i)$$

$$H_{1i+1} = x^2/l_i(x/l_i - 1)$$

The planned manipulation task is to move the flexible beam from a location to another location. These two locations are linked with a continuous trajectory generated by joints' trajectories which are calculated with polynomial functions. The manipulation task is performed by tracking of the joints' trajectories while dump out vibration of the flexible beam.

The control scheme is implemented based on (10), (13), and (14). The feedback gain matrices are chosen as K_v=*diag*[12, 11], K_p=*diag*[60, 50], K_m=10.

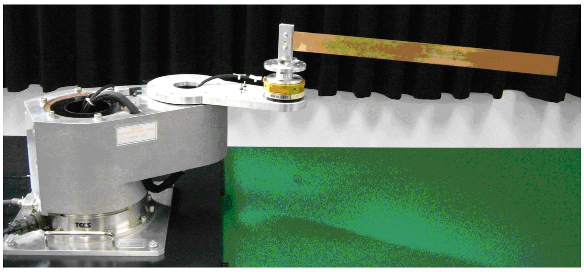

Fig.2. 2-link DD robot arm with flexible payload

Table 1. Specifications of the robot arm

	Link 1	Link 2
Length (m)	0.2	0.2
Weight (kg)	22	8
	Joint 1	Joint 2
Moment of inertia (kg-m^2)	8.5x10^{-2}	2.1x10^{-2}
Maximum torque (N-m)	70	15
Maximum rotation velocity (degree/sec.)	720	864

Figure3 and Figure4 show the planned trajectories and the tracking results. Figure5 presents flexible object vibration measured by the torque sensor. Figure6 are control torque.

4.2 FLEXIBLE OBJECT MANIPULATION EXPERIMENTS

We carried out flexible object manipulation experiments under the condition and same control scheme used in the simulation. Figure7 and Figure8 show the trajectory tracking results. Figure10 gives control torque generated by the motors on the joints. Figure9 shows flexible beam vibration measured by the torque sensor whereas Figure11 shows the vibration without torque feedback control (K_m was set as 0) for comparison.

From the experimental results, it can be seen that vibration of the object is damped effectively and excellent stability of the system is achieved by using both the force feedback. Hereby, we confirmed that the proposed control method is very useful and effective for flexible object manipulating.

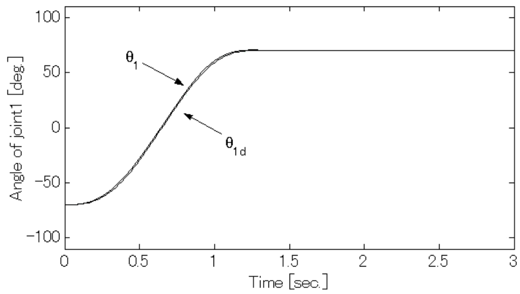

Fig. 3. Planned joint 1 trajectory and tracking result with vibration control in flexible payload manipulating simulation

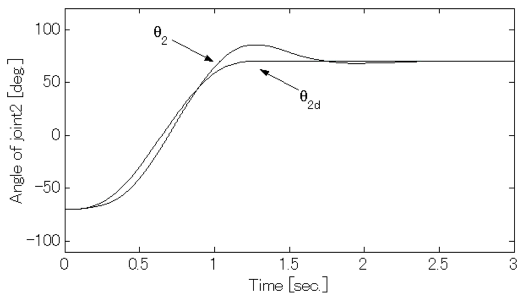

Fig. 4. Planned joint 2 trajectory and tracking result with vibration control in flexible payload manipulating simulation

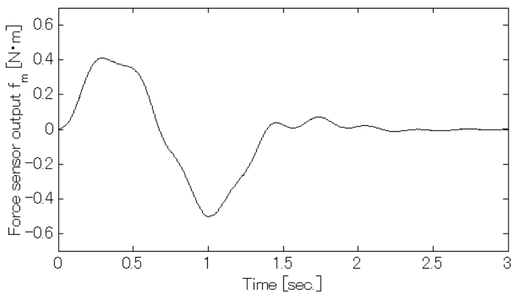

Fig. 5. Vibration measured by the torque sensor with vibration control in flexible payload manipulating simulation

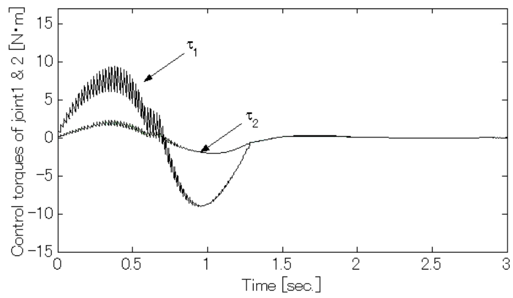

Fig. 6. Control torque with vibration control in flexible payload manipulating simulation

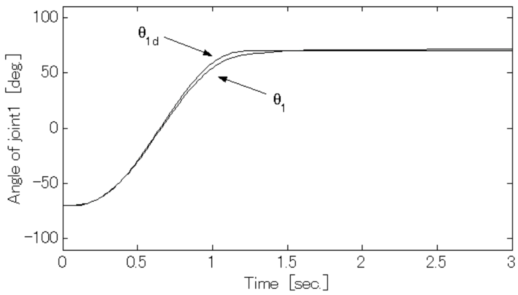

Fig. 7. Planned trajectory of joint 1 and tracking result with vibration control in flexible payload manipulating experiment

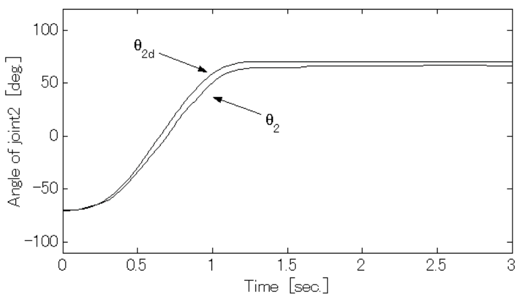

Fig. 8. Planned trajectory of joint 2 and tracking result with vibration control in flexible payload manipulating experiment

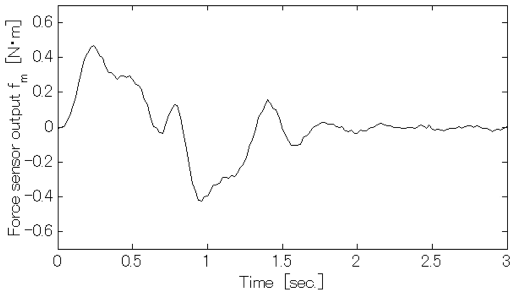

Fig. 9. Vibration measured by the torque sensor with vibration control in flexible payload manipulating experiment

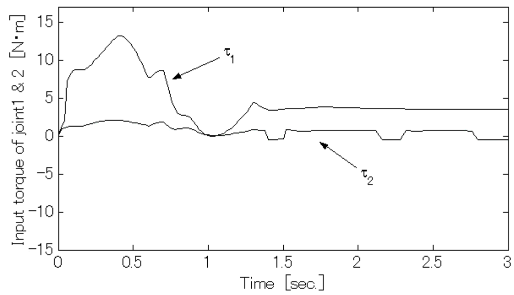

Fig. 10. Control torque sensor with vibration control in flexible payload manipulating experiment

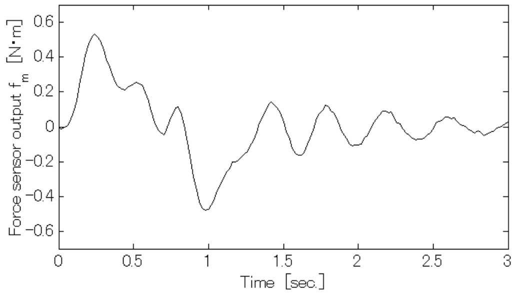

Fig.11 Vibration measured by the torque sensor without vibration control in flexible payload manipulating experiment

5. CONCLUSIONS

In this paper, a new control method was introduced based on force/torque feedback for suppressing of vibration of flexible objects manipulated by a robot arms. The vibration was measured using a force/torque sensor equipped at the end of the robot. Dynamic relationship among the robot motion, flexible behavior of object, and force sensor information were analyzed. From the results, it was clarified that a linear function of deflections of the flexible object becomes the main part of force/torque sensor output when the robot moves with low speed. Vibration control and manipulating experiments for the flexible beam were performed on 2-link DD robot, and the results demonstrated the feasibility and effectiveness of the proposed flexible object manipulating strategy.

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