A Torque Controller Design of Flexible Joint Robot Arm Using Disturbance Observer

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***Abstract*— In this paper, we propose a robust torque controller method for a flexible joint robot arm. Considered flexible joint robot arm can measure the joint torque by the torque sensor. In this robot arm system, there are undesirable effects e.g, parameter variation, errors in parameter identification and external disturbances as well as disturbance. To reduce the disturbance effects on the system performance, the disturbance observer scheme is used, and the system dynamics is reformulated to apply the disturbance observer. Using simulations of one degree of freedom flexible joint robot arm, we have demonstrated the performance of the proposed controller.**

***Keywords*— Flexible joint, Disturbance observer.**

1. INTRODUCTION

Because of the rapid development of the robotic technology, robots became popular in many fields of modern society. The safe behavior of robots became hot issue recently as a result of the increased use of service robots: the service robot works closer to human beings than other industrial robots. One of the options that ensure the safety is to equip the torque sensor at each joint of robots which allows measuring the external force. However, the torque sensor derives another problem, joint flexibility.

Actually, there have been much research on this problem based on feedback linearization[5], singular perturbation[6], sliding-mode[7], passivity, and adaptive methods[8]. Still, disturbance remains as a difficulty of controlling flexible joint to perform its functions. The disturbance includes parameter variations during operation, errors in system modeling and external disturbances.

This paper deals with the controller design of torque sensor based flexible joint robot arm using disturbance observer. The torque sensor equipped on the joint of the robot makes possible to directly measure the torque that occurs in the joints. The controller introduced in this paper could get feedback of the torque sensor signal and cancel the effect of disturbance which can be estimated by the disturbance observer. In order to confirm the performance of the controller, an one degree of freedom flexible joint robot is modeled and used in simulations.

In the following section and section 3, we describe system model of 1 D.O.F. flexible joint and basic concept of disturbance observer. In section 4, we deal with design of the proposed controller. In section 5, the simulation results are shown, respectively and finally conclusion is given in section 6.

2. Modeling of One D.O.F. Flexible Joint

Fig. 1 shows the mechanical structure of one degree of freedom flexible joint robot, and whole dynamics of considered robot can be expressed by in [1]

$$\tau = J_l\ddot{q} + mgl\sin q \tag{1}$$

$$\tau_m = J_m\ddot{\theta}_m + b_m\dot{\theta}_m + \tau + \rho_m \tag{2}$$

$$\tau = k_s\left(\frac{\theta_m}{n} - q\right) \tag{3}$$

where q and θ are the link angle and the motor angle. τ is the joint torque which is measured by the torque sensor. J_l and J_m are the link inertia and the motor inertia, m is the link mass, g means the gravity acceleration, l is the link length, and b_m denotes the motor friction. n is the gear ratio between motor and link, ρ_m is the unknown disturbance, k_s is the stiffness, and τ_m is the motor output torque.

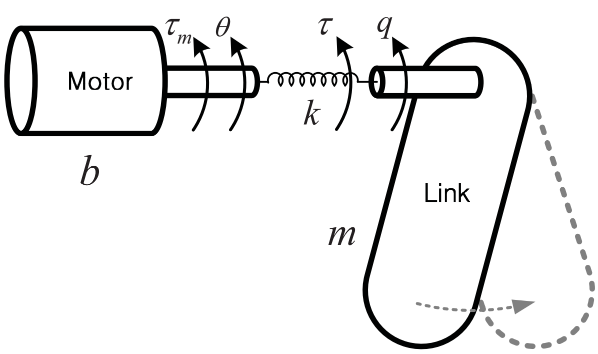

Fig. 1: 1 D.O.F. Flexible joint robot

3. Basic Concept of the Disturbance Observer

The idea of a disturbance observer was first proposed in [2] and its basic concept is shown in Fig. 2. In the figure, ε shows the control input, T_d is the unknown disturbance, u is the reference input, y denotes the output, and $P(s)$ means the real plant. In the observer part, $P_n(s)$ denotes a nominal plant, and $Q(s)$ is a low-pass filter to be determined.

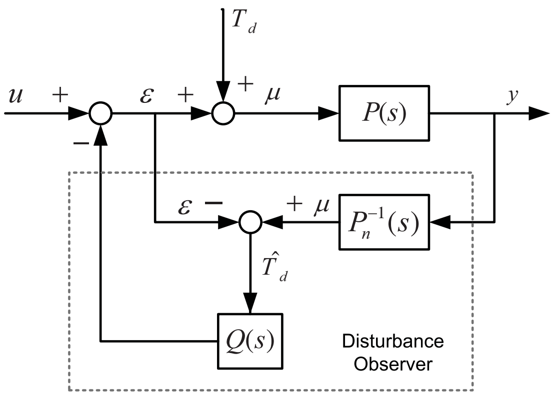

Fig. 2: Basic concept of disturbance observer

If it is assumed that $Q(s) = 1$ to see how the system based on the disturbance observer behaves, the following relation can be easily verified

$$\hat{T}_d = \left(1 - \frac{P_n}{P}\right) u + T_d , \tag{4}$$

then the output is expressed as

$$y = P(u + T_d - \hat{T}_d) = P_n u . \tag{5}$$

Now, the input-output relation between u and y is characterized by the nominal model. It shows that disturbance observer makes the characteristic of actual plant to that of nominal plant.[4]

However, the disturbance observer cannot be implemented if $Q(s) = 1$. It is noticed that $1/P_n(s)$ is not realizable by itself but that $Q(s)/P_n(s)$ can be realizable by letting the relative degree of $Q(s)$ be equal to or greater than that of $P(s)$.

From the block diagram in Fig. 2, y is expressed as

$$y = G_{uy}(s)u + G_{T_d y}(s)T_d \tag{6}$$

where

$$G_{uy}(s) = \frac{PP_n}{P_n + (P - P_n)Q}$$

$$G_{T_d y}(s) = \frac{PP_n(1-Q)}{P_n + (P - P_n)Q} .$$

These equations shows that the disturbance observer is dependent on $Q(s)$ which is the most significant parameter to determine robustness and disturbance suppression performance.

The disturbance observer regards the difference between the actual input ε and output of the inverse of nominal plant μ as an equivalent disturbance $\widehat{T_d}$ applied to the nominal plant. It estimates the equivalent disturbance and the estimate is utilized as a cancelation signal. This cancelation signal is effective for not only the disturbance compensation but also for the parameter identification in the mechanical system.

4. Controller Design

For torque tracking control, given equations (1), (2), and (3) can be reformulated to make the system take τ_m and τ as the system input and output.

$$\ddot{\tau} + a\tau + \rho \;=\; b\tau_m \tag{7}$$

with

$$a = k_s\left(\frac{1}{n^2 J_m} + \frac{1}{J_l}\right) , \; b = \frac{k_s}{nJ_m}$$

and

$$\rho = \frac{k_s}{nJ_m}(b_m\dot{\theta}_m + \rho_m) - \frac{k_s}{J_l} mgl \sin q .$$

To assume the nominal plant , $P_n(s)$, the following transfer function is obtained by taking Laplace transformation for eq. (7) which the disturbance term is removed and the link inertia J_l is exchanged for the nominal link inertia J_{ln}.

$$P_n(s) \;=\; \frac{b}{s^2 + a_n} \tag{8}$$

with

$$a_n = k_s\left(\frac{1}{n^2 J_m} + \frac{1}{J_{ln}}\right)$$

The design of Q-filter, $Q(s)$ is one of the important parts in the disturbance observer structure , and one of them is a binomial model as suggested in [3],[4].

$$Q(s) \;=\; \frac{1 + \sum_{k=1}^{N-r} a_k (f_c s)^k}{1 + \sum_{k=1}^{N} a_k (f_c s)^k} \tag{9}$$

where N is the order of $Q(s)$, f_c is a filter time constant, and r is the relative degree of $Q(s)$. To satisfy the causality, the relative degree of Q should be greater than or equal to that of the transfer function describing the nominal plant. In this paper, $Q_{31}(s)$ is chosen to design a disturbance observer as a third-order binomial filter of the form

$$Q_{31}(s) \;=\; \frac{3(f_c s) + 1}{(f_c s)^3 + 3(f_c s)^2 + 3(f_c s) + 1} , \tag{10}$$

and Fig. 3 shows the bode plot of $Q(s)$ with $f_c = 0.01s$.

The whole control algorithm is shown in Fig. 4. In the figure, block $C(s)$ is the conventional PD controller to make the output torque follow the input desired torque as

$$u = K_p(\tau_d - \tau) + K_d(\dot{\tau}_d - \dot{\tau}) \tag{11}$$

Note that the controller is using the joint torque, τ, which is measured by the torque sensor directly, so we call this as torque sensor based.

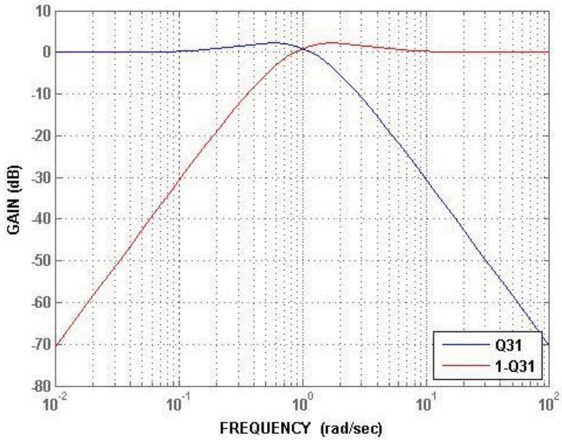

Fig. 3: Bode Plot of $Q(s)$: when $f_c = 0.01s$.

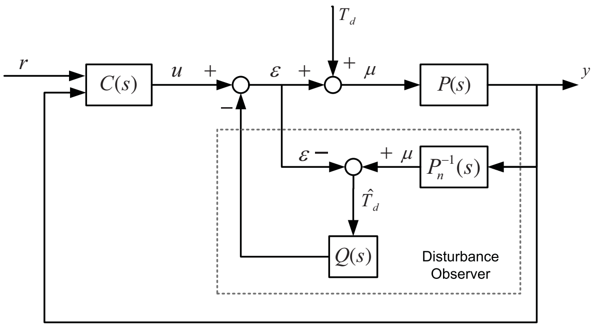

Fig. 4: Block diagram of proposed controller

5. SIMULATION

In this section, we show the performance of the proposed controller by simulation in which the regulation case and the tracking case are considered. The simulation parameters are shown in Table 1. We assume that there is error by 10% between the actual link inertia and the nominal link inertia. In both simulation cases, the frequency and the amplitude of the disturbance are 20π rad/s and 40.

First, the regulation performances of PD controller and proposed controller are compared. Fig. 5 is the result of PD controller without disturbance observer, and Fig. 6 is the result of proposed controller. We can see that the disturbance effect is reduced in the regulation case. In order to compare the tracking performance of PD controller and proposed controller, the desired torque trajectory is generated as

$$\tau_d = 2\sin(2t)\,, \tag{12}$$

and Fig. 7 and Fig. 8 are the results of PD controller without disturbance observer and proposed controller. From the figures, the proposed controller shows good performance in disturbance cancelation and tracking.

6. CONCLUSIONS

This paper suggested a torque tracking controller of flexible joint robot arm using the disturbance observer. Since

Table 1: Simulation parameters

Parameters	Name of parameters	Value	Unit
k	stiffness	114	kNm/rad
m	Mass of link	3.6	kg
n	Gear ratio	300	-
l	Length of link	0.5	m
J_l	Inertia of link	0.2219	kgm^2
J_m	Inertia of motor	0.004	kgm^2
b_m	Damping of motor	0.001	-
g	Gravity acceleration	9.81	m/s^2
N	Order of Q-filter	3	-
r	Relative degree of Q-filter	2	-
f_c	Time constant of Q-filter	0.01	sec
J_n	Nominal inertia of link	0.2	kgm^2

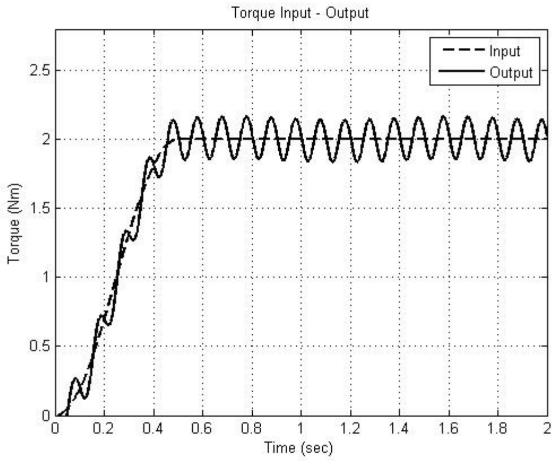

Fig. 5: Step response for PD controller: desired(dashed) and measured(solid)

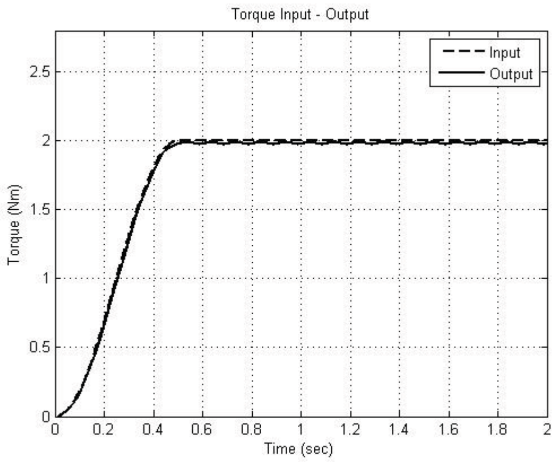

Fig. 6: Step response of PD + DOB controller: desired(dashed) and measured(solid)

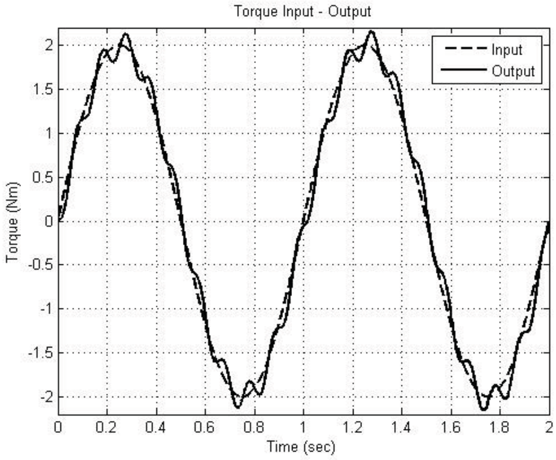

Fig. 7: Step response for PD controller: desired(dashed) and measured(solid)

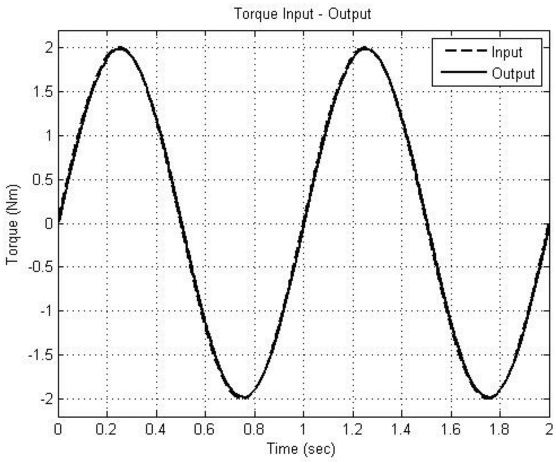

Fig. 8: Step response of PD + DOB controller: desired(dashed) and measured(solid)

the disturbance including parameter variations, parameter identification error and external disturbances affects the performance of the controller directly, the disturbance observer which estimates the disturbance of the system was applied to the controller. As a result, the performance of robot system was improved to resist the disturbance. and it was confirmed by computer simulation with 1 D.O.F. flexible Joint Robot.

ACKNOWLEDGEMENTS

This work was supported in part by Center for Cognitive Robotics Research (CCRR), Korea Institute of Science and Technology (KIST) through Cognitive Robot Project.

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