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Disturbance Observer Based Force Control of Robot Manipulator without Force Sensor

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Abstract

In this paper, a force estimation method is proposed for force control without force sensor. For this, a disturbance observer is applied to each joint of an n degrees of freedom manipulator to obtain a simple equivalent robot dynamics(SERD) being represented as an n independent double integrator system. To estimate the output of disturbance observer due to internal torque, the disturbance observer output estimator(DOOE) is designed, where uncertain parameters of the robot manipulator are adjusted by the gradient method to minimize the performance index which is defined as the quadratic form of the error signal between the output of disturbance observer and that of DOOE. When the external force is exerted, the external force is estimated by the difference between the output of disturbance observer and DOOE, since output of disturbance observer includes the external torque signal as well as the internal torque estimated by the output of DOOE. And then, a force controller is designed for force feedback control employing the estimated force signal. To verify the effectiveness of the proposed force estimation method, several numerical examples and experimental results are illustrated for the 2-axis direct drive robot manipulator.

Keywords : disturbance observer, force estimation, force control

1. Introduction

Many robotic tasks, such as deburring, grinding and precision assembly, require the end-effector of the robot to establish and maintain contact with environment. For successful execution of such tasks, both the force control and the position control of robot manipulator must be simultaneously controlled. Although the force control is needed for the precision control of robot manipulator, it is not popular in industrial application due to the high price of sensors and lacks of appropriate control algorithms. Moreover, when the robot manipulator is affected by environmental uncertainties such as high temperature and large noise, the force sensor cannot be mounted to it. To overcome these problems, several force estimation methods have been suggested[2,3,4,5].

Recently, disturbance observer based robust control algorithm has been reported to compensate modeling uncertainties as well as external disturbance[1,8,9,10]. The disturbance observer regards the difference between the actual output and the output of nominal model as an equivalent disturbance applied to the nominal model. When the robot manipulator contact with environments, the equivalent disturbance signal includes not only the modeling uncertainties but also the external force exerted by environments. Therefore, the problem of the force estimation based on disturbance observer is to find only the external force from the equivalent disturbance signal.

Ohishi and his coworkers proposed the force estimation method based on disturbance observer[4]. In this scheme, the modeling uncertainties are constructed by using experimentally obtained data, and the external torques are obtained by subtracting the established modeling uncertainties from the output of disturbance observer. However, those data seems not to completely include the inertia force, Coriolis and centrifugal force and so on. It is remarked that although an advantage of using disturbance observer is not to require the accurate robot modeling, their approach needs to accurate nominal model. Thus, the modeling uncertainties may cause the force estimation errors. Hacksel and Salcudean proposed the observer based force estimation scheme to get force signal[5]. The basic idea of this algorithm is to consider the observer error dynamics as a damped spring-mass system driven by environment. However, the proposed observer is based on the robot model and if the accurate robot modeling is not acceptable, the estimated force can be deviated from actual force signal.

In this paper, to obtain the force information from the equivalent disturbance signal, the modeling uncertainties are modeled by using robot dynamic equation. To estimate the output of disturbance observer in the absence of external force, a disturbance observer output estimator is designed, where the uncertain parameters of the robot manipulator are adjusted by the gradient method to minimize the performance index defined as the quadratic form of error signal between the output of disturbance observer and that of DOOE. When robot manipulator contacts with the environments, the

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external torque is estimated by the difference between the output of DOOE and that of disturbance observer, and the exerted force is computed from the estimated torque using kinematic relationship. A force feedback controller whose output is specified as position displacement in Cartesian space is designed by employing the estimated force signal[6,7].

To verify the effectiveness of the proposed force estimation method, numerical simulations and real experiments are performed for two degrees of freedom SCARA type direct-drive arm as shown in Fig.1.

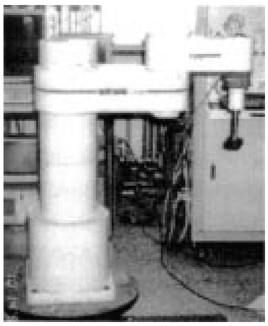


Fig.1. Two DOF SCARA type direct-drive arm.

2. Disturbance Observer Based Robot Dynamics

Consider dynamics of an n link robot manipulator given by a set of highly nonlinear and coupled differential equations as

$$\boldsymbol{M(q)\ddot{q} + c(q,\dot{q}) + g(q) + f(\dot{q})} = \boldsymbol{\tau}, \tag{1}$$

where $\boldsymbol{M(q)}$ is the $n \times n$ inertia matrix and $\boldsymbol{c(q,\dot{q})}$, $\boldsymbol{g(q)}$, $\boldsymbol{f(\dot{q})}$ are, respectively, the $n \times 1$ vectors of the Coriolis and centrifugal forces, the gravity loading, and the friction force. And $\tau \equiv [\tau_1 \cdots \tau_n]^T$ is the $n \times 1$ torque vector applied to the joint of robot manipulator. $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ are the $n \times 1$ vectors representing angular position, velocity and acceleration, respectively. Now, the robot dynamics in Eq.(1) can be rewritten as a fixed inertia term plus an equivalent disturbance torque given by

$$\boldsymbol{\overline{M}\ddot{q} + \tau_d(q,\dot{q},\ddot{q})} = \boldsymbol{\tau}, \tag{2}$$

where $\overline{\boldsymbol{M}} \equiv diag\{\overline{M}_{11} \cdots \overline{M}_{nn}\}$ is the $n \times n$ diagonal matrix. Here, $\overline{M}_{ii}$ is the constant-valued nominal inertia term of the ith axis which can be approximately measured by frequency response. Specifically, a frequency response for the ith axis can be obtained by locking all other actuators except the ith actuator. Then, by assuming that the dynamics of the ith axis can be treated as $\tau_i = \overline{M}_{ii}\ddot{q}_i$, $\overline{M}_{ii}$ can be experimentally measured by using a frequency response for the torque input and the velocity output. In Eq.(2), $\boldsymbol{\tau_d(q,\dot{q},\ddot{q})} \equiv [\tau_{1d} \cdots \tau_{nd}]^T$ is the $n \times 1$ vector implying equivalent disturbance including all the unmodeled dynamics, such as nonlinearity, coupling effects and payload uncertainty. τ_d can be rewritten as Eq.(3).

$$\boldsymbol{\tau_d = (M(q) - \overline{M})\ddot{q} + c(q,\dot{q}) + g(q) + f(\dot{q})} \tag{3}$$

If the equivalent disturbance in Eq.(3) can be obtained, dynamics of each axis can be decoupled by eliminating the equivalent disturbance. Thus, a simple control strategy is sufficient to track a desired trajectory $\boldsymbol{q}_d(t)$. The equivalent disturbance can be estimated by disturbance observer[5,9] and can be suppressed by adding the estimated disturbance signal to the control input. Fig.2 shows a structure of the disturbance observer for the ith single axis which is based on inverse model of nominal plant. In Fig.2, $P_{in}(s)$ is the nominal plant of the real system $P_i(s)$ where $P_{in}(s)$ is given as $1/\overline{M}_{ii}\,s$, and $Q_i(s)$ is a low pass filter which is employed to realize $P_{in}^{-1}(s)$ and to reduce the effect of measurement noise.

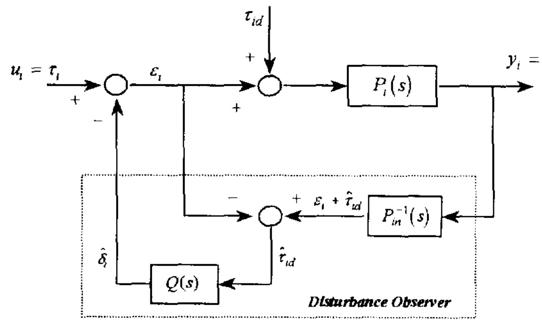


Fig.2. A structure of disturbance observer.

From the block diagram in Fig.2, input-output relation is obtained as follows;

$$y_i = G_{uy_i}(s)\,u_i + G_{\tau_{id}y_i}(s)\,\tau_{id}, \tag{4}$$

where

$$G_{u_iy_i} = \frac{P_i(s)P_{in}(s)}{P_{in}(s) + (P_i(s) - P_{in}(s))Q_i(s)}, \tag{5}$$

and

$$G_{\tau_{id}y_i} = \frac{P_i(s)P_{in}(s)(1 - Q_i(s))}{P_{in}(s) + (P_i(s) - P_{in}(s))Q_i(s)}. \tag{6}$$

From these equations, we can observe that in the design of disturbance observer, $Q_i(s)$ plays the most significant role of determining robustness and disturbance suppression performance of the system. If $Q_i(s) \approx 1$, the transfer functions is reduced to

$$G_{u_i v_i}(s) \approx P_{ni}(s), \text{ and } G_{\tau_{di}}(s) \approx 0 . \tag{7}$$

Therefore, a sensible choice for the design of $Q_i(s)$ is to let the low frequency dynamics of $Q_i(s)$ remain close to unity for disturbance rejection and for coping with model uncertainties[10]. This implies that for a disturbance signal whose maximum frequency is lower than cut-off frequency of $Q_i(s)$, the disturbance signal is effectively rejected and the real plant behaves as a nominal plant. Therefore, if such a disturbance observer is employed for every joint of a manipulator, then the robot dynamics can be considered as the simple equivalent dynamic(SERD) system given by

$$\overline{M}\ddot{q} = \tau . \tag{8}$$

3. Disturbance Observer Based Force Estimator

When the external force is not exerted, the output of disturbance observer can be written as

$$\tau_d = W(q,\dot{q},\ddot{q})\varphi + v , \tag{9}$$

where φ is the $r \times 1$ unknown parameter vector and $W(q,\dot{q},\ddot{q})$ and v, respectively, are an $n \times r$ matrix and an $n \times 1$ vector of robot functions depending on the joint variables. This matrix and vector may be found for any given robot arm[11]. The output of disturbance observer output estimator(DOOE) can be given as

$$\begin{aligned}\hat{\tau}_d &= (\hat{M}(q(q)) - \overline{M})\ddot{q} + \hat{c}(q,\dot{q}) + \hat{g}(q) + \hat{f}(\dot{q}) \\ &= W(q,\dot{q},\ddot{q})\hat{\varphi} + v\end{aligned} \tag{10}$$

where $\hat{\varphi}$ is the estimation of the unknown parameter vector. The error between the output of disturbance observer and that of DOOE is defined as $\tilde{\tau}_d = \tau_d - \hat{\tau}_d$, and if the performance index of DOOE is defined as

$$J = \frac{1}{2}\tilde{\tau}_d{}^T\tilde{\tau}_d , \tag{11}$$

then the parameter update rule for reducing the error by using the gradient method can be written as

$$\dot{\hat{\varphi}} = -\Gamma W^T(q,q,q)\tilde{\tau}_d , \tag{12}$$

where Γ is the $r \times r$ diagonal matrix that represents the positive valued parameter update rate. The block diagram of DOOE is depicted in Fig.3.

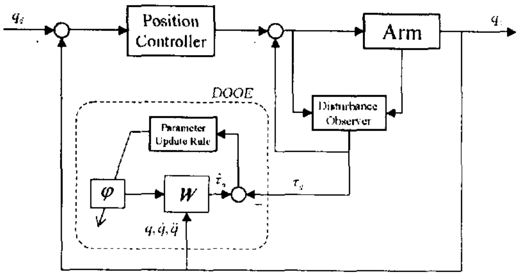


Fig.3 The block diagram of DOOE

When the robot manipulator contacts with the environments, the output of disturbance observer include the external force exerted by environments and it can be written as

$$\tau_d = (M(q) - \overline{M})\ddot{q} + c(q,\dot{q}) + g(q) + f(\dot{q}) + \tau_e \tag{13}$$

where τ_e is an $n \times 1$ external torque vector. Thus, external torque can be obtained by subtracting the output of observer estimator from the output of disturbance observer which include external torque. That is, external torque is obtained as

$$\hat{\tau}_e = \tau_d - \hat{\tau}_d . \tag{14}$$

The external force can be obtained using Jacobian matrix as follows.

$$\hat{f}_e = (J^T(q))^{-1}\hat{\tau}_e \tag{15}$$

The block diagram of force estimator using observer estimator and disturbance observer is shown in Fig.4.

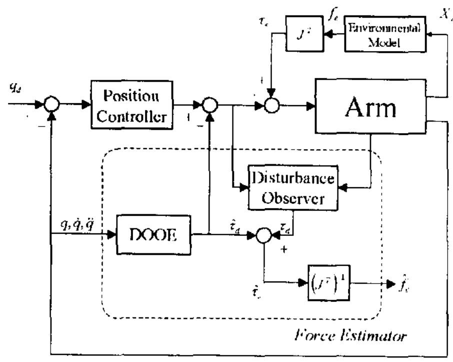


Fig.4 The block diagram of force estimator

When the end-effector contacts with an external environment, the relationship between force displacement and position displacement can be expressed as

$$\delta f = K_E \delta x \tag{16}$$

where δf and δx, respectively, are $n \times 1$ displacement of force and position, and K_E is $n \times n$ environment stiffness matrix in Cartesian space. The relationship of minimal displacement between the Cartesian coordinate and the joint coordinate can be shown as

$$\delta \boldsymbol{x} = \boldsymbol{J(q)}\delta \boldsymbol{q} . \tag{17}$$

By substituting Eq.(17) into Eq.(16), Eq.(18) can be obtained as

$$\delta \boldsymbol{f} = \boldsymbol{K}_E \boldsymbol{J(q)}\delta \boldsymbol{q} . \tag{18}$$

Eq.(18) can be converted to Eq.(19) by multiplying the inverse matrices at each sides.

$$\delta \boldsymbol{q} = \boldsymbol{J(q)}^{-1} \boldsymbol{K}_E^{-1} \delta \boldsymbol{f} \tag{19}$$

For force feedback controls whose output is given as the position displacement in Cartesian space, the controller design problem is to find δf as a function of force error signal. Here we employ typical hybrid position and force control using force estimator as shown in Fig.5, even though there may be some problems indicated in [12].

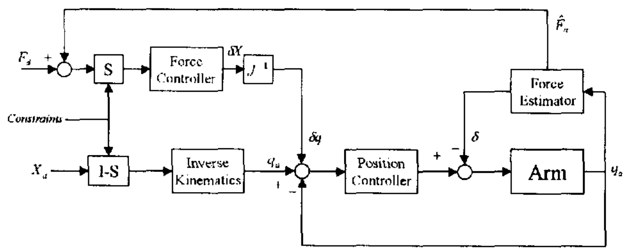


Fig.5 The block diagram of hybrid position and force control using force estimator

To show the efficiency of the proposed force estimation method, numerical simulations are performed with a two DOF planar type robot manipulator depicted in Fig.6. The dynamic equation of the robot manipulator in Fig. 6 can be written as

$$\boldsymbol{M(q)}\ddot{q} + \boldsymbol{c(q,\dot{q})} + \boldsymbol{g(q)} + \boldsymbol{f(\dot{q})} = \tau . \tag{20}$$

where $\boldsymbol{M(q)}$, $\boldsymbol{c(q,\dot{q})}$ and $\boldsymbol{g(q)}$ are given as

$$\boldsymbol{M(q)} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}, \tag{21}$$

$$m_{11} = (m_1 + m_2)l_1^2 + m_2 l_2^2 + 2m_2 l_1 l_2 \cos q_2 ,$$

$$m_{12} = m_{21} = m_2 l_2^2 + m_2 l_1 l_2 \cos q_2 ,$$

$$m_{22} = m_2 l_2^2 ,$$

$$\boldsymbol{c(q,\dot{q})} = [c_1 \quad c_2]^T , \tag{22}$$

$$c_1 = -m_2 l_1 l_2 \sin q_2 \dot{q}_2^2 - 2m_2 l_1 l_2 \sin q_2 \dot{q}_1 \dot{q}_2 ,$$

$$c_2 = m_2 l_1 l_2 \sin q_2 \dot{q}_1^2 ,$$

$$\boldsymbol{g(q)} = [g_1 \quad g_2]^T , \tag{23}$$

$$g_1 = (m_1 + m_2) g l_1 \cos q_1 + m_2 g l_2 \cos(q_1 + q_2) ,$$

and

$$g_2 = m_2 g l_2 \cos(q_1 + q_2) ,$$

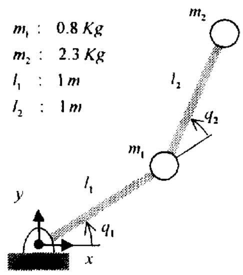


Fig. 6 A two DOF planar type robot manipulator

For estimation of disturbance observer output, the uncertain constant parameter is defined as $\hat{\varphi} = [\hat{m}_1, \hat{m}_2]^T$, where $\hat{m}_i$ is the estimation of the mass of ith axis. Then, $\boldsymbol{W(q,\dot{q},\ddot{q})}$ and $\boldsymbol{v}$ in Eq.(10) can be represented as

$$\boldsymbol{W(q,\dot{q},\ddot{q})} = \begin{bmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{bmatrix}, \tag{24}$$

$$w_{11} = l_1^2 \ddot{q}_1 + g l_1 \cos q_1 ,$$

$$\begin{aligned} w_{12} = {} & (l_1^2 + l_2^2 + 2l_1 l_2 \cos q_2)\ddot{q}_1 + (l_2^2 + 2l_1 l_2 \cos q_2)\ddot{q}_2 \\ & - (l_1 l_2 \sin q_2 \dot{q}_2 + 2l_1 l_2 \sin q_2 \dot{q}_1 \dot{q}_2) \\ & + g l_1 \cos q_1 + g l_2 \cos(q_1 + q_2) \end{aligned} ,$$

$$w_{12} = 0 ,$$

$$\begin{aligned} w_{22} = {} & (l_2^2 + 2l_1 l_2 \cos q_2)\ddot{q}_1 + l_2^2 \ddot{q}_2 + l_1 l_2 \sin q_2 \dot{q}_1^2 \\ & + g l_2 \cos(q_1 + q_2) \end{aligned} ,$$

$$v = [v_1 \quad v_2]^T , \tag{25}$$

$$v_1 = (-(\overline{m}_1 + \overline{m}_2) l_1^2 - \overline{m}_2 l_2^2 - 2\overline{m}_2 l_1 l_2)\ddot{q}_1 + f_1(\dot{q}) ,$$

and

$$v_2 = -\overline{m}_2 l_2^2 \ddot{q}_2 + f_2(\dot{q}) ,$$

where g is acceleration of gravity and $f_i(\dot{q})$ is friction force of ith axis. When the external torque is not exerted, the position command is given as $\boldsymbol{q}_d = [\sin t \ \cos t]^T$. The estimated parameter $\hat{\varphi}$ is updated by gradient method which minimize the difference between the output of disturbance observer and that of DOOE. Fig. 7 show the results of parameter estimation when the initial mass is given as $\hat{\varphi} = [1 \quad 3]^T Kg$, where the estimated mass converges to the mass value of the robot manipulator in 3 [sec]. It is remarked that the convergence of estimated value implies that the outputs of DOOE converge to the output of disturbance observer and thus the difference of two outputs goes to zero. The outputs of DOOE and disturbance observer are shown in Fig. 8.

For force feedback controls using the estimated force signal, a PD type force controller in Fig. 5 is designed. Fig. 9 shows the results of force control where the dotted line, dashed line and solid line represent the desired force command, real force signal from force sensor and the estimated force signal respectively. Although the force control scheme doesn't employ the explicit force sensor, the external force is satisfactorily estimated by the force estimator and the force output can follow the force command.

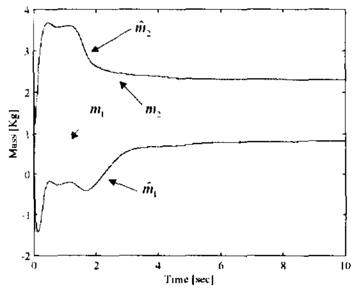


Fig. 7 The mass estimation by DOOE

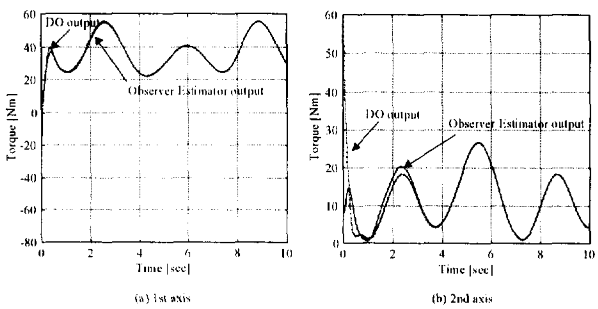


Fig. 8 The output of DOOE and the output of disturbance observer

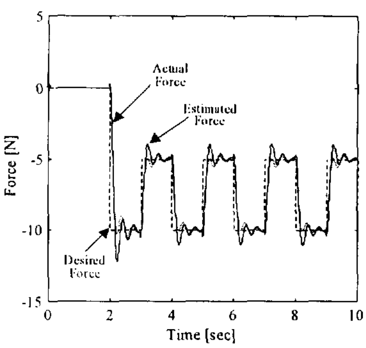


Fig. 9 The force response using the proposed force estimator

4. Experimental Results

All experiments were performed by employing a 2 DOF SCARA type direct-drive arm as shown in Fig.1. The control algorithm is written in C language and tested our prototype robot controller, where a 32-bit microprocessor (FORCE30) embedded VxWorks and DSP board for servo control are used for real-time operation as sketched in Fig.10.

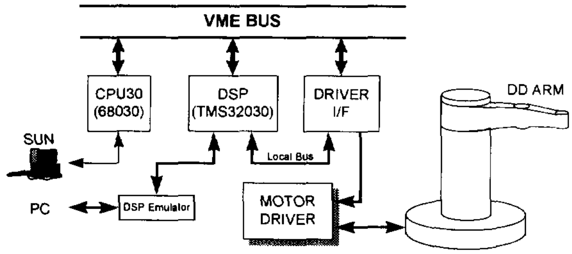


Fig.10. Experimental Setup

The friction terms of each joint in Eq.(3) can be experimentally obtained by the constant velocity motion[4] and the results are depicted in Fig.11. When the external torque is not exerted, the position command is given as $q_d = [\sin 2t \;\; \sin 2t]^T$ to estimate the uncertain constant parameter. The estimated parameter $\hat{\varphi} = [m_1 \;\; m_2]^T$ is updated by gradient method. Fig. 12 shows the results of parameter estimation when the initial mass is given as $\hat{\varphi} = [20 \;\; 2]^T Kg$, where the estimated mass converges to $\varphi = [29 \;\; 5.5]^T Kg$ which is the mass value of the robot manipulator. The output of DOOE and that of disturbance observer are shown in Fig. 13. It is observed that the output of DOOE goes to the output of disturbance observer as the estimated mass values converge to real mass values during the robot motion.

When the force feedback controller employing the proposed force estimator is constructed, force response is depicted in Fig. 14. The output response is satisfactory in the sense of small overshoot and fast settling time. From these experimental results, it may be concluded that our proposed force estimator can be a good way to use for force control in the situations having difficulties in mounting force sensor.

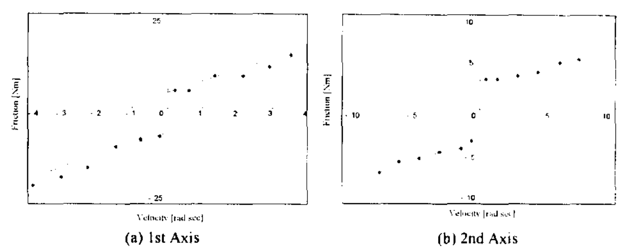


Fig. 11 Friction Model

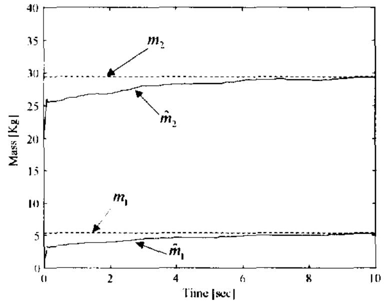
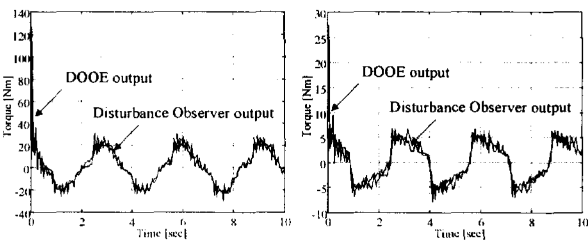


Fig.12 The mass estimation by DOOE



(a) 1st axis (b) 2nd axis

Fig. 13 The output of DOOE and the output of disturbance observer

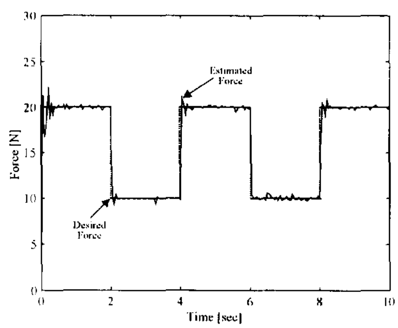


Fig. 14 The force response using the proposed force estimator

5. Conclusion

A force estimation method was proposed for force control without force sensor. For estimation of the output of disturbance observer in the absence of external force, DOOE was designed. When the external force is exerted, the external force is estimated using the difference between the output of disturbance observer which include the external torque signal and the output of DOOE. And then, a force controller was designed for force feedback control employing the estimated force signal. It was experimentally shown that the proposed force estimator successfully estimated the external force signal and can be a good alternative replacing an expensive force/torque sensor.

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