Robust Control of Series Elastic Actuator Using ISMC and DOB

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***Abstract*—This paper deals with the control problem of a series elastic actuator (SEA) which can realize a muscle strengthening robot at low cost. We designed and fabricated SEA with improved structure and designed robust controller for it. The robust controller implements the state feedback controller without the effect of disturbance by using the integral sliding mode control(ISMC) with the state feedback controller as a nominal controller. At the same time, by adding a disturbance observer, it can cope with the larger range of disturbance, and the chattering phenomenon is reduced by decreasing the gain of the variable control input, thereby improving the control performance of the SEA.**

***Index Terms*—robust control, series elastic actuator, integral sliding mode, disturbance observer**

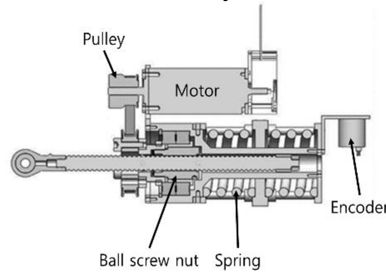
I. Introduction

The SEA used for the muscle strength enhancement is an actuator including an elastic element and has a structure in which the motor torque is transmitted to the mechanism through an elastic element such as a spring [1]. The elastic element is to measure the force from its displacement and also to have external compliance characteristics [2]. Industrial robots can use high-torque motors, but in the usual case of muscle-strengthening robots or humanoids, the volume and capacity of the motors are limited. Therefore, the motors with relatively high speed and low torque are usually used and high torque is realized by harmonic gears [3]. Harmonic gears, however, raise the price of robots with torque sensors at high prices. In order to overcome this difficulty, a SEA has been developed [4][5][6] that uses a ball screw to have high gear ratios and can measure the force using spring displacement. Among the various types of SEA, the electric SEA of the bolt drive type is getting attention considering the small size and light weight of the SEA and the performance. The UT-SEA is a typical bolt-driven SEA, in which the power of the motor is transmitted to the ball screw through a timing belt and the displacement of the spring is measured using an encoder [6]. In this paper, the motor torque is directly connected to the ball screw and the spring with low spring constant is adopted so that the force can be measured with a low-cost variable resistance. For the SEA, the control problems with robustness has been important issues. In this paper, we deal with the robust control of the developed SEA. As the robust control scheme, the integral sliding mode control is used in this paper. At first time, the integral sliding mode control has been proposed to solve the arrival time problem, which is a disadvantage of sliding mode control, but it is widely used because its robustness can be combined with the control performance of other controllers [7][8]. However, when the disturbance is large, the performance may be degraded due to the limited variable control input size, or the input chattering problem due to the large control input may degrade the control performance [9].

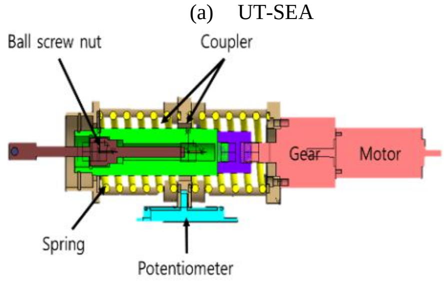
In this paper, we have implemented an integral sliding mode controller with improved control performance by adding a disturbance observer. This paper uses the most widely used disturbance observer which uses the inverse transfer function and low-pass filter [10][11]. The state feedback controller is used as a nominal controller for the integral sliding mode

II. New SEA and Mathematical Model

The SEA of this paper removes the pulley and timing belt which are structural disadvantage of the UT-SEA, and transmits the power of the motor through the proposed coupling element to reduce the loss in power transmission and to have an easy structure.



(a) UT-SEA



(b) New SEA

Figure 1. Structure of SEA (a) UT-SEA and (b) New SEA

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In the Fig. 1 (a), UT-SEA transmits motor power through the pulley to rotate the nut of the ball screw. In the Fig. 1 (b), the improved SEA is more compact and lightweight by suggesting the coupling part which connects the motor and the nut directly.

The dynamic characteristics model of the existing UT-SEA and the improved SEA is the same and is shown in the following figure. Fig. 2 shows the structure of the SEA and the dynamic model of the SEA is shown in Fig. 3 as follows.

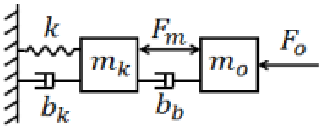

Figure 2. SEA Model

where k is the spring constant, x is the displacement of the spring, the force transmitted from the motor to the screw, the disturbance, the friction coefficient at the spring, the friction coefficient at the screw, the mass at the motor, and the mass at the screw.

For the force control of the SEA, a transfer function between output displacements to the force input is required. Fig. 3, transfer function is obtained when high load applied.

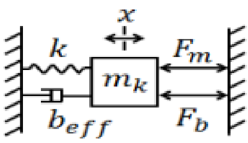

Figure 3. SEA Model with High Impedance

The force applied to the load in the state, where the screw movement is restricted in the high resistance to the output load, can be expressed as follows.

$$f_o = f_{m_k} + f_{b_{eff}} + f_k = m\ddot{x} + b_{eff}\dot{x} + kx \quad (1)$$

When the output of the transfer function is spring displacement, the transfer function of SEA is expressed as follows.

$$P_c = \frac{1}{m_k S^2 + b_{eff} S + k} \quad (2)$$

In this paper, the transfer function of SEA is obtained by using the system identification method.

III. Integral Sliding Mode Control and Disturance Observer

Robustness to disturbance and system uncertainty plays an important role in enhancing the control performance of the SEA. In this paper, integral sliding mode control is used as a robust controller.

Integral sliding mode control configures the s-plane to have dynamic characteristics of the nominal system which has the performance of other control method. In addition, since the initial sliding function can be zero by using the initial value of the virtual state, the reaching phase problem is solved.

In this paper, to increase the allowable range of the disturbance and reduce the input chattering of the integral sliding mode control, the disturbance observer is combined with ISMC and applied to the SEA.

A. Integral Sliding Mode Control

The state equation of a linear system with disturbance is as follows.

$$\dot{X} = AX + B(u + d) \quad (3)$$

where X is the state of the system, u is the input, and d is the input disturbance.

The s-plane of the integral sliding mode control is designed as follows.

$$\mathrm{S} = \mathrm{X} - \mathrm{Z} \quad (4)$$

$$\dot{Z} = AX + Bu_0 \quad (5)$$

where u_0 is the nominal input.

The dynamic characteristics of the s-plane (4) is as follows.

$$\dot{X} = AX + Bu_0 \quad (6)$$

In other words, the dynamic characteristics of the system above the s-plane follow the dynamic characteristics of the nominal system without being affected by external disturbance. The control input of the ISMC is obtained based on the Lyapunov stability.

Select the Lyapunov candidate function as follows.

$$\mathrm{V(S)} = \frac{1}{2} S^T S \quad (7)$$

For S to converge to zero, the derivative of the Lyapunov candidate function must be less than zero.

$$\dot{V}(s) = \frac{1}{2}(\dot{S^T} S + S^T \dot{S})$$

$$= S^T(AX + B(u_0 + u_d + d) - (AX + Bu_0))$$

$$= S^T B(u_d + d)$$

Thus, to satisfy $\dot{V}(s) < 0$ the following input is determined.

$$u_d = -D_{max} * sign(S^T B) \ \ (D_{max} > |d|) \quad (8)$$

The ISMC input ensures robustness against disturbance and guarantee the performance of the nominal control system.

B. Disturbance Observer Based Control

The overall scheme of the disturbance observer based control is shown in Fig. 4.

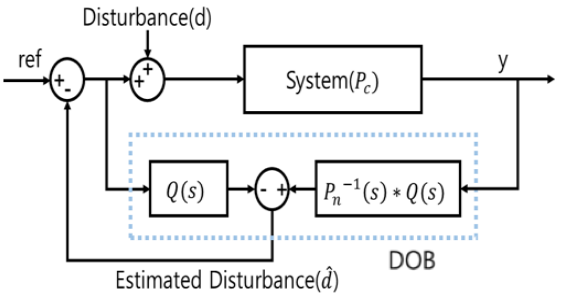

Figure 4. Disturbance observer based control

P_c is the transfer function of the actual system and P_n the is the transfer function of the nominal system. Q(s) is a low pass filters.

The output y of the actual plant can be expressed as follows.

$$y = y_u + y_d \tag{9}$$

The output is used to estimate the disturbance.

$$d_e = \frac{Q(s)}{P_n(s)} * y - Q(s) * u \tag{10}$$

$$= \frac{Q(s)}{P_n(s)} * (y_u + y_d) - Q(s) * u$$

$$= \frac{Q(s)}{P_n(s)} * (P_c u + P_c y_d) - Q(s) * u$$

If the nominal plant((P_n) and the actual system(P_c) are identical, the estimated disturbance(d_e) can be the same one with the actal disturbance.

$$d_e = d \tag{11}$$

C. Integral Sliding Mode Control with Disturbance Observer

The ISMC and DOB are integrated together to improve the robustness. The overall scheme is shown in the following Fig. 5.

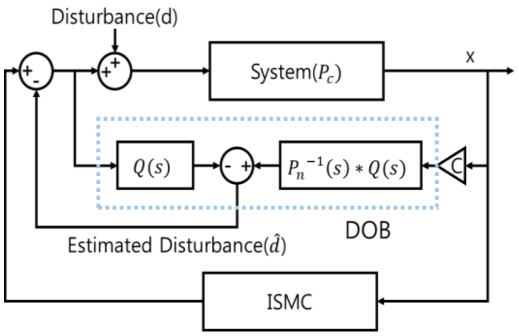

Figure 5. Robust control system using integral sliding mode control and disturbance observer

IV. Transfer Dunction Estimation of SEA and Simulation of Control

A. System Identification

To obtain the SEA mathematical model, the MATLAB System Identification ToolBox was used. To obtain a system transfer function that includes various frequencies, a linear chirp signal was used as an input.

The transfer function of the identified system is

$$G(s) = \frac{0.6945}{S^2+21.57S+49.95} \tag{12}$$

The integral sliding mode requires the model in the form of a state equation as follows.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -49.95 & -21.57 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \tag{13}$$

$$y = \begin{bmatrix} 0.6945 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Before the experiment, the simulation results show the control performance of a robust control system which combine the disturbance observer and integral sliding mode control.

B. Simulation of Integral Sliding Mode Control

Nominal controller of the integral sliding mode has been designed as a state feedback controller with the desired eigenvalue of –4 and –5.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -49.95 & -21.57 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_0$$

$$u_0 = \begin{bmatrix} k_1 & k_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$k_1 = 29.95, \qquad k_2 = 12.57$$

The sliding surface is as follows.

$$S = X - Z$$

$$\dot{Z} = \begin{bmatrix} 0 & 1 \\ -49.95 & -21.57 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_0$$

The control input u_d to satisfy the conditions of $\dot{V}(s) < 0$ according to the Lyapunov stability is shown as follows.

$$u_d = -D_{max} * sign(s_2)$$

The state response and control input of the SEA when input disturbance d = 200[N], and integral sliding mode control with d_{max} = 250 are shown in Fig. 6, Fig. 7.

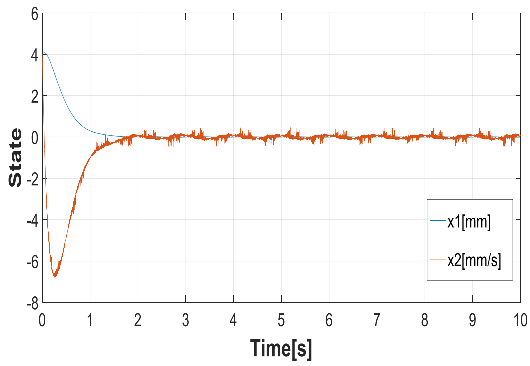

Figure 6. State response of SEA

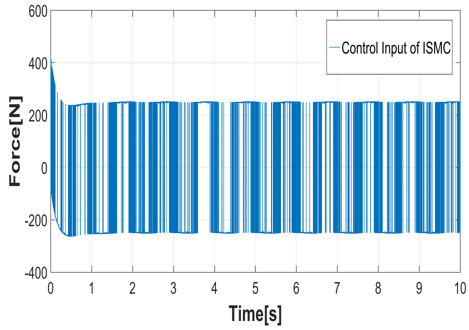

Figure 7. Control Input of Integral Sliding Mode Control

C. Simulation of Robust Control Combining Integral Sliding Mode Control and Disturbance Observer

The Q (s) used in the disturbance observer is a second-order low-pass filter. The cut-off frequency of Q (s) is set to 5 [Hz].

$$Q(s) = \frac{w_c^2}{s^2+1.4142*w_c^2*s+w_c^2} \tag{14}$$

The control input and states of the ISMC with DOB are in the Fig. 12 and Fig. 13. The estimated disturbance of the DOB can be reflected to a wide range of disturbances, and the robustness of the ISMC can be achieved with the lower d_{max}, thereby reducing the input chattering phenomenon.

$$d_{max} = estimated\ disturbance * 0.15 \tag{15}$$

The control performance of a robust control system that mitigates the input chattering of the ISMC is shown in the Fig. 8.

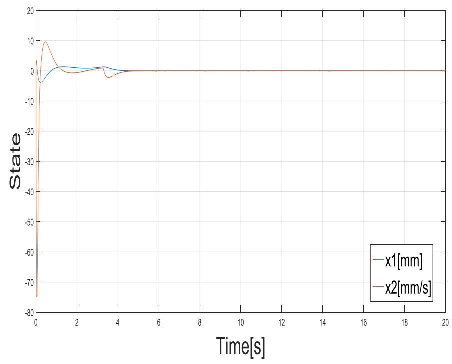

Figure 8. State response of Robust Control using ISMC and DOB

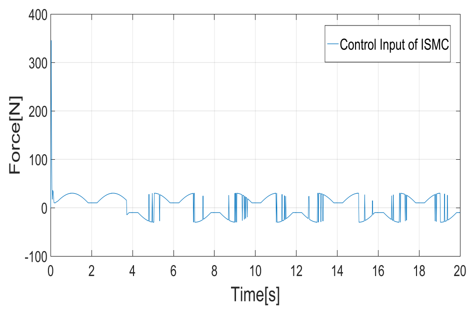

Figure 9. Control Input of ISMC on Robust Control using ISMC and DOB

The Fig. 9 shows that the effects of input disturbances are reduced by proposed controller.

D. SEA Development and Experiment

Hardware configuration of the control system of the SEA is shown in the following figures.

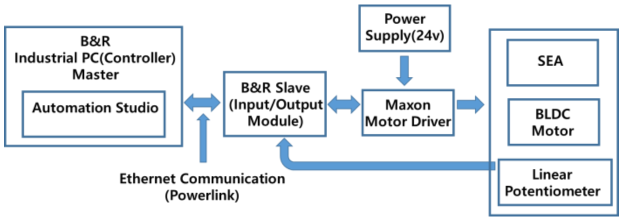

Figure 10. Hardware configuration of SEA control system

The SEA developed in this paper is shown in the Fig 11.

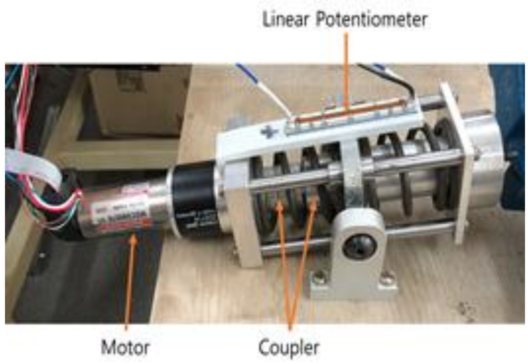

Figure 11. SEA Hardware

The Fig. 12 shows the comparison of the disturbance estimations.

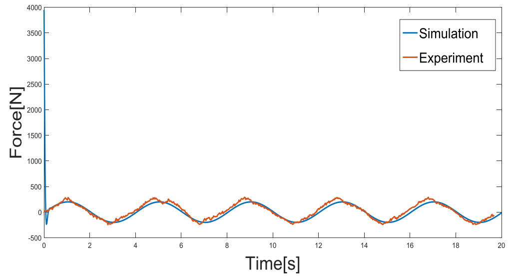

Figure 12. Comparison of the estimated disturbance in the simulation and actual experiment

The Fig. 13 shows the outputs of the SEA.

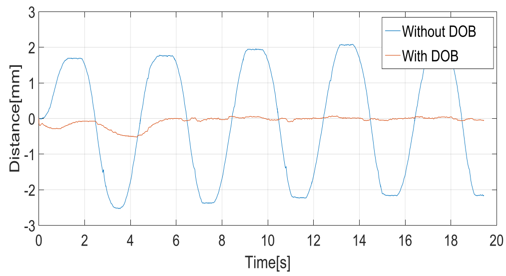

Figure 13. Outputs with DOB and without DOB

As expected in the simulation results, the actual experiment results of the SEA shows the robustness improvement of the ISMC with DOB.

V. Conclusions

The structure of SEA is improved for the energy efficiency and ease of design and the robust controller is constructed by combining ISMC and DOB. Based on the identified model of the SEA system, the proposed controller designed and applied well to the actual SEA system. The proposed controller can cover lager allowable range of the disturbance compare to the existing ISMC.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Lee conducted the hardware work and experiment; Park provided theoretical background; Kwak conducted the simulation; all authors had approved the final version.

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