Design and Experimental Evaluation of a Robust Force Controller for a 6-Link Electro-Hydraulic Manipulator via H_∞ Control Theory

KyoungKwan Ahn*, ByungRyong Lee, SoonYong Yang
School of Mechanical and Automotive Engineering, University of Ulsan,
San 29, Muger 2dong, Nam-gu, Ulsan 680-764, Korea

Uninterrupted power supply has become indispensable during the maintenance task of active electric power lines as a result of today's highly information-oriented society and increasing demand of electric utilities. This maintenance task has the risk of electric shock and the danger of falling from high place. Therefore it is necessary to realize an autonomous robot system using electro-hydraulic manipulators because hydraulic manipulators have the advantage of electric insulation and power/mass density. Meanwhile an electro-hydraulic manipulator using hydraulic actuators has many nonlinear elements, and its parameter fluctuations are greater than those of an electrically driven manipulator. So it is relatively difficult to realize not only stable contact work but also accurate force control for the autonomous assembly tasks using hydraulic manipulators. In this paper, the robust force control of a 6-link electro-hydraulic manipulator system used in the real maintenance task of active electric lines is examined in detail. A nominal model for the system is obtained from experimental frequency responses of the system, and the deviation of the manipulator system from the nominal model is derived by a multiplicative uncertainty. Robust disturbance observers for force control are designed using this information in an H_∞ framework, and implemented on the two different setups. Experimental results show that highly robust force tracking by a 6-link electro-hydraulic manipulator could be achieved even if the stiffness of environment and the shape of wall change.

Key Words: Fluid Power System, Robust Force Control, Impedance Control, Disturbance Observer, Hydraulic Manipulators, H Infinity Control

1. Introduction

Uninterrupted power supply has become indispensable during the maintenance task of active electric power lines as a result of today's highly information-oriented society and increasing demand of electric utilities. Outage-free maintenance techniques for overhead distribution power lines have been developed and used recently by several companies in order to fulfill this requirement (Nakashima, 1995 ; Mukaida, 1995 ; Takaoka, 2001).

In the conventional maintenance techniques, workers have to do their job on a live electric power line indirectly with various kinds of insulated hot-sticks or directly touching the line with rubber gloves from an insulated bucket. Therefore, work is performed in a hazardous environment with both the risk of electrical shock and the danger of falling from a high place. In addition, workers have to be very skillful and have to work cooperatively under very demanding tasks. In the near future, it is anticipated to

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* Corresponding Author,
E-mail : kkahn@mail.ulsan.ac.kr
TEL : +82-52-222-1404; **FAX** : +82-52-259-1680
School of Mechanical and Automotive Engineering, University of Ulsan, San 29, Muger 2dong, Nam-gu, Ulsan 680-764, Korea. (Manuscript **Received** September 9, 2002; **Revised** April 15, 2003)

Fig. 1 Maintenance task of a 6-link electro-hydraulic manipulator

develop an autonomous manipulator system in the maintenance task of active electric line. At present, a semi-automatic hot-line work robot has been developed shown in Fig. 1. This robot is composed of a 6-link electro-hydraulic manipulator with dual arm because hydraulic system is superior to electrically driven robot system in the electrical insulation.

The live electric line maintenance task encompasses a series of operations (insulator string replacement, opening/closing bridges, etc.), which is made of highly standardized manipulation procedures, some of which are common to different operations. To realize the maintenance task of an active high-voltage distribution line autonomously, accurate position and robust force control is necessary. In particular, it is also necessary to realize the stable contact work and robust force control without respect to the variation of the environment stiffness.

Force control in hydraulic actuators is a difficult problem because of large extent of model uncertainties, which originate from fluctuation in supply pump pressure, variation of some hydraulic parameters such as bulk modulus and changes in the environment stiffness for force control tasks. This paper addresses the problem of robust force control for hydraulic actuators that experience uncertainties in both the environment and the hydraulic manipulator.

In the literature, several force control strategies have been proposed for hydraulic actuators. Alleyne et al. (1998) showed that conventional PID controllers do not yield reasonable performance over a wide range of operating conditions. Chen et al. (1990) designed a variable structure force controller for a single-rod hydraulic cylinder. Using position, velocity, acceleration, force and pressure feedback signals, the variable structure controller proved to be capable in both static and dynamic force control tasks. The controller, however, showed steady-state errors for step inputs and the control signal was discontinuous. Alleyne and Hedrick (1995) applied an adaptive force control for an active suspension system driven by a double-rod hydraulic cylinder. The nonlinear dynamics of the electro-hydraulic actuator was considered and was used to formulate a nonlinear control law. Vossoughi and Donath (1995) formulated a feedback linearization method for the control of an electro-hydraulic servo system. Their approach took into account nonlinearities associated with asymmetric actuation, variations in the tapped fluid volume, pressure-flow characteristics and valve underlapping. Since feedback linearization incorporates auxiliary measurements of some states, the method relies on measurements of at least the load's position, velocity and the hydraulic line pressures. Wu et al. (1998) applied a generalized predictive force control algorithm to a hydraulic actuator. The controller was experimentally evaluated for various environment stiffness. The method, however, relies heavily on on-line parameter estimation and consequently demands large computational time. Conrad and Jensen (1987) used combinations of velocity feedforward, output feedback, and a Luenberger observer with state estimate feedback for force control of a double-rod hydraulic actuator. The simulation and experimental results for force regulation problem showed superior performance of the proposed method over conventional PI force feedback controllers. However, the variations of load and supply pressure were not considered in their study. Robust control algorithms have also been studied to design hydraulic force controllers.

Despite the existence of a great number of force control concepts, methods and algorithms, there is still a large gap between theory and industrial practice and there is not any application example of force control with multi-link electro-hydraulic manipulator implemented in the real task.

In the previous research results related to this paper, accurate trajectory control and stable contact work was realized by the disturbance observer and impedance control algorithm in the free and the constrained space (Yamamoto, 1998; Ahn, 1998).

In this paper, a robust force control algorithm using force disturbance observer is proposed and applied to the 6-link electro-hydraulic manipulator, which is used in the real maintenance task of an active electric line. A systematic design procedure of force disturbance observer in an H_∞ framework for a 6-link electro-hydraulic manipulator is introduced. The uncertainties and nominal model for the system are obtained from the experimental frequency response estimates by using PRBS(pseudo random binary signal), and the deviation of the system from the nominal model is expresssed by multiplicative uncertainty. The robust force controller is designed by using the nominal model and the uncertainties derived by experiments in an H_∞ framework. It is shown that the 6-link electro-hydraulic manipulator maintains robust stability with respect to the 50 times change of the stiffness of contact wall and 2 types of wall shape.

2. Experimental Apparatus

The schematic diagram of the 6-link electro-hydraulic manipulator is shown in Fig. 2. The supply pressure to this system is 10 MPa. Each control algorithm is calculated at the sampling rate of 1 kHz by using microcomputer (NEC PC-9821V20, Pentium (200 MHz)) and the calculated command input controls the servo valves (Tokyo Seimitsu Sokki, model 401F-110) by servo amplifiers (Tokyo Seimitsu Sokki, model SA-201) through 12-bit D/A board (CONTEC, model DA12-16). The rotational angle of each axis is calculated using a rotary encoder (Canon R-10), which is the input to the computer through the 16-bit Up/Down Counter (Micro Science, model UPC-4298XPC). The contact force is measured by 6-axis force sensor (Nitta, model USF-4520A-150) through th 12-bit A/D board (Micro Science, model ADM1498BPC). The working principle of the 6-link electro-hydraulic manipulator is shown in Fig. 3. Each axis is driven directly by rack and pinion using

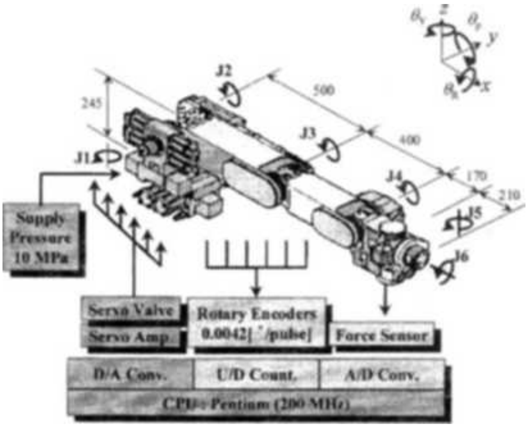


Fig. 2 System configuration of a 6-link electro-hydraulic manipulator

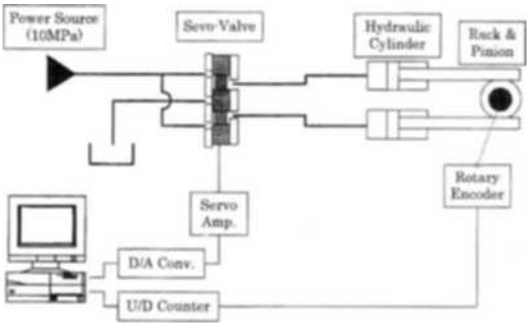
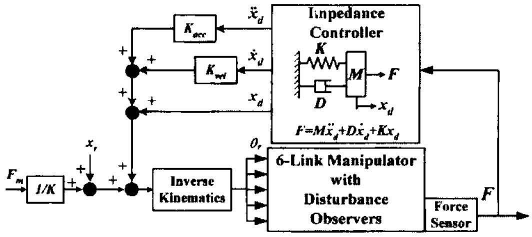


Fig. 3 Working principle of a 6-link electro-hydraulic manipulator

hydraulic cylinders except the 3rd axis. The 3rd axis is driven by chain and sprocket to reduce the total weight of a manipulator.

3. System Model and its Uncertainty

The hydraulic manipulator has many nonlinear elements such as the viscosity of working fluids, the deadband of servovalve and the condition of working environment, particularly in contact work. To capture the system dynamics of the total 6-link electrohydraulic manipulator, it is necessary to consider nonlinear models for friction, coriolis's effects and so on. However, for the purpose of control, linear models for the system will be used for synthesis. The block diagram of a 6-link electro-hydraulic manipulator with an impedance controller is shown in Fig. 4 and this model is already proved to realize stable contact work in the case of this hydraulic manipulator (Yamamoto, 1998). As an identification method to find this nominal model, a series of experimental frequency response by pseudo random binary signal (PRBS) is performed. PRBS is easily derived as a random ordered maximal length sequence (m-sequence) of logic ones and zeros, emanating from a specially configured m stage linear feedback shift register, which repeats after a characteristic length $L=2^m-1$. PRBS is deployed in the identification process, at a clock frequency of 1 kHz. The PRBS register length is set to be 9 and the bit magnitude is set to be ±3[mm], which is the command input to the manipulator in the x-direction. In the identification process, 4 types of environment material (sponge, rubber, plastic and steel), 4 types of compliance gain and 2 types of manipulator attitudes are used. Thus total 32 types of experiments are carried out in the process of identification. One sample experimental result is shown in Fig. 5. This result corresponds to the case when rubber is used as environment material, the attitude of manipulator is in the minimum moment of inertia condition and the impedance gain is set to K=1500[N/m] and D=490[Ns/m]. To identify the system model, ARX function in Matlab (Lennart, 1995) is used where the sampling time is 0.01[s], the order of discrete model is 2 and delay time is set to 3 sampling times. As shown in the upper part of Fig. 5, the simulation results coincides well with those of experiment. Total 32 experiments with different environment material, attitudes of manipulator and impedance model are executed and a set of frequency response estimates for the system is generated. A transfer function is selected to minimize the weighted least-square error between the experimental frequency response and the model. We call this transfer function the nominal model ($\mathbf{P}_n(s)$) of



F_m : Force command to the manipulator
F : Contact force
x_r : Reference trajectory
K_{acc} : State feedback gain for acceleration
K_{vel} : State feedback gain for velocity
x_d : Virtual displacement
$\dot{x}_d$: Virtual velocity
$\ddot{x}_d$: Virtual acceleration
θ_r : Reference angle for each axis in 6-link manipulator
M : Virtual mass in the impedance model
D : Virtual damping in the impedance model
K : Virtual stiffness in the impedance model

Fig. 4 System model with impedance control loop

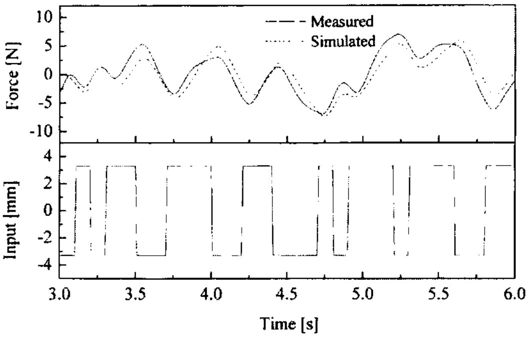


Fig. 5 Identification of system model using PRBS

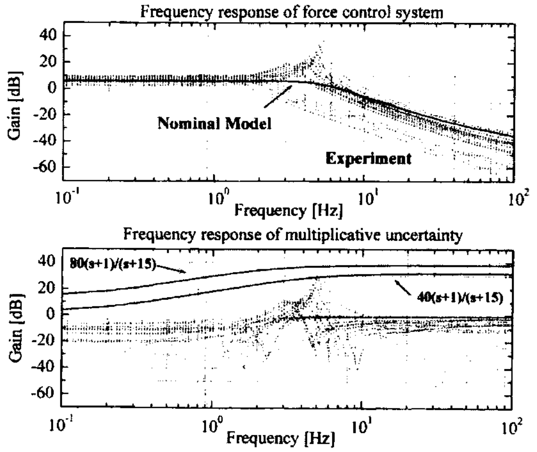


Fig. 6 Frequency response of the system, nominal model, and 2 types of multiplicative uncertainty

the system, which is shown in Fig. 6. Moreover, the variation of each frequency response estimate from the nominal model $\left(\left|\frac{\mathbf{P}(jw)}{\mathbf{P}_n(jw)}-1\right|\right)$ can be expressed by a multiplicative uncertainty. We define $\mathbf{\Pi}$ as the family of possible models which includes all the experimental frequency response estimates. Then the real manipulator system can be expressed by the following relationship.

$$\forall \mathbf{P}(s) \in \mathbf{\Pi},\ \mathbf{P}(s)=(1+\Delta(s)\mathbf{W}(s))\mathbf{P}_n(s) \quad (1)$$

Where $\mathbf{W}(s)$ is the fixed transfer function, called the uncertainty weighting function, and $\Delta(s)$ is the memoryless operator of induced norm less than unity (Doyle, 1989). Note that in this representation, $\Delta(s)\mathbf{W}(s)$ gives the normalized system variation away from 1 at each frequency expressed by the following equation.

$$\frac{\mathbf{P}(jw)}{\mathbf{P}_n(jw)}-1=\Delta(jw)\mathbf{W}(jw) \quad (2)$$

Hence, since $|\Delta(jw)|\leq 1$, then

$$\left|\frac{\mathbf{P}(jw)}{\mathbf{P}_n(jw)}-1\right|\leq|\mathbf{W}(jw)|,\ \forall w \quad (3)$$

By plotting the system variations for all experimental frequency response estimates of the system $\left(\left|\frac{\mathbf{P}(jw)}{\mathbf{P}_n(jw)}-1\right|\right)$ and estimating an upper bound to those variations as a transfer function, the multiplicative uncertainty weighting function $\mathbf{W}(s)$ will be obtained. Figure 6 illustrates the empirical frequency responses of the 6-link electro-hydraulic force control system, its nominal model and its uncertainty. The nominal model is found to be a good fit to a second order stable transfer function as follows:

$$\mathbf{P}_n(s)=\frac{-10s+2000}{s^2+40s+1000} \quad (4)$$

Using Eq. (3), the system variations for 32 typical frequency response estimates are illustrated in Fig. 6. The uncertainty weighting function is designed by trial and error, and the following 2 types of weighting functions are finally selected to investigate the effect of the uncertainty weighting function.

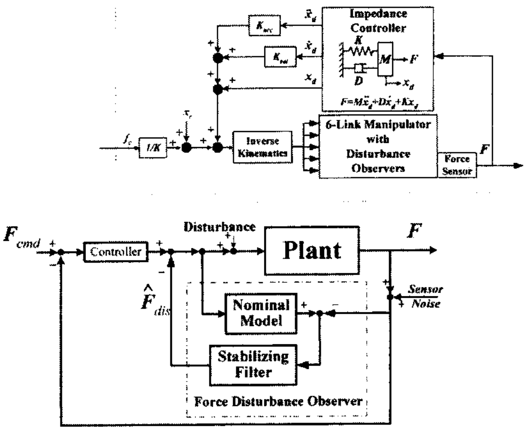
$$\mathbf{W}_{3a}(s)=\frac{40(s+1)}{(s+15)} \quad (5)$$

$$\mathbf{W}_{3b}(s)=\frac{80(s+1)}{(s+15)} \quad (6)$$

Here, $\mathbf{W}_{3b}(s)$ is selected to have $+6$[dB] margins compared to $\mathbf{W}_{3a}(s)$.

4. Robust Force Disturbance Observer Synthesis

Figure 7 is a proposed robust force control strategy by force disturbance observer. The force disturbance observer (Komada, 1991 ; Komada, 1992) estimates the disturbance F_{dis} caused by the variation of parameters of manipulator and environment. The influence of the disturbance is compensated by the feedback of the estimated disturbance. Since the stiffness of the environment changes widely particularly in this manipulator system, the force control system may become unstable in the case of the wide parameter variation. Therefore it is necessary to design force disturbance observer actively including the parameter variation of manipulator itself and the environment. To design the force disturbance observer actively, robust force controllers are designed using this information in an H_∞ framework illustrated in Fig. 8. For multiplicative uncertainty,



F_{cmd}: Force command to the manipulator
$\hat{F}_{dis}$: Estimated disturbance by observer
F : Contact force

Fig. 7 Proposed impedance-force-control system

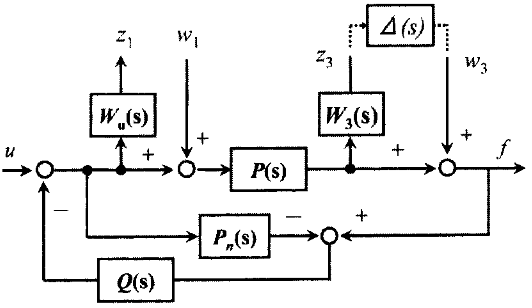


Fig. 8 Setup of generalized plant

robust stability is guaranteed if the complementary sensitivity T has a norm less than unity by small gain theorem (Zames, 1996). Weighting functions $W_u(s)$ is considered to normalize and assign frequency content of the performance objectives on the saturation of control input, and W is the multiplicative uncertainty weighting function. Now the augmented system has one input u, and two outputs z_1 and z_3, in which the transfer function from the input to the outputs corresponds to weighted actuator effort, and weighted complementary sensitivity, respectively. The objectives now will be reduced to finding the disturbance observer $Q(s)$ which minimizes the induced norm of the transfer function matrix from input u to the output vector $z=[z_1, z_3]$. This problem has optimal and suboptimal solution algorithms. The μ-synthesis toolbox of Matlab uses this algorithm iteratively to find the best suboptimal solution achievable (Balas, 1991). Performance weighting functions are selected considering the physical limitations of the system. The actuator saturation weighting function is considered to be a constant, by which the maximum expected input amplitude never saturates the actuator. Its value is estimated to be 0.001 for the force control system. Using the nominal model and weighting functions from Eq. 4~6, two controllers were designed using m-synthesis toolbox of Matlab. For $W_{3a}(s)$, which has no margin in the uncertainty weighting function, the transfer function of force disturbance observer is :

$$Q_{fa}(s)=3.145\times10^{8}\frac{(s+53.2)(s+(20\pm24.5j))(s-12.0)}{(s+1.0)(s+52.6)(s+200.0)(s+1.26\times10^{4})(s+4.0\times10^{5})} \quad (7)$$

while for $W_{3b}(s)$, which has $+6$[dB] margin compared to $W_{3a}(s)$ in the uncertainty weighting function, the transfer function of force disturbance observer is :

$$Q_{fb}(s)=4.668\times10^{10}\frac{(s+40.9)(s+(20\pm24.5j))(s-6.2)}{(s+1.0)(s+44.9)(s+200.0)(s+7.6\times10^{5})(s+8.0\times10^{5})} \quad (8)$$

Figure 9 shows the Bode plot of the two force disturbance observer multiplying nominal model (i.e. $P_n(s)\times Q(s)$), where the force disturbance observer by $W_{3a}(s)$, has larger gain in the low frequency range.

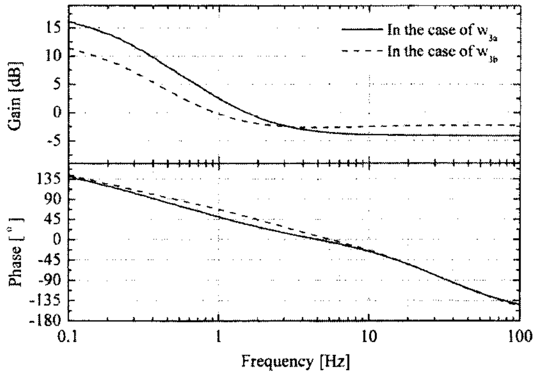


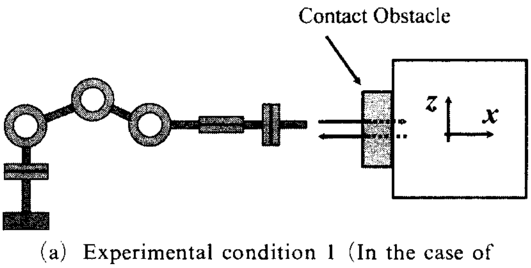
Fig. 9 The frequency response of the two designed controllers

5. Force Control Experiments

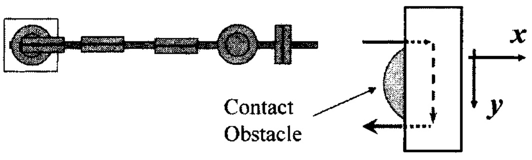
5.1 Experimental conditions

To investigate the effectiveness of the proposed force disturbance observer, 2 different force control experiments are executed, which is shown in Fig. 10. In force control experiments, the initial position of the manipulator is set to (x, y) = (1.44 [m], 0.43[m]) and the attitude of the end-effector of hydraulic manipulator is vertical to the contact wall. In the experimental condition 1, the material of contact wall is changed from low stiffness to high stiffness, i.e. changed from sponge, rubber, plastic to steel. The approximate stiffness of these materials are 350, 30000, 80000 and 200000[N/m], respectively. In experimental condition 2, the force control experiment with respect to the round contact wall is conducted. In each experiment, the reference trajectory of manipulator is set up as shown in Fig. 10 and the force control algorithm is applied when the end-effector of manipulator makes contact with the wall.

The reference force is set to −40[N] in the x direction and the control objective is to regulate the contact force of manipulator to maintain −40 [N] in the x-direction. In the experiments, the disturbance observer by Yamamoto (1998) is applied in the position control loop, and the virtual damper and spring are set to be 800[Ns/m] and 2000[N/m] in the impedance control loop. In the force control loop, the PI controller is applied where the proportional and integral gains are 1.5 and 2.5 respectively.



(a) Experimental condition 1 (In the case of changing the stiffness of environment)



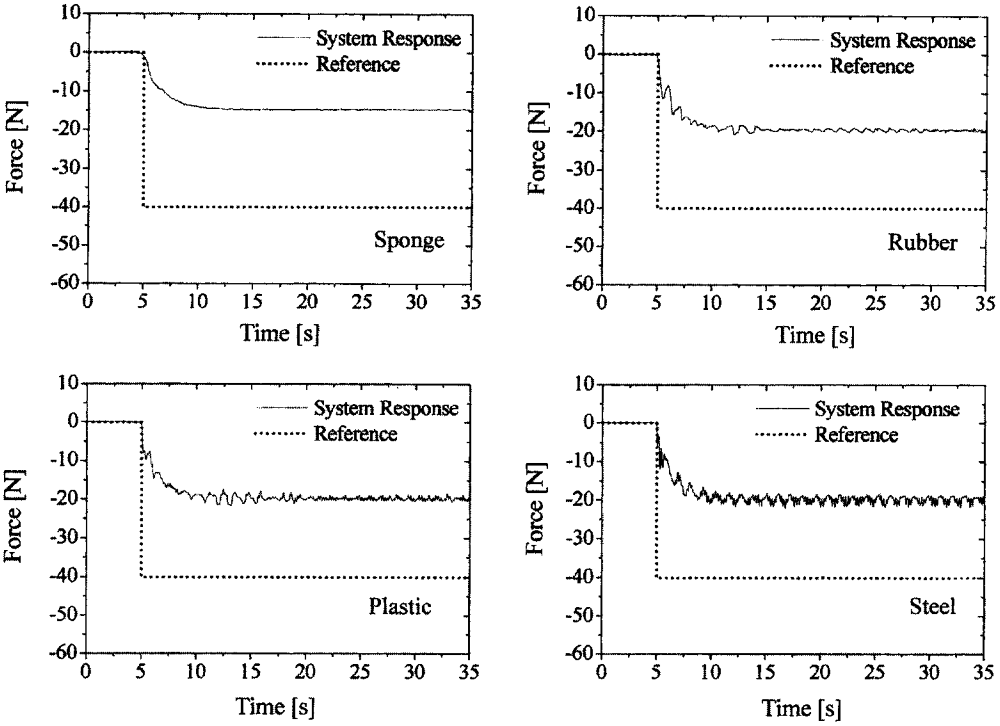
(b) Experimental condition 1 (In the case of curved wall)

Fig. 10 Experimental setups for force control

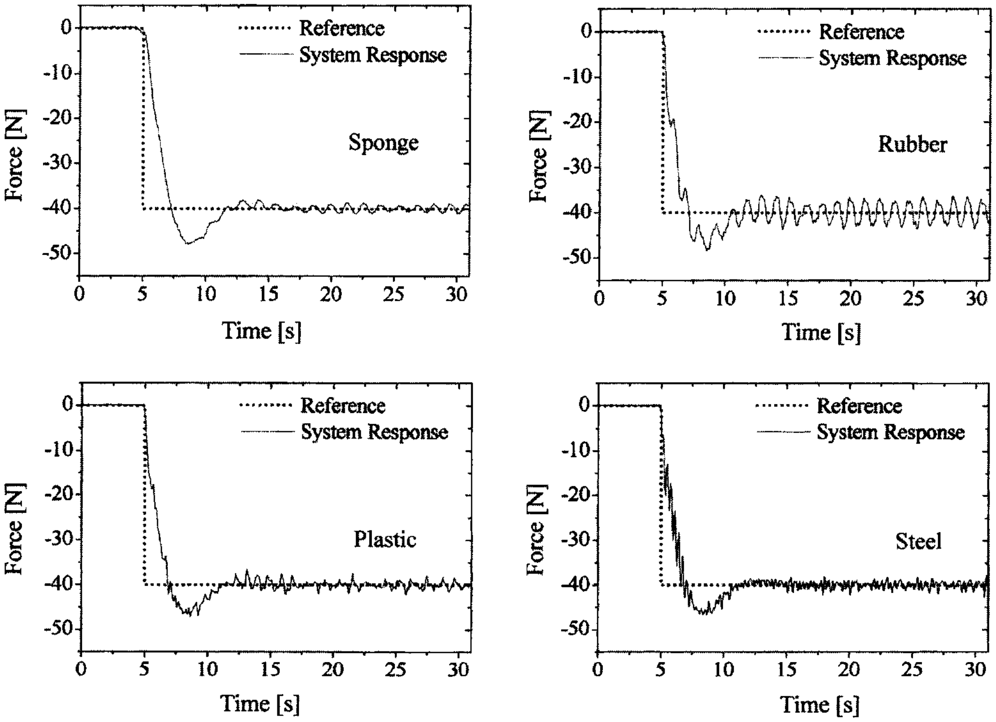
5.2 Experimental results

The goal of the experiments presented here was to demonstrate the feasibility of the proposed force disturbance observer and to illustrate the capability of the proposed approach for designing controllers for hydraulic manipulators with significant system parameter variations. The test results are shown in Fig. 11. The position controller is fixed to the disturbance observer proposed previously and 4 different force controllers (P, PI, force disturbance observer Q_{fa} and Q_{fb}) are applied. In the case of proportional force controller, the force response contains significant steady-state errors and it is understood that the force control is impossible only by proportional control and it needs integral action in the control loop. In the PI control, the force response contains significant oscillations particularly in the case of rubber. This is because PI controllers cannot cover the full range of stiffness even though we obtain good force response in some material where the PI gain is set. The force responses of force disturbance observer are shown in Fig. 11(c) and (d). From these results, the system responses remained insensitive and robust stable and the steady state errors are small in spite of an environmental stiffness variation of about 50 times. However, some oscillation arises in the case of steel because the system response is too fast and it was regarded as large disturbance by the force disturbance observer. System responses are almost the same between force disturbance observers with and without margin in the robust stabilizing weight.

To investigate the effect of underlying position controller, the proportional control was applied in the position control loop and the experimental results are shown in Fig. 12 which shows very oscillatory force response in the case of steel and it is understood that the underlying position controller is very important in realizing robust force

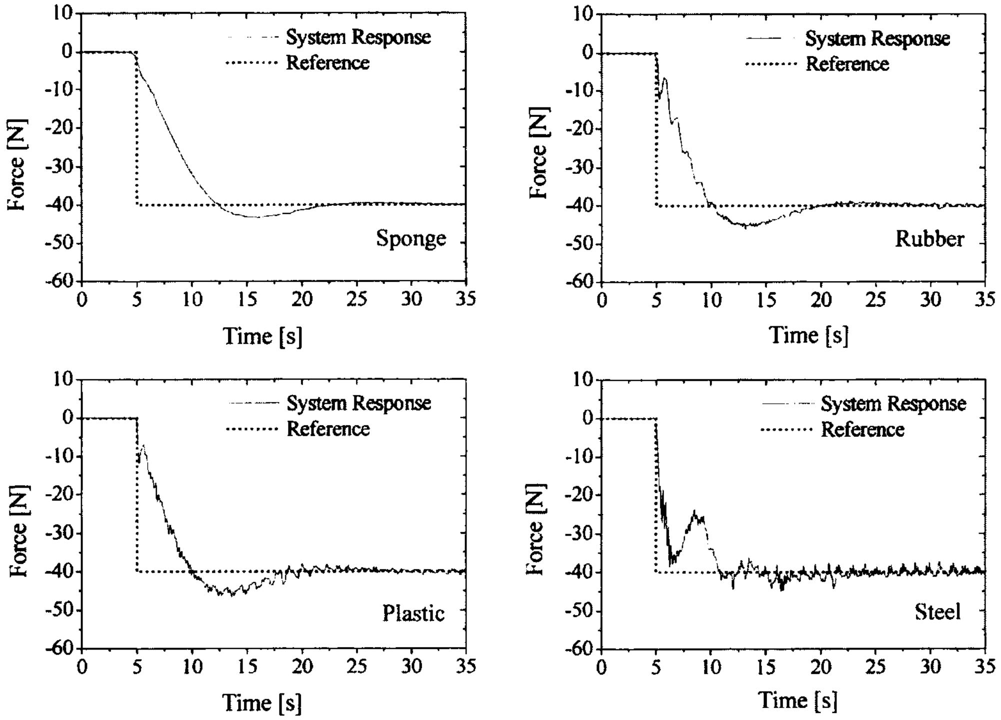


(a) In the case of proportional force controller

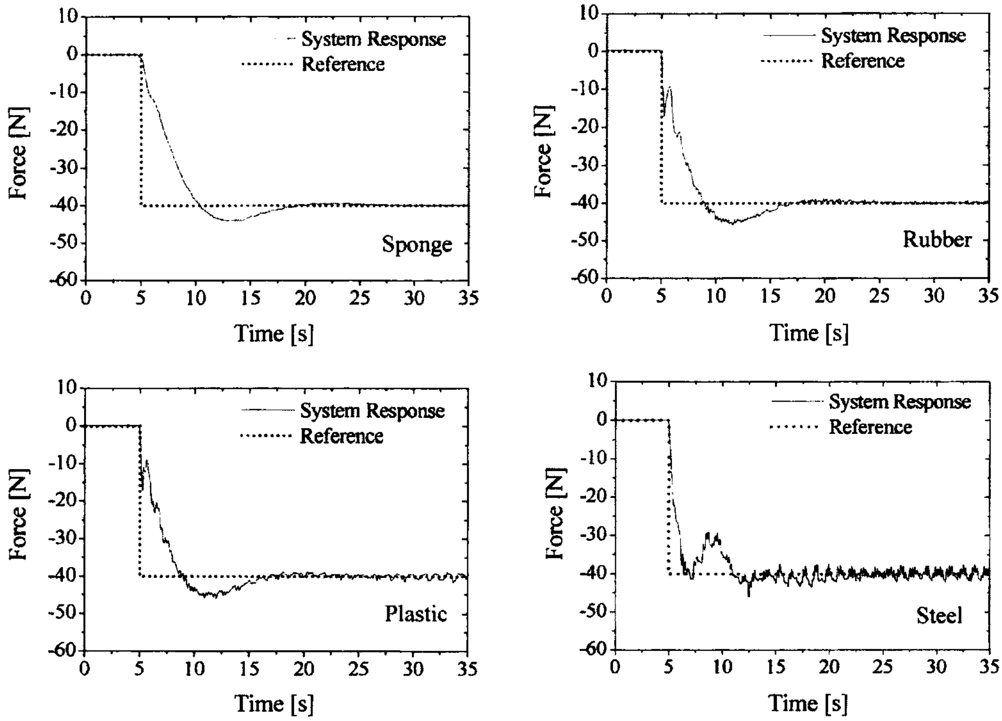


(b) In the case of proportional integral (PI) force controller

Fig. 11 Experimental results of force control in the experimental setup 1



(c) In the case of force disturbance observer $Q_{fa}(s)$



(d) In the case of force disturbance observer $Q_{fb}(s)$

Fig. 11 Experimental results of force control in the experimental setup 1

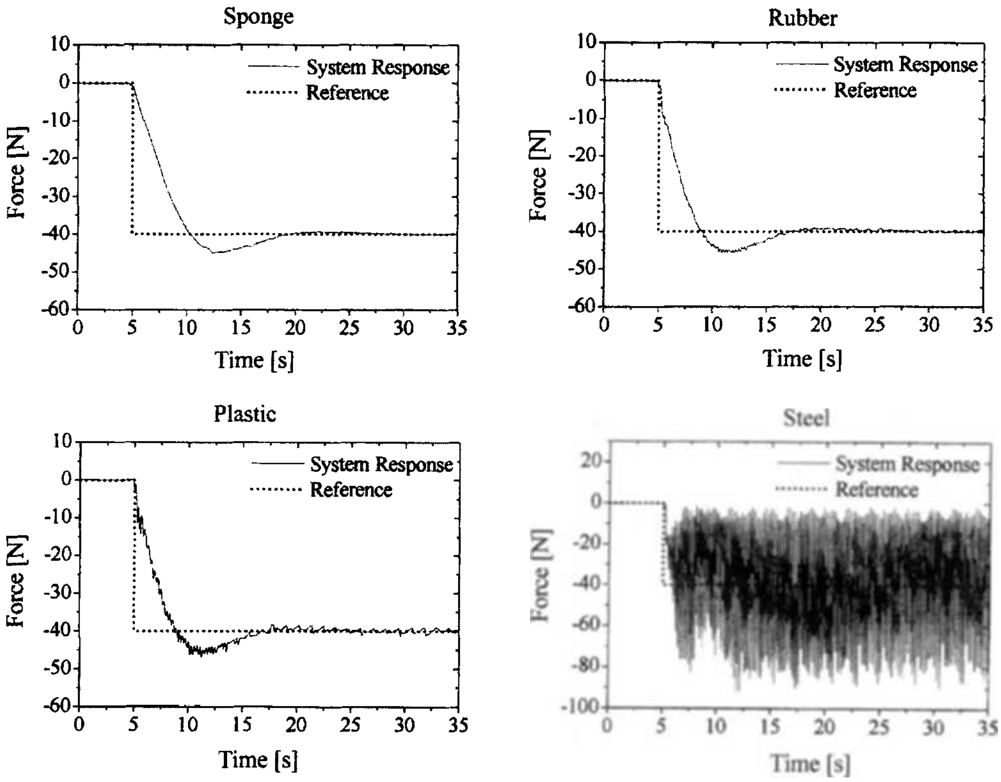


Fig. 12 Experimental results with proportional position controller

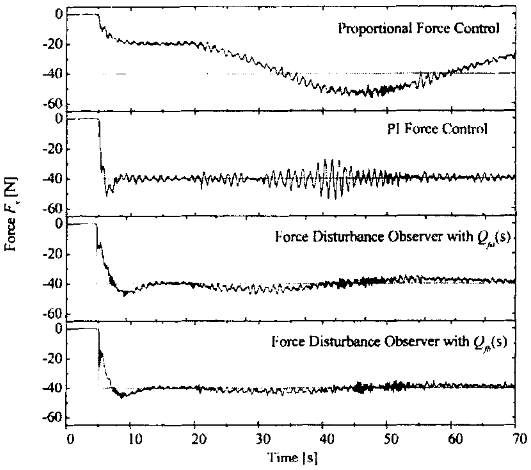


Fig. 13 Experimental results of force control in the experimental setup 2

control. Figure 13 shows the experimental results of experimental condition 2 where we used steel as the contact wall. From the experimental results, there are a steady state error in the case of proportional control and some oscillations in the case of PI control. Meanwhile, it is understood from Fig. 13 that good force regulation is realized in the case of force disturbance observer, also without having oscillatory force response. Particularly the force response is more comfortable in the case of force disturbance observer with 6 dB margin.

6. Conclusions

This paper presented the systematic approach of the design and experimental evaluation of a force controller for a 6-link electro-hydraulic manipulator with several uncertainties, within the framework of the H infinity control theory. A nominal model and the multiplicative uncertainty of the manipulator are obtained from the experimental frequency responses using control input by pseudo random binary signal (PRBS). Robust force disturbance observers for force control are designed using this information in an H infinity frame work.

The designed controller was implemented on an 6-link electro-hydraulic manipulator for the real active electric line maintenance task. Several tests were performed under different conditions including variations up to 5,000% in environmental stiffness and different shapes of contact wall. The experimental results demonstrated the robustness of the force disturbance observer designed by H infinity theory to the real parameter variations and good performance in spite of significant manipulator conditions. The results of this paper showed an effective and systematic tool for the control design of multi-link hydraulic manipulator. Moreover, in this paper, force disturbance observer was experimentally evaluated on a real field problem, which has been rarely reported in the literature. The application of the methodology presented here is currently being investigated in the automation of real field tasks of active electric power maintenance task and other out-door tasks such as hydraulic excavator machines.

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