Position-Based Impedance Control of Cylinder for Oil Hydraulic Servo Systems

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ABSTRACT

The oil hydraulic cylinder has been used as industrial actuators, because it is inexpensive and also has a high power to weight ratio. However the accurate control of the oil hydraulic actuators is difficult because of very complex and high nonlinearity due to flow-pressure relationship and large friction force. Recently, to overcome those problems an impedance or hybrid force/position control concept has been suggested. This study proposes an impedance control of an oil hydraulic servo system with a position-based approach where an optimal servo system using the LQ optimization technique is constructed inside the force feedback loop. And also to attain the desired impedance over extensive operating conditions, we use an impedance parameter modulation law. From some experiments, an impedance parameter modulation law incorporating the optimal servo system shows good static force control ability and excellent performance in dynamic tasks such as collision force reduction.

KEY WORDS

Hydraulic Servo System, Compliance, Impedance Control, Sliding Mode Control

NOMENCLATURE

\( A \): Piston area [m^2]
\( C \): Viscous friction coefficient [N*s/m]
\( F \): Generating force of a control cylinder [N]
\( K \): Stiffness [N/m]
\( k_1, k_2 \): Linear approximation parameters
\( M \): Inertial mass [kg]
\( p_l \): Load pressure [Pa]
\( q_l \): Load flow rate [m^3/s]
\( y \): Displacement [m]
\( V \): Volume of hydraulic fluid [m^3]

INTRODUCTION

The oil hydraulic system is widely used in the industrial world, and the application range is being expanded. Moreover, there is the feature that is
inexpensive and also has a high power to weight ratio, and is easy to secure electric insulation. So, the application to the manipulator for live-wire work is beginning to research recently \[1\][2]. Since there are many works in a high place and with the danger of an electric shock, when performing the assembly work and contact work by the manipulator, the demand to autonomy is increasing. In order to perform such works, it is necessary to control both a position/posture and force/moment, and according to the force that generates in case an object contacts a manipulator, it is necessary to control flexibly. One of the basic approaches is compliance control. The compliance control is the method of controlling a system flexibly by changing the generating force measured by the force sensor into the displacement, and using it for a control input. As those methods, there are the stiffness control using the imaginary stiffness and the impedance control using the imaginary stiffness, imaginary inertial mass, and imaginary viscous friction. Moreover, Sasaki et al. tried the impedance-modulation law \[3\]. It is to change the imaginary stiffness of the target impedance on-line, and also is the method of adjusting the imaginary stiffness into the optimum to improve stability. This research applies the sliding mode control using the smoothing function for the stiffness modulation of the impedance modulation law, and tries the reduction of chattering and the improvement of stability in the force response.

**OIL HYDRAULIC SERVO SYSTEM**

The schematic of the experimental apparatus is shown in Fig. 1. The oil hydraulic servo system consists of the composition that a double rod cylinder opposed to a single rod cylinder through a flange joint. The double rod cylinder is the “control” cylinder and the single rod one is the “load” cylinder. The proportional solenoid valve controls the control cylinder. The pressure sensors are attached to both the head and rod sides of the control cylinder, and the generating force of the control cylinder is calculated from these pressure differences. Here, the load cylinder is assumed to the environmental stiffness and it can give any loading state by the electrical relief valve. Moreover, the piston displacement of a control cylinder is measured by the laser displacement sensor.

**MODELING OF THE OIL HYDRAULIC SERVO SYSTEM**

The system transfer function \( G_0 \) or \( G_1 \) is assumed that both compressibility of hydraulic fluid and dynamics of the proportional valve are ignored or not, respectively.

The equation of motion of the load is written by

\[
M_l \frac{d^2 \Delta y}{dt^2} + C_l \frac{d\Delta y}{dt} + K_l \Delta y = A \Delta p_l
\]  

where \( M_l \) is the load mass, \( C_l \) is the viscous friction coefficient, \( K_l \) is the spring constant, \( y \) is the displacement of the load, and \( A \) is the piston area. If the compressibility of hydraulic fluid is ignored, the equation of continuity is written by

\[
A \frac{d\Delta y}{dt} = \Delta q_l
\]  

The transfer function \( G_0 \) of the oil hydraulic system is described as:

\[
G_0(s) = \frac{k_1}{As + \frac{1}{A} k_2 (M_l s^2 + C_l s + K_l)}
\]  

where \( k_1 \) and \( k_2 \) are the linear approximation parameters. Next, the equation of continuity with consideration of the compressibility of hydraulic fluid is written by

\[
A \frac{d\Delta y}{dt} = \Delta q_l - \frac{V}{2K} \frac{d\Delta p_l}{dt}
\]  

When the dynamic characteristic of the valve is
approximated by the second-order lag, it is described as:

\[ G_{\text{valve}}(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  

(5)

From this, the plant \( G_1 \) with consideration to the compressibility of hydraulic fluid and the dynamic characteristic of the valve can be written by

\[ G_1(s) = \frac{k_1}{A(s) + \frac{1}{A}(k_1 + \frac{V}{2K})(M_x s^2 + C_x s + K_x)} G_{\text{valve}}(s) \]  

(6)

**CONTROL SYSTEM DESIGN**

In this study, after establishing the robustness in position control, we constructed the position based force control system. The schematic of the mechanical impedance model to this oil hydraulic system is shown in Fig. 2. It expresses the control cylinder sides of the oil hydraulic system composed of the inertial mass \( M \), the viscous friction coefficient \( C \), and the stiffness \( K \). \( F \) is the generating force of the control cylinder and we define the case of only the fixed force \( F' \) being applied from the load cylinder side as the non-contact condition. Moreover, in addition to \( F' \), we define the case where the environmental stiffness \( K \) is included as contact condition.

**DESIGN OF IMPEDANCE CONTROL SYSTEM**

Impedance control is performed by conversion from the force to the displacement by using three parameters of the inertial mass \( M \), the viscous friction coefficient \( C \), and the stiffness \( K \). From Fig.2, the target impedance can be defined by the following equation:

\[ M\ddot{X}_r + C(\dot{X}_r - \dot{X}_r) + K(X_r - X_r) = F_r - F \]  

(7)

When \( X_r = 0 \) and Laplace transform is carried out, the transfer function of the impedance model will be obtained as follows

\[ M_x = \frac{K}{Ms^2 + Cs + K} \]  

(8)

\[ M_f = \frac{1}{Ms^2 + Cs + K} \]  

(9)

Here, \( M_x \) and \( M_f \) calculate the new target value \( X_t \) to obtain the desirable position and force, and \( X_r \) constitutes the desired value of the position control system. In this study, the target impedance parameter is set to \( M = 89.3 \text{kg} \), \( C = 119.4 \text{N} \cdot \text{s/m} \), and \( K = 373.3 \text{kN/m} \). The load cylinder is supplied at \( F' = 0.755 \text{kN} \) as initial conditions, and the environmental stiffness is set to \( K_e = 41.6 \text{kN/m} \) by controlling the load pressure. The block diagram of the position based impedance system is shown in Fig. 3.

**IMPEDANCE PARAMETER MODULATION**

Although the target impedance parameters can be designed freely, the target performance is not obtained if the suitable target impedance is not designed. Then, in order to dissolve the unstable problem of the system at the case of low stiffness, we considered always keeping the target impedance to a good state against variation of the environmental conditions of the subject by changing stiffness on-line. This method modulates the stiffness on-line, namely, if the force \( F \) is larger than the desired value \( F_r \), then the target impedance \( K \) is multiplied by \((1-\varepsilon)\), and if the force \( F \) is smaller than \( F_r \), \( K \) is multiplied by \((1+\varepsilon)\), where \( \varepsilon \) is a modulation parameter and \( \varepsilon << 1 \), that is,
The system response for the two cases is shown in Fig.4 where the stiffness is adapted, or fixed to $K=1867$ kN/m. When adaptive in $K$, there is no overshoot and the system settles to a desired value, so the impedance modulation is effective. However, in connection with the modulation of $K$, chattering occurs in the force response.

**SMC MODULATION**

The impedance modulation is carrying out by change of the stiffness, and the force is able to converge to a desired value. However, it has the fault that chattering occurs in the force response. Therefore, the smoothing function to be the chattering control technique of the sliding mode control is applied to the impedance modulation, so we tried the improvement in stability and elimination of the chattering of a force response. The nonlinear control input term of a sliding mode control is shown by the equation (11).

$$u_{nc} = -K \text{sgn}(\sigma) = -K \frac{\sigma}{\|\sigma\|}$$  \hspace{1cm} (11)

When the smoothing function is used for the equation (11), the nonlinear control input will be given by

$$u_{nc} = -K \frac{\sigma}{\|\sigma\| + \delta}$$  \hspace{1cm} (12)

where $\delta$ is a positive small constant.

In this study, the above mentioned sliding mode control is applied to the modulation of the stiffness. When the switching function $\sigma$ of the sliding mode control is considered to be on the error hyper plane of force, it will be given by the following equation,

$$\sigma = F_r - F$$  \hspace{1cm} (13)

The modulation of stiffness by the sliding mode control is given by

$$K(n+1) = K(n) - \kappa \times \frac{\sigma}{\|\sigma\| + \delta} \quad \kappa \ll 1$$  \hspace{1cm} (14)

**EXPERIMENTAL RESULTS AND DISCUSSION**

The experiment was carried out at the supply pressure 3.8 MPa, the desired position 40 mm, the desired force 2.2 kN, and the oil temperature 40°C.

**Experiment No.1:** The step response test with the load pressure 1.0, 1.5, and 2.0 MPa was performed supposing a manipulator to grasp a subject. The desired position was set to 40 mm, and the desired force was set to 1.3, 1.8, and 2.2 kN.

Response of the impedance modulation in experiment No.1 is shown in Fig. 5. The initial value of a target impedance parameter was set to $M=89.3$ kg, $C=119.4$ Ns/m, and $K=1867$ kN/m. The force response reaches the desired value quickly, but the chattering by switching of $K$ occurs. This seems to produce bad results for the grasp work also by a real manipulator.

**Experiment No.2:** The experiment supposing the case of colliding with a subject like a press is carried out. The step response is performed the following condition. When the position response reaches 95% of a desired value, the maximum load 2.0 MPa is supplied. Where,
the desired position was set to 40mm, and the desired force was set to 2.2kN.

Response of the impedance modulation in experiment No.2 is shown in Fig. 6. From the result of a force response, when the load is applied, it converges on the desired value quickly. Furthermore it is possible to restrain to a desired value by the stiffness changing on-line to a sudden load change. However, the chattering by switching of $K$ occurs in the force response.

Next, as for the SMC modulation the experiment was carried out similarly, in which the smoothing function in a sliding mode control is applied to the modulation of stiffness. The system response of the SMC modulation in experiment No.1 is shown in Fig. 7. The chattering is eliminated although a force response occurs an overshoot compared with the impedance modulation. The system response of the SMC modulation in experiment No.2 is shown in Fig. 8. In the force response, the stable response is obtained also to a sudden load change. From the results, the impedance control using the SMC modulation is promising in the application to the work that collides with a subject.

**CONCLUSIONS**

In this study, the experiment of the position and force control by the impedance modulation and the SMC modulation in impedance control was carried out. The results obtained by this study are summarized in the following.

1. Since the stiffness is changed on-line, the impedance modulation has the excellent control performance to the characteristic of the position response, and to sudden load change. However, a chattering occurs in the force response.
2. The SMC modulation using the smoothing function of the sliding mode control, the chattering of the force response is eliminated, and stability improves. Therefore, it is effective in the application to contact work with the subject by the oil hydraulic manipulator, etc.
Fig. 7 Results of impedance control with adaptive stiffness using SMC at experiment NO.1

Fig. 8 Results of impedance control with adaptive stiffness using SMC at experiment NO.2

REFERENCES

