Position Based Impedance Control of Electro-Hydrostatic Actuator

Guozhe Zhou1*, Xin Lv1, Tieshan Feng1 and Luoning Gan1

1 China Academy of Launch Vehicle Technology, Beijing, 100076, China
*Corresponding author’s e-mail: zhouguozhe12@163.com

Abstract. This paper presents a method for implementing position based impedance control (PBIC) in an electro-hydraulic actuator (EHA). Impedance control provides the actuator with compliance and facilitates the interaction with environment. Whereas most impedance control applications utilize electrical or valve-controlled hydraulic actuators, this work enables impedance control in a compact and efficient EHA. The selection of target impedance parameters is analysed and illustrated via root locus technique. The effectiveness of PBIC used in EHA and compliance of cylinder is shown in the impact test with several experimental results.

1. Introduction
Impedance control has been extensively used in robotic manipulators since it was introduced [1]. The method, differing from the force-control or position-control, can adapt the evident dynamics of the actuator system.

There are two types of the impedance control: position based impedance control (PBIC) and torque based impedance control (TBIC). The inner loop of PBIC is a position loop and the desired position is adjusted based on the interaction force. In contrast, a torque controller is required in the inner loop in TBIC. Based on the impedance model, the actual position signal modifies the desired torque to achieve the required impedance. In robotic applications, TBIC not only demands an accurate dynamics model of the system including nonlinearity and friction, but also is sensitive to time-variant parameters and uncertainties [2]. PBIC, on the other hand, only demands the robotic inverse kinematics which is simple to be obtained. Furthermore, PBIC is quite appropriate for the hydraulic system due to the difficulty of force control [3].

Much of the research in hydraulic impedance control focused on valve-controlled actuators and valve control method suffer from throttling losses of the servovalves. In contrast, electro-hydrostatic actuators (EHAs) that are directly driven by pumps contribute to increase energy efficiency. Consequently, it is critical to discuss the applications of impedance control to EHAs. With respect to published work in this area, Kaminaga et al. [4-6] designed backdrivable EHAs and applied them to the humanoid robot, robot hand and knee power assist device with impedance control. However, these inherently flexible EHAs belong to the passive compliance actuators. Due to the inability to achieve high positioning accuracy, they are not appropriate in applications that require precise impedance relationships between position and force. Impedance control of the common EHA without flexibility has not yet been developed. Certainly there is a need for more research on the applications of PBIC applied to common EHAs.

The article is presented as follows. The diagrammatic sketch of the PBIC system is shown in Section 2. Section 3 and Section 4 introduce the implementation of PBIC. The impact test results are
provided in Section 5. Conclusions are presented in Section 6.

2. Position based impedance control

The diagrammatic sketch of a typical PBIC is shown in figure 1.

The diagrammatic sketch of a typical position based impedance control.

Figure 1. Diagrammatic sketch of typical position based impedance control.

The inner loop of PBIC is a common position control loop. The position controller creates a control signal \( u_c \) to regulate the piston position \( x_p \) of the EHA which interacts with the environment. According to the target impedance, the command position, \( x_c \), is generated by the desired position, \( x_d \), the desired force, \( F_d \), and the load force, \( F_L \), which is originated from the environment. For the sake of realizing expected dynamics, the target impedance transfer function, \( G_{TI} \), is designed as below:

\[
G_{TI}(s) = \frac{1}{M_s s^2 + B_s s + K_s} 
\]

where \( M_t \), \( B_t \) and \( K_t \) represent the target mass, damping and stiffness, respectively. According to this formulation, the target impedance relationship is then written as:

\[
M_t(\dot{x}_c - \dot{x}_d) + B_t(\ddot{x}_c - \ddot{x}_d) + K_t(x_c - x_d) = F_d - F_L 
\]

where \( \dot{x}_c \) and \( \ddot{x}_c \) refer to the command velocity and acceleration, respectively; \( \dot{x}_d \) and \( \ddot{x}_d \) denote the desired velocity and acceleration, respectively. The following content will be expanded basing on this system.

3. Position control and force signal filter

For position control, the conventional linear PI controller is written below:

\[
u_c(t) = K_pe(t) + K_i I(t) 
\]

\[
e(t) = x_c(t) - x_p(t) 
\]

\[
I(t) = I(t - \Delta t) + e(t)\Delta t 
\]

where \( e \) is the position error and \( I \) is the integral of error. The controller gains of \( K_p=550V/m \) and \( K_i=100V/sm \) are found through trial-and-error. Both the transient response and steady-state accuracy are acceptable.

From figure 1, load force signal is required for PBIC. The force sensor employed in this work has the white noise which affects the signal quality of the load force and disturbs the control performance significantly. As a result, a second-order Butterworth filter is introduced in the feedback loop. The cut-off frequency of EHA position control loop is 2.45 Hz. In order to reduce the influence on the system dynamic, the cut-off frequency of the filter is set to 3 Hz. The transfer function of Butterworth filter, \( G_F \), is expressed as:

\[
G_F(s) = \frac{355.3}{s^2 + 26.7s + 355.3} 
\]
4. Target impedance parameters selection

In the applications of PBIC, the operating modes of the actuator are divided into free motion and constrained motion. In free motion, the load force is zero and the dynamics and stability of the system depend on the position controller. The target impedance parameters influence the constrained motion only.

It is shown first that how the target impedance affect the dynamics of system. The linear PI position controller \((K_P=550\text{V/m}, K_I=100\text{V/s/m})\) is utilized and the stiffness dominant environment is considered. The actuator is placed in contact with the spring of 170kN/m stiffness. The desired position, \(x_d\), is set to zero and the desired force, \(F_d\), is set as a step of 2000N. The target mass and stiffness are fixed and various target damping are used. The target mass \(M_t\) and stiffness \(K_t\) are set to 150kg and 120kN/m, respectively. The step responses are shown in figure 2 and figure 3.

![Figure 2. Step responses of controlled actuator with various target damping interacting with a stiffness dominant environment \((K_e=170\text{kN/m})\).](image)

![Figure 3. Step response of controlled actuator with 2.0kNs/m target damping interacting with a stiffness dominant environment \((K_e=170\text{kN/m})\).](image)

In figure 2, the motion is over damping and the response speed declines when the target damping is larger than 97.3kNs/m. When the target damping is 21.4kNs/m, the motion has overshoot. In figure 3, the target damping is 2.0kNs/m and the motion experiences sustained oscillation.

These results can be explained by root locus method. From figure 1, the transfer functions block diagram of PBIC system is depicted in figure 4.
Figure 4. Block diagram of PBIC system transfer functions.

As shown in figure 4, $G_{TI}$ is transfer function of target impedance, $G_{PC}$ is transfer function of position controller, $G_{EHA}$ is transfer function of EHA system, $G_{EI}$ is transfer function of environment impedance and $G_F$ is transfer function of filter. Using the identified model of EHA, the open-loop transfer function of system is obtained. There are 9 closed-loop poles in the system. Root locus presents how these poles change with variable target damping. Only two dominant poles of the root locus are depicted in figure 5.

Figure 5. Root locus of two dominant poles of controlled actuator interacting with a stiffness dominant environment ($K_e=170$ kN/m) as target damping $B_t$ increases.

With reference to figure 5, as the target damping gets closer to 2.0 kNs/m, the dominant poles move closer to the imaginary axis so that the motion does not converge. When the target damping is larger than 97.3 kNs/m, the dominant poles both locate on the real axis and the motion is over damping. For values of target damping between 2.0 kNs/m and 97.3 kNs/m, the motion is under damping. The dominant poles in right-half-plane mean that the system is unstable. In this example, on account of the compromise between speed and oscillatory motion, the target damping of 97.3 kNs/m is used.

5. Impact test result

During the impact test, the compliance in constrained motion of the PBIC system can be examined and the position tracking ability in free motion can be checked. In this test, the desired position, $x_d$, is set as a sine wave so that the actuator is regulated to track the sine wave trajectory. However, a spring of 170 kN/m stiffness as the obstacle is placed at zero position, cutting the sine trajectory in half. The desired force, $F_d$, is set to zero. The target impedance settings are $M_t=150$ kg, $B_t=97.3$ kNs/m, and $K_t=120$ kN/m which are previously selected. The test result is manifested in figure 6.
Figure 6. Impact test using 97.3kNs/m target damping and environment stiffness $K_e$=170kN/m: (a) load force $F_L$ and desired force $F_d$; (b) piston position $x_p$, desired position $x_d$ and environment natural position.

The compliance is achieved in constrained motion and the actuator tracks the position trajectory well in free motion. For comparison, the target damping $B_t$ is modified to 2.0kNs/m which is used in figure 3. The same test is conducted without any other changes and the result is shown in figure 7.

Figure 7. Impact test using 2.0kNs/m target damping and environment stiffness $K_e$=170kN/m: (a) load force $F_L$ and desired force $F_d$; (b) piston position $x_p$, desired position $x_d$ and environment natural position.
During this test, the position trajectory tracking is followed in free motion, but the oscillation appears in constrained motion.

6. Conclusions
In this paper, the position based impedance control (PBIC) was realized for an industrial electro-hydrostatic actuator (EHA). The target impedance not only influenced the stability of control system, but also determined the compliance of actuator. Thus, the selection of target impedance parameters was analysed. During the impact test, the motion kept stable all the time and the actuator interacting with the environment was compliant.

References
[1] Hogan N 1985 Impedance control: an approach to manipulation, Parts I, II, III ASME J Dyn Syst. Meas Cont 107(1) 1-24
[2] Fateh MM and Babaghasabha R 2013 Impedance control of robots using voltage control strategy Nonlinear Dyn 74(1) 277-286
[3] Heinrichs B 1996 Position-based impedance control of an industrial hydraulic manipulator: theory and experiments M.Sc. Thesis, Department of Mechanical Engineering, University of Manitoba
[4] Kaminaga H, Ono J, Nakashima Y and Nakamura Y 2009 Development of backdrivable hydraulic joint mechanism for knee joint of humanoid robots IEEE International Conference on Robotics and Automation 1577-1582
[5] Kaminaga H, Amari T, Katayama Y, Ono J, Shimoyama Y and Nakamura Y 2010 Backdrivability analysis of Electro-Hydrostatic Actuator and series dissipative actuation model IEEE International Conference on Robotics and Automation 4204-4211
[6] Kaminaga H, Amari T, Niwa Y and Nakamura Y 2010 Development of knee power assist using backdrivable electro-hydrostatic actuator IEEE/RSJ International Conference on Intelligent Robots and Systems 5517-5524