*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 22-23, 2025*

# Efficient Flow Control for Agile Motion of Hydraulic Manipulator

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***Keywords :** hydraulic manipulator, flow control, high-speed motion, accumulator

## 1. Introduction

One of the biggest challenges in the mobilization of hydraulic systems is the miniaturization of the hydraulic power unit. HPU must provide sufficient energy for stable operation while efficiently utilizing limited energy to maximize operating time. Additionally, changes in hydraulic fluid temperature alter its viscosity and characteristics, directly affecting the stability and performance of the system, making effective thermal management essential.

This study proposes the utilization of an accumulator as an auxiliary power source to enhance the energy efficiency and performance of a mobile hydraulic manipulator. To evaluate the proposed approach, we conducted performance assessments using the ARMstrong dual-arm hydraulic manipulator and the micro hydraulic power unit (m-HPU), both under development at the Korea Atomic Energy Research Institute (KAERI).

## 2. Flow Rate Estimation-Based Control

### *2.1. Flow rate model*

#### 2.1.1. Fixed-Displacement Gear Pump

The m-HPU uses a fixed-displacement gear pump, and its supply flow rate is determined by the product of the pump displacement and rotational speed:

(1) $Q_{pump} = D_{pump} \cdot \omega_{pump}$

#### 2.1.2. Diaphragm accumulator

A diaphragm-type nitrogen-charged accumulator is used. The state variation of the internal nitrogen gas is approximated using a polytropic process:

(2) $P_g V_g^n = P_{g,pre} V_{g,pre}^n$

(3) $Q_{accumulator} = \frac{1}{n} \frac{V_{g,pre}}{P_o} \left(\frac{P_{g,pre}}{P_o}\right)^{\left(\frac{1}{n}\right)} \dot{P}_o$

### *2.2. Estimation of Required Flow Rate for the Hydraulic Manipulator*

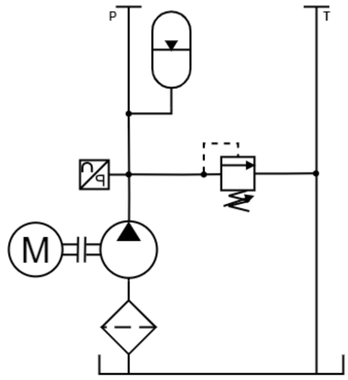


Fig. 1. Hydraulic circuit of m-HPU

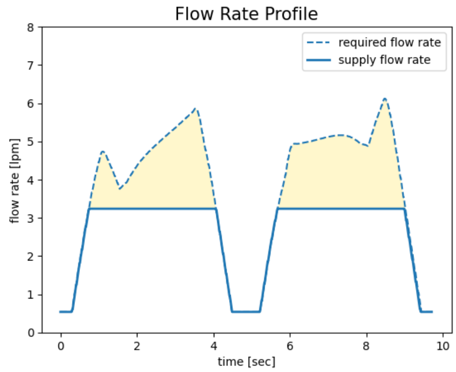


Fig. 2. Pump controller command with limited supply flow to utilize stored hydraulic fluid in the accumulator

The ARMstrong manipulator consists of hydraulic cylinders and motors configured as a four-bar linkage mechanism. The required flow rate for each joint is derived based on its position and velocity, and the total flow demand is estimated by summing the required flow rates of all actuators.

### *2.3. Flow Rate Estimation-Based Controller Design*

#### 2.3.1 Flow Rate Estimation-Based Controller

The flow rate estimation-based control (FRE-based control) uses the estimated flow demand as the pump control input, minimizing energy loss.

#### 2.3.2 Advanced Flow Rate Estimation-Based Controller

The advanced FRE-based controller intentionally limits the pump supply flow to utilize the stored hydraulic fluid in the accumulator. The pressure variation of the nitrogen gas inside the accumulator is determined using Equation (2), which allows the estimation of the stored hydraulic fluid volume. This estimated volume is then used to adjust the control command for the pump. The pump command is redesigned to ensure that the total flow deficit due to supply limitation does not exceed the available stored fluid volume, as illustrated in Fig. 2.

The ARMstrong manipulator consists of hydraulic cylinders and motors configured as a four-bar linkage mechanism. The required flow rate for each joint is derived based on its position and velocity, and the total flow demand is estimated by summing the required flow rates of all actuators.

### 3. Experiments and Validation

Experiments were conducted to validate the proposed control methods in terms of manipulator performance and system energy efficiency. The experiments involved high-speed movements exceeding the pump's maximum supply capacity.

#### *3.1. High-Speed Motion*

The high-speed motion test was conducted to assess system performance and energy efficiency under flow demand conditions exceeding the maximum pump capacity. Fig. 3. presents the pump control commands for both the FRE and advanced FRE controllers. The experiments were conducted with and without an accumulator for comparison.

#### *3.2. Experimental Results*

The high-speed motion test was conducted to assess system performance and energy efficiency under flow demand conditions exceeding the maximum pump capacity. Fig. 3. presents the pump control commands for both the FRE and advanced FRE controllers. The experiments were conducted with and without an accumulator for comparison. Fig. 4. shows the performance results of the high-speed motion test, displaying the average position error (solid line) and system pressure (dotted line) for each control method. Without an accumulator, the FRE controller exhibited large position errors and pressure drops when the flow demand exceeded the pump's supply capacity. By incorporating an accumulator, errors were reduced, and system pressure was maintained. The advanced FRE controller with an accumulator demonstrated stable performance.

Fig. 5. presents the current consumption during motion, indicating that the advanced FRE controller with an accumulator had the lowest energy consumption and minimal variations, suggesting improved energy efficiency and operational stability.

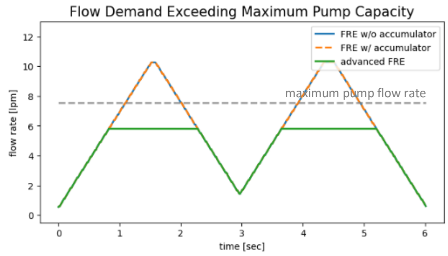


Fig. 3. Pump controller command in case of required flow rate exceeding pump capacity with FRE control without accumulator, FRE with accumulator and advanced FRE control with accumulator

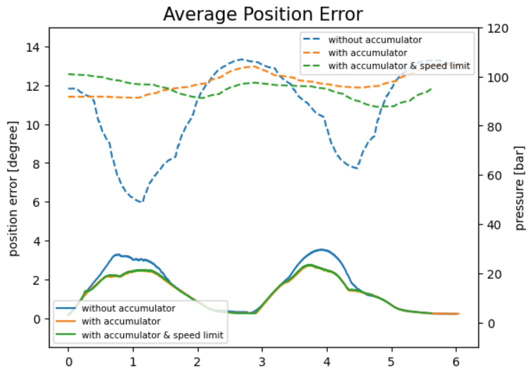


Fig. 4. Average position error of high-speed motion experiment

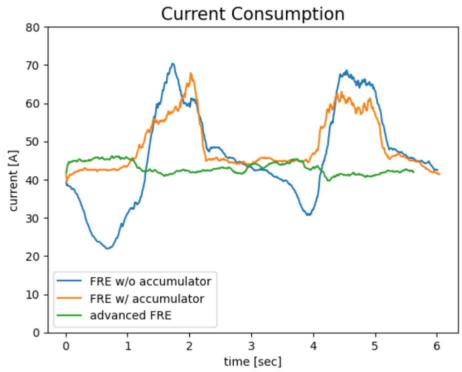


Fig. 5. Current consumption of high-speed motion experiment

### 4. Conclusion and Future Work

This study proposes a control strategy to enhance the performance and energy efficiency of hydraulic manipulators using a compact hydraulic power pack. The approach addresses flow supply limitations by integrating an accumulator and designing control methods that utilize stored hydraulic fluid. The study develops flow rate estimation-based control and an advanced version that restricts pump supply to optimize accumulator usage. Experimental validation confirms the effectiveness of the proposed control methods in improving system performance and energy efficiency.

The current study applies the proposed control method only to pre-defined motion patterns, making it unsuitable for teleoperated tasks. Future work will focus on extending the control approach to accommodate teleoperation by analyzing operator intent and integrating it into the control strategy.

## ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(Ministry of Science and ICT)(No. RS-2022-00144468).

## REFERENCES

[1] Jaebeom Park, Dohyun Lim, Jongwon Park, Seul Jung. (2022). Experimental Studies on Design of a Dual Arm Manipulator with Hydraulic System for Disaster Accidents. Journal of Institute of Control, Robotics and Systems, 28(11), 1080-1087.

[2] Dohyun Lim, Jaebeom Park, Jongwon Park, Seul Jung. (2023). Sliding Mode Control of a Heavy Duty Dual Arm Robot with Hydraulic Systems to Improve Motion-Following Performance. Journal of Institute of Control, Robotics and Systems, 29(2), 147-154.

[3] Cho, B., Kim, M. S., Kim, S. W., Shin, S., Jeong, Y., Oh, J. H., & Park, H. W. (2021). Design of a compact embedded hydraulic power unit for bipedal robots. IEEE Robotics and Automation Letters, 6(2), 3631-3638.

[4] Cui, Z., Rong, X., Li, Y. (2022). Design and control method of a hydraulic power unit for a wheel-legged robot. Journal of Mechanical Science and Technology 36 (4) (2022) 2043~2052.