Active Control for Rock Grinding Works of an Underwater Construction Robot Consisting of Hydraulic Rotary and Linear Actuators

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Abstract. The rock grinding, one of the purposes of the underwater construction robot, is done by the rotation torque of the rock grinding machine. The rotation torque of the rock grinding machine is proportional to the force that the robot arm applies to the rock grinding machine. If the robot arm applies excessive force the rock grinding machine halts. In contrast, unless the force is sufficient, the rock grinding machine bounces. Thus, the force applied to the rock grinding machine by the robot arm for rock grinding should always be adequate. When the underwater construction robot is remotely controlled, the operator has to repeatedly manipulate the proportional control valve to maintain an optimal torque, which requires advanced operating skills even on land and causes tiredness even for skilled operators. The present paper proposes an active control technique for maintaining the optimal torque and speed for the rock grinding machine. In order to evaluate the effect of the proposed control method, the simulations and experiments were performed.

Keywords: Underwater construction · Rock grinding · Hydraulic robot · Velocity control · Torque control · Valve-controlled hydraulic system

1 Introduction

The underwater construction robot project in Korea started since 2013 is intended to develop an underwater construction robot to be used for building some offshore structures at about 500 meters below sea level. Above all, the underwater construction robot for heavy work is a track-based robot platform capable of performing underwater tasks including moving around, burying pipelines and grinding rocks under the geological condition of at least 20 MPa compressive strength [1].

The underwater construction robot for heavy work is driven by a hydraulic system, whose water resistance is greater than that of any electric motor system. And a hydraulic system has several advantages in the application to robots. First of all, since it is possible to easily gain higher force just by adjusting the cylinder area, the system can be designed to be smaller and lighter than electric motors that use gear equipment. This advantage enables robots to be stable and energy-efficient by concentrating mass of the

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robots to their bodies. Moreover, the hydraulic system is robust to external impact thereby increasing robot's durability. Due to the above advantages, the hydraulic systems are mainly used in robot manipulators and industrial or military equipment that require a larger driving force in ground or underwater environments [2, 3].

As in Fig. 1, the rock grinding, one of the purposes of the underwater construction robot, is done by the rotation torque of the rock grinding machine. The rotation torque of the rock grinding machine is proportional to the force that the robot arm applies to the rock grinding machine. If the robot arm applies excessive force the rock grinding machine halts. In contrast, unless the force is sufficient, the rock grinding machine bounces. The underwater construction robot has a valve-controlled type hydraulic drive circuit mounted on its platform. The valve-controlled type supplies the power generated in the HPU (Hydraulic Power Unit) to each actuator by controlling the proportional control valve. Thus, the force applied to the rock grinding machine by the robot arm for rock grinding should always be adequate. When the underwater construction robot is remotely controlled, the operator has to repeatedly manipulate the proportional control valve to maintain an optimal torque, which requires advanced operating skills even on land and causes tiredness even for skilled operators. The fragments arising from the rock grinding work under the sea increase the concentration of underwater floaters, which makes it difficult to secure a clear view and proceed with the work [4].

To address the challenge, the present paper proposes an active control technique for maintaining the optimal torque in the underwater construction robot's rock grinding work and verifies its applicability with a simulations and experiments.

Fig. 1. Rock grinding of the underwater construction robot [4]

2 Active Control of Rock Grinding

Hydraulic systems are sub-classified into a valve-controlled system and a variable hydraulic pump-controlled system depending on the method of flow control. In general, the hydraulic valve control refers to a unidirectional rotation of the hydraulic pump to generate the flow and control the flow supplied to the hydraulic actuator with the valve. In contrast, the variable hydraulic pump control refers to directly controlling the hydraulic pump with an electric motor to supply the flow to the actuator without drawing on the valve [4, 5].

The underwater construction robot is controlled with the hydraulic valve. Figure 2 shows the hydraulic circuit for the simulation of rock grinding.

The actuator consists of the hydraulic cylinder moving the robotic arm and the hydraulic motor generating the rotation force of the rock grinding machine. The torque generated by the hydraulic motor arises from the load pressure as in the Eq. (1).

$$T = P_L \frac{V_m \eta_t}{2\pi} \tag{1}$$

T denotes the hydraulic motor torque. P_L denotes the load pressure. V_m denotes the volume of the motor. η_t denotes the motor's overall efficiency [6]. Unless the load pressure is given, the motor produces no torque. As the hydraulic cylinder imposes the external load on the hydraulic motor, the proportional control valve for the hydraulic cylinder need be controlled to maintain a certain level of load torque [4].

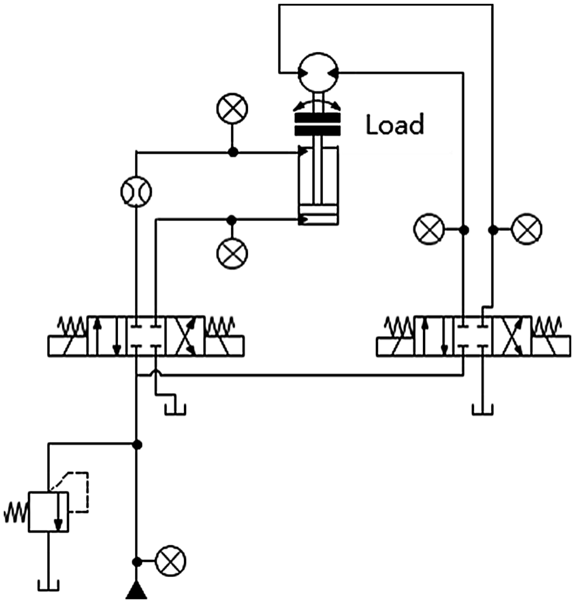


Fig. 2. Hydraulic circuit for the simulation of rock grinding [4]

The variation of the cylinder load pressure is equivalent to the difference in the pressure variation between the input and output chambers. Also, the variation of pressure in the cylinder chamber is considered to result from the compressed hydraulic fluid inside the chamber. Below is the continuity equation of the cylinder chamber [3, 7].

$$Q_b - Q_a - A_p\frac{dy}{dt} - \frac{(P_A - P_B)}{R_i} = \frac{V_c + A_p y}{\beta}\frac{dP_A}{dt} \tag{2}$$

$$Q_c - Q_d + A_p\frac{dy}{dt} + \frac{(P_A - P_B)}{R_i} = \frac{V_c - A_p y}{\beta}\frac{dP_B}{dt} \tag{3}$$

where Q_a, Q_b, Q_c and Q_d denote the flow rate at point a, b, c and d, respectively. P_A and P_B denote the pressure in chamber A and B, respectively. A_p and β are piston area and bulk modulus of oil, respectively. R_i is a resistance to internal leakage.

Assuming that the piston volumes are constant which is Vavg and the leakage is zero ($Q_a = Q_c = 0$), the subtraction between the Eqs. 1 and 2 can be expressed as below [3].

$$\frac{dP_A}{dt} - \frac{dP_B}{dt} = \frac{\beta}{V_{avg}}\left\{Q_b + Q_d - 2A_p\frac{dy}{dt} - \frac{2(P_A - P_B)}{R_i}\right\} \tag{4}$$

As in the Eq. (4), the rate of change of the load pressure is equal to the difference between the rates of change of pressure A and B. The rate of change of the pressure in cylinder chambers is caused by compressing the hydraulic oil. Hence, the important feature is that when cylinder velocity is increased, the required flow rate for compressing oil is increased. This is called natural velocity feedback [8]. However, the force control depends on the flow only, assuming the hydraulic cylinder moves very slowly without any inner oil leakage in the rock grinding work.

Therefore, the active control algorithm for maintaining the optimal torque in rock grinding could be implemented as in Fig. 3.

The load torque of the hydraulic motor is generated by maintaining a constant spool position of the proportional control valve for the hydraulic motor and by adjusting the

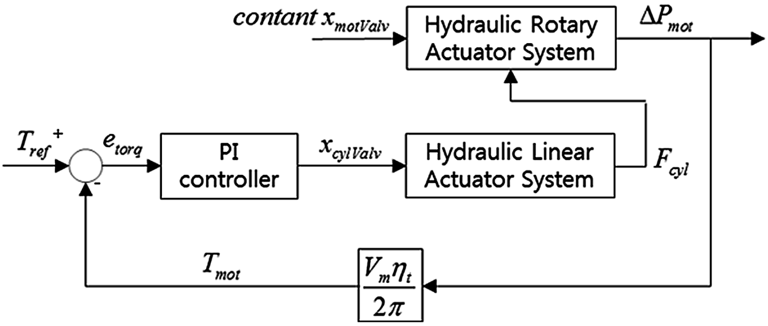


Fig. 3. Block diagram of the active control algorithm for maintaining the optimal torque in rock grinding [4]

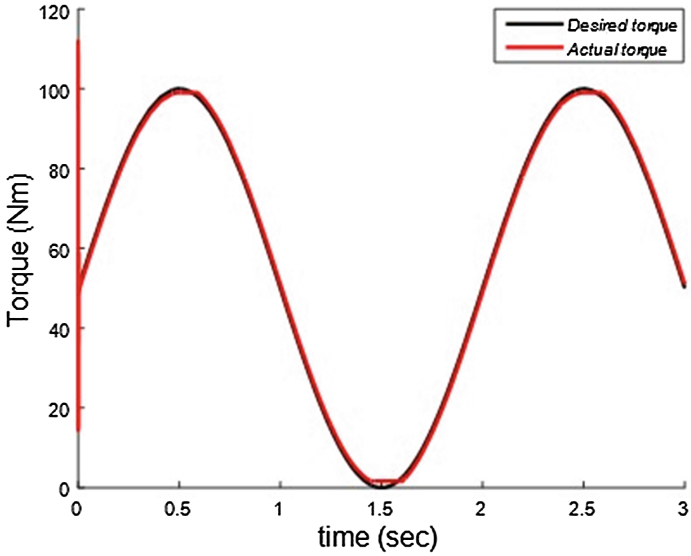


Fig. 4. Torque tracking performance of the active control algorithm for maintaining the optimal torque in rock grinding [4] (Color figure online)

spool position of the proportional control valve for the hydraulic cylinder. That is, the load pressure of the hydraulic motor is sensed and converted to the load torque with feedback given to control the hydraulic cylinder with the PI controller and to maintain the reference torque [4].

Figure 4 shows the result of the simulation. When the pure sine wave input is given as the motor's target load force, the motor's load force output successfully tracks the target.

However, if the hydraulic motor rotates at a velocity that uses up the entire flow generated by the pump, the hydraulic cylinder cannot be controlled due to the lack of the flow. Thus, the rotational speed of the hydraulic motor need be controlled.

The Eq. (5) shows the motor's rotational speed, ω, where the oil leakage and the compression volume are ignored [7].

$$\omega = \frac{Q_L}{D_m} = \frac{2\pi}{V_m} Q_L \tag{5}$$

The following Orifice equation represents the flow for the valve [7].

$$Q = C_d a(u_v)\sqrt{\frac{2\Delta p}{\rho}} = C_d W u_v \sqrt{\frac{2\Delta p}{\rho}} = \frac{C_d W \sqrt{2}}{\sqrt{\rho}} u_v \sqrt{\Delta p} = K_v u_v \sqrt{\Delta p} \tag{6}$$

where,

W: area gradient [m^2/A]

C$_d$: discharge coefficient

ρ: oil density
K_v: Valve gain
Δ_p: differential pressure the orifice
V_m: motor's displacement

Equation (5) and (6) yield the equation of relationship for the supply current to the valve at the following velocity.

$$u_v = \frac{V_m \omega}{2\pi K_v \sqrt{\Delta P}} \tag{7}$$

As the differential pressure is directly proportional to the output flow, a small spool displacement is needed.

$$K_f = \frac{V_m}{2\pi K_v \sqrt{\Delta P}} \tag{8}$$

The feedforward gain, K_f with the u_v from the Eq. (7) applied, and the speed controller with the dead-zone compensation and anti-windup applied are presented in Fig. 5.

The active control loop for maintaining the optimal torque in rock grinding is combined with the speed-control loop as Fig. 6. The load pressure of the hydraulic motor is sensed and converted to the load torque with feedback given to control the hydraulic cylinder with the PI controller and to maintain the reference torque. Furthermore, the load pressure is converted to the model-based feedforward gain for velocity control.

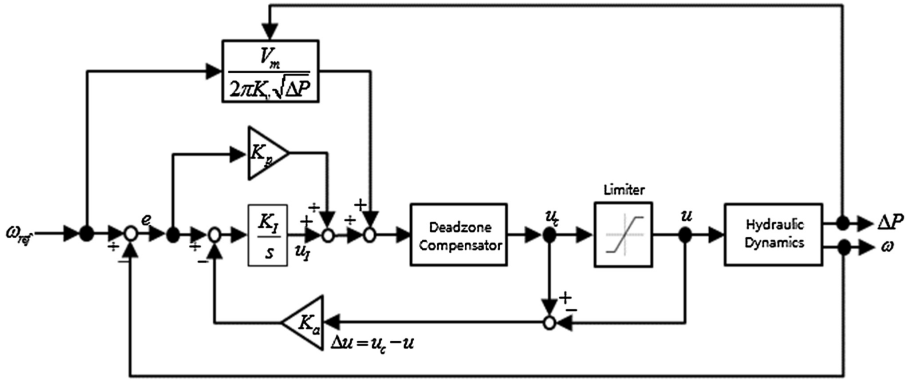


Fig. 5. Block diagram of the active control algorithm for maintaining the optimal velocity in rock grinding

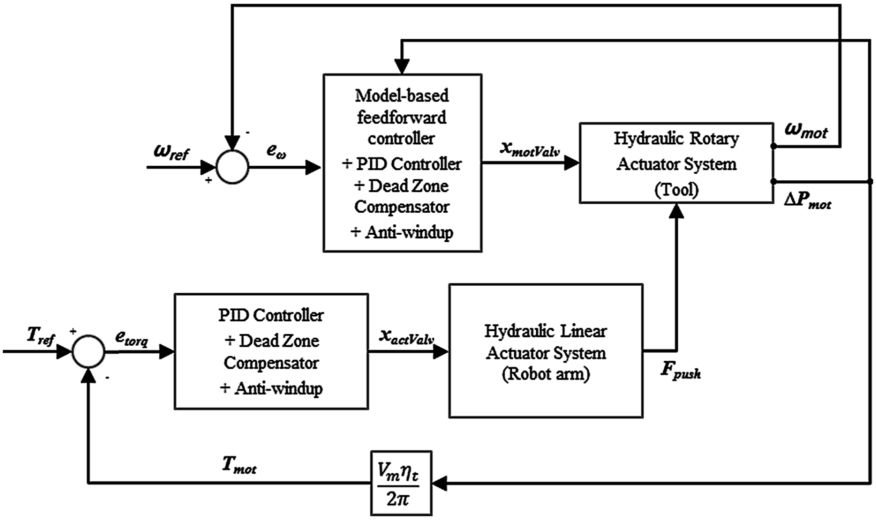


Fig. 6. Block diagram of the active control for rock grinding works of an underwater construction robot

3 Experimental Results

Figure 7 shows the experimental setup for evaluating the active control algorithm for rock grinding works of an underwater construction robot. The illustrated hydraulic circuit in the Fig. 2 is devised. The device is designed to impose the load force with the hydraulic cylinder in the perpendicular direction to the hydraulic motor's rotation axis.

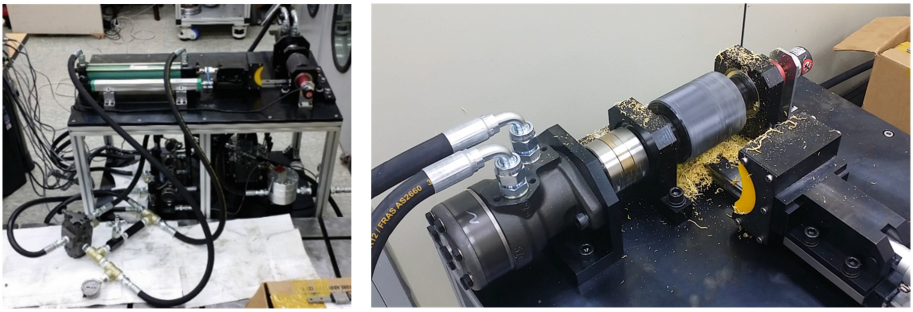
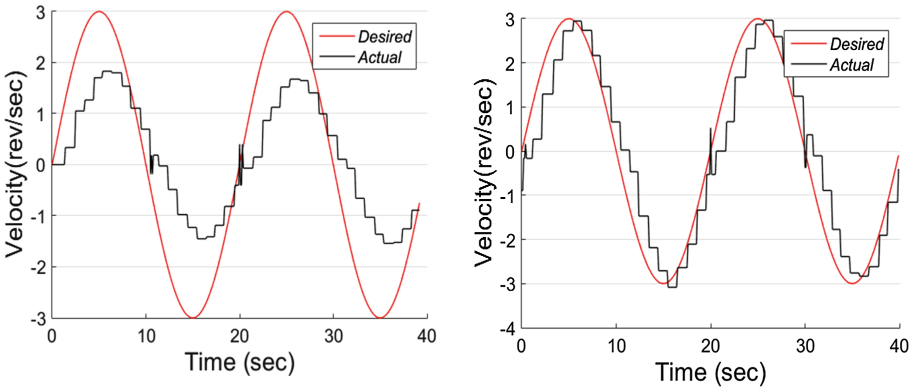


Fig. 7. Experimental setup

The hydraulic motor's load pressure increases with the pushing force of the cylinder. For measuring the load pressure, pressure sensors are equipped in the hydraulic circuit.



(a) PID control (b) Proposed velocity control

Fig. 8. Velocity tracking performance in wave response experiment

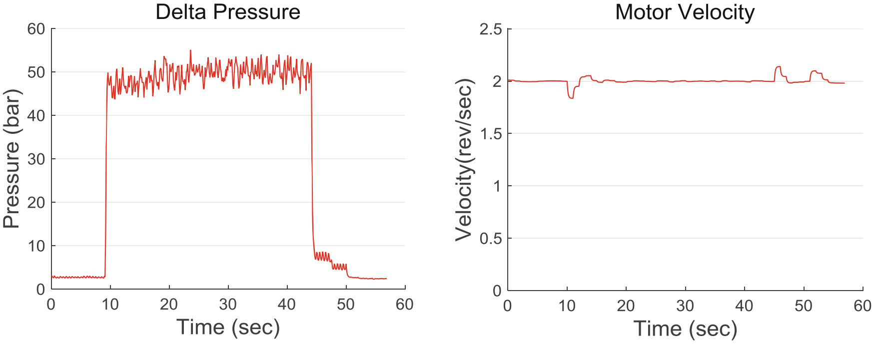


Fig. 9. The optimal torque and velocity tracking performance in rock grinding experiment

When the reference velocity is a sine wave, velocity tracking performance of PID controller and proposed velocity controller are represented in Fig. 8. The result shows that the velocity tracking error of the proposed velocity control method is smaller than that of the PID controller.

Furthermore, Fig. 9 represents the optimal torque and velocity tracking performance. When the 50-bar target load is tracked with the load varying, the velocity of 2 rev/sec is tracked. Therefore, the active rock grinding is viable only by specifying the optimal speed and torque values for rock grinding without the need of repetitive valve operation.

4 Conclusion

The present paper mathematically models the hydraulic motor and cylinder driven in rock grinding work by an underwater construction robot, and establishes that the hydraulic motor speed control in rock grinding requires the compensation for the volume variation in the motor chambers and that the hydraulic cylinder force control depends on the flow only. Based on these findings, the present paper proposes an active control technique for maintaining the optimal torque and speed for the rock grinding machine.

The simulation highlights that the rock grinding machine's optimal torque is controlled by the force imposed on the motor by the cylinder. To determine if the proposed technique could be implemented in a real system, a simulated rock grinding unit including the hydraulic cylinder and motor is set up.

The proposed active controller for rock grinding applied to the unit successfully tracks the target optimal torque and speed. The proposed method is expected to shorten the time taken to master the robot operation for rock grinding and thus increase the work efficiency once it is applied to a real system.

The proposed active control technique for rock grinding will be applied to an underwater construction robot to verify its viability through a field test in a future study.

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