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Nonlinear Control of Hydraulic Manipulator for Decommissioning Nuclear Reactor

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1. Introduction

Robot technique is need to decommission nuclear reactor because of high radiation environment. Especially, Manipulator systems are useful for dismantling complex structure in a nuclear facility. In addition, Hydraulic system is applied to handle heavy-duty object. Since hydraulic system can demonstrate high power. The manipulator with hydraulic power is already developed [4]. However, control algorithm of hydraulic manipulator is complex due to nonlinear characteristics such as hysteresis. To solve this problem, various nonlinear control method includes acceleration control. But, it is difficult because acceleration value is highly noisy.

In this paper, the nonlinear control algorithm without acceleration control is studied. To verify, the hydraulic manipulator model had been developed. Furthermore, the numerical simulation is carried out.

2. Hydraulic Manipulator Modeling

2.1 Manipulator Dynamics Model

The developed hydraulic manipulator is showed in Fig. 1. It is comprised six degree of freedom such as five revolute joints and one translational joint. In addition, the manipulator is serial type for wide work space. The length of manipulator is about 2.95m and the payload is maximum 250kg.

Fig. 1. Developed hydraulic manipulator

To increase performance, multibody dynamics(MBD) is applied. In addition, relative joint formulation is used for efficient joint control. The equations of motions are derived as eq.(1). The $\mathbf{M}_{qq}$ is mass and inertia matrix, the $\ddot{\mathbf{q}}$ is joint acceleration vector, the $\mathbf{P}_q$ is gravity and Coriolis force vector, the $\boldsymbol{\tau}_m$ is hydraulic motor torque vector and the $\mathbf{B}_m$ is viscous damping coefficient of oil.

$$\mathbf{M}_{qq}\ddot{\mathbf{q}} = \mathbf{P}_q + \boldsymbol{\tau}_m - \mathbf{B}_m\dot{\mathbf{q}} \tag{1}$$

2.2 Hydraulic Servo System Model

The hydraulic servo system consists of servo valve, geared rotary motor, sensors and controller. Especially, the servo valve is nozzle-flapper type valve. When the input current is supplied at coil of servo valve, the flapper will bend and the spool will be moved by supply pressure. Then, the geared motor can be actuated by oil.

The hydraulic equation is derived through Bernoulli's and continuity equations in eq.(2). The $\mathbf{P}_L$ is load pressure difference, the β_e is bulk modulus, the V_t is total contained volume of cambers, the $\mathbf{K}_q$ is flow gain, the $\mathbf{K}_v$ is valve gain, the $\mathbf{u}$ is input current, the $\mathbf{D}_m$ is volumetric displacement, the $\dot{\mathbf{q}}$ is angular velocity and the $\mathbf{K}_c$ is flow-pressure gain.

$$\dot{\mathbf{P}}_L = (4\beta_e / V_t)(\mathbf{K}_q\mathbf{K}_v\mathbf{u} - \mathbf{D}_m\dot{\mathbf{q}} - \mathbf{K}_c\mathbf{P}_L) \tag{2}$$

The hydraulic motor torque follows eq.(3). The $\boldsymbol{\eta}$ is mechanical efficient value.

$$\boldsymbol{\tau}_m = \boldsymbol{\eta}\mathbf{D}_m\mathbf{P}_L \tag{3}$$

3. Nonlinear Control Algorithm

In industry, PID controller is popular. Since, it is very simple and easy. However, PID is not enough for hydraulic system due to nonlinear characteristics. For accuracy, the nonlinear controller such as sliding mode control (SMC) which is typical robust control method is added.

The sliding surface with integral term is defined as eq.(4). Integral term is effective means for increasing tracking performance. The $\mathbf{e}$ is position error, the $\dot{\mathbf{e}}$ is velocity error, the $\boldsymbol{\zeta}$ is damping ratio and the $\boldsymbol{\omega}_n$ is natural frequency.

$$\mathbf{s} = \dot{\mathbf{e}} + 2\boldsymbol{\zeta}\boldsymbol{\omega}_n\mathbf{e} + \boldsymbol{\omega}_n^2\int\mathbf{e} \tag{4}$$

The input current is designed as eq.(5). The sat() function which is saturation function performed to decrease chattering problem.

$$\begin{aligned}\mathbf{u} &= \mathbf{u}_{PID} + \mathbf{u}_{SMC} \\ &= \mathbf{K}_p\mathbf{e} + \mathbf{K}_i\int\mathbf{e} + \mathbf{K}_d\dot{\mathbf{e}} + \mathbf{K}_s\,\mathrm{sat}(\mathbf{s},\ \phi)\end{aligned} \tag{5}$$

For tracking performance, the PID gains are decided through time delayed control(TDC) theorem as eq.(6). he $\bar{\mathbf{m}}$ is inertia matrix and the T is sampling time.

$$\mathbf{K}_d = \bar{\mathbf{m}}/T, \quad \mathbf{K}_p = 2\zeta\boldsymbol{\omega}_n\mathbf{K}_d, \quad \mathbf{K}_i = \boldsymbol{\omega}_n^2\mathbf{K}_d \qquad (6)$$

This method not requires acceleration parameter but it has same effect as nonlinear controller. This is advantage of suggested control algorithm.

Figure 2 shows control scheme of hydraulic manipulator. Using eq.(4)~(6), the control input current is calculated by feedback properties. If input current is determined, compute the load pressure difference($\mathbf{P}_L$) from eq.(2). Then, the hydraulic motor torque is decided by eq.(3). Finally, the position and velocity of manipulator is calculated by eq.(1). In this paper, the Runge-Kutta 4th order method is applied.

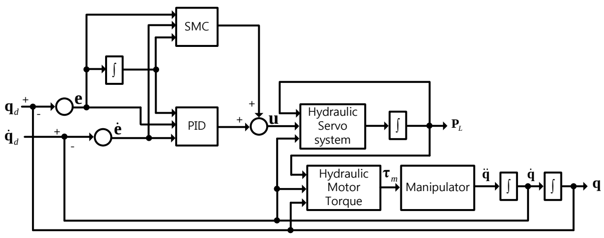
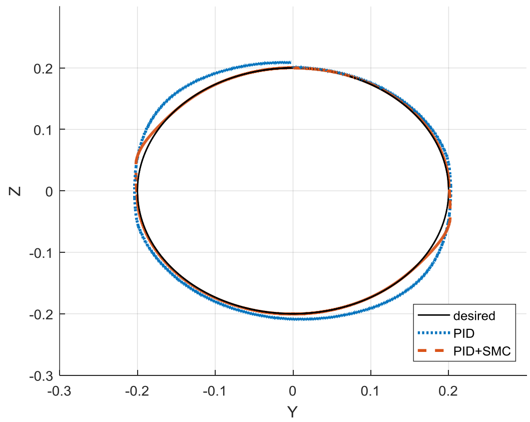


Fig. 2. Control block diagram.

4. Numerical Simulation

The simulation of hydraulic manipulator is described as fig. 3. The simulation is circular planning motion at Y-Z plane with 250kg payload. In addition, typical PID control and suggest control are compared.

The black line is desired position, the blue dash line is position of end effector with PID and the red double dash line is position of end effector with PID+SMC. The maximum tracking error is represented on Table I.



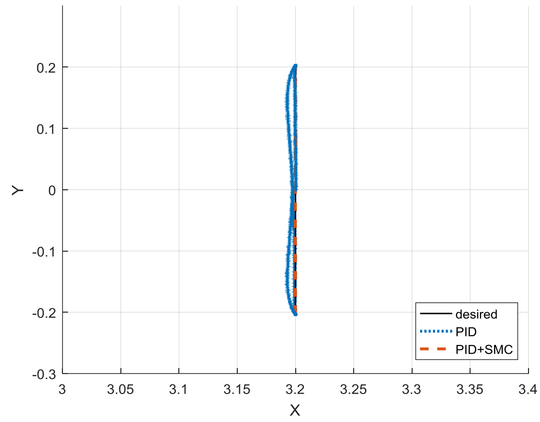


Fig. 3. Numerical simulation result

In the simulation result, the suggest method is better than PID control. Especially, tracking performance is good although acceleration control is not used.

Table I: Maximum Tracking Error

	X	Y	Z
PID	8.27mm	20.94mm	57.67mm
PID+SMC	0.55mm	9.19mm	18.53mm

5. Conclusions

The nonlinear control without acceleration parameter method is developed for hydraulic manipulator. To verify control algorithm, the manipulator is modeled by MBD and the hydraulic servo system is also derived. In addition, the numerical simulation is also carried out. Especially, PID gain is determined though TDC algorithm. In the result of numerical simulation, tracking performance is good without acceleration control. Thus, the PID though TDC with SMC is good for hydraulic manipulator control.

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