Fuzzy Sliding Mode Control for a Hydraulic Elevator Controlled by Inverter

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Abstract: In this paper, a design methodology of fuzzy sliding mode control scheme for a hydraulic elevator controlled by inverter is presented. The proposed scheme uses a fuzzy sliding mode controller(FSMC), which is designed based on the similarity between the fuzzy logic control(FLC) and the sliding mode control(SMC). The proposed method has advantages that the stability and the robustness of the FLC are proved and ensured by the sliding mode control law, and the computation burden could be reduced greatly. The validity and the effectiveness of the proposed control method have been shown through the real world industrial application results.

Keywords: Fuzzy logic controller, Sliding mode control, Hydraulic elevator

1. Introduction

A hydraulic elevator is a system that support the passenger car directly or indirectly by hydraulic jacks. Generally, the hydraulic elevator has larger energy consumption than the rope type elevator, and gives uncomfortable feeling to passengers due to the abrupt start and stop of the motor. In order to solve these problems, a hydraulic elevator driven by inverters which control the quantity of flow in the hydraulic pump has been developed[1]. The hydraulic elevator controlled by inverters has advantages that low power consumption and comfortable feeling during the ride. The system, however, has complex structure and mechanical vibration including motor, hydraulic pump, hydraulic cylinder, rope, and nonlinearities varied according to the temperature and the load. Especially, the system has resonance on 2~3Hz first and on 12~15Hz second in acceleration and deceleration[2]. These deteriorate on the feeling of ride.

To overcome these problems, several methods have been suggested, for example [3] and [4].

During last decade, due to the advantage of fuzzy logic control(FLC) methods, a fuzzy logic-based control has been implemented for many industrial applications[6].

The FLC scheme could be very useful for the system hard to modeling like the hydraulic elevator controlled by inverter. However, the critical drawbacks on implementing FLC for control of the hydraulic elevator controlled by inverter are; i) the FLC scheme is hard to prove the stability, and ii) the FLC scheme requires a large computation time[5]. In this paper, we propose a design methodology of a fuzzy sliding mode control scheme, which overcomes those drawbacks, for control of the hydraulic elevator controlled by inverter.

We design a FLC based on the sliding mode control law. These are the design methods based on the similarity between the FLC and the SMC, and this method permits us to use more formalized, engineering type of knowledge to construct the FLC. With this method, the stability and the robustness of the proposed fuzzy logic control algorithm are proved and ensured by the sliding mode control law.

To show the effectiveness, the proposed method has been applied to the entire elevator driving system, and experimental results are given.

2. Modelling of a Hydraulic Elevator Controlled by Inverter

2.1 System Configuration

A hydraulic elevator system is largely divided into an electric system, including motors and control units, a hydraulic system, including hydraulic pumps, and a mechanical system, including cars and ropes.

The mechanical modeling of the hydraulic elevator system is shown as Fig. 1, which the equation of motion for the mechanical systems can be expressed as

$$M_c \ddot{x}_c + C_r(\dot{x}_c - 2\dot{x}_j) + K_r(x_c - 2x_j) = -M_c \cdot g$$
$$M_j \ddot{x}_j + 2C_r(2\dot{x}_j - \dot{x}_c) + 2K_r(2x_j - x_c) = P_j A_j - M_j \cdot g \qquad (1)$$

where, K_r: equivalent spring constant of rope[N/m], C_r: equivalent damping constant of rope, [N · sec/m], M_c: Car Weight+ load Weight[kg], x_c: displacement of car[m], x_j: displacement of cylinder rod[m], P_j: Pressure in cylinder[N/m²], A_j: cross sectional area of cylinder rod[m²], M_j: Weight of the cylinder and Pulley[kg]

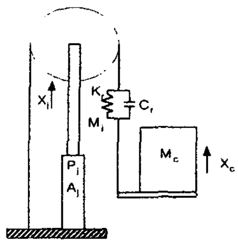


Fig. 1. Mechanical modeling of the hydraulic elevator system

2.2 Structure of the control unit

Structure of the control unit of hydraulic elevator controlled by inverter is shown in Fig. 2. The power unit is submarine type that motor rotate in oil, and pressure sensor that can measure pressure of pump and cylinder, is attached at check valve. Also pump and oil deposit type encoder is attached on motor in power unit to detect motor speed. Another encoder is attached on upper position of the car to detect speed of the car. The motor is three phase 380V, 48Kw, so Capacity of IGBT Converter, IGBT inverter are set to 1200V, 300A.

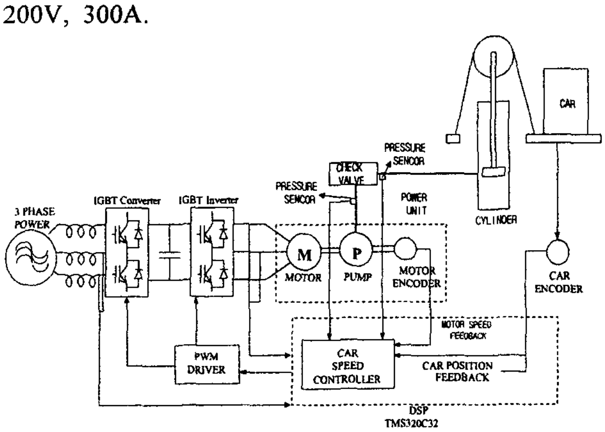


Fig. 2. Configuration of a hydraulic elevator controlled by inverter

3. Problem Formulation

The eq. (1) cancan be expressed as

$$(M_c+\Delta M_c)\ddot{x}_c+\frac{1}{2}M_j\ddot{x}_j+f_1(\dot{x}_j)+\frac{J_p}{2V_0}\ddot{\theta}_p + \frac{C_p\sqrt{\nu}}{2V_0}\dot{\theta}_p=\frac{1}{2V_0}A_jT_p \quad (2)$$

$$\Rightarrow M_c\ddot{x}_c+\Delta M_c\ddot{x}_c+f_2(\ddot{x}_j,\dot{x}_j)+f_3(\ddot{\theta}_p,\dot{\theta}_p)=Bu \quad (3)$$

with

$$u=T_p,\ \Delta M=\Delta_{mass},\ f_1(\dot{x}_j)=\Delta_{stic}+\Delta_{vis}\dot{x}_j,$$
$$B=\frac{1}{2V_0}A_j,\ f_2=\frac{1}{2}M_c\ddot{x}_j+f_1(\dot{x}_j), \quad (4)$$
$$f_3(\ddot{\theta}_p,\dot{\theta}_p)=\frac{J_p}{2V_0}\ddot{\theta}_p+\frac{C_p\sqrt{\nu}}{2V_0}\dot{\theta}_p$$

In this paper, the control problem for an elevator system is to synthesize a control law for the press pump's torque T_p such that the feedback car position (x_c) traces the desired car trajectory, x_c^d, with a certain precision defined by

$$e=[e\,\dot{e}]^T, |e|=|x_c-x_c^d|\le\gamma_1, |\dot{e}|=|\dot{x}-\dot{x}_d|\le\gamma_2, \gamma_1>0, \gamma_2>0 \quad (5)$$

It is assumed that $x_c^d(t)$ and $\dot{x}_c^d(t)$ are well defined and bounded for all operational time t.

Generally, the transient dynamics of SMC(sliding mode control) consists of two conditions: a reaching condition and a sliding condition. Under the reaching condition, the desired response aims to reach the switching manifold in finite time. The switching manifold S is written as [7]

$$S=\{\,e\,|\,s(e)=0\} \quad (6)$$

where s denotes a switching function,

$$s(t)=\dot{e}+\lambda e,\ \lambda>0 \quad (7)$$

4. Sliding Mode Based Fuzzy Logic Control

Figure 4 shows the structure of the proposed fuzzy sliding mode controller. The proposed controller consists of two different controllers, namely load compensation controller, sliding mode based fuzzy controller, and fuzzy logic controller. The load compensation controller is used to reach the pressure of cylinder equal to the pressure of oil pump before the passenger car of the elevator is starting to be moved. Sliding mode based fuzzy controller is used to calculate motor output torque S_{ref} from the motor speed, trajectory errors of the car, variation of trajectory errors of the car.

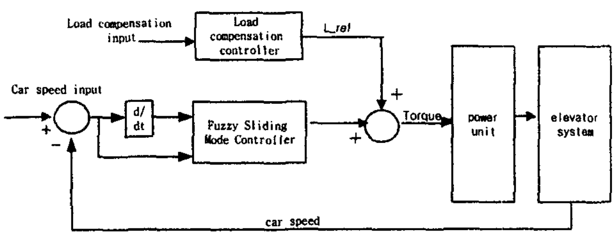


Fig. 4. Block diagram of a hybrid fuzzy sliding mode controller

In the following we will develop a sliding mode based fuzzy logic controller to calculate control input, T_p, to solve the control problem (2). A possible sliding mode control(SMC) law to calculate control input, u, to solve the control problem (3) is [8]

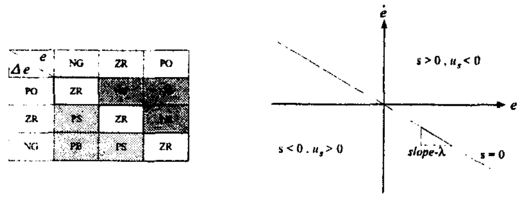
$$u = -u_{nom} - u_s \tag{8}$$

$$u_s = \begin{cases} \bar{\eta}\frac{s}{|s|} & \text{if } |s| > \varepsilon \\ & ;1>\varepsilon>0,\ \bar{\eta}>0 \\ \bar{\eta}\frac{s}{\varepsilon} & \text{otherwise} \end{cases}$$

where ε is a boundary layer, and

$$u_{nom} = k_1 \dot{e} + k_2 e + M_c B^{-1} \ddot{x}_c^d \tag{9}$$

Then control rules are designed to assign a fuzzy set of the control input u_s for each combination of fuzzy sets of the e and Δe depending on $s = \Delta e + \lambda e$. Fig. 5(a) shows one of possible control rules. The similarity between the FLC and the SMC is shown in Fig. 5(b).



(a) (b)

Fig. 5. Similarity between the FLC and the SMC
(a) The rule base of FLC (b) The output characteristic of a SMC.

From the similarity between the FLC and the SMC, the structure of a fuzzy sliding mode control(FSMC)(sliding mode based FLC) including the membership functions of input fuzzy sets, is shown in Fig. 6(a):

The rule-base used in Fig. 6 can be designed with partitioning the universes of the two parameters, the error e and its first difference Δe. Now the control law for the uncertain system (2) is designed as the fuzzy sliding mode control law

$$u = -u_{nom} - u_s^*,\ k_1 > 0$$
$$u_s^* = \text{Output of FLC} \tag{10}$$

Figure 6(b) shows the structure of fuzzy logic controller. In Figure 7, the rule base is for the rule to calculate the weighting gain of the sliding mode based fuzzy logic controller and the PID controller. The inputs of the FLC are motor speed, Wp, and trajectory error of car, e, and the output of the FLC is the weighting gain K_h.

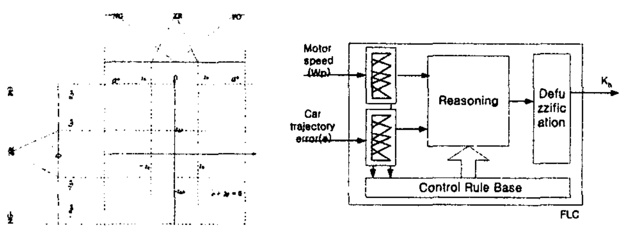


Fig. 6. (a) The membership functions
(b) Structure of FLC

5. Stability of Fuzzy Sliding Mode Control System

Dynamic equation of a hydraulic elevator controller by inverter can be expressed as (3), or can also be expressed single input 2nd order equation as

$$\ddot{x}_c(t) = M_c^{-1}\{-\Delta M_c \ddot{x}_c - f_2(\dot{x}_j, x_j) - f_3(\dot{\theta}_p, \theta_p) + Bu\}$$
$$= f(x_c) + \Delta f(\dot{x}_j, \dot{\theta}_p, t) + u \tag{11}$$

From (7) and (11), the fuzzy sliding mode system can be denoted as

$$\dot{s} = \ddot{x}_c^d - f - \Delta f - u_{nom} - u_s^* \cdot + \lambda \dot{e}$$
$$= -\eta s + F(x,t) - u_s^* + \eta s, \quad \eta > 0 \tag{12}$$

where $F(x,t) = \ddot{x}_c^d - f - \Delta f - u_{nom} + \lambda \dot{e}$. Then, we have following results.

Theorem 1: Assume that the system of (12) satisfies

$$\rho(\cdot) \geq F_{\max} + \eta|s|, \quad \eta > 0,\ \rho(\cdot) > 0$$
$$F_{\max} = \max_{\forall x,t} |\ddot{x}_c^d + \lambda \dot{e} - f - u_{nom} - \Delta f| \tag{13}$$

then the closed-loop system is globally stable.

Proof: Choose the Lyapunov function candidate

$$V(z) = \frac{1}{2} z^T P z \tag{14}$$

where $P = \begin{bmatrix} 2\eta\lambda & 0 \\ 0 & 1 \end{bmatrix}$ and $z = [e, s]^T$.

By applying (12) into (14), $\dot{V}$ cna be obtained as

$$\dot{V} = \begin{bmatrix} e \\ s \end{bmatrix}^T P \begin{bmatrix} \dot{e} \\ \dot{s} \end{bmatrix}$$
$$= -z^T \begin{bmatrix} 2\eta\lambda^2 & -2\eta\lambda \\ 0 & \eta \end{bmatrix} z + s\{F + \eta s\} - s \cdot u_s^*$$
$$\leq -\lambda_{\min}\left(\begin{bmatrix} 2\eta\lambda^2 & -2\eta\lambda \\ 0 & \eta \end{bmatrix}\right)\|z\|^2 \tag{15}$$

where $\lambda_{\min}(\cdot)$ means minimum eigenvalue of $(\cdot)$. We see in (15) that $\begin{bmatrix} 2\eta\lambda^2 & -2\eta\lambda \\ 0 & \eta \end{bmatrix}$ is positive definite matrix. Thus, $\dot{V}(z) \leq 0$. This shows that theorem 1 is satisfied.

6. Experimental Results

Fig. 8 shows the experimental system configurations of a Hydraulic Elevator Controlled by Inverter.

For the experiment, we designed a new TMS320C32 (50㎒) DSP chip mounted control board. Other peripherals used on the controller board are; two of AD7891AS-1(Analog devices) 8-channel 1.2 μ sec conversion time 12-Bit ADC to measure the motor current; AD7226 (Analog devices) 4-channel 8-bit DAC; AM29F010-120(AMD) to store the program; four of KM68257CJ-15(Sam Sung Semiconductor) 15 μ sec access time RAM, etc.

For a hydraulic motor, HYZTA180-28 (ZIEHL-ABEGG), 380V 48Kw is used, for a hydraulic pump, SUC280-46(ALLWEILER, German) is used. Two of pressure censer, one for a cylinder pressure and another for pump pressure, are used.

Maximum speed of the hydraulic elevator is 45m/min, and maximum load is 1600kg(approx. 24 people). To sensor the elevator car positions, an 1024pulse optical encoder is attached on the top of the car. Results of the experiments are measured using Tektronix Digital Storage Oscilloscope TDS 420, which can be measured and stored 4channel inputs.

Table 2 shows the detailed test tower specification of hydraulic inverter-fed elevator used for the experiment. In the experiment, result signals are measured wile the elevator is operated to move up and down from second floor to third floor with no load condition.

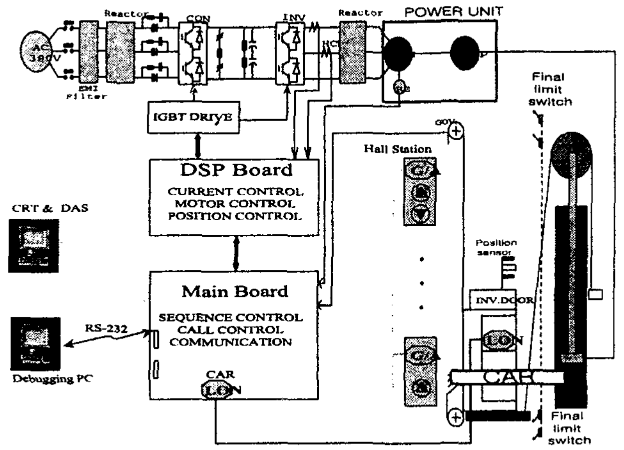
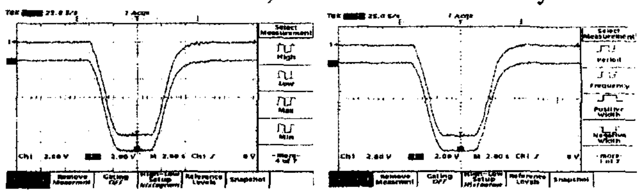


Fig. 8. Configuration of hydraulic elevator controlled by inverter.

Table 2 Test tower specification of hydraulic inverter-fed elevator

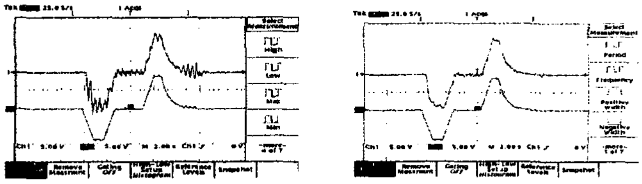
capacity	24 person
diameter of Jack(mm)	180
Jack weight(Kg)	329.344
initial oil volume(m^3)	0.037388
car weight(Kg)	2600
capacity of motor(Kw)	48
pump specification	SUC-280-46
Rated speed(m/min)	45
capacity of passenger(Kg)	1600
rope length(m)	9.3

Figure 11 and Figure 12 show the experimental results of the passenger car speed and car acceleration, respectively, under PID controlled system and FSMC. Figure 11(b) shows that the car starts without overshoot and stops without vibration under FSMC. Figure 12(b) shows that the vibration of the car acceleration reduced to less than 5gal, and there exists no vibration on the zero-crossing region under FSM controlled system. It can be seen that the proposed fuzzy sliding mode controled hydraulic elevator system can effectively suppress the vibration of hydraulic elevator in acceleration, deceleration and steady state.



(a) (b)

Fig. 11 Car speed under (a) PID controller (b) FSMC(2V/9m/min, 2V/div)



(a) (b)

Fig. 12 Car acceleration (a) PID controller (b) FSMC (5V/25gal, 5V/div)

7. CONCLUSIONS

In this paper, a FLC based on the sliding mode control law has been designed, based on the similarity between the FLC and the SMC. The design method permits us to use more formalized, engineering type of knowledge to construct the FLC, and the stability and the robustness of the proposed fuzzy logic control algorithm are proved and ensured by the sliding mode control law.

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