韓國港灣學會 第15卷 第1號, pp. 37～46. 2001.

論 文

Design of the Adaptive Fuzzy Control Scheme and its Application on the Steering Control of the UCT

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무인 컨테이너 운송 조향 제어의 적응 퍼지 제어와 응용

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Key Words : FLC(퍼지논리제어기), UCT(무인컨테이너수송차량), Steering Control(조향제어)

Abstract

Fuzzy logic control(FLC) is composed of three parts: fuzzy rule-bases, membership functions, and scaling factors. Well-defined fuzzy rule-base should contain proper physical intuition on the plant, so are needed lots of experiences of the skillful expert. When membership functions are considered, some parameters on the membership function such as function shape, support, allocation density should be selected well. The rule of scaling factors is 'scaling'(amplifying or reducing) for both input and output signals of the FLC to fit in the membership function support and to operate the plant intentionally.

To get a better performance of the FLC, it is necessary to adjust the parameters of the FLC. In general, the adaptation of the scaling factors is the most effective adjustment scheme, compared with that of the fuzzy rule-base or membership function parameters. This study proposes the adaptation scheme of the scaling factors. When the adaptation is performed on-line, the stability of the adaptive FLC should be guaranteed. The stable FLC system can be designed with stability analysis in the sense of Lyapunov stability. To

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adapt the scaling factors for the error signals, the concept of the conventional MRAC would be introduced into slightly modified form. A tracking accuracy of the control system would be enhanced by the modified shape and support of the membership function.

The simulation is achieved on the pilot plant with the hydraulic steering control of a UCT(Unmanned Container Transporter) of which modeling dynamics have lots of severe uncertainties and modeling errors.

1. Introduction

Generally, industrial heavy instruments such as an excavator and the UCT (unmanned container transporter) are equipped with an EHSS (Electro-Hydraulic Servo System). An electro-hydraulic steering system of the industrial heavy instruments is implemented by applying the EHSS to the tie-rod in the steering part. The EHSS is a closed-loop control system that consists of electronic signal processing units and hydraulic driving devices. It has a lot of advantages such as high control accuracy, rapid response, flexible signal processing, high ratio of power to weight, compact structure, and so on.

The EHSS is, however, a complex, inherently nonlinear and time-variable system. The nonlinearities mainly result from electro-hydraulic signal transformer and characteristics of amplifiers such as throttling traits, as well as from hydraulic executive components' features of viscous stagnancy, insensitive area. As the EHSS works, the viscosity of working fluid changes with temperature; meanwhile, the bulk modulus of the elasticity of working fluid changes with temperature as well as gas content. All these changes largely affect the performance of the system. It is reasonable to employ a control technique which has an adaptive structure to solve these problems.

A FLC(Fuzzy Logic Control) is one of popular intelligent controls. The characteristics of the FLC is that it is a human linguistic-based control, performs satisfactory result on the plant with uncertainties and nonlinearities, and actual implementation can be easily possible.

Generally, the FLC consists of three parts: fuzzy rule-bases, membership functions, and scaling factors. The rule-base is called as an 'inference engine' which should generate a proper control input. Well-defined fuzzy rule-base must contain suitable physical intuition and operating situation on the plant; so are needed the experiences of the skillful expert. When membership functions are considered, some parameters of the membership function such as function shape(triangular, trapezoid, and gaussian), support(range of fuzzy variable covered by a membership function), allocation density(the degree of how many membership functions are allocated in the specific range of the fuzzy variable) should be selected well. The rule of scaling factors is to amplify or reduce both input and output signals of the FLC to fit in membership function support and to operate the plant on purpose.

To get a better performance of the FLC, it is necessary to adjust parameters of the FLC. Usually, the tuning of the scaling factors is the most effective adjustment scheme compared with that of the fuzzy rule-base or membership function parameters, because it affects control input directly.

The paper shows the enhanced performance of the control system by the adaptation scheme of the scaling factors. When the adaptation is performed on-line, the stability of the adaptive FLC should be guaranteed. The stable FLC system can be designed with stability analysis in the sense of Lyapunov stability. To adapt the scaling factors for the error signals, the concept of the conventional MRAC is quoted with a little modification. Also, to enhance the tracking accuracy of the control system, the modification of the shape and the support of the membership function is introduced.

To verify the performance of the proposed method, the simulation is supposed to be achieved in the pilot plant of the EHSS with parametric uncertainties.

2. FLC Design

The FLC Configuration

The FLC generates a control input based on error information. Most commonly used configuration of the FLC is shown in Fig. 1.

It makes control input according to error and error rate. In Fig. 1, *ISF* and *OSF* means *'Input Scaling Factor'* and *'Output Scaling Factor,'* respectively. The rule of both SFs are mentioned in the introduction.

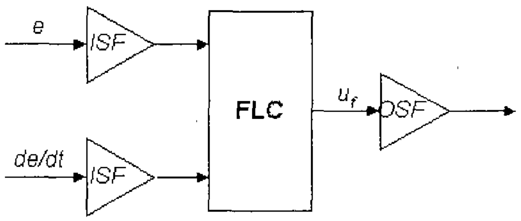

Fig. 1 General configuration of FLC

For better performance, it is advantageous to adapt ISF and OSF. But in the case of Fig. 1, the adaptations of three SFs should be considered simultaneously, and it is not so easy because it is one of 3-DOF problems. So the ISF should be assumed as a constant value and only adaptation of OSF would be considered in this paper. Adaptation scheme is following in the next section.

Selection of rule-base and membership function

The control input by the FLC should compensate for the errors of the control system. The rule-base used in this paper is shown in Table 1.

Table 1 Fuzzy rule-base

R ╲ *E*	*NB*	*NM*	*NS*	*ZE*	*PS*	*PM*	*PB*
PB	ze	ps	pm	pb	pb	pb	pb
PM	ns	ze	ps	pm	pb	pb	pb
PS	nm	ns	ze	ps	pm	pb	pb
ZE	nb	nm	ns	ze	ps	pm	pb
NS	nb	nb	nm	ns	ze	ps	pm
NM	nb	nb	nb	nm	ns	ze	ps
NB	nb	nb	nb	nb	nm	ns	ze

,where *E* and *R* means error and error rate, respectively. Each symbols in the table, *'PB/PM/PS'*, *'NB/NM/NS'*, and *'ZE'* stands for *'Positive Big/Medium/Small'*, *'Negative Big/Medium/Small'*, and *'ZEro,'* respectively.

The rule-base in Table 1 makes the FLC to generate a control input like that of sliding mode control. Let the state *ze* in Table 1 be a pseudo sliding surface. It means the sliding input which makes the system states sliding in the pseudo sliding surface, and the other symbols mean reaching input which makes the system states approach to the pseudo sliding surface. This is shown in Fig. 2.

It doesn't have a crisp value, for the symbol *ze* is a fuzzy variable. That is, exact zero input can not be generated by the FLC, but high degree of almost zero-like value can be produced by defuzzification of the membership function in the FLC.

In general, the supports of membership functions about fuzzy variables in the FLC are set as the same length in Fig. 3. But it is reasonable to generate a large control input when the state is far away from pseudo sliding surface, and small control input when the state is near pseudo sliding surface. In this criterion, membership functions can be defined in Fig. 4.

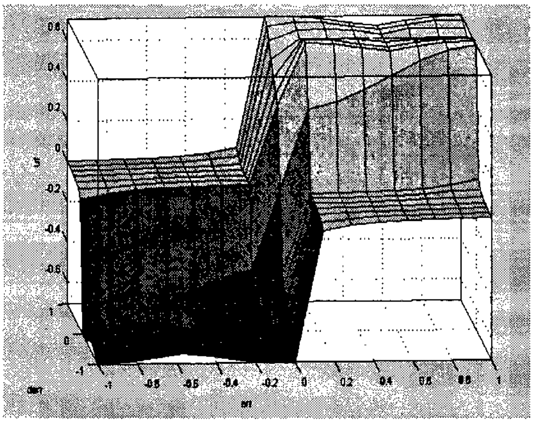

Fig. 2 Rule-base surface

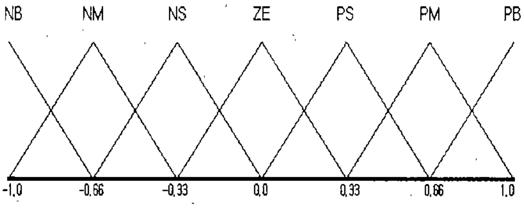

Fig. 3 Membership functions with equal support

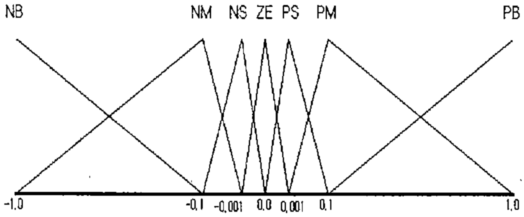

Fig. 4 Membership functions with non-equal support

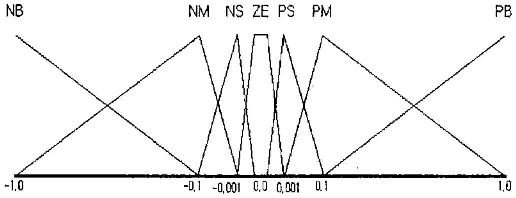

Fig. 5 Membership functions with modified support

If system states come to reach in the pseudo sliding surface, the length of support of membership function for fuzzy variable *ze* affects on the tracking accuracy and the chattering of plant output. Long support degenerates tracking accuracy and enhances less chattering; for short support, vice versa. To solve this dilemma, we propose the configuration of the membership function like Fig. 5.

The upper side of trapezoid membership function is set to zero; It acts like 'dead zone' of the control input of the FLC. Fig. 6, Fig. 7, and Fig. 8 show simple simulation results of each configuration of the membership functions. In the simulation, the transfer function for a linear time-invariant plant and the reference input is Eq. (1) and Eq. (2), respectively.

$$G(s) = \frac{10}{s^2 + s} \qquad (1)$$

$$u_{ref} = \sin t \qquad (2)$$

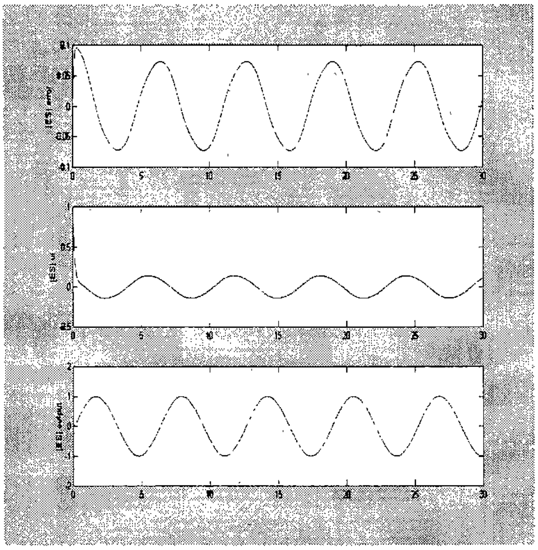

Fig. 6 Simulation with the membership function configuration of Fig. 3.

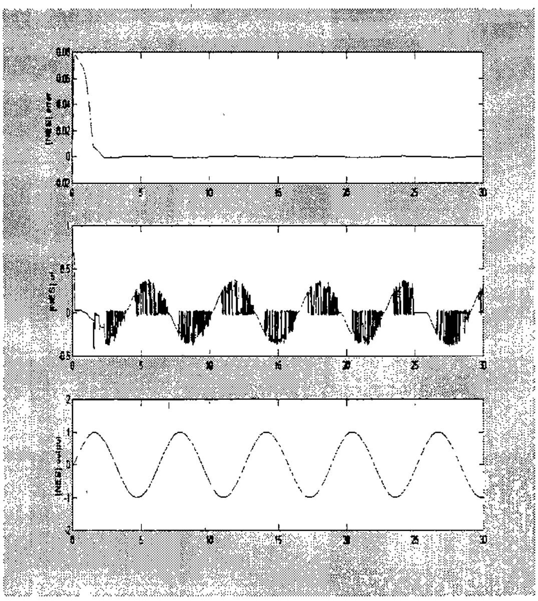

Fig. 7 Simulation with the membership function configuration of Fig. 4.

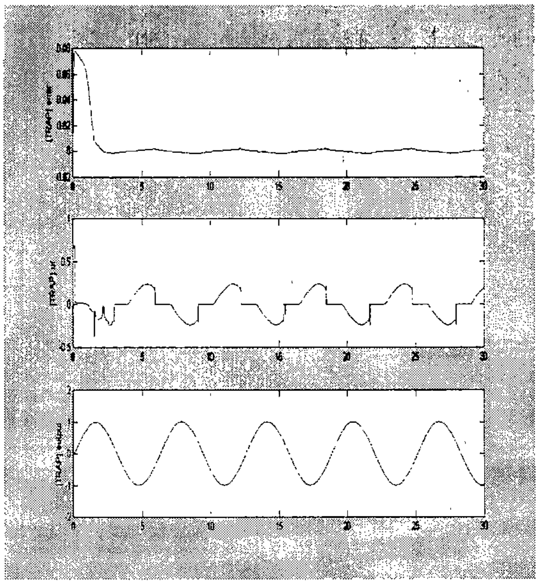

Fig. 8 Simulation with the membership function configuration of Fig. 5.

Among three figures, Fig. 7 shows the best tracking accuracy while there is a high chattering of the control input. On the other hand, Fig. 6 shows the mildest control input with no ignorable residual tracking error.

Fig. 8, in which trapezoid membership function is incorporated, can be chosen as the compromise between the tracking accuracy and the chattering of the control input.

Conceptually, the rule of the trapezoid membership function is similar to that of the boundary layer of the variable structure control[1]. As a consequence, the membership function in Fig. 5 is selected in this paper.

The OSF Adaptation

The configuration of control system is illustrated into Fig. 9. When the OSF is adapted in on-line, the guarantee for the stability is important. Now, we analyze the system stability and design a control scheme in the process of the OSF adaptation.

The control input for the plant is represented into Eq. (3).

$$u = K \cdot F \cdot e \qquad (3)$$

,where K is the OSF, F is the FLC, and e is the error.

Let the reference input be u_c and the plant output be y_p, then the overall transfer function becomes into Eq. (4).

$$y_p = \frac{KFP}{1+KFP} u_c \qquad (4)$$

With the appliance of the MRAC, the formula Eq. (5) is made by the use of the formula Eq. (6), an MIT rule.

$$\frac{\partial e}{\partial K} = -\frac{\partial y}{\partial K} = -\frac{KFP}{1+KFP}\frac{e}{K} \approx -\frac{e}{K} \qquad (5)$$

$$\frac{dK}{dt} = \eta \frac{e^2}{K} \qquad (6)$$

,where η is a positive real adaptation gain. Eq. (6) is an adaptive law of the OSF. To analyze the system stability in the sense of Lyapunov stability, the Liapunov function candidate is as follows.

$$V = \frac{1}{2} e^2 \qquad (7)$$

$$\begin{aligned} \dot{V} &= e\left(\frac{\partial e}{\partial K}\dot{K} + \frac{\partial e}{\partial t}\right) \\ &= -\eta\left(\frac{e^2}{K}\right)^2 + e\dot{e} \end{aligned} \qquad (8)$$

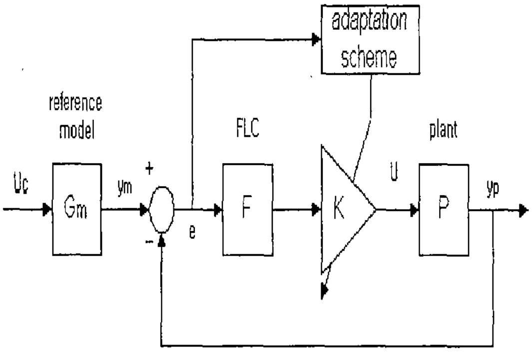

Fig. 9 Control system configuration

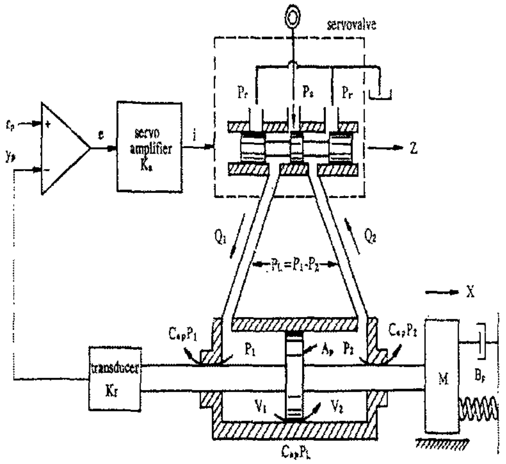

Fig. 10 EHSS configuration

The first term in the right side of Eq. (8) is always negative if η is positive; the second term is stable according to [2]. So the adaptation of the OSF does not affect on the system stability.

3. Plant Selection and Simulation

Conventional EHSS consists of the servo valve and the hydraulic cylinder. The configuration is illustrated in Fig. 10.

The approximate transfer function of the servo valve and the hydraulic cylinder is Eq. (9) and Eq. (10), respectively. The Eq. (9) can be found by frequency-response method, and The Eq. (10) is derived by some physical and mathematical assumptions and the linearization of nonlinear components.

$$TF_{SV}(s) = \frac{Z(s)}{I(s)} = \frac{K_A \cdot w_n^2}{s^2 + 2\zeta w_n s + w_n^2} \tag{9}$$

$$TF_{CYL}(s) = \frac{X(s)}{Z(s)} = \frac{K_1}{A_P s + \frac{\left(C_t + \frac{V_t}{4\beta}s + K_2\right)(ms^2 + cs + k)}{A_P}} \tag{10}$$

,where the transfer function $I(s)$ means an input current of the servo valve, $Z(s)$ means a spool displacement of the servo valve, and $X(s)$ means a displacement of the cylinder rod. Each parameters in the hydraulic cylinder transfer function, TF_{CYL}, are physical parameters for hydraulic components that consist of the hydraulic cylinder such as the area of cylinder rod, the leakage coefficient, and the load.

In this paper, the EHSS presented in [3] is regarded as a pilot plant of the UCT electro-hydraulic steering system. The transfer function of the EHSS, which is expressed in the fifth order rational function in s-domain, can be reduced into the third order transfer function. Physical parameters are shown in [3], in detail.

With the above parameters and the order reductions, the nominal transfer function of the system is represented into Eq. (11).

$$\begin{aligned} G_0(s) &= \frac{m_0}{p_0 s^3 + q_o s^2 + r_0 s} \\ &= \frac{346100}{s^3 + 502.1s^2 + 16350s} \end{aligned} \tag{11}$$

To consider the system uncertainties, the variation are permitted in the range between -30 and +30 percentages for alll nominal parameters .

The simulation is performed for both the case of Fig. 3, Fig. 4, and Fig. 5 with the OSF adaptation. The reference model and the command input are as follows

$$G_m(s) = \frac{1}{0.1s + 1} \tag{12}$$

$$u_c = 100 \sin t \tag{13}$$

The simulation results are shown in Fig. 11, Fig. 12, and Fig. 13. In these cases, the expectation about the simulation that based on the results of the Fig. 6, Fig. 7, and Fig. 8—like the above simple simulation, we can expect that Fig. 11 will show mild control input somewhat with residual error, Fig. 12 will show more accurate tracking performance with the chattering of the control input, and Fig. 13 will show the compromised result—can not be directly applied because the plant is the time-varying system.

Fig. 11 has the worst result among three simulations; it has a critical residual tracking error and chattering of the control input in the large range, compared with both Fig. 12 and Fig. 13. Fig. 12 shows better performance than that of Fig. 13 when both the tracking error and the control input chattering are considered. But if the variation ranges of the system parameters are not so wide, we can expect that configuration in Fig.

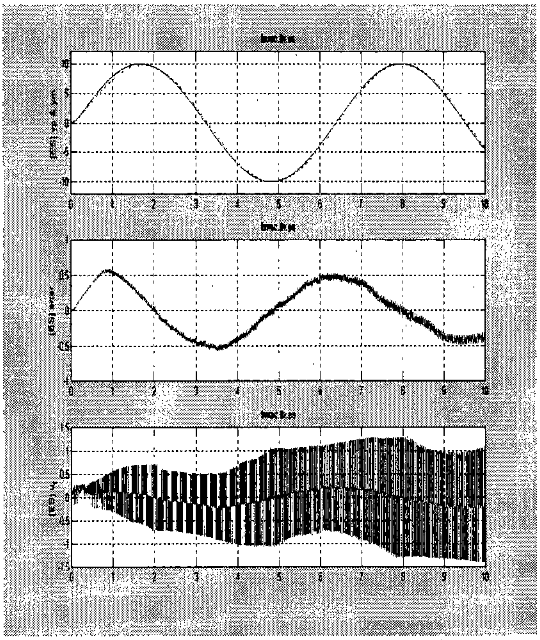

Fig. 11 Simulation with the configuration of the Fig. 3.

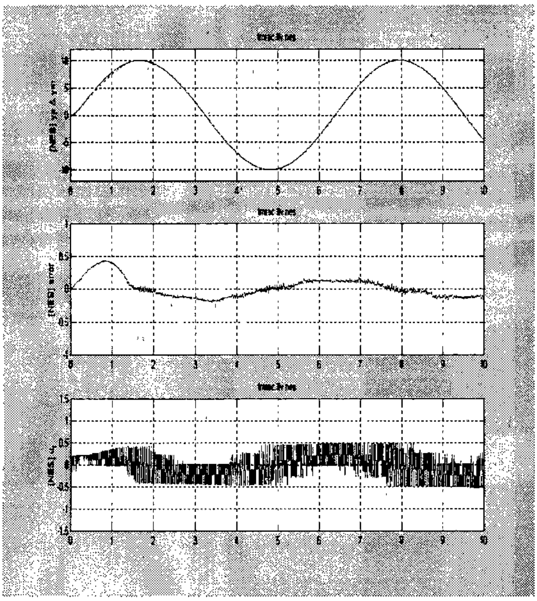

Fig. 12 Simulation with the configuration of the Fig. 4.

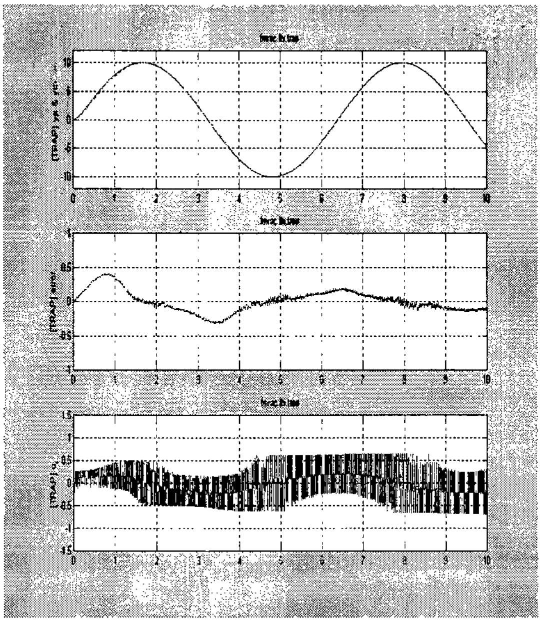

Fig. 13 Simulation with the configuration of the Fig. 5.

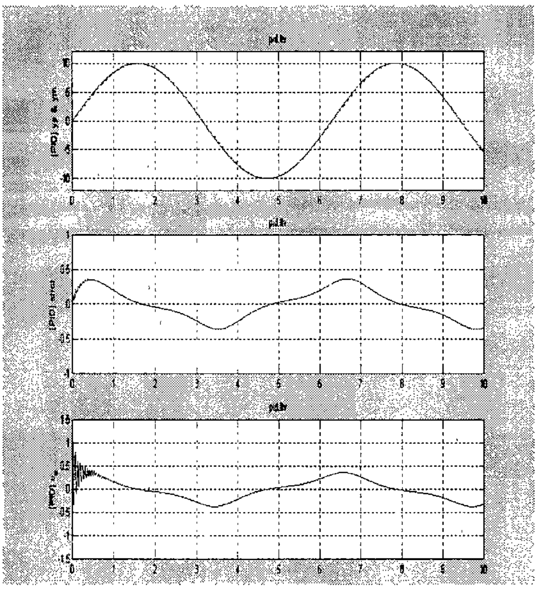

Fig. 14 Simulation with the conventional PID control

5 would have be the best performance based on the result of the simple simulation.

In addition, to compare with the result of the conventional control method, we simulated the same plant with PID controller. The given controller gains are set as follows: K_P: 1.0, K_I: 0, and K_D: 0.1. All values of the gains are acquired by 'trial-and-error' method and the simulation result is shown in Fig. 14. The fact that just PID controlling shows a satisfactory result is not surprising, becuase the parametric variation of the plant is not 'wild'(i.e., in all simulations, the sine value according to the time is taken as the variation) and also the plant itself is 'mild', that means just applying the feedback and the proportional control makes the system to track the reference command input in a sense. If the system variation is wild and the user cannot formulate the parametric uncertainties, the proposed algorithms just can be used as one of the solutions.

4. Conclusion and Further Research

In this paper, we designed the adaptive FLC for the EHSS which involves parametric uncertainties, and enhanced the performance by adaptive scheme for OSF and by the modification of the membership function shape. In the time-invariant system, the configuration in Fig. 5 and the OSF adaptation showed the remarkable performance. On the other hand, in the case of the time-varying system, the configuration of Fig. 4 and the OSF adaptation also showed the improved performance. Therefore, if system uncertainties are small and the variation of the parameters are not wide, Fig. 5 can be a better choice.

Although the proposed algorithms show satisfactory results, it is still needed to attenuate the chattering of the control input as much as possible. As the converge speed of the OSF K is alos heavily dependent on the initial value of K, so is needed to find a proper initial value to get a better and quick response.

Followings are remained for the further research:

1. Reducing the chattering by filtering or smoothing.
2. Seeking out a proper initial value of the OSF K by an optimal searching algorithm such as genetic algorithms or evolutionary computation.
3. Developing the adaptation scheme for the ISF.

요 약

퍼지 논리 제어기는 3부분으로 구성되어있다. 즉 퍼지 규칙 기반, 멤버쉽 함수와 스케일링 요소로 구성되어있다. 잘 정의된(Well-defined) 퍼지 규칙 기반은 플랜트에 대한 적절한 물리적인 직관력을 포함해야 하므로 능숙한 전문가의 많은 경험을 요한다. 멤버쉽 함수가 고려되어질 때는 멤버쉽 함수의 몇 파라미터들(함수의 모양, 지지도, 할당도)이 잘 선택되어져야 한다. 스케일링 요소들의 규칙은 퍼지 논리 제어기의 입력과 출력 신호들에 대한 스케일링(확대 또는 감소)인데, 멤버쉽 함수 지지도를 적합하게 하거나 플랜트를 의도적으로 작동하게 한다. 퍼지 논리 제어기의 더 좋은 성능을 얻기 위해서는 퍼지 논리 제어기의 파라미터들을 조정하는 것이 반드시 필요하다.

일반적으로, 스케일링 요소들의 적응은 퍼지 규칙 기반 또는 멤버쉽 함수 파라미터들의 방법과 비교했을 때 가장 효과적인 조정 기법이다. 본 연구에서는 스케일링 요소를 이용한 적응기법을 제안한다. 적응이 온라인으로 수행되어질 때, 적응

퍼지 논리 제어기의 안정도는 보장되어져야한다. 안정한 퍼지 논리 제어시스템은 리아프노프 안정도의 관점에서 해석되어지고 설계되어질 수 있다. 오차신호들에 대한 스케일링 요소들을 적응시키기 위해서 기존의 모델기준적응제어의 개념이 약간 변형된 형태로 소개되어질 것이다. 제어시스템의 추종 정확도는 변형된 멤버쉽 함수의 형태와 지지도에 의해 향상되어질 것이다. 또한 동력학에 많은 심각한 불확실성과 모델링 오차를 가진 무인 콘테이너 수송차량에 적용하여 유압 조향 제어를 가진 파일럿 플랜트에 시뮬레이션을 수행하고 그에 대한 결과를 제시한다.

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