Fuzzy Logic-Based Fast Gain Scheduling Control Using Fuzzy Preprocessor

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Abstracts This paper proposes the fuzzy logic-based fast gain scheduling(FFGS) controller for regulation problem in nonlinear systems. It utilizes the fuzzy scheduling variable which reflects the derivative information on the original scheduling variable in order to achieve better performance than the existents. Moreover, we apply the proposed control scheme to control active suspension systems with nonlinear components.

Keywords Gain Scheduling, FFGS, Fuzzy Preprocessor, Active Suspension System

1. Introduction

Recently there has been considerable progress in the theory of gain scheduling[1]-[5]. The control law for the systems with slowly varying parameters has been developed[1]-[5]. [6] proposed a gain scheduling control law in nonlinear systems with bounded uncertain time varying inputs. Moreover, in order to obtain better performance for fast time varying inputs the state feedback control laws with the derivative information on the scheduling variables are proposed[7]. Use of derivatives was proven to be beneficial, though often it was difficult to precisely characterize the advantages. However, the control methodology contained two disadvantages when applied to practical plants. One is that the set of nonlinear systems to which the proposed fast gain scheduling controllers can be applied is confined to only those that satisfy required assumptions. In other words, the derivative information is not useful for all plants. The other serious problem is that the noise and fuzziness in observing both the scheduling variable and its derivative cause undesirable output response or destabilize the overall system. Therefore, in order to overcome such limitations we compute the fuzzy scheduling variable which reflects the derivative information on the original scheduling variable in itself. Then, we schedule appropriate designed control gains according to the fuzzy scheduling variable. We check the proposed control scheme in the control of vehicle active suspension systems containing nonlinear components, where the control methodology of [7] is not available to improve system performance.

2. Fuzzy Logic-Based Fast Gain Scheduling(FFGS)

We consider a plant given by

$$\begin{aligned} \dot{x}(t) &= f(x(t), w(t), u(t)) \\ y(t) &= h(x(t), w(t), u(t)), \quad x(0) = x_0, \quad t \geq 0 \end{aligned} \qquad (1)$$

where x is the $(n \times 1)$ state vector, u is the plant input, w is the exogenous signal, and y is the plant output. The functions f and h are assumed to be continuously differentiable. The control law which achieves the control objective to minimize ϵ while rejecting w such that $\lim_{t\to\infty} \|r_d - y(t)\| \leq \epsilon$ is given by $u(t) = k(x(t), w(t))$ where r_d is the reference input. The proposed FFGS controller is composed of the state feedback controller $k(x, w)$ and the fuzzy preprocessor as shown in Fig. 1. Here, we assume that w is applied to the fuzzy preprocessor with disturbance $d(t)$. Generally, $k(x, w)$ is constructed with the following assumption.

Assumption 1 There exist an open neighborhood Γ *of the origin in* R *and smooth functions* $\mathbf{x}(w)$ *and* $\mathbf{u}(w)$ *for each constant value* $w \in \Gamma$ *such that*

$$\begin{aligned} 0 &= f(\mathbf{x}(w), w, \mathbf{u}(w)) \\ \mathbf{r_d} &= h(\mathbf{x}(w), w, \mathbf{u}(w)) \\ \mathbf{u}(w) &= k(\mathbf{x}(w), w) \end{aligned} \qquad (2)$$

and $\partial f_c(\mathbf{x}(w), w)/\partial x$ *is Hurwitz for each* $w \in \Gamma$ *where* $f_c(x, w) = f(x, w, k(x, w))$.

Thus, the control law is obtained by

$$u(t) = k(x, w) = \mathbf{u}(w) + K_1(w)(x - \mathbf{x}(w)) \qquad (3)$$

where $K_1(w)$ is determined so that the eigenvalues of $\partial f_c(\mathbf{x}(w), w)/\partial x$ should have specified values with negative real parts for each w[2].

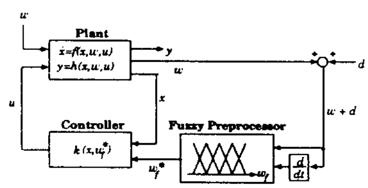

Fig. 1: Block diagram of the proposed FFGS control system

3. Fuzzy Preprocessor

The fuzzy preprocessor computes the fuzzy scheduling variable w_f^* by using both w and $\dot{w}$ as inputs of the rule table. Letting

$$w_{min} = \inf_t w(t) \quad \text{and} \quad w_{max} = \sup_t w(t) \qquad (4)$$

we construct membership functions as shown in Fig. 2 where R(resolution) is the number of membership functions in both w and $\dot{w}$ respectively, and the number of membership functions in w_f is $2R$. The division distance D defined by

$$D = \frac{w_{max} - w_{min}}{R} \qquad (5)$$

is the interval of the centers of membership functions. Here, we notice the centers of a family of the membership functions $\{i_0, i_1, i_2, \cdots, i_{(R-1)}\}$ are equal to that of $\{k_0, k_2, k_4, \cdots, k_{(2R-2)}\}$. We construct the rule table for the fuzzy preprocessor as shown in Table 1. The rule table is constructed by the following simple concept. If $\dot{w}$ is ZE, i.e., $j_{(\frac{R-1}{2})}$ then the selected output membership functions are $\{k_0, k_2, k_4, \cdots, k_{(2R-2)}\}$ for the inputs $\{i_0, i_1, i_2, \cdots, i_{(R-1)}\}$. This is similar to the general gain scheduling idea in the point that the selected output membership functions contain no derivative information. However, if $\dot{w}$ is positive then the selected output membership functions have equal or larger centers than those of $\{k_0, k_2, k_4, \cdots, k_{(2R-2)}\}$, and if negative then equal or smaller centers respectively. Thus, in this manner the combined membership function by reasoning contains the derivative information on both w and $\dot{w}$. In defuzzification, COG method which is widely used is adopted such that

$$w_f^* = \frac{\int_{w_{min}}^{w_{max}} w_f \cdot \mu(w_f) dw_f}{\int_{w_{min}}^{w_{max}} \mu(w_f) dw_f} \qquad (6)$$

where w_f^* is the defuzzified value and $\mu(w_f)$ is the value of the output membership function corresponding to w_f.

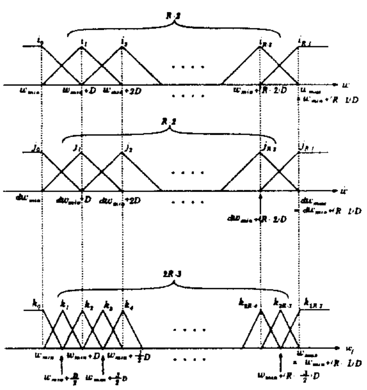

Fig. 2: Membership functions for w, $\dot{w}$, and w_f in fuzzy preprocessor

4. Example : Active Suspension System

In this Section, we apply FFGS to the control of active suspension system. Despite the complexity of the engineering task, a class of nonlinear springs and dampers was used in suspension system design. Generally, the linearization methodology was used when there exist nonlinearities in suspension systems. However, it confined the system performance, because the linearized model holds good at local operating points. In this paper, we construct a nonlinear controller in active suspension system with a nonlinear element, i.e., gas-spring. Moreover, the main objective is to maintain not the ride-comfort but the roadholding, i.e., stability property by regulating the body mass in the simplified quarter car model. The gas-spring has the following properties. (i) It shows nonlinear property. (ii) The spring force can be almost infinitely adjustable. (iii) It operates faster and more smoothly than the mechanical one. (iv) It has lower weight and smaller size than the mechanical one.

Table 1: Rule table for FFGS

	$\dot{w} \backslash w$	i_0	i_1	i_2	$\cdots$	$i_{(R-2)}$	$i_{(R-1)}$
NB	j_0	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\vdots$	$j_{(\frac{R-5}{2})}$	k_0	k_0	k_2	$\cdots$	$k_{(2R-6)}$	$k_{(2R-4)}$
$\vdots$	$j_{(\frac{R-3}{2})}$	k_0	k_1	k_3	$\cdots$	$k_{(2R-5)}$	$k_{(2R-3)}$
ZE	$j_{(\frac{R-1}{2})}$	k_0	k_2	k_4	$\cdots$	$k_{(2R-4)}$	$k_{(2R-2)}$
$\vdots$	$j_{(\frac{R+1}{2})}$	k_1	k_3	k_5	$\cdots$	$k_{(2R-3)}$	$k_{(2R-2)}$
$\vdots$	$j_{(\frac{R+3}{2})}$	k_2	k_4	k_6	$\cdots$	$k_{(2R-2)}$	$k_{(2R-2)}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
PB	$j_{(R-1)}$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

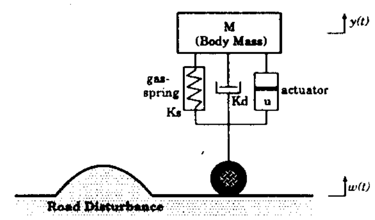

Fig. 3: Quarter car model of a vehicle suspension system

The model of nonlinear gas-spring is given by $F_s(s) = K_s s^3$ where s is the spring stroke and K_s is the spring constant. Letting $x_1 = y$ and $x_2 = \dot{y}$, the model of the active suspension system in Fig. 3 is given by

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -\tfrac{K_s}{M}(x_1 - w)^3 - \tfrac{K_d}{M}x_2 + \tfrac{K_d}{M}\dot{w} + \tfrac{1}{M}u \qquad (7) \\ y &= x_1 \end{aligned}$$

where M is the body mass and K_d is the suspension damper constant. We notice that the control methodology of [7] is not available, i.e., the derivative gain that reflect the derivative information on the scheduling variable is obtained by zero in this plant. Thus, we apply FFGS to the plant and obtain following state feedback control law

$$u = k(x, w) \quad = \quad -K_s w^3 + 3(-120\lambda^2 + K_s w^2)x_1$$

Table 2: Rule table for ASS ($R = 7$)

	$\hat{w} \backslash w$	i_0	i_1	i_2	i_3	i_4	i_5	i_6
NB	j_0	k_0	k_0	k_1	k_3	k_5	k_7	k_9
NM	j_1	k_0	k_0	k_2	k_4	k_6	k_8	k_{10}
NS	j_2	k_0	k_1	k_3	k_5	k_7	k_9	k_{11}
ZE	j_3	k_0	k_2	k_4	k_6	k_8	k_{10}	k_{12}
PS	j_4	k_1	k_3	k_5	k_7	k_9	k_{11}	k_{12}
PM	j_5	k_2	k_4	k_6	k_8	k_{10}	k_{12}	k_{12}
PB	j_6	k_3	k_5	k_7	k_9	k_{11}	k_{12}	k_{12}

Table 3: Constants used in simulation(KIA-Motor Concord)

Component	Constant	Value
Body mass	M	$360\ kg$
Suspension gas-spring constant	K_s	$2 \times 10^6\ N/m$
Suspension damper constant	K_d	$1 \times 10^3\ N \cdot sec/m$

$$+40(25 - 18\lambda)x_2 \qquad (8)$$

where λ is the eigenvalue of the linearized closed loop system. The rule table for $R = 7$ is given by Table 2.

The simulation is executed with data in Table 3. The road disturbance is assume to be periodic sinusoidal signal and $d(t)$ is Gaussian noise. Fig. 4 shows the output response of passive suspension system when no control action is applied. It shows undesirable body oscillation with large output error. In Fig. 5, the general gain scheduling controller guarantees the output error below $0.4cm$. Fig. 6 shows the output of the fuzzy preprocessor w_f^* using the observed w with disturbance d. Finally, Fig. 7 shows that the output result from the proposed FFGS controller reduces the output error to below $0.25cm$. Fig. 8 shows the output error for various R for $d(t) = 0$ and it can be derived that the output error is exponentially decreased according to R.

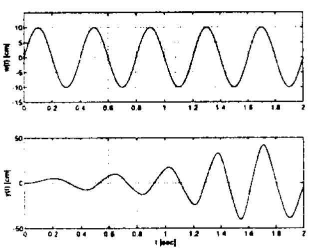

Fig. 4: Results of passive suspension system

5. Conclusions

This paper proposes the fuzzy logic based fast gain scheduling controller for regulation problem. The proposed controller utilizes the fuzzy scheduling variable which reflects the derivative information on the original scheduling variable from the fuzzy preprocessor. The proposed control scheme can be applied to various nonlinear systems whereas the previously developed fast gain scheduling controllers need some requirement for available systems. By illustrating example, we conclude that the proposed control scheme provides smaller output error for the fast scheduling variable and shows robust property for the Gaussian noise added gain scheduling variable.

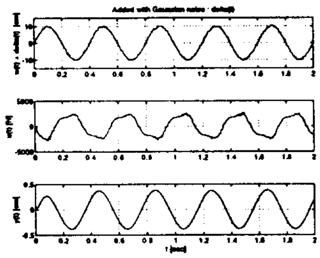

Fig. 5: Results of the general gain scheduling control

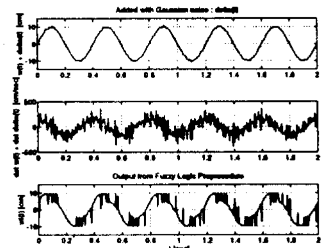

Fig. 6: Input and output signal of fuzzy preprocessor

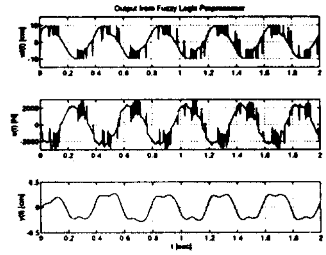

Fig. 7: Results of FFGS control

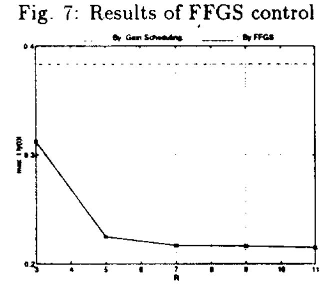

Fig. 8: Plot of output error versus various R

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