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외란 예측기가 포함된 슬라이딩 모드 퍼지 제어기의 응용

Application of Sliding Mode Fuzzy Control with Disturbance Prediction

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ABSTRACT

A sliding mode fuzzy control (SMFC) algorithm is applied to design a controller for a benchmark problem on a wind-excited building. The structure is a 76-story concrete office tower with a height of 306 meters, hence the wind resistance characteristics are very important for the serviceability as well as the safety. A control system with an active tuned mass damper is assumed to be installed on the top floor. Since the structural acceleration is measured only at a limited number of locations without measurement of the wind force, the structure of the conventional continuous sliding mode control may have the feed-back loop only. So, an adaptive least mean squares (LMS) filter is employed in the SMFC algorithm to generate a fictitious feed-forward loop. The adaptive LMS filter is designed based on the information of the stochastic characteristics of the wind velocity along the structure. A numerical study is carried out, and the performance of the present SMFC with the adaptive LMS filter is investigated in comparison with those of other control algorithms such as linear quadratic Gaussian control, frequency domain optimal control, quadratic stability control, continuous sliding mode control, and $H_{\infty/\mu}$ control, which were reported by other researchers. The effectiveness of the adaptive LMS filter is also examined. The results indicate that the present algorithm is very efficient.

1. Introduction

Vibration control of large structures has become an important subject in civil engineering. Many studies were carried out to apply various control methods on civil infrastructures such as high-rise buildings, long span bridges, and large offshore structures. Particularly, active control is considered as one of the practical alternatives for design of tall buildings subjected to wind excitation (Koh *et al.* 1999). Recently, Spencer, et al initiated a series of benchmark studies on structural control where various control strategies were tested and their performances were compared (Spencer *et al.* 1998). The 2nd Benchmark problem for response control of wind-excited tall buildings was formulated by Yang *et al.* (1998). In this paper, a sliding mode fuzzy control (SMFC) algorithm is applied to design a controller for the benchmark problem. The SMFC is one of the nonlinear and intelligent control methods. It is generally robust with the uncertainty of the

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system parameter and unknown disturbance. However, to improve the control performance, an adaptive least mean squares (LMS) filter is introduced in this study, where a fictitious disturbance vector is generated for the un-measurable wind forces.

2. Design of the Sliding Mode Fuzzy Controller

2.1. Modeling of Structure

The dynamic behavior of a wind-excited building with a control device can be modeled as

$$\mathbf{M}_s\ddot{\mathbf{y}}_s(t)+\mathbf{C}_s\dot{\mathbf{y}}_s(t)+\mathbf{K}_s\mathbf{y}_s(t)=\mathbf{f}_s(t)+\mathbf{B}_s\mathbf{u}_s(t) \tag{1}$$

where $\mathbf{y}_s(t)$, $\mathbf{f}_s(t)$, and $\mathbf{u}_s(t)$ = displacement, wind force, and control force vectors; $\mathbf{M}_s$, $\mathbf{C}_s$, and $\mathbf{K}_s$ = mass, damping, and stiffness matrices; and $\mathbf{B}_s$ = boolean matrix representing the effects of the control force. By converting into a state space form and selecting appropriate control and measurement variables, the following state and measurement equations can be obtained

$$\begin{aligned}\dot{\mathbf{x}}(t)&=\mathbf{A}\mathbf{x}(t)+\mathbf{B}_u\mathbf{u}_s(t)+\mathbf{B}_f\mathbf{f}_s(t)+\mathbf{B}_w\mathbf{w}(t)\\ \mathbf{y}_c(t)&=\mathbf{C}_c\mathbf{x}(t)+\mathbf{D}_{cu}\mathbf{u}_s(t)+\mathbf{D}_{cf}\mathbf{f}_s(t)+\mathbf{D}_{cw}\mathbf{w}(t)\\ \mathbf{y}_m(t)&=\mathbf{C}_m\mathbf{x}(t)+\mathbf{D}_{mu}\mathbf{u}_s(t)+\mathbf{D}_{mf}\mathbf{f}_s(t)+\mathbf{D}_{mw}\mathbf{w}(t)+\mathbf{v}(t)\end{aligned} \tag{2}$$

where $\mathbf{x}(t)$, $\mathbf{y}_c(t)$, $\mathbf{y}_m(t)$, $\mathbf{w}(t)$, and $\mathbf{v}(t)$ = state, control signal, measured signal, un-modeled error, and measurement noise vectors; and $\mathbf{A}$, $\mathbf{B}_u$, $\mathbf{B}_f$, $\mathbf{B}_w$, $\mathbf{C}_c$, $\mathbf{D}_{cu}$, $\mathbf{D}_{cf}$, $\mathbf{D}_{cw}$, $\mathbf{C}_m$, $\mathbf{D}_{mu}$, $\mathbf{D}_{mf}$, and $\mathbf{D}_{mw}$ = system matrices.

Before designing the controller, two stages of pre-design were carried out. The first stage is for model reduction. For the computational efficiency, the control law is designed based on a reduced model obtained using the balanced truncation method. The state space system is transformed into a balanced system, of which the controllability and observability Gramians are diagonal and identical. Then taking the largest Hankel singular values, a reduced-order system can be obtained. The second stage is for design of observer. The Kalman-Bucy filter is used to estimate the state from the measured signal as

$$\dot{\hat{\mathbf{x}}}_r=\mathbf{A}_r\hat{\mathbf{x}}_r(t)+\mathbf{B}_{ru}\mathbf{u}_s(t)+\mathbf{L}_{obs}(\mathbf{y}_m(t)-\mathbf{C}_{mr}\hat{\mathbf{x}}(t)-\mathbf{D}_{mru}\mathbf{u}_s(t)) \tag{3}$$

where $\hat{\mathbf{x}}_r$ = estimated state vector; and $\mathbf{L}_{obs}=\left(\mathbf{P}_{obs}\mathbf{C}_{mr}^T+\mathbf{B}_{rw}\mathbf{S}_{obs}\right)\mathbf{R}_{obs}^{-1}$ = observer gain matrix. The observer gain matrix can be obtained by solving the following algebraic Riccati equation for P_{obs}

$$\overline{\mathbf{A}}_r\mathbf{P}_{obs}+\mathbf{P}_{obs}\overline{\mathbf{A}}_r^T-\mathbf{P}_{obs}\mathbf{C}_{mr}^T\mathbf{R}_{obs}^{-1}\mathbf{C}_{mr}\mathbf{P}_{obs}+\mathbf{B}_{rw}\mathbf{Q}_{obs}\mathbf{B}_{rw}^T-\mathbf{B}_{rw}\mathbf{S}_{obs}\mathbf{R}_{obs}^{-1}\mathbf{S}_{obs}^T\mathbf{B}_{rw}^T=\mathbf{0} \tag{4}$$

where $\overline{\mathbf{A}}_r=\mathbf{A}_r-\mathbf{C}_{mr}^T\mathbf{R}_{obs}^{-1}\mathbf{S}_{obs}^T\mathbf{B}_{rw}^T$,

and $\begin{bmatrix}\mathbf{Q}_{obs} & \mathbf{S}_{obs}\\ \mathbf{S}_{obs}^T & \mathbf{R}_{obs}\end{bmatrix}\delta(\tau)=E\left[\begin{Bmatrix}\mathbf{w}_r(t)\\ \mathbf{v}_r(t)\end{Bmatrix}\begin{Bmatrix}\mathbf{w}_r(t)\\ \mathbf{v}_r(t)\end{Bmatrix}^T\right]$ = covariance matrix.

2.2. Structure of Sliding Mode Fuzzy Control

As in a sliding mode control (SMC), the basic strategy of the SMFC is forcing the state of the system to stay on the sliding surface, where the response of the system can be reduced rapidly. The structure of the SMC is constructed by the Lyapunov's direct method. Then the controller is composed of a conventional feed-back part and a feed-forward part as

$$\mathbf{u}_s(t) = -(\mathbf{PB}_{ru})^{-1}(\mathbf{PA}_r + [\ddots \eta \ddots]\mathbf{P})\hat{\mathbf{x}}_r(t) - (\mathbf{PB}_{ru})^{-1}\mathbf{PB}_{rf}\hat{\mathbf{f}}_s(t) \tag{5}$$

where $\hat{\mathbf{f}}_s$ = a fictitious disturbance vector generated using an adaptive LMS filter which will be described later; $\mathbf{P} = [P_1 \ \cdots \ P_{n_u}]^T$; and P_i = direction vector of the sliding surface for the i-th control force. Converting the above continuous sliding mode control (CSMC) into a fuzzy form, a SMFC can be obtained as (Kim *et al.* 1999)

$$\mathbf{u}_s(t) = \mathbf{K}_{Fuzzy}(t, \hat{\mathbf{x}}_r(t), \hat{\mathbf{f}}_s(t)) \tag{6}$$

where K_{Fuzz} is the fuzzy controller. Figure 1 shows the overall structure of the SMFC with an adaptive LMS filter.

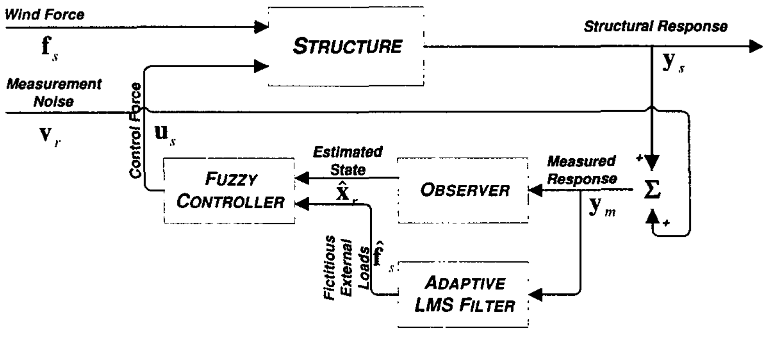

Figure 1. Schematic Diagram of SMFC with LMS Filter Design of Fuzzy Control

The present fuzzy controller consists of 5 modules : (1) Normalization, (2) Fuzzification, (3) Inference Engine, (4) De-Fuzzification, and (5) De-Normalization. In the first module named *Normalization*, the observed signal are normalized as

$$\mathbf{s}_n(t) = \alpha_n \mathbf{K}_n \mathbf{x}_{rE}(t), \quad \mathbf{s}_t(t) = \alpha_t \mathbf{K}_t \mathbf{x}_{rE}(t), \quad \mathbf{s}_f(t) = \alpha_f \mathbf{K}_f \hat{\mathbf{f}}(t) \tag{7}$$

where $\mathbf{K}_n = (\mathbf{PB}_{ru})^{-1}(\mathbf{PA}_r + [\ddots \eta \ddots]\mathbf{P})$; $\mathbf{K}_t = \|\mathbf{B}_{ru}\|^{-1}\|\mathbf{K}_n\|\mathbf{B}_{ru}^T - (\|\mathbf{K}_n\|\|\mathbf{B}_{ru}\|)^{-1}\mathbf{K}_n\mathbf{B}_{ru}\mathbf{K}_n$; $\mathbf{K}_f = -(\mathbf{PB}_{ru})^{-1}\mathbf{PB}_f$; $\mathbf{s}_n(t)$ and $\mathbf{s}_t(t)$ = normal and tangential components of the state vectors with respect to the transformed sliding surface; $\mathbf{s}_f(t)$ = auxiliary state representing the feed-forward control force; and α_n, α_t and α_f are scale factors.

Fuzzification module converts the scaled crisp values to fuzzy numbers with singleton membership functions. *Fuzzy Rule Base* is constructed based on the SMC as shown in Table 1. In this study, the implication of the fuzzy relation from *If-then* rule is conducted by Mamdani's method, and triangular membership functions are used for various fuzzy numbers as in Figure 2. Aggregation for several fuzzy relations is conducted by disjunction. In the module of *Inference Engine*, approximate reasoning is conducted using generalized modus ponens. In the module of *De-Fuzzification*, the fuzzy control force is transformed into a form of crisp number by the center of gravity method.

Table 1. Rule Table for $\tilde{\mathbf{u}}_{FB}$

$\tilde{S}_t \backslash \tilde{S}_n$	NB	NM	NS	Z	PS	PM	PB
PB	Z		NS		NM		NB
PM		Z		NS		NM	
PS	PS		Z		NS		NM
Z		PS		Z		NS	
NS	PM		PS		Z		NS
NM		PM		PS		Z	
NB	PB		PM		PS		Z

Note : The first character in the fuzzy number denotes negative or positive, and the second character denotes big, medium, or small. Z means zero.

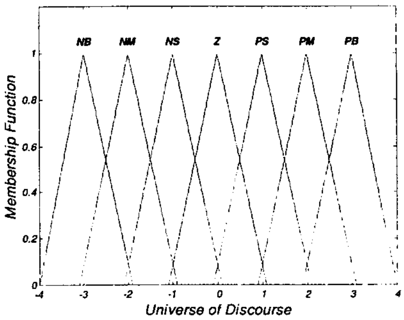

Figure 2. Triangular Membership Functio

3. Design of Adaptive LMS Filter

The stochastic wind force $\mathbf{f}_s(s)$ can be modeled by its spectral density function as

$$\mathbf{f}_s(s) = \mathbf{H}_{fw}(s)\mathbf{w}_f(s) \tag{8}$$

where $\mathbf{S}_{\mathbf{f}_s}(\omega) = \overline{\mathbf{H}}_{fw}(j\omega)\mathbf{H}_{fw}(j\omega)^T$; $\mathbf{S}_{\mathbf{f}_s}(\omega)$= spectral density matrix of wind force; $\mathbf{w}_f$= white noise source; and $\mathbf{H}_{fw}(s)$= transfer function. The transfer function model can be converted into a following discrete auto-regressive with auxiliary input (ARX) model as

$$\mathbf{f}_s[k+1] = \mathbf{A}_{fD}\mathbf{f}_s[k] + \mathbf{B}_{fwD}\mathbf{w}_f[k] \tag{9}$$

where $\mathbf{A}_{fD}$ and $\mathbf{B}_{fwD}$= ARX coefficient matrices ($\mathbf{H}_{fw}(z) \approx (z\mathbf{I} - \mathbf{A}_{fD})^{-1}\mathbf{B}_{fwD}$).
Measurement error equation can be derived as

$$e_f[k] = \mathbf{y}_{mr}[k] - \mathbf{D}_{mrf}\mathbf{A}_{fD}\hat{\mathbf{f}}_s[k-1 \mid k-1] + \mathbf{C}_{mr}\hat{\mathbf{x}}_r[k] + \mathbf{D}_{mru}\mathbf{u}_s[k] \tag{10}$$

By minimizing the measurement error equation, following one step ahead predictor form can be obtained as

$$\hat{\mathbf{f}}_s[k \mid k] = \mathbf{A}_{fD}\hat{\mathbf{f}}_s[k-1 \mid k-1] + \mathbf{M}_{LMS}[k]e_f[k] \tag{11}$$

where $\mathbf{M}_{LMS}[k] = \mathbf{P}_{LMS}[k \mid k-1]\mathbf{D}_{mrf}^T(\mathbf{R}_{LMS} + \mathbf{D}_{mrf}\mathbf{P}_{LMS}[k \mid k-1]\mathbf{D}_{mrf}^T)^{-1}$

$\mathbf{P}_{LMS}[k \mid k] = (\mathbf{I} - \mathbf{M}_{LMS}[k]\mathbf{D}_{mrf})\mathbf{P}_{LMS}[k \mid k-1]$

$$\mathbf{P}_{LMS}[k+1|k] = \mathbf{A}_{fD}\mathbf{P}_{LMS}[k|k]\mathbf{A}_{fD}^T + \mathbf{B}_{fwD}\mathbf{Q}_{LMS}\mathbf{B}_{fwD}^T$$

and $\mathbf{M}_{LMS}[k]$ = filter gain matrix; and $\mathbf{P}_{LMS}[k|k]$ and $\mathbf{P}_{LMS}[k+1|k]$ = prediction error covariance matrices.Design of Adaptive LMS Filter

4. Numerical Simulation Study for Benchmark Problem

A numerical simulation study is carried out on the 2nd benchmark structure to verify the proposed control algorithm. Detailed data related to this problem were given at the web site of the problem organizer (Agrawal, 2000). The structure is a 76-story concrete office tower with an active tuned mass damper (ATMD) installed on the top floor. It is modeled a system with 24 dof's. 12 indices are defined to compare the control performance by the problem organizer. J1 and J2 are for rms acceleration performance, J3 and J4 are for rms displacement performance, and J5 and J6 are performance related to rms displacement and velocity of the ATMD. J7 and J8 are for peak acceleration performance, J9 and J10 are for peak displacement performance, and J11 and J12 are performance related to peak displacement and velocity of the ATMD. Control performance of the present SMFC is compared with those by other methods in Table 2.
The results indicate that the overall performance of the proposed SMFC is as good as the other methods. However, the SMFC requires slightly larger displacement and velocity of the ATMD as the performance indices J5, J6, J11 and J12 indicate. The results also show that most of the performance indices improve as the adaptive LMS filter is introduced, which indicates that the wind force prediction using the LMS filter makes the control algorithm more effective. Figure 3 shows time histories of the wind force at 14.5m above ground, the responses of the top floor for uncontrolled and controlled cases and the control force.

5. Concluding Remarks

A sliding mode fuzzy control is presented for the vibration reduction of a wind-excited structure. An adaptive LMS filter is employed to consider the unmeasured wind forces at each instance. The results from the simulation study indicate the effectiveness of the present algorithm.

Table 2. Comparison of Control Performance Criteria

	LQG'	FWLQG' (Filter 1)	$H_{\infty/\mu}$'	Quadratic' Stability	SMC5'	SMFC w/o LMS Filter	SMFC w/ LMS Filter
J1	0.369	0.351	0.357	0.418	0.367	**0.383**	**0.373**
J2	0.606	0.614	0.608	0.584	0.608	**0.589**	**0.575**
J3	0.509	0.501	0.490	0.515	0.507	**0.520**	**0.536**
J4	0.491	0.499	0.509	0.484	0.493	**0.480**	**0.464**
J5	1.870	1.817	1.879	1.481	1.858	**2.492**	**2.250**
J6	1.891	1.840	2.046	1.580	1.889	**2.327**	**2.309**
J7	0.481		0.476	0.542	0.477	**0.500**	**0.483**
J8	0.460		0.438	0.423	0.464	**0.412**	**0.394**
J9	0.569		0.569	0.568	0.568	**0.559**	**0.569**
J10	0.423		0.423	0.423	0.424	**0.434**	**0.424**
J11	2.401		2.551	2.027	2.369	**2.562**	**2.401**
J12	2.618		2.898	2.278	2.617	**2.581**	**2.619**

Note : ' The results are from the references (Yang *et al.* 1998, Jin *et al.* 1998, Watanabe *et al.* 1998, Srivastava *et al.* 1998, and Wu *et al.* 1998)

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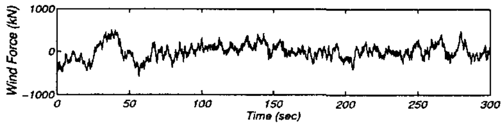
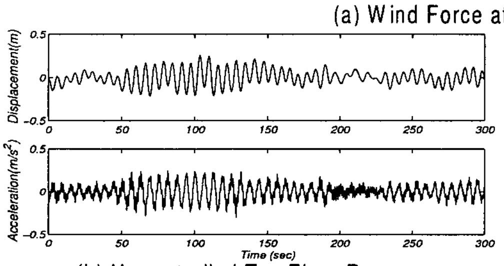
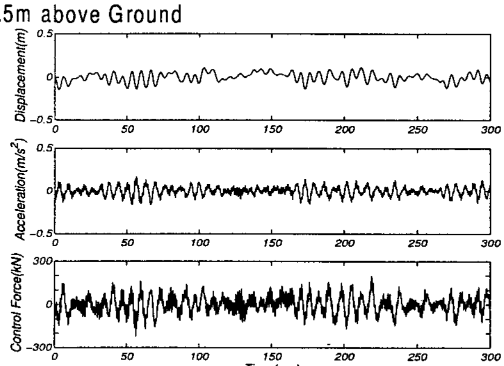


(a) Wind Force at 14.5m above Ground



(b) Uncontrolled Top Floor Responses



(c) Controlled Top Floor Responses

Figure 3. Time Histories of Wind Force and Responses for Uncontrolled and Controlled Structures