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# CONSTRUCTION OF AN ACTIVE CONTROL SYSTEM FOR SEISMICALLY EXCITED STRUCTURES USING FUZZY LOGIC TECHNIQUES

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## SUMMARY

The design and analysis of seismically excited structural control systems should be based on the best available knowledge and information instead of the simplest available model when handling uncertainties in the civil structural system. Therefore, seismic structural control system is developed using fuzzy logic due to its capacity to formalize approximate reasoning processes, i.e., a knowledge-based method. This paper focuses on the application of fuzzy logic in the construction of active controls of seismically excited structures. The inference rule base of fuzzy controller is designed based on the input/output data obtained from the performance of the control system with a state feedback controller. To test the performance of fuzzy logic based control of seismic structures, a simulation system was built using MATLAB/Simulink software. The simulation results show that the fuzzy control method is robust and efficient for reducing seismically excited structural vibrations in low frequency regions. In addition, the benefits and limitations of the fuzzy logic based control are discussed.

## INTRODUCTION

Active structural control has been received increasing attention in reducing seismic structural response during the last decade [3]. A lot of literature has been published about this topic since the concept was introduced in civil engineering for the design of earthquake resistant buildings by Yao in 1972 [9]. Most of them are the design of control algorithms based on conventional optimal control theories [1], such as, LQR control. The main drawback of these approaches is that they are difficult to be implemented in real

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time online due to the requirement of enormous computation and lead to the problem of time delay in control activities. Therefore, we have to seek a new approach to solve this problem.

There are a couple of reasons to use fuzzy logic control in reducing earthquake excited structural response [2] and [4]. It is well known that civil structures are complex and large structural system. They generally have distributed parameters and are of complex geometries making them difficult to model and analyze. They are subjected not only to static loading but also to a variety of complex dynamic loading, including winds, and earthquakes.
The complexity in these structures generally arises from uncertainties in structural models, parameters and geometries. Some uncertainties are not random in nature. An intensive review on representation of uncertainties in civil structures can be found in [2]. Normally, a precise mathematical model is difficult to be obtained for describing an entire large structural system. Conventional structural analysis models are built based on many simplifications and assumptions on structural system to reach the goal of precision. All these provide the motivation to use fuzzy logic technique in design of earthquake resistant structures.

Fuzzy set theory [5] as an extension and complementary for conventional mathematical approaches, provides a new way to deal with the imprecise and uncertainty information. Fuzzy logic technique is a model free approach; it can mimic the human being to handle the vague concepts and produces the control commands. It allows resolution of imprecise or uncertain information. Fuzzy logic control has found many applications in automatic control industry. The use of fuzzy control for reducing seismic structural response is still relatively new.

A construction approach for fuzzy control system is presented in reducing seismic structural response in this paper. To illustrate the effectiveness of the proposed fuzzy logic control system, numerical simulation was implemented for a three story building in MATLAB/Simulink [6] environments. It is shown that the controller provides robust performance when large parameter variations in structural system are presented.

## DESIGN OF FUZZY LOGIC BASED CONTROL SYSTEM

Fuzzy logic control is knowledge based control system. It can mimic human thinking using natural language to produce the control commands for a dynamic system. In fuzzy logic control system, the uncertainties in the ground motion data and structural dynamic response can be easily treaded by fuzzy sets using linguistic variables.
Figure 1 shows the architecture of a fuzzy logic controller for seismically exited building. It consists of three well known stages: (i) the fuzzification stage, (ii) the knowledge base stage, and (iii) the defuzzification stage.

Fuzzification and defuzzification interfaces are to transform data between crisp and fuzzy sets, because measurements of dynamic excitation and response and control actions are still designed for crisp data in the control system. Whereas, knowledge base unit containing a rule base (fuzzy IF-THEN rules) and a data base (membership functions used in the fuzzy system).

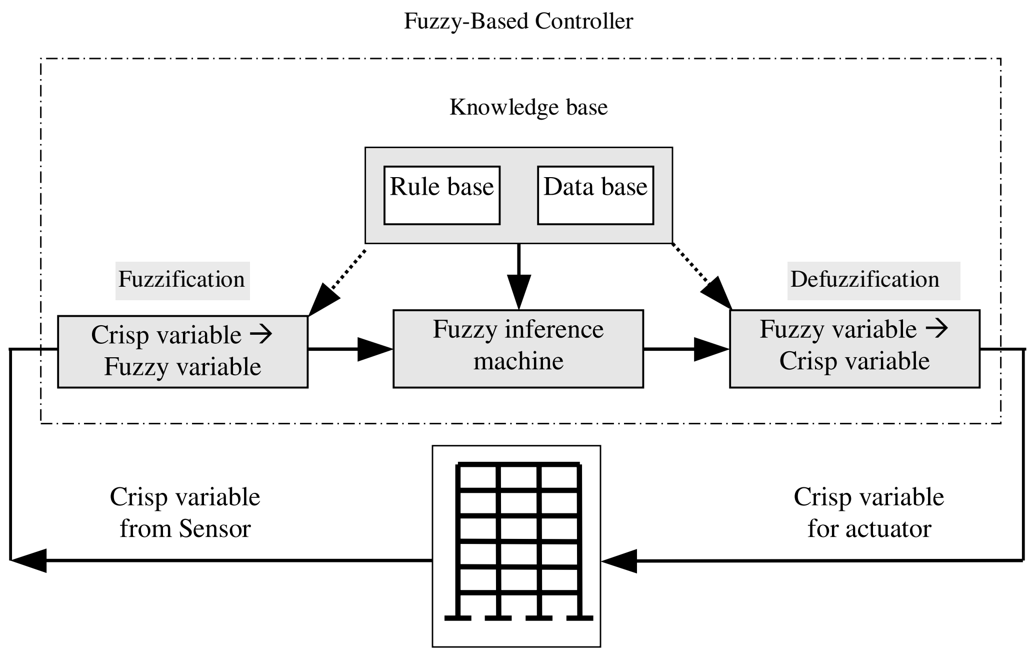


Figure 1. Architecture of fuzzy logic controller for seismically exited building

In our study, the dynamic response of building roof in term velocity $\dot{x}$ and the ground motion $\ddot{x}_o$ are used as input variables to the fuzzy controller.

**Fuzzification**

Fuzzification maps the crisp input variables into fuzzy variables with their associated degrees of membership. Then, each value of the input variable is transformed into fuzzy term sets with associated degrees of memberships. Once the degrees of memberships of crisp inputs are known, they are passed onto the inference (decision making logic) block.

Fuzzy sets represent the grade of crisp input items in antecedent parts of rules. Figure 2 depicts examples of such fuzzy sets (membership function). The following lingual variables are used:

NB = negative big, NM = negative medium, NS = negative small, ZR= zero,
PB = positive big, PM = positive medium, PS = positive small.

The fuzzy controller uses the triangular membership function, the *min* interaction operator and correlation product inference procedure.

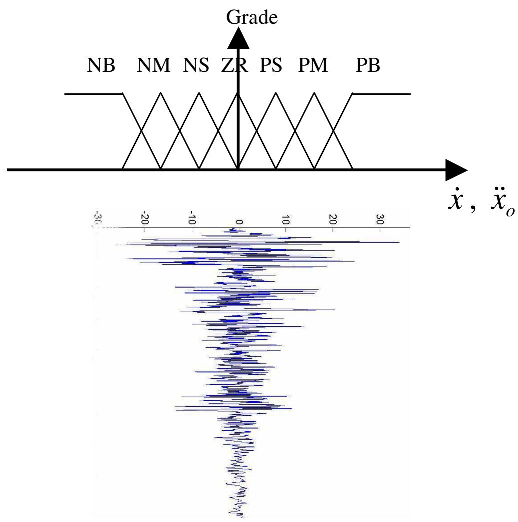


Figure 2. Example of the membership function for antecedent

## Inference rules

Fuzzy rule base is the heart of fuzzy control system, which is determined based on the human expertise. The fuzzy rule defines the relationship between input and output fuzzy (linguistic) variables. The rule consists of two parts: antecedent and consequence part. It is constructed by several IF-THEN statements. Each rule has the following form:

$$R_j : \text{ IF } x_i \quad is \quad A_i^j \text{ and } y_i \quad is \quad B_i^j \text{ then } u_i \quad is \quad C_i^j \tag{1}$$

where $R_j$ denotes the *j*-th rule of the fuzzy inference rule, $j = 1, 2, \ldots$ n;

$x_i$ and $y_i$ are the input of the fuzzy controller

$A_i^j$ and $B_i^j$ are the linguistic value associated with $x_i$ of rule *j* and $y_i$ of rule *j*,

$u_i$ is the output of the fuzzy controller and

$C_i^j$ is a fuzzy singleton function defined by designer.

The fuzzy inference rule is completely based on the selected input variables. In our study, we choose the relative velocity of structural vibration and ground acceleration in the antecedent part. The consequence part is the control force in fuzzy set. The inference rules are the important part in fuzzy logic control. General control rules do not exist for structural vibration control. It has to use the trial-error method to estimate based on the experts knowledge.

The maximum number of rules in the system is equal to the number of possible combinations of input sets.

For example, the multiple-input multiple-output IF–THEN rules of the fuzzy logic control system are constructed as shown in Table 1.

Table 1. Rule table for fuzzy command $\tilde{u}$

| | | Acceleration | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NB | NM | NS | ZR | PS | PM | PB |
| | NB | PB | PB | PB | PB | PB | PB | PB |
| | NM | | | | PM | | | |
| Velocity | NS | NB | NM | NS | PS | PS | PM | PB |
| | ZR | | | | ZR | | | |
| | PS | NB | NM | NS | NS | PS | PM | PB |
| | PM | | | | NM | | | |
| | PB | NB | NB | NB | NB | NB | NB | NB |

Antecedent: fuzzy sets of ground acceleration $\ddot{x}_0$ and structural response in term of velocity $\dot{x}$
Consequent: fuzzy sets of control force *u*

**Defuzzification**

After the inference process, there is a fuzzy set to be produced. To control the structural dynamic response, it has to convert the fuzzy set to a crisp value. Then, the actuator can be driven with a concrete value. This converting process, from output of fuzzy set to concrete value, is defuzzification.
In this work here, Larsen's product rule is used for the combination of fuzzy values and the center of gravity method (COG) is used for the defuzzification. This process is the inverse of fuzzification.

The defuzzification process can be formulated as:

$$u^* = \sum_{i=1}^{n} w_i u_i \Big/ \sum_{i=1}^{n} w_i \tag{2}$$

Where $u^*$ is the crisp control output, *n* is the total number of rules and $w_i$ is a weight implying the truth value of the *i*th rule and is given by

$$w_i = \prod_{j=1}^{n} \mu^i_{\tilde{X}_j}(x_i) \tag{3}$$

The centroid defuzzification is the most widely used technique because it has several desirable properties: (1) the defuzzification values tend to move smoothly around the output fuzzy region; that is, changes in the fuzzy set topology from one model frame to the next usually result in smooth changes in the expected value; (2) it is relatively easy to calculate; and (3) is can be applied to both fuzzy and singleton output set geometries.

## NUMERICAL SIMULATION

A three-story building structure is taken as example for the numerical simulation. The system matrices are summarized in table 2. This model was used in previous active structural control study [8]. Table 2 shows the structural parameters used in the simulation.

Table 2. Structural matrices of three-story building

| | |
|---|---|
| Mass matrix, ***M*** | $M = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} \quad kg$ |
| Damping matrix, ***C*** | $C = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} \quad N/(m/s)$ |
| Stiffness matrix, ***K*** | $K = \begin{bmatrix} 12.0 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \quad 10^5\ N/m$ |

The earthquakes El Centro 1940 NS component is used as the input ground motion in the simulation.

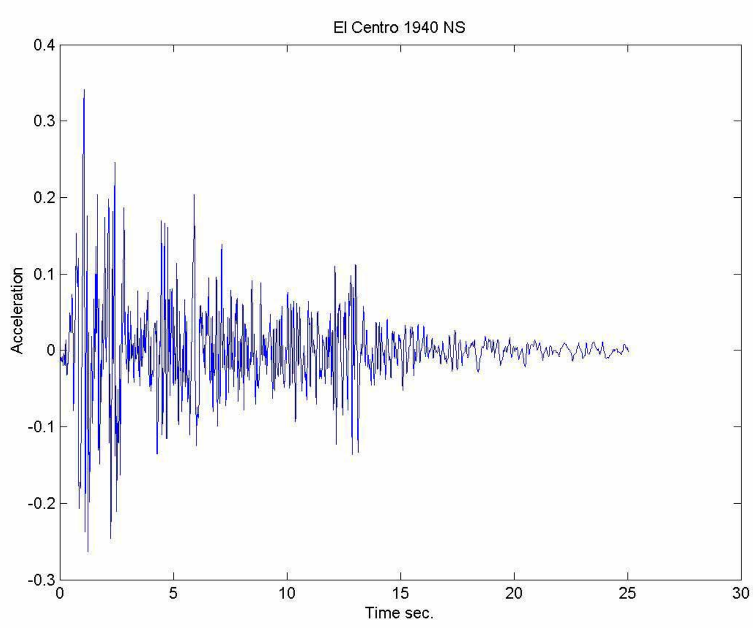


Figure 3. Earthquakes record: El Centro 1940 NS component

The simulation was performed in MATLAB/Simulink environment to demonstrate the effectiveness of the designed fuzzy logic structural controller.

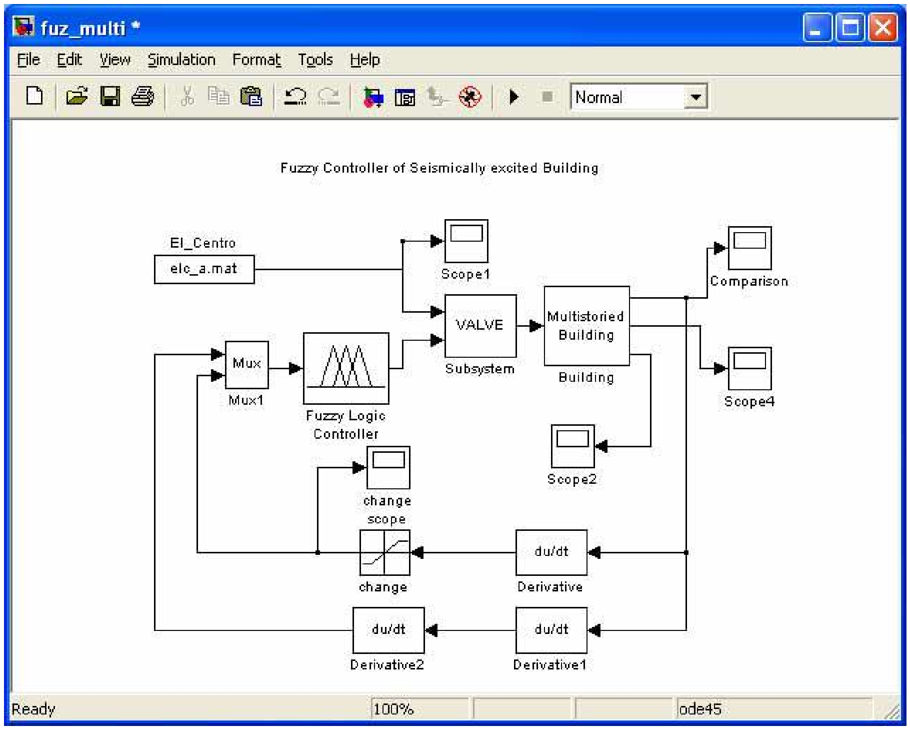


Figure 4. Simulation environment of fuzzy logic control using MATLAB/Simulink

## CONCLUSIONS

A methodology of using fuzzy logic technique for earthquake excited structural control is presented in this paper. Results of this study have shown that the fuzzy logic technique can be robust to control structural response under earthquake loadings.

We should point out that the performance of fuzzy based control system relies mainly on the inference rules and rational selection of parameters and shapes of memberships function. To obtain optimized inference rules is not an easy task. One approach to meet this question is to utilize the learning capability of neural networks for rules generation. Further developments are in progress toward the integration of fuzzy logic and neural networks for construction of neuro-fuzzy based control system.

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