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Keywords

nonlinear, excited, buildings, seismically, application, controller, fuzzy

Disciplines

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Application of a Fuzzy Controller to Seismically Excited Nonlinear Buildings

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Abstract

This paper focuses on the benchmark control problems for seismically excited nonlinear buildings defined by Ohtori et al, [1]. This benchmark study focuses on three typical steel structures, 3-, 9- and 20-storey buildings designed for the SAC project for Los Angeles in California region. The first stage of applying the fuzzy controller to this benchmark study for the 3-storey building is reported. The main advantage of the fuzzy controller is its inherent robustness and ability to handle the non-linear behaviour of the structure. This benchmark study is based on a number of evaluation criteria and control constraints and these limitations are considered in the design of the fuzzy controller. The performance of the controller is validated through the computer simulation on MATLAB. The results of the simulation show a good performance of the fuzzy controller to reduce the response of the building under different earthquake excitations. In the next stage, the study of the fuzzy controller will be extended to the 9- and 20-storey buildings specified in this benchmark study.

I. INTRODUCTION

The protection of civil engineering structures from environmental loads such as strong wind and severe earthquake, including their impact on building contents and occupants, is a worldwide priority. Passive, semi-active and active schemes are becoming an integral part of the structural systems over the past two decades [2-3].

Most of the studies in the area of structural control have focused on the application of the linear control theory, because of the large body of proven linear control methods available and the tendency of keeping the structural response in the linear range. The mathematical model used for tall buildings is usually linear. However, such a model does not fully represent the behaviour of the building when subjected to severe wind or earthquake.

The main objective of this work is to apply an intelligent controller, fuzzy logic controller, to the benchmark building of 3-storeies defined by Ohtori et al [1] to handle the non-linearity of the system. Fuzzy logic is one of the model free approaches to system identification and control. A fuzzy logic controller is robust and capable of handling nonlinear behaviour of the structure. The main advantages in adopting a fuzzy control scheme can be summarized as follows:

- The uncertainties of the input data from the wind or earthquake and structural vibration sensors are treated in a much easier way by fuzzy control theory than by classical control theory. Fuzzy logic, which is the basis of the fuzzy controller, intrinsically accounts for such uncertainties. The implementation of fuzzy controllers makes use of linguistic synthesis and therefore they are not affected by

the selection of a specific mathematical model. As a consequence, the resulting fuzzy controller possesses an inherent robustness.

- Fuzzy controller has the ability to handle the nonlinear behavior of the structure. The linear models do not include disturbances caused by large displacement or material non-linearity and damage.
- The whole fuzzy controller can be easily implemented in a fuzzy chip, which guarantees immediate reaction times and autonomous power supply.

In the course of paper, the building under consideration and the fuzzy controller will be described and the results presented and analyzed.

II. BENCHMARK STRUCTURE

The building used in this work is the 3-storey benchmark structure defined by Ohtori et al [1]. The building is 36.58 m by 54.87 m in plan, and 11.89 m in height. The bays are 9.15 m, in both directions, with four bays in the north-south (N-S) direction and six bays in the east-west (E-W) direction. The seismic mass of the entire structure is 2.95×10^6 kg. The first three natural frequencies of the building are 0.99, 3.06 and 5.83 Hz, respectively. The 3-storey N-S frame is shown in "Fig. 1". The three-mode shapes for the 3-storey building model are shown in "Fig. 2".

A. Nonlinear Analysis

During large seismic events, structural members can yield, resulting in nonlinear response behaviour that may be significantly different than a linear approximation. Therefore, an efficient implementation of the Newmark-time-step integration method was developed in MATLAB for this purpose [4].

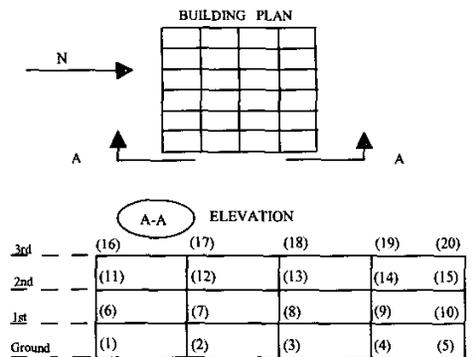


Fig. 1. 3-Storey benchmark building N-S direction

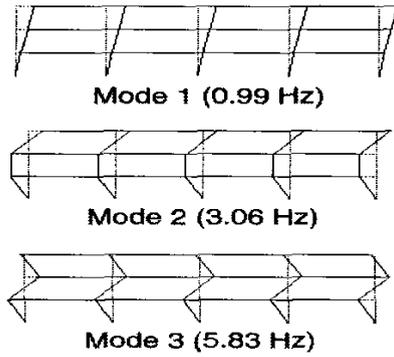


Fig. 2. Mode shapes for the 3-storey building

The Newmark method is used to solve the incremental equation of motion. The incremental equation of motion for the nonlinear structural system takes the following form:

$$M\Delta\ddot{U} + C\Delta\dot{U} + K\Delta U = -MG\Delta\ddot{x}_g + P\Delta f + \Delta F_{err} \quad (1)$$

Where, M , C , K are mass, damping and stiffness matrices of the building, ΔU is the incremental response vector, G is a loading vector for the ground acceleration, $\Delta\ddot{x}_g$ is the ground acceleration increment, P is a loading vector for the control force, Δf is the incremental control force and ΔF_{err} is the vector of unbalanced forces. The unbalanced force is the difference between the restoring force evaluated using the hysteresis model and the restoring force assuming constant linear stiffness at time t during the time interval $(t, t + \Delta t)$. This unbalanced force is handled at the next time step.

B. Evaluation Criteria

In order to evaluate the performance of the fuzzy controller, two far-field and two near-field historical ground motion records are selected: El Centro 1940, Hachinohe 1968, Northridge 1994 and Kobe 1995 earthquakes. The absolute peak acceleration of the earthquake records are 0.3417, 0.2250, 0.8267 and 0.8178 g, respectively as shown in "Fig. 3". The evaluation criteria are divided into four categories: building response, building damage, control devices and control requirements.

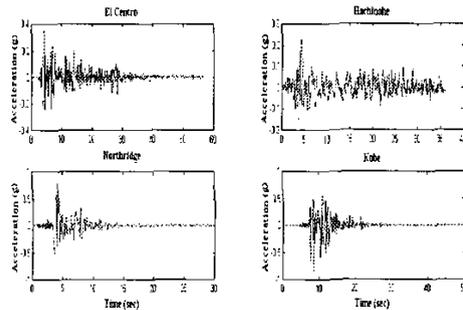


Fig. 3. Time histories of earthquake records used: El Centro; Hachinohe; Northridge; Kobe

The first three criteria are based on the ratio of peak inter-storey drift (J_1), floor acceleration (J_2) and base shear (J_3). The next three criteria are based on the ratio of normed inter-storey drift (J_4), floor acceleration (J_5) and base shear (J_6). The seventh and eighth criteria are the ductility factor (J_7) and dissipated energy of the curvatures at the end of members (J_8). The ninth criterion (J_9) is the ratio of the plastic connections sustained by the structure and (J_{10}) criterion is the normed ductility factor. (J_{11}), (J_{12}) and (J_{13}) criteria show the peak control force, the peak control device stroke and the peak power used for control, respectively and (J_{14}) criterion is a measure of total power for the control of the structure. The last three criteria (J_{15}), (J_{16}) and (J_{17}) are the total number of control devices implemented to control the benchmark building, the number of control sensors used for the control and the assessment of the computational resources required for the control algorithm, respectively. For more details refer to the Ohtori et al [1].

III. FUZZY LOGIC CONTROLLER

Fuzzy logic, introduced by Zadeh, [5], enables the use of linguistic directions as a basis for control. Generally very robust and capable of handling nonlinear systems, fuzzy logic controllers (FLC) usually require expert knowledge in their construction. The most widely used fuzzy control inference M is the "if-then" rule, which can be written as follows when two input data are used in their antecedent parts [6]:

$$M^i: \text{if } X_1=A_i \text{ and } X_2=B_i \text{ then } Y=C_i$$

Where i is the number of control rules. X_1 and X_2 are the variables of the antecedent parts. Y is the variable of the sequent part. A_i , B_i , and C_i are the fuzzy variables. The basic structure of a typical fuzzy logic controller has four components; Fuzzification, Knowledge Base, Decision Making and Defuzzification. In this paper, the preliminary design of the controller will couple the Larsen's minimum product rule [7], to combine the membership values for each rule, with the center of gravity (COG) defuzzification scheme, to obtain the output crisp value.

IV. FUZZY CONTROLLER DESIGN

The fuzzy controller uses crisp data directly from a number of sensors; these data are then converted into linguistic or fuzzy membership functions through the fuzzification process. The number of sensors used in the system is dependent on the number of input variables used in the controller.

The controller is designed using two input variables, each one having seven membership functions, and one output variable with eleven membership functions. The membership functions chosen for the input and output variables are triangular shaped as illustrated in "Figs. 4 and 5", respectively. The fuzzy variables used to define the fuzzy space are described in Table I. The self-organizing fuzzy logic controller (SOFLC) is used to find the final Fuzzy Associative Memory (FAM) as shown in Table II. The fuzzy controller is implemented into the SIMULINK program, shown in "Fig. 6",

using an integration time step of 0.005 seconds and the control signal is computed every 0.005 seconds.

The control actuators are located on each storey of the structure to provide forces to adjacent floors. The size of the actuators is limited to provide a maximum control force of 1000 kN and actuators with this capacity are readily available. To provide larger forces, five actuators are employed on the 3rd floor and one actuator on both the 1st and 2nd floors. Each actuator is implemented in the structure using a chevron brace configuration, in which the actuator is horizontal and rigidly attached between two consecutive levels of the building. Thus, the actuators placed on the first level will produce equal and opposite control forces on the first and second floors. The fuzzy controller is implemented on each floor as shown in Fig. 7.

TABLE I
FUZZY VARIABLES

PVL	Positive and Very Large
PL	Positive and Large
PM	Positive and Medium
PS	Positive and Small
PVS	Positive and Very Small
ZR	Zero
NVS	Negative and Very Small
NS	Negative and Small
NM	Negative and Medium
NL	Negative and Large
NVL	Negative and Very Large

TABLE II
FUZZY ASSOCIATIVE MEMORY (FAM) OF THE FUZZY CONTROLLER

		2 nd Input							
		U	NL	NM	NS	ZR	PS	PM	PL
1 st Input	NL	NVL	NL	NM	NS	NS	PVS	PS	PM
	NM	NL	NM	NS	NS	PVS	PS	PM	
	NS	NM	NS	NVS	NVS	PVS	PS	PM	
	ZR	NM	NS	NVS	ZR	PVS	PS	PM	
	PS	NM	NS	NVS	PVS	PVS	PS	PM	
	PM	NM	NS	NVS	PS	PS	PM	PL	
	PL	NM	NS	NVS	PS	PM	PL	PVL	

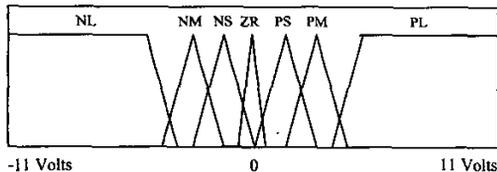


Fig. 4. Membership function for the acceleration of the 1st and the 2nd input

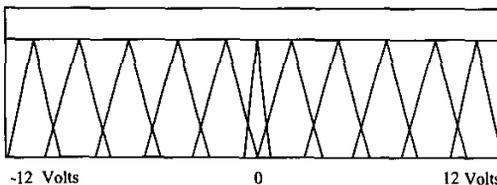


Fig. 5. Membership function for the control force

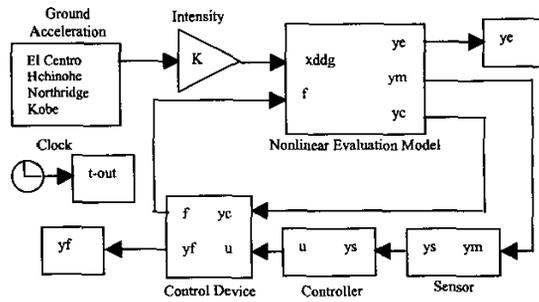


Fig. 6. 3-Storey SIMULINK block diagram for vibration control simulator

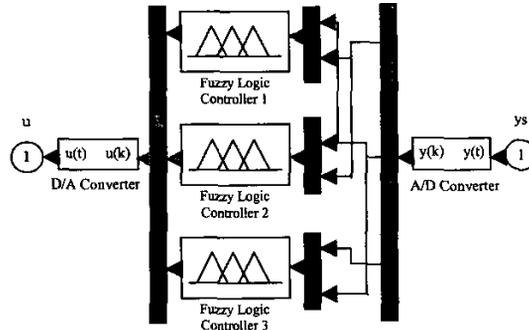


Fig. 7. SIMULINK block representing the fuzzy controller

V. CONTROL PERFORMANCE

The performance of the fuzzy controller is checked according to the evaluation criteria specified ($J_1 - J_{17}$). These criteria are calculated as a ratio of the controlled and the uncontrolled responses. The uncontrolled response calculated is the maximum value due to four earthquake records used in the simulation and these values are compared with the controlled results for each of the four earthquake records. In this study, five actuators are employed on the 3rd floor with a maximum control force of 907.2 kN for each actuator and one actuator employed on the 1st and 2nd floors with a maximum control force of 0.96 kN. The force required for the 1st and 2nd floors is very small compared to the force required for the 3rd floor and as a result, it is possible to have a simple bracing installed in 1st and 2nd floors without any actuators and reduce the cost of the system in the process.

Table III shows the results of the peak uncontrolled and controlled responses of the 3-storey benchmark building. For the uncontrolled response, the table shows that the largest response is associated with Kobe and Northridge Earthquake records. Also, These results show the ability of the fuzzy controller to reduce the response of the building for the four earthquake records but this reduction is varied between them. For El Centro and Hachinohe earthquake records, the reductions in terms of peak displacement are 13% and 25%, respectively, and in terms of peak acceleration are only 3% and 10%, respectively but still well away from the maximum response case. For Kobe and Northridge earthquake records, the reductions in terms of peak displacement are 15% and 22%,

respectively, and in terms of peak acceleration are 31% and 14%, respectively.

Table IV shows the earthquake evaluation criteria ($J_1 - J_{17}$) for the 3-storey benchmark building. The results show a reasonable performance of the fuzzy controller in reducing the peak drift ratio, peak acceleration level, peak base shear and plastic connections for the four earthquake records. Meanwhile, the performance is slightly worse for the norm drift ratio, norm base shear, ductility and energy dissipation especially for the Kobe record. Another advantage of the fuzzy controller is that it does not need any computation resources as illustrated in Table IV, ($J_{17} = 0$).

VI. CONCLUSIONS

In this paper, the focus of the study was on the benchmark control problems for seismically excited nonlinear buildings defined by Ohtori et al, [1]. The first stage of applying the fuzzy controller to this benchmark study for the 3-storey building was reported. Fuzzy logic controller was adopted to drive the control system. The performance of the fuzzy controller was checked thorough a number of evaluation criteria specified for this benchmark study.

The performance of the fuzzy controller was checked for four earthquake records: El Centro 1940, Hachinohe 1968, Northridge 1994 and Kobe 1995. The results of the simulation show the ability of the fuzzy controller to reduce the response of the building due to the four earthquake records. In the next stage of the study, the fuzzy controller will be implemented in the 9- and 20-storey buildings specified in this benchmark study.

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TABLE III
PEAK RESPONSE OF THE 3-STORY BENCHMARK BUILDING WITH AND WITHOUT CONTROL

		El Centro	Hachinohe	Northridge	Kobe
Displacement No Control (m)	L1	0.047	0.041	0.100	0.086
	L2	0.103	0.099	0.187	0.193
	L3	0.151	0.147	0.272	0.307
Displacement with Control (m)	L1	0.054	0.050	0.106	0.116
	L2	0.106	0.095	0.194	0.235
	L3	0.132	0.110	0.212	0.263
Velocity No Control (m/sec)	L1	0.315	0.333	0.737	0.656
	L2	0.571	0.580	0.970	0.951
	L3	0.955	0.890	1.411	1.875
Velocity with Control (m/sec)	L1	0.370	0.268	0.647	0.711
	L2	0.702	0.559	1.178	1.255
	L3	0.809	0.676	1.299	1.684
Acceleration No Control (m/sec ²)	L1	4.180	4.401	9.590	12.04
	L2	5.359	4.867	9.078	10.53
	L3	6.539	6.480	8.590	8.835
Acceleration with Control (m/sec ²)	L1	5.010	4.332	8.185	6.340
	L2	5.763	5.879	8.333	8.268
	L3	6.350	5.200	7.106	7.871

TABLE IV
EARTHQUAKE EVALUATION CRITERIA FOR THE 3-STORY BENCHMARK BUILDING

	El Centro	Hachinohe	Northridge	Kobe
J_1 Peak Drift Ratio	0.397	0.345	0.729	0.842
J_2 Peak Level Acceleration	0.528	0.489	0.692	0.687
J_3 Peak Base Shear	0.758	0.763	0.952	0.940
J_4 Norm Drift Ratio	0.271	0.311	0.846	1.179
J_5 Norm Level Acceleration	1.001	1.038	0.890	1.057
J_6 Norm Base Shear	1.096	1.198	0.999	1.166
J_7 Ductility	0.489	0.457	1.057	1.124
J_8 Dissipated Energy	0.610	0.200	0.876	2.036
J_9 Plastic Connections	0.364	0.364	0.818	0.939
J_{10} Norm Ductility	0.318	0.362	1.198	1.422
J_{11} Control Force	0.031	0.031	0.031	0.031
J_{12} Device Stroke	0.431	0.357	0.691	0.857
J_{13} Control Power	0.060	0.039	0.077	0.136
J_{14} Norm Control Power	0.055	0.059	0.051	0.075
J_{15} Control Devices	7	7	7	7
J_{16} Sensors	3	3	3	3
J_{17} Computation Resources	0	0	0	0

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