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Exploration of the Use of a Proportional-Integral-Derivative Controller for Mitigation of Seismic Base Excitation in Civil Structures

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Proportional-Integral-Derivative controller for mitigation of seismic base excitation in civil structures

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Introduction

Civil infrastructures are at risk of damage due to external forces such as earthquakes. To prevent this risk, active control systems are executed. In this study, a Proportional Integral Derivative (PID) controller was used to minimize the impact of an earthquake disturbance on a multi-story structure. The gains of the controller were obtained using Particle Swarm Optimization (PSO). The effectiveness of the PID controller was validated in simulation on a five-story structure.

PID Control Algorithm

The PID controller integrates three terms to produce effective control results: the proportional term, K_p, an integral term, K_I, and a derivative term, K_d. This results in the calculated control force, $u(t)$,

$$u(t) = K_P \cdot e(t) + K_I \int_0^t e(\tau)\,dt + K_D \frac{d}{dt}(e(t))$$

$\mathbf{K_P}$: proportional gain matrix $\mathbf{K_I}$: integral gain matrix $\mathbf{K_D}$: derivative gain matrix $e(t)$: error signal

Particle Swarm Optimization Algorithm

Particle swarm optimization (PSO) was used to optimize the PID parameters.

Algorithm equations:

$$v_i(k+1) = \lambda v_i(k) + \rho_1\gamma_1\left(x_{b,i}(k) - x_i(k)\right) + \rho_2\gamma_2\left(g(k) - x_i(k)\right)$$
$$x_i(k+1) = x_i(k) + v_i(k+1)$$
$$\lambda = \lambda \times \tau$$

ρ_1 and ρ_2 ⇒ random numbers between 0 and 1

i ⇒ particle number

γ_1 and γ_2 ⇒ acceleration coefficients

λ ⇒ inertia weight

τ ⇒ inertia damping constant

x ⇒ particle position

v ⇒ particle velocity

k ⇒ iteration step

Application specific parameters:

- x - 1*15 vector containing $[\mathbf{K_P}\ \mathbf{K_I}\ \mathbf{K_D}]$ ⇒ $\mathbf{K_P}, \mathbf{K_I}, \mathbf{K_D}$: 1x5 vectors with each entry corresponding to a floor
- 50 particles are initialized in the search space
- Algorithm runs until a better solution is not found for 50 iterations

Quantification of Control Effectiveness

Five cost functions[1] were used to assess the effectiveness of the PID controller.

$$J_1 = \frac{max(|d(t)_{controlled}|)}{max(|d(t)_{uncontrolled}|)}$$

$$J_2 = \frac{\|d(t)_{controlled}\|}{\|d(t)_{uncontrolled}\|}$$

$$J_3 = \frac{max(|\ddot{y}(t)_{controlled}|)}{max(|\ddot{y}(t)_{uncontrolled}|)}$$

$$J_4 = \frac{\|\ddot{y}(t)_{controlled}\|}{\|\ddot{y}(t)_{uncontrolled}\|}$$

$$J_5 = \frac{max(|f(t)|)}{W_s}$$

$\ddot{y}(t)_{controlled}$ ⇒ time history of the acceleration for all floors without any implementation of control

$\ddot{y}(t)_{uncontrolled}$ ⇒ acceleration of all floors when subject to PID control

$d(t)_{uncontrolled}$ ⇒ time history of the inter-story drift for all floors without any implementation of control

$d(t)_{controlled}$ ⇒ inter-story drift of all floors when subject to PID control

$f(t)$ ⇒ time history of the control force for each floor

W_s ⇒ seismic weight of the building based on the above ground mass of the structure

$|\cdot|$ ⇒ absolute value function

m ⇒ number of floors in the structure

PSO Objective Function: $O = \sum_{l=1}^{m} J_{1,l} + J_{2,l} + J_{3,l} + J_{4,l} + 5J_{5,l}$

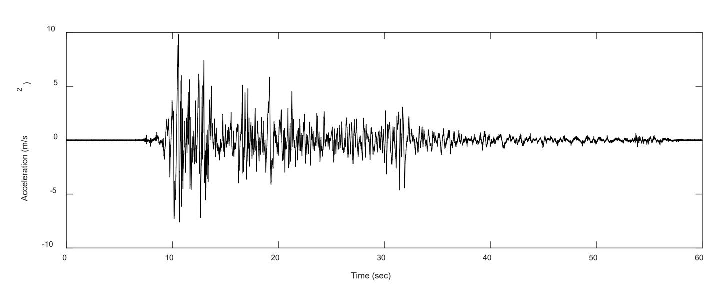
[1] Ohtori et al., 2004

5-Story Benchmark Structure

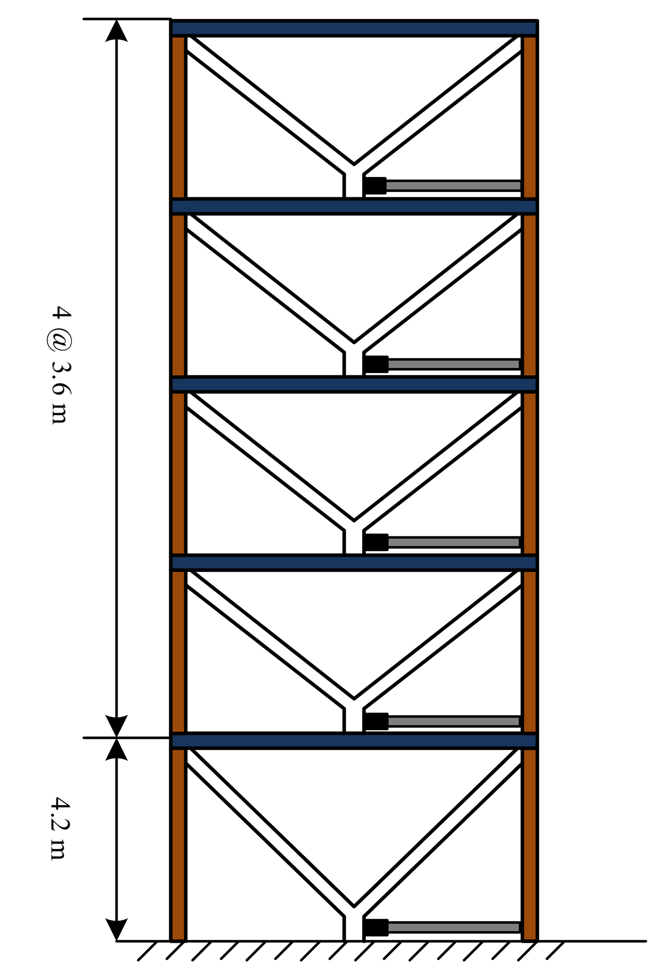
A five-story benchmark structure based on the Kajima Shizuoka building was implemented in simulation to validate the proposed PID-PSO control.

Structure Properties and Assumptions:

- Natural frequencies: 1.0, 2.82, 4.49, 5.80, 6.77 Hz
- 5% damping based on Rayleigh damping
- Transducer on each floor to measure inter-story displacement
- Ideal actuator on each floor
- Subject to seismic base isolation (El Centro earthquake)



El Centro acceleration time history profile

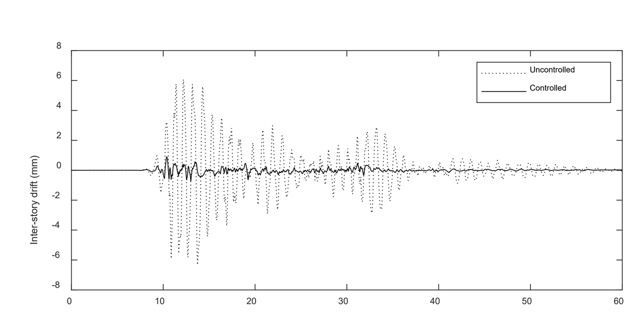


Schematic of the Kajima Shizuoka building

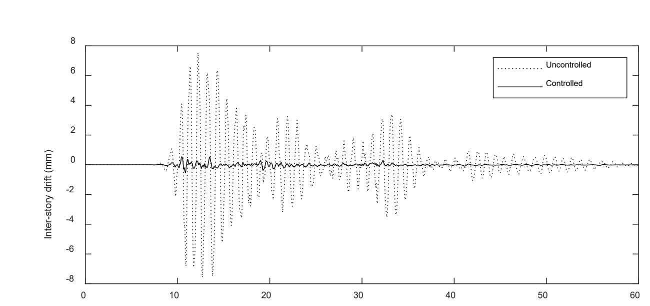
Results

Scenario 1: Actuators on all floors and displacement information sent from all floors

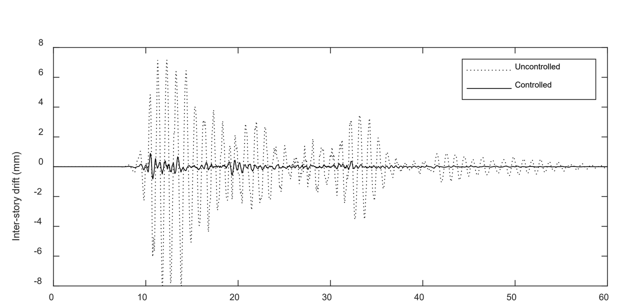
Floor	1	2	3	4	5
J_1	0.143	0.072	0.107	0.102	0.067
J_2	0.131	0.109	0.110	0.124	0.182
J_3	0.803	0.683	0.588	0.598	0.446
J_4	0.420	0.309	0.276	0.227	0.208
J_5	0.163	0.151	0.160	0.189	0.157



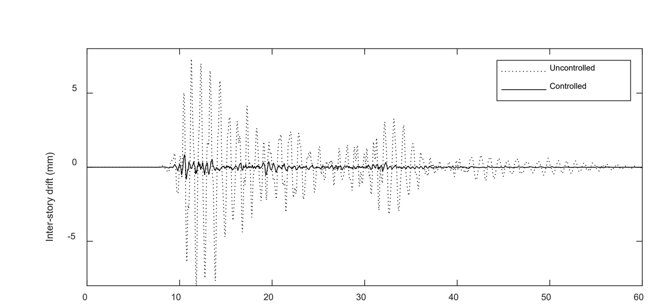
Uncontrolled and Controlled Drift of Floor 1



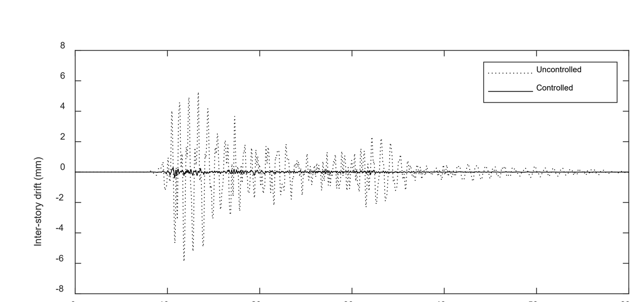
Uncontrolled and Controlled Drift of Floor 2



Uncontrolled and Controlled Drift of Floor 3



Uncontrolled and Controlled Drift of Floor 4



Uncontrolled and Controlled Drift of Floor 5

Results (continued)

Scenario 2: Actuators on floor 1 and displacement information from only floor 1

Floor	1	2	3	4	5
J_1	0.742	0.432	0.454	0.534	0.567
J_2	0.722	0.597	0.602	0.683	1.002
J_3	0.905	0.641	0.713	0.747	0.611
J_4	0.507	0.539	0.560	0.564	0.546
J_5	0.184	-	-	-	-

Scenario 3: Actuators on floor 1 and displacement information from all floors

Floor	1	2	3	4	5
J_1	1.0116	0.8081	0.8278	0.8886	0.9529
J_2	1.8054	1.4934	1.5048	1.7086	2.5045
J_3	1.0299	1.0210	0.9876	0.8523	0.9651
J_4	1.1024	1.1273	0.9882	0.8466	0.9224
J_5	0.1940	-	-	-	-

Conclusions

- Scenario 1 was the most effective control with cost functions significantly below 1 which indicates that the control of the PID was effective in counteracting the effects of the El Centro earthquake. The total objective function is 9.811
- The cost functions of Scenario 2 were larger than Scenario 1 but less than 1. These results show that while some control was achieved, Scenario 1 had a more effective control. The total objective function for Scenario 2 is 16.126
- Scenario 3 had an ineffective control with most cost functions greater than 1. The total objective for this scenario is 24.319
- From these results it is evident that PID control, when paired with the PSO algorithm, is effective in reducing the seismic response for systems using a multi-input, multi-output framework

Future Steps

- Model actuator motor dynamics in order to investigate the performance of PID control in a more realistic environment
- Implement algorithm on a small-scale, experimental testbed

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