A Damping Element Model for Energy Dissipation Characterization in Building Structures

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Motivation

- Problems raised by the use of Rayleigh damping
- Spurious damping force at DOFs with small inertia and underestimate of displacement demands.
- Unable to capture damping ratios in higher modes.
- Implementation for 3-D building models.

\[ C = \alpha M + \beta K \]
Motivation

- Amplitude-dependent damping
  - Observations

- Probabilistic models for modal damping calibration
Proposed Model
Motivation

- Energy Dissipation mechanism
  - Viscous damping, velocity-dependent
  - Friction and slippage between structural and non-structural members and connections, amplitude-dependent
  - Structural element nonlinear excursions
  - Soil-structure interaction

- CSMIP database
  - 94 buildings, with a total of 1045 distinct seismic event records
  - For SMRF records, GM PGA up to 0.299g, and those less than 0.2g are selected
Models

Two-Beam Continuum Model

Time domain
System ID

Miranda, 2005

\[ \alpha_0 = H \left( \frac{G A_0}{E I_0} \right)^{1/2} \]

23516, 3-story SMRF, Landers

\[ \alpha_0, EI, GA \equiv \alpha_0 \text{ Model} \]
\[ \text{or} \]
\[ \rho, I_b, I_c \equiv \rho \text{ Model} \]
Models

\[ \alpha_0 \text{ Model with damping element} \]

\[ \rho \text{ Model with damping element} \]

\[ F_y^+ \]

\[ K_e \]

\[ \delta_y^- \]

\[ \delta_y^+ \]

\[ F_y^- \]

\[ EI, GA, c, K, \delta_y \]

\[ I_b, I_c, c, K, \delta_y \]
Methodology

- Hamiltonian Monte Carlo
- Truncated Unscented Kalman Filter

\[ \frac{\partial x}{\partial t} = \frac{\partial K(p)}{\partial p} \]
\[ \frac{\partial p}{\partial t} = -\frac{\partial U(x)}{\partial x} \]
Methodology

\[ x_t^+, P_t^+ \rightarrow Z_t^+ \rightarrow x_{t+1}, P_{t+1} \]

- Selection
  - Determine parents
- Crossover
  - Create offspring
- Mutation
  - Offspring mutation
- Evaluation
  - Objective function

Genetic Algorithm

- \( y_{t+1} \)
- \( y_{t+1}^+ \)
- \( x_{t+1}^{trun}, P_{t+1}^{trun} \)
Truncated UKF

- Simulated data (#23516, 3-story SMRF, Landers, 2% NSR)
Truncated UKF

- Recorded data

\( \alpha_0 \) Model

\( \rho \) Model
Genetic Algorithm

- **Simulated data**

<table>
<thead>
<tr>
<th></th>
<th>EI</th>
<th>GA</th>
<th>c</th>
<th>K</th>
<th>$\delta_y$</th>
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</thead>
<tbody>
<tr>
<td>Real</td>
<td>3.5e9</td>
<td>2e5</td>
<td>30</td>
<td>400</td>
<td>0.05</td>
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<tr>
<td>Optimized</td>
<td>3.4e9</td>
<td>1.8e5</td>
<td>28.1</td>
<td>435</td>
<td>0.042</td>
</tr>
</tbody>
</table>

- **Recorded data (#23516, 3-story SMRF, Landers, PGA = 0.1g)**

$$J(\theta) = \sum_{i=1}^{n} \sum_{j=1}^{N} \frac{(y_{ij} - \tilde{y}_{ij})^2 \cdot |y_{ij}|}{\max(y_{i,k,N})}$$

$n$: # of sensors, $N$: # of data points

<table>
<thead>
<tr>
<th>PFA (in/s²)</th>
<th>1st floor</th>
<th>2nd floor</th>
<th>3rd floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recorded</td>
<td>44.7</td>
<td>82.8</td>
<td>97.3</td>
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<tr>
<td>Reconstructed</td>
<td>46.8</td>
<td>75.1</td>
<td>86.3</td>
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</table>

<table>
<thead>
<tr>
<th>Max IDR</th>
<th>1st floor</th>
<th>2nd floor</th>
<th>3rd floor</th>
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<tbody>
<tr>
<td>Recorded</td>
<td>0.14%</td>
<td>0.25%</td>
<td>0.08%</td>
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<tr>
<td>Reconstructed</td>
<td>0.17%</td>
<td>0.18%</td>
<td>0.11%</td>
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</tbody>
</table>
Results - Acceleration

1st floor

2nd floor

3rd floor

Time (sec)
Results - Displacement

1st floor

2nd floor

3rd floor

Time(sec)
Results – Floor Acceleration Spectrum

1st floor

2nd floor

3rd floor

Period (sec)

0 1 2 3 4 5 6 7 8 9 10

0 100 200 300

Sa (in/s^2)

recorded
reconstructed

recorded
reconstructed

recorded
reconstructed
Energy Dissipation

- Viscous Damper Removed

![Graphs showing energy dissipation for different floors with recorded and reconstructed data.](image-url)
Energy Dissipation

- Frictional Damper Removed

![Graphs showing energy dissipation at different floors with recorded and reconstructed data.]
Energy Dissipation

- #23516, 3-story SMRF, Landers, PGA = 0.1g, Dampers between 2\textsuperscript{nd} floor and roof

\[ E_{vis} : E_{fric} \]

<table>
<thead>
<tr>
<th></th>
<th>1\textsuperscript{st} floor</th>
<th>2\textsuperscript{nd} floor</th>
<th>3\textsuperscript{rd} floor</th>
<th>total</th>
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<td>2.4 : 1</td>
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57357, 13-story, LomaPrieta-Xdir, Accel.
57357, 13-story, LomaPrieta-Xdir, Displ.
57357, 13-story, LomaPrieta-Xdir, Spec

![Graphs showing recorded vs reconstructed data for 1st, 2nd, 3rd, and 4th sensors over periods of 0 to 10 seconds.](image-url)
## Results

<table>
<thead>
<tr>
<th>Building ID</th>
<th># of story</th>
<th># of sensors</th>
<th>X(ft), Y(ft)</th>
<th>PGA(g)</th>
<th>dir</th>
<th>c(kips x s/in)</th>
<th>K(kips)</th>
<th>δ_y(in)</th>
<th>E_{vis}/E_{fri}</th>
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<td>3</td>
<td>144 132</td>
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## Results

- Properties such as $c$ and $K$ are consistent within one structure.
- Direction with shorter frame has smaller $K$.
- Energy dissipated by viscous damper is much higher than that by frictional damper when subject to GMs with low intensity.

<table>
<thead>
<tr>
<th>ID</th>
<th>PGA(g)</th>
<th>dir</th>
<th>$c$(kips x s/in)</th>
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Conclusion and Future work

- A damping element model which captures both viscous and frictional energy dissipation mechanism is proposed.
- Several optimization methods are tested to match reconstructed signals and recorded signals, the results so far are based on genetic algorithm.
- Effects of viscous and frictional damping are studied in 15 cases containing 5 SMRF buildings with 3 GMs each building.

- Structural nonlinearity will be included in future work as GMs with higher intensity will be applied to the nonlinear model. Bayesian approaches will be adopted where parameters estimated from linear model will serve as prior information.
- Correlation between energy dissipation and story area, story height, GM intensity measure, structure types, etc, will be statistically analyzed.