SYSTEM IDENTIFICATION AND MODEL UPDATING STUDIES

OUTLINE

• Introduction
• System Identification
• Model Updating
• Conclusions

Factor Building
Four Seasons
Factor Building

- 15 story steel SMF
- 200k SF of offices and biomedical facilities
- Permanently instrumented with 72 accelerometer
  - USGS installed 1994
  - CENS upgrade 2003

LWT concrete on metal decking
INTRODUCTION

2004 Parkfield EQ
9/28/2004 10:15am
Mw = 6.0

Ambient Vibrations
4/29/2004 3:00am
Minimal traffic

INTRODUCTION

Four Seasons Building
• 4-story RC perimeter SMF, PT-slabs w/ drop panels
• Damaged in Northridge – yellow tagged
  – punching shear failure at interior connections (0.75in)
  – joint shear cracks and concrete spalling at perimeter beams
  – severe degradation of NSCs

Typical Floor Plan
Typical Section

Skolnik, et al.
nees@UCLA Pilot Project 2004
- Tri-axial accelerometers at slab corners
- Inertial mass shakers on roof

INTRODUCTION

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  - Model Updating
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- Four Seasons
**SYSTEM IDENTIFICATION**

**N4SID Algorithm**

- Discrete *time domain* method, origins in control theory
- State-space models for multivariable systems subjected to known or *unknown excitation*

\[
X_{k+1} = AX_k + BU_k + \omega_k \\
Y_k = CX_k + DU_k + \nu_k
\]

\[
f_i = |\lambda_i|/2\pi \\
\zeta_i = \text{Re}(\lambda_i)/2\pi f_i \\
\phi_i = |C\psi_i| \text{sign}[\text{Re}(C\psi_i)]
\]

\[
\begin{align*}
Y_k & \quad U_k \\
\text{Assembled block} & \quad \text{Hankel matrices} \\
\text{Ortho/oblique} & \quad \text{projections & SVD} \\
\hat{X}_k & \quad \text{Estimated Kalman state sequence} \\
\text{Least squares} & \quad \text{solution} \\
A & \quad B & \quad C & \quad D & \quad \text{System matrices}
\end{align*}
\]

---

**Factor Building**

| Mode Shape | | Earthquake | | Ambient | | Ambient / EQ |
|------------|---|-------------|---|-------------|---|
|            | | $f_i$ (Hz) | $\zeta_i$ (%) | $f_i$ (Hz) | $\zeta_i$ (%) | $f_i/f_i$ | $\zeta_i/\zeta_i$ |
| 1 EW       | | 0.467 | 4.80 | 0.545 | 5.10 | 1.17 | 1.06 |
| 2 NS       | | 0.506 | 4.70 | 0.588 | 8.30 | 1.16 | 1.77 |
| 3 Tor      | | 0.681 | 5.80 | 0.807 | 10.80 | 1.19 | 1.86 |
| 4 EW       | | 1.488 | 5.40 | 1.626 | 2.10 | 1.09 | 0.39 |
| 5 NS       | | 1.665 | 4.90 | 1.795 | 1.40 | 1.08 | 0.29 |
| 6 Tor      | | 2.362 | 7.40 | 2.485 | 2.90 | 1.05 | 0.39 |
| 7 EW       | | 2.677 | 4.40 | 2.825 | 2.20 | 1.06 | 0.50 |
| 8 NS       | | 2.862 | 4.90 | 3.061 | 1.30 | 1.07 | 0.27 |
| 9 Tor      | | 3.826 | 4.60 | 4.017 | 2.90 | 1.05 | 0.63 |

**Four Seasons Building**

| Mode Shape | | Forced | | Ambient | | Ambient / Forced |
|------------|---|--------|---|-------------|---|
|            | | $f_i$ (Hz) | $\zeta_i$ (%) | $f_i$ (Hz) | $\zeta_i$ (%) | $f_i/f_i$ | $\zeta_i/\zeta_i$ |
| 1 EW       | | 0.88  | 5.60 | 1.09  | 3.40 | 1.24 | 0.61 |
| 2 NS       | | 0.94  | 6.90 | 1.25  | 3.10 | 1.33 | 0.45 |
| 3 Tor      | | 1.26  | 6.00 | 1.55  | 2.10 | 1.23 | 0.35 |
| 4 EW       | | 2.73  | 5.60 | 3.23  | 3.00 | 1.18 | 0.54 |
| 5 NS       | | 2.94  | 7.70 | 3.63  | 3.10 | 1.23 | 0.40 |
| 6 Tor      | | 3.44  | 6.10 | 4.16  | 2.10 | 1.21 | 0.34 |
Algorithm

- FEM based on A&S drawings and idealized assumptions
- Model updating is performed to reduce discrepancies, better predict building responses, physical interpretation of updated parameters
- A parameter-sensitivity based method
  - parameters based on physical properties not readily modeled
  - initial model is appended with parameter based quantities and error residual using modal properties and FRFs

\[
\begin{align*}
    r_M &= \left| \frac{\Omega - \Omega(p)}{\Phi - \Phi(p)} \right| \\
    r_F &= \left| L - B(p, \omega)\bar{H}(\omega) \right|
\end{align*}
\]

- Linearize \( r(p) \) by expanding into a truncated Taylor series

\[
\min_{\Delta p} \left\| r - S\Delta p \right\|_{L_2}^2
\]
Constrained Minimization

- Sensitivity matrix is evaluated numerically, often **ill-conditioned**
  - correlation coefficients between parameter sensitivities
  - weighting matrix for relative confidence in measured quantities

\[
S_M = \left[ \begin{array}{c} \frac{\partial \Omega(p)}{\partial p} \\ \frac{\partial \Phi(p)}{\partial p} \end{array} \right]^T, \quad S_F = \left[ \frac{\partial \mathcal{B}(p, \omega)}{\partial p} \right] \tilde{H}(\omega)
\]

\[
R_{i,j} = \frac{C_{i,j}}{\sqrt{C_{i,i}C_{j,j}}}
\]

\[
\min_{\Delta p} \| W_r - W S \Delta p \|^2
\]

such that

\[
0 \leq p_i \leq 1 \quad \text{and} \quad |p_i - p_j| \leq (1 - R_{i,j})
\]

Factor Building Parameters

- Initial FE model **underestimates** actual building mass and stiffness
  - effective story stiffness of NSCs
  - live and superimposed dead load

\[
m = (1 - p_i) \times m_{\text{max}}
\]

\[
k = p_j \times k_{\text{max}}
\]

\[
K = K_{FE} + K(p)
\]

\[
M = M_{FE} + M(p)
\]
## Factor Building

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>Identified</th>
<th>Initial Model</th>
<th>Updated Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_m$ (Hz)</td>
<td>$\xi$ (%)</td>
<td>$f_i$ (Hz)</td>
</tr>
<tr>
<td>1 EW</td>
<td>0.467</td>
<td>4.80</td>
<td>0.51</td>
</tr>
<tr>
<td>2 NS</td>
<td>0.506</td>
<td>4.70</td>
<td>0.51</td>
</tr>
<tr>
<td>3 Tor</td>
<td>0.681</td>
<td>5.80</td>
<td>0.67</td>
</tr>
<tr>
<td>4 EW</td>
<td>1.488</td>
<td>5.40</td>
<td>1.51</td>
</tr>
<tr>
<td>5 NS</td>
<td>1.665</td>
<td>4.90</td>
<td>1.45</td>
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<tr>
<td>6 Tor</td>
<td>2.362</td>
<td>7.40</td>
<td>1.90</td>
</tr>
<tr>
<td>7 EW</td>
<td>2.677</td>
<td>4.40</td>
<td>2.53</td>
</tr>
<tr>
<td>8 NS</td>
<td>2.862</td>
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<td>2.39</td>
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<tr>
<td>9 Tor</td>
<td>3.826</td>
<td>4.60</td>
<td>3.19</td>
</tr>
</tbody>
</table>

### MODEL UPDATING

![Graph showing identified, initial, and updated model frequencies and MAC values for different modes and shapes.](image-url)
Four Seasons Building

- Effective stiffness values (FEMA 356, Paulay & Priestley)
  - Columns: $0.5EI_g$
  - Beams: $0.42EI_g$
  - Slabs: $0.4EI_g$

- Parameters
  - additional story mass, damping ratios not identified, group stiffness factors

### MODEL UPDATING

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>Identified $f_m$ (Hz)</th>
<th>$\zeta$ (%)</th>
<th>Initial Model $f_i$ (Hz)</th>
<th>$f_i / f_m$</th>
<th>MAC</th>
<th>Updated Model $f_u$ (Hz)</th>
<th>$f_u / f_m$</th>
<th>MAC</th>
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</thead>
<tbody>
<tr>
<td>1 EW</td>
<td>0.88</td>
<td>5.66</td>
<td>0.89</td>
<td>1.01</td>
<td>0.98</td>
<td>0.89</td>
<td>1.01</td>
<td>1.00</td>
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<tr>
<td>2 NS</td>
<td>0.94</td>
<td>6.94</td>
<td>1.08</td>
<td>1.15</td>
<td>0.99</td>
<td>0.96</td>
<td>1.02</td>
<td>0.99</td>
</tr>
<tr>
<td>3 Tor</td>
<td>1.26</td>
<td>6.01</td>
<td>1.29</td>
<td>1.02</td>
<td>1.00</td>
<td>1.26</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>4 EW</td>
<td>2.73</td>
<td>5.61</td>
<td>2.64</td>
<td>0.97</td>
<td>0.90</td>
<td>2.72</td>
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<td>0.99</td>
</tr>
<tr>
<td>5 NS</td>
<td>2.94</td>
<td>7.69</td>
<td>2.99</td>
<td>1.02</td>
<td>0.94</td>
<td>2.93</td>
<td>1.00</td>
<td>0.98</td>
</tr>
<tr>
<td>6 Tor</td>
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<td>6.14</td>
<td>3.42</td>
<td>0.99</td>
<td>0.93</td>
<td>3.44</td>
<td>1.00</td>
<td>0.99</td>
</tr>
</tbody>
</table>
### Updated Parameters

- Columns: 0.5EIg
- Beams: 0.42EIg
- Slabs: 0.4EIg

<table>
<thead>
<tr>
<th>Effective Stiffness Factors</th>
<th>2F</th>
<th>3F</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS of Interior, North &amp; South Frame Columns</td>
<td>0.40</td>
<td>0.48</td>
</tr>
<tr>
<td>NS of East Frame Columns</td>
<td>0.36</td>
<td>0.41</td>
</tr>
<tr>
<td>NS of West Frame Columns</td>
<td>0.49</td>
<td>0.39</td>
</tr>
<tr>
<td>EW of Interior, East</td>
<td></td>
<td>0.62</td>
</tr>
<tr>
<td>EW of North</td>
<td></td>
<td>0.52</td>
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<tr>
<td>EW of South</td>
<td></td>
<td>0.56</td>
</tr>
<tr>
<td>East Frame</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>West Frame</td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td>South Frame</td>
<td></td>
<td>0.32</td>
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<tr>
<td>North Frame</td>
<td></td>
<td>0.57</td>
</tr>
<tr>
<td>Slab-Column NS</td>
<td>0.43</td>
<td>0.19</td>
</tr>
<tr>
<td>Slab-Column EW</td>
<td>0.44</td>
<td>0.30</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

- Introduction
- System Identification
- Model Updating

#### OUTLINE

- Factor Building
- Four Seasons
CONCLUSIONS

N4SID identifies first 6-9 modes

- Ambient vibrations represent a **stiffer, less-damped** structure than earthquake and forced vibrations

Modal- FRF-sensitivity based updating method

- Numerical issues w/ ill-conditioning were addressed by introducing a novel parameter constraint based on **correlation coefficients**
- Factor building parameters based on additional mass and stiffness **not readily modeled**
- Four Seasons building, the predicted reduction in **effective stiffness** factors were in general agreement with observed damage patterns
- Nevertheless, these results **cannot be considered unique** despite the dense sensor arrays, because they ultimately depend upon user-defined weights and constraints

Thank You!

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http://www.seas.ucla.edu/~skolnik
http://factor.gps.caltech.edu
http://nees.ucla.edu/fourseasons.htm