Wave Method for Structural System Identification and Health Monitoring: Review of Recent Developments

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Motivation

Downtown Los Angeles
• Repeatedly shaken by large and distant and moderate but near earthquakes
• Questions that comes to mind each time immediately after an earthquake:
  – Is the building safe to occupy?
  – Evacuate immediately or not?
• Answer:
  – Traditional method: walk-in inspection (time consuming, subjective).
  – Advanced technology: Structural Health Monitoring System (response in near real-time; based on sensory data)
Structural Health Monitoring System

Sensing & Recording

Sensors, Data transmission: Cables or Wireless transmission

Data Acquisition Unit

Data Transmission (Internet)

Reporting

Results Interpretation and Decision Making

Methodology - Algorithm

Rahmani, Ph.D. Thesis
Requirements

Requirements:
• Assessment must be **reliable** and **accurate** to be useful:
  • **No failures** to detect significant damage.
  • **No false alarms** – imagine e.g. needless evacuation of a hospital.
• Method must be
  • **Robust**
  • **Sensitive** to damage and **Not sensitive** to other factors (SSI, weather, etc.)
  • **Accurate**

Benefits:
• **Prevent loss of life and injuries** caused by collapse of a weakened structure during aftershocks
• **Avoid monetary losses** caused by needless evacuation
• Emergency response: **use as shelters** buildings cleared to be safe
Wave Method for SHM

- Damage sensitive parameter: velocity of wave propagation through the structure. Structural damage => reduction of wave velocity
- Measurement of wave velocity: Deconvolution interferometry
  - Deconvolved waveforms = System Impulse Response Functions (IRF) => propagating pulses from a virtual source
  - Simplest method – measure time delay: \( v = \frac{h}{\tau} \).
- Advantages: Robust, not sensitive to soil-structure interaction effects

\[
TF \equiv \hat{h}_i(\omega) = FT\left\{\frac{\hat{u}_i(\omega)}{\hat{u}_{\text{ref}}(\omega)}\right\}
\]

\[
IRF \equiv h_i(t) = FT^{-1}\left\{\hat{h}_i(\omega)\right\}
\]

Los Angeles
54-story Office Building

CSMIP 24629
Stages of Development

- D’Alembert (1747): \textbf{wave eqn solution}: \(u_{tt} = c^2 u_{xx} \Rightarrow u = A(x - ct) + B(x + ct)\)
- Şafak (1999): wave velocity as a damage sensitive parameter
- Snieder and Şafak (2006): Deconvolution interferometry – to measure time delay
- 
  \textbf{Waveform inversion} by LSQ fit of simple beam models
  - Why waveform inversion? – Measuring time shifts is not very accurate. Trade off between spatial resolution and accuracy; dispersion is a problem, Todorovska and Rahmani (SCHM 2013)
  - Why beam models? Smaller number of unknown parameters => more stable fit
  - Shear beam (nondispersive) – good for tall steel frame buildings, gives biased estimates for structures with significant bending deformation; Rahmani and Todorovska (SDEE 2013).
  - Moving window analysis – Rahmani et al. (EESD 2015).
  - More detailed models and case studies: in progress
- 
  \textbf{Challenges}: increase both the spatial resolution and accuracy
Applications

- **Damaged buildings:**
  - Proof of concept studies on severely damaged buildings: Imperial County Services Bldg and Van Nuys 7-story Hotel, both severely damaged (Todorovska and Trifunac, SDEE 2008; SCHM 2008).
  - Lightly damaged: Sherman Oaks 12-story Hotel, Torre Central in Chile.
  - Conclusions: robust, detected change in wave velocity is correlated with location and degree of observed damage.

- **Undamaged buildings** excited by multiple earthquakes:
  - Conclusions: recoverable nonlinearity and permanent changes detected in a building without observed damage.

- **Shake table specimen** – Full-scale slice of a 7-story RC building (UCSD-NEES shake table; J. Str. Eng. 2016)

- **Historic heritage structures (ambient vibration data):**
  - Two towers in Bologna, Full-scale slice of a 7-story RC building
Two medieval towers in Bologna, Italy

- Asinelli tower – 97 m high – layered Timoshenko beam (0 - 6.5 Hz)
- Garisenda tower – 48 m high – uniform Timoshenko beam (0 - 20 Hz)

Parameters obtained from geometry and density of building materials:
W=7.5 m; H=45 m; ρ = 1,360 kg/m³

Parameters obtained by LSQ fit of Impulse Responses:

\[ C_\text{S} = 735 \text{ m/s}; \quad R=0.312; \quad \text{RMS Error} = 42\% \]

\[ C_1 = \text{phase velocity of 1st wave mode} \]
\[ g_r = \text{group velocity of 1st wave mode} \]
\[ C_\text{S} = \text{velocity of shear waves in the beam material} \]
\[ \bullet = \text{nonparametric estimate of phase velocity} \]

(Zaccarelli et al., 26th IUGG General Assembly, 2015; Data credit: IGNV)
Example: Lightly damaged building

Torre Central, Santiago, Chile

Maule earthquake, 2/27/2010, M=8.8, R=393 km, EW Response

Layer 1 (3rd to 8th)

Layer 2 (2nd bsm to 3rd)

Equiv. uniform beam (2nd bsm to 8th)

(Rahmani et al., 16WCEE, 2017; Data from by co-author R. Boroschek, U. Chile)
Example: Lightly damaged building

(Rahmani et al., 16WCEE, 2017; Data credits: U. Chile, Prof. Boroschek)
Example: undamaged building

Los Angeles 54-story Office Building

54-story, moment resisting **perimeter steel frame**, on concrete mat foundation; alluvium over sedimentary rock

(Rahmani and Todorovska, Spectra, 2015)
Full-scale slice of a 7-story building

Progressively damaged by 4 earthquakes

Damage States: S0, S1, S2, S31, S32, S4

Data available: AV, WN 0.03g, WN 0.05g, Earthquake

Example: UCSD shake table experiment

Evidence of recoverable nonlinearity even for small amplitude response

Comparison of change in $f_1$ and $c_L$
CGS - CSMIP Station 58389; a.k.a. One Rincon Hill Tower

**72-channels** of acceleration. Performance based design w/dynamic response modification features (**tuned liquid sloshing dampers** and **buckling-restrained braces**).
Total height =188.31 m; Site geology: sedimentary rock.

Concrete core shear walls with supplemental tall outrigger columns of steel reinforced concrete in the transverse direction. The core is attached to outrigger columns by steel buckling restrained braces. Water tanks at the top of the building are part of the "tuned liquid-mass damper" system to reduce wind induced motions. Concrete mat foundation (12 feet beneath the tower) bearing on bedrock.(CESM web site).
System ID by the wave method: Fitting uniform and 6-layer Timoshenko beam by minimizing LSQ error of observed and model IRFs (Ebrahimian and Todorovska, J. Eng. Mech. 2015).
Data: South Napa earthquake, 24 Aug. 2014, M=6; R=49 km. Peak acc.=0.005g (gnd), 0.021g (str.)
**Example: Special structure - San Francisco 62-story Resid. Bldg.**

**CGS - CSMIP Station 58389**

**System ID: NS  6-layer Timoshenko beam**

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<th>Layer No.</th>
<th>$h$ m</th>
<th>$r$ kg/m$^2$</th>
<th>$c_s$ m/s</th>
<th>$c_l$ m/s</th>
<th>$R=G/E$</th>
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**Data:** South Napa EQ, 24 Aug. 2014, M=6; R=49 km.
Peak acc.=0.005g (gnd), 0.021g (str.)

**Phase and Group velocities**

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The chart on the right illustrates the phase and group velocities for the system. The graph compares observed data with model predictions across different frequencies and time scales, highlighting the accuracy of the Timoshenko beam model in capturing the seismic behavior of the structure.
System ID: EW 6-layer Timoshenko beam

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<th>$c_L$ (m/s)</th>
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CGS - CSMIP Station 58389

Data credits: CESMD
Conclusions

• Method is:
  • Robust
  • Sensitive even to nonvisible damage
  • Not sensitive to SSI under certain conditions
  • Needs further calibration
  • Work in progress…

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  • Center for Engineering Strong Motion Data (www.strongmotioncenter.org/);
  • University of Chile
  • Italian Institute for Vulcanology and Geophysics
  • UCSD
Thank You!

More information at: http://earthquake-eng.usc.edu/