2.04A Class Project: the “Tower”

with Active Damping
Problem

• Wind loading of skyscrapers causes tall building sway.

• Upper floor occupants suffer from motion sickness when the building sways in the wind since people are sensitive to accelerations as small as 0.05 m/s² (0.005 g).

• Too much building sway can also lead to long-term structural damage.

• The Hancock Tower in Boston had a problem with falling windows. (The Hancock Tower now has two passively controlled 300 ton sliding masses on the 58th floor.)
Simplified Building Model

• We can model a tall building as a single degree of freedom lumped-parameter system.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Best Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>240 m</td>
</tr>
<tr>
<td>Breadth: Depth: Height ratio</td>
<td>2:5:1</td>
</tr>
<tr>
<td>Number of stories</td>
<td>60</td>
</tr>
<tr>
<td>Natural frequency of fundamental mode</td>
<td>0.14 Hz</td>
</tr>
<tr>
<td>Damping ratio of fundamental mode</td>
<td>1%</td>
</tr>
</tbody>
</table>
Passive Vibration Damping

One way to stabilize these tall builds from swaying too much during earthquakes or from high winds is to install enormous pendulum weights. When the building sways sideways the pendulum doesn't want to move (inertia) and exerts a pull in the opposite direction.
Skyscrapers

Burj Khalifa Skyscraper became the tallest building (828 meters or 2,717 feet) in the world when it was officially opened on 4th January 2010.

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2.004 Spring '13 Lecture 09 – Wednesday, Feb. 27
Burj Khalifa (http://www.burjkhalifa.ae/)

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91st Floor [380.60 m]
(Outdoor Observation Deck)

89th Floor [382.20 m]
(Indoor Observation Deck)

88th Floor

87th Floor

Courtesy of Stefan Tan. Used with permission.
The Tuned Mass Damper in Taipei 101

The passive wind damper with a diameter of 5.5 meters and weighting 660 metric tons, is also the largest in the world now.

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The actuator is commanded by a control system, which requires sensor feedback.
Experimental System

- voice-coils
- air-bearings
- wire spring
- accelerometer
- “tall building”
System Modeling
Available Impulse Response Data
(Course Lockers\2.004\Labs\Tower Data)

Building Response

Damper Response

\[ B_1 \text{ and } K_1 \]

\[ B_2 \text{ and } K_2 \]

Compare your transfer function impulse response to this one.

Open Loop System Response
Estimating Parameters (Building)

\[ \tau = \frac{1}{\zeta \omega_n} \]

Logarithmic decrement method

\[ \delta = \ln \frac{x_1}{x_2} = \frac{1}{N-1} \ln \frac{x_1}{x_N} \]

\[ \delta = \frac{2\pi \zeta}{\sqrt{1 - \zeta^2}} \Rightarrow \]

\[ \zeta = \frac{2\pi}{\sqrt{1 + \left( \frac{\delta}{2\pi} \right)^2}} \]

Damped period

\[ \omega_d = \omega_n \sqrt{1 - \zeta^2} = \frac{2\pi}{t_d} \]

\[ m\ddot{x} + b\dot{x} + kx \quad \leftrightarrow \quad s^2 + 2\zeta \omega_n s + \omega_n^2 \]
Estimating Parameters (Damper)

Impulse Response with Damper

\[ v_{impulse}(t) = 4\omega_n \sqrt{1 - \zeta^2} e^{-\zeta \omega_n t} \sin \left( \omega_n \sqrt{1 - \zeta^2} t \right) \]

From this (after some algebra) we obtain

\[ \zeta = \frac{c}{\sqrt{\pi^2 + c^2}}, \quad \text{where} \]

\[ c \equiv -\ln \frac{v_{peak}}{4\omega_d} \]

\[ m\ddot{x} + b\dot{x} + kx \quad \leftrightarrow \quad s^2 + 2\zeta \omega_n s + \omega_n^2 \]
2.04A Systems and Controls
Spring 2013

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