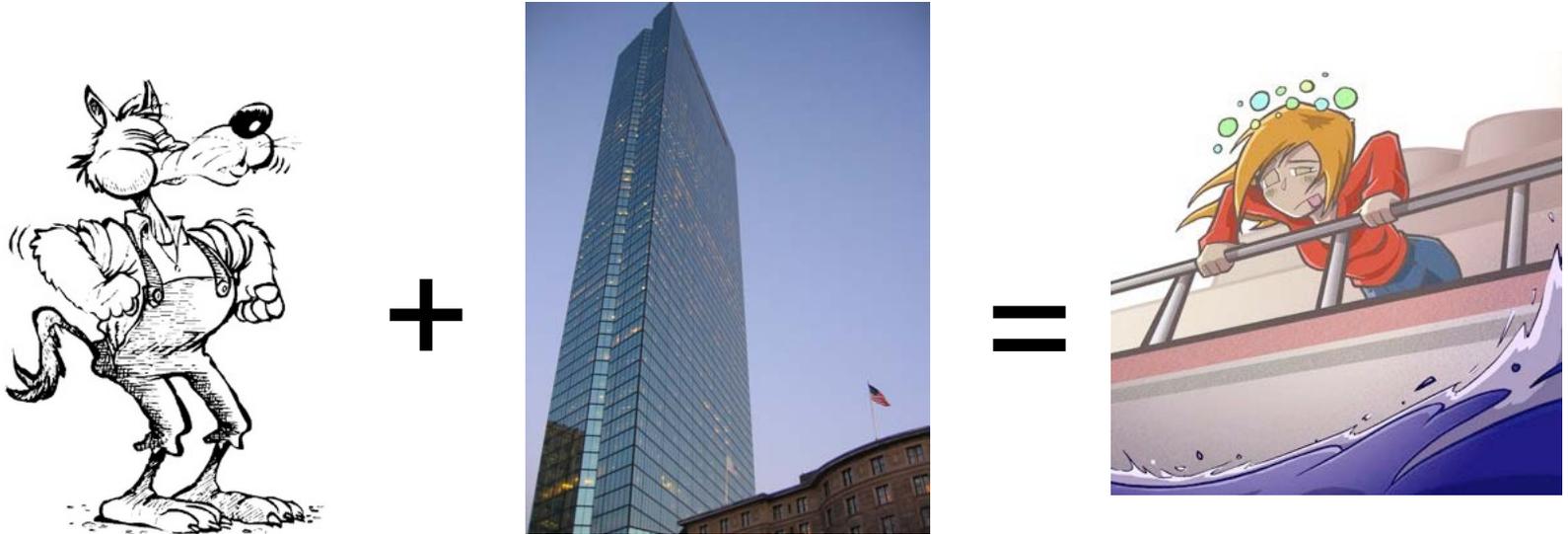


# **2.04A Class Project: the “Tower” with Active Damping**

# 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  $0.05 \text{ m/s}^2$  (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 58<sup>th</sup> floor.)



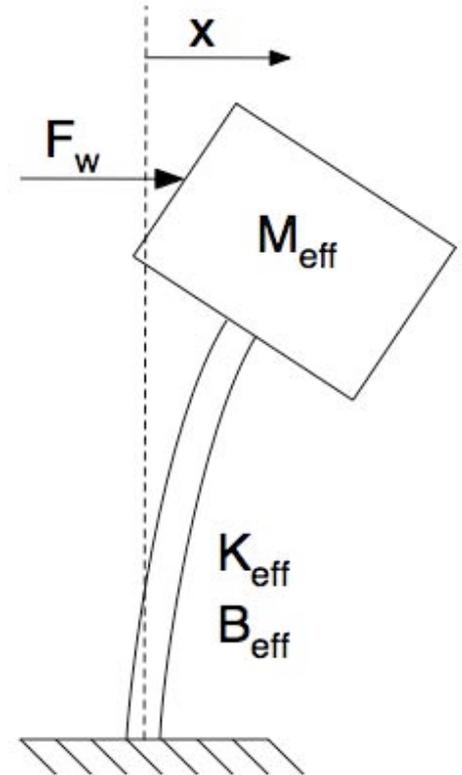
Courtesy of [Rob Pongsajapan](#) on flickr. CC-BY

&DUMROV VRXUFHV XONQRZ Q \$@WJ KW LHVHUYHG 7KLV FROMQOVW H[ FOXGHG IURP RXU &LHDVWYH  
&RP P ROV @FHOVH ) RUP RUH LOIRUP DVRO VHH KWS RFZ P LVHGX KHCS IDT IDLW XVH

# Simplified Building Model

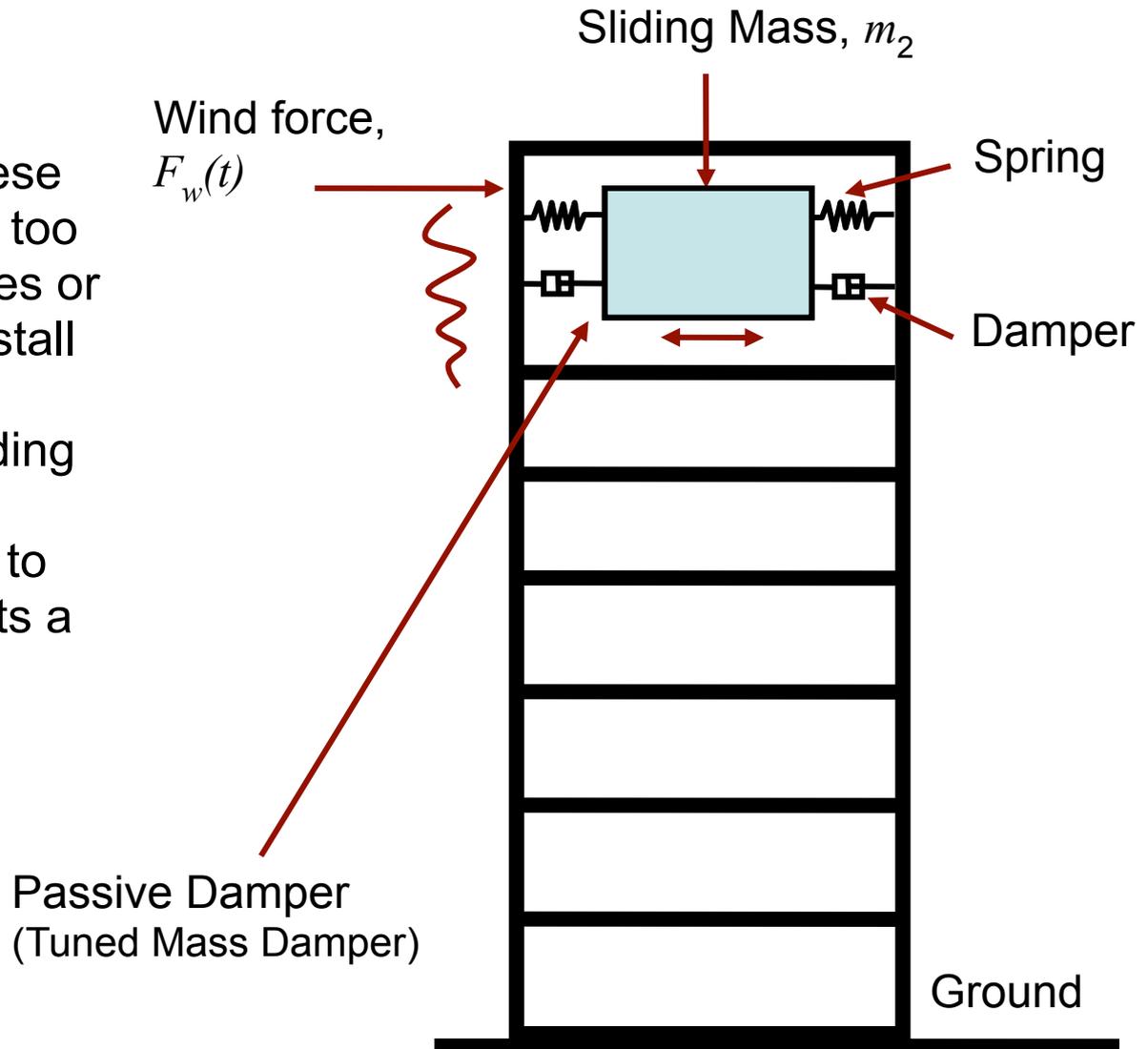
- We can model a tall building as a single degree of freedom lumped-parameter system.

<i>John Hancock Tower, Boston</i>	
Specifications	Best Estimate
Height	240 m
Breadth: Depth: Height ratio	2: 5: 1
Number of stories	60
Natural frequency of fundamental mode	0.14 Hz
Damping ratio of fundamental mode	1%



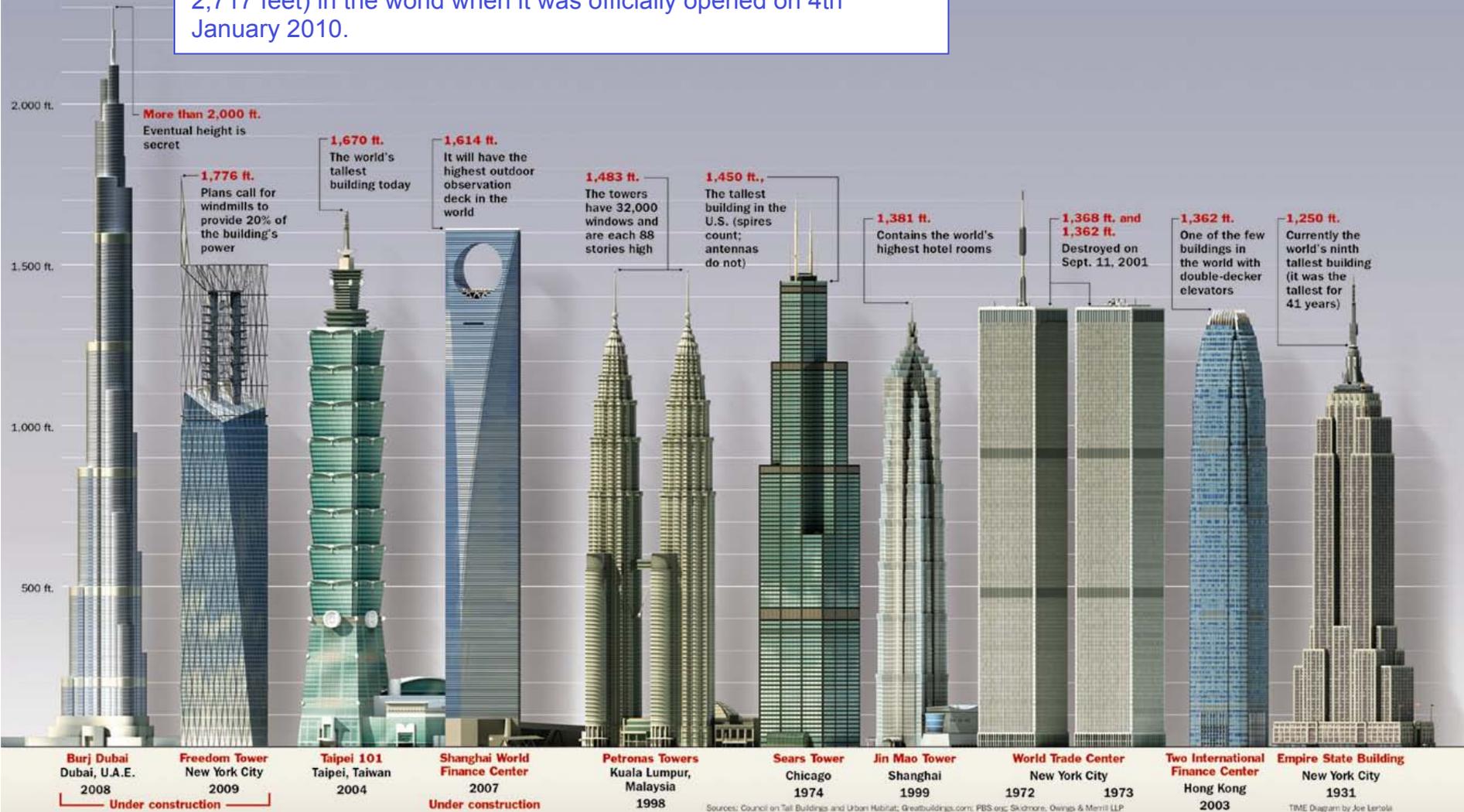
# Passive Vibration Damping

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.



TIME Diagram by Joe Lertola © Time, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see <http://ocw.mit.edu/help/faq-fair-use/>.

# Burj Khalifa (<http://www.burjkhalifa.ae/>)



Courtesy of [ADTeasdale](#) on flickr. CC-BY



Courtesy of Natalie of [designedbynatalie.com](http://designedbynatalie.com). CC-BY-NC

# Taipei 101 (<http://www.taipei-101.com.tw>)



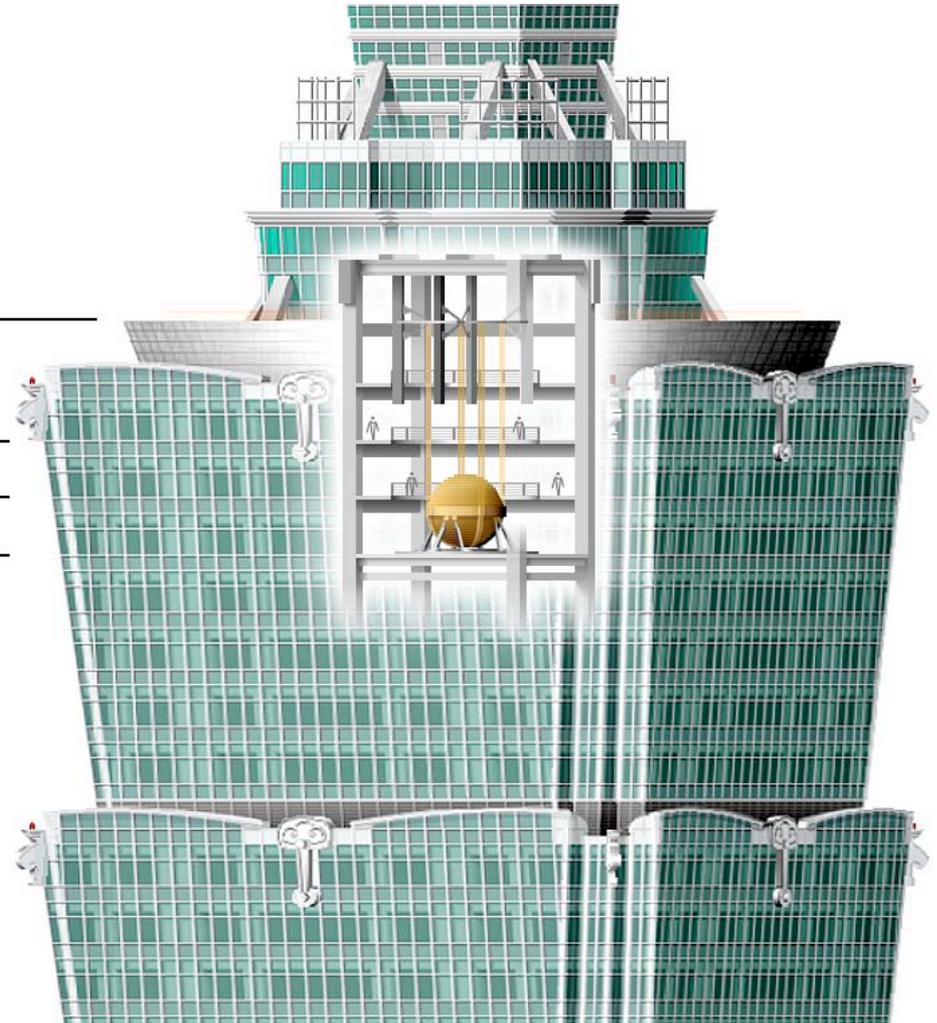
Courtesy of [Jirka Matousek](#) on flickr. CC-BY

91st Floor [390.60 m]  
(Outdoor Observation Deck)

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

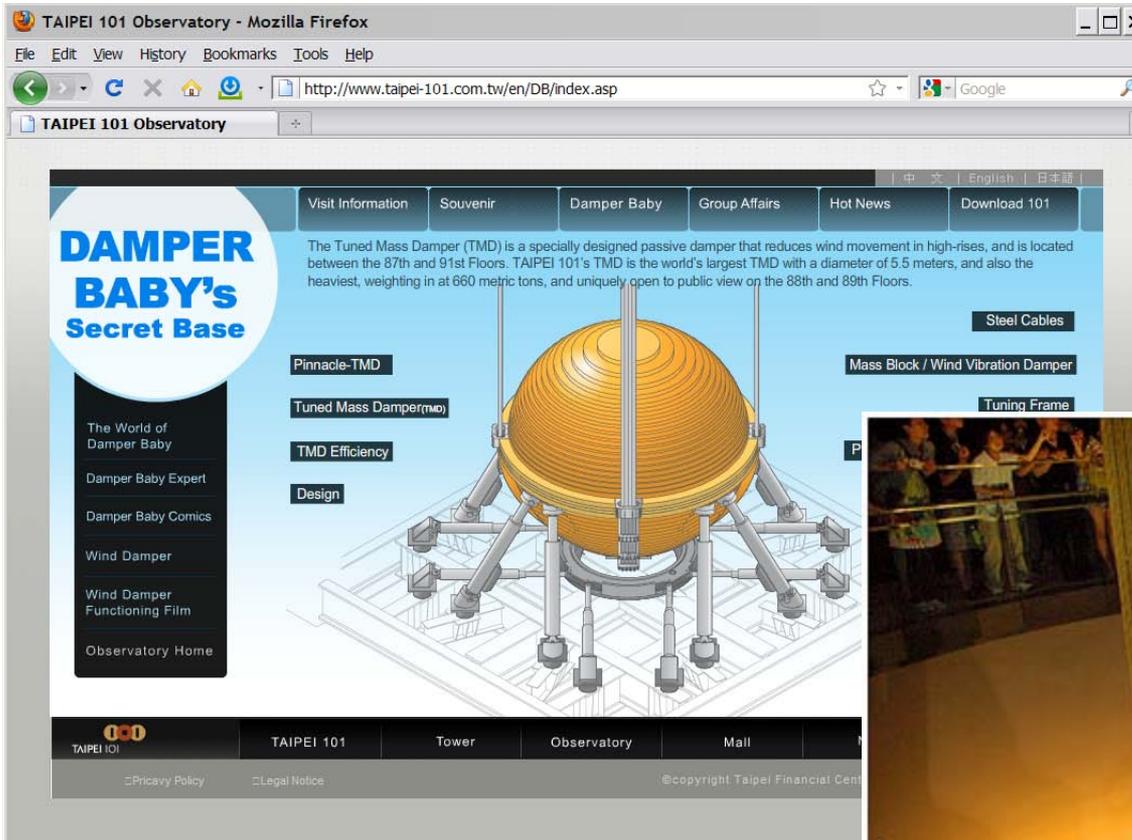
88th Floor

87th Floor



Courtesy of [Stefan Tan](#). Used with permission.

# The Tuned Mass Damper in Taipei 101



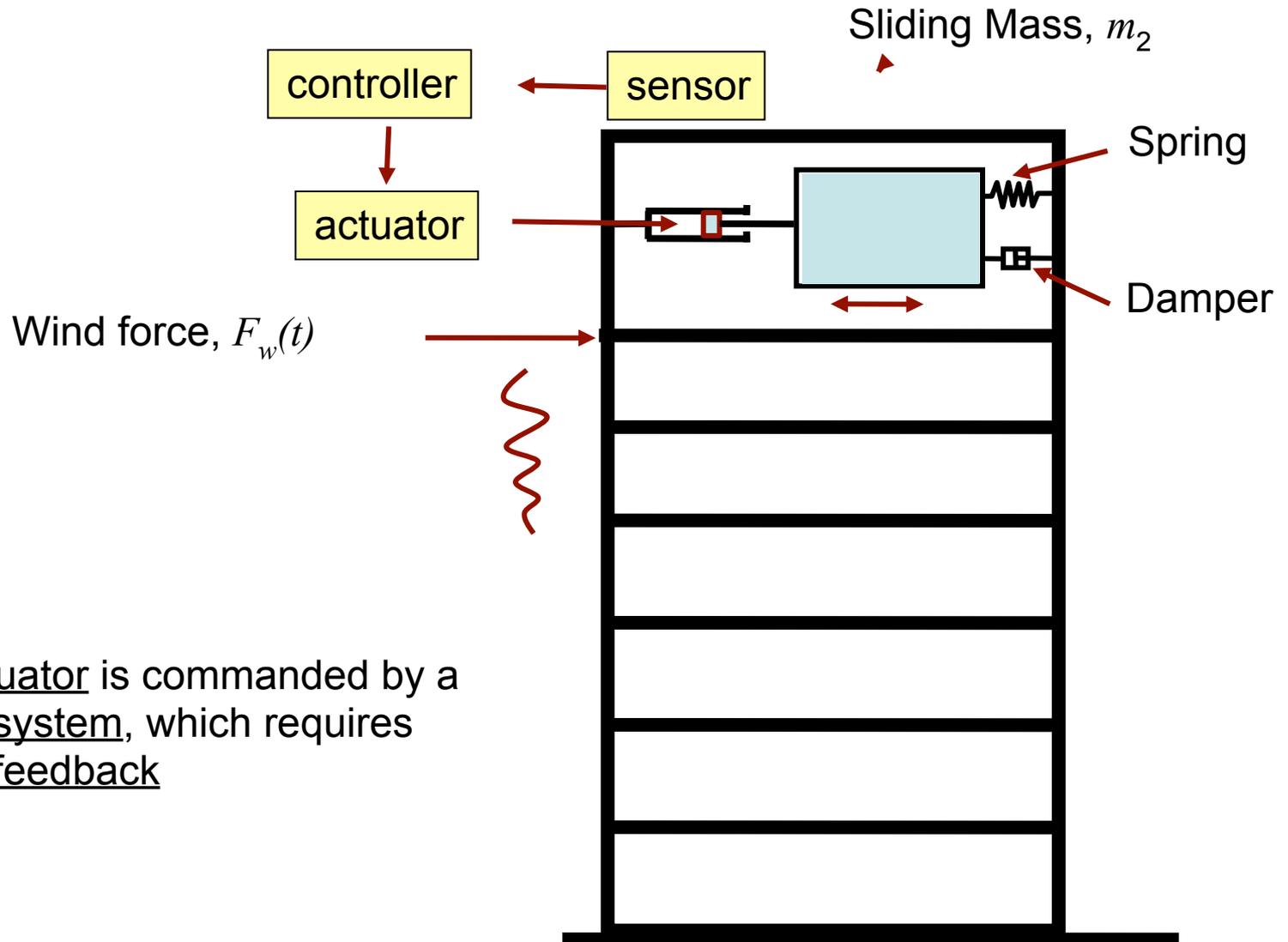
The passive wind damper with a diameter of 5.5 meters and weighting 660 metric tons, is also the largest in the world now.



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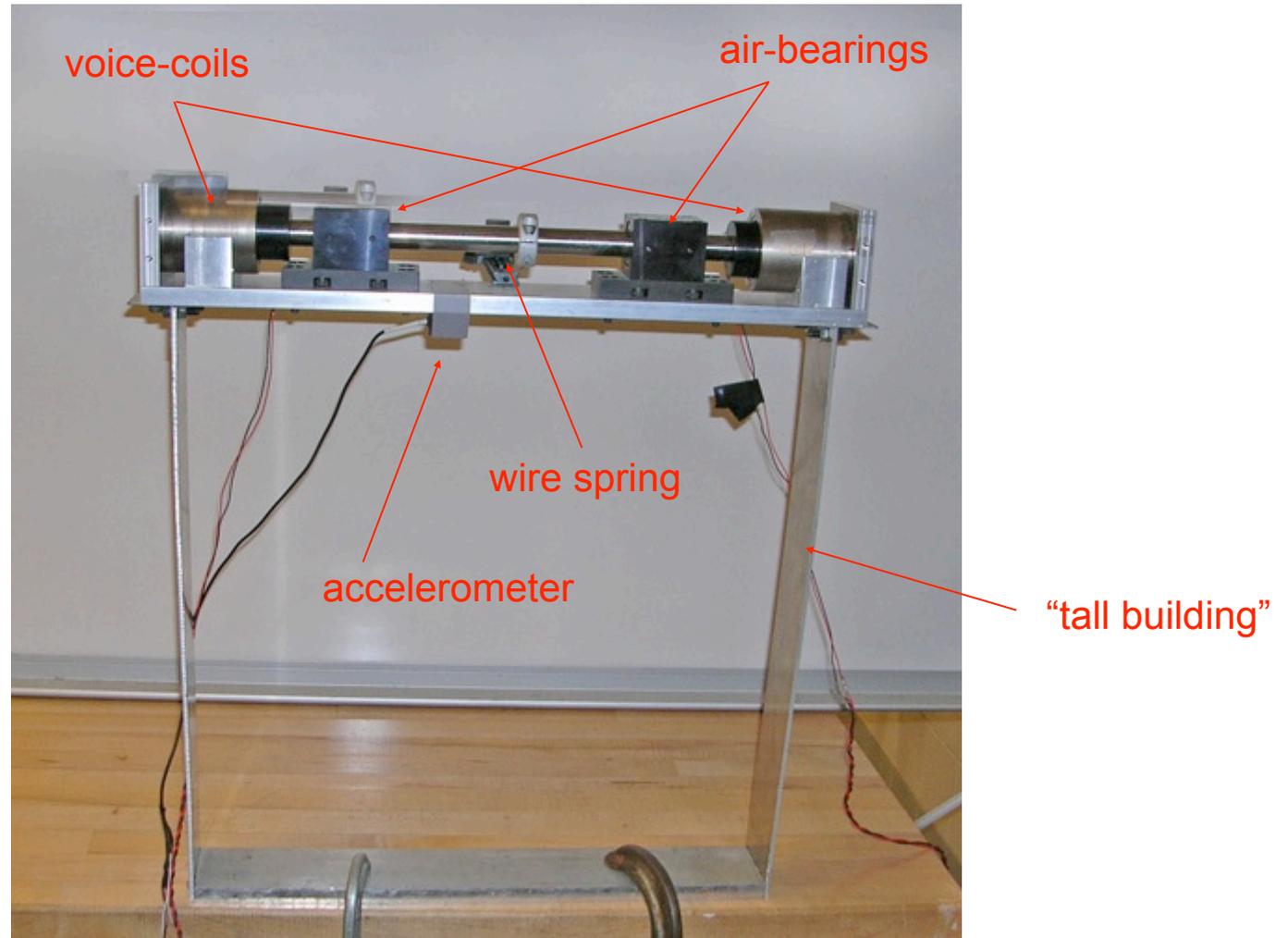
Courtesy of Daniel M. Shih. Used with permission.

# Active Damper Design

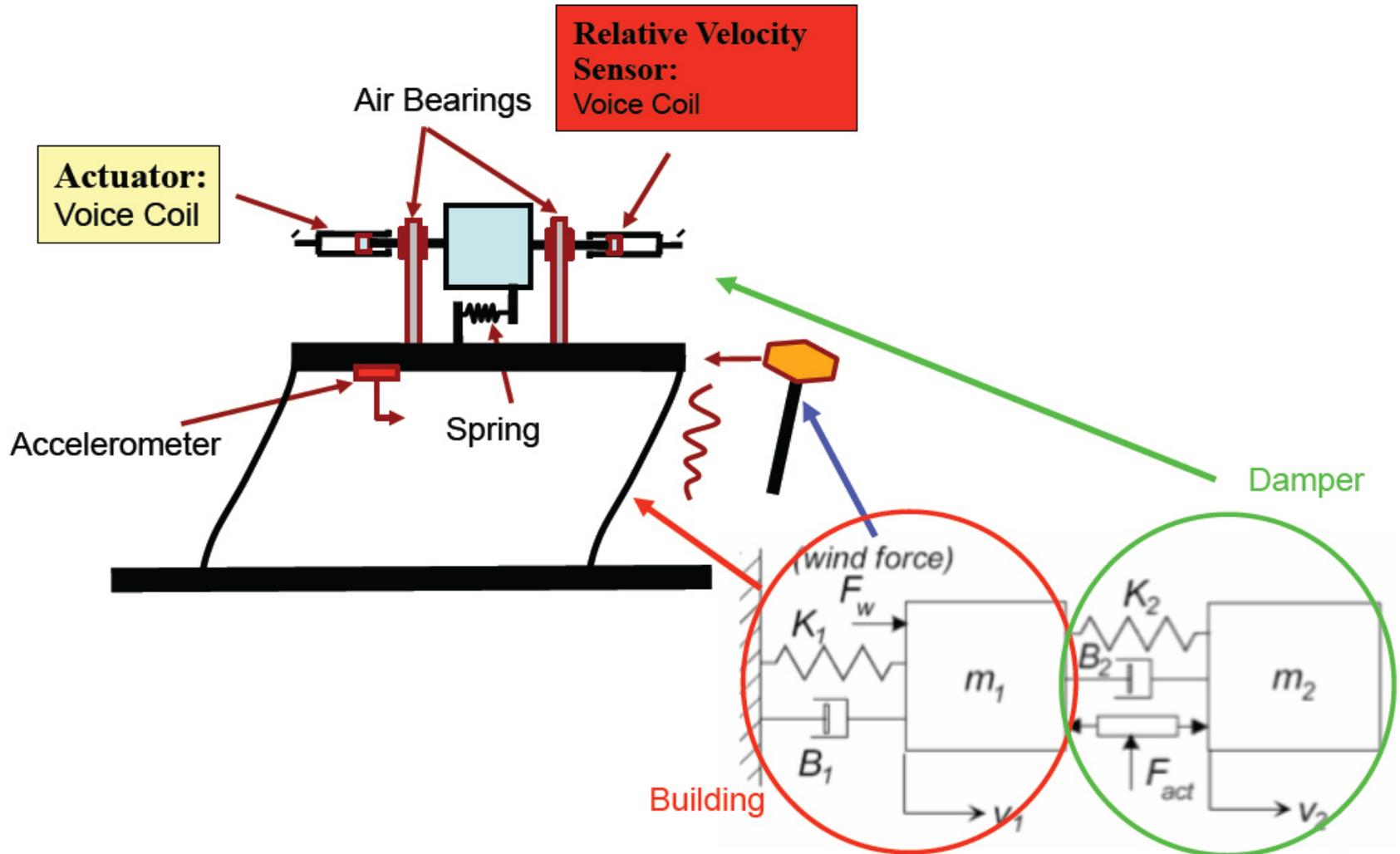


The actuator is commanded by a control system, which requires sensor feedback

# Experimental System

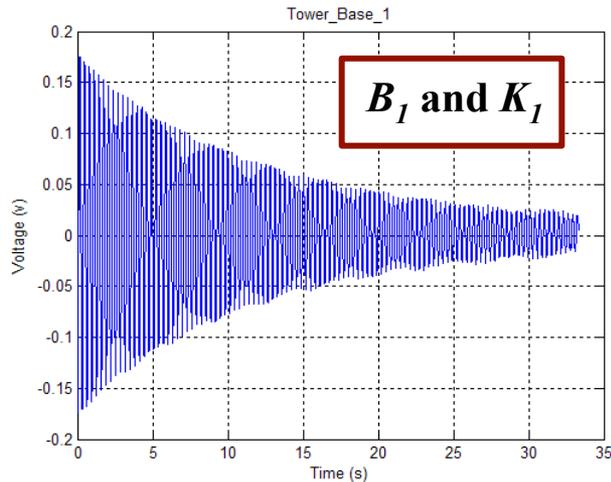


# System Modeling

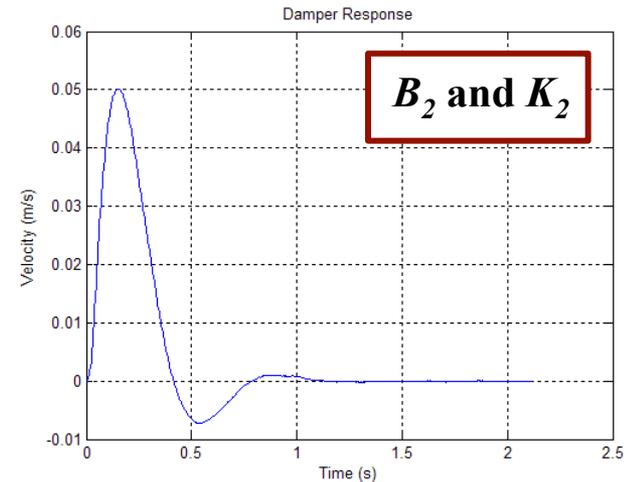


# Available Impulse Response Data (Course Lockers\2.004\Labs\Tower Data)

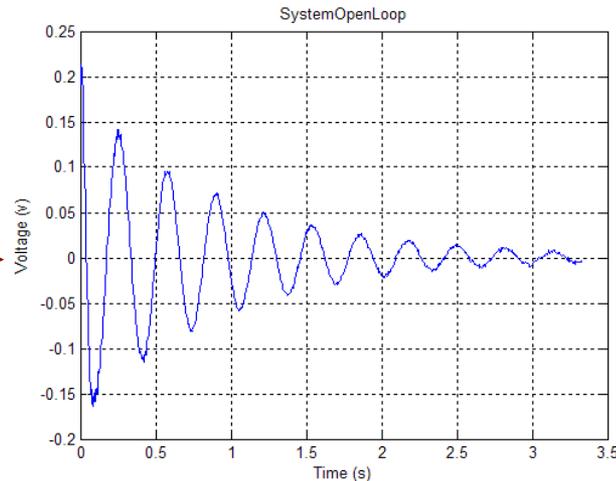
## Building Response



## Damper Response

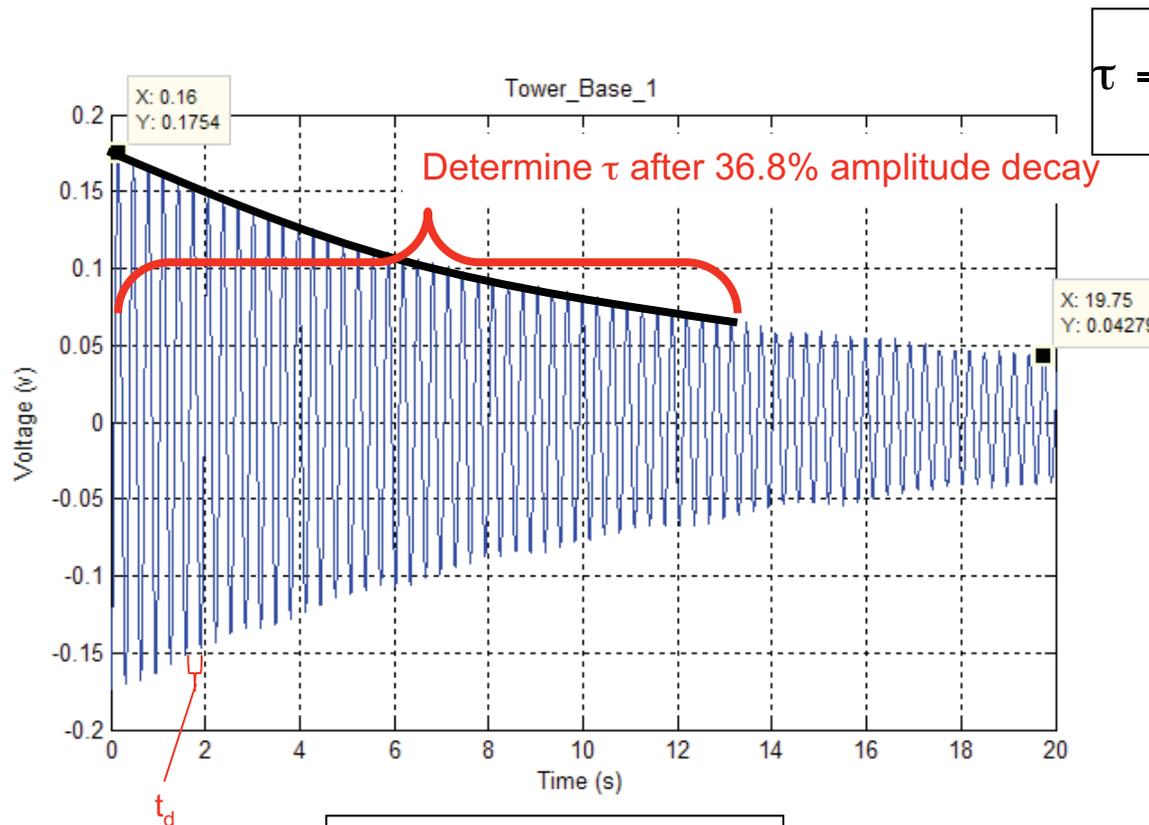


*Compare your transfer function impulse response to this one.*



## Open Loop System Response

# Estimating Parameters (Building)



$$\tau = \frac{1}{\zeta \omega_n}$$

*Logarithmic decrement method*

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

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

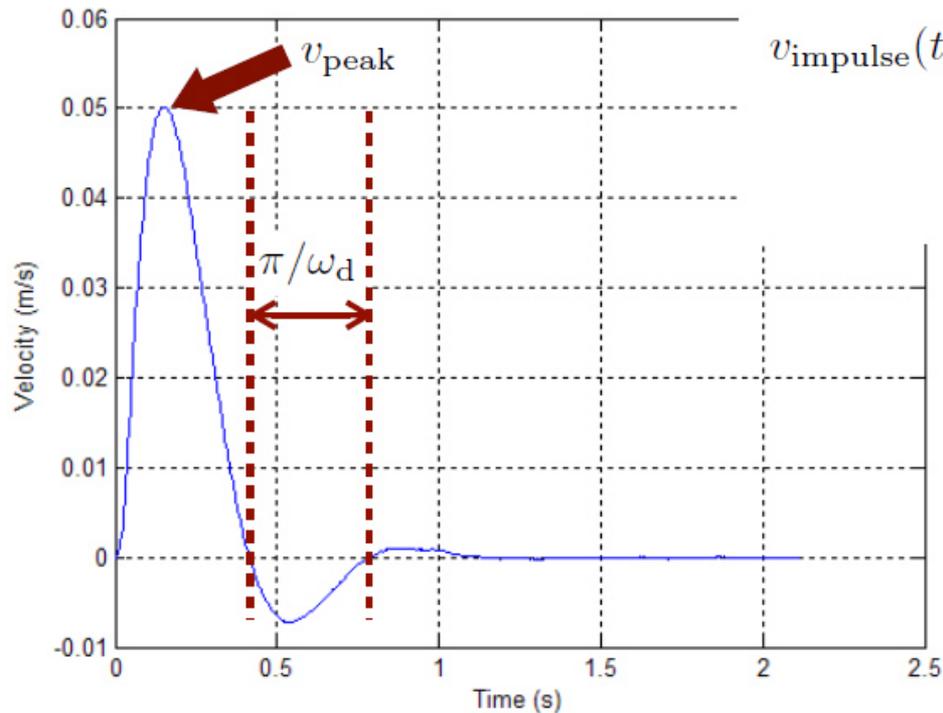
$$\zeta = \frac{\frac{\delta}{2\pi}}{\sqrt{1 + \left(\frac{\delta}{2\pi}\right)^2}}$$

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

$$m\ddot{x} + b\dot{x} + kx \longleftrightarrow s^2 + 2\zeta\omega_n s + \omega_n^2$$

# Estimating Parameters (Damper)

Impulse Response with Damper



Impulse response:

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

From this (after some algebra)  
we obtain

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

$$c \equiv -\ln \frac{v_{\text{peak}}}{4\omega_d}$$

$$m\ddot{x} + b\dot{x} + kx$$



$$s^2 + 2\zeta\omega_n s + \omega_n^2$$

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2.04A Systems and Controls  
Spring 2013

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