2.04A Class Project

Tall Building 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/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 58th floor.)

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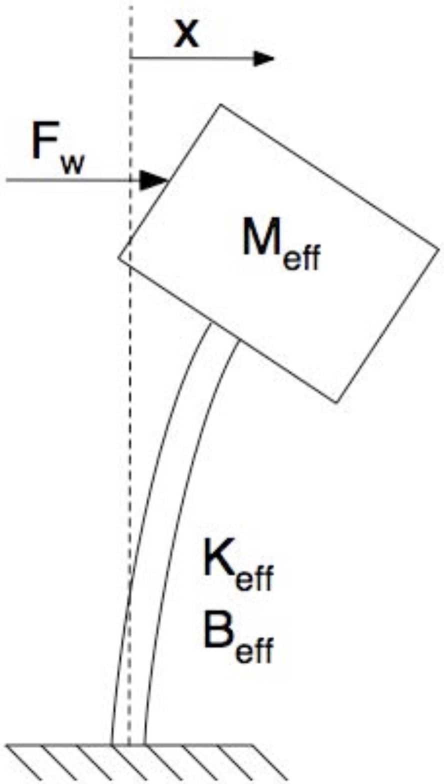
Simplified Building Model

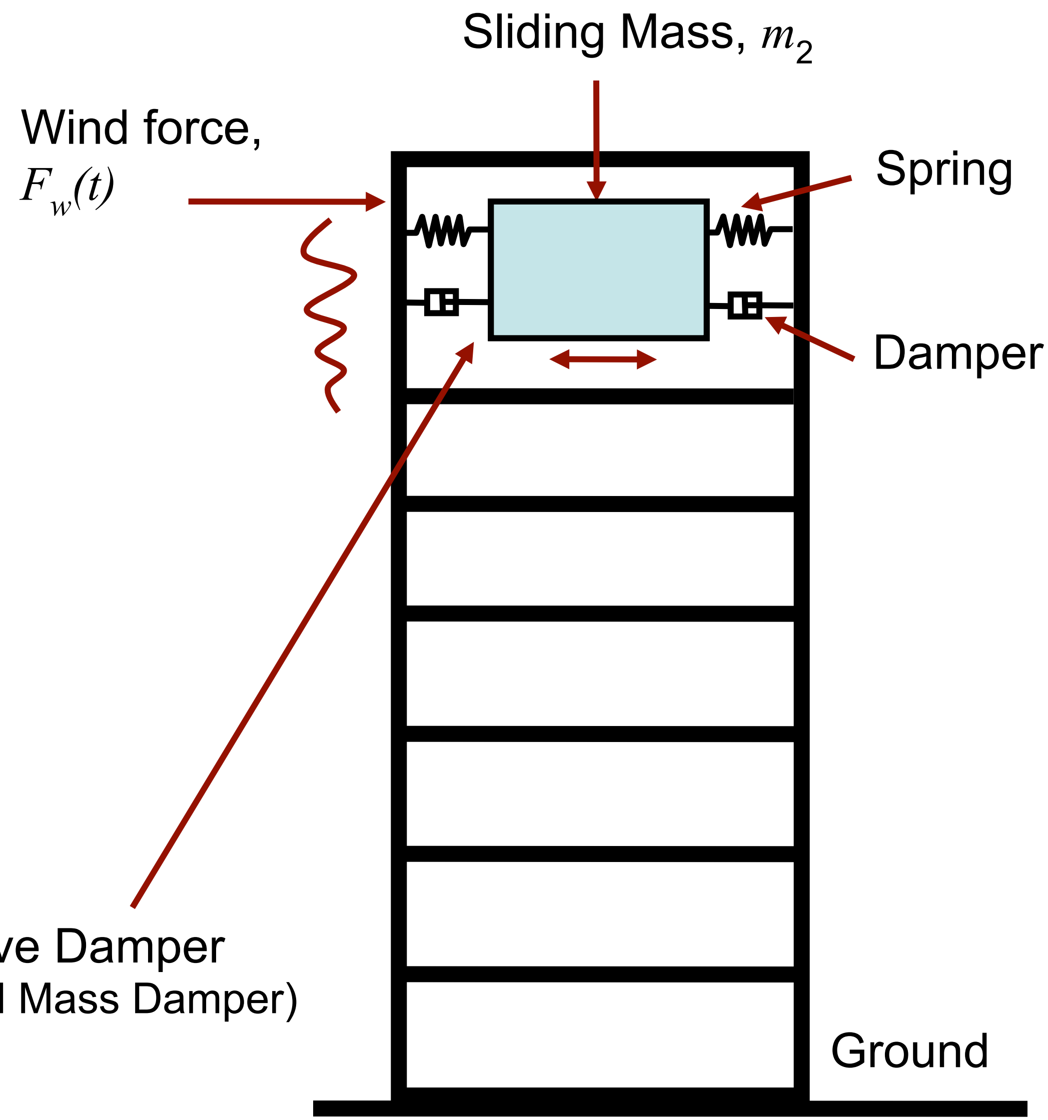
- We can model a tall building as a single degree of freedom lumped-parameter system.

John Hancock Tower, Boston	
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%

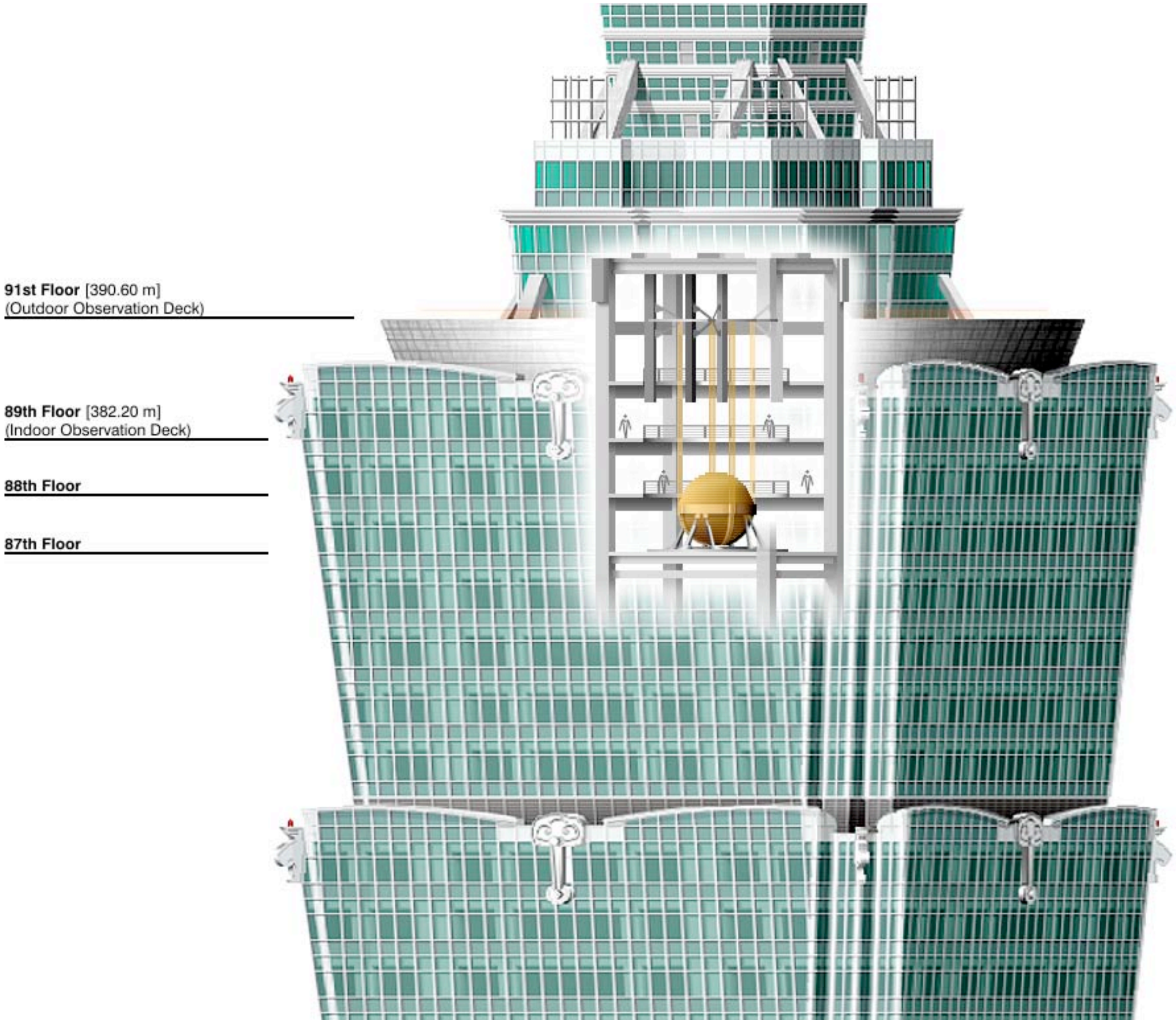


Passive Vibration Damping

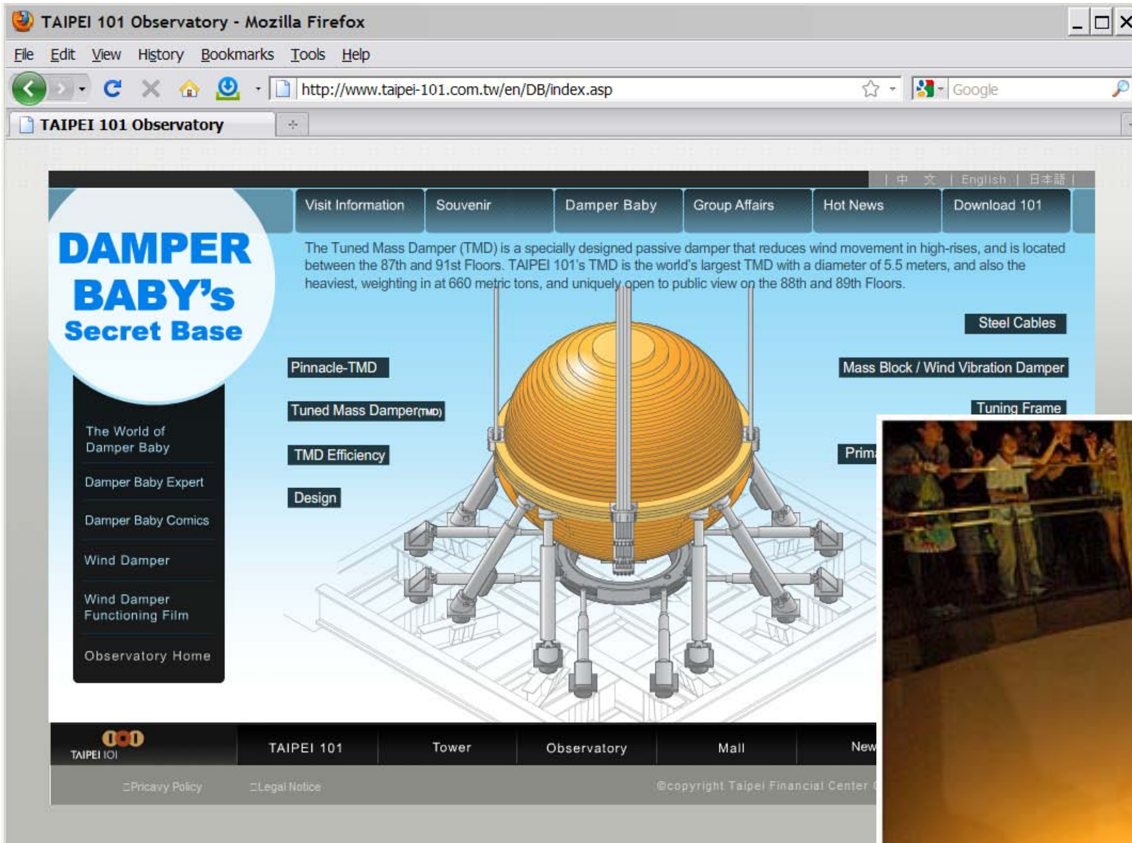
One way to stabilize these tall builds from swaying too much during earthquakes or from high winds is to install enormous pendulum weights. When the building sways sideways the pendulum doesn't want to move (inertia) and exerts a pull in the opposite direction.



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



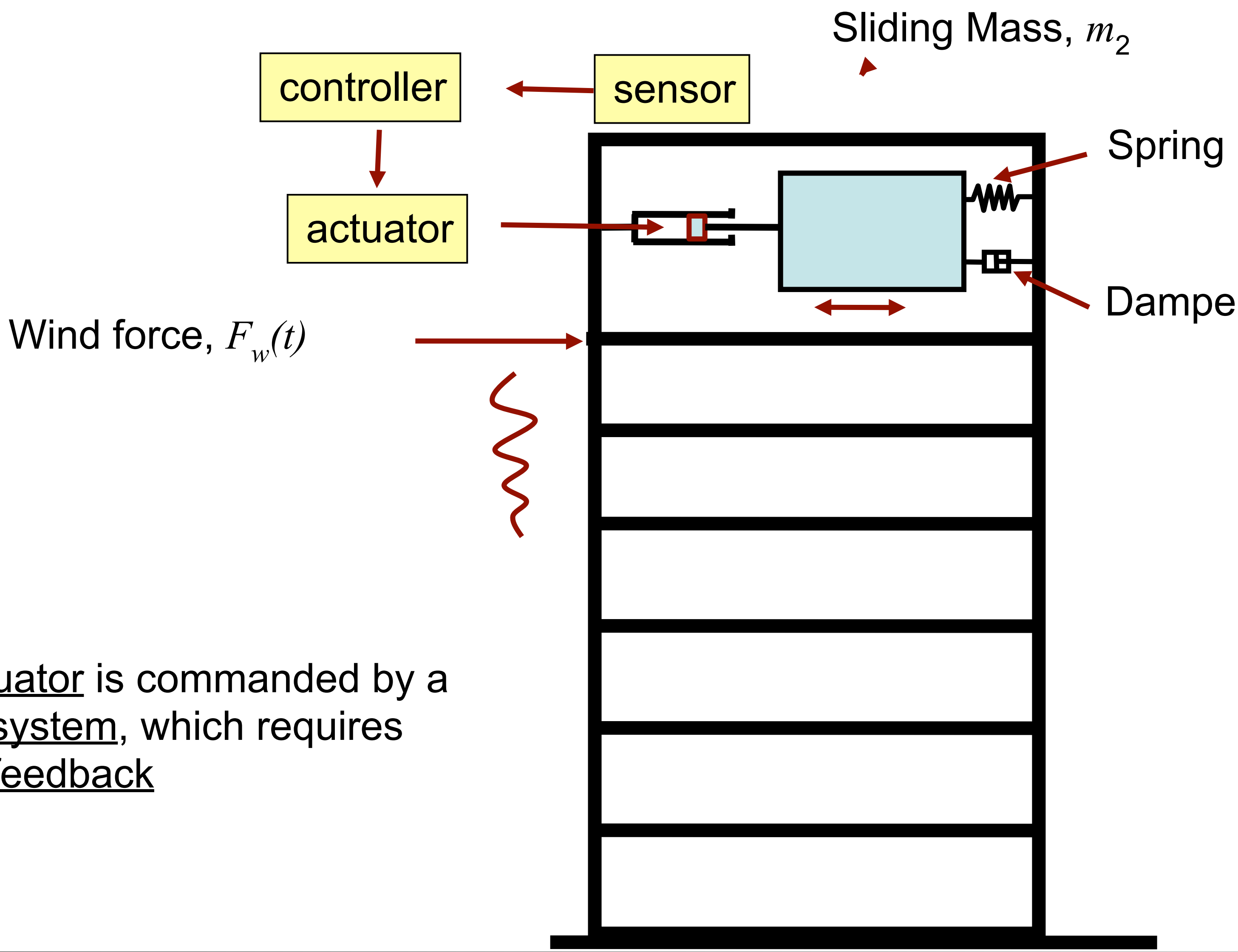
The Tuned Mass Damper in Taipei 101



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

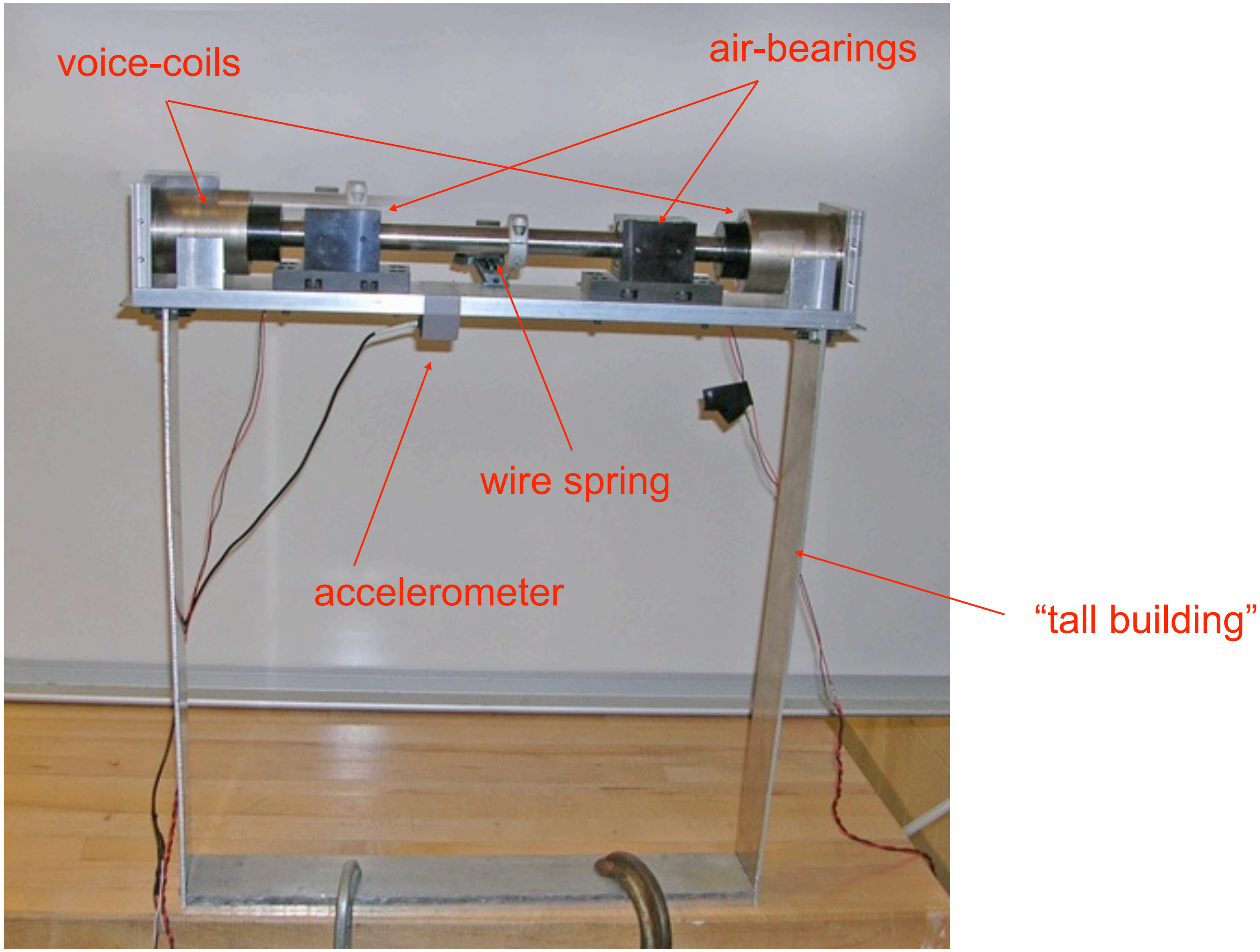
Courtesy of Daniel M. Shih. Used with permission.

Active Damper Design

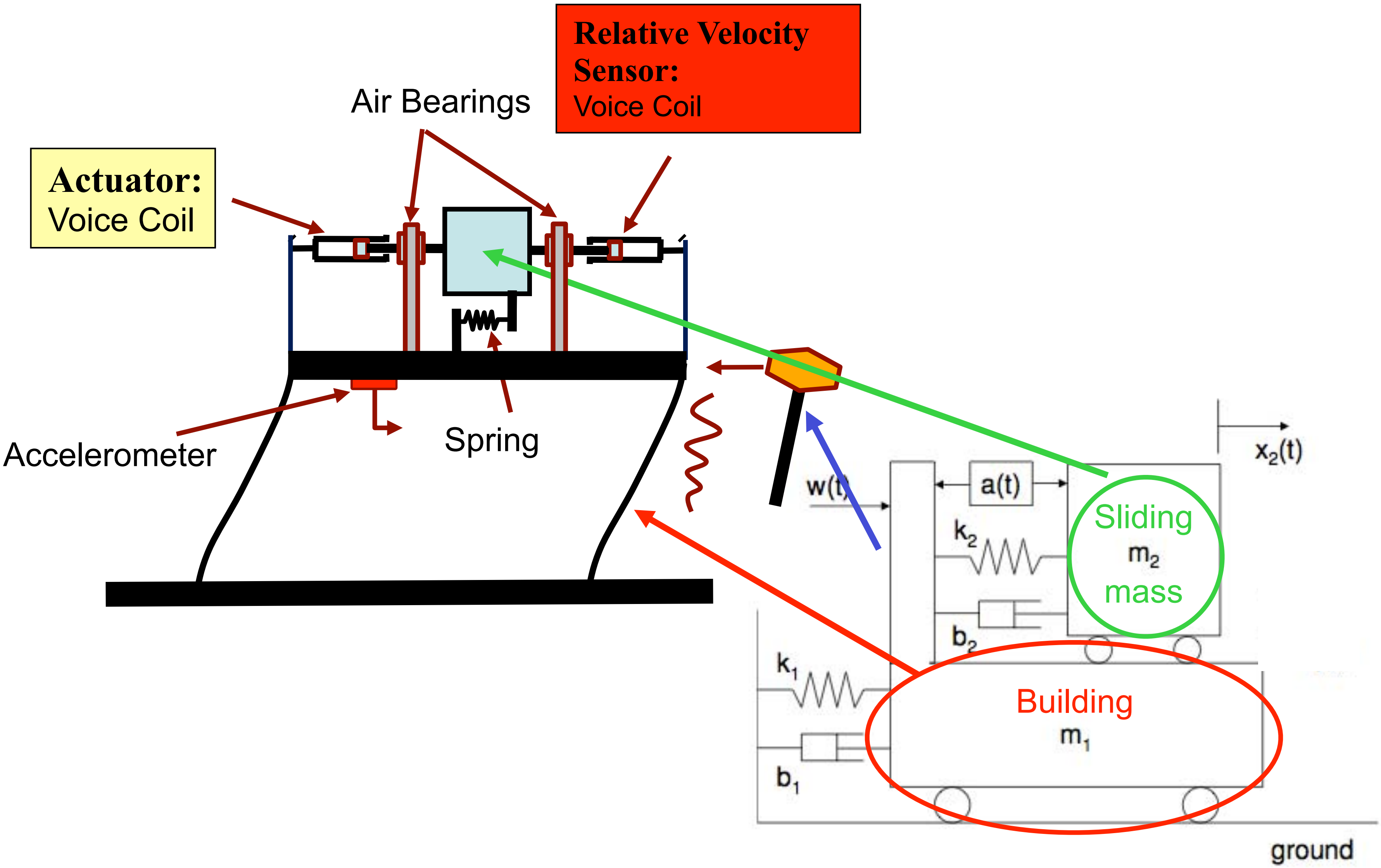


The actuator is commanded by a control system, which requires sensor feedback

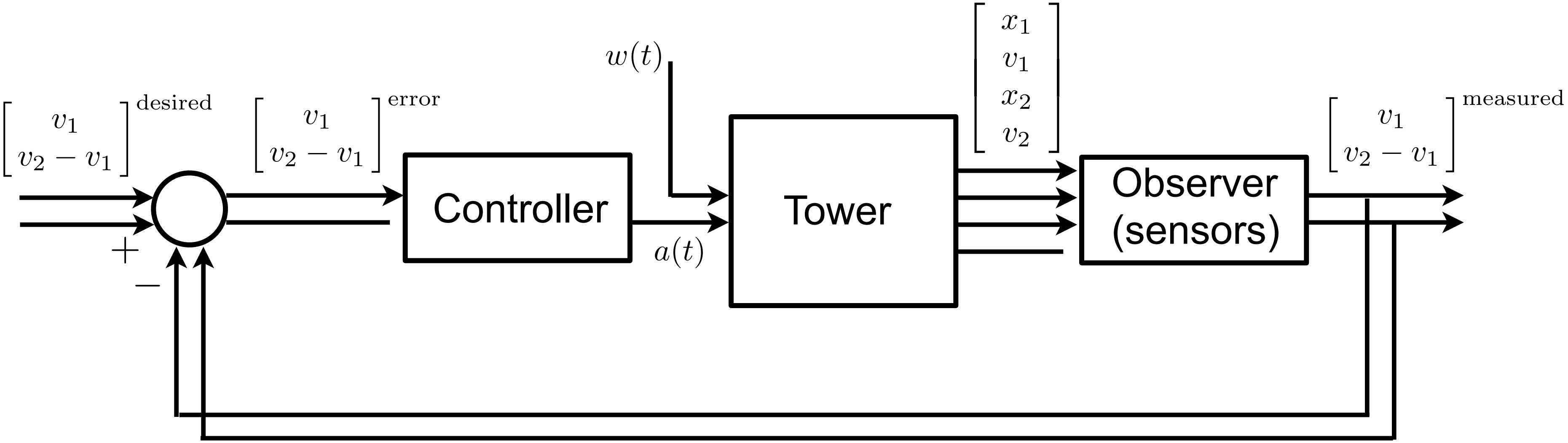
Experimental System



System Modeling



Tower feedback schematic



$$\boxed{\begin{aligned} \dot{\mathbf{q}} &= \mathbf{Aq} + \mathbf{Bu} \\ \mathbf{y} &= \mathbf{Cq} + \mathbf{Du} \end{aligned}}$$

$$\mathbf{q} \equiv \begin{bmatrix} x_1 \\ v_1 \\ x_2 \\ v_2 \end{bmatrix} \quad \text{(state vector)} \qquad \mathbf{y} = \begin{bmatrix} v_1 \\ v_2 - v_1 \end{bmatrix} \quad \text{(observation vector)}$$

$$\mathbf{u} = \begin{bmatrix} w(t) \\ a(t) \end{bmatrix} \quad \text{(disturbance \& actuation vector)}$$

$w(t)$ disturbance input (force due to wind)

$a(t)$ actuation input (force due to voice coil)

- ➡ We will attempt to control the Tower using *only* the v_2-v_1 signal as input to a PID controller. Thus, we can apply all that we learnt on SISO controllers in the class so far; performance, however, will be limited.
- ➡ Using both output signals as input to the controller constitutes what is known as *state-space* control. It is the most powerful of all, but falls outside the scope of our introductory class. Next week we will play around with a state-space controller to see what it can do, without going too much into the details.

Procedure #1

- Obtain the Tower's equation of motion
- Derive the state-space representation of the system

$$\dot{\mathbf{q}} = \mathbf{A}\mathbf{q} + \mathbf{B}\mathbf{u}$$
$$\mathbf{y} = \mathbf{C}\mathbf{q} + \mathbf{D}\mathbf{u}$$

$$\text{where} \quad \mathbf{q} \equiv \begin{bmatrix} x_1 \\ v_1 \\ x_2 \\ v_2 \end{bmatrix} \qquad \text{(state vector)}$$

$$\mathbf{u} = \begin{bmatrix} w(t) \\ a(t) \end{bmatrix} \qquad \text{(disturbance \& actuation vector)}$$

$$\mathbf{y} = \begin{bmatrix} v_1 \\ v_2 - v_1 \end{bmatrix} \qquad \text{(observation vector)}$$

Hint: see also Problem 4 of PSet 4

Procedure #2

- The "*PID_template.m*" code template provided under "Additional Materials" in the "Lecture Notes & Labs" contains all system physical parameters and it allows you to convert the system state-space transfer function to transfer functions of each output respect to each input. Numerical values for the system parameters are on the last page of this handout.

  Download the template file and make sure you understand its contents compared to the mathematical state-space representation.

  Enter your A, B, C, D state-space matrices into the template and comment on the open-loop system response to an impulse in w(t) [abrupt and very brief "knock" by a wind gust.]

Procedure #3 - Controlling the actuation force

- The force from the wind w(t) is the "disturbance," whereas the force from the actuator is the "controller" which is meant to cancel the disturbance. Both can be thought of as inputs to the tower plant. The outputs are the velocity $v_1(t)$ and relative velocity $v_2(t)-v_1(t)$, because this is what our sensors measure. Thus, this is a MIMO (multiple-input, multiple-output) system.
- The input to the feedback system is the difference between the outputs from the sensors and the desired outputs (recall that the desired outputs are the input commands). To "quiet" the Tower, the input command/desired output requires the vibration of motion to equal "zero," i.e. $(v_1(t) = 0 \text{ and } v_2(t) - v_1(t) = 0)$. Obtain a SISO model that "equivalently" models this MIMO system [we will help you.]

Procedure #4 - Controlling the actuation force

- Design a PID controller using graphical tuning and analysis plots from MATLAB SISOTOOL.
  - You will have to move around the zeros of the PID controller and play around with the gains quite a bit to obtain a reasonable response (i.e., “quieting” the Tower.)
  - However, **all controller gain values <u>must</u> be limited to <2.0**

- Verify your controller design first using a simulation (uncomment the last part of “*PID_template.m*”). Save and print some representative responses from “good” and “bad” controllers.

Procedure #5 - Design verification

- Test on the real system. Don't be surprised if you find yourself having to experimentally modify your PID design slightly compared to the simulation; this is because our model can not fully represent the real system. Also, don't expect any dramatic improvements; the PID controller is quite limited in what it can do.
- Turn in plots with the responses of the experimental and explain your reasoning of the design process. Clearly note your final controller design. Compare your system performance with and without the controller. (*Hint*: use a characteristic time).
- Demonstrate your PID design effectiveness on the actual system to the instructors.

System Parameters

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\begin{aligned}
m_1 &= 5.11 \text{ kg} \\
m_2 &= 0.945 \text{ kg} \\
k_1 &= 1120 \text{ N/m} \\
k_2 &= 75 \text{ N/m} \\
b_1 &= 0.87 \text{ N-sec/m} \\
b_2 &= 8.4 \text{ N-sec/m} \\
K_{\text{act}} &= 7.1 \text{ N/A} \\
K_{\text{sensor}} &= 7.1 \text{ Volts-sec/m} \\
K_{\text{a}} &= 2 \text{ Amp/Volt}
\end{aligned}
$$