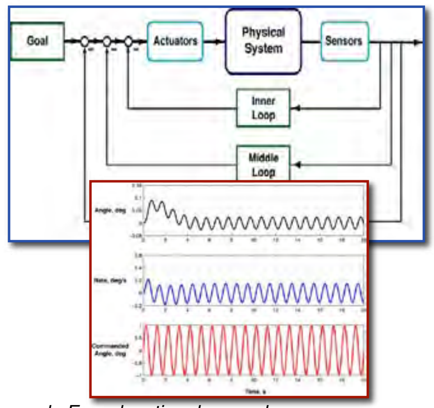
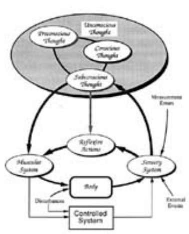
Dynamic Effects of Feedback Control

Robert Stengel
Robotics and Intelligent Systems MAE 345, Princeton University, 2015

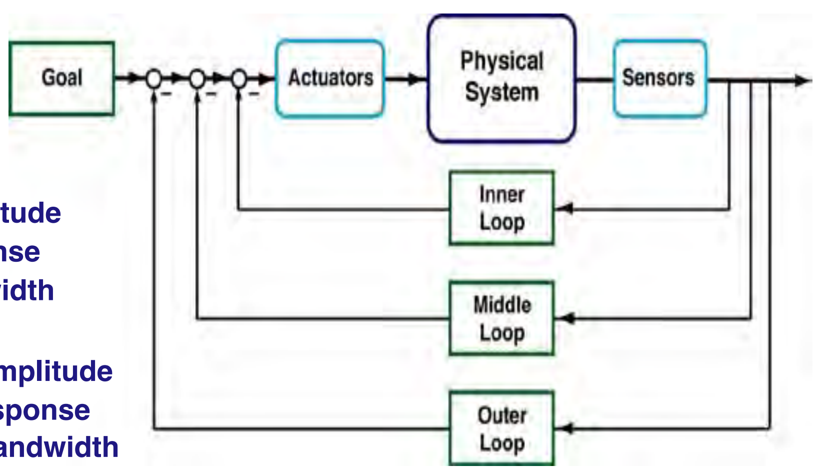
- Inner, Middle, and Outer Feedback Control Loops
- Step Response of Linear, Time-Invariant (LTI) Systems
- Position and Rate Control
- Transient and Steady-State Response to Sinusoidal Inputs



http://www.princeton.edu/~stengel/MAE345.html



Outer-to-Inner-Loop Control Hierarchy



- **Inner Loop**
  - Small Amplitude
  - Fast Response
  - High Bandwidth
- **Middle Loop**
  - Moderate Amplitude
  - Medium Response
  - Moderate Bandwidth
- **Outer Loop**
  - Large Amplitude
  - Slow Response
  - Low Bandwidth

- **Feedback**
  - Error between command and feedback signal drives next inner-most loop

Natural Feedback Control

Inner Loop

Chicken Head Control - 1

http://www.youtube.com/watch?v=_dPlkFPowCc

Middle Loop

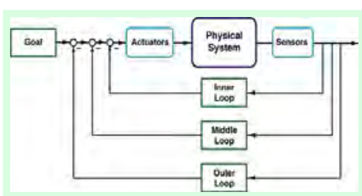
Hovering Red-Tail Hawks

http://www.youtube.com/watch?v=-VPVZMSEvwU

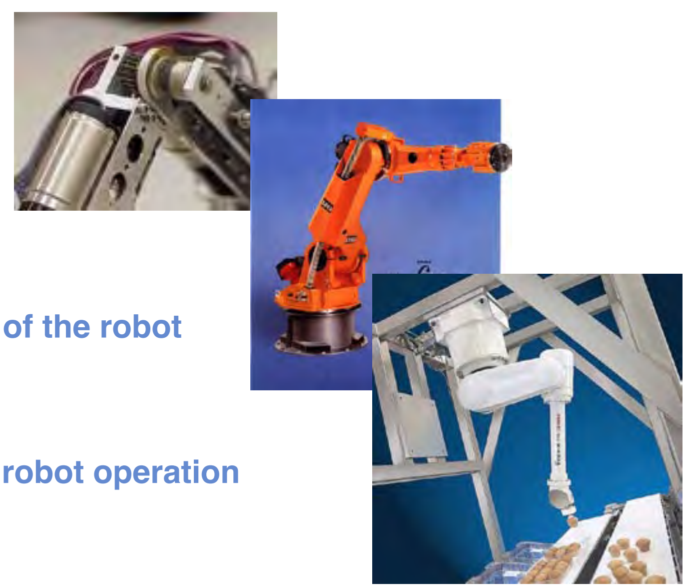
Outer Loop

Osprey Diving for Fish

http://www.youtube.com/watch?v=qrgpl9-N6jY



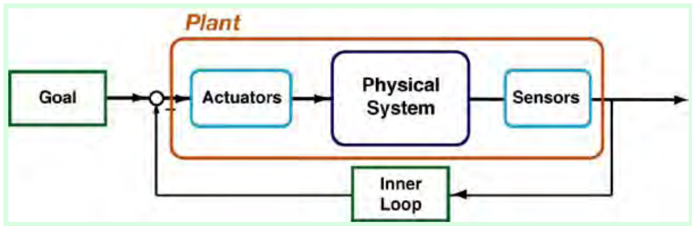
Outer-to-Inner-Loop Control Hierarchy of an Industrial Robot



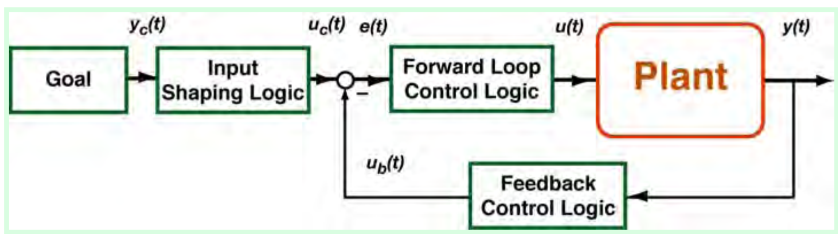
- **Inner Loop**
  - Focus on control of individual joints
- **Middle Loop**
  - Focus on operation of the robot
- **Outer Loop**
  - Focus on goals for robot operation

Inner-Loop Feedback Control

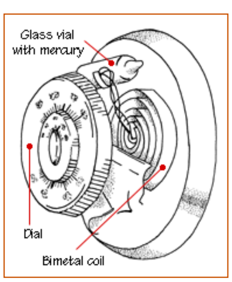
Feedback control design must account for actuator-system-sensor dynamics

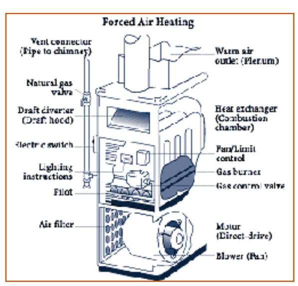


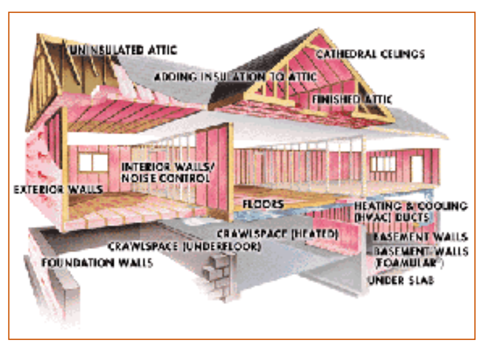
Single-Input/Single-Output Example, with forward and feedback control logic ("compensation")



Thermostatic Temperature Control

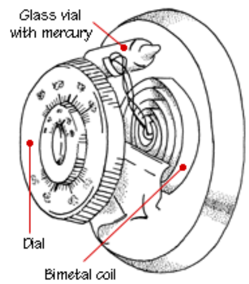




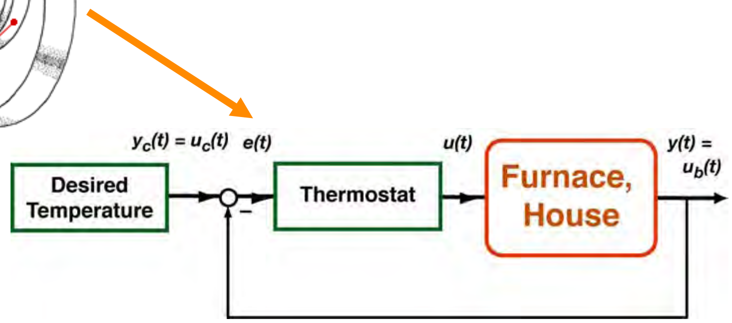


- **Dynamics**
  - Delays
  - Dead Zones
  - Saturation
  - Coupling
- **Structure**
  - Layout
  - Insulation
  - Circulation
  - Multiple Spaces
- **External Effects**
  - Solar Radiation
  - Air Temperature
  - Wind
  - Rain, Humidity

... all controlled by a simple (but nonlinear) on/off switch



Thermostat Control Logic



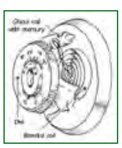
- **Control Law** ***[i.e., logic that drives the control variable, u(t)]***

$$e(t) = y_c(t) - y(t) = u_c(t) - u_b(t)$$

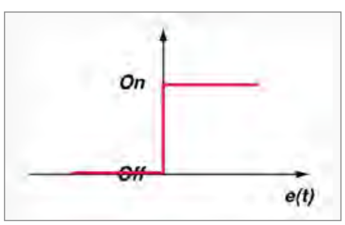
$$< \text{Thermostat} >$$

$$u(t) = \begin{cases} 1\,(on), & e(t) > 0 \\ 0\,(off), & e(t) \le 0 \end{cases}$$

- y_c: Desired output variable (command)
- y: Actual output
- u: Control variable (forcing function)
- e: Control error



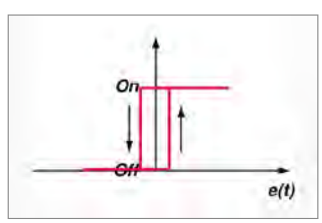
Thermostat Control Logic



$$u(t) = \begin{cases} 1\,(on), & e(t) > 0 \\ 0\,(off), & e(t) \le 0 \end{cases}$$

- **...but control signal would "chatter" with slightest change of temperature**
- **Solution: Introduce *lag* to slow the switching cycle, e.g., *hysteresis***

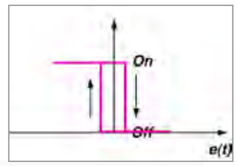
$$u(t) = \begin{cases} 1\,(on), & e(t) - T > 0 \\ 0\,(off), & e(t) + T \le 0 \end{cases}$$

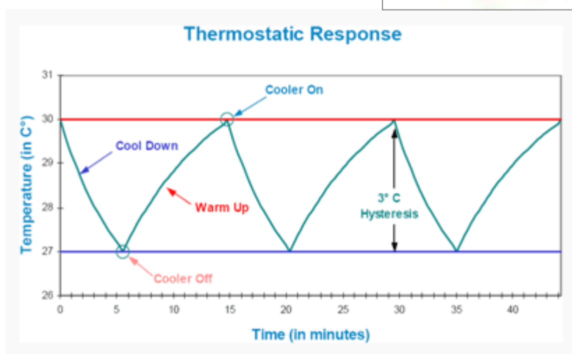


Thermostat Control Logic with Hysteresis

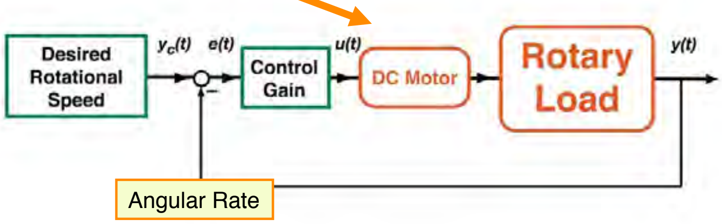
Hysteresis delays the response
System responds with a *limit cycle*

- Cooling control is similar with sign reversal





Speed Control of Direct-Current Motor



Linear Feedback Control Law *(c = Control Gain)*

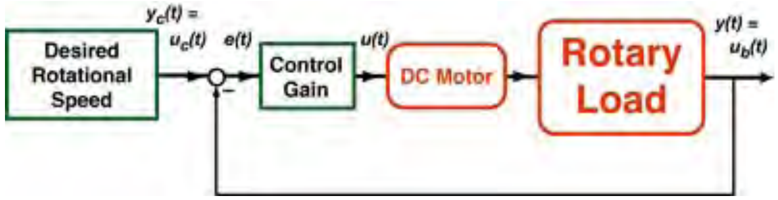
$$u(t) = c\,e(t)$$

where

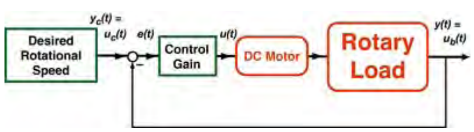
$$e(t) = y_c(t) - y(t)$$

How would *y(t)* be measured?

Characteristics of the Model



- **Simplified Dynamic Model**
  - **Rotary inertia, *J*, is the sum of motor and load inertias**
  - **Internal damping neglected**
  - **Output speed, *y(t)*, rad/s, is an integral of the control input, *u(t)***
  - **Motor control torque is proportional to *u(t)***
  - **Desired speed, $y_c(t)$, rad/s, is constant**



Model of Dynamics and Speed Control

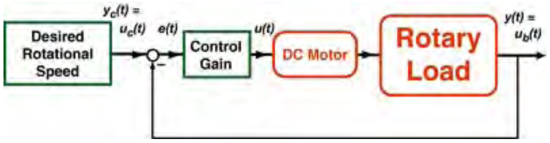
First-order LTI ordinary differential equation

$$\boxed{\frac{dy(t)}{dt} = \frac{1}{J}u(t) = \frac{c}{J}e(t) = \frac{c}{J}\left[y_c(t) - y(t)\right], \quad y(0) \ \text{given}}$$

Integral of the equation, with $y(0) = 0$

$$\boxed{y(t) = \frac{1}{J}\int_0^t u(t)\,dt = \frac{c}{J}\int_0^t e(t)\,dt = \frac{c}{J}\int_0^t \left[y_c(t) - y(t)\right]dt}$$

- Direct integration of $y_c(t)$
- Negative feedback of $y(t)$



Step Response of Speed Controller

Step input :

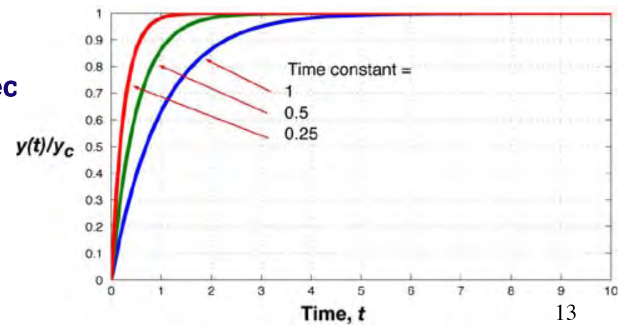
$$y_C(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases}$$

- **Solution of the integral**

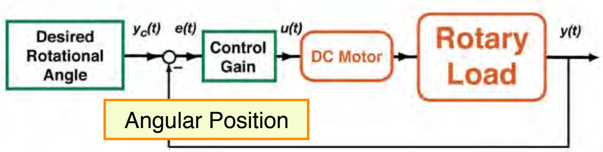
$$y(t) = y_c\left[1 - \exp^{-\left(\frac{c}{J}\right)t}\right] = y_c\left[1 - \exp^{\lambda t}\right] = y_c\left[1 - \exp^{-t/\tau}\right]$$

- **where**
  - λ = $-c/J$ = eigenvalue or root of the system (rad/sec
  - τ = J/c = time constant of the response (sec)

What does the shaft angle response look like?



Angle Control of Direct-Current Motor



- **Simplified Dynamic Model**
  - Rotary inertia, ***J***, is the sum of motor and load inertias
  - Output angle, ***y(t)***, is a double integral of the control, ***u(t)***
  - Desired angle, $y_c(t)$, is constant

Feedback Control Law

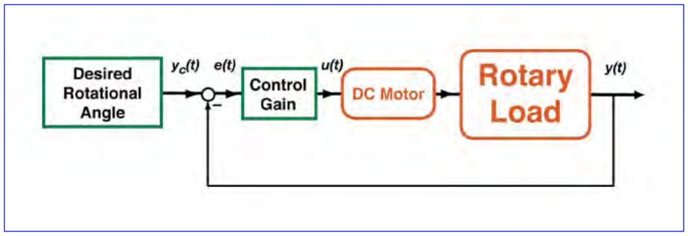
$$u(t) = c\,e(t)$$

where

$$e(t) = y_c(t) - y(t)$$

How would *y(t)* be measured?

Model of Dynamics and Angle Control



Output angle, *y(t)*, as a function of time

$$y(t) = \frac{1}{J}\int_0^t\int_0^t u(t)\,dt\,dt = \frac{c}{J}\int_0^t\int_0^t e(t)\,dt\,dt = \frac{c}{J}\int_0^t\int_0^t \left[y_c - y(t)\right]dt\,dt$$

Associated 2nd-order, linear, time-invariant ordinary differential equation

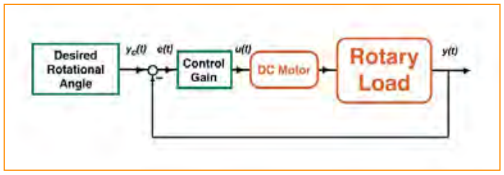
$$\frac{d^2 y(t)}{dt^2} = \ddot{y}(t) = \frac{c}{J}\left[y_c - y(t)\right]$$

Model of Dynamics and Angle Control

- **Corresponding set of 1st-order equations, with**
  - **Angle:** $x_1(t) = y(t)$
  - **Angular rate:** $x_2(t) = dy(t)/dt$

$$\dot{x}_1(t) = x_2(t)$$

$$\dot{x}_2(t) = \frac{u(t)}{J} = \frac{c}{J}\left[y_c - y(t)\right] = \frac{c}{J}\left[y_c - x_1(t)\right]$$



State-Space Model of the DC Motor

Open-loop dynamic equation

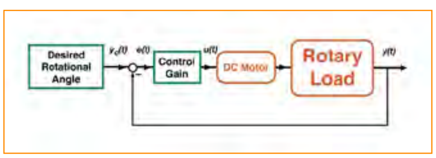
$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 1/J \end{bmatrix} u(t)$$

Feedback control law

$$u(t) = c\left[y_c(t) - y_1(t)\right] = c\left[y_c(t) - x_1(t)\right]$$

Closed-loop dynamic equation

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -c/J & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ c/J \end{bmatrix} y_c$$

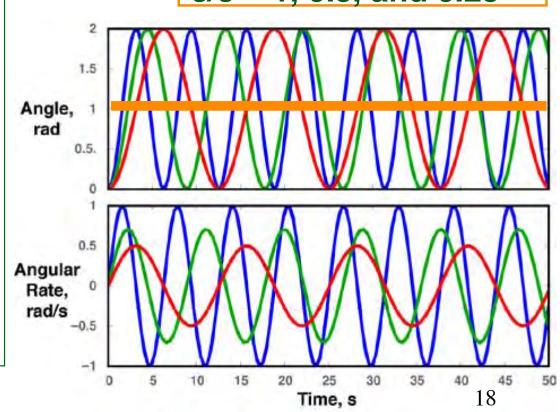


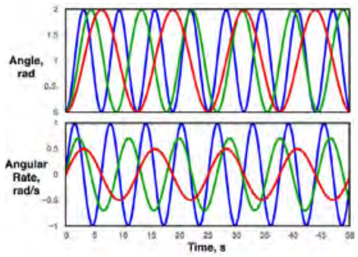
Step Response with Angle Feedback

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -c/J & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ c/J \end{bmatrix} y_c$$

```
%   Step Response of Undamped Angle Control

   F1  =  [0 1;-1 0];
   G1  =  [0;1];
   F2  =  [0 1;-0.5 0];
   G2  =  [0;0.5];
   F3  =  [0 1;-0.25 0];
   G3  =  [0;0.25];
   Hx  =  [1 0;0 1];

   Sys1    =  ss(F1,G1,Hx,0);
   Sys2    =  ss(F2,G2,Hx,0);
   Sys3    =  ss(F3,G3,Hx,0);

   step(Sys1,Sys2,Sys3)
```

***c/J* = 1, 0.5, and 0.25**



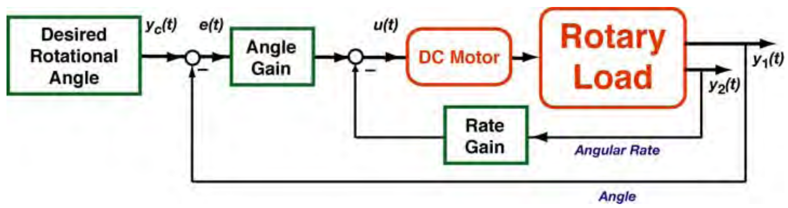


What Went Wrong?

- **No damping!**
- **Solution: Add rate feedback in the control law**

- **Control law with rate feedback**

$$u(t) = c_1\left[y_c(t) - y_1(t)\right] - c_2 y_2(t)$$



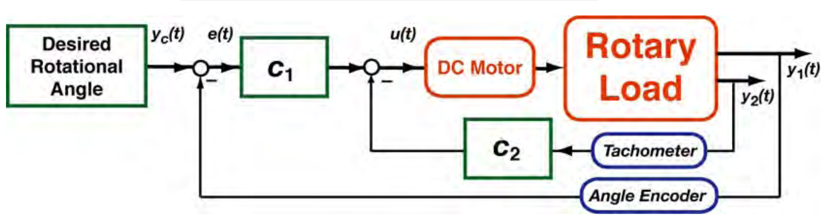
Closed-loop dynamic equation

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -c_1/J & -c_2/J \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ c_1/J \end{bmatrix} y_c$$

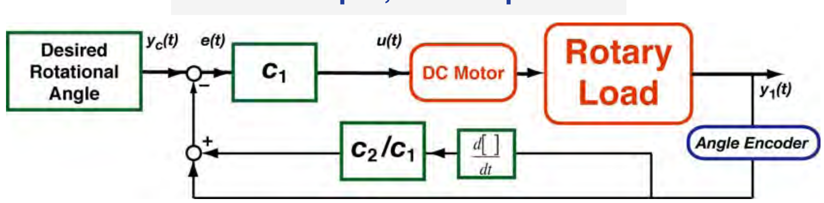
Alternative Implementations of Rate Feedback

$$u(t) = c_1\left[y_c(t) - y_1(t)\right] - c_2 y_2(t) = c_1\left[y_c(t) - y_1(t)\right] - c_2 \frac{dy_1(t)}{dt}$$

One input, two outputs



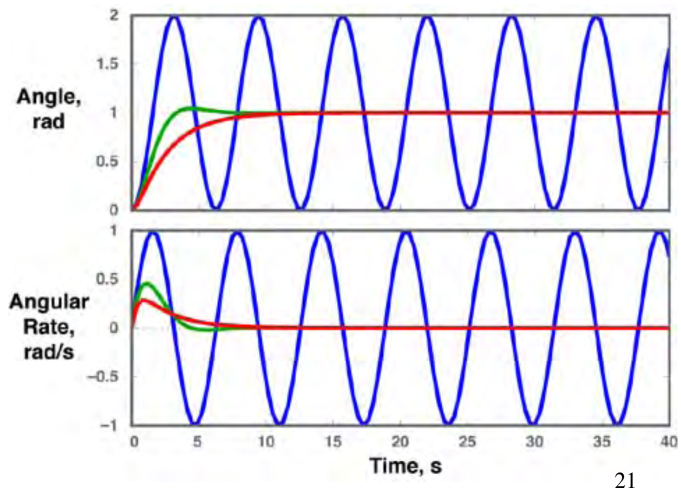
One input, one output



Step Response with Angle and Rate Feedback

$c_1 / J = 1$
$c_2 / J = 0,\ 1.414,\ 2.828$

```
%   Step Response of Damped
Angle Control

   F1  =  [0 1;-1 0];
   G1  =  [0;1];

   F1a = [0 1;-1 -1.414];
   F1b = [0 1;-1 -2.828];

   Hx  =  [1 0;0 1];

   Sys1   =  ss(F1,G1,Hx,0);
   Sys2   =  ss(F1a,G1,Hx,0);
   Sys3   =  ss(F1b,G1,Hx,0);

   step(Sys1,Sys2,Sys3)
```

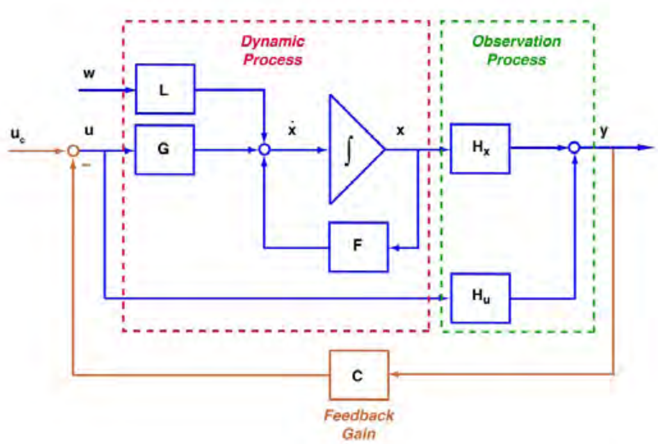


LTI Model with Feedback Control

- **Command input, $\mathbf{u}_c$, has dimensions of $\mathbf{u}$**

$$\mathbf{u}(t) = \mathbf{u}_c(t) - \mathbf{C}\mathbf{y}(t)$$

$$\dot{\mathbf{x}}(t) = \mathbf{F}\,\mathbf{x}(t) + \mathbf{G}\,\mathbf{u}(t) + \mathbf{L}\mathbf{w}(t)$$
$$\mathbf{y}(t) = \mathbf{H}_x\mathbf{x}(t) + \mathbf{H}_u\mathbf{u}(t)$$



Effect of Feedback Control on the LTI Model

$$\dot{\mathbf{x}}(t) = \mathbf{F}\,\mathbf{x}(t) + \mathbf{G}\,\mathbf{u}(t) = \mathbf{F}\,\mathbf{x}(t) + \mathbf{G}\left[\mathbf{u}_c(t) - \mathbf{C}\mathbf{y}(t)\right]$$
$$= \mathbf{F}_{open\ loop}\,\mathbf{x}(t) + \mathbf{G}\left\{\mathbf{u}_c(t) - \mathbf{C}\left[\mathbf{H}_\mathbf{x}\mathbf{x}(t)\right]\right\}$$

$$= \left[\mathbf{F} - \mathbf{G}\mathbf{C}\mathbf{H}_\mathbf{x}\right]\mathbf{x}(t) + \mathbf{G}\,\mathbf{u}_c(t)$$
$$\triangleq \mathbf{F}_{closed\ loop}\mathbf{x}(t) + \mathbf{G}\,\mathbf{u}_c(t)$$

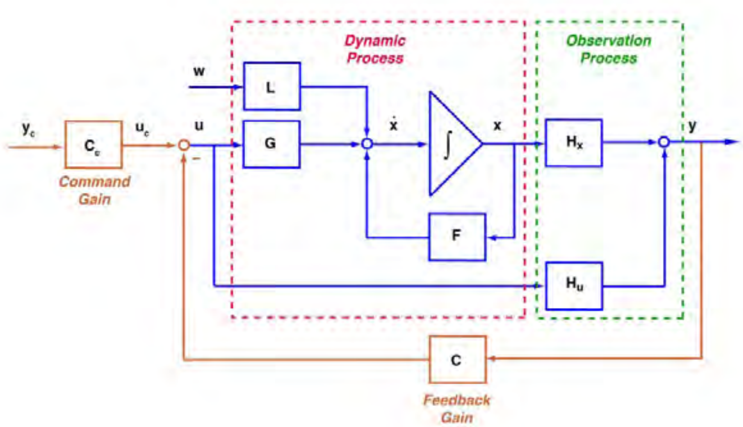
Feedback modifies the stability matrix of the closed-loop system

Convergence or divergence

Envelope of transient response

LTI Model with Feedback Control and Command Gain

Command input, $\mathbf{y}_c$, is "shaped" by $\mathbf{C}_c$



$$\mathbf{u}(t) = \mathbf{u}_c(t) - \mathbf{C}\mathbf{y}(t)$$
$$= \mathbf{C}_c\mathbf{y}_c(t) - \mathbf{C}\mathbf{y}(t)$$

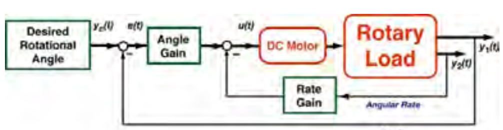
Effect of Command Gain on LTI Model

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{F}\mathbf{x}(t)+\mathbf{G}\mathbf{u}(t)=\mathbf{F}\mathbf{x}(t)+\mathbf{G}\left\{\mathbf{C}_c\mathbf{y}_c(t)-\mathbf{C}\mathbf{y}(t)\right\}\\ &= \mathbf{F}\mathbf{x}(t)+\mathbf{G}\left\{\mathbf{C}_c\mathbf{y}_c(t)-\mathbf{C}\left[\mathbf{H}_\mathbf{x}\mathbf{x}(t)\right]\right\}\\ &= \left[\mathbf{F}-\mathbf{G}\mathbf{C}\mathbf{H}_\mathbf{x}\right]\mathbf{x}(t)+\mathbf{G}\mathbf{C}_c\mathbf{y}_c(t)\end{aligned}$$

- **Steady-state response of the system** $\dot{\mathbf{x}}(t)=\mathbf{0}$

$$\mathbf{x}^*(t)=-\left[\mathbf{F}-\mathbf{G}\mathbf{C}\mathbf{H}_\mathbf{x}\right]^{-1}\mathbf{G}\mathbf{C}_c\mathbf{y}_c^*(t)$$

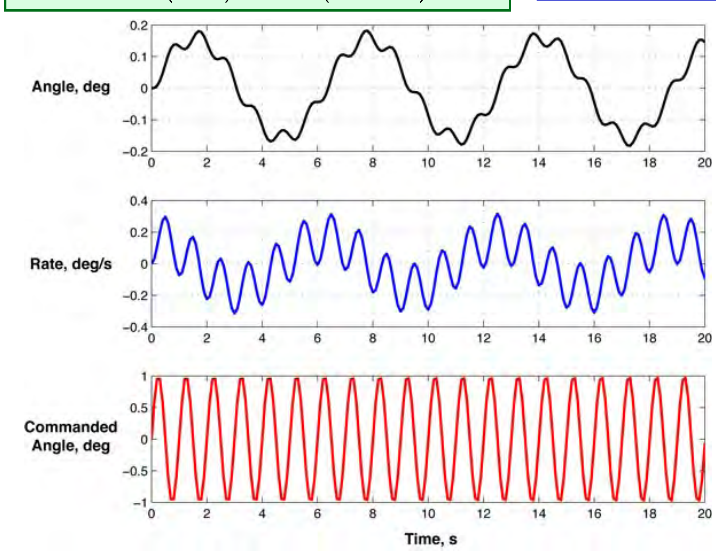
- **Command gain adjusts the steady-state response**
- **Has no effect on the stability of the system**



Response to Sine Wave Input with Angle Feedback: No Damping

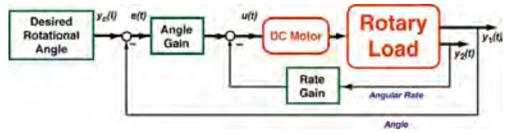
$$y_c(t)=\sin(\omega t)=\sin(6.28\,t),\ \text{deg}$$

$c_1/J = 1;\ c_2/J = 0$



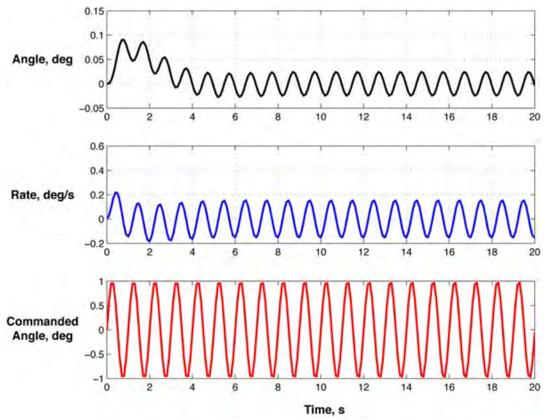
- **Why are there 2 oscillations in the output?**
  - ***Undamped transient response to the input***
  - ***Long-term dynamic response to the input***
- **System has a natural frequency of oscillation, ω_n**
- **Long-term response to a sine wave is a sine wave**

Response to Sine Wave Input with Rate Damping

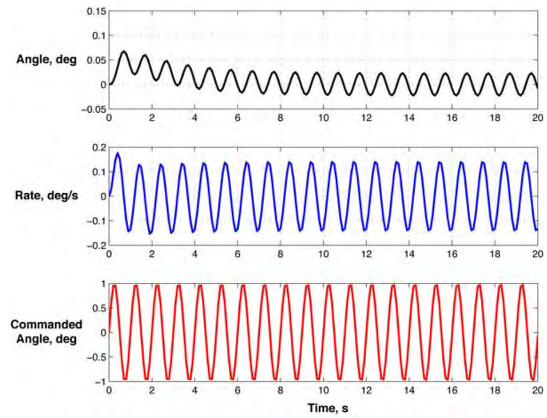


$$y_c(t) = \sin(\omega\, t) = \sin(6.28\, t), \text{deg}$$

$c_1/J = 1$; $c_2/J = 1.414$



$c_1/J = 1$; $c_2/J = 2.828$



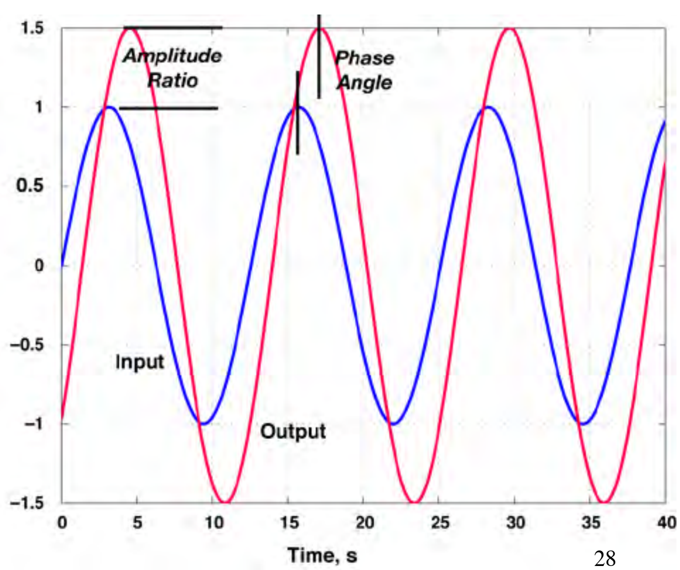
- With damping, transient response decays
- In this case, damping has negligible effect on long-term response

System Dynamics Produces Differences in Amplitude and Phase Angle of Input and Output

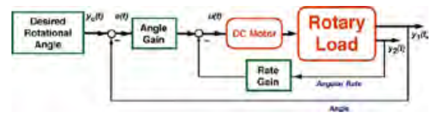
$$\text{Amplitude Ratio } (AR) = \frac{y_{peak}}{y_{C_{peak}}}$$

$$\text{Phase Angle} = -360 \frac{\Delta t_{peak}}{Period}, \text{deg}$$

- Amplitude ratio and phase angle characterize the system model



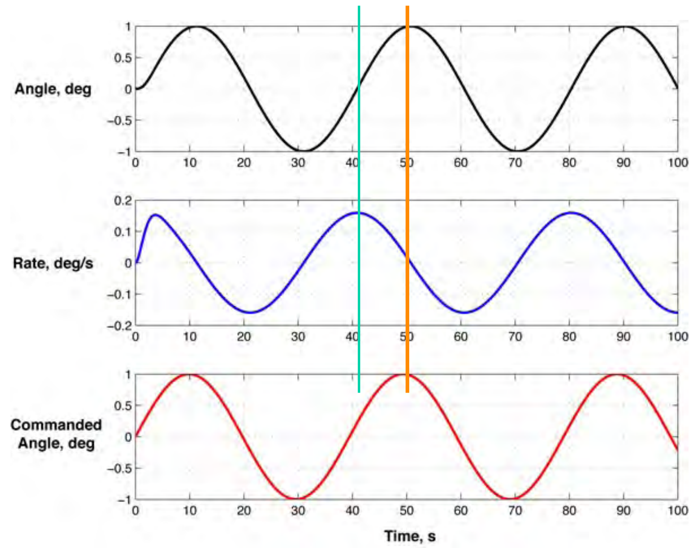
Effect of Input Frequency on Output Amplitude and Phase Angle



$y_c(t) = \sin(t/6.28)$, deg

$c_1/J = 1$; $c_2/J = 1.414$

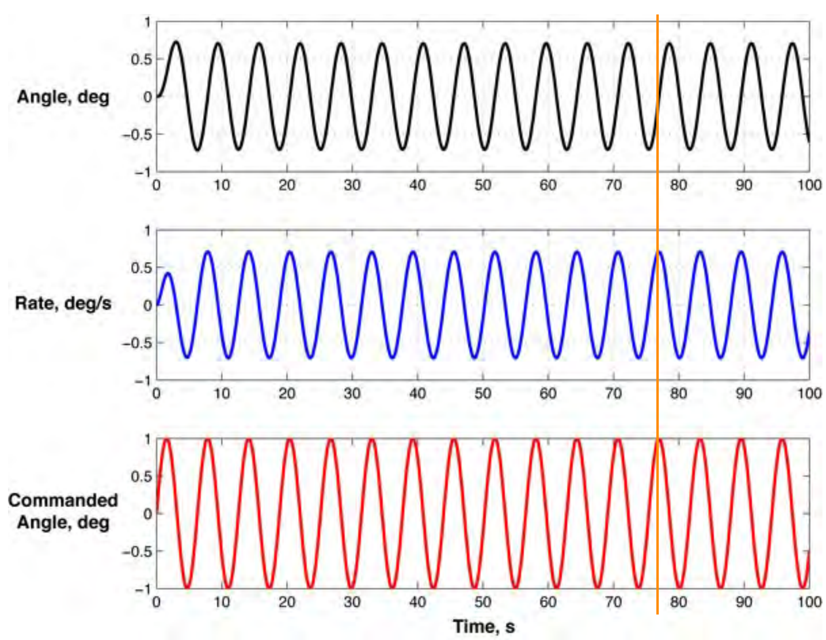
- With low input frequency, input and output amplitudes are about the same
- Lag of angle output oscillation, compared to input, is small
- Rate oscillation “leads” angle oscillation by ~90 deg



At Higher Frequency, Phase Angle Lag Increases

$c_1/J = 1$; $c_2/J = 1.414$

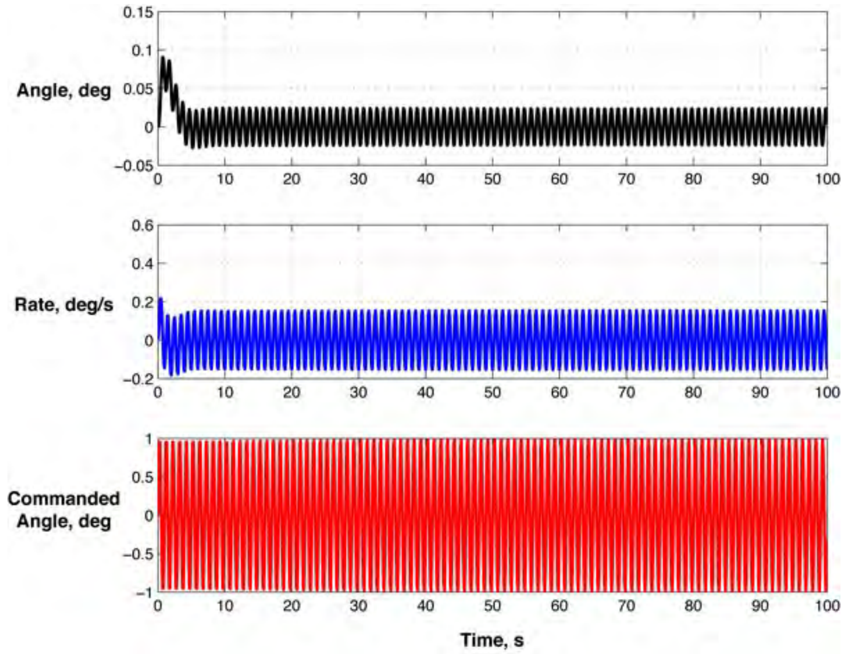
$y_c(t) = \sin(t)$, deg



$c_1/J = 1$; $c_2/J = 1.414$

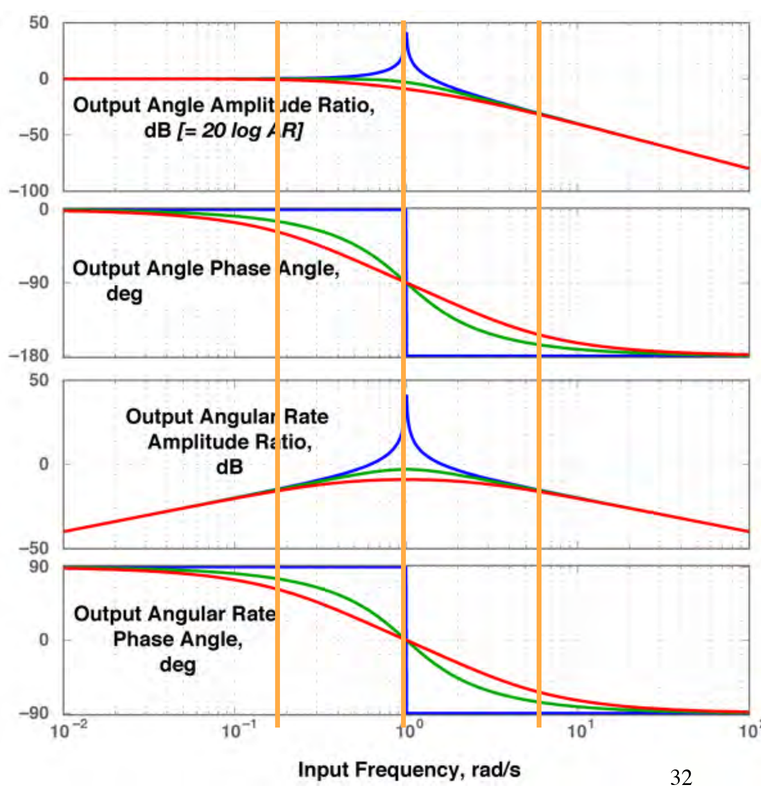
$y_c(t) = \sin(6.28\,t)$, deg

At Even Higher Frequency, Amplitude Ratio Decreases



Frequency Response of the DC Motor with Feedback Control

- Long-term response to sinusoidal inputs over range of frequencies
  - Determine experimentally or
  - from the transfer function
- Transfer function based on the Laplace transform of the system
- Frequency response depicted in the Bode Plot



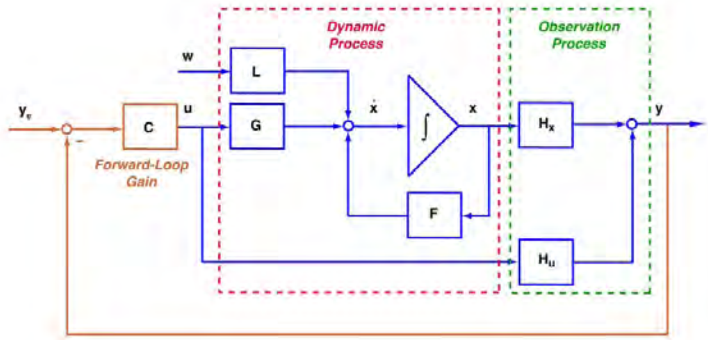
Next Time:
Analog and Digital Control Systems

Supplemental Material

LTI Control with Forward-Loop Gain

$$\mathbf{u}(t) = \mathbf{C}\left[\mathbf{y}_c(t) - \mathbf{y}(t)\right]$$

$$\dot{\mathbf{x}}(t) = \mathbf{F}\,\mathbf{x}(t) + \mathbf{G}\,\mathbf{u}(t) + \mathbf{L}\mathbf{w}(t)$$
$$\mathbf{y}(t) = \mathbf{H}_\mathbf{x}\mathbf{x}(t) + \mathbf{H}_\mathbf{u}\mathbf{u}(t)$$



With C_c = C, command input, y_c, has dimensions of y