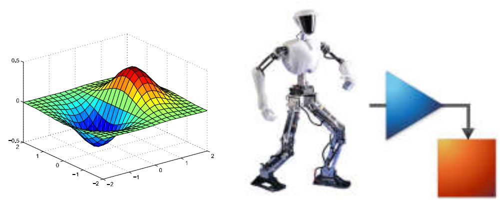
Control Engineering Sessional

Dr. Harunur Rashid
Md. Zahirul Islam
Md. Abu Jafar Rasel



Fall 2016

Gratitude

I am immensely grateful to the following person for the preparation and revision of this lecture.

- Mr. Md. Minal Nahin, Graduate Research Assistant , ME, IUPUI
- Mr. Anjan Goswami, Assistant Professor, MPE, AUST
- Dr. Md. Zahurul Haq, Professor , ME, BUET
- Dr. Sumon Saha, Assistant Professor , ME, BUET

Course Content & Syllabus

Tentative Course Plan [1]

Topic	Week[2]
Plotting and Linear Equations	1-2
Polynomials and Curve Fitting	3
Math Operations and Linear Equations in Simulink	4
Differential Equations and System Response	5
Transfer Functions, Zero-Poles and Stability	6
Laplace Transform and Residue	7
System Modelling and Controllers	8
PID Controller Tuning	9
Experiment	10
Experiment	11
Experiment	12
Final Examination	13

[1] with Mr. Abu Jafar Rasel

[2] Each lecture is approximately 120 min.

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1. Quizes 50%
2. Classwork 40%
3. Assignment 10%

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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9. For rough calculations you will need to use MATLAB command window.

Introduction

- **Control engineering** or **control systems engineering** is the engineering discipline that applies control theory to design systems with desired behaviors.
- The practice uses sensors to **measure** the output performance of the device being controlled and those measurements can be used to give **feedback** to the input **actuators** that can make corrections toward desired performance.
- When a device is designed to perform without the need of human inputs for correction it is called **automatic control** (such as cruise control for regulating a car's speed).
- Multi-disciplinary in nature, control systems engineering activities focus on implementation of control systems mainly derived by mathematical modeling of systems of a diverse range.

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Control Systems *MATLAB* *SIMULINK* *Response* *Modeling* *Feedback-Control*

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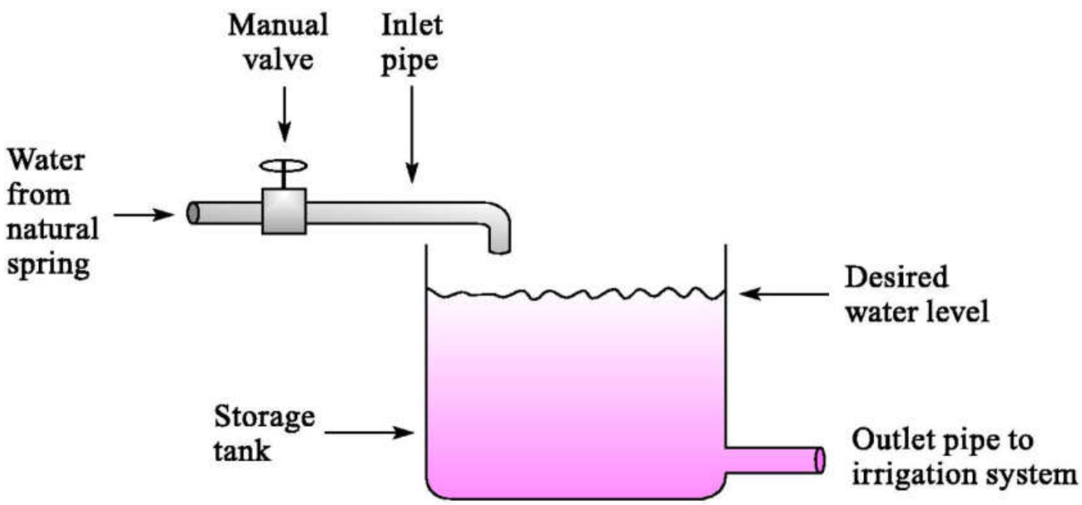
Liquid Level Control



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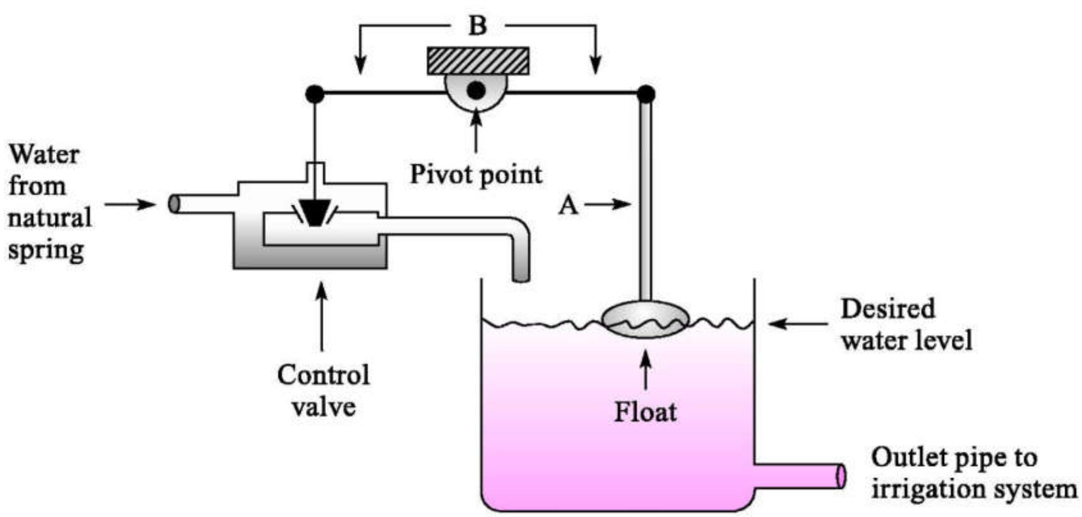
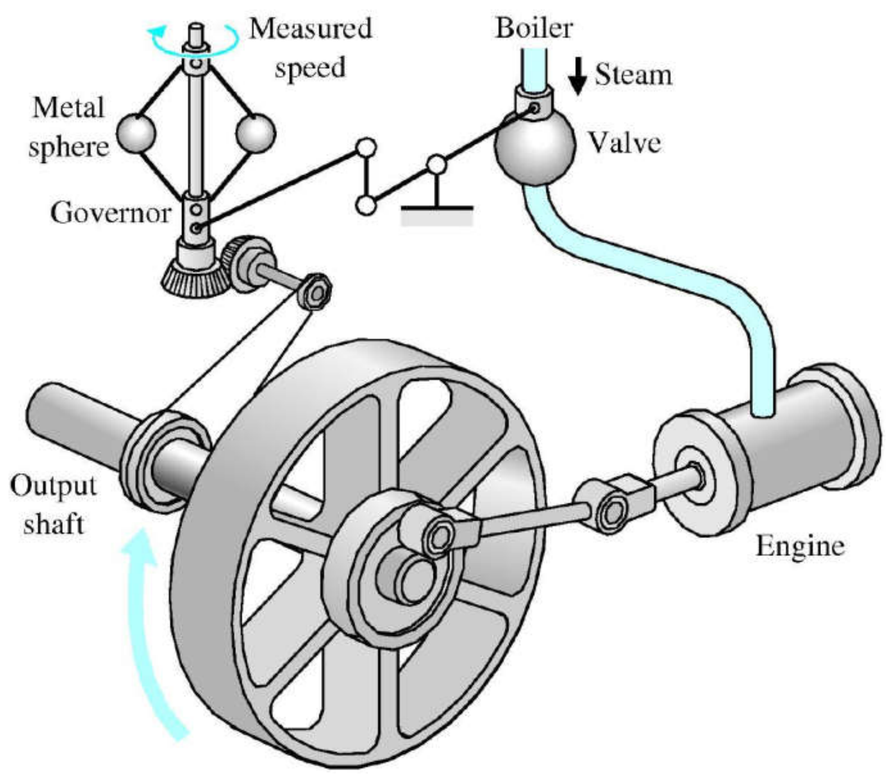
Automatic Control

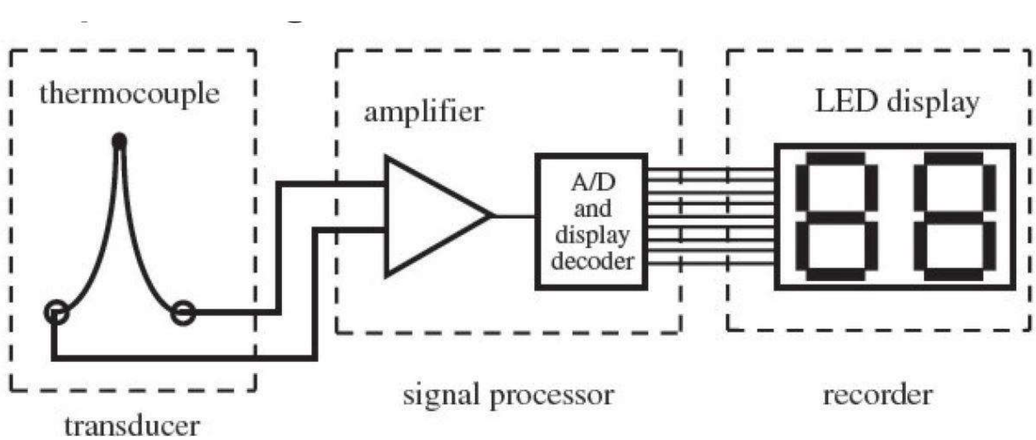


Watt's Flyball Governor



Elements of Measurement System

Consists of 3 basic elements



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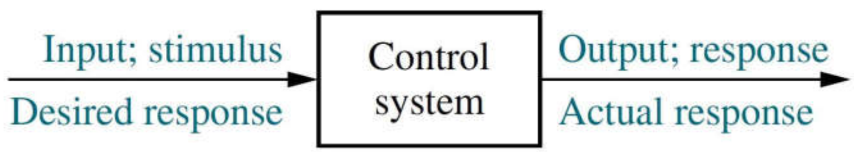
- The term **Control** means to regulate, to direct or to command.
- A **control system** is defined as a combination of devices and components connected or related so as to command, direct or regulate itself or another system.



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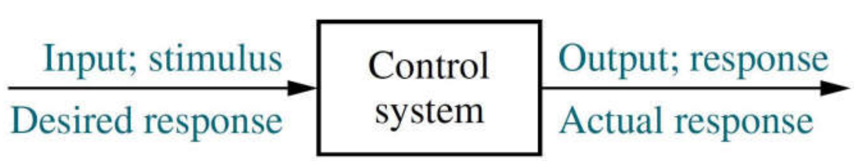

Classification of Control Systems

Toaster **Air Conditioner**

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- **Open Loop System :** Does not correct for feedback/disturbance. Also called non-feedback system.
- **Close Loop System :** Corrects for feedback/disturbance. Also called feedback system.

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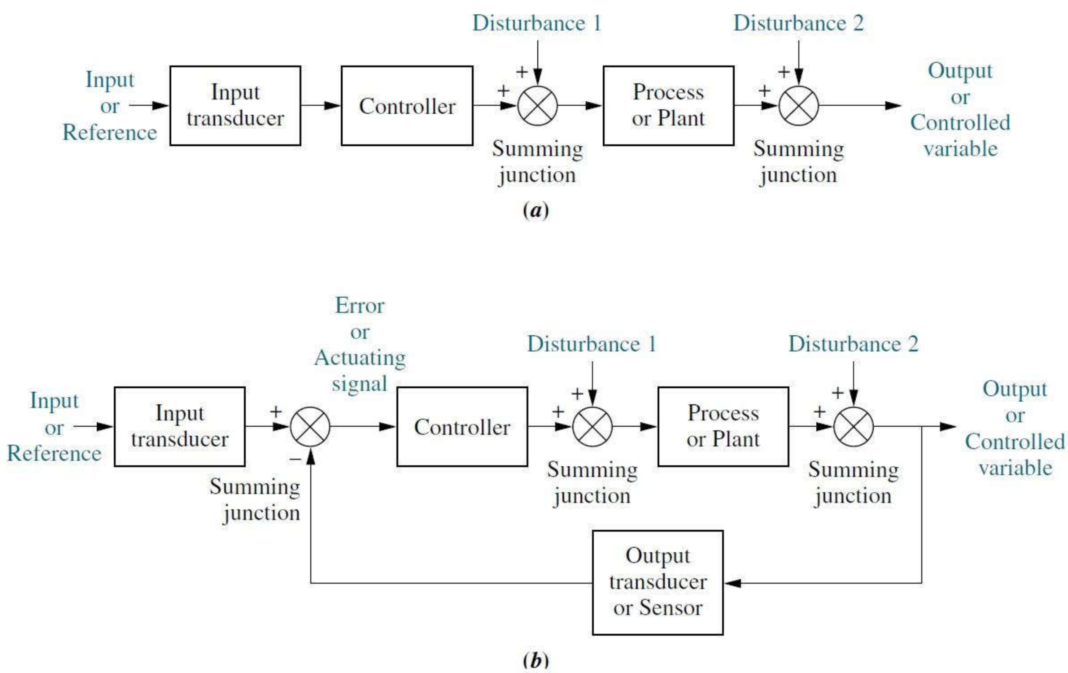
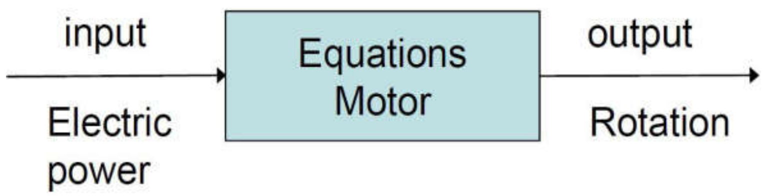


Block diagrams of control systems: **a.** open-loop system; **b.** closed-loop system

Definition and Modeling of Systems

- A **system** can be thought of as a box which has an input and an output.
- **Equations** are used to describe the relationship between the input and output of a system.
- **Response** of a system is a measure of its fidelity to its purpose.
- **Modeling** is the process of representing the behavior of a system by a collection of mathematical equations & logics.
- **Simulation** is the process of solving the model and it is performed on a computer.
- In this course, we're going to learn to simulate systems using **MATLAB-Simulink**



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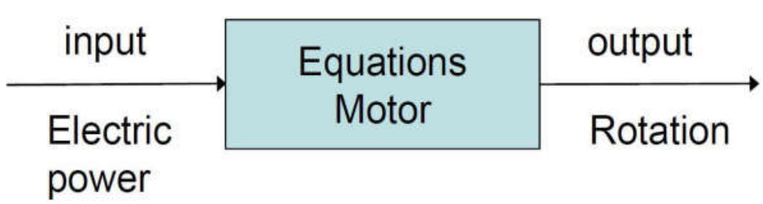

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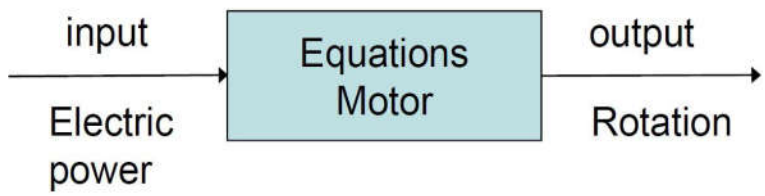

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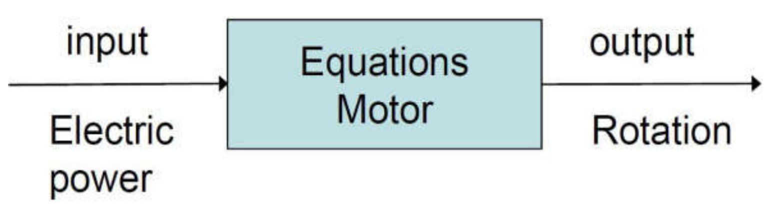

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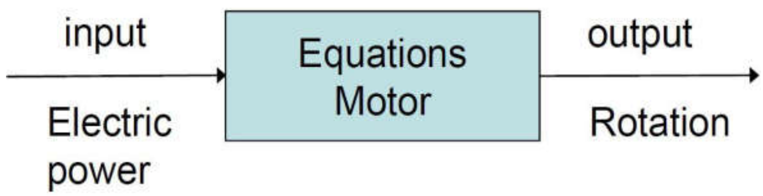

Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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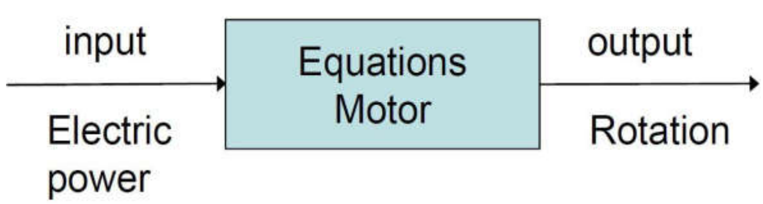

Introduction

- **MATLAB** developed by *The MathWorks Inc.*, stands for Matrix Laboratory.
- It is primarily used to perform scientific computation and visualization.
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  1. Command Window: *To execute commands.*
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  3. Workspace: *Collection of all variables, their data type and size.*
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Basic Plotting (2D & 3D)

plot(x,y)

Plot the function $y = x - 3$ over the range $-1 \le x \le 1$

Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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- $\rightarrow x = linspace(-1, 1)$

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Meshgrid & Surf

Plot the function $z = e^{-x^2-y^2}$ over the range $-2 \leq x \leq 2$ and $-2 \leq y \leq 2$

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>> [X,Y] = meshgrid(x,y);
>> Z= exp(-X.^2 -Y.^2);
>> surf(X,Y,Z)
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Note the use of Plot tools

Try mesh(X,Y,Z) instead of surf(X,Y,Z)

Practice

Plot the function $c = a^2 - b^2$ over the range $-2 \leq a \leq 2$ and $-2 \leq b \leq 2$
Plot the function $y = sinx$ over the range $-2\pi \leq x \leq 2\pi$
Plot the function $y = x^3 - x^2 + 3$ over the range $-4 \leq x \leq 4$

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5. **legend('a,b')** ⇒ Creates legend in figure window.
6. **shading interp** ⇒ Changes shading of plot(faceted, flat and interp).

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Some useful functions for plotting

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10. **bar(x,y)** ⇒ plots bar graph .
11. **mesh(x,y,z)** ⇒ same as **surf(x,y,z)** except patches between lines are not filled.

Solving Linear Equations : linsolve function

Any linear system of equations must have 0, 1 or infinite number of solutions.

linsolve(A,B) takes coefficient matrix A and constant matrix B as input and solves the system.

Solve the following system.

$$\text{System of Linear equations} \begin{cases} x + 3y + z = 5 \\ 2x - y + 2z = 17 \\ 3x + 4y + 5z = 26 \end{cases}$$

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Solution visualization

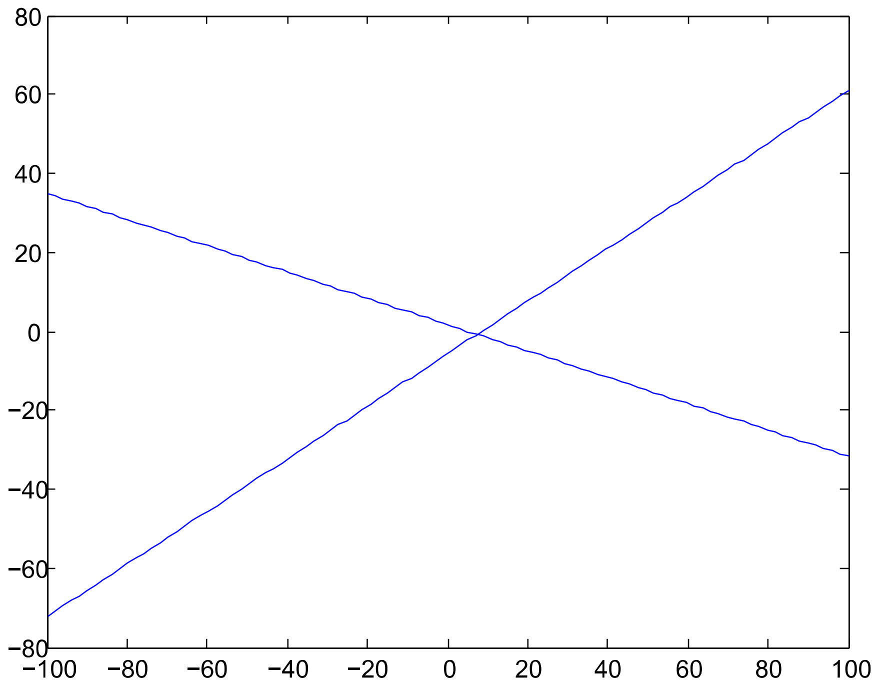
Draw the plot of the following equations in same graph.

$$\text{System of Linear equations with one solution} \begin{cases} x + 3y = 5 \\ 2x - y = 17 \end{cases}$$

Draw the mesh plot of the following equations in same graph.

$$\text{System of Linear equations with infinite solutions} \begin{cases} x + 3y + z = 5 \\ 2x - y + 2z = 17 \end{cases}$$

Solution visualization (contd.)



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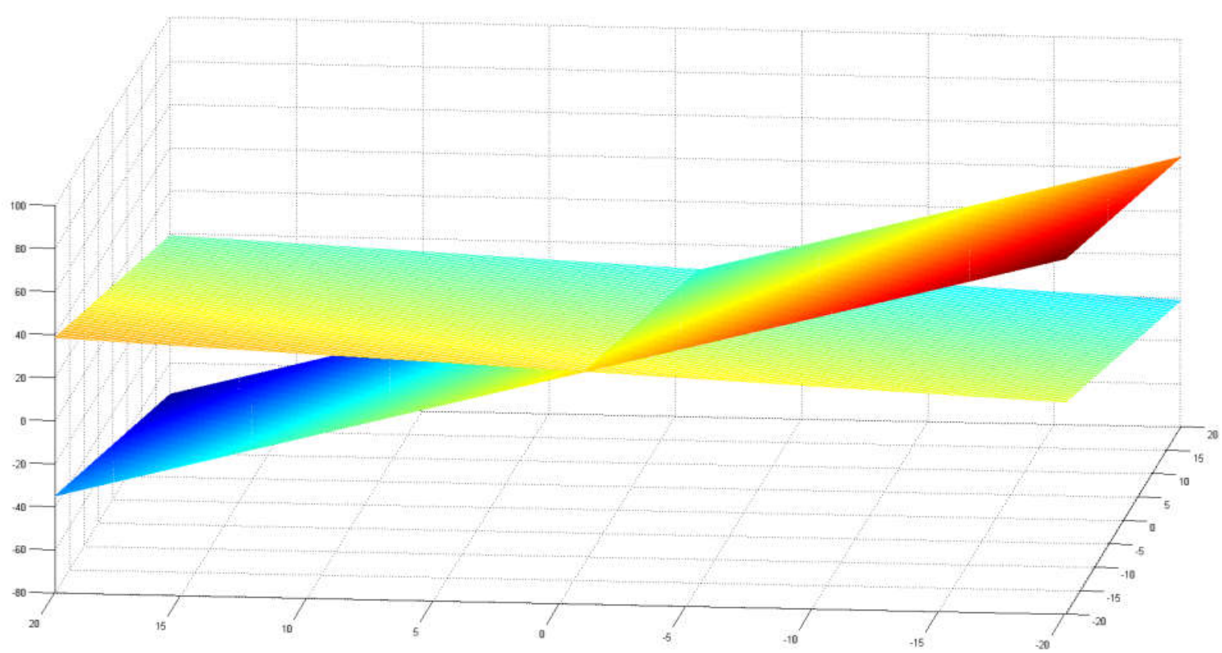

Polynomials

- **MATLAB** interprets an **nth** order polynomial as a row vector of $n+1$
- *Consider a polynomial* $P(s) = s^4 + 3s^3 - 15s^2 - 2s + 9$
- Enter it in MATLAB as row vector P as follows
- **P = [1 3 -15 -2 9]** $\leftarrow$
- or **P = [1, 3, -15, -2, 9]** $\leftarrow$
- To evaluate the value of P at $s = 3$ or P(3) use the following command **polyval(P,s)**
- **polyval(P,3)** $\leftarrow$
- MATLAB will show you the value of P(3) to be 30.
- If there are missing terms, zeros must be entered at the appropriate places.

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Practice

Evaluate the value of $y = 2s^2 + 3s + 4$ at $s = 1, -3$

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Answer: $y(1) = 9$ $y(-3) = 13$

Practice

Evaluate the value of $y = 2s^3 + 1$ at $s = -4$

Practice

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Answer: $y(-4) = -127$

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Find the roots of $s^2 + 3s + 2$

Answer: $-2, -1$

Find the Polynomial

- If you know the roots(r) of a polynomial P, **MATLAB** can find the polynomial by the command **poly(r)**

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Find the polynomial whose roots are -5.5745,2.5836,-0.7951,0.7860 .

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Find the polynomial whose roots are -5.5745,2.5836,-0.7951,0.7860 .

Answer: $P(s) = s^4 + 3s^3 - 15s^2 - 2s + 9$

Conv(x,y) Function: Convolution

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Multiply $(s + 2)$ and $s^2 + 4s + 8$

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Multiply $(s+2)$ and s^2+4s+8

Answer: $s^3+6s^2+16s+16$

Practice

Evaluate the product of $(s+3)$, $(s+6)$ and $(s+2)$

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Answer: $s^3 + 11s^2 + 36s + 36$

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Practice

Evaluate the division of $(s^2 - 1)$ by $(s + 1)$

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Practice

Evaluate the division of $(s^2 - 1)$ by $(s + 1)$

Answer: $(s - 1) + 0$

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Curve fitting: polyfit function

From Data to Equation.

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- k specifies the order of the desired polynomial.
- The result c will be a row vector containing the coefficients of the polynomial.

Practice

Find a second order polynomial to predict the discharge(Q) of a pump after 1.5 seconds from the given data.

t(s)	0	1	2	4
Q(L/s)	1	6	20	100

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t(s)	0	1	2	4
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Answer:

1. t=[0 1 2 4];
2. Q=[1 6 20 100];
3. c=polyfit(t,Q,2)
4. MATLAB returns, c = 7.3409 -4.8409 1.6818
5. $\therefore Q = 7.3409t^2 - 4.8409t + 1.6818$ is the equation of discharge.
6. Use **polyval(c,1.5)** to get the answer 10.9375 L/s.

Advanced Polynomial Operations

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Advanced Polynomial Operations

- **MATLAB** can differentiate a polynomial y(s) analytically by the command **polyder(y)**
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Practice this commands using the polynomial $s^4 + 4s^3 + 8s^2 + 16$

SIMULINK

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  2. Discontinuous
  3. Math Operations
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  6. Signal Routing
  7. Ports and subsystems

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

SIMULINK Library Browser

- Note that there are many blocks to conveniently model dynamic systems.
- Frequently used blocks are collected under **Commonly Used Blocks.**
- In this course we'll be using blocks from the following

1. Continuous
2. Discontinuous
3. Math Operations
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Basic Math Operations

Demonstration

Scope Vs. Display

Demonstration

1. Add two numbers and check the output in both Scope and Display
2. Subtract two numbers and check the output in both Scope and Display
3. Multiply two numbers and check the output in Scope and Display
4. Divide two numbers and check the output in Scope and Display

Demonstration

View the response of $50 + 60sin(0.25t + \phi)$

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View the response of $50 + 60sin(0.25t + \phi)$ using 'add' and 'gain' operator.

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Mux

Show the three input in a single graph.

- $100 + sin(0.25t + 2)$
- $50 + sin(0.5t)$
- $75 + sin(0.75t + 1)$

System of Equations

- **Simulink** can solve both linear and nonlinear system of equations.

System of equations $\begin{cases} 2x + 3y = 13 \\ 5x - y = 7 \end{cases}$

System of Equations

Write the equations in the following form:

$$2x + 3y = 13$$

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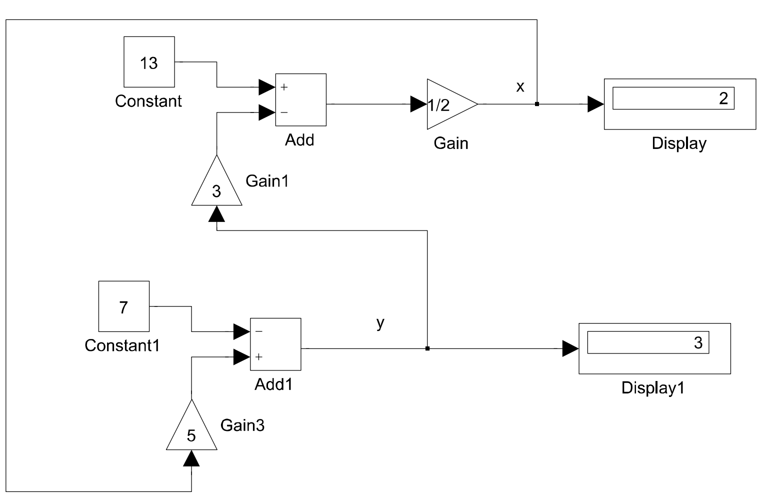

Classwork

Solve the following system.

$$\text{System 1}\begin{cases} x+3y+z=5 \\ 2x-y+2z=17 \\ 3x+4y+5z=26 \end{cases}$$

Classwork

Solve the following system.

$$\text{System 2}\begin{cases} a+b+c=6 \\ 2a+3b+4c=15 \\ a+2b-c=10 \end{cases}$$

Solution of ODE

Demonstration

If $\frac{dy}{dt} = 0.5t^2$ find y.
$y(0) = 0$

Demonstration

$\frac{dx}{dt} - 3t^2 = 2t + sin(0.25t)$; $x(0) = 0$

General System Modelling

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F(t) $\rightarrow$ Forcing Function
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Order of a system is designated by order of the differential equation.

Zeroth Order System

$$x = kF(t)$$

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- Represents ideal dynamic performance.
- Example: Potentiometer, ideal spring etc.

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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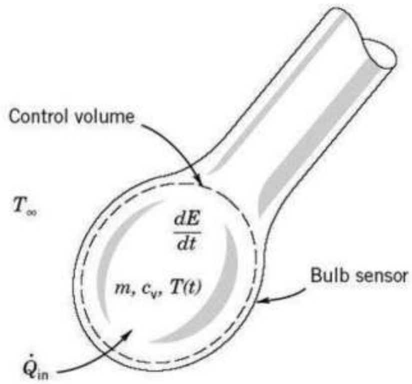
- May be written as

$$\tau\frac{dq(t)}{dt} + q(t) = \frac{u(t)}{b}$$

First Order System



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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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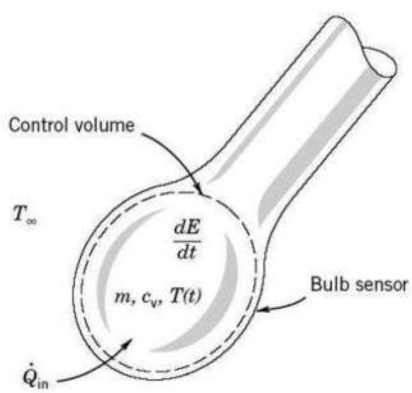

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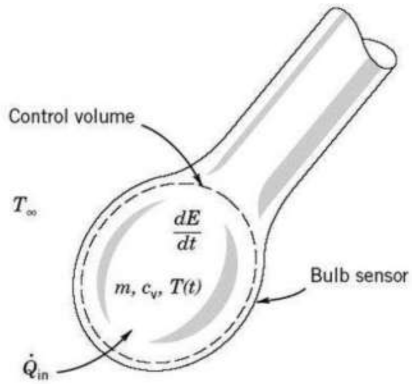

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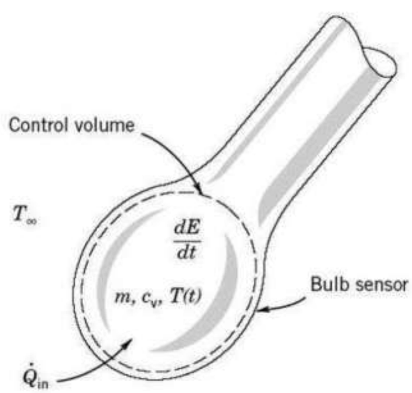

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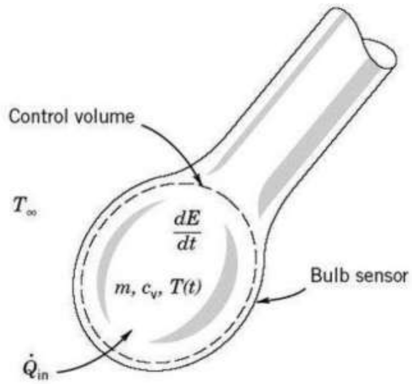

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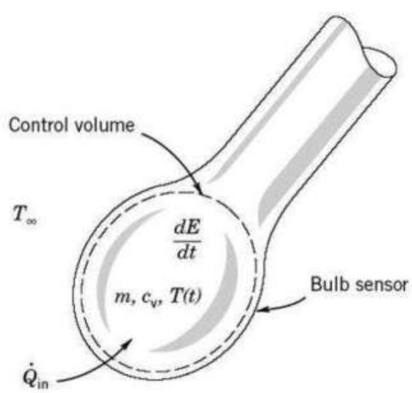

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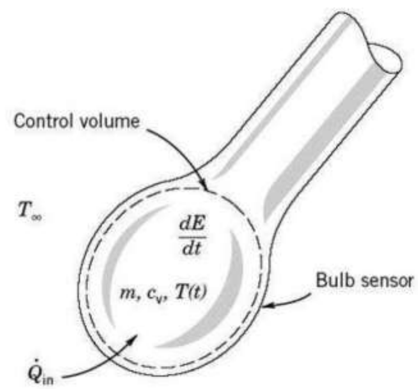

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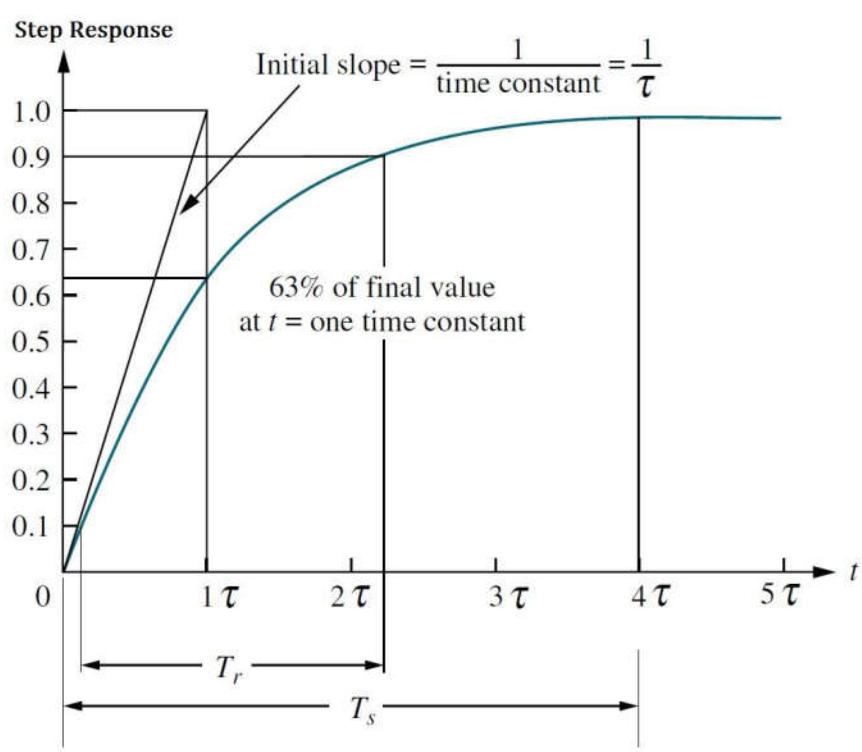
6. Where $\tau = \frac{mC_v}{hA}$

Response - 1st Order System: Step Input



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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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Transfer Function

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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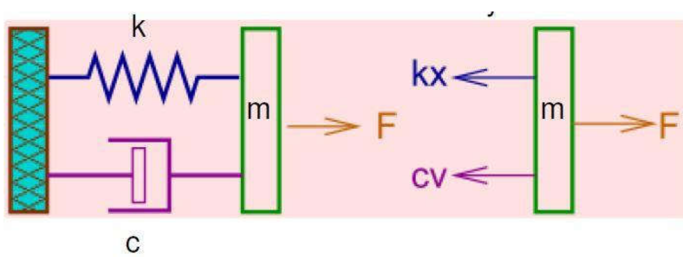
$$\Rightarrow \frac{X(s)}{F(s)} = G(s) = \frac{k}{(\tau s + 1)}$$

Second Order System

Write Newton's 2nd Law for the system.

$$\sum F = ma$$



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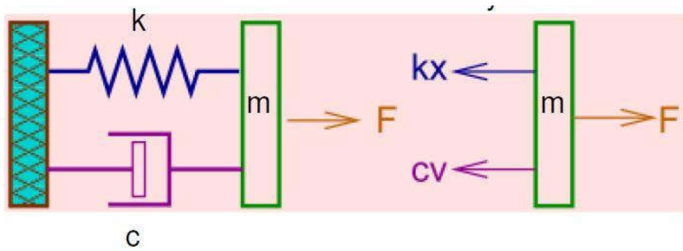

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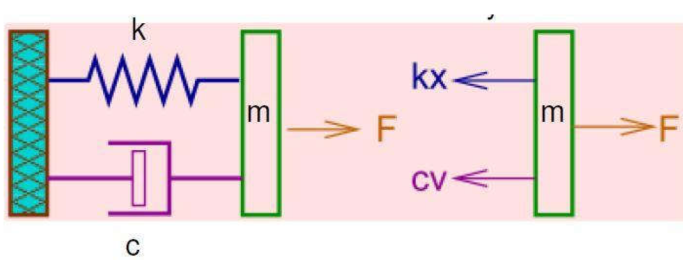

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$$\Rightarrow ma + cv + kx = F$$

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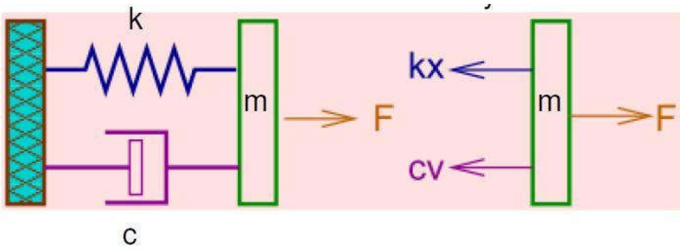

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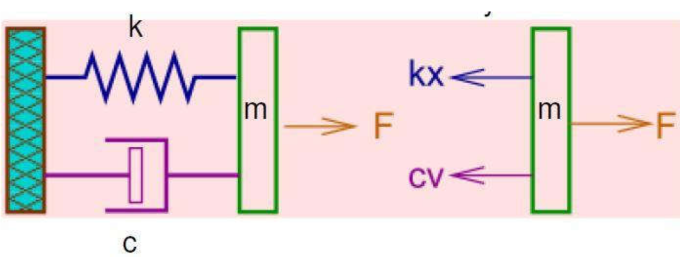
Second Order System



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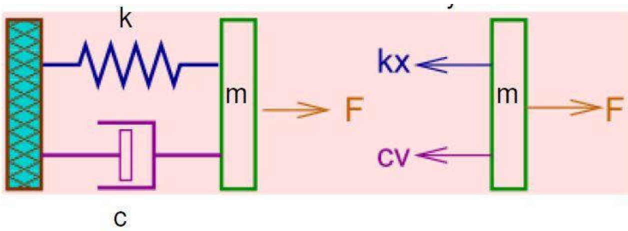
Substitute the following:

$\omega_n = \sqrt[k]{m}$ = Undamped Natural Frequency (rad/s)
$C_c = 2\sqrt{mk}$ = Critical Damping Coefficient
$\zeta = \frac{c}{C_c}$ = Damping Ratio

TF of Second Order System

$$\Rightarrow m\frac{d^2x}{dt} + c\frac{dx}{dt} + kx = F(t)$$



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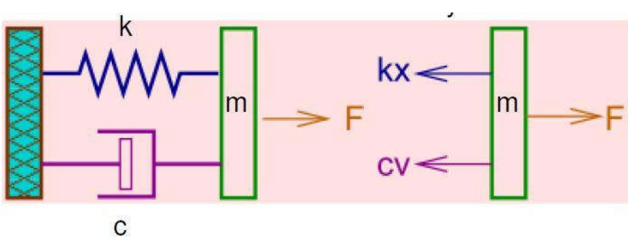

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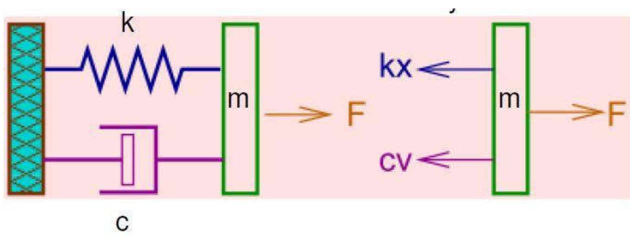

$$\Rightarrow \frac{1}{\omega_n^2}\frac{d^2x}{dt} + 2\frac{\zeta}{\omega_n}\frac{dx}{dt} + x = \frac{F(t)}{k}$$

Taking Laplace Transform of both sides.

$$\frac{d^nx(t)}{dt^n} \Rightarrow s^nX(s) \text{ \& } F(t) \Rightarrow F(s)$$

TF of Second Order System

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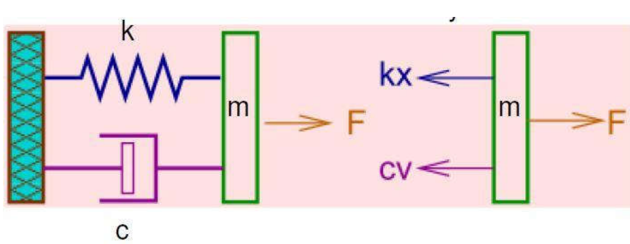

$$\Rightarrow \frac{1}{\omega_n^2}\frac{d^2x}{dt} + 2\frac{\zeta}{\omega_n}\frac{dx}{dt} + x = \frac{F(t)}{k}$$

Taking Laplace Transform of both sides.

$$\frac{d^nx(t)}{dt^n} \Rightarrow s^nX(s) \text{ \& } F(t) \Rightarrow F(s)$$

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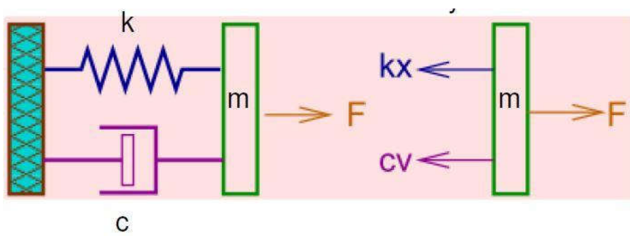

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TF of Second Order System(contd.)

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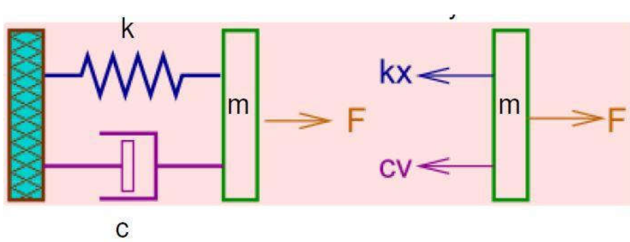

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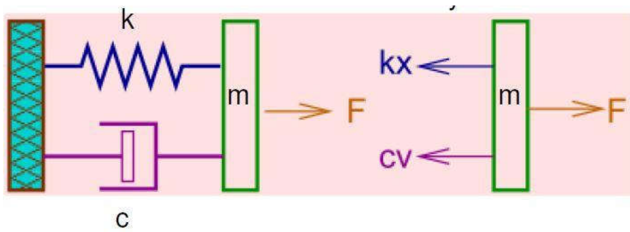

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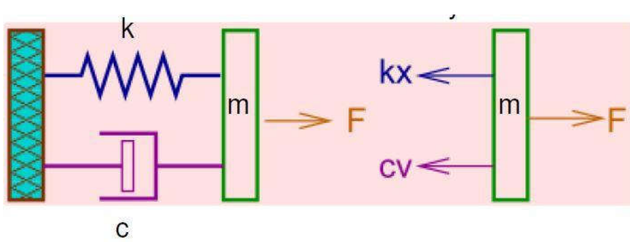

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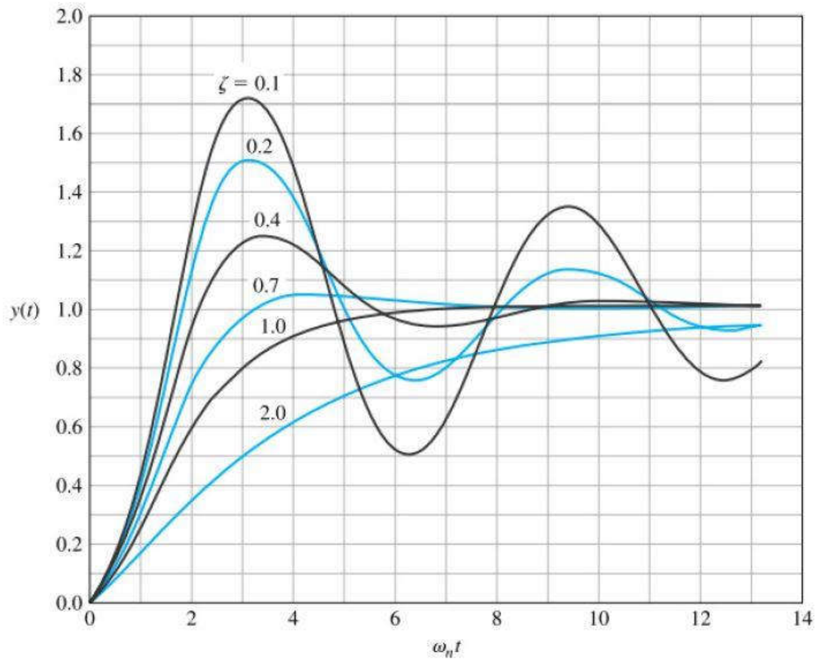
Response of a 2nd Order System: Step Input



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Practice

1.Consider TF of a system , $G(s) = \frac{36}{s^2+4.2s+36}$ with gain k =1. Check the response in Simulink.

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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Transfer Function in MATLAB

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Answer:

1. n = [5 15 10]
2. d = [1 7 20 24 0]
3. sys = tf(n,d)

Transfer Function in MATLAB

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Practice separating the numerator and Denominator of $G(s) = \frac{5s^2+15s+10}{s^4+7s^3+20s^2+24s}$

Practice

Define a transfer function,
$$G(s) = \frac{s(s+1)(s+2)}{s(s+3)(s^2+4s+8)}$$

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Hint: Use poly and conv functions

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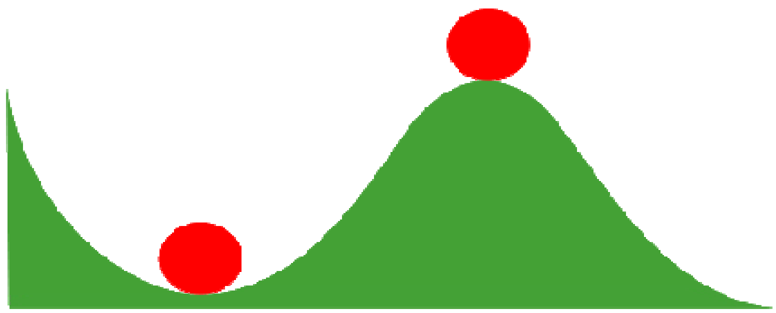
Define a transfer function, $G(s) = \frac{s+1}{s-4}$

Answer:

1. s = tf('s')
2. G = (s+1)/(s-4)

Stability Criteria

A necessary and sufficient condition for a feedback system to be stable is that all the poles of the system transfer function have negative real parts.



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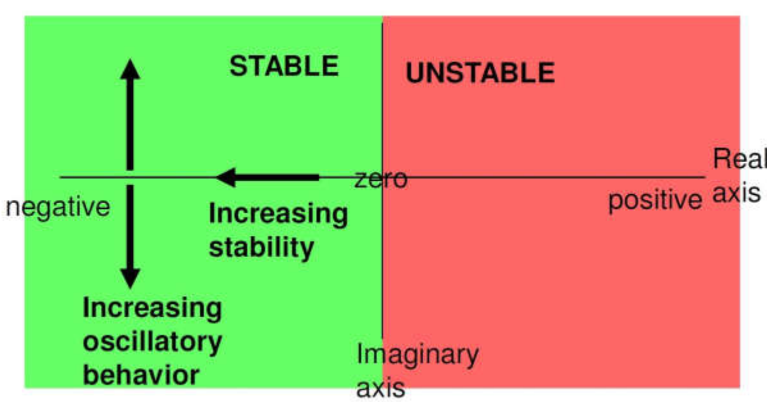
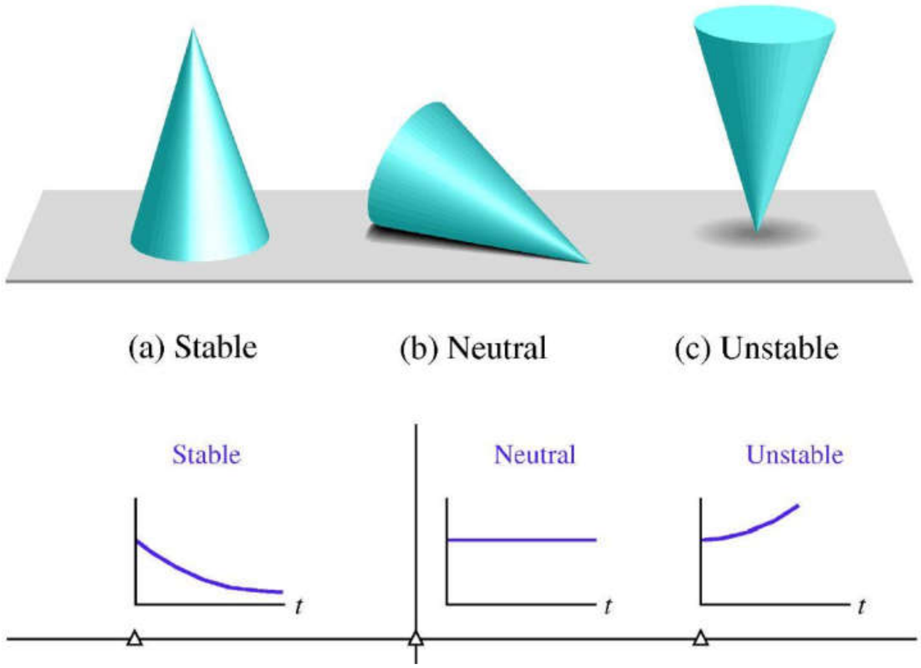


Stability

A stable system is a dynamic system with a bounded response to a bounded input. (BIBO)



Zeros and Poles

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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- **[n,d] = zp2tf(z,p,k);**
- The command **pzmap(n,d)** plots the **pole-zero map** of a given transfer function.

Practice

Zero, Pole, Pole-zero map, Stability

Find the location of zeros and poles and plot the pole-zero map of , $G(s) = \frac{2s^3+8s+6}{s^4+6s^3+12s^2+24s}$
Is the system stable?

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Answer: In column matrix form,
z= -3, -1, p= 0, -4.5198, $-0.7401 \pm 2.1822i$, k = 2. No.

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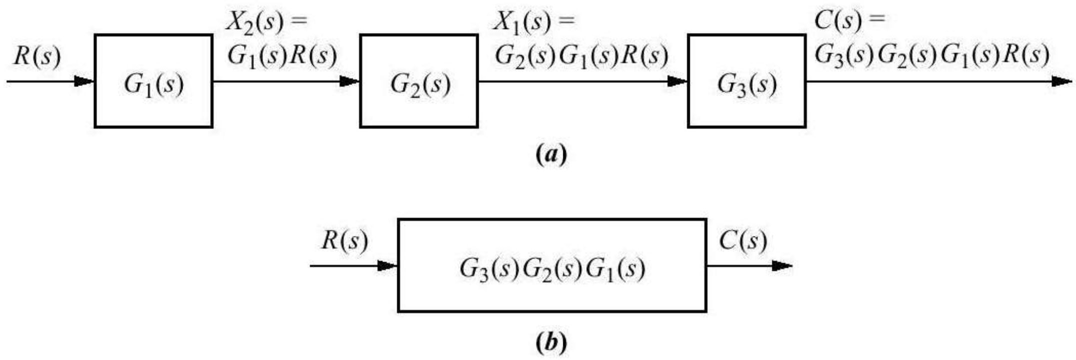
11. **parallel(sys1,sys2)** ⇒ Equivalent parallel transfer function.
12. **feedback(sys1,sys2)** ⇒ Equivalent feedback transfer function.

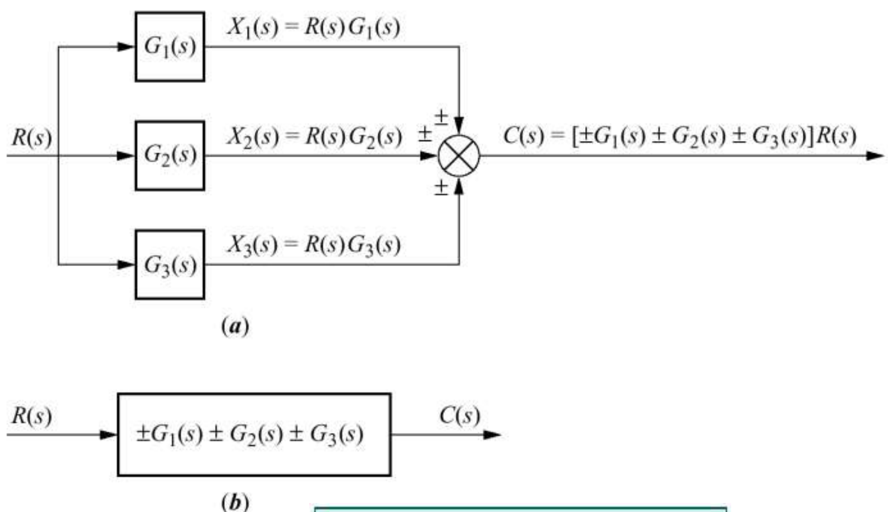
TF manipulation: Series



$$G_e(s) = G_3(s)G_2(s)G_1(s)$$

Homework: Take $G = \frac{1}{s+1}$ and $H = \frac{1}{s-1}$ to check **series(G,H)**.

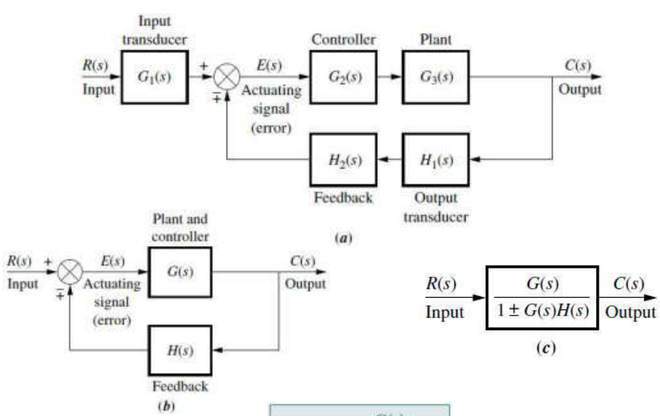
TF manipulation: Parallel



$G_e(s) = \pm G_1(s) \pm G_2(s) \pm G_3(s)$

Homework: Take $G = \frac{1}{s+1}$ and $H = \frac{1}{s-1}$ to check **parallel(G,H)**.

TF manipulation: Feedback



$G_e(s) = \frac{G(s)}{1 \pm G(s)H(s)}$

Figure: a) Feedback Control System.
b) Simplified Model.
c) Equivalent Transfer Function.

**Closed Loop System H=1

Homework: Consider,

$$G = \frac{1}{s+1}$$

$$H = \frac{1}{s-1}$$

- Negative feedback system: $G_{eqv} = \frac{G}{1+GH}$ use **feedback(G,H)** [a].
- Positive feedback system: $G_{eqv} = \frac{G}{1-GH}$ use **feedback(G,H,+1)**

[a] same as feedback(G,H,-1)

Laplace Transform ($\mathscr{L}$) in MATLAB

- Laplace transform helps to convert differential equations which describes the behavior of a dynamic systems into algebraic equations of a complex variable ’s’.

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- Determine the Laplace Transform of $f(t) = e^{-t}(1 - sin(t))$

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syms t ←

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ft = exp(-t) * (1 $- sin(t)$); ←

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fs = laplace(ft)←;
The result is shown as
fs = 1/(1+s) - 1/(2 + 2s + s^2)

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Practice

- Determine the Laplace Transform of $f(t) = e^{-t}(1 - sin(t))$

Use the following command:

syms t ←
ft = exp(-t) * (1 $- sin(t)$); ←
fs = laplace(ft)←;
The result is shown as
fs = 1/(1+s) - 1/(2 + 2s + s^2)
i.e.,
$F(s) = \frac{1}{s+1} - \frac{1}{((s+1)^2+1)}$

Inverse Laplace Transform ($\mathscr{L}^{-1}$) in MATLAB

- Inverse Laplace transform converts the Laplace Transform F(s) to the time function f(t).

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```
syms s t ←
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syms s t ←
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Residue Function

Determine the Partial Fraction expansion of $F(s) = \frac{s^3+9s+1}{s^3+s^2+2s+2}$

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1. n = [1 0 9 1]; ←
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MATLAB outputs the following

r =
1.0000 - 1.7678i
1.0000 + 1.7678i
-3.0000
p =
0.0000 - 1.4142i
0.0000 + 1.4142i
-1
k =
1

Residue Function

MATLAB output:
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∴ the partial fraction expansion is

$$F(s) = \frac{s^3 + 9s + 1}{s^3 + s^2 + 2s + 2} = 1 + \frac{1.0000 - 1.7678i}{s - 1.4142i} + \frac{1.0000 + 1.7678i}{s + 1.4142i} - \frac{3}{s+1}$$

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Practice

Determine the Partial Fraction expansion of $F(s) = \frac{s+1}{s^4+7s^3+16s^2+12s}$

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Practice

Determine the Partial Fraction expansion of $F(s) = \frac{s+1}{s^4+7s^3+16s^2+12s}$

Answer: $F(s) = \frac{0.6667}{s+3} + \frac{-0.75}{s+2} + \frac{0.5}{(s+2)^2} + \frac{0.0833}{s+0}$

Reverse Residue

$$F(s) = 1 + \frac{1.0000 - 1.7678i}{s - 1.4142i} + \frac{1.0000 + 1.7678i}{s + 1.4142i} - \frac{3}{s+1}$$

Find the numerator and denominator of F(s).

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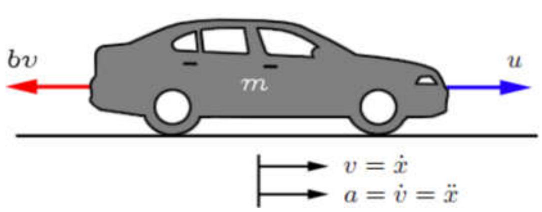
Car Cruise Control



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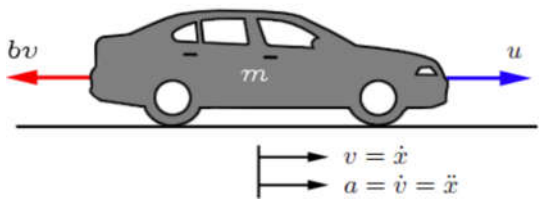
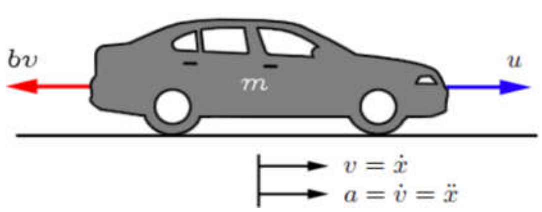


Physical Parameters
u = force generated between the road/tire interface = 500 N
b = rolling resistance proportionality constant = 50 Ns/m
m = mass of the car = 1000 kg

Car Cruise Control



Consider, a simple cruise control system with the assumption that rolling resistance and air drag are proportional to the car's speed (v).

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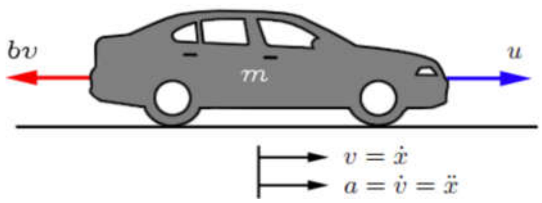

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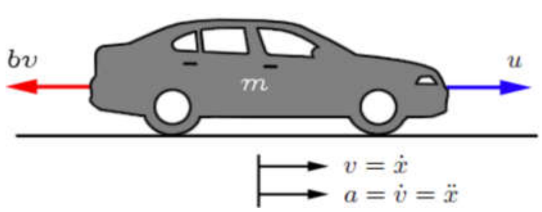

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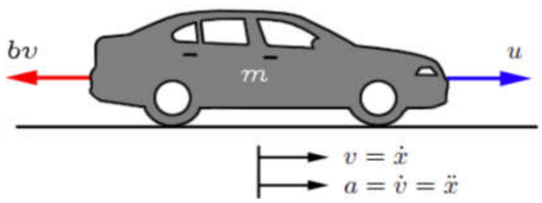

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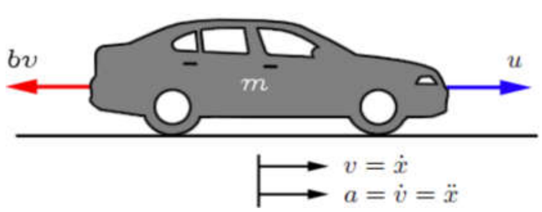

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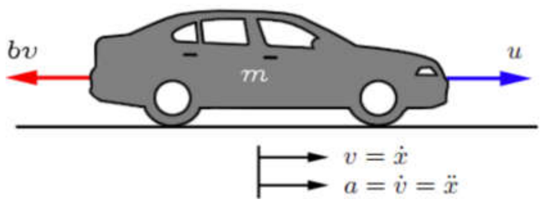

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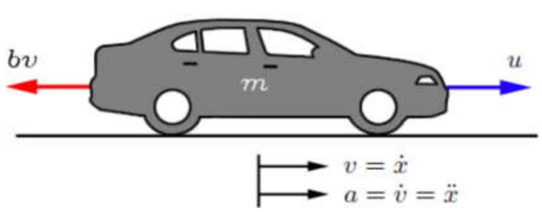
Car Cruise Control



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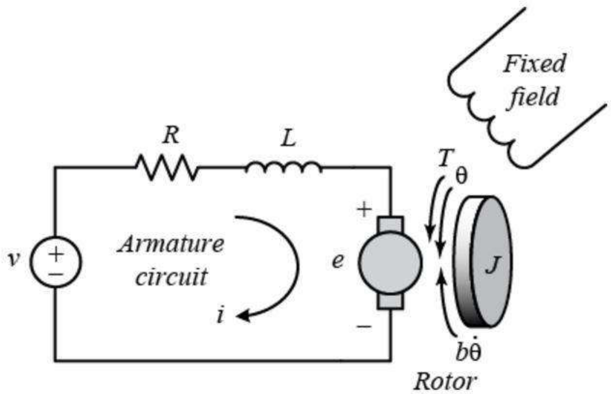
$$\therefore \frac{dv}{dt} = \frac{1}{m} \times (u - bv)$$

Response of a DC motor



- All physical systems can be modeled using differential equations.

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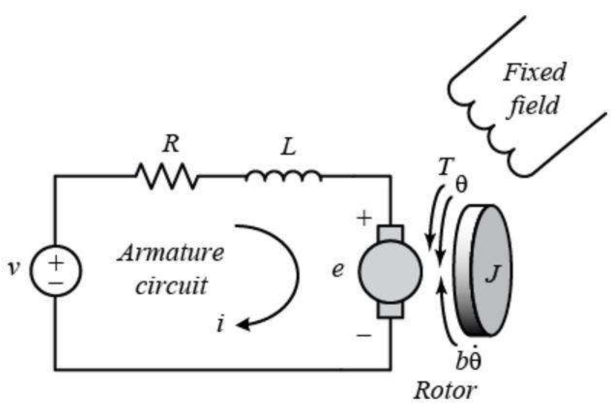

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- Response of such systems can be found by simultaneously solving the governing DEQ's.

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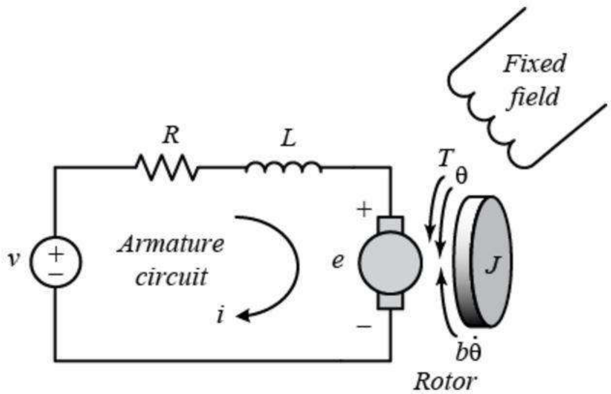

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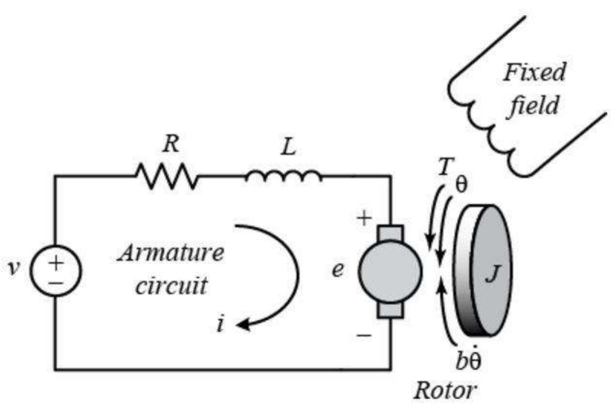
Physical Parameters

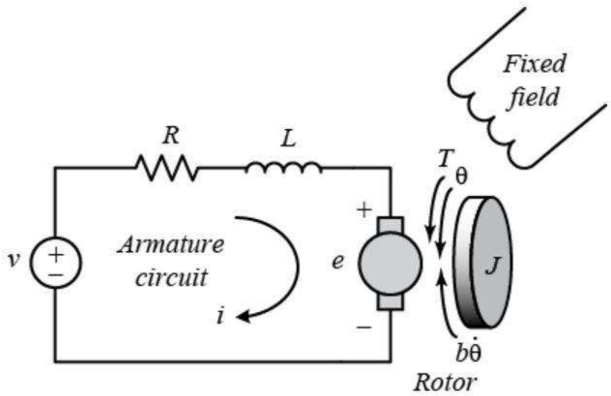
J = moment of inertia of the rotor (kgm^2)
b = motor viscous friction constant (Nms)
K_e = electromotive force constant (V/rad/sec)
K_t = motor torque constant (Nm/Amp)
R = electric resistance (Ohm)
L = electric inductance (H)

Response of a DC motor(contd.)



From Newton's 2nd Law of Motion, $\sum F = ma$

Response of a DC motor(contd.)



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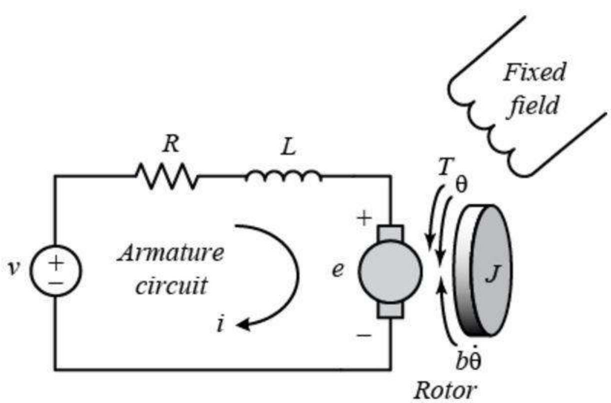
For rotational systems, $\Rightarrow \sum T = J\alpha$

Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

Response of a DC motor(contd.)



From Newton's 2nd Law of Motion, $\sum F = ma$

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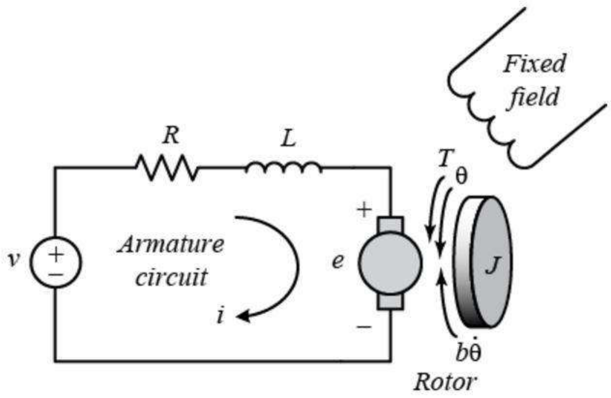
$$\Rightarrow T - b\frac{d\theta}{dt} = J\frac{d^2\theta}{dt^2}$$

Response of a DC motor(contd.)



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Motor Torque is proportional to Armature Current.

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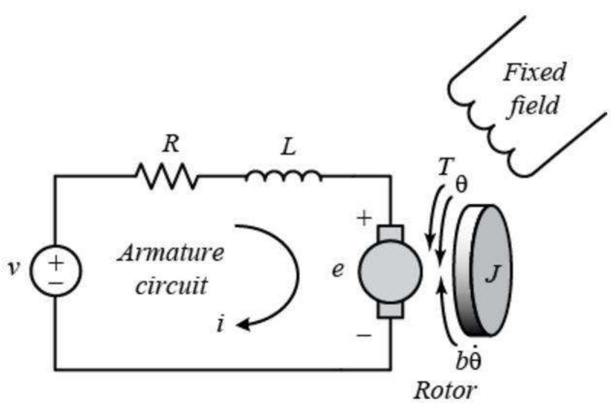
Response of a DC motor(contd.)



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$$\therefore T = K_t i$$

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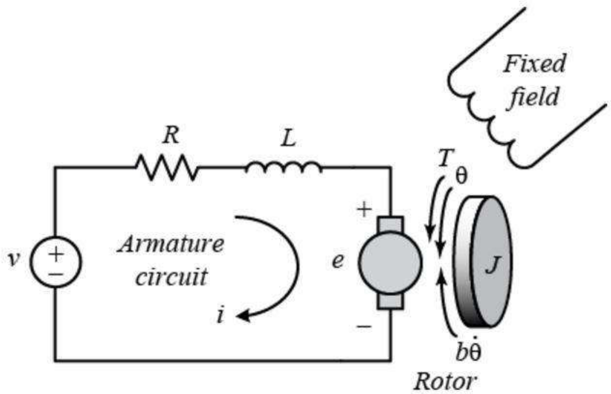
Response of a DC motor(contd.)



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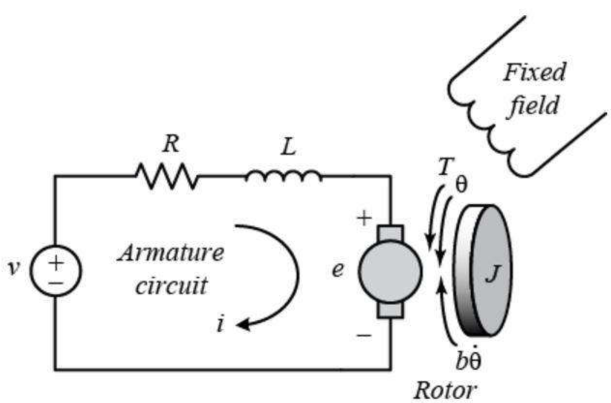

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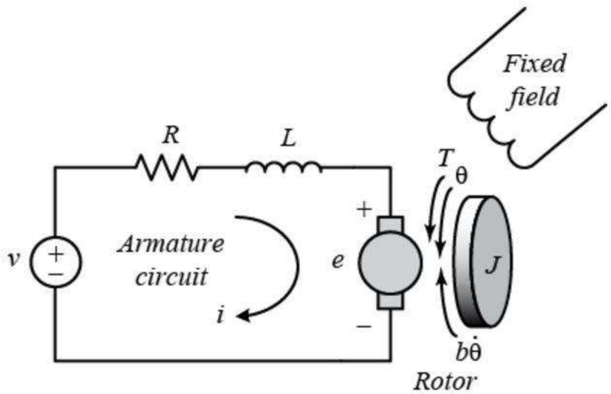
$$\Rightarrow K_t i - b\frac{d\theta}{dt} = J\frac{d^2\theta}{dt^2}$$

$$\therefore \frac{d^2\theta}{dt^2} = \frac{1}{J}(K_t i - b\frac{d\theta}{dt}) \quad (1)$$

Response of a DC motor(contd.)



From Kirchoff's Voltage Law, $\sum V = 0$

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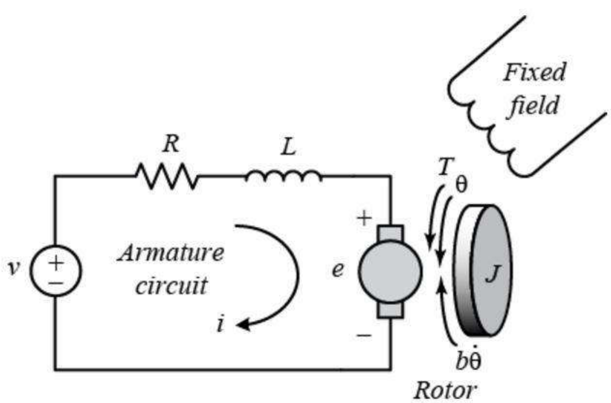
Response of a DC motor(contd.)



From Kirchoff's Voltage Law, $\sum V = 0$

$$\Rightarrow V = L\frac{di}{dt} + iR + e$$

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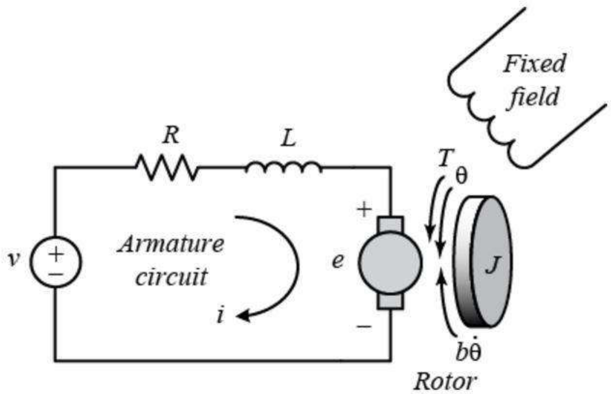
Response of a DC motor(contd.)



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Back emf(e),is proportional to the angular velocity of shaft.

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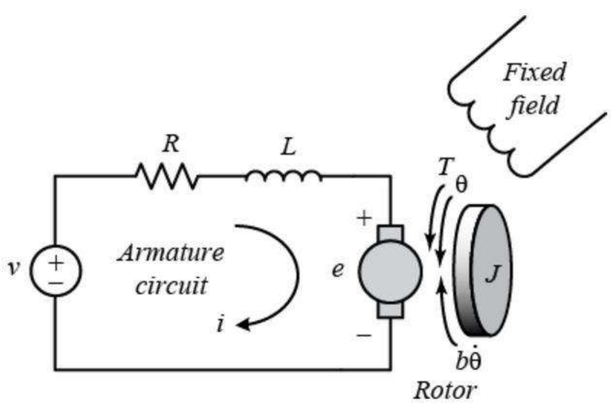
Response of a DC motor(contd.)



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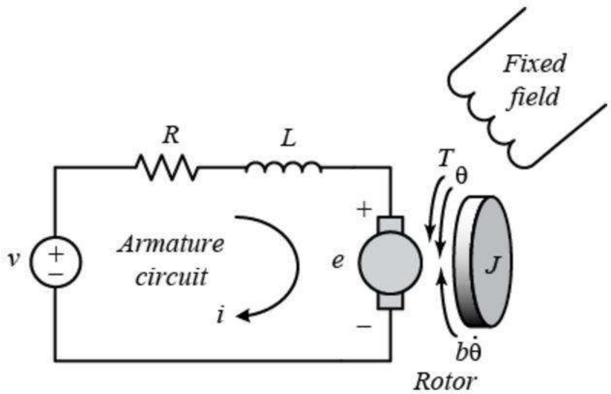
Response of a DC motor(contd.)



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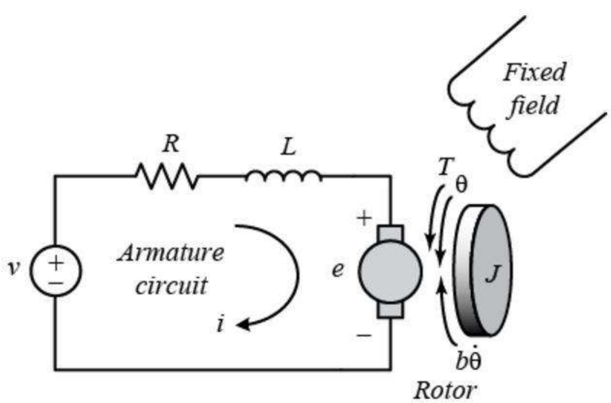
$$\Rightarrow L\frac{di}{dt} = V - iR - K_e\frac{d\theta}{dt}$$

Response of a DC motor(contd.)



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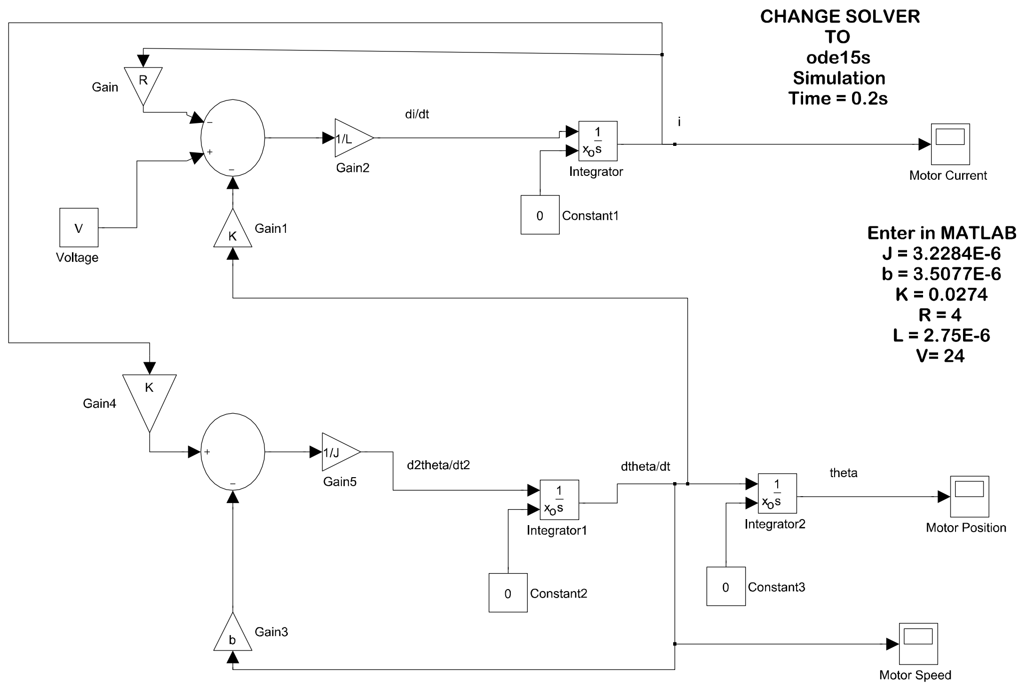
$$\therefore e = K_e\frac{d\theta}{dt}$$

$$\Rightarrow L\frac{di}{dt} = V - iR - K_e\frac{d\theta}{dt}$$

$$\therefore \frac{di}{dt} = \frac{1}{L}(V - iR - K_e\frac{d\theta}{dt}) \qquad (2)$$

Solve equation (1) and (2) simultaneously in Simulink for speed/position of motor rotor.

DC Motor Simulink Model



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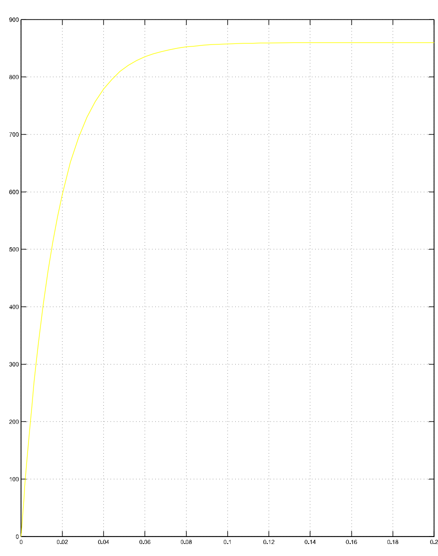


Figure: Motor Speed

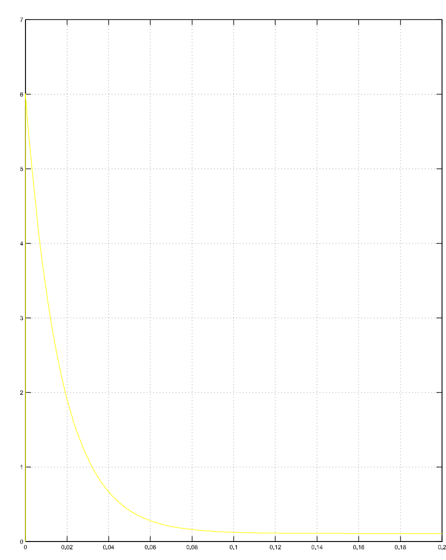


Figure: Motor Current

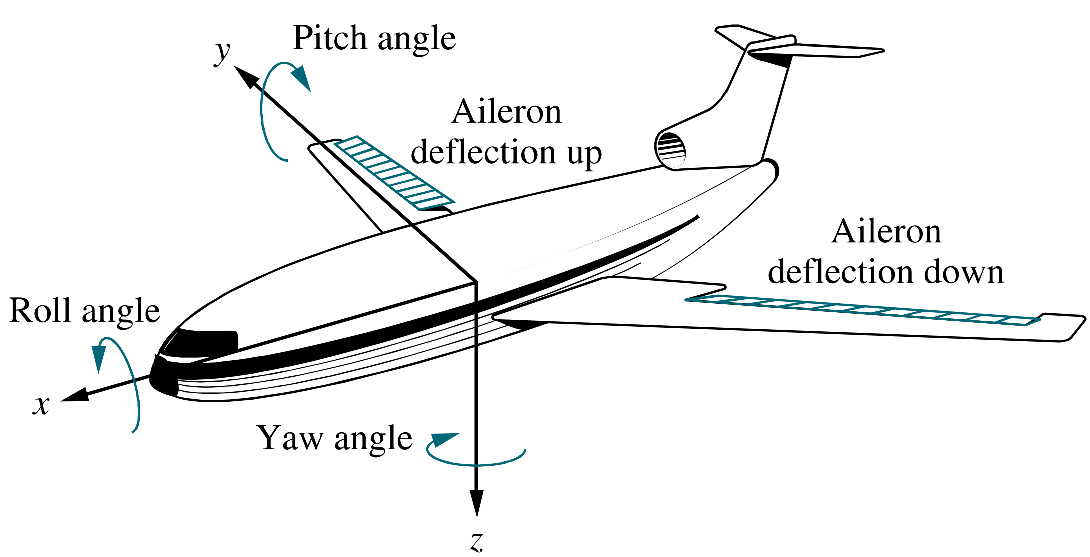
Estimating TF (Motor Speed)

Use the following data to estimate TF of motor (I=Voltage, O=Speed).

Parameter	Value
Moment of inertia of the rotor	0.01 kgm^2
Motor viscous friction constant	0.1 Nms
Electromotive force constant	0.01 $Vradsec$
Motor torque constant	0.01 $NmAmp$
Electric resistance	1 Ohm
Electric inductance	0.5 H

1. Declare Subsystem.
2. **Set Input and output linearization points. Go to Tools/Control Design/Linear Analysis Tool.**
3. Linearize Model. Export model to workspace from LTI viewer.
4. Use the command zpk(modelname).
5. $\frac{2}{(s+9.997)(s+2.003)}$ is the approximate transfer function.

Aircraft Pitch Control



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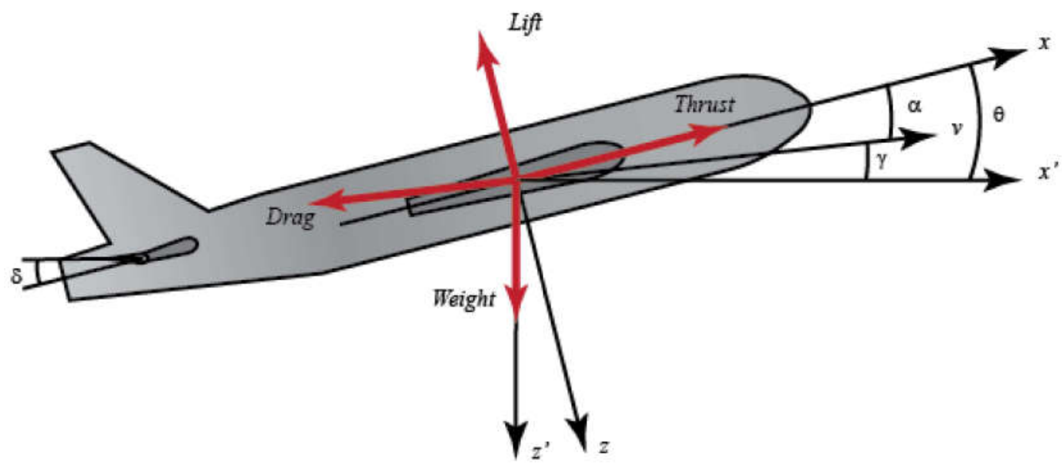
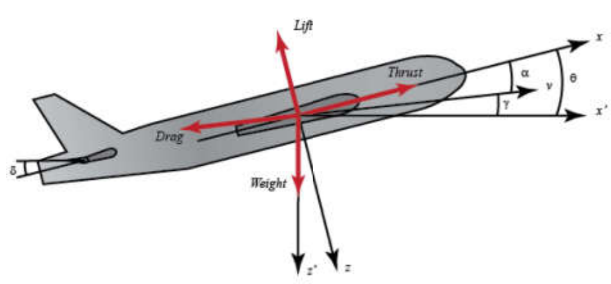


Transfer function, $G(s) = \frac{\Theta(s)}{\Delta(s)} = ??$

Aircraft Pitch Control



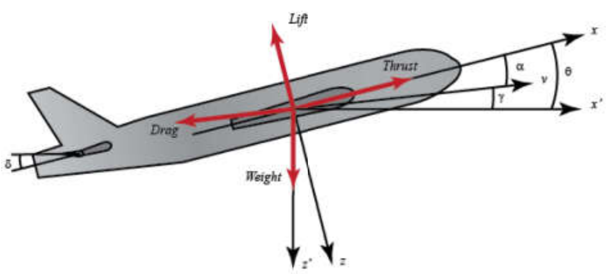
Physical Parameters

α = Angle of attack
q = Pitch Rate
θ = Pitch rate
δ = Elevator deflection

Physical Parameters

ρ = Density of air
S = Platform area of wing
$\bar{c}$ = Average chord length
m = Mass of aircraft
$\mu = \frac{\rho S \bar{c}}{4m}$
U = Equilibrium flight speed
C_T = Coefficient of thrust
C_D = Coefficient of drag
C_L = Coefficient of lift
C_W = Coefficient of weight
C_M = Coefficient of pitch moment
γ =Flight path angle
$\Omega = \frac{2U}{\bar{c}}$
$\sigma = \frac{1}{1+\mu C_L}$ = constant
i_{yy} = Normalized moment of inertia
$\eta = \mu\sigma C_M$ = constant

Aircraft Pitch Control



The equations governing the motion of an aircraft are a very complicated set of six nonlinear coupled differential equations.Therefore, in order to simplify, we will assume that the aircraft is in steady-cruise at constant altitude and velocity; thus, the thrust, drag, weight and lift forces balance each other in the x- and y-direction and that a change in pitch angle will not change the speed of the aircraft under any circumstance (unrealistic but simplifies the problem a bit!).

Under these assumptions, the following 3 governing equations are used by one of Boeing's commercial aircraft.

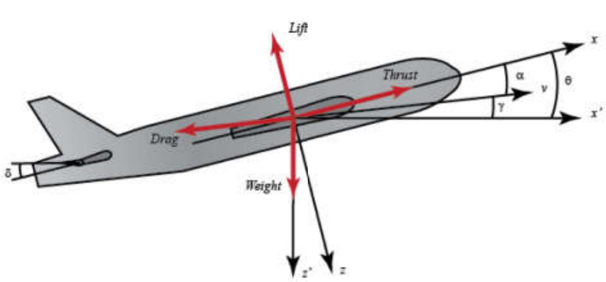
$$\frac{d\alpha}{dt} = -0.313\alpha + 56.7q + 0.232\delta$$

$$\frac{dq}{dt} = -0.0139\alpha - 4.426q + 0.0203\delta$$

$$\frac{d\theta}{dt} = 56.7q$$

Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

Aircraft Pitch Control



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Ans: $G(s) = \frac{1.151s+0.1774}{s^3+0.739s^2+0.921s}$

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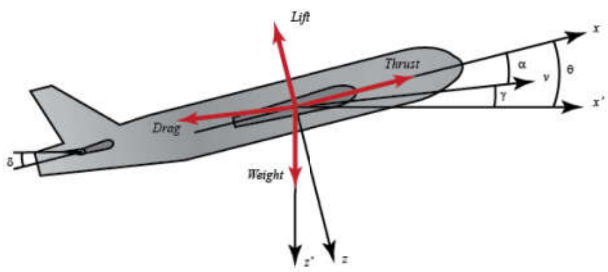
Aircraft Pitch Control



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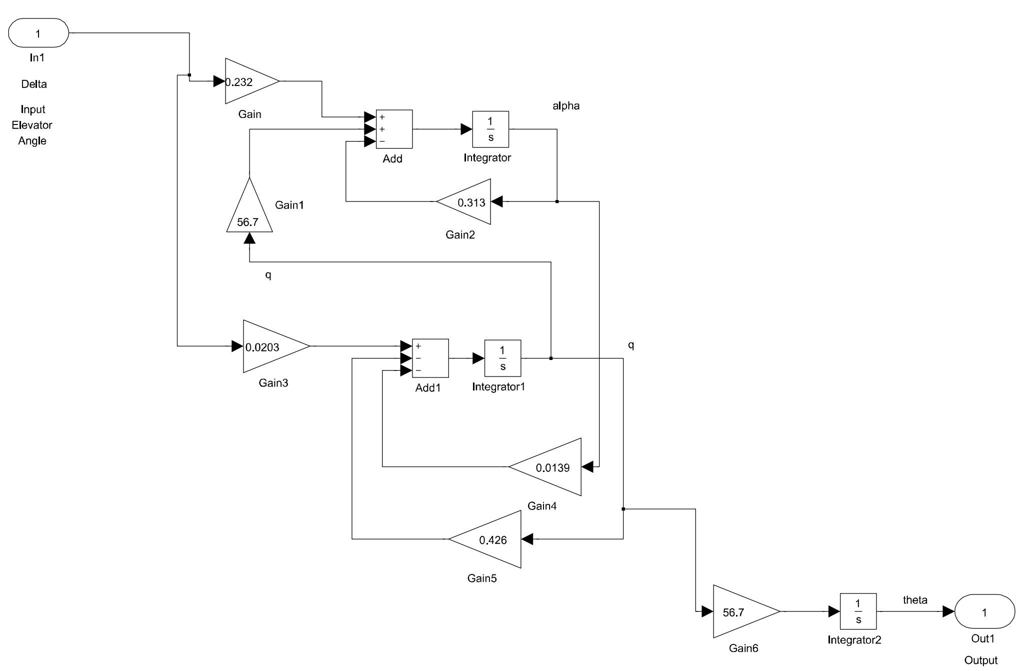
Is the system stable?

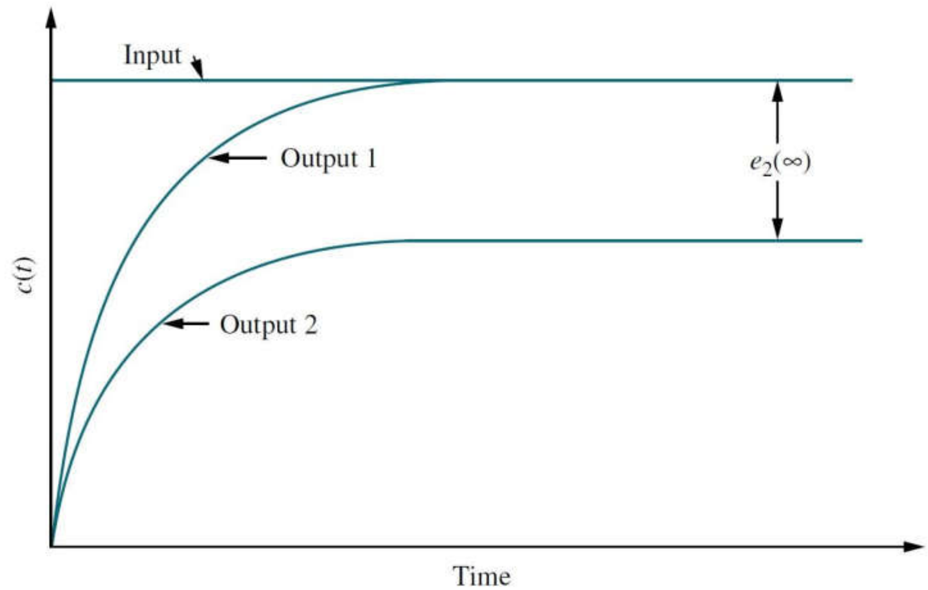
Draw step response when elevator deflection is 0.2 rad.

Aircraft Pitch Control

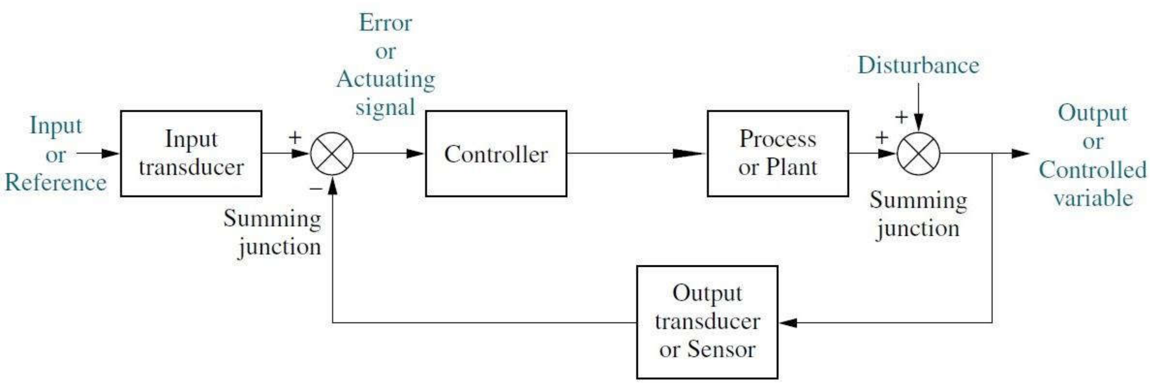


Steady State Error

The difference between the input and output for a prescribed test input as time, t approaches ∞.



Feedback Control



closed-loop system

Feedback Control

- In feedback control , the objective is to reduce error signal to zero.

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

Feedback Control

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- $e(t) =$ Error Signal
- $y_{sp}(t) =$ Set Point
- $y_m(t) =$ Measured value of the controlled or process variable (equivalent sensor signal)
- Although the error signal equation implies that set point is time varying but in many applications it is kept constant over a long period of time.

Different types of feedback control

Proportional Control (P)

- For Proportional Control , the objective is to reduce error signal to zero.
- $p(t) = \bar{p} + K_p e(t)$
- $p(t)$ = Controller output
- $\bar{p}$ = Bias or steady state value
- K_p = Proportional Controller Gain

Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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Integral Control (I)

- For Integral Control , the rate of change of controller output is proportional to the error signal.
- $p(t) = \bar{p} + K_I \int e(t)$ i.e., $\frac{dp}{dt} = K_I e(t)$
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Different types of feedback control(contd.

Derivative Control (D)

- For Derivative Control , the controller output is proportional to the rate of change of error signal.
- $p(t) = \bar{p} + K_d \frac{de(t)}{dt}$
- $p(t)$ = Controller output
- $\bar{p}$ = Bias or steady state value
- K_d = Derivative Controller Gain

How PID affects a process/system

CL Response	Rise Time	Overshoot	Settling Time	S-S Error
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small change	Decrease	Decrease	No change

1. A proportional controller (K_p) reduces the rise time and will reduce but never eliminate the steady-state error.
2. An integral control (K_i) eliminates the steady-state error for a constant or step input, but it may make the transient response slower.
3. A derivative control (K_d) increases the stability of the system, reducing the overshoot, and improving the transient response.
4. Note that these correlations may not be exactly accurate, because K_p, K_i, and K_d are dependent on each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only be used as a reference when you are determining the values for K_i, K_p and K_d.

PID Controller Design: Step Input, Unit Feedback

```
%%Controller Design for Unit feedback
clc
clear all
disp('PID Controller Design for Unit feedback');
disp(' ');
Kp = input('Input Kp = ');
Ki = input('Input Ki = ');
Kd = input('Input Kd = ');

C=tf([Kd Kp Ki], [1 0]); % Defines the PID Controller

num = input('Input Plant TF numerator vector = ');
den = input('Input Plant TF denominator vector = ');

P = tf(num,den); % Defines the Process Transfer Function

step(P); % Draws step response of P
hold on; % Uses the same figure for next plot

T= feedback(C*P,1); % Unit feedback is fed to the controlled system

t=0:0.01:2;  %Sets simulation time

step(T,t); % Draws step response of closed loop feedback system T
```

PID Controller Tuning

Problem

Manually tune a PID controller for a plant having $G(s) = \frac{1}{s^2+10s+20}$. Your goal is to achieve -

- fast rise time
- minimum overshoot
- no steady-state error

Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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Open Loop Response

- Put $K_P = 0$, $K_d = 0$, $K_I = 0$ in the code.
- The steady-state error is as much as 95%.
- Settling time is 1.5 sec.

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P-Controller

- Put $K_P = 300$ in the code.
- Steady-state error is reduced.
- Rise time is reduced.
- Overshoot increased.
- Settling time slightly reduced.

Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

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Control Systems MATLAB SIMULINK Response Modeling Feedback-Control

PID Controller Tuning(contd.)

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- Steady-state error is slightly reduced.
- Rise time is slightly reduced.
- Overshoot reduced.
- Settling time reduced.

PI-Controller

- Put $K_P = 30$ $K_I = 70$ in the code.
- Proportional gain is reduced because integral controller alone reduces the rise time and increases the overshoot effect.
- If both of them have high values it will create a double effect.
- This controller eliminates the steady-state error.

PID Controller Tuning(contd.)

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- This controller eliminates the steady-state error.

PID-Controller

- Put $K_P = 350$ $K_I = 300$ $K_D = 5500$ in the code.
- Very fast rise time.
- No overshoot.
- No steady-state error