

Ongoing Lectures Collection

**CS241**

# **Linear Control Systems**

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Latest version  
**Lectures Collection**

## Ongoing Lectures Collection



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### Colophon

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# Preface

I'm using  $\text{\LaTeX}$ , hoping that this work will continue existing. I don't have much else to say, so I will just insert some blind text. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

*Ahmed Waleed*

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# First Lecture

# 1

## 1.1 Introduction

**Analysis of linear continuous system** analysis of a system means simply checking the goodness of its measure of performance. Analysis could be done in two different ways:

- In the lab: by putting test input to the system and checking if the output satisfies the measure of performance.
- Using analytical techniques: which is our concern in this course.

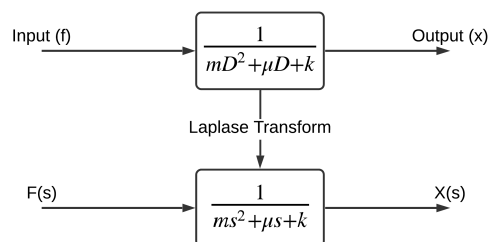
**The first step** is to make a mathematical model to the system.

$$\Sigma F_x = m\ddot{x}$$

$$F - \mu\dot{x} - kx = m\ddot{x}$$

$$\therefore \boxed{F = m\ddot{x} + \mu\dot{x} + kx}$$

**Then** defining the measure of performance and studying how we can check these measure of performance.

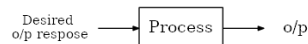


**Transfer function** ratio between Laplace transform of the output and Laplace transform of the input, assuming zero initial conditions.

## 1.2 Control Systems

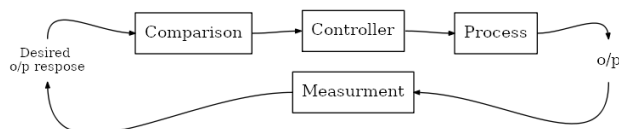
A control system is an interconnection of components forming a system configuration that will provide a desired system response.

**Open-loop control system (without feedback):**



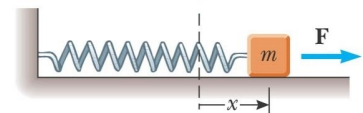
**Figure 1.3:** Its output does not track the input, and it is more affected by noise.

**Closed-loop feedback control system (with feedback):**



**Figure 1.4:** Closed loop control can improve accuracy, also the actuating signal is a function of the output.

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**Figure 1.1:** A block attached to a spring. ©

**Figure 1.2:** Since D is an operator (can't have a value), the transfer function is obtained by the Laplace transform of the first relation.

### 1.3 Mathematical Model

Any linear continuous system can be represented either by a linear algebraic equation or an ordinary differential equation such as:

$$(mD^2 + \mu D + k) x(t) = y(t)$$

Solving the differential equation using Laplace transform assuming zero initial conditions made it possible to get the transfer function.

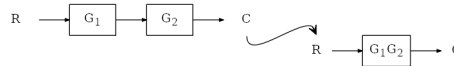
### 1.4 Block Diagram Reduction

A Block Diagram is a shorthand pictorial representation of the cause-and-effect relationship of a system. Control systems require the arithmetic manipulation in order to obtain the overall transfer function and this is the start point for the analysis of the system.

Table 1.1: Terminology

|   |  |
|---|--|
| R | : reference input / desired output response. |
| E | : actuating / error signal.                  |
| G | : control element and controlled system.     |
| C | : controlled variable / actual output.       |
| H | : feedback / backward transfer element.      |
| B | : primary feedback.                          |
| s | : summation point.                           |
| t | : takeoff point.                             |

Cascade connection :



Parallel connection :



Summation point :

a small circle, with plus or minus sign associated with the inputs, and the output is the algebraic sum of the inputs.

Take-off point :

a takeoff (or pickoff) point is used in order to have the same signal input to more than one block.

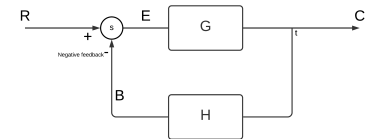


Figure 1.5: Canonical feedback loop.

### Overall transfer function (feedback loop elimination):

Applying reduction techniques mentioned above, we can obtain the overall transfer function of Figure 1.5

$$@ s : E = R - B \quad (\text{summation point})$$

$$\therefore B = CH \quad (\text{block})$$

$$\therefore E = R - CH$$

$$\therefore C = GE \quad (\text{block})$$

$$\therefore C = G(R - CH)$$

$$C + CGH = GR$$

$$C(1 + GH) = GR$$

$$\boxed{\frac{C}{R} = \frac{G}{1 + GH}}$$

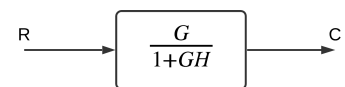


Figure 1.6: Feedback loop equivalent



## 2.1 Introduction to Mathematical Models

We will be studying single output linear continuous systems. If a system has more than one input the superposition principle will be applied.

### Super Position Principle

The superposition property, states that, for all linear systems, the net response caused by two or more stimuli is the sum of the responses that would have been caused by each stimulus individually.

$$F(x_1 + x_2) = F(x_1) + F(x_2)$$

(It can be used to prove linearity)

### Simple Systems Equations

The purpose of this section is to present methods of writing the differential equations for a variety of electrical and mechanical systems. This is the first step that must be mastered by the would-be control systems engineer.

#### Series Resistor-Inductor-Capacitor Circuit

$$v_L = (LD) i$$

$$v_R = R i$$

$$v_C = \left(\frac{1}{CD}\right) i$$

$$v = \left(LD + R + \frac{1}{CD}\right) i$$

(*R* : resistor, *L* : inductor, *C* : capacitor)

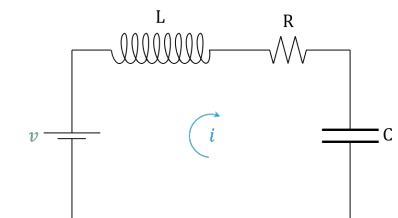


Figure 2.1: Simple electrical system.

#### Simple Mechanical Translation System

$$f_M = (MD^2) x$$

$$f_B = (BD) x$$

$$f_K = K x$$

$$f = (MD^2 + BD + K) x$$

(*M* : mass, *B* : damping or viscous friction, *K* : elastance or stiffness)

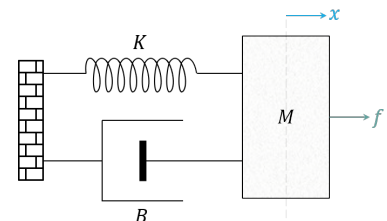


Figure 2.2: Mechanical translation system.

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## Simple Mechanical Rotational System

$$\tau_J = (JD^2) \theta$$

$$\tau_B = (BD) \theta$$

$$\tau_K = K \theta$$

$$\tau = (JD^2 + BD + K) \theta$$

( $J$  : moment of inertia)

## Single-stage Rotating Amplifier

$$v_F = (DL_F + R_F) i_F$$

$$v_G = K_G i_F$$

$$v_F = \left( \frac{DL_F + R_F}{K_G} \right) v_G$$

( $F$  : field,  $G$  : generator)

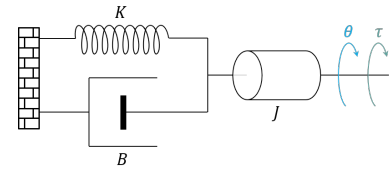


Figure 2.3: Mechanical rotational system.

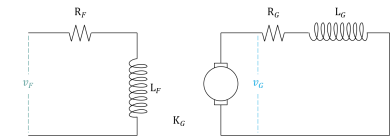


Figure 2.4: Field controlled generator.

## D-C Servomotor

## Armature Controlled Motor

$$v_M = (K_b D) \theta_M$$

$$\tau = K_T i_M$$

$$i_M = \left( \frac{JD^2 + BD}{K_T} \right) \theta_M$$

$$v_A = v_M + (L_M D + R_M) i_M$$

$$v_A = \left[ \frac{(L_M J) D^3 + (L_M B + R_M J) D^2 + (R_M B + K_b K_T) D}{K_T} \right] \theta_M$$

( $M$  : motor,  $A$  : armature)

Keep in mind the mechanical rotational system equation.

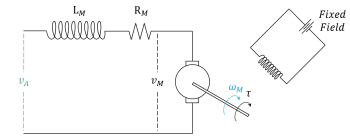


Figure 2.5: Armature controlled motor.

## Field Controlled Motor

$$\tau = K_F i_F$$

$$i_F = \left( \frac{JD^2 + BD}{K_F} \right) \theta_M$$

$$v_F = (DL_F + R_F) i_F$$

$$v_F = \left[ \frac{(JD^2 + BD)(DL_F + R_F)}{K_F} \right] \theta_M$$

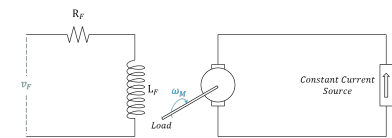


Figure 2.6: Field controlled motor.

## 2.2 Reduction Techniques (Moving Points)

Summing point behind a block:



Summing point ahead a block:



Take-off point behind a block:



Take-off point ahead a block:



**Homework** Convert Motor-generator control schematic diagram to block diagram and simplify it.

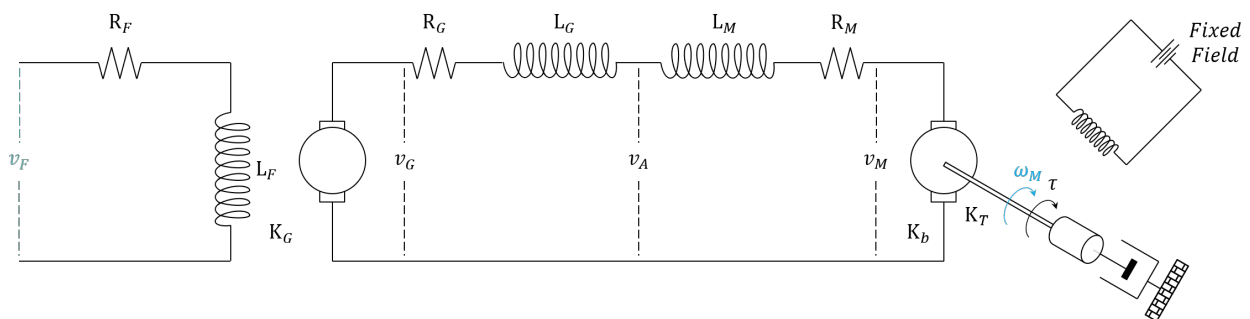
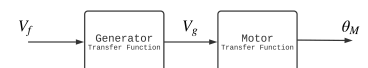
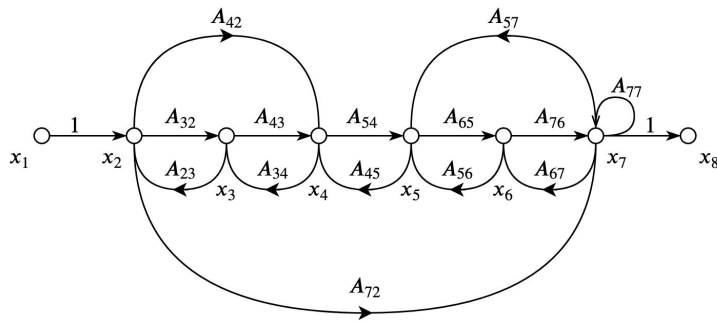


Figure 2.7: Motor-generator control.

**Hint** The last step should be:



## 3.1 Signal Flow Graphs



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Figure 3.1: Signal flow general graph.

### Nodes

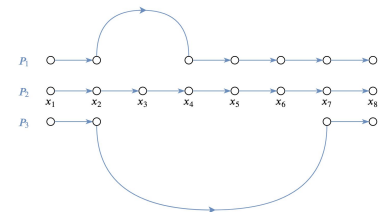
**Source Nodes** Represent independent variables and have only outgoing branches. ( $x_1$ )

**Sink Nodes** Represent dependent variables and have only incoming branches. ( $x_8$ )

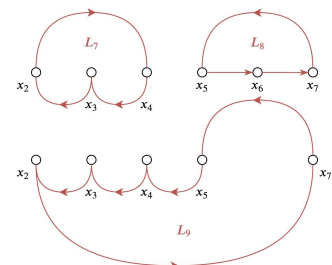
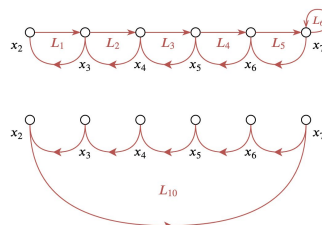
**Mixed Nodes** Have both incoming and outgoing branches. ( $x_2 \rightarrow x_7$ )

### Paths

**Forward Path** From the input node to the output node.



**Feedback loop** Originates and terminates on the same node.



**Self loop** A feedback loop consisting of a single branch.



## Non-touching loops

### Two at a time

|          |          |          |
|----------|----------|----------|
| $L_1L_3$ | $L_2L_4$ | $L_3L_6$ |
| $L_1L_4$ | $L_2L_5$ | $L_4L_6$ |
| $L_1L_5$ | $L_2L_6$ | $L_4L_7$ |
| $L_1L_6$ | $L_2L_8$ | $L_5L_7$ |
| $L_1L_8$ | $L_3L_5$ | $L_7L_8$ |

### Three at a time

|             |
|-------------|
| $L_1L_3L_5$ |
| $L_1L_3L_6$ |
| $L_1L_4L_6$ |
| $L_2L_4L_6$ |

### Four at a time

...

## Gain

**Path Gain** Product of branch gains encountered in a path. ( $P_3 : A_{72}$ )

**Loop Gain** Product of the branch gains of the loop. ( $L_3 : A_{54}A_{45}$ )

## 3.2 Block Diagram to Signal Flow Graph ↗

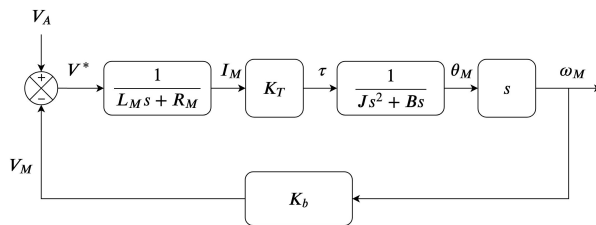
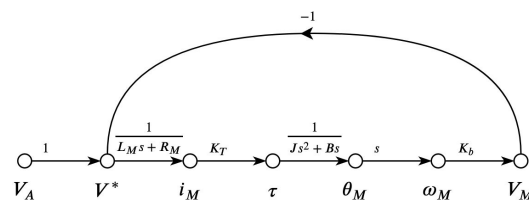


Figure 3.2: Motor block diagram.

**Step 1** Represent all the signals, variables, summing points and take-off points of block diagram as nodes in signal flow graph.

**Step 2** Represent the blocks of block diagram as branches in signal flow graph.

**Step 3** Represent the transfer functions inside the blocks of block diagram as gains of the branches in signal flow graph.<sup>1</sup>



1: Connect the nodes as per the block diagram. If there is connection between two nodes (but there is no block in between), then represent the gain of the branch as one.

Figure 3.3: Motor flow-graph diagram.

## 3.3 Flow-graph Algebra ☒

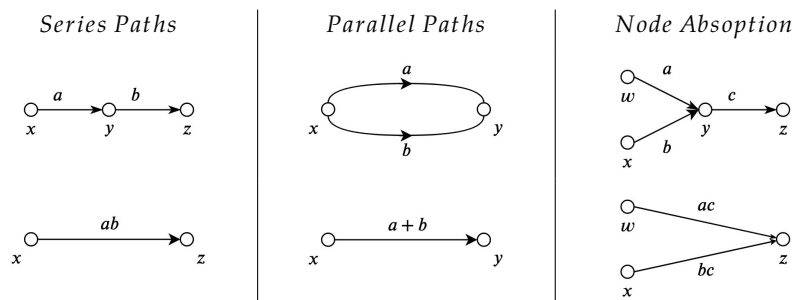


Table 3.1: Simplification rules.

## Feedback paths

The equations for the feedback system of Figure 3.4 are:

$$\begin{aligned} C &= GE \\ E &= R - HC \end{aligned}$$

**Step 1** The node  $E$  can be eliminated to produce a graph with a self-loop.

**Step 2** The final simplification is to eliminate the self-loop to produce the over-all transmittance.

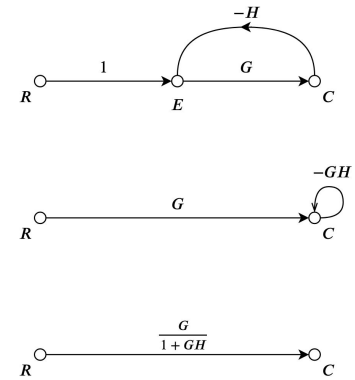


Figure 3.4: Reduction of a feedback path.

## 3.4 The Mason Rule

The block diagram reduction technique requires successive application of fundamental relationships in order to arrive at the system transfer function. On the other hand, Mason's rule for reducing a signal-flow graph to a single transfer function requires the application of one formula.

$$\frac{C(s)}{R(s)} = \frac{1}{\Delta} \cdot \sum_{i=1}^n P_i \Delta_i$$

- $n$  Number of forward paths.
- $P_i$  The  $i^{th}$  forward path gain.
- $\Delta$  Determinant of the system.
- $\Delta_i$  Determinant of the  $i^{th}$  forward path.

### Graph determinant $\Delta$

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### Systematic approach

- Step 1** Calculate forward path gain  $P_i$  for each  $i$  forward path.
- Step 2** Calculate all loops transfer functions.
- Step 3** Consider non-touching loops 2 at a time, 3 at a time, ... etc.
- Step 4** Calculate  $\Delta$  from steps 2 and 3.
- Step 5** Calculate  $\Delta_i$  as portion of  $\Delta$  not touching  $i$  forward path.

#### Step 1

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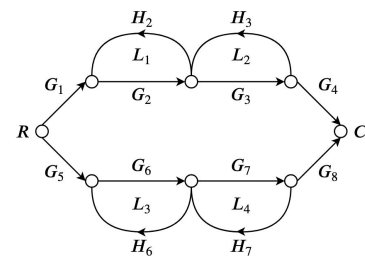


Figure 3.5: Mason rule example.

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## Step 5

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## Fourth Lecture

# 4

### 4.1 Singularities of a Function

### 4.1 Singularities of a Function .

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# APPENDIX

# A

## Laplace Transforms

**Remember** that we consider all functions are defined only on  $t \geq 0$ .

| $f(t)$               | $\mathcal{L}[f(t)] = \int_0^\infty f(t) e^{-st} dt = F(s)$ |
|----------------------|--|
| $a$                  | $\frac{a}{s}$  |
| $\delta(t - a)$      | $e^{-as}$  |
| $\mathcal{U}(t - a)$ | $\frac{1}{s} e^{-as}$                                      |
| $e^{at}$             | $\frac{1}{s - a}$  |
| $\sin at$            | $\frac{a}{s^2 + a^2}$                                      |
| $\cos at$            | $\frac{s}{s^2 + a^2}$                                      |
| $\sinh at$           | $\frac{a}{s^2 - a^2}$                                      |
| $\cosh at$           | $\frac{s}{s^2 - a^2}$                                      |
| $t^p$                | $\frac{\Gamma(p + 1)}{s^{p+1}}, p > -1$                    |

| $f(t)$                     | $\mathcal{L}[f(t)] = \int_0^\infty f(t) e^{-st} dt = F(s)$ |
|----------------------------|--|
| $\frac{d^n}{dt^n}$         | $s^n \text{note } \rightsquigarrow a$                      |
| $e^{-at} \sin \omega t$    | $\frac{\omega}{(s + a)^2 + \omega^2}$                      |
| $e^{-at} \cos \omega t$    | $\frac{s + a}{(s + a)^2 + \omega^2}$                       |
| $\int_{-\infty}^t f(x) dx$ | $\frac{1}{s} F(s) + \frac{1}{s} \int_{-\infty}^0 f(x) dx$  |

( $a$  : constant,  $x$  : dummy variable,  $p$  : real number,  $n$  : integer)

**Gamma function** which is defined as:

$$\Gamma(p) = \int_0^\infty e^{-x} x^{p-1} dx \rightsquigarrow$$

If  $n$  is a positive integer then,

$$\Gamma(n + 1) = n!$$

**Table A.1:** Theorems

| $f(t)$                        | $\mathcal{L}[f(t)] = \int_0^\infty f(t) e^{-st} dt = F(s)$                    |
|-------------------------------|---|
| $f(at)$                       | $\frac{1}{a} F\left(\frac{s}{a}\right)$                                       |
| $\dot{f}(t)$                  | $sF(s) - f(0)$  |
| $\int_0^t f(x) dx$            | $\frac{1}{s} F(s)$  |
| $tf(t)$                       | $-\dot{F}(s)$   |
| $\frac{1}{t} f(t)$            | $\int_s^\infty F(x) dx$ , if $\lim_{t \rightarrow 0} \frac{1}{t} f(t)$ exists |
| $e^{at} f(t)$                 | $F(s - a)$  |
| $f(t - a) \mathcal{U}(t - a)$ | $e^{-as} F(s)$  |
| $\int_0^t f(x) g(t - x) dx$   | $F(s) G(s)$   |

**Table A.2:** General transforms ©

**Table A.3:** Specific transforms ☞

<sup>a</sup> Since all the initial conditions are assumed to be zero.

# B

## Identification of Energy Functions

### B.1 Electric Circuits

| Element          | Kinetic energy<br>$T$ | Potential energy<br>$V$     | Dissipation function<br>$D$ |
|------------------|-----------------------|-----------------------------|-----------------------------|
| Inductance, $L$  | $\frac{1}{2}Li^2$     | —                           | —                           |
| Capacitance, $C$ | —                     | $\frac{1}{2C}(\int i dt)^2$ | —                           |
| Resistance, $R$  | —                     | —                           | $\frac{1}{2}Ri^2$           |

Table B.1: Forcing function is  $v$  voltage

| Element          | Kinetic energy<br>$T$ | Potential energy<br>$V$     | Dissipation function<br>$D$ |
|------------------|-----------------------|-----------------------------|-----------------------------|
| Inductance, $L$  | —                     | $\frac{1}{2L}(\int v dt)^2$ | —                           |
| Capacitance, $C$ | $\frac{1}{2}Cv^2$     | —                           | —                           |
| Conductance, $G$ | —                     | —                           | $\frac{1}{2}Gv^2$           |

Table B.2: Forcing function is  $i$  current

### B.2 Mechanics

| Element        | Kinetic energy<br>$T$   | Potential energy<br>$V$   | Dissipation function<br>$D$           |
|----------------|-------------------------|---------------------------|---------------------------------------|
| Mass, $M$      | $\frac{1}{2}M\dot{x}^2$ | —                         | —                                     |
| Elastance, $K$ | —                       | $\frac{1}{2}K(x_o - x)^2$ | —                                     |
| Damping, $B$   | —                       | —                         | $\frac{1}{2}B(\dot{x}_o - \dot{x})^2$ |

Table B.3: Forcing function is  $F$  force

| Element        | Kinetic energy<br>$T$        | Potential energy<br>$V$             | Dissipation function<br>$D$                     |
|----------------|------------------------------|-------------------------------------|---|
| Inertia, $J$   | $\frac{1}{2}J\dot{\theta}^2$ | —                                   | —   |
| Elastance, $K$ | —                            | $\frac{1}{2}K(\theta_o - \theta)^2$ | —   |
| Damping, $B$   | —                            | —                                   | $\frac{1}{2}B(\dot{\theta}_o - \dot{\theta})^2$ |

Table B.4: Forcing function is  $\tau$  torque

**Reference** Feedback control system analysis and synthesis.\*

(John j. Dazzo, Constantine h. Houpis)

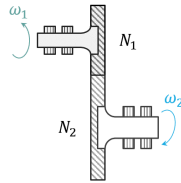
\* Tables 2-6, 2-7, 2-8, and 2-9 "2nd Edition"

# C

## Not Simple Systems Equations

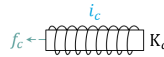
Gear train, rotational transformer

$$\frac{\omega_2}{\omega_1} = \frac{N_1}{N_2}$$



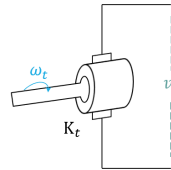
Solenoid, magnetic force

$$\frac{f_c}{i_c} = K_c$$



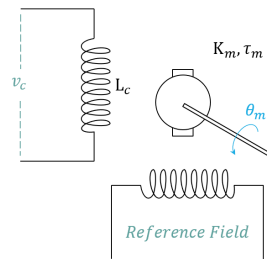
Tachometer, velocity sensor

$$\frac{v_t}{\omega_t} = K_t$$



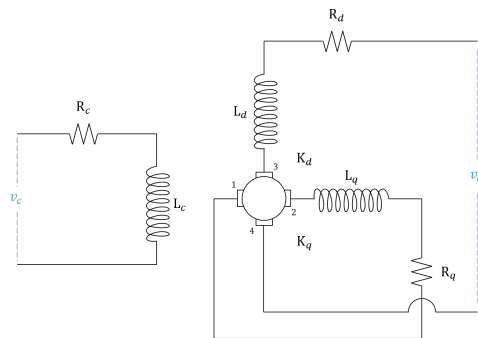
AC motor, two-phase control field

$$\frac{\Theta_m}{V_c} = \frac{K_m}{s(\tau_m s + 1)}$$



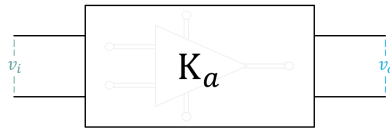
Amplidyne, rotary amplifier

$$\frac{V_o}{V_c} = \frac{K_q}{sL_c + R_c} \cdot \frac{K_d}{sL_q + R_q}$$



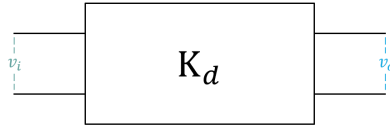
DC amplifier, 0 Hz amplifier

$$\frac{v_o}{v_i} = K_a$$



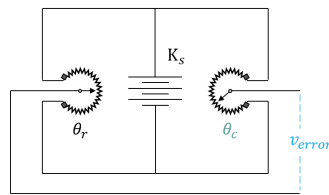
Demodulator, AC modulated signal to DC

$$\frac{v_o}{v_i} = K_d$$



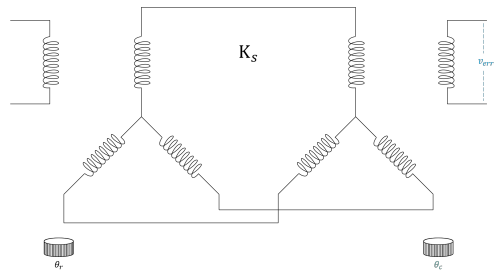
Potentiometer, used in "Error detector bridge"

$$\frac{v_{error}}{\theta_r - \theta_c} = K_s$$



Synchro, as "Error detector"

$$\frac{v_{error}}{\theta_r - \theta_c} = K_s$$



**Table C.1:** Transfer functions

**Reference** Modern control systems.\*

(Richard c. Dorf, Robert h.Bishop)

\* Tables 2-4 "International Edition"

# Greek Letters with Pronunciation

| Character          | Name                      | Character            | Name                             |
|--------------------|---------------------------|----------------------|----------------------------------|
| $\alpha$           | alpha <i>AL-fuh</i>       | $\nu$                | nu <i>NEW</i>                    |
| $\beta$            | beta <i>BAY-tuh</i>       | $\xi, \Xi$           | xi <i>KSIGH</i>                  |
| $\gamma, \Gamma$   | gamma <i>GAM-muh</i>      | $\omicron$           | omicron <i>OM-uh-CRON</i>        |
| $\delta, \Delta$   | delta <i>DEL-tuh</i>      | $\pi, \Pi$           | pi <i>PIE</i>                    |
| $\epsilon$         | epsilon <i>EP-suh-lon</i> | $\rho$               | rho <i>ROW</i>                   |
| $\zeta$            | zeta <i>ZAY-tuh</i>       | $\sigma, \Sigma$     | sigma <i>SIG-muh</i>             |
| $\eta$             | eta <i>AY-tuh</i>         | $\tau$               | tau <i>TOW (as in cow)</i>       |
| $\theta, \Theta$   | theta <i>THAY-tuh</i>     | $\upsilon, \Upsilon$ | upsilon <i>OOP-suh-LON</i>       |
| $\iota$            | iota <i>eye-OH-tuh</i>    | $\phi, \Phi$         | phi <i>FEE, or FI (as in hi)</i> |
| $\kappa$           | kappa <i>KAP-uh</i>       | $\chi$               | chi <i>KI (as in hi)</i>         |
| $\lambda, \Lambda$ | lambda <i>LAM-duh</i>     | $\psi, \Psi$         | psi <i>SIGH, or PSIGH</i>        |
| $\mu$              | mu <i>MEW</i>             | $\omega, \Omega$     | omega <i>oh-MAY-guh</i>          |

Capitals shown are the ones that differ from Roman capitals.