

Ongoing Lectures Collection

CS241

Linear Control Systems

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Latest version

Lectures Collection

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Colophon

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Preface

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Ahmed Waleed

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Introduction

1

1.1 Basic Information

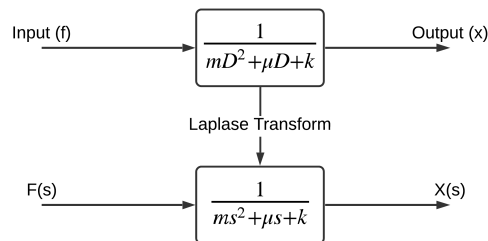
Analysis of linear continuous system analysis of a system means simply checking the goodness of its measure of performance. Analysis could be done in two different ways:

- 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.

$$\begin{aligned}\Sigma F_x &= m\ddot{x} \\ F - \mu\dot{x} - kx &= m\ddot{x} \\ \therefore \boxed{F = m\ddot{x} + \mu\dot{x} + kx}\end{aligned}$$

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):

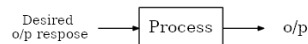


Figure 1.3: Its output does not track the input, and it is more affected by noise.

Closed-loop feedback control system (with feedback):

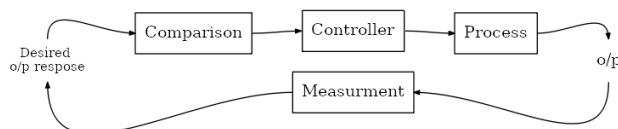


Figure 1.4: Closed loop control can improve accuracy, also the actuating signal is a function of the output.

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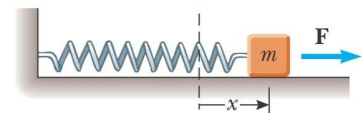


Figure 1.1: A block attached to a spring. ©

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.

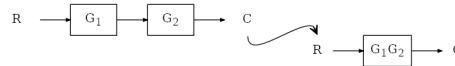
1.4 Block Diagram Reduction

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.

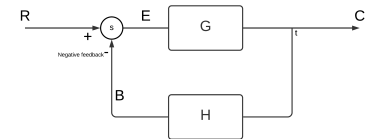


Figure 1.5: Canonical feedback loop.

Overall transfer function (feedback loop elimination):

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

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

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

$$\therefore E = R - CH$$

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

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

$$C + CGH = GR$$

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

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

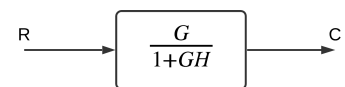


Figure 1.6: Feedback loop equivalent

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)

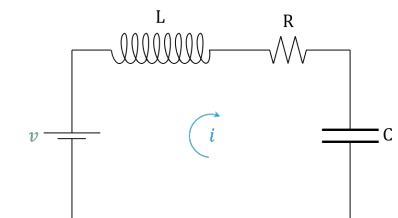


Figure 2.1: Simple electrical system.

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)

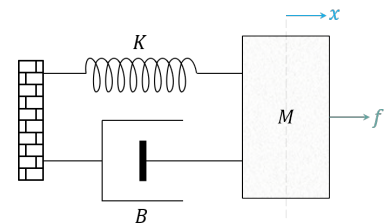


Figure 2.2: Mechanical translation system.

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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)

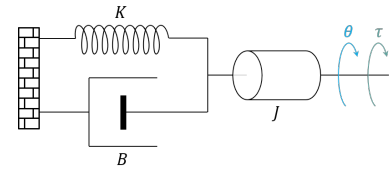


Figure 2.3: Mechanical rotational system.

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)

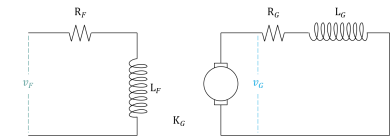


Figure 2.4: Field controlled generator.

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.

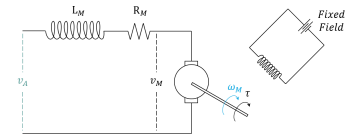


Figure 2.5: Armature controlled motor.

Field Controlled Motor

$$\tau = K_F i_F$$

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

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

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

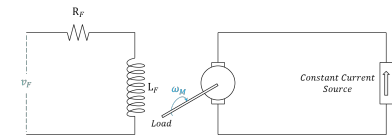
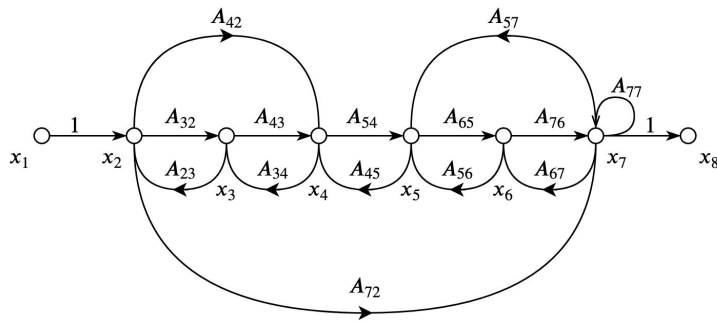


Figure 2.6: Field controlled motor.

Signal Flow Graphs

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3.1 Definitions



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Figure 3.1: Signal flow general graph.

Nodes

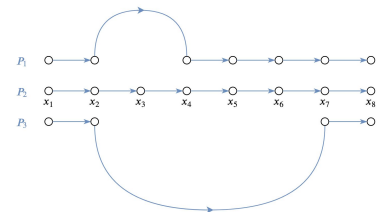
Source Nodes Represent independent variables and have only outgoing branches. (x_1)

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

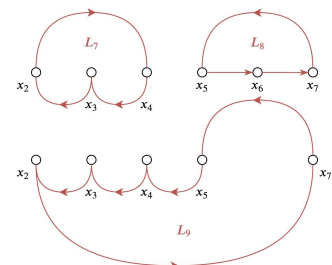
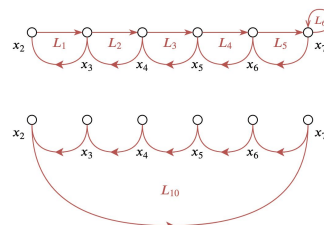
Mixed Nodes Have both incoming and outgoing branches. ($x_2 \rightarrow x_7$)

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 ↗

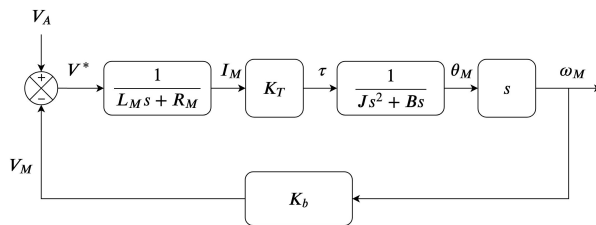
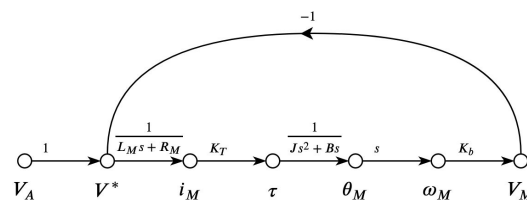


Figure 3.2: Motor block diagram.

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.¹



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 ☒

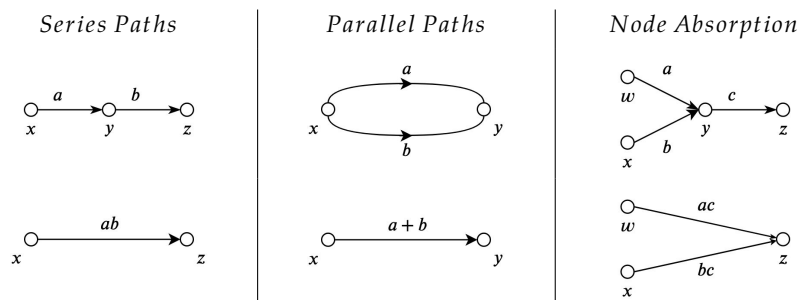


Table 3.1: Simplification rules.

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.

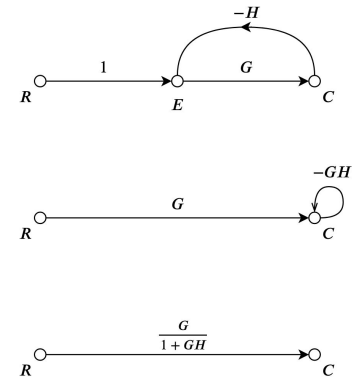


Figure 3.4: Reduction of a feedback path.

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.
- Δ Determinant of the system.
- Δ_i Determinant of the i^{th} forward path.

Graph determinant Δ

$\Delta = 1 - (\text{sum of all individual loop gains}) + (\text{sum of the products of the gains of all possible two loops that do not touch each other}) - \dots$ and so forth with sums of higher number of non-touching loop gains.

Δ_i = value of Δ for the part of the flow graph that does not touch the i^{th} forward path.²

2: $\Delta_i = 1$ if there are no non-touching loops to the i^{th} path.

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 Δ from steps 2 and 3.
- Step 5** Calculate Δ_i as portion of Δ not touching i forward path.

Step 1

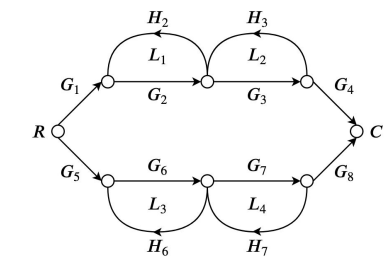
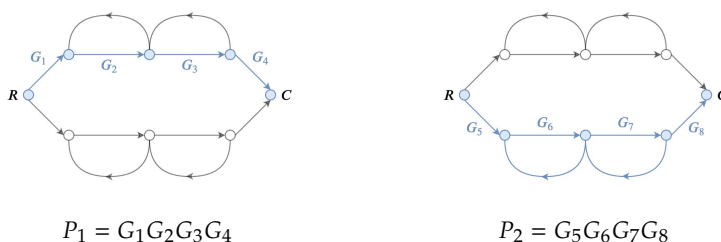


Figure 3.5: Mason rule example.

Step 2

$$\begin{cases} L_1 = G_2 H_2 \\ L_2 = G_3 H_3 \\ L_3 = G_6 H_6 \\ L_4 = G_7 H_7 \end{cases}$$

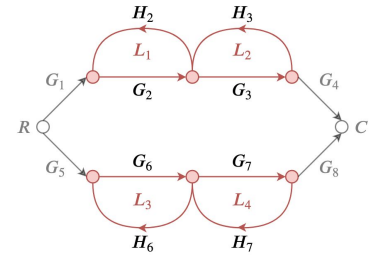


Figure 3.6: Loops considered.

Step 3

Two at a time

Three at a time

$$\begin{cases} L_1 L_3 \\ L_1 L_4 \\ L_2 L_3 \\ L_2 L_4 \end{cases}$$

...

Step 4

$$\Delta = 1 - (L_1 + L_2 + L_3 + L_4) + (L_1 L_3 + L_1 L_4 + L_2 L_3 + L_2 L_4)$$

$$\Delta = 1 - (G_2 H_2 + H_3 G_3 + G_6 H_6 + G_7 H_7) + (G_2 H_2 G_6 H_6 + G_2 H_2 G_7 H_7 + H_3 G_3 G_6 H_6 + H_3 G_3 G_7 H_7)$$

Step 5

Eliminate forward path-1:

$$\Delta_1 = 1 - (L_3 + L_4)$$

$$\Delta_1 = 1 - (G_6 H_6 + G_7 H_7)$$

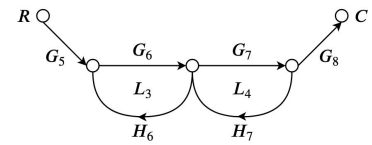


Figure 3.7: P_1 eliminated.

Eliminate forward path-2:

$$\Delta_2 = 1 - (L_1 + L_2)$$

$$\Delta_2 = 1 - (G_2 H_2 + H_3 G_3)$$

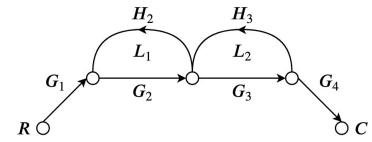


Figure 3.8: P_2 eliminated.

Applying Mason's rule

$$\frac{C(s)}{R(s)} = \frac{P_1 \Delta_1 + P_2 \Delta_2}{\Delta}$$

$$\frac{C(s)}{R(s)} = \frac{G_1 G_2 G_3 G_4 [1 - (G_6 H_6 + G_7 H_7)] + G_5 G_6 G_7 G_8 [1 - (G_2 H_2 + H_3 G_3)]}{1 - (G_2 H_2 + H_3 G_3 + G_6 H_6 + G_7 H_7) + (G_2 H_2 G_6 H_6 + G_2 H_2 G_7 H_7 + H_3 G_3 G_6 H_6 + H_3 G_3 G_7 H_7)}$$

4.1 Singularities of a Function

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4.2 Routh's Stability Criterion . . 11

System is stable if for bounded input the output is bounded BIBO.

System stability can be determined from the Transfer Function.

$$T.F = \frac{N(s)}{D(s)} = \frac{b_m s^m + b_{m-1} s^{m-1} + \dots + b_1 s + b_0}{a_n s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0}$$

Can be written in terms of factors:

$$T.F = \frac{N(s)}{D(s)} = K \frac{(s - Z_1)(s - Z_2) \dots (s - Z_{m-1})(s - Z_m)}{(s - P_1)(s - P_2) \dots (s - P_{n-1})(s - P_n)}$$

-> Roots of $D(s)$: P_1, P_2, \dots, P_n are called poles.

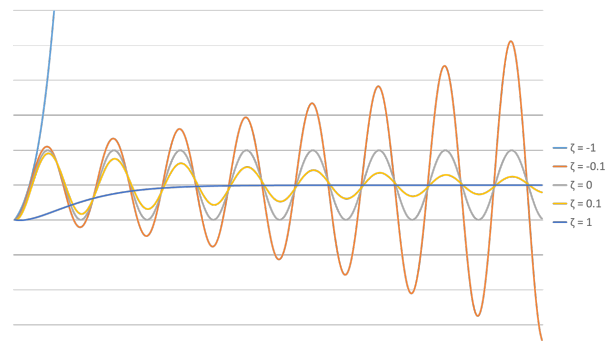
-> Roots of $N(s)$: Z_1, Z_2, \dots, Z_m are called zeros.

(where $m < n$)

All coefficients of $D(s), N(s)$ are real -> poles and zeros must be real or complex conjugate.

$$T.F = K \left(\frac{A_1}{s - P_1} + \frac{A_2}{s - P_2} + \dots + \frac{A_{n-1}}{s - P_{n-1}} + \frac{A_n}{s - P_n} \right)$$

For a second order systems: Root $(-\omega_n[\zeta \pm \sqrt{\zeta^2 - 1}])$



$$F(s) = \frac{A}{s}$$

Root is zero ($s = 0$):

-> unstable: $\int_0^\infty f(t) dt$ is not bounded.

Stability Condition:

all poles lie in the left half of s-plane

-> all coefficients of $D(s)$ must be real and positive.

-> all powers of s from s^1 to s^n should be present, however all odd powers of s or all even power of s may be missing.

(necessary conditions, but not sufficient)

4.2 Routh's Stability Criterion

5.1 Standard Test Signals

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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:

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

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 ☞

^a Since all the initial conditions are assumed to be zero.

B

Identification of Energy Functions

B.1 Electric Circuits

Element	Kinetic energy T	Potential energy V	Dissipation function 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 T	Potential energy V	Dissipation function 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 T	Potential energy V	Dissipation function 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 T	Potential energy V	Dissipation function 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 τ torque

Reference Feedback control system analysis and synthesis.*

(John j. Dazzo, Constantine h. Houpis)

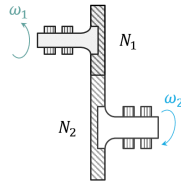
* Tables 2-6, 2-7, 2-8, and 2-9 "2nd Edition"

C

Not Simple Systems Equations

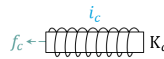
Gear train, rotational transformer

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



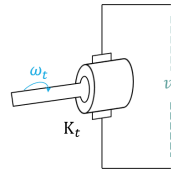
Solenoid, magnetic force

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



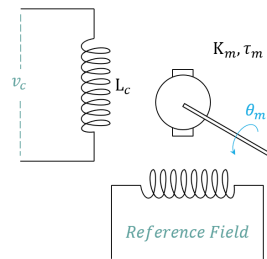
Tachometer, velocity sensor

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



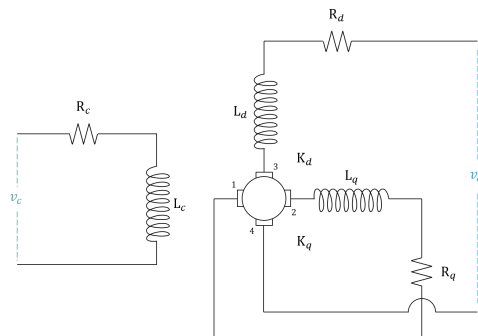
AC motor, two-phase control field

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



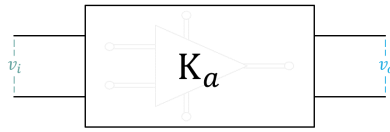
Amplidyne, rotary amplifier

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



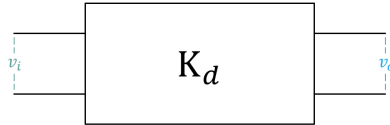
DC amplifier, 0 Hz amplifier

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



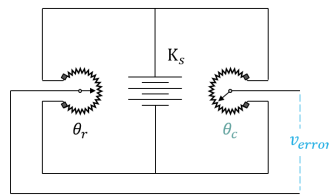
Demodulator, AC modulated signal to DC

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



Potentiometer, used in "Error detector bridge"

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



Synchro, as "Error detector"

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

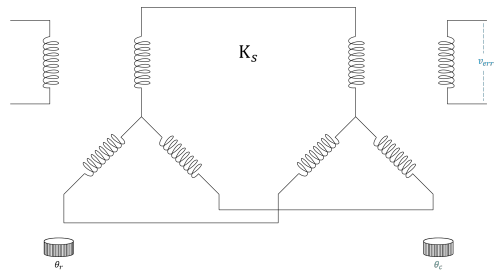


Table C.1: Transfer functions

Reference Modern control systems.*

(Richard c. Dorf, Robert h.Bishop)

* Tables 2-4 "International Edition"

Greek Letters with Pronunciation

Character	Name	Character	Name
α	alpha <i>AL-fuh</i>	ν	nu <i>NEW</i>
β	beta <i>BAY-tuh</i>	ξ, Ξ	xi <i>KSIGH</i>
γ, Γ	gamma <i>GAM-muh</i>	\omicron	omicron <i>OM-uh-CRON</i>
δ, Δ	delta <i>DEL-tuh</i>	π, Π	pi <i>PIE</i>
ϵ	epsilon <i>EP-suh-lon</i>	ρ	rho <i>ROW</i>
ζ	zeta <i>ZAY-tuh</i>	σ, Σ	sigma <i>SIG-muh</i>
η	eta <i>AY-tuh</i>	τ	tau <i>TOW (as in cow)</i>
θ, Θ	theta <i>THAY-tuh</i>	υ, Υ	upsilon <i>OOP-suh-LON</i>
ι	iota <i>eye-OH-tuh</i>	ϕ, Φ	phi <i>FEE, or FI (as in hi)</i>
κ	kappa <i>KAP-uh</i>	χ	chi <i>KI (as in hi)</i>
λ, Λ	lambda <i>LAM-duh</i>	ψ, Ψ	psi <i>SIGH, or PSIGH</i>
μ	mu <i>MEW</i>	ω, Ω	omega <i>oh-MAY-guh</i>

Capitals shown are the ones that differ from Roman capitals.