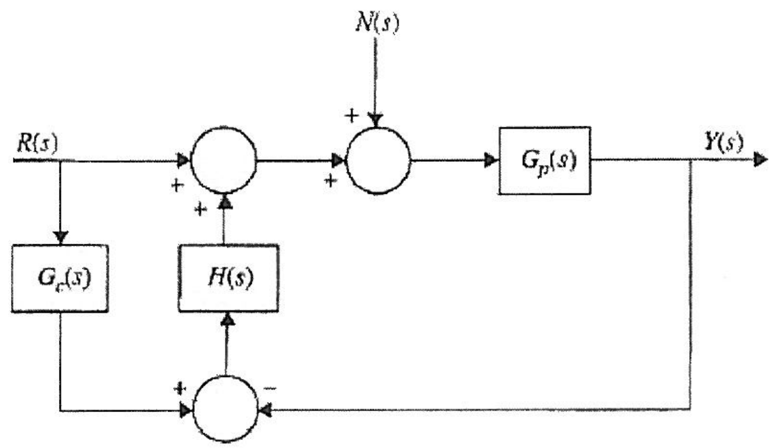
I The following differential equation is part of mathematical modeling of DC motor:

$$J_m \frac{d^2\theta_m(t)}{dt^2} = T_m(t) - T_L(t) - B_m \frac{d\theta_m(t)}{dt}$$

(a) What is the Laplace transform of above differential equation?
(b) Draw a block diagram that represents differential equation.

II The block diagram of a feedback control system is shown below.
(a) Draw equivalent signal flow graph of the block diagram.
(b)Using Mason gain formula find closed loop transfer function Y(s)/R(s) and Y(s)/N(s)



For EE's only

III

Determine the transfer function $V_0(s)/V(s)$ for the op-amp circuit shown in Figure E2.27 [1]. Let $R_1 = 167\ \text{k}\Omega$, $R_2 = 240\ \text{k}\Omega$, $R_3 = 1\ \text{k}\Omega$, $R_4 = 100\ \text{k}\Omega$, and $C = 1\ \mu\text{F}$. Assume an ideal op-amp.

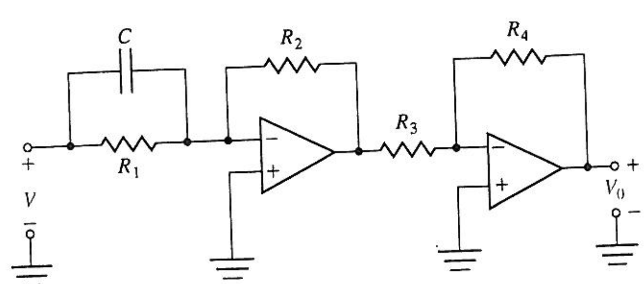
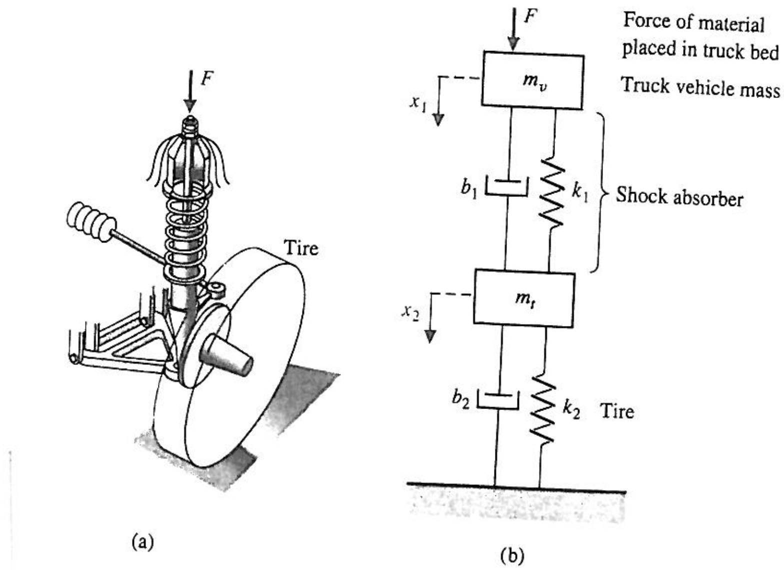


FIGURE E2.27
Op-amp circuit.

AE/ME only

III A load added to a vehicle (truck/aircraft) results in a force F on the support spring, and the tire flexes as shown in the figure (a) below. A model for the tire movement is also shown in the figure (b). Determine the transfer function $X_1(s)/F(s)$.



IV A unity negative feedback system has a open loop transfer function:

$$L(s) = \frac{K}{s^4 + 12s^3 + 64s^2 + 128s}$$

(a) Find the range of K for the closed loop system to be stable.
(b) When the system is marginally stable, find the frequency of oscillations.

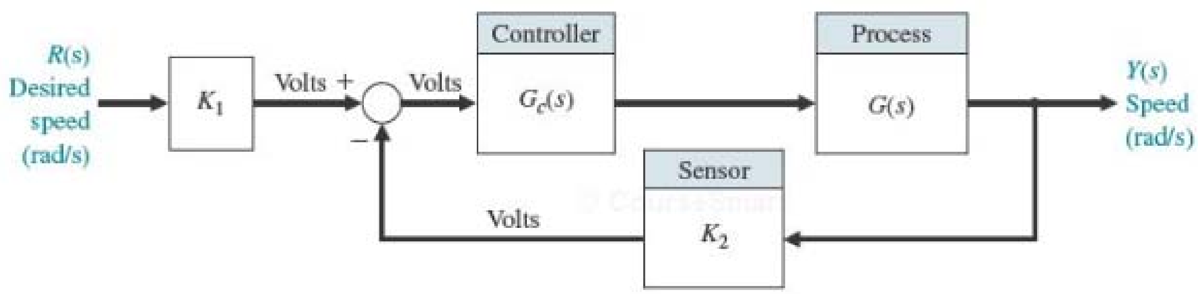
I The following differential equation is part of mathematical modeling of DC motor:

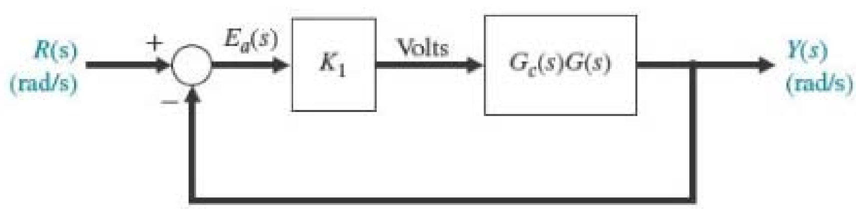
$$J_m \frac{d^2\theta_m(t)}{dt^2} = T_m(t) - T_L(t) - B_m \frac{d\theta_m(t)}{dt}$$

where $T_m(t)$ is motor torque, $T_L(t)$ is load torque, B_m the damping and J_m the moment of inertia.

(a) What is the Laplace transform of above differential equation? Assume zero initial conditions.
(b) Draw a block diagram that represents differential equation.

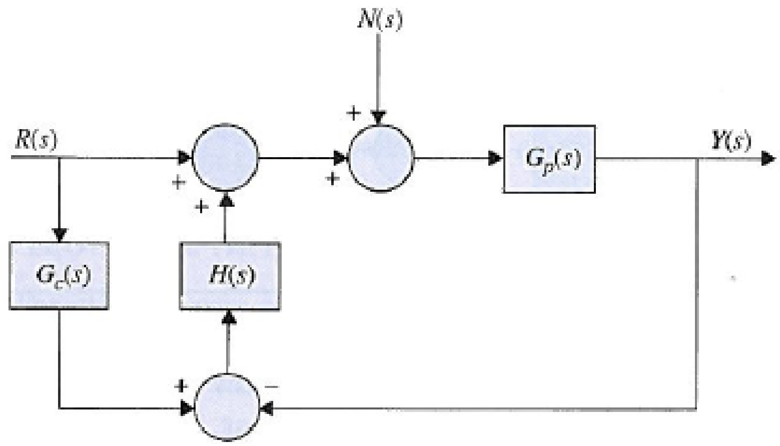
II Sometimes there is a need to convert nonunity feedback systems to unity feedback systems for example in finding error constants. Consider the nonunity feedback and unity feedback systems for a speed control system below:





Under what condition both systems are equivalent? Hint - look at closed loop transfer functions.

III The block diagram of a linear feedback control system is shown in the next page.
(a) Draw equivalent signal flow graph of the block diagram.
(b) Using Mason gain formula find closed loop transfer function Y(s)/R(s) and Y(s)/N(s)
(c) Find output Y(s) due to both R(s) and N(s) inputs.



For EE's only

IV Consider the inverting op-amp circuit(Proportional Integral Derivative (PID) below.
Find the transfer function $V_o(s)/V_i(s)$. Show the transfer function can be expressed as:

$$G(s) = \frac{V_o(s)}{V_i(s)} = K_P + \frac{K_I}{s} + K_D s$$

Where the gains K_P, K_I, and K_D are functions of C_1, C_2, R_1 and R_2.

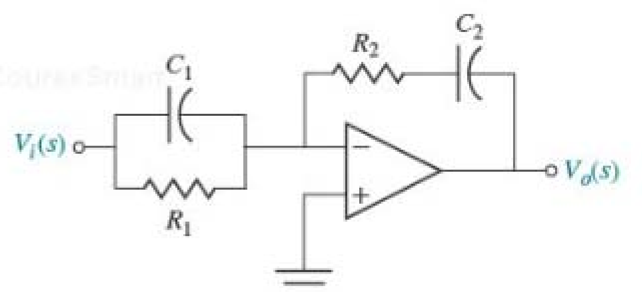
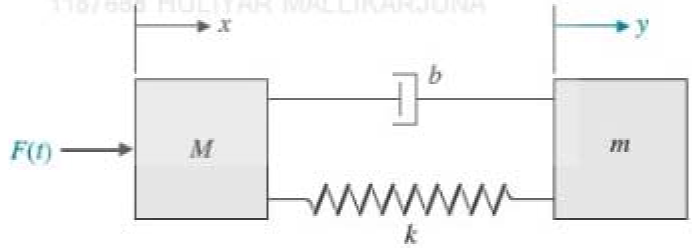


FIGURE AP2.9 An inverting operational amplifier circuit representing a PID controller.

AE/ME only

IV A robot includes significant flexibility in the arm members with a heavy load in the gripper. A two mass model of the robot arm is shown below. Find the transfer function Y(s)/F(s).



V A unity negative feedback system has a open loop transfer function:

$$L(s)=\frac{K}{s^4+12s^3+64s^2+128s}$$

(a) Find the range of K for the closed loop system to be stable.
(b) When the system is marginally stable, find the frequency of oscillations.

3-2-6 Gain Formula for SFG

Given an SFG or block diagram, the task of solving for the input-output relations by algebraic manipulation could be quite tedious. Fortunately, there is a general gain formula available that allows the determination of the input-output relations of an SFG by inspection.

Given an SFG with N forward paths and K loops, the gain between the input node y_{in} and output node y_{out} is [3]

$$M=\frac{y_{out}}{y_{in}}=\sum_{k=1}^{N}\frac{M_k\Delta_k}{\Delta} \tag{3-31}$$

where

y_{in} = input-node variable
y_{out} = output-node variable
M = gain between y_{in} and y_{out}
N = total number of forward paths between y_{in} and y_{out}
M_k = gain of the kth forward path between y_{in} and y_{out}

$$\Delta=1-\sum_i L_{i1}+\sum_j L_{j2}-\sum_k L_{k3}+\cdots \tag{3-32}$$

L_{mr} = gain product of the mth ($m=i,j,k,\ldots$) possible combination of r nontouching loops ($1\le r<K$).

or

Δ = 1 − (sum of the gains of **all individual** loops) + (sum of products of gains of all possible combinations of **two** nontouching loops) − (sum of products of gains of all possible combinations of **three** nontouching loops) + ⋯ (3-33)

Δ_k = the Δ for that part of the SFG that is nontouching with the kth forward path.

• The SFG gain formula can only be applied between an input node and an output node.

The gain formula in Eq. (3-31) may seem formidable to use at first glance. However, Δ and Δ_k are the only terms in the formula that could be complicated if the SFG has a large number of loops and nontouching loops.

Care must be taken when applying the gain formula to ensure that it is applied between an **input node** and an **output node**.

TABLE 2-1 Theorems of Laplace Transforms

Multiplication by a constant	$\mathcal{L}[kf(t)] = kF(s)$
Sum and difference	$\mathcal{L}[f_1(t) \pm f_2(t)] = F_1(s) \pm F_2(s)$
Differentiation	$\mathcal{L}\left[\frac{df(t)}{dt}\right] = sF(s) - f(0)$
	$\mathcal{L}\left[\frac{d^n f(t)}{dt^n}\right] = s^n F(s) - s^{n-1}f(0) - s^{n-2}f^{(1)}(0) - \cdots - sf^{(n-2)}(0) - f^{(n-1)}(0)$ where $f^{(k)}(0) = \left.\frac{d^k f(t)}{dt^k}\right\vert_{t=0}$
Integration	$\mathcal{L}\left[\int_0^t f(\tau)d\tau\right] = \frac{F(s)}{s}$
	$\mathcal{L}\left[\int_0^{t_1}\int_0^{t_2}\cdots\int_0^{t_n} f(t)d\tau dt_1 dt_2 \cdots dt_{n-1}\right] = \frac{F(s)}{s^n}$
Shift in time	$\mathcal{L}[f(t-T)u_s(t-T)] = e^{-Ts}F(s)$
Initial-value theorem	$\lim_{t\to 0} f(t) = \lim_{t\to\infty} sF(s)$
Final-value theorem	$\lim_{t\to\infty} f(t) = \lim_{s\to 0} sF(s)$ if $sF(s)$ does not have poles on or to the right of the imaginary axis in the s-plane.
Complex shifting	$\mathcal{L}[e^{\mp\alpha t}f(t)] = F(s \pm \alpha)$
Real convolution	$F_1(s)F_2(s) = \mathcal{L}\left[\int_0^t f_1(\tau)f_2(t-\tau)d\tau\right] = \mathcal{L}\left[\int_0^t f_2(\tau)f_1(t-\tau)d\tau\right] = \mathcal{L}[f_1(t) * f_2(t)]$

I The following differential equation is part of mathematical modeling of spring-mass-damper linear system:

$$v(t) = \frac{dy(t)}{dt}$$

$$M\frac{dv(t)}{dt} + bv(t) + k\int_0^t v(t)dt = r(t)$$

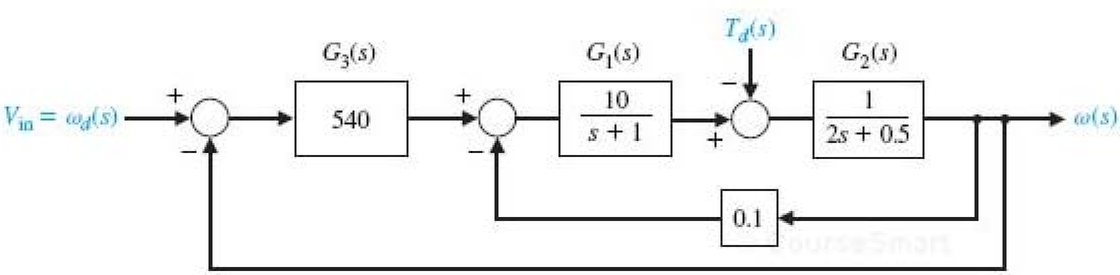
(a) What is the Laplace transform of above differential equations? Assume zero initial conditions.
(b) Draw a single block diagram that represents differential equation with r(t) as input and y(t) as output .

II The block diagram of an electric motor drive for railway vehicle is shown below.

(a) Draw equivalent signal flow graph of the block diagram. Use $\omega_1(s)$ and $\omega_2(s)$ be the outputs at 2nd and 3rd summing junctions for consistency.

(b) Using Mason gain formula find closed loop transfer functions $\omega(s)/\omega_d(s)$ and $\omega(s)/T_d(s)$.

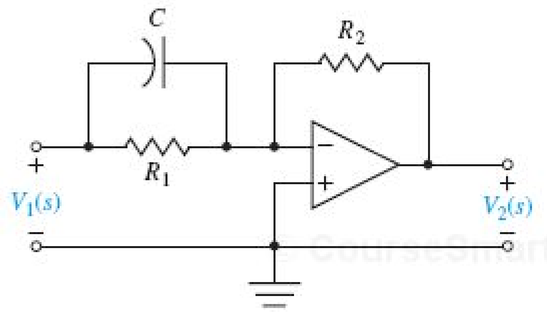
(c) What is the output $\omega(s)$ due to both inputs V_{in} and $T_d(s)$?



EE's only

III For the circuit below find the transfer function $V_2(s)/V_1(s)$. For sake of simplicity assume capacitor is 1 Farad and both resistors are 1 Ohm each:

(Turn Over)



BMEs ONLY

The development of robotic microsurgery devices will have major implications on delicate eye and brain surgical procedures. The microsurgery devices employ feedback control to reduce the effects of the surgeon's muscle tremors. Precision movements by an articulated robotic arm can greatly help a surgeon by providing a carefully controlled hand. One such device is shown in Figure below. The microsurgical devices have been evaluated in clinical procedures and are now being commercialized. Sketch a block diagram of the surgical process with a microsurgical device in the loop being operated by a surgeon. Assume that the position of the end-effector on the microsurgical device can be measured and is available for feedback. Note the diagram should show input, controller, devoice, sensor and other relevant blocks.

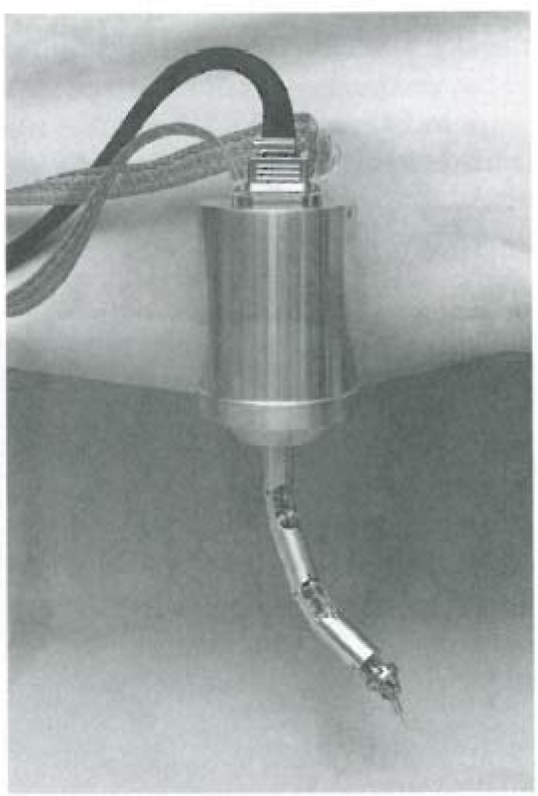
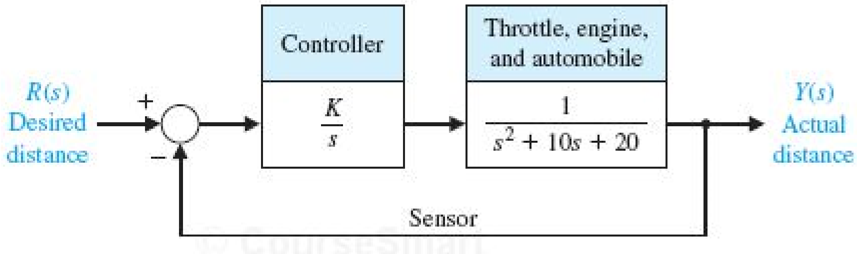


FIGURE AP1.1 Microsurgery robotic manipulator. (Photo courtesy of NASA.)

IV A traffic control system is designed to control the distance between the vehicles is shown below:



(a) Find the range of K for the stable closed loop system.
(b) When the system is marginally stable, find the frequency of oscillations.

I The following differential equation is part of mathematical modeling of spring-mass-damper linear system:

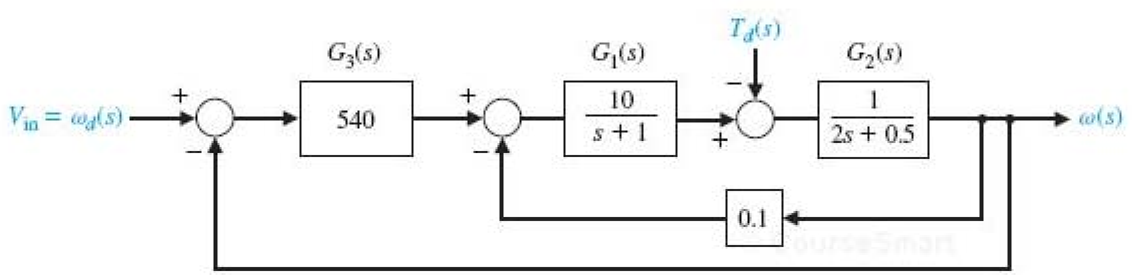
$$v(t) = \frac{dy(t)}{dt}$$

$$M\frac{dv(t)}{dt} + bv(t) + k\int_0^t v(t)dt = r(t)$$

(a) What is the Laplace transform of above differential equations? Assume zero initial conditions.
(b) Draw a single block diagram that represents differential equation with r(t) as input and y(t) as output .

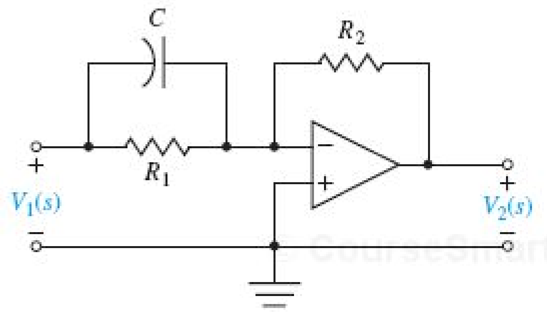
II The block diagram of an electric motor drive for railway vehicle is shown below.

(a) Draw equivalent signal flow graph of the block diagram. Use $\omega_1(s)$ and $\omega_2(s)$ be the outputs at 2nd and 3rd summing junctions for consistency.
(b) Using Mason gain formula find closed loop transfer functions $\omega(s)/\omega_d(s)$ and $\omega(s)/T_d(s)$.
(c) What is the output $\omega(s)$ due to both inputs V_{in} and $T_d(s)$?



EE's only

III For the circuit below find the transfer function $V_2(s)/V_1(s)$. For sake of simplicity assume capacitor is 1 Farad and both resistors are 1 Ohm each:



BMEs ONLY

The development of robotic microsurgery devices will have major implications on delicate eye and brain surgical procedures. The microsurgery devices employ feedback control to reduce the effects of the surgeon's muscle tremors. Precision movements by an articulated robotic arm can greatly help a surgeon by providing a carefully controlled hand. One such device is shown in Figure below. The microsurgical devices have been evaluated in clinical procedures and are now being commercialized. Sketch a block diagram of the surgical process with a microsurgical device in the loop being operated by a surgeon. Assume that the position of the end-effector on the microsurgical device can be measured and is available for feedback. Note the diagram should show input, controller, devoice, sensor and other relevant blocks.

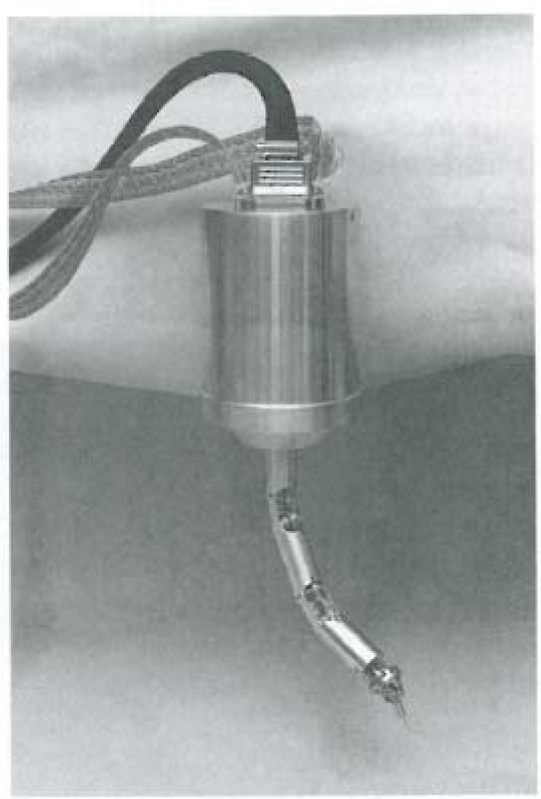
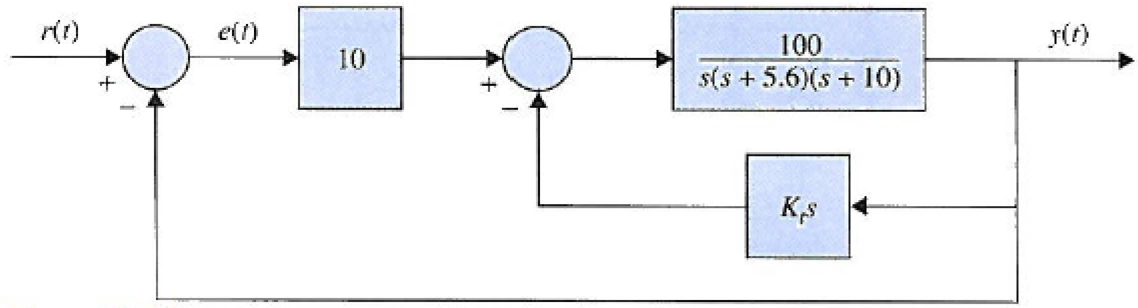


FIGURE AP1.1 Microsurgery robotic manipulator. (Photo courtesy of NASA.)

(Turn Over)

IV The block diagram of a motor-control system with tachometer feedback is shown below:



(a) Find the range of K_t for the stable closed loop system.
(b) If the system is marginally stable, find the frequency of oscillations in the output.

Routh Array Procedure

$$a_6 s^6 + a_5 s^5 + \cdots + a_1 s + a_0 = 0$$

s^6	a_6	a_4	a_2	a_0
s^5	a_5	a_3	a_1	0
s^4	$\dfrac{a_5 a_4 - a_6 a_3}{a_5} = A$	$\dfrac{a_5 a_2 - a_6 a_1}{a_5} = B$	$\dfrac{a_5 a_0 - a_6 \times 0}{a_5} = a_0$	0
s^3	$\dfrac{A a_3 - a_5 B}{A} = C$	$\dfrac{A a_1 - a_5 a_0}{A} = D$	$\dfrac{A \times 0 - a_5 \times 0}{A} = 0$	0
s^2	$\dfrac{BC - AD}{C} = E$	$\dfrac{C a_0 - A \times 0}{C} = a_0$	$\dfrac{C \times 0 - A \times 0}{C} = 0$	0
s^1	$\dfrac{ED - C a_0}{E} = F$	0	0	0
s^0	$\dfrac{F a_0 - E \times 0}{F} = a_0$	0	0	0

Properties of Laplace Transforms

TABLE 2-4 Theorems of Laplace Transforms

Multiplication by a constant	$\mathcal{L}[kf(t)] = kF(s)$
Sum and difference	$\mathcal{L}[f_1(t) \pm f_2(t)] = F_1(s) \pm F_2(s)$
Differentiation	$\mathcal{L}\left[\dfrac{df(t)}{dt}\right] = sF(s) - f(0)$ $\mathcal{L}\left[\dfrac{d^n f(t)}{dt^n}\right] = s^n F(s) - s^{n-1} f(0) - s^{n-2} f(0)$ where $f^{(k)}(0) = \left.\dfrac{d^k f(t)}{dt^k}\right\rvert_{t=0}$
Integration	$\mathcal{L}\left[\int_0^t f(\tau)d\tau\right] = \dfrac{F(s)}{s}$ $\mathcal{L}\left[\int_0^{t_n}\int_0^{t_{n-1}} \cdots \int_0^{t_1} f(t)d\tau dt_1 dt_2 \cdots dt_{n-1}\right] = \dfrac{F(s)}{s^n}$
Shift in time	$\mathcal{L}[f(t-T)u_s(t-T)] = e^{-Ts}F(s)$
Initial-value theorem	$\lim_{t \to 0} f(t) = \lim_{s \to \infty} sF(s)$
Final-value theorem	$\lim_{t \to \infty} f(t) = \lim_{s \to 0} sF(s)$ if $sF(s)$ does not have poles on or to the right of the imaginary axis in the s-plane.

Given an SFG with N forward paths and K loops, the gain between the input node y_{in} and output node y_{out} is [3]

$$M = \frac{y_{\text{out}}}{y_{\text{in}}} = \sum_{k=1}^{N} \frac{M_k \Delta_k}{\Delta} \tag{3-54}$$

where

y_{in} = input-node variable

y_{out} = output-node variable

M = gain between y_{in} and y_{out}

N = total number of forward paths between y_{in} and y_{out}

M_k = gain of the kth forward paths between y_{in} and y_{out}

$$\Delta = 1 - \sum_i L_{i1} + \sum_j L_{j2} - \sum_k L_{k3} + \ldots \tag{3-55}$$

L_{mr} = gain product of the mth $(m = i, j, k, \ldots)$ possible combination of r nontouching loops $(1 \le r \le K)$.

or

Δ = 1 − (sum of the gains of **all individual** loops) + (sum of products of gains of all possible combinations of **two** nontouching loops) − (sum of products of gains of all possible combinations of **three** nontouching loops) + ⋯

Δ_k = the Δ for that part of the SFG that is nontouching with the kth forward path.

I The following differential equation is part of mathematical modeling of spring-mass-damper linear system:

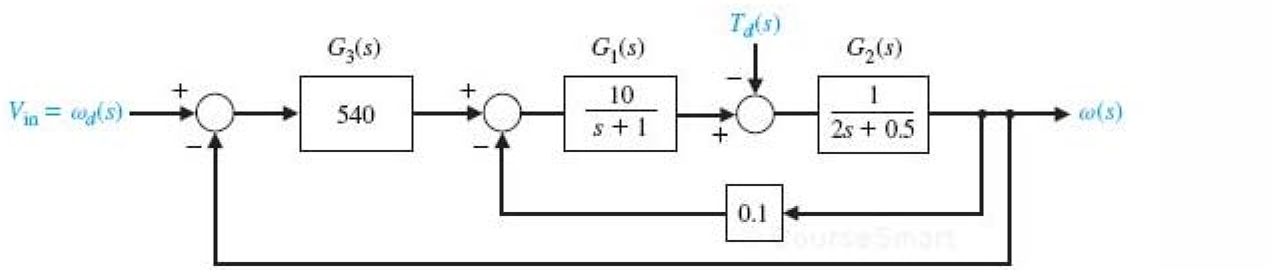
$$v(t) = \frac{dy(t)}{dt}$$

$$M\frac{dv(t)}{dt} + bv(t) + k\int_0^t v(t)dt = r(t)$$

(a) What is the Laplace transform of above differential equations? Assume zero initial conditions.
(b) Draw a single block diagram that represents differential equation with r(t) as input and y(t) as output .

II The block diagram of an electric motor drive for railway vehicle is shown below.

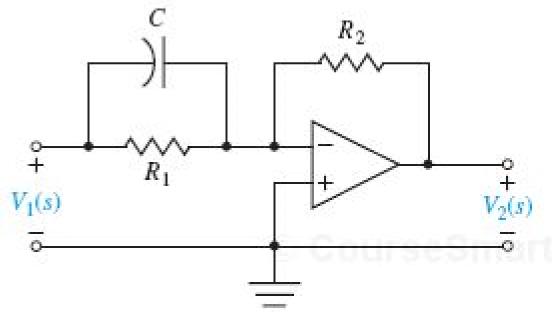
(a) Draw equivalent signal flow graph of the block diagram. Use $\omega_1(s)$ and $\omega_2(s)$ be the outputs at 2nd and 3rd summing junctions for consistency.
(b) Using Mason gain formula find closed loop transfer functions $\omega(s)/\omega_d(s)$ and $\omega(s)/T_d(s)$.
(c) What is the output $\omega(s)$ due to both inputs V_{in} and $T_d(s)$?



EE's and BME only

III For the circuit below find the transfer function $V_2(s)/V_1(s)$. For sake of simplicity assume capacitor is 1 Farad and both resistors are 1 Ohm each:

(Turn Over)



OR

AE/ME only

III A load added to a truck results in a force F on the support spring, and the tire flexes as shown in the figure (a) and the model in fug (b) below:

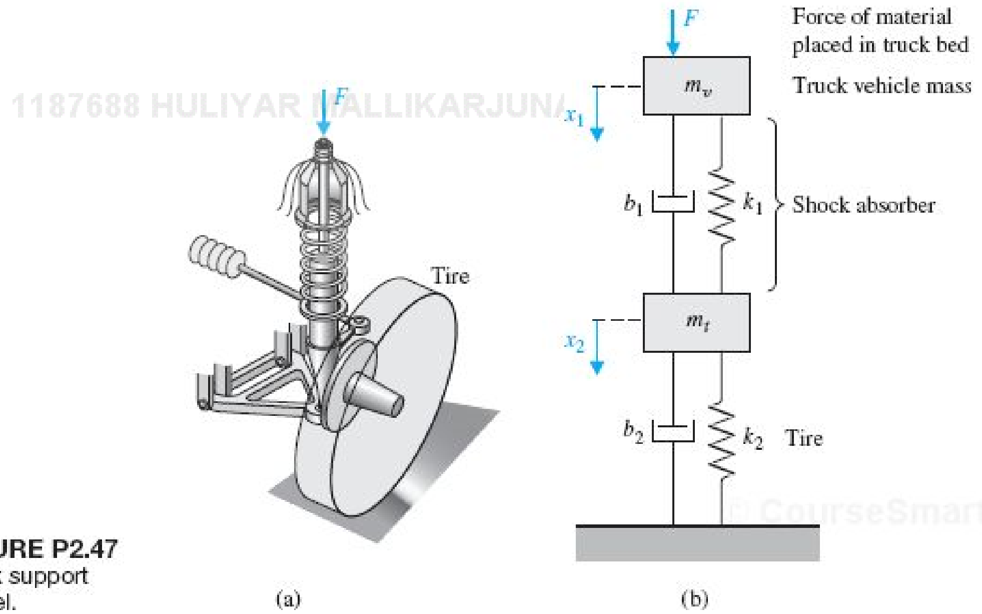
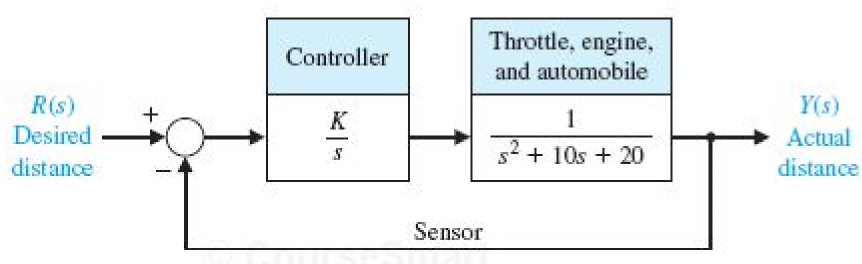


FIGURE P2.47
Truck support model.

Find the transfer function $X_1(s)/F(s)$.

IV A traffic control system is designed to control the distance between the vehicles is shown below:

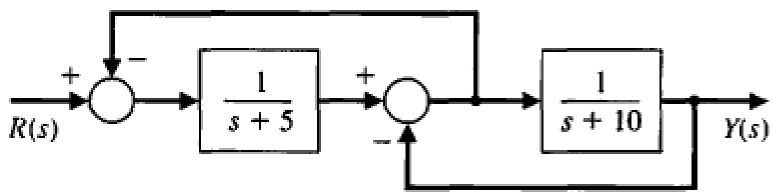


(a) Find the range of K for the stable closed loop system.
(b) When the system is marginally stable, find the frequency of oscillations.

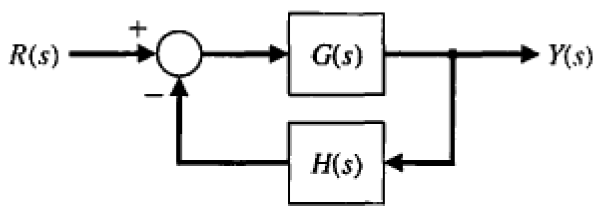
NOTE: Total of Four Problems

I Consider the two equivalent systems shown below.

(a) Determine G(s) and H(s) of the block diagram shown in fig (b) that are equivalent to those of the block diagram in fig (a)
(b) Determine Y(s)/R(s)
(c) Find y(t) if r(t)=u(t); u(t) being step input that will make r(t) to be step response.



(a)



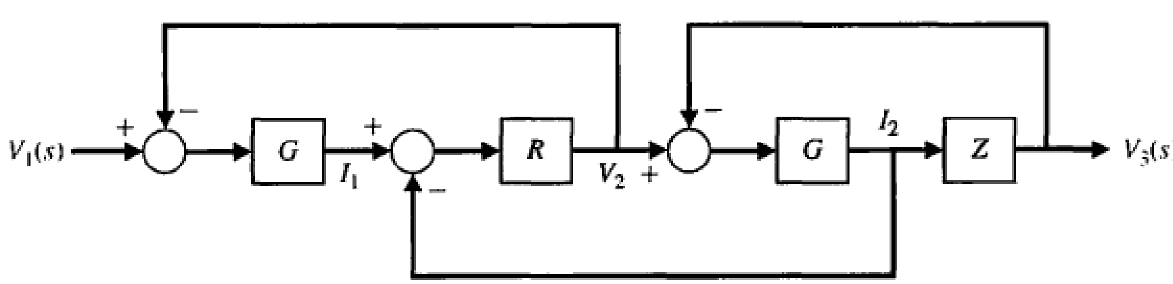
(b)

Block diagram Equivalence

II The block diagram of an electrical low-pass filter is shown below.

(a) Draw equivalent signal flow graph of the block diagram. Use V', V'' and V''' be the outputs at 1st, 2nd and 3rd summing junctions for consistency.

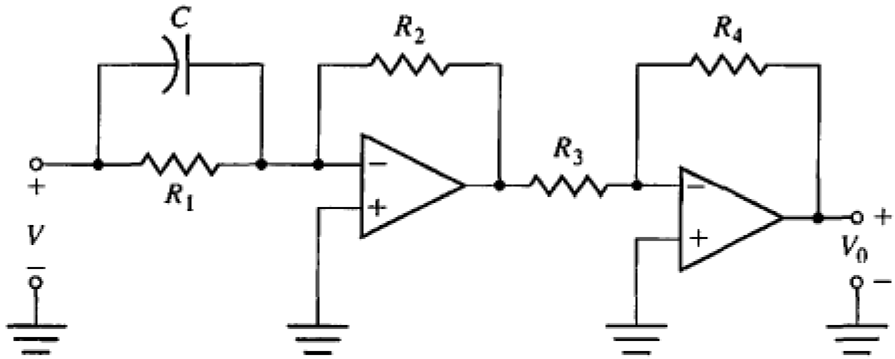
(b) Using Mason gain formula find closed loop transfer functions $V_3(s)/V_1(s)$ and also $V_3(s)/V_2(s)$.



(Turn Over)

EE's and BME only

III For the circuit below find the transfer function $V_0(s)/V(s)$. For sake of simplicity assume capacitor is 1 Farad and resistors are 1 Ohm each:



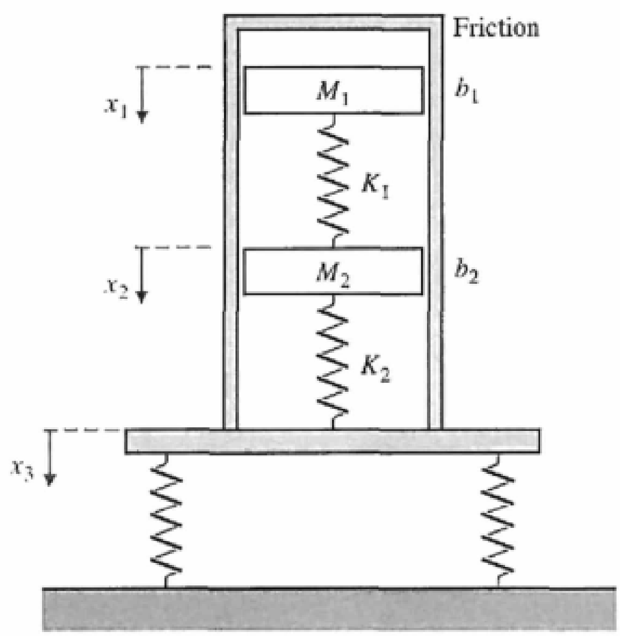
OR

AE/ME only

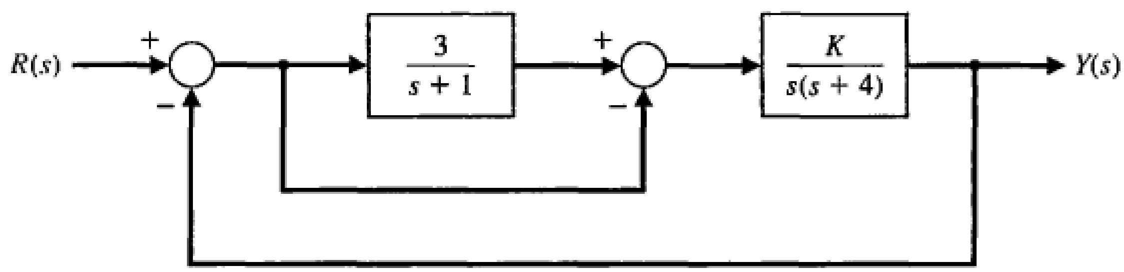
III A mechanical system is shown in Figure below, which is subjected to a known displacement $x_3(t)$ with respect to the reference,

(a) Determine the two independent equations of motion

(b) Obtain the equations of motion in terms of the Laplace transform, assuming that the initial conditions are zero.



IV A certain control system has a block diagram structure shown below:



(a) Find the range of K for the stable closed loop system.
(b) When the system is marginally stable, find the frequency of oscillations.

Equations

Table 2.3 Important Laplace Transform Pairs

$f(t)$	$F(s)$
Step function, $u(t)$	$\frac{1}{s}$
e^{-at}	$\frac{1}{s+a}$
$\sin \omega t$	$\frac{\omega}{s^2+\omega^2}$
$\cos \omega t$	$\frac{s}{s^2+\omega^2}$
t^n	$\frac{n!}{s^{n+1}}$
$f^{(k)}(t) = \frac{d^k f(t)}{dt^k}$	$s^k F(s) - s^{k-1} f(0^-) - s^{k-2} f'(0^-) - \ldots - f^{(k-1)}(0^-)$
$\int_{-\infty}^{t} f(t)\, dt$	$\frac{F(s)}{s} + \frac{1}{s}\int_{-\infty}^{0} f(t)\, dt$
Impulse function $\delta(t)$	1
$e^{-at} \sin \omega t$	$\frac{\omega}{(s+a)^2+\omega^2}$
$e^{-at} \cos \omega t$	$\frac{s+a}{(s+a)^2+\omega^2}$
$\frac{1}{\omega}[(\alpha - a)^2 + \omega^2]^{1/2} e^{-at} \sin(\omega t + \phi)$,	$\frac{s+\alpha}{(s+a)^2+\omega^2}$

(For More Fun equations – Turn Over)

Mason's Gain Formula M(s)

$$M = \frac{y_{\text{out}}}{y_{\text{in}}} = \sum_{k=1}^{N} \frac{M_k \Delta_k}{\Delta} \tag{3-54}$$

where

y_{in} = input-node variable

y_{out} = output-node variable

M = gain between y_{in} and y_{out}

N = total number of forward paths between y_{in} and y_{out}

M_k = gain of the kth forward paths between y_{in} and y_{out}

$$\Delta = 1 - \sum_i L_{i1} + \sum_j L_{j2} - \sum_k L_{k3} + \ldots \tag{3-55}$$

L_{mr} = gain product of the mth $(m = i, j, k, \ldots)$ possible combination of r nontouching loops $(1 \leq r \leq K)$.

or

Δ = 1 − (sum of the gains of **all individual** loops) + (sum of products of gains of all possible combinations of **two** nontouching loops) − (sum of products of gains of all possible combinations of **three** nontouching loops) + ⋯

Δ_k = the Δ for that part of the SFG that is nontouching with the kth forward path.

I Consider the armature controlled dc motor shown below where the field current is held constant in the system. The parameters include:

$i_a(t)$ = armature current	L_a = armature inductance
R_a = armature resistance	$e_a(t)$ = applied voltage
$e_b(t)$ = back emf	K_b = back-emf constant
$T_L(t)$ = load torque	ϕ = magnetic flux in the air gap
$T_m(t)$ = motor torque	$\omega_m(t)$ = rotor angular velocity
$\theta_m(t)$ = rotor displacement	J_m = rotor inertia
K_i = torque constant	B_m = viscous-friction coefficient

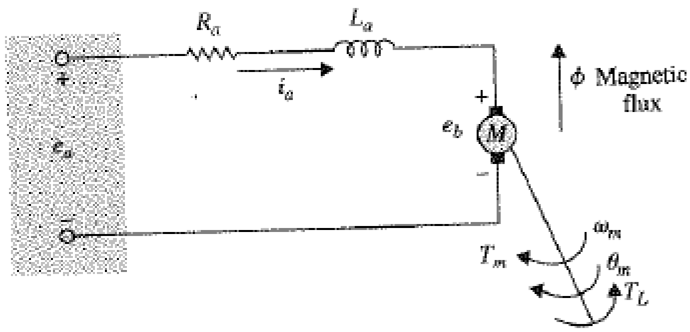


Figure 4-43 Model of a separately excited dc motor.

The equations that mathematically model the system are:

$$T_m(t) = K_i i_a(t)$$

where K_i is the **torque constant** in N-m/A, lb-ft/A, or oz-in/A.

Starting with the control input voltage $e_a(t)$, the cause-and-effect equations motor circuit in Fig. 4-43 are

$$\frac{di_a(t)}{dt} = \frac{1}{L_a}e_a(t) - \frac{R_a}{L_a}i_a(t) - \frac{1}{L_a}e_b(t)$$

$$T_m(t) = K_i i_a(t)$$

$$e_b(t) = K_b\frac{d\theta_m(t)}{dt} = K_b\omega_m(t)$$

$$\frac{d^2\theta_m(t)}{dt^2} = \frac{1}{J_m}T_m(t) - \frac{1}{J_m}T_L(t) - \frac{B_m}{J_m}\frac{d\theta_m(t)}{dt}$$

(a) Assuming initial conditions are zero **write** Laplace transform for each of the above four equations.
(b) Write block diagram representing each equation in (a).
(c) Write a single block diagram that represents model of DC motor with $E_a(s)$, $T_L(s)$ as inputs, $\theta_m(s)$ as output, and $I_a(s)$, $E_b(s)$, $T_m(s)$, $\Omega_m(s)$ as signals.

II Consider the block diagram of an active suspension system of a vehicle shown below:

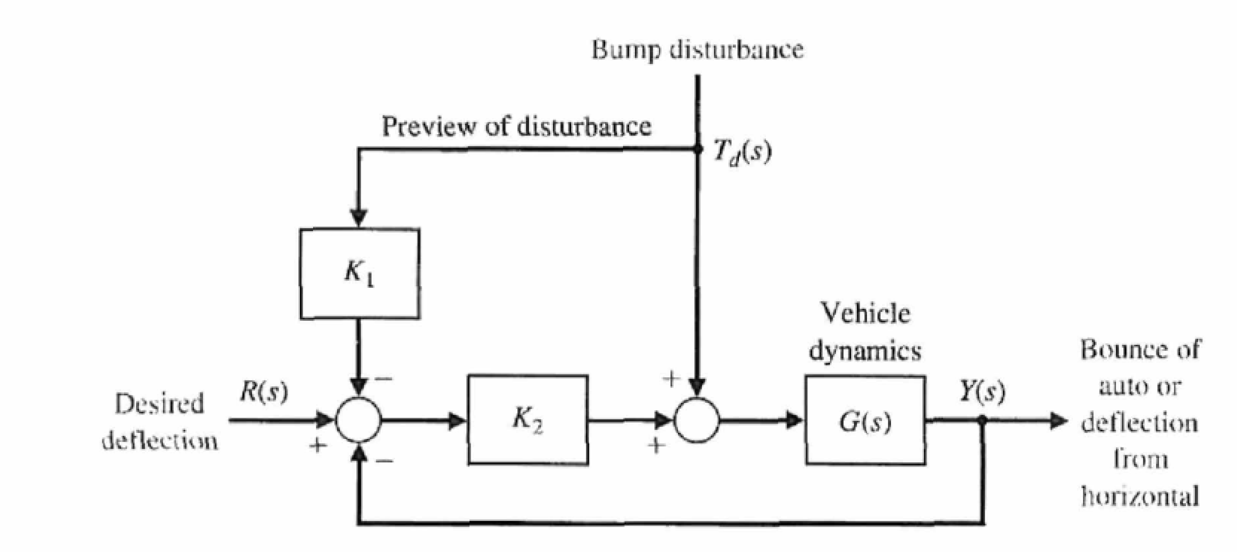


FIGURE E2.12 Active suspension system.

(a) Draw the equivalent signal flow graph of the above system
(b) Use Mason's gain formula to find $Y(s)/R(s)$, $Y(s)/T_d(s)$
(c) Find the output $Y(s)$ due to both $R(s)$ and $T_d(s)$

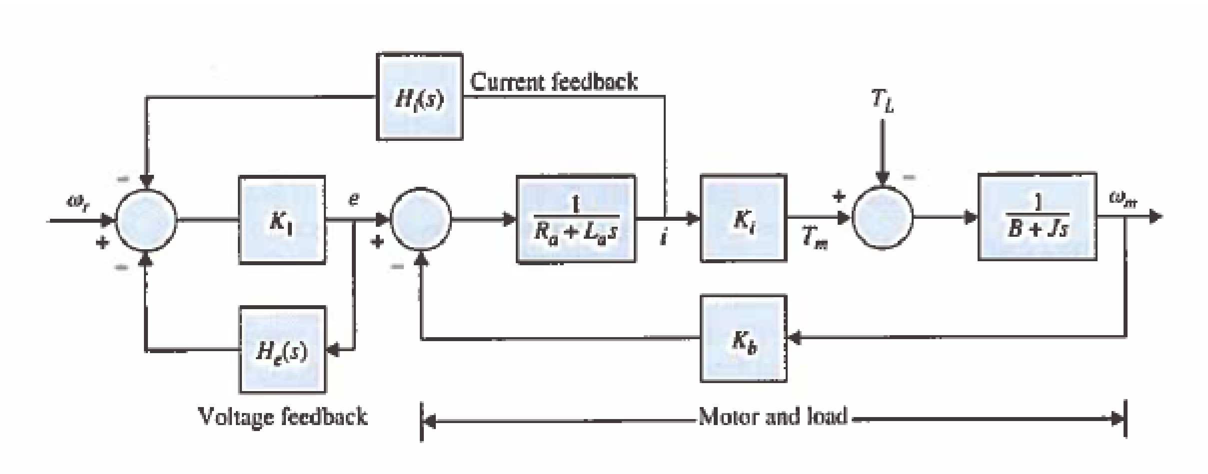
III

In the following **Word Match** problems, match the term with the definition by writing the correct letter in the space provided.

a. Routh-Hurwitz criterion	A performance measure of a system.	______
b. Auxiliary polynomial	A dynamic system with a bounded system response to a bounded input.	______
c. Marginally stable	The property that is measured by the relative real part of each root or pair of roots of the characteristic equation.	______
d. Stable system	A criterion for determining the stability of a system by examining the characteristic equation of the transfer function.	______
e. Stability	The equation that immediately precedes the zero entry in the Routh array.	______
f. Relative stability	A system description that reveals whether a system is stable or not stable without consideration of other system attributes such as degree of stability.	______
g. Absolute stability	A system possesses this type of stability if the zero input response remains bounded as $t \to \infty$.	______

- Please staple the test to your work
- Number of unauthorized classes you have missed in this class __________

I Consider a DC motor system below utilized for speed control which is implemented with voltage and current feedbacks.



(a) Draw signal flow graph for the feedback control system.

(b) Find the transfer function $\frac{\Omega_m(s)}{\Omega r(s)}$ [with $T_L(s) = 0$] using Mason's gain formula.

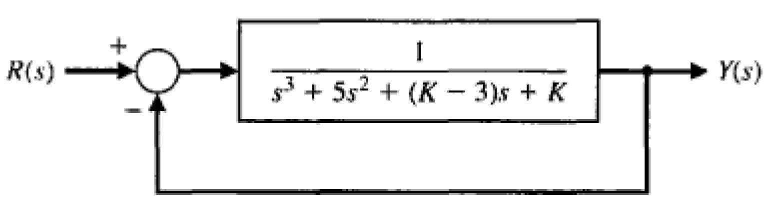
(c) Find the transfer function $\frac{\Omega_m(s)}{T_L(s)}$ [with $\Omega r(s) = 0$] using Mason's gain formula.

(d) Let K_1 be a very high gain of the amplifier. Show that when $H_i(s)/H_e(s) = -(R_a + sL_a)$, the motor velocity $\omega_m(t)$ is totally independent of the load disturbance torque T_L.

(e) Find the output $\Omega_m(s)$ due to both inputs $\Omega r(s)$ and $T_L(s)$.

II A thermistor has a response to temperature represented by $R = R_0 e^{-0.1T}$ where $R_0 = 10{,}000$ ohms, R is the resistance, and T is temperature in degrees Celsius. Show that linearized model for the thermistor operating at T = 20 degrees Celsius and for a small range of variation of temperature is $\Delta R = -135\Delta T$.

III A unity feedback control system is as shown below:



(a) Find the range of K for stability of the closed loop system using Routh-Hurwitz criterion

(b) For what values of K, does the system have poles on the imaginary axis?

(c) What are the frequencies of oscillations when the system is marginally stable?