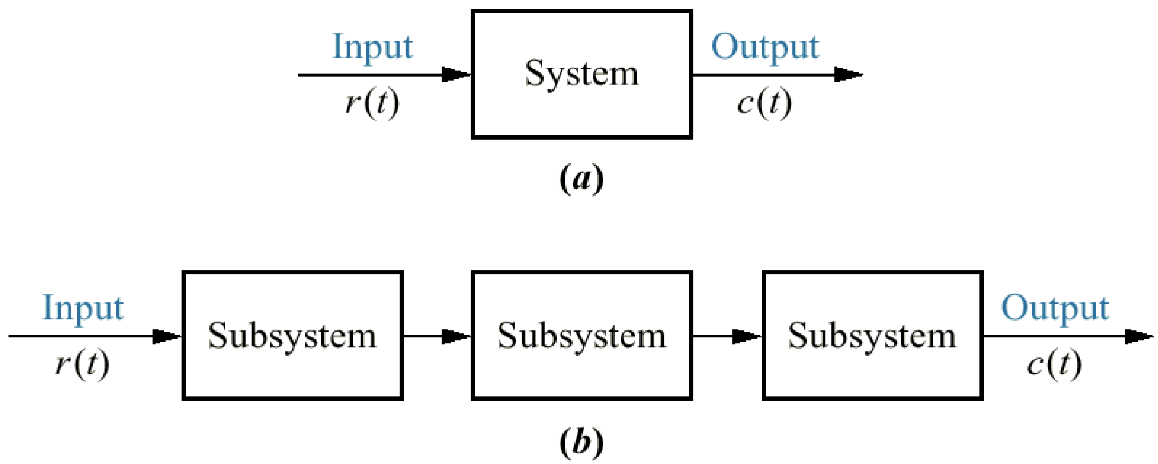
Figure 2.1

a. Block diagram representation of a system; **b.** block diagram representation of an interconnection of subsystems



Note: The input, $r(t)$, stands for *reference input*.
The output, $c(t)$, stands for *controlled variable*.

Item no.	f(t)	F(s)
1.	$\delta(t)$	1
2.	$u(t)$	$\frac{1}{s}$
3.	$tu(t)$	$\frac{1}{s^2}$
4.	$t^n u(t)$	$\frac{n!}{s^{n+1}}$
5.	$e^{-at}u(t)$	$\frac{1}{s+a}$
6.	$\sin \omega t u(t)$	$\frac{\omega}{s^2+\omega^2}$
7.	$\cos \omega t u(t)$	$\frac{s}{s^2+\omega^2}$

Table 2.1

Laplace transform table

Item no.	Theorem		Name
1.	$\mathscr{L}[f(t)] = F(s)$	$= \int_{0-}^{\infty} f(t)e^{-st}dt$	Definition
2.	$\mathscr{L}[kf(t)]$	$= kF(s)$	Linearity theorem
3.	$\mathscr{L}[f_1(t) + f_2(t)]$	$= F_1(s) + F_2(s)$	Linearity theorem
4.	$\mathscr{L}[e^{-at}f(t)]$	$= F(s+a)$	Frequency shift theorem
5.	$\mathscr{L}[f(t-T)]$	$= e^{-sT}F(s)$	Time shift theorem
6.	$\mathscr{L}[f(at)]$	$= \frac{1}{a}F\left(\frac{s}{a}\right)$	Scaling theorem
7.	$\mathscr{L}\left[\frac{df}{dt}\right]$	$= sF(s) - f(0-)$	Differentiation theorem
8.	$\mathscr{L}\left[\frac{d^2f}{dt^2}\right]$	$= s^2F(s) - sf(0-) - \dot{f}(0-)$	Differentiation theorem
9.	$\mathscr{L}\left[\frac{d^nf}{dt^n}\right]$	$= s^nF(s) - \sum_{k=1}^{n} s^{n-k}f^{k-1}(0-)$	Differentiation theorem
10.	$\mathscr{L}\left[\int_{0-}^{t} f(\tau)\,d\tau\right]$	$= \frac{F(s)}{s}$	Integration theorem
11.	$f(\infty)$	$= \lim_{s\to 0} sF(s)$	Final value theorem[1]
12.	$f(0+)$	$= \lim_{s\to \infty} sF(s)$	Initial value theorem[2]

[1] For this theorem to yield correct finite results, all roots of the denominator of $F(s)$ must have negative real parts and no more than one can be at the origin.
[2] For this theorem to be valid, $f(t)$ must be continuous or have a step discontinuity at $t = 0$ (i.e., no impulses or their derivatives at $t = 0$).

Table 2.2
Laplace transform theorems

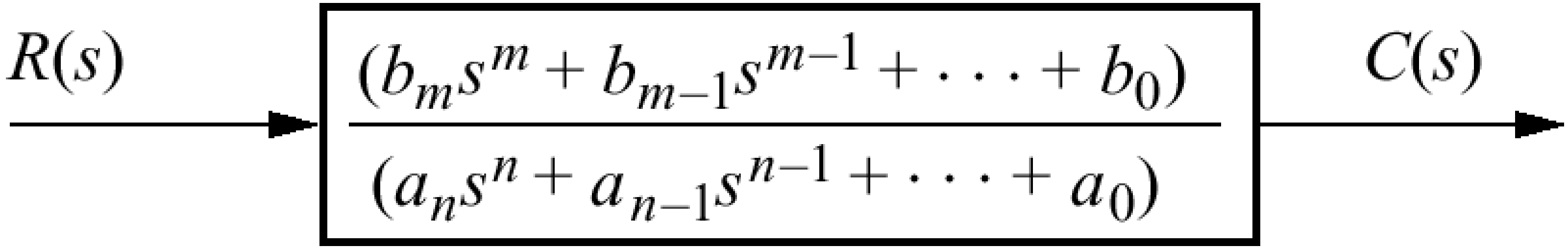
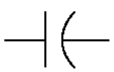
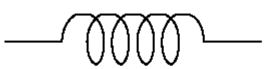


Figure 2.2
Block diagram of a transfer function

Table 2.3

Voltage-current, voltage-charge, and impedance relationships for capacitors, resistors, and inductors

 Capacitor	$v(t) = \frac{1}{C}\int_0^t i(\tau)\,d\tau$	$i(t) = C\frac{dv(t)}{dt}$	$v(t) = \frac{1}{C}q(t)$	$\frac{1}{Cs}$	Cs
 Resistor	$v(t) = Ri(t)$	$i(t) = \frac{1}{R}v(t)$	$v(t) = R\frac{dq(t)}{dt}$	R	$\frac{1}{R} = G$
 Inductor	$v(t) = L\frac{di(t)}{dt}$	$i(t) = \frac{1}{L}\int_0^t v(\tau)d\tau$	$v(t) = L\frac{d^2q(t)}{dt^2}$	Ls	$\frac{1}{Ls}$

Note: The following set of symbols and units is used throughout this book: $v(t)$ = V (volts), $i(t)$ = A (amps), $q(t)$ = Q (coulombs), C = F (farads), R = Ω (ohms), G = ℧ (mhos), L = H (henries).

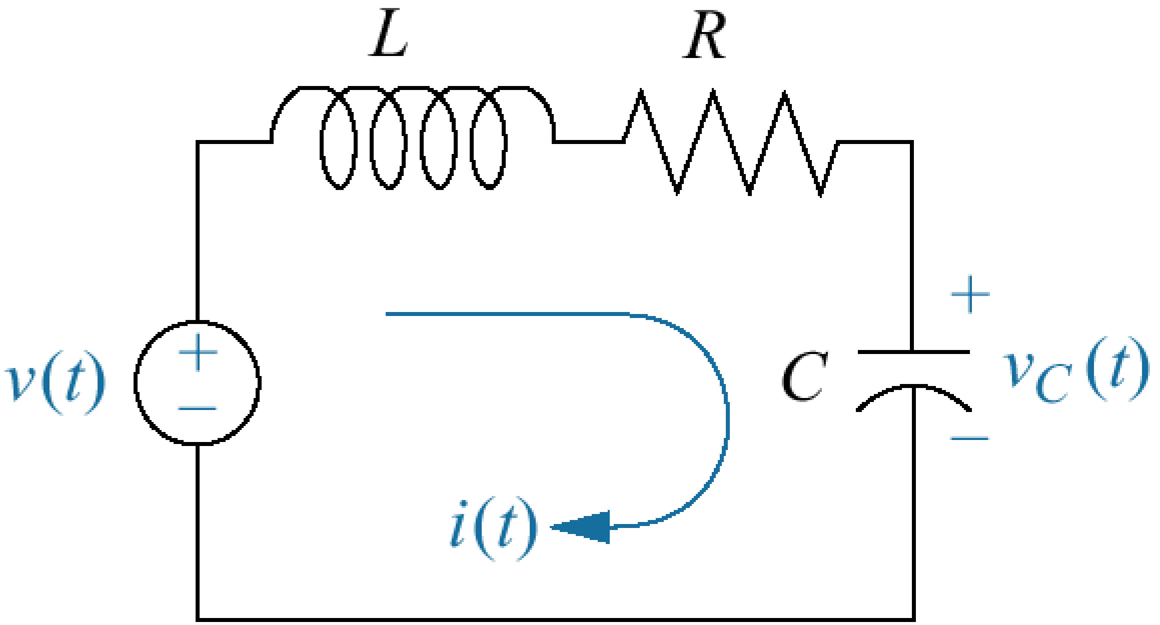
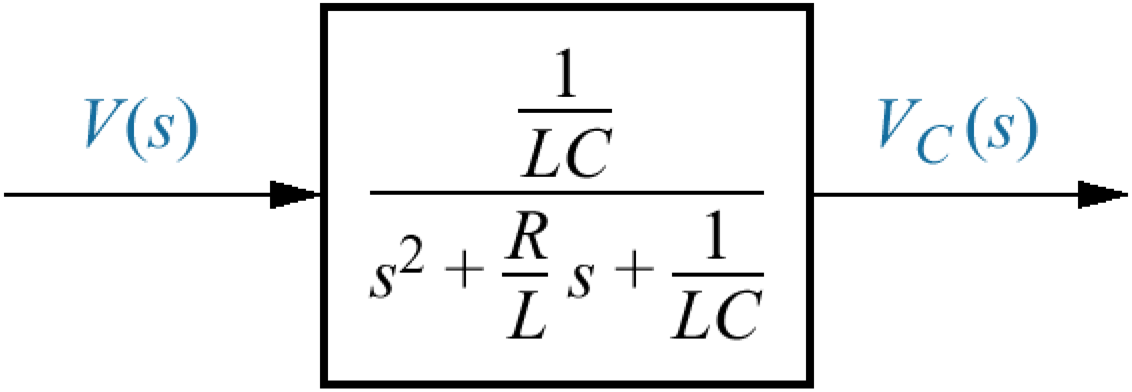


Figure 2.3
RLC network

Figure 2.4
Block diagram
of series RLC electrical
network



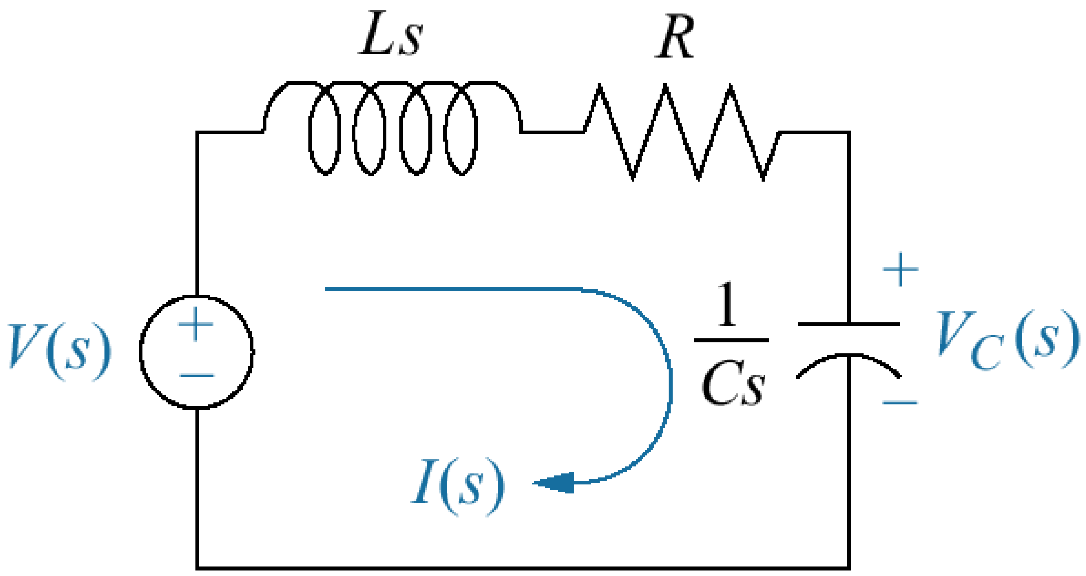


Figure 2.5
Laplace-transformed network

Figure 2.6

a. Two-loop electrical network;
b. transformed two-loop electrical network;
c. block diagram

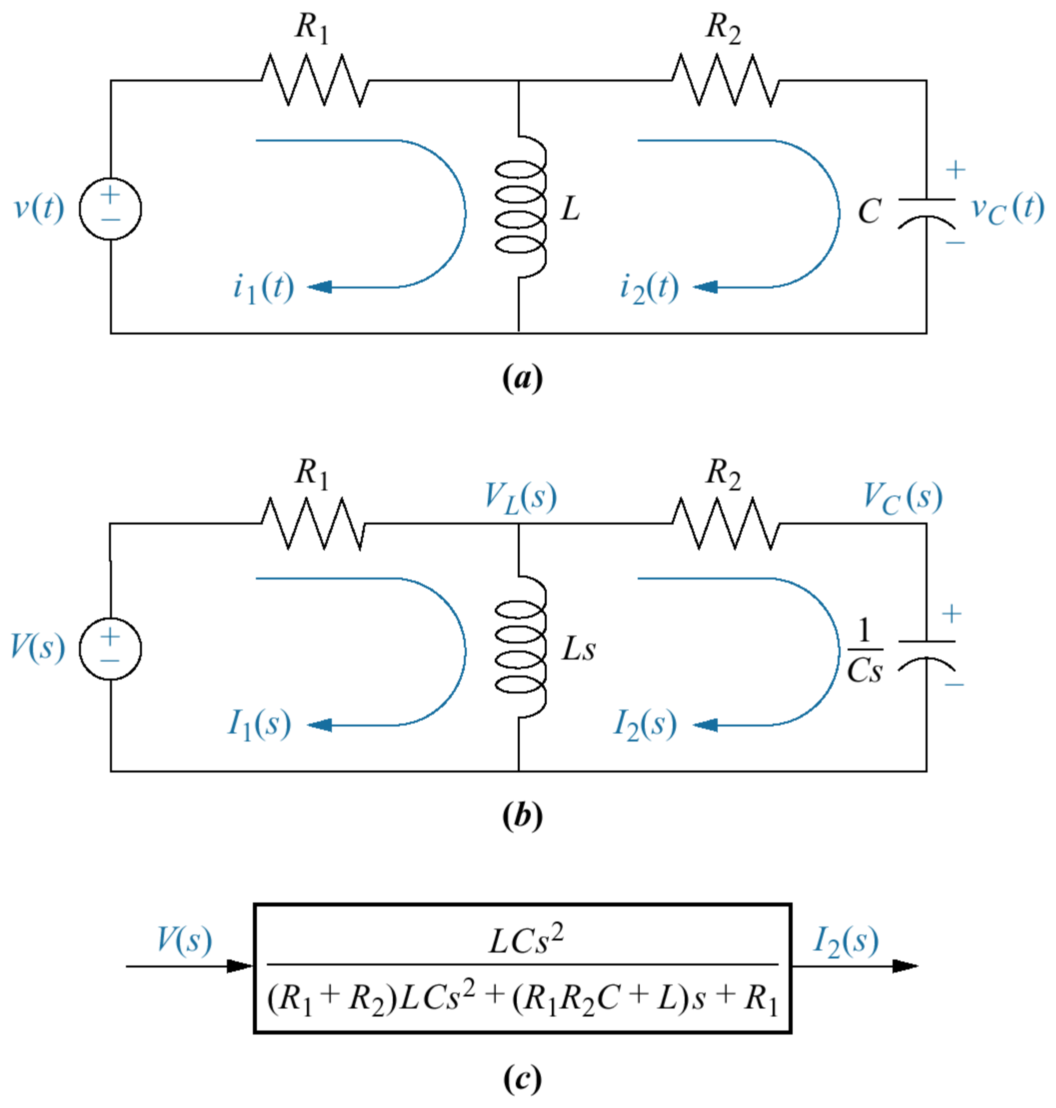


Figure 2.7
Block diagram of the network of Figure 2.6

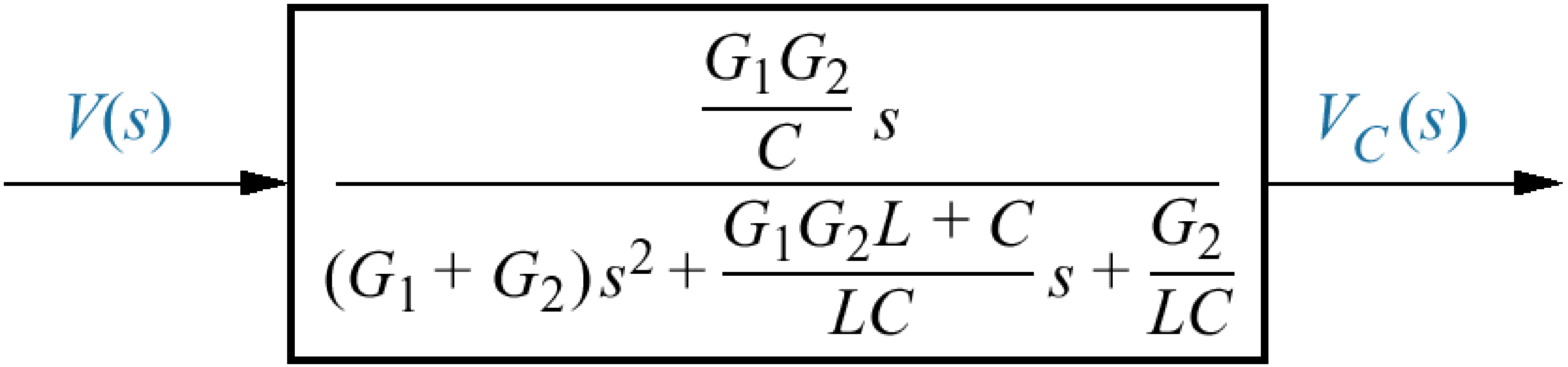


Figure 2.8
Transformed network ready for nodal analysis

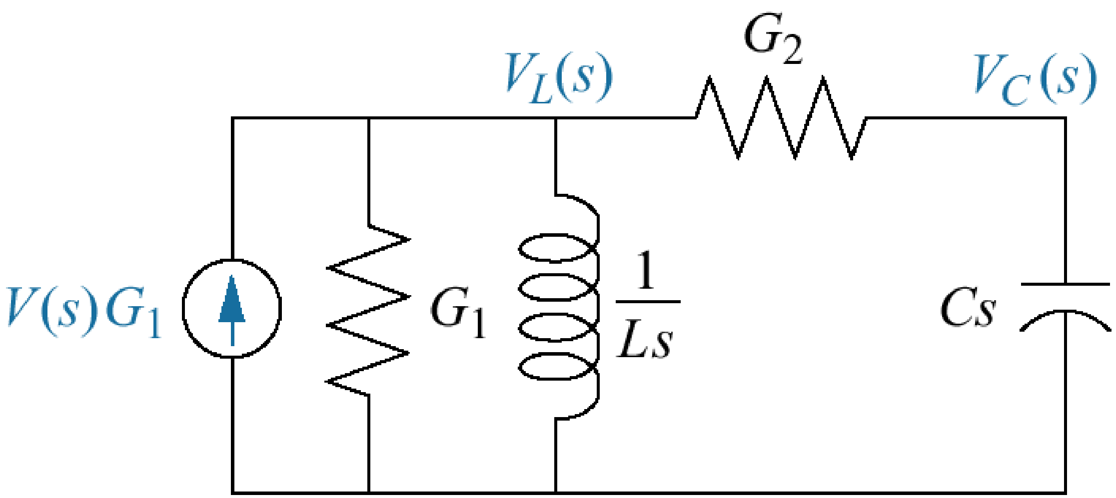


Figure 2.9
Three-loop
electrical network

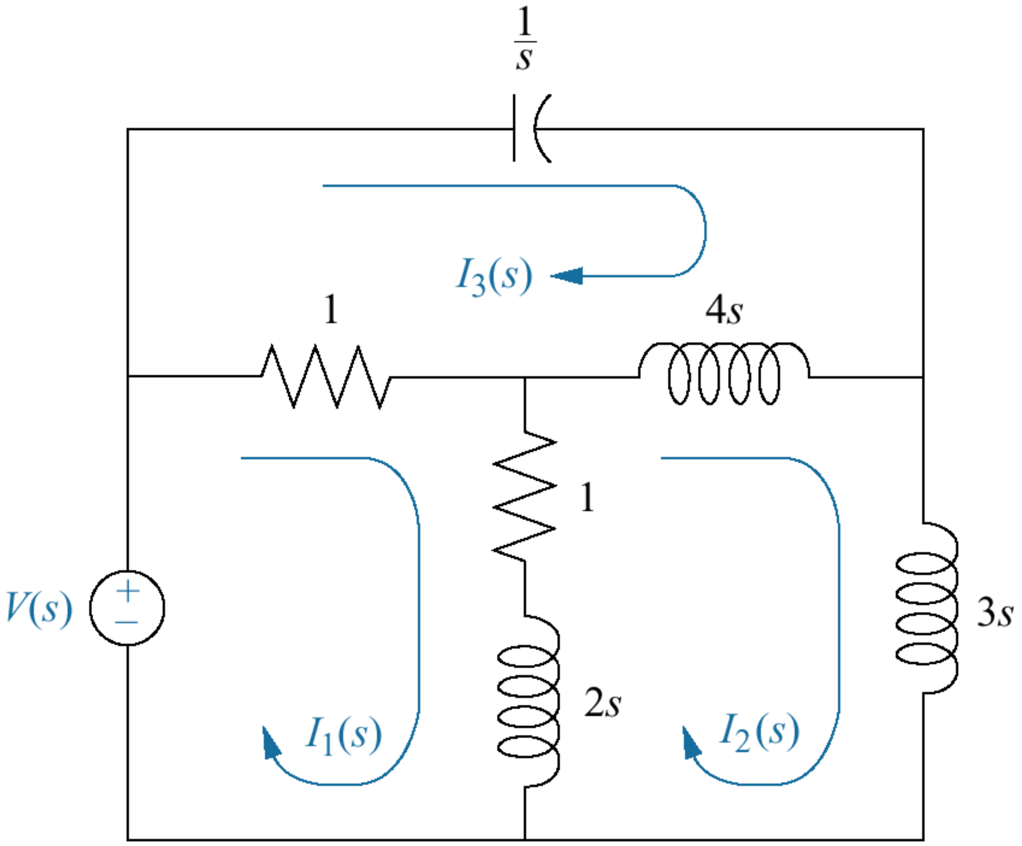


Figure 2.10

a. Operational amplifier;

b. schematic for an inverting operational amplifier;

c. inverting operational amplifier configured for transfer function realization. Typically, the amplifier gain, A, is omitted.

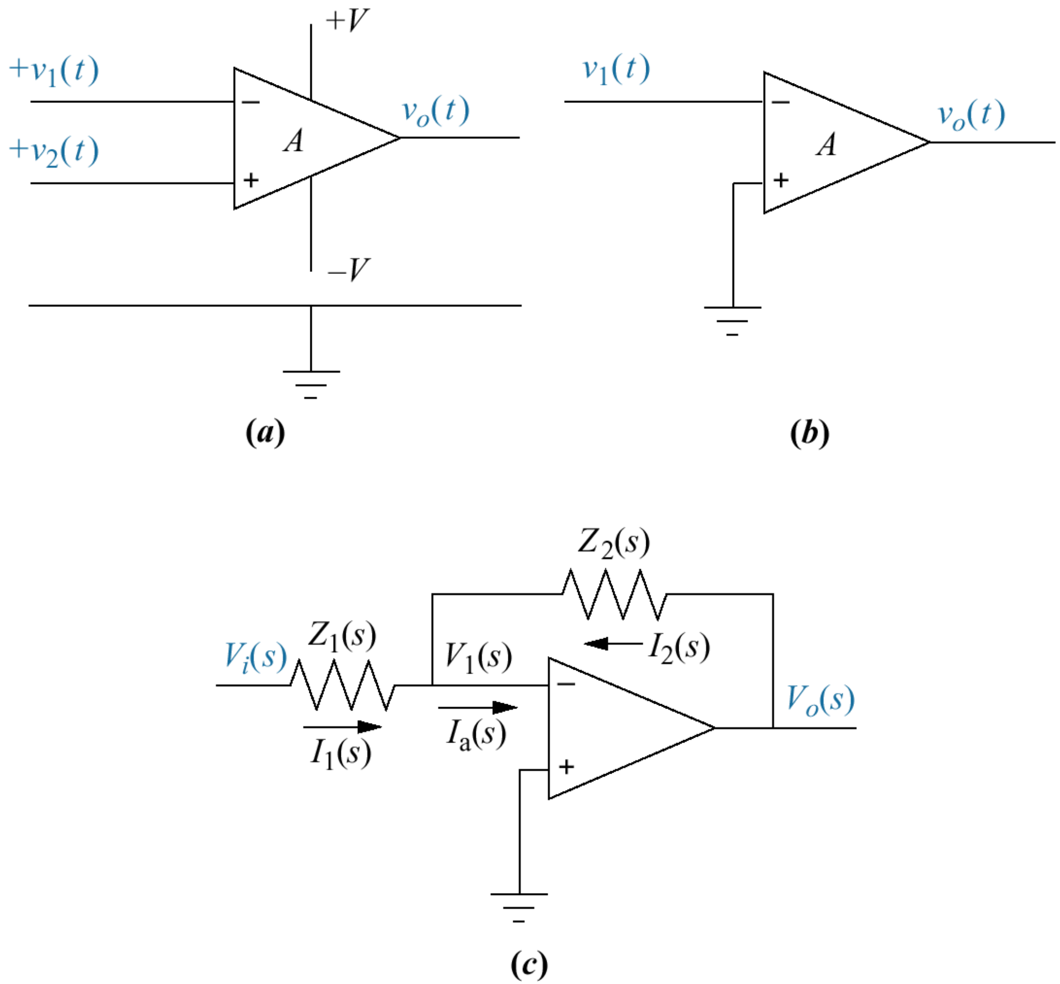


Figure 2.11
Inverting operational amplifier circuit for Example 2.14

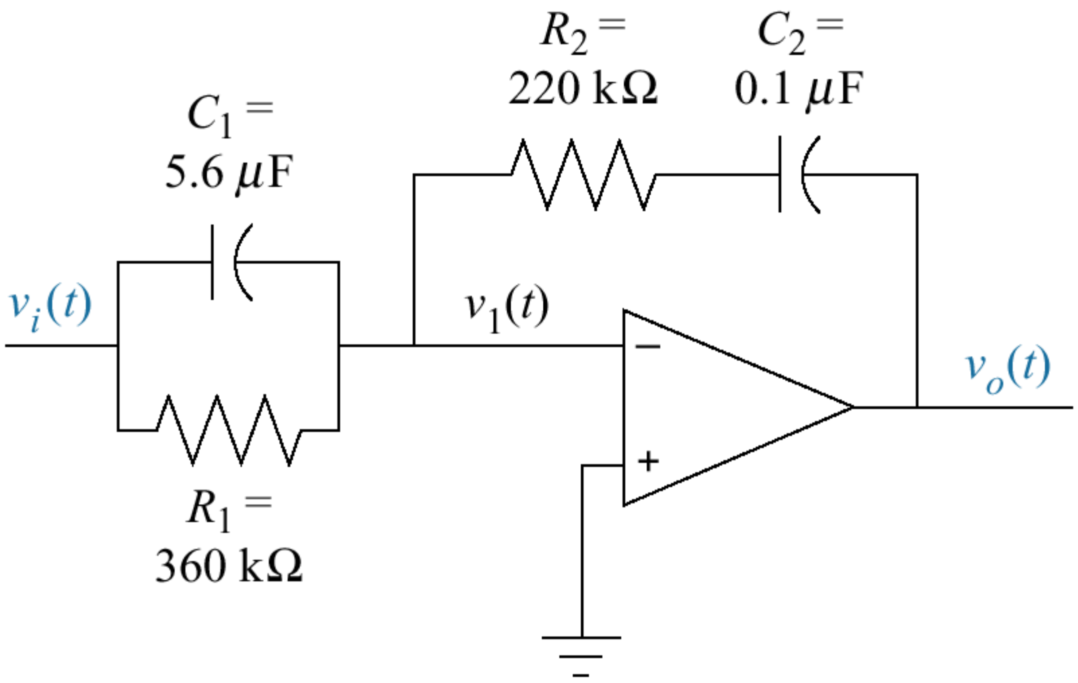


Figure 2.12
General noninverting operational amplifier circuit

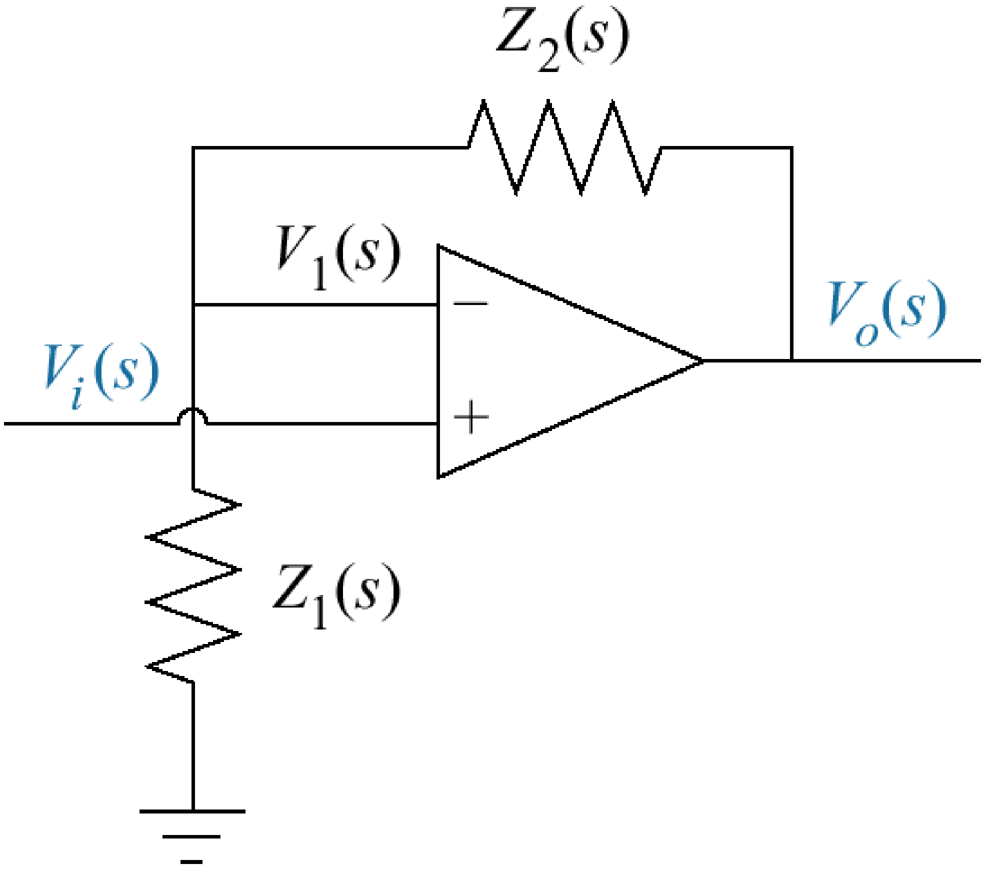
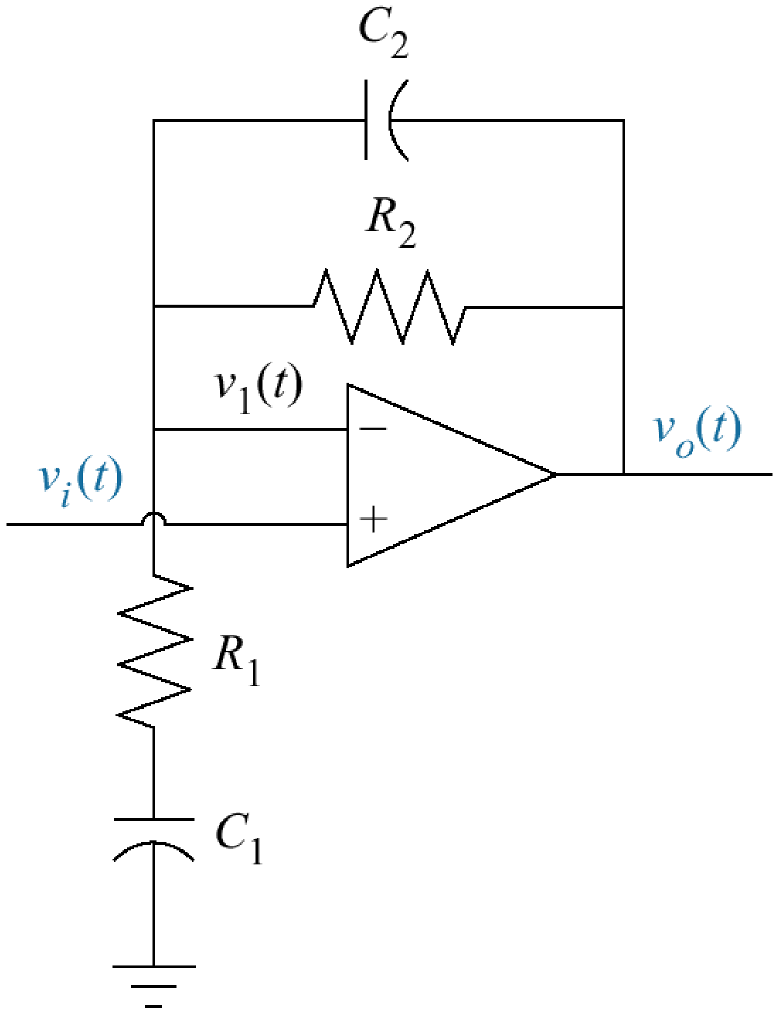


Figure 2.13
Noninverting operational amplifier circuit for Example 2.15



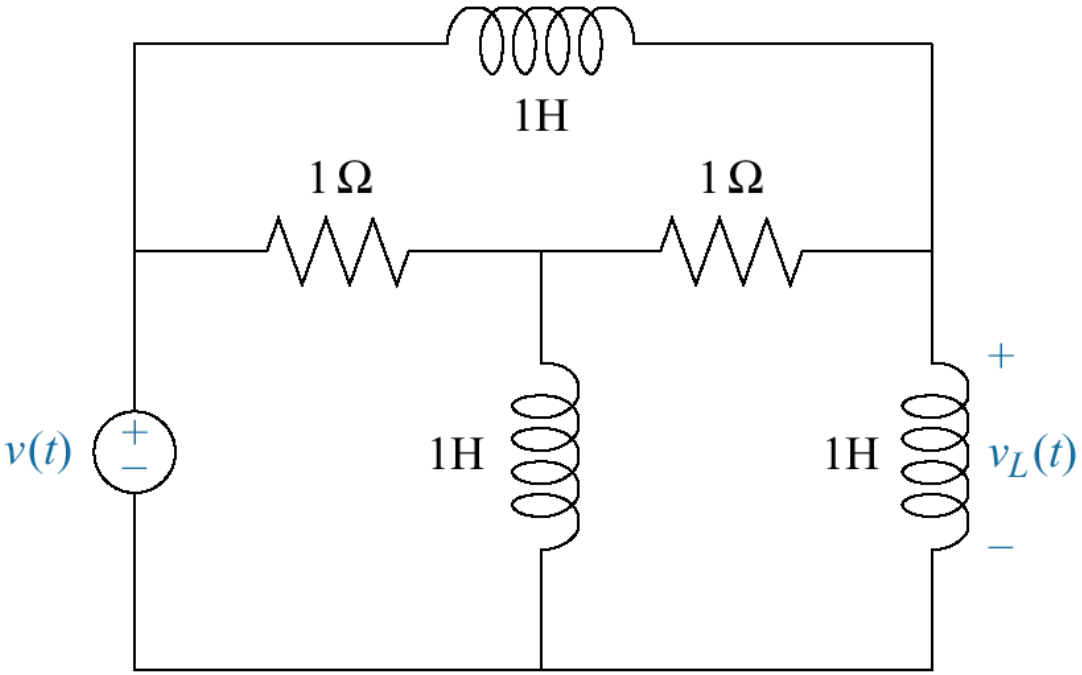
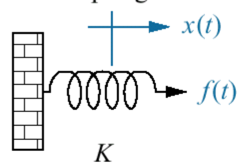
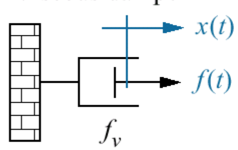
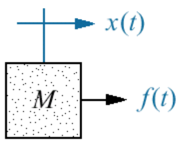


Figure 2.14
Electric circuit for Skill-Assessment Exercise 2.6

Table 2.4

Force-velocity, force-displacement, and impedance translational relationships
for springs, viscous dampers, and mass

Component	Force-velocity	Force-displacement	Impedance $Z_M(s) = F(s)/X(s)$
	$f(t) = K\int_0^t v(\tau)\,d\tau$	$f(t) = Kx(t)$	K
	$f(t) = f_v v(t)$	$f(t) = f_v \frac{dx(t)}{dt}$	$f_v s$
	$f(t) = M\frac{dv(t)}{dt}$	$f(t) = M\frac{d^2x(t)}{dt^2}$	Ms^2

Note: The following set of symbols and units is used throughout this book: $f(t)$ = N (newtons), $x(t)$ = m (meters), $v(t)$ = m/s (meters/second), K = N/m (newtons/meter), f_v = N-s/m (newton-seconds/meter), M = kg (kilograms = newton-seconds^2/meter).

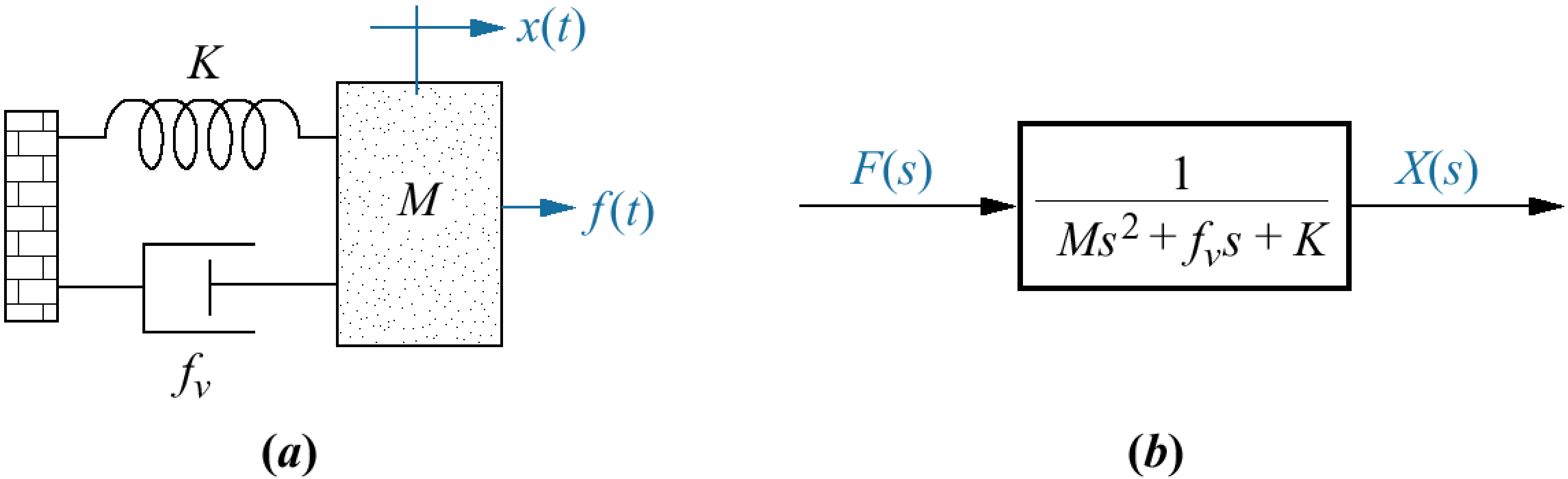


Figure 2.15
a. Mass, spring, and damper system;
b. block diagram

Figure 2.16

a. Free-body diagram of mass, spring, and damper system;

b. transformed free-body diagram

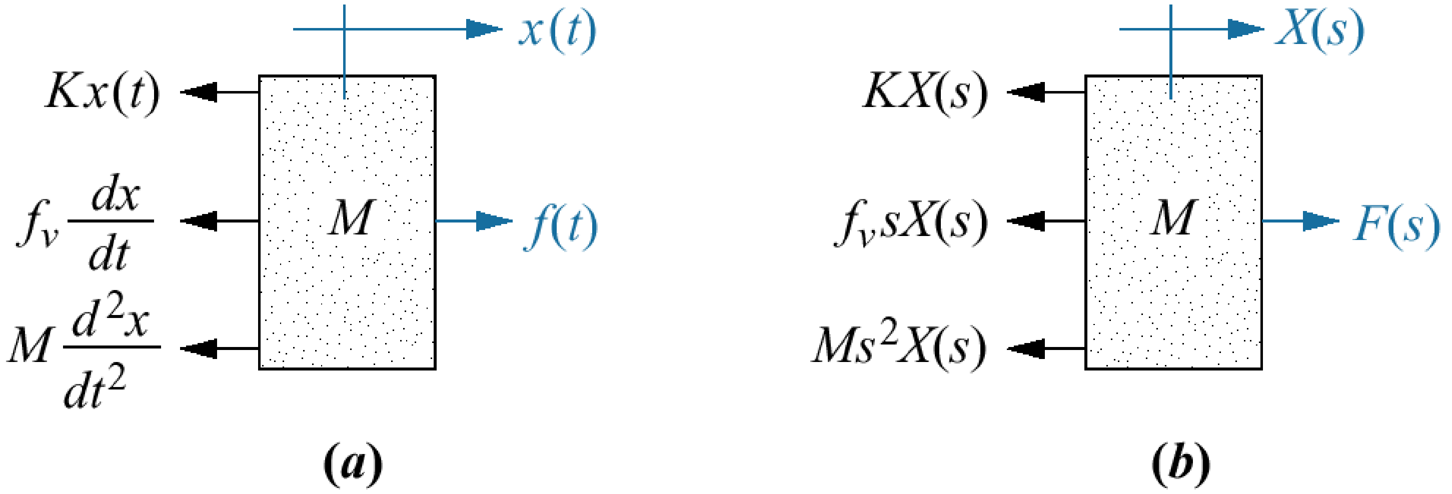
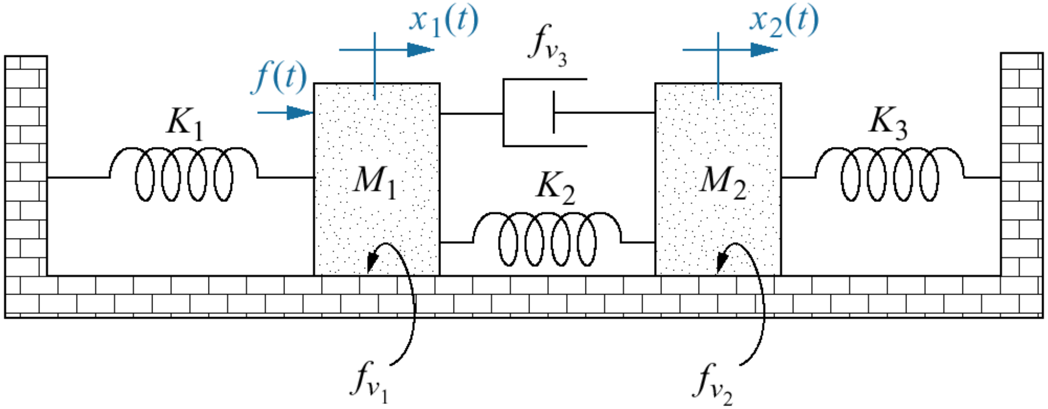
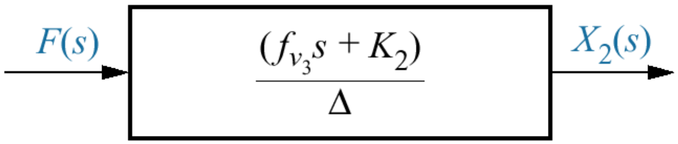


Figure 2.17

a. Two-degrees-of-freedom translational mechanical system[8];
b. block diagram



(a)



(b)

Figure 2.18

a. Forces on M_1 due only to motion of M_1
b. forces on M_1 due only to motion of M_2
c. all forces on M_1

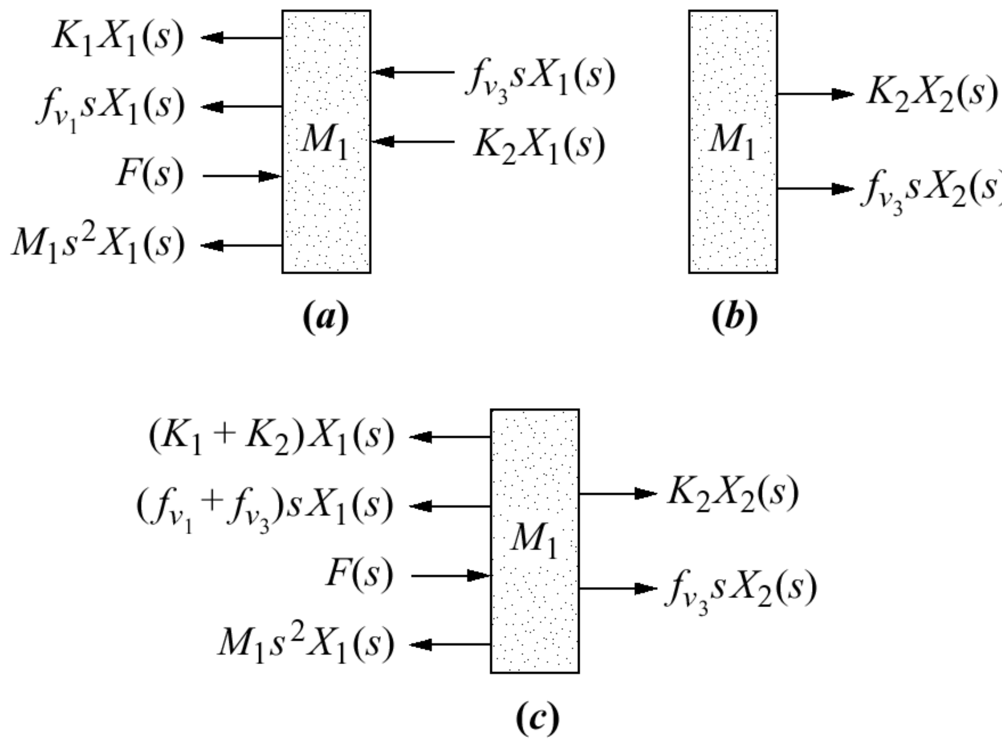


Figure 2.19

a. Forces on M_2 due only to motion of M_2;
b. forces on M_2 due only to motion
of M_1;
c. all forces on M_2

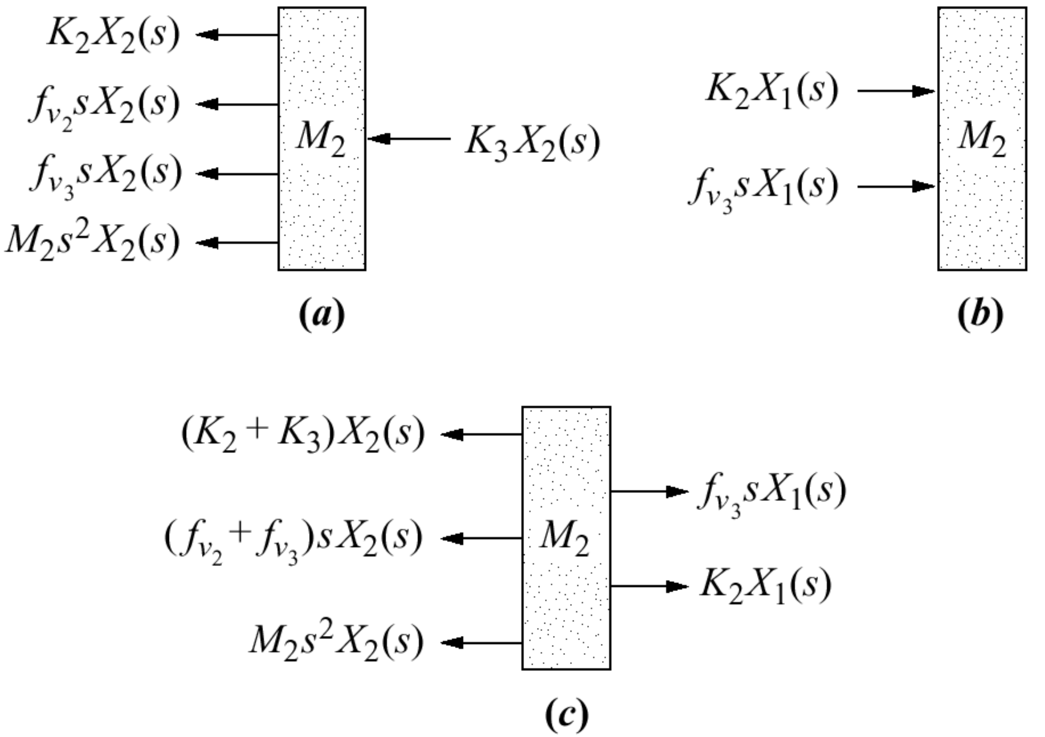


Figure 2.20
Three-degrees-of-freedom
translational
mechanical system

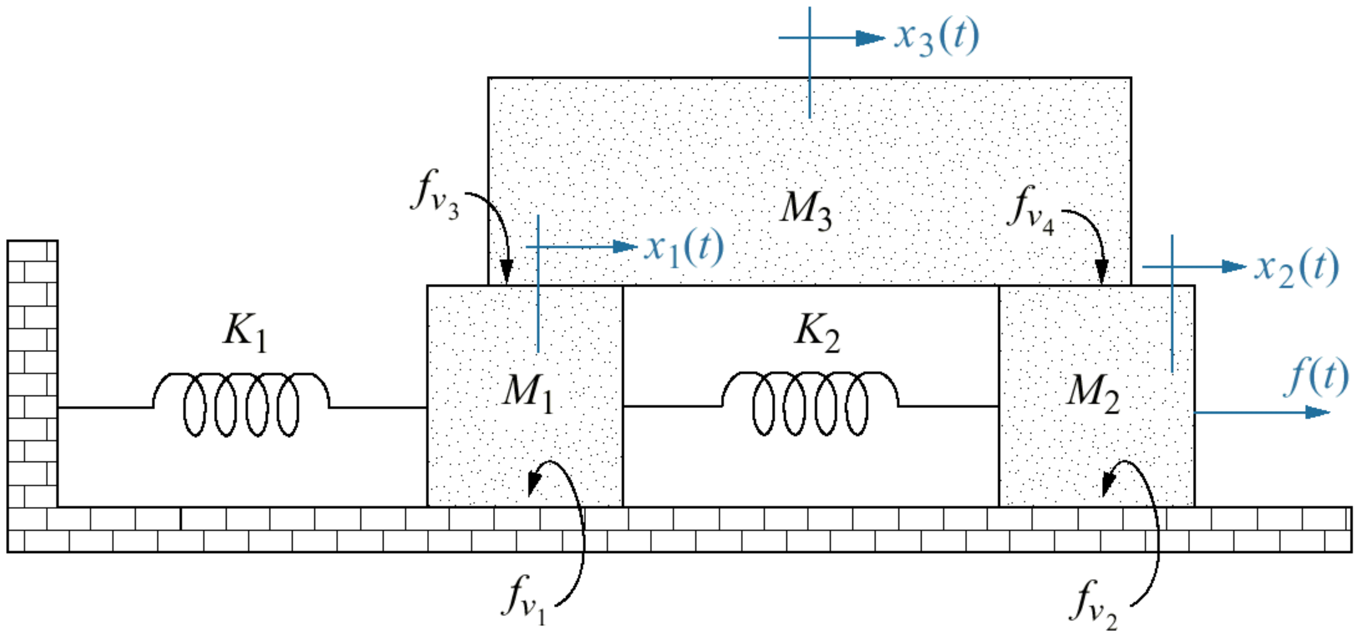


Figure 2.21
Translational mechanical system for Skill-Assessment Exercise 2.8

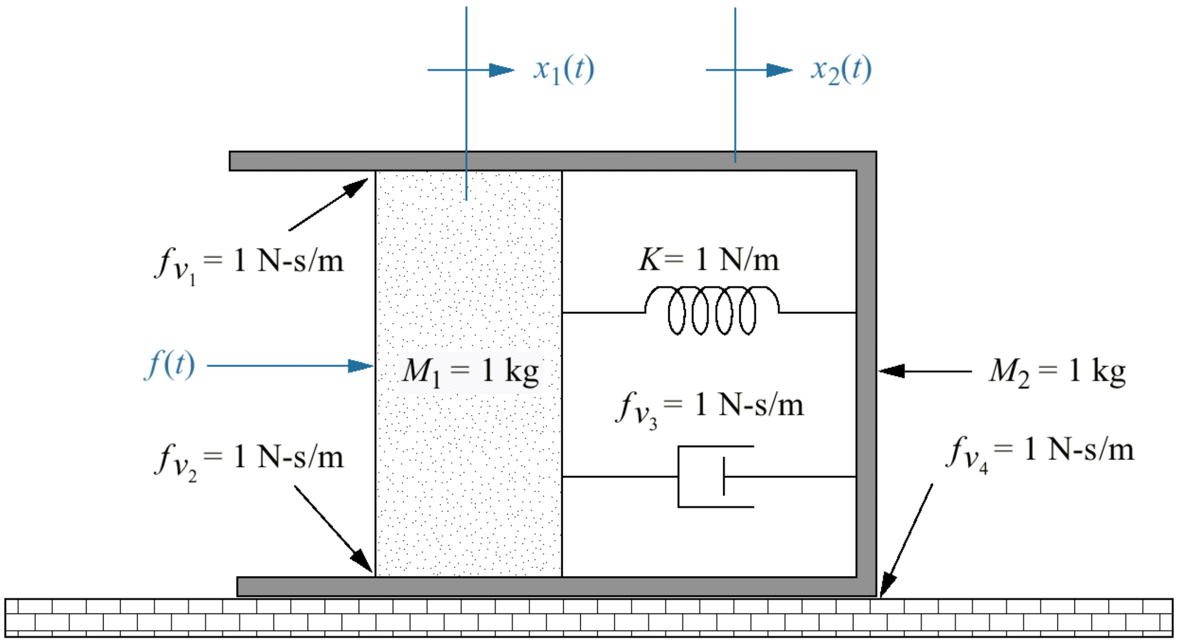
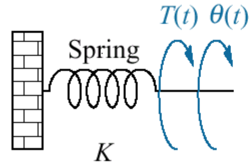
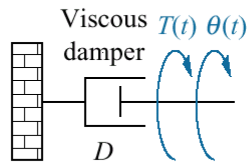
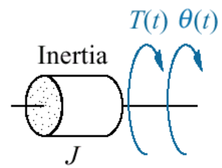


Table 2.5

Torque-angular velocity, torque-angular displacement, and impedance rotational relationships for springs, viscous dampers, and inertia

Component	Torque-angular velocity	Torque-angular displacement	Impedance $Z_M(s) = T(s)/\theta(s)$
	$T(t) = K\int_0^t \omega(\tau)\,d\tau$	$T(t) = K\theta(t)$	K
	$T(t) = D\omega(t)$	$T(t) = D\dfrac{d\theta(t)}{dt}$	Ds
	$T(t) = J\dfrac{d\omega(t)}{dt}$	$T(t) = J\dfrac{d^2\theta(t)}{dt^2}$	Js^2

Note: The following set of symbols and units is used throughout this book: $T(t)$ = N-m (newton-meters), $\theta(t)$ = rad (radians), $\omega(t)$ = rad/s (radians/second), K = N-m/rad (newton-meters/radian), D = N-m-s/rad (newton-meters-seconds/radian), J = kg-m^2 (kilogram-meters^2 = newton-meters-seconds^2/radian).

Figure 2.22
a. Physical system;
b. schematic; **c.** block diagram

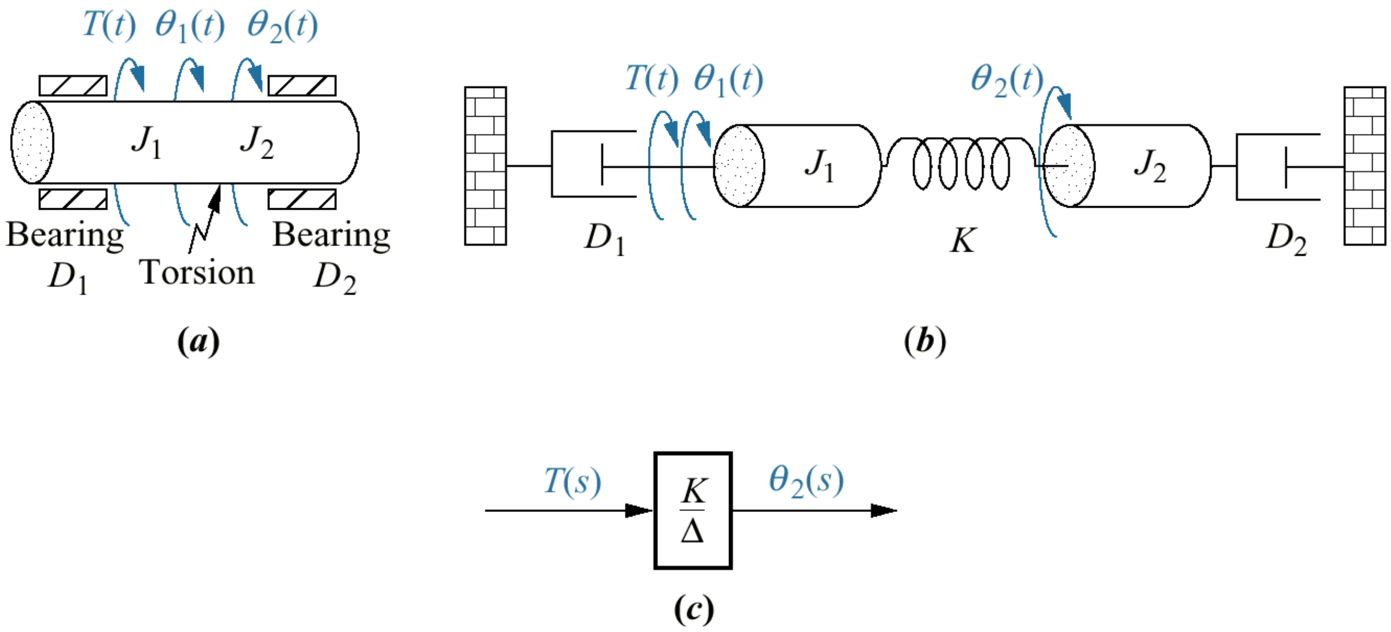
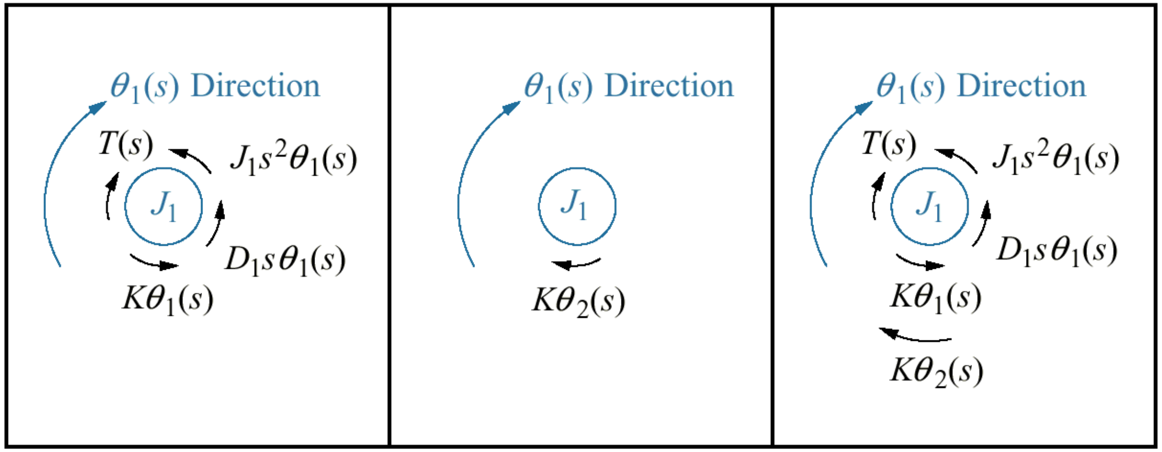


Figure 2.23

a. Torques on J_1 due only to the motion of J_1
b. torques on J_1 due only to the motion of J_2
c. final free-body diagram for J_1



(a) (b) (c)

Figure 2.24

a. Torques on J_2 due only to the motion of J_2;
b. torques on J_2 due only to the motion of J_1
c. final free-body diagram for J_2

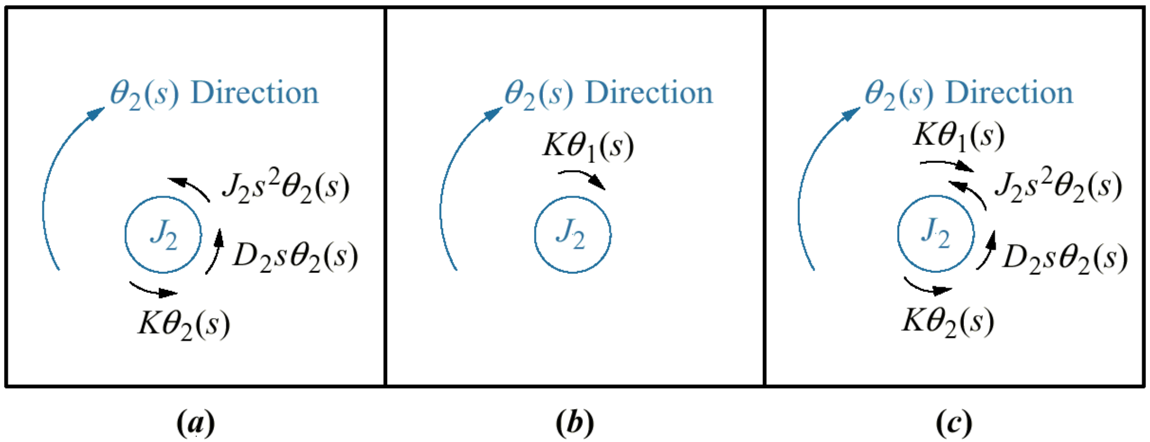


Figure 2.25

Three-degrees-of-freedom rotational system

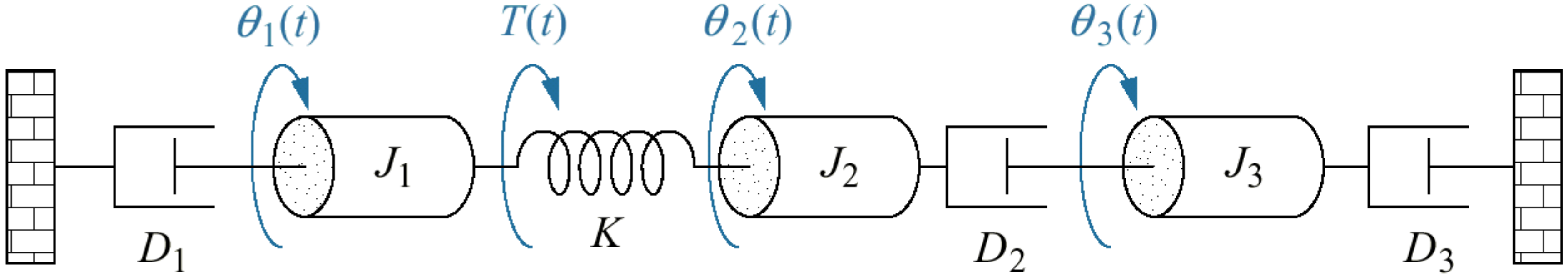


Figure 2.26
Rotational mechanical system for Skill-Assessment
Exercise 2.9

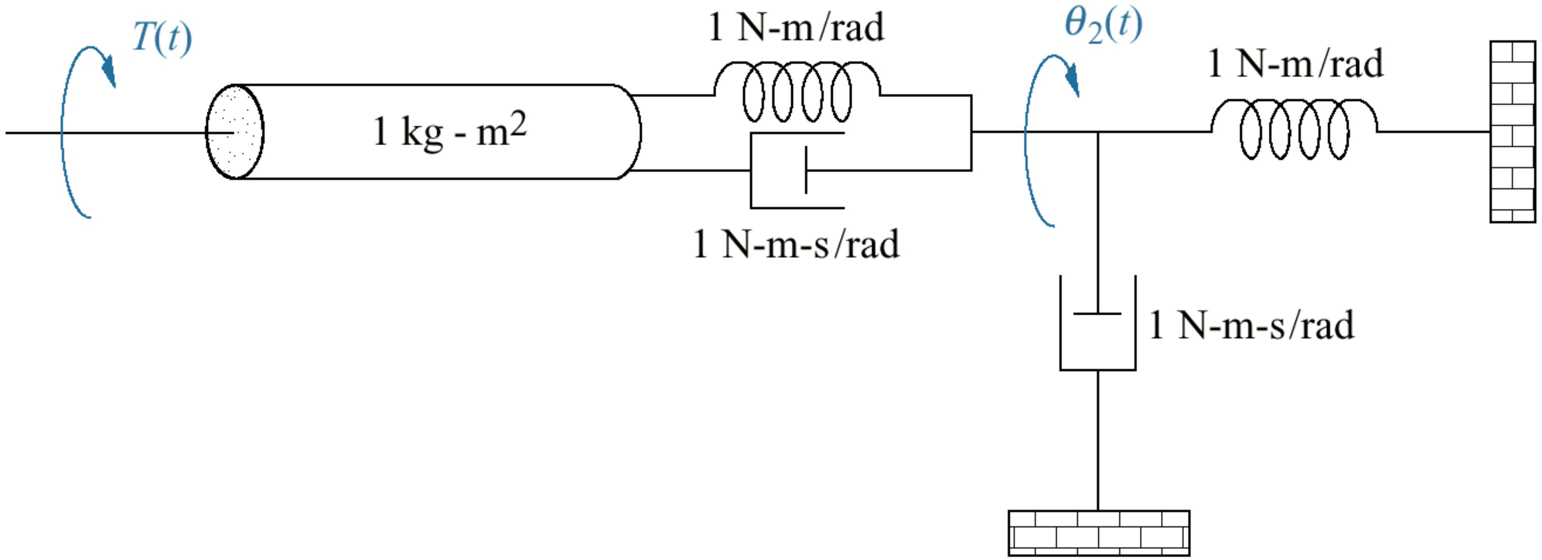


Figure 2.27
A gear system

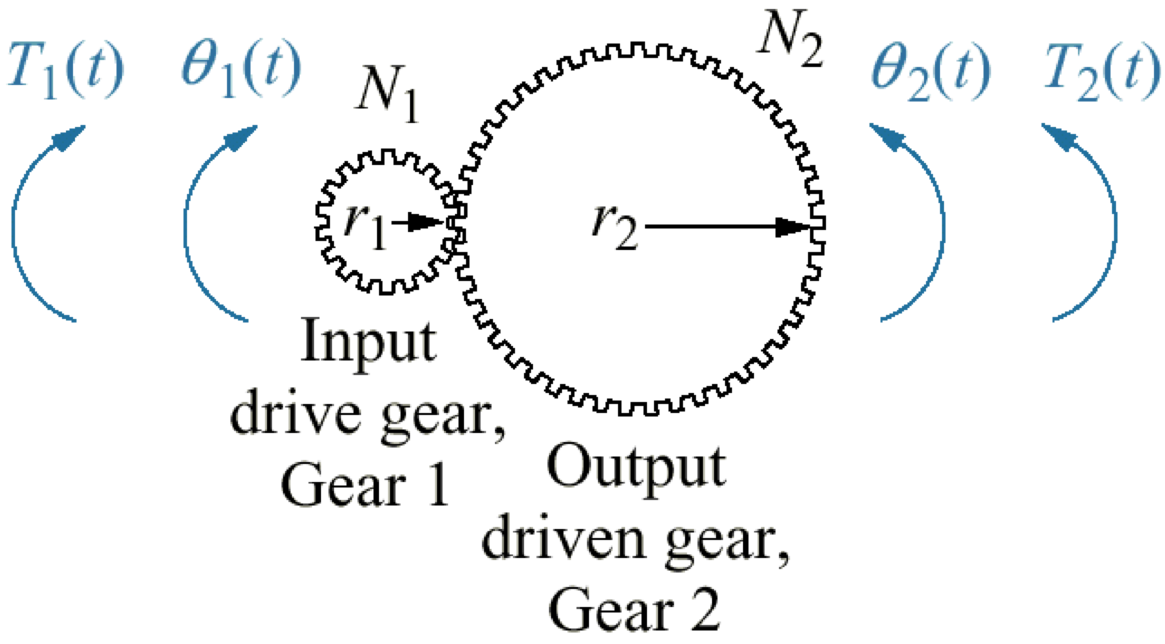


Figure 2.28

Transfer functions for **a.** angular displacement in lossless gears and **b.** torque in lossless gears

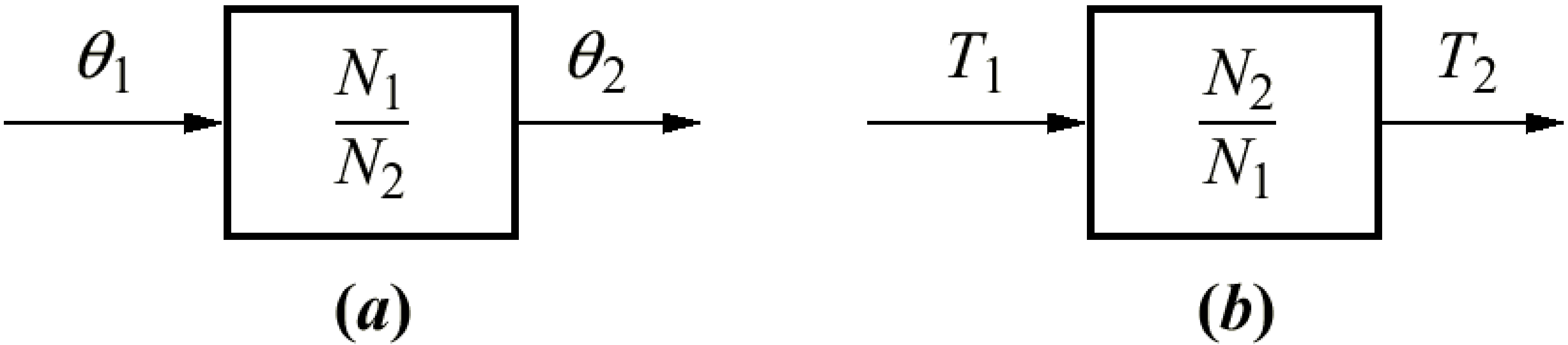


Figure 2.29

a. Rotational system driven by gears;
b. equivalent system at the output after reflection of input torque;
c. equivalent system at the input after reflection of impedances

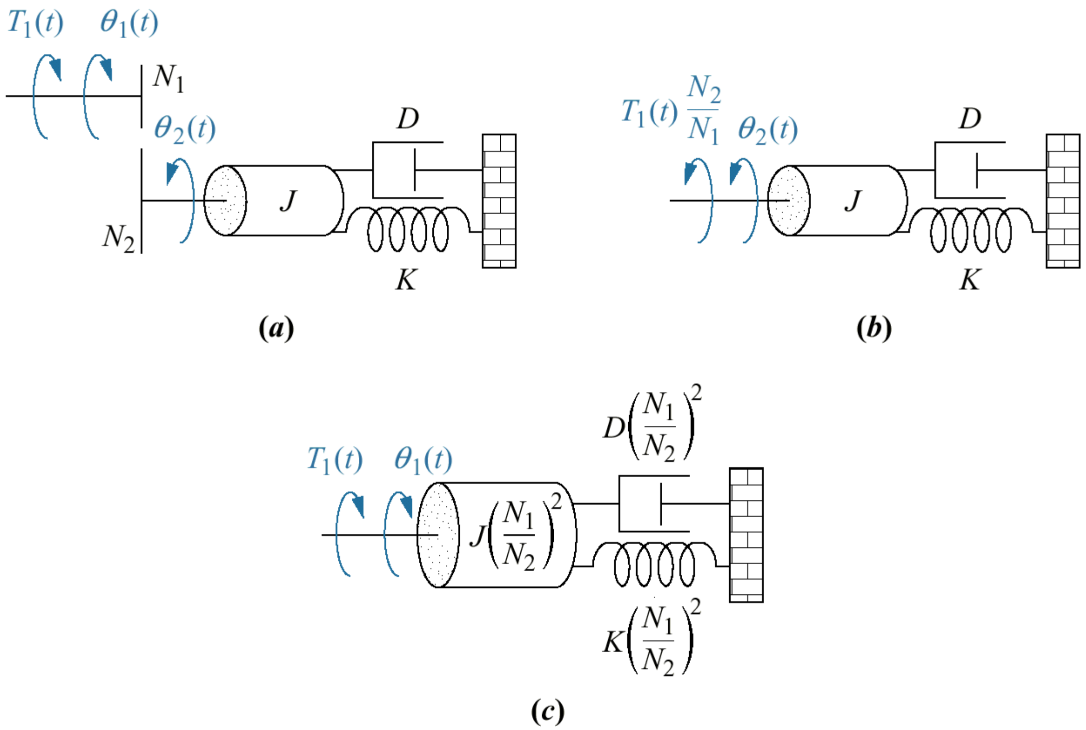


Figure 2.30

a. Rotational mechanical system with gears;
b. system after reflection of torques and impedances to the output shaft;
c. block diagram

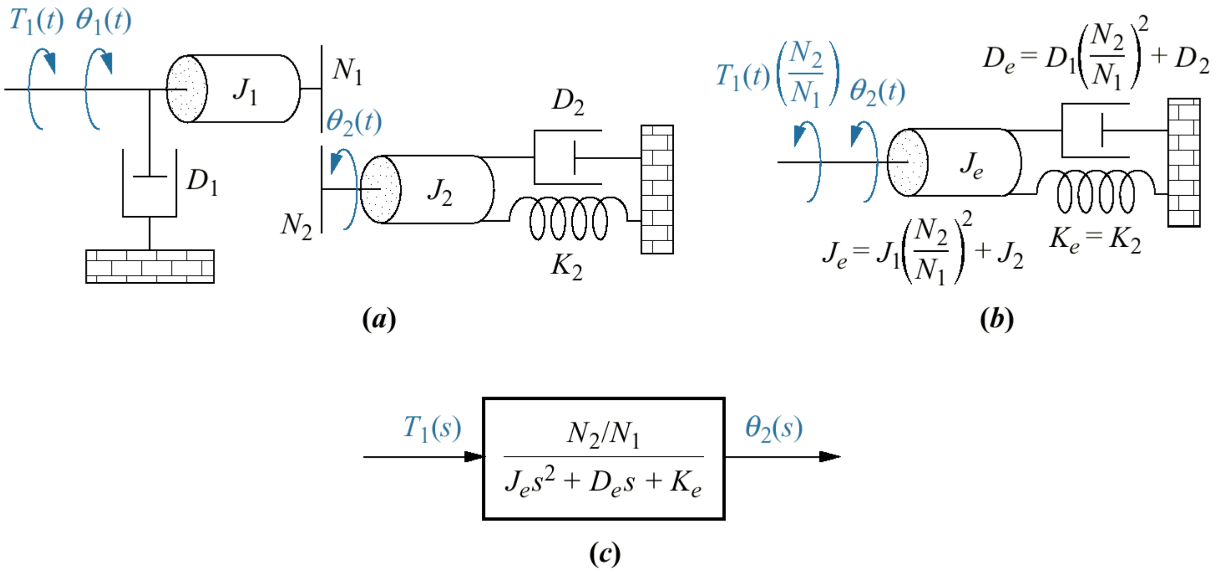


Figure 2.31

Gear train

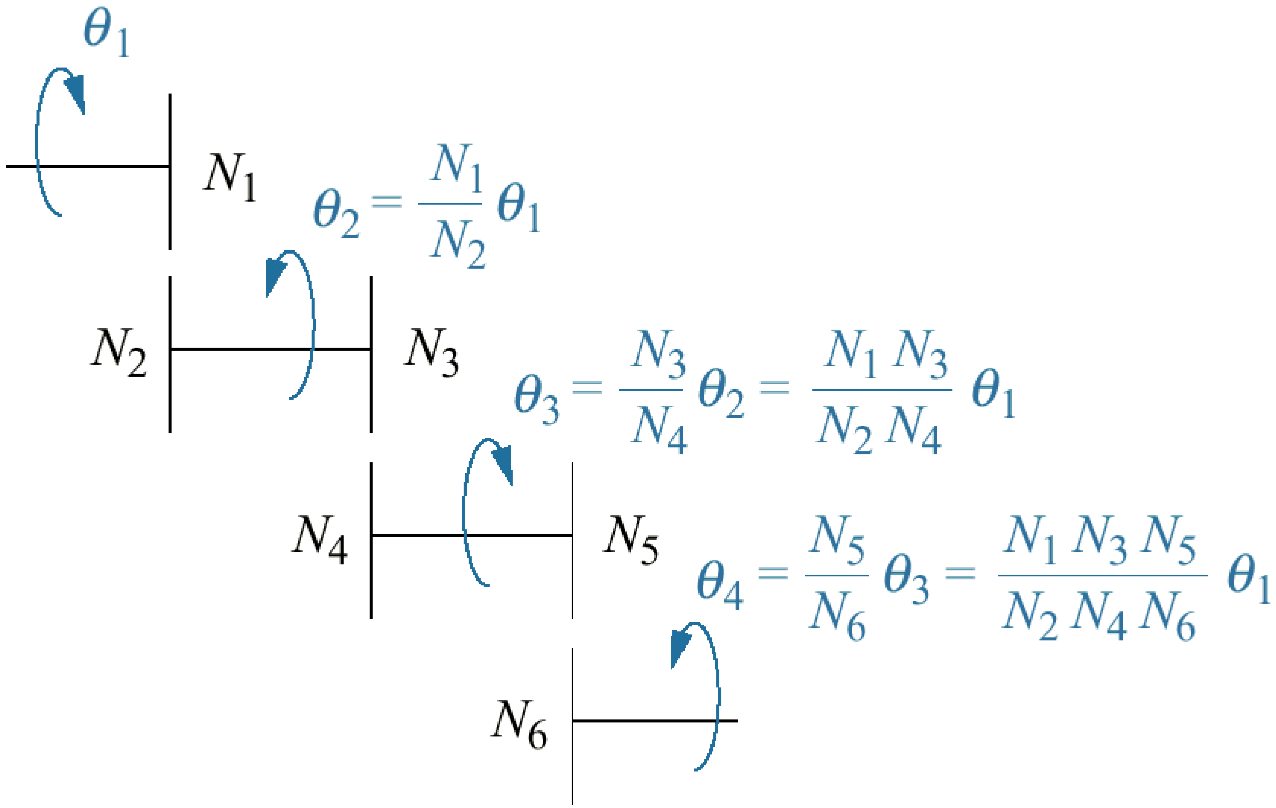


Figure 2.32

a. System using a gear train;

b. equivalent system at the input;

c. block diagram

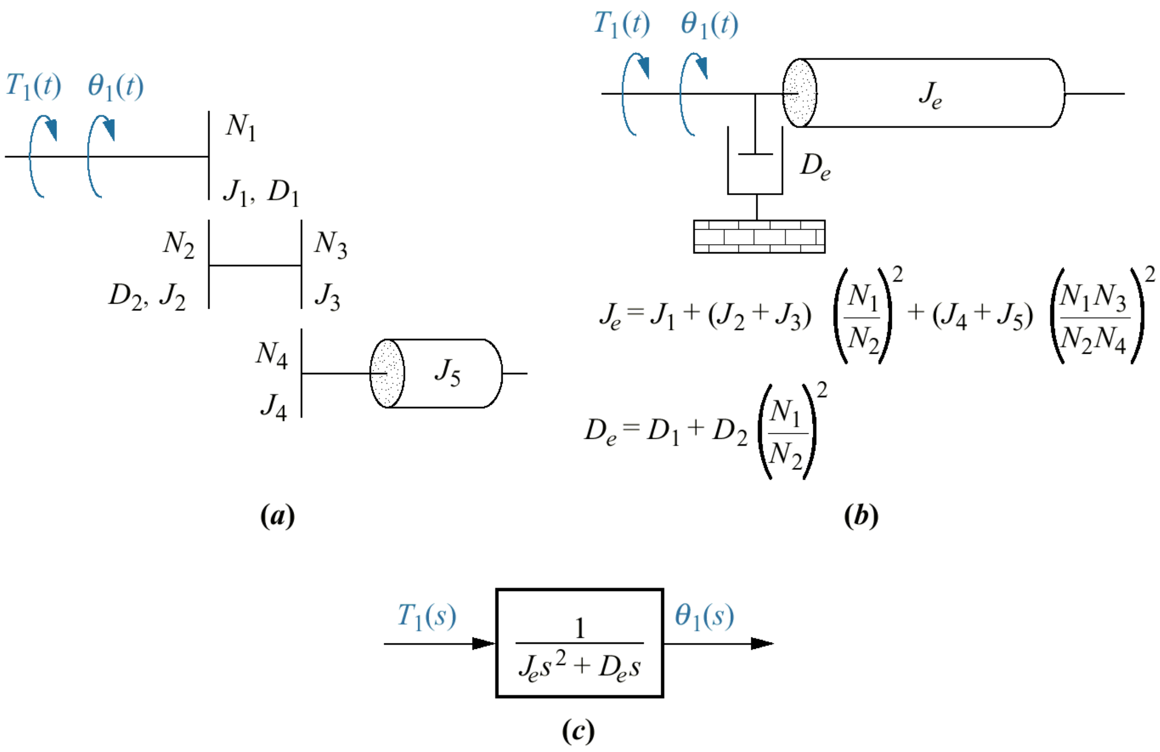


Figure 2.33

Rotational mechanical system with gears for Skill-Assessment Exercise 2.10

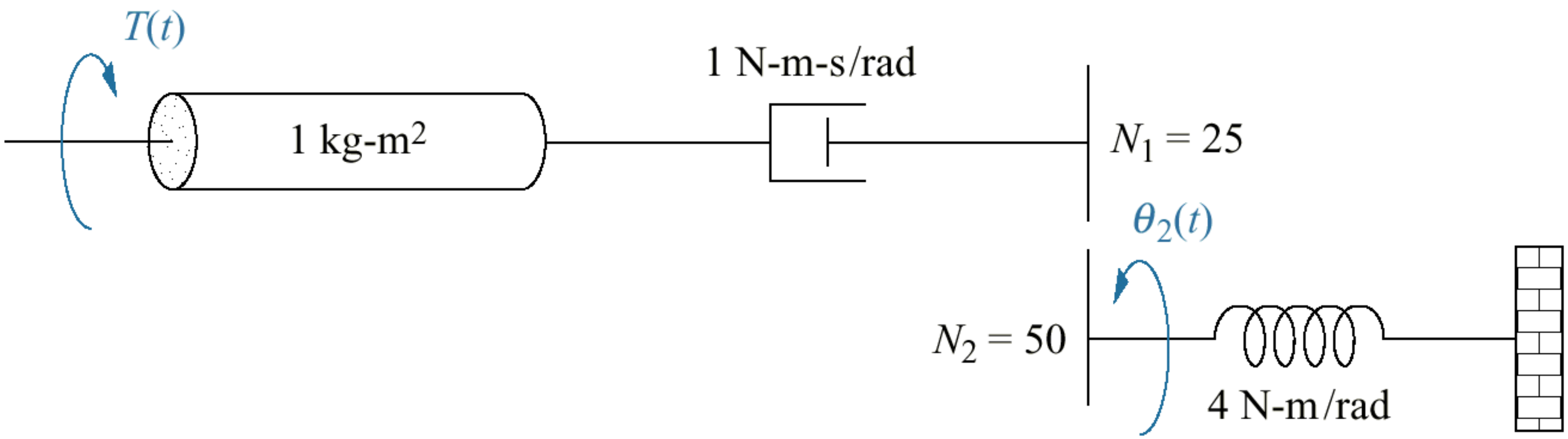


Figure 2.34
NASA flight simulator robot arm with electromechanical control system components

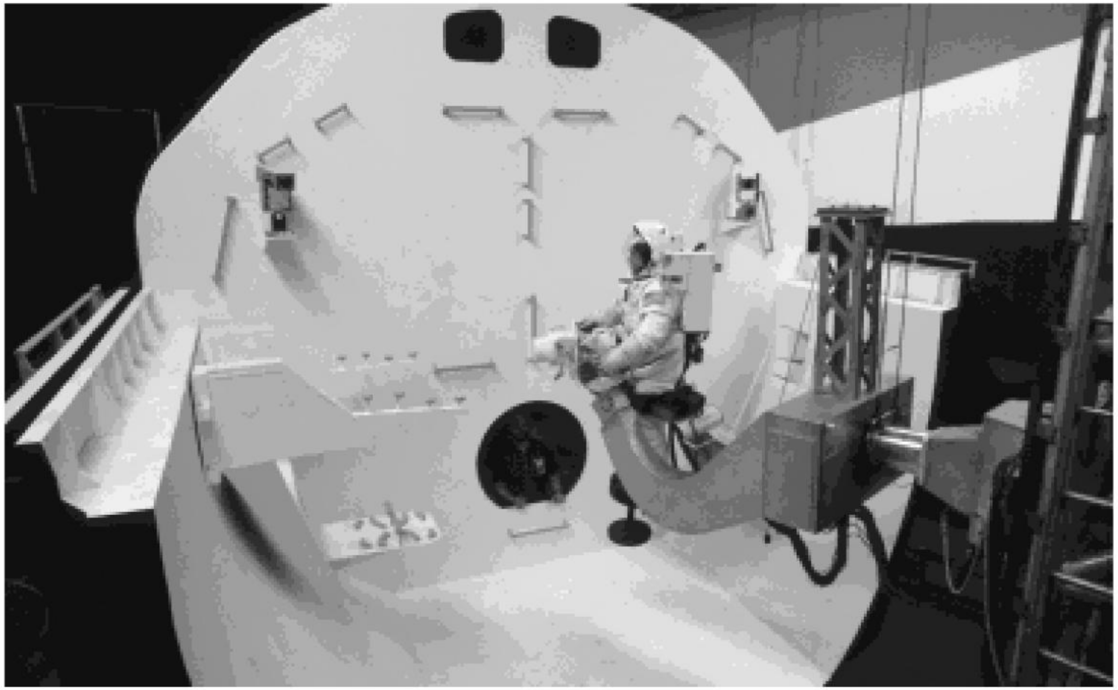
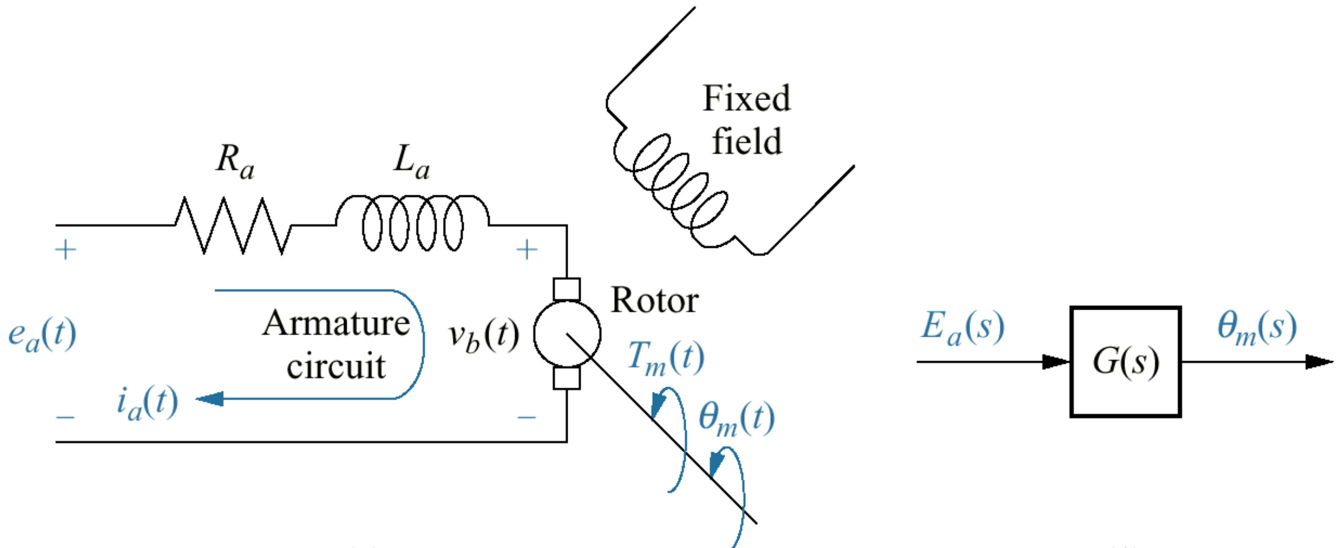


Figure 2.35
DC motor:
a. schematic[12];
b. block diagram



(*a*) (*b*)

Figure 2.36
Typical equivalent mechanical loading on a motor

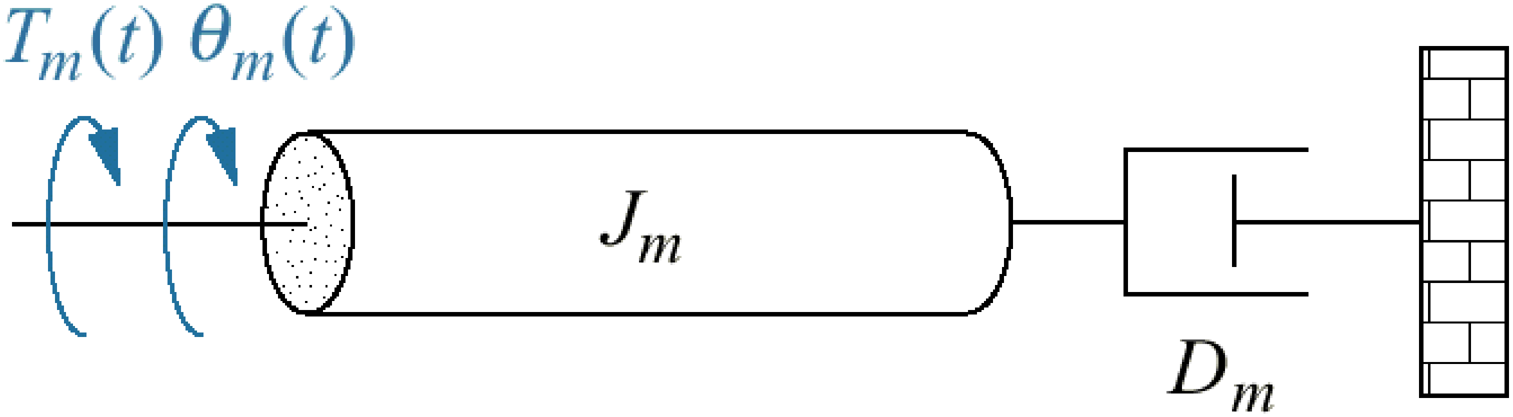


Figure 2.37

DC motor driving a rotational mechanical load

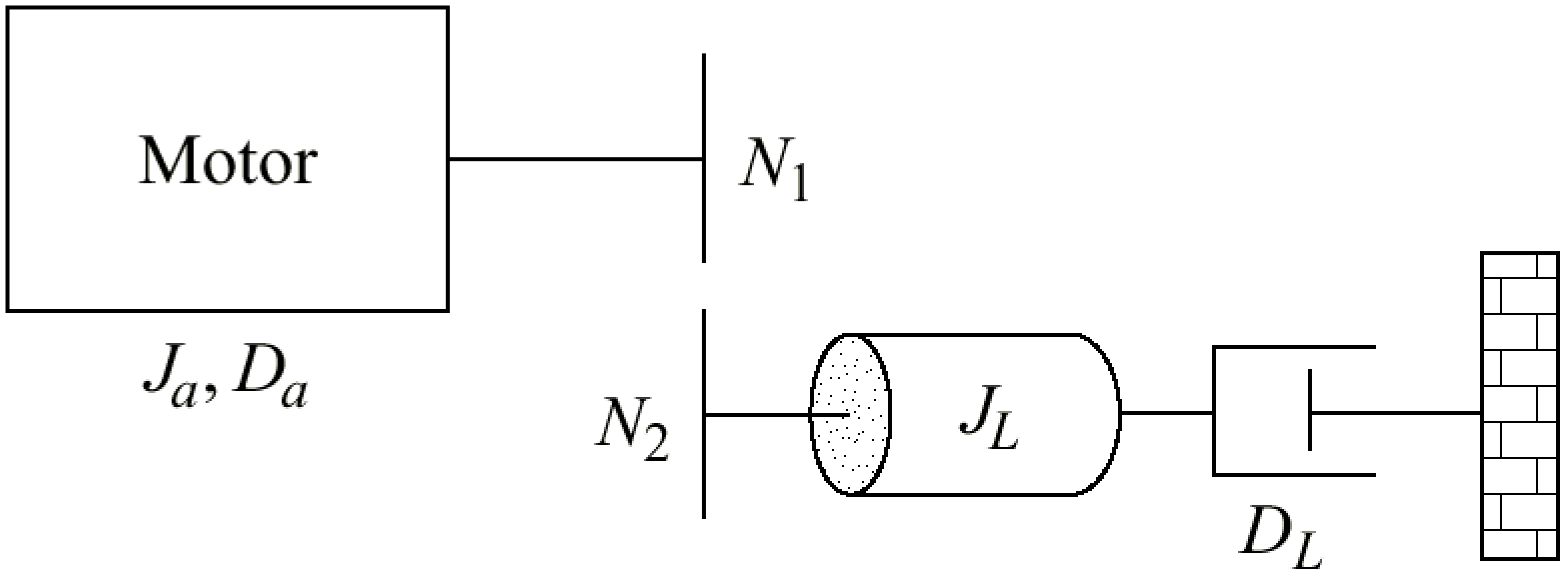


Figure 2.38

Torque-speed curves with an armature voltage, e_a, as a parameter

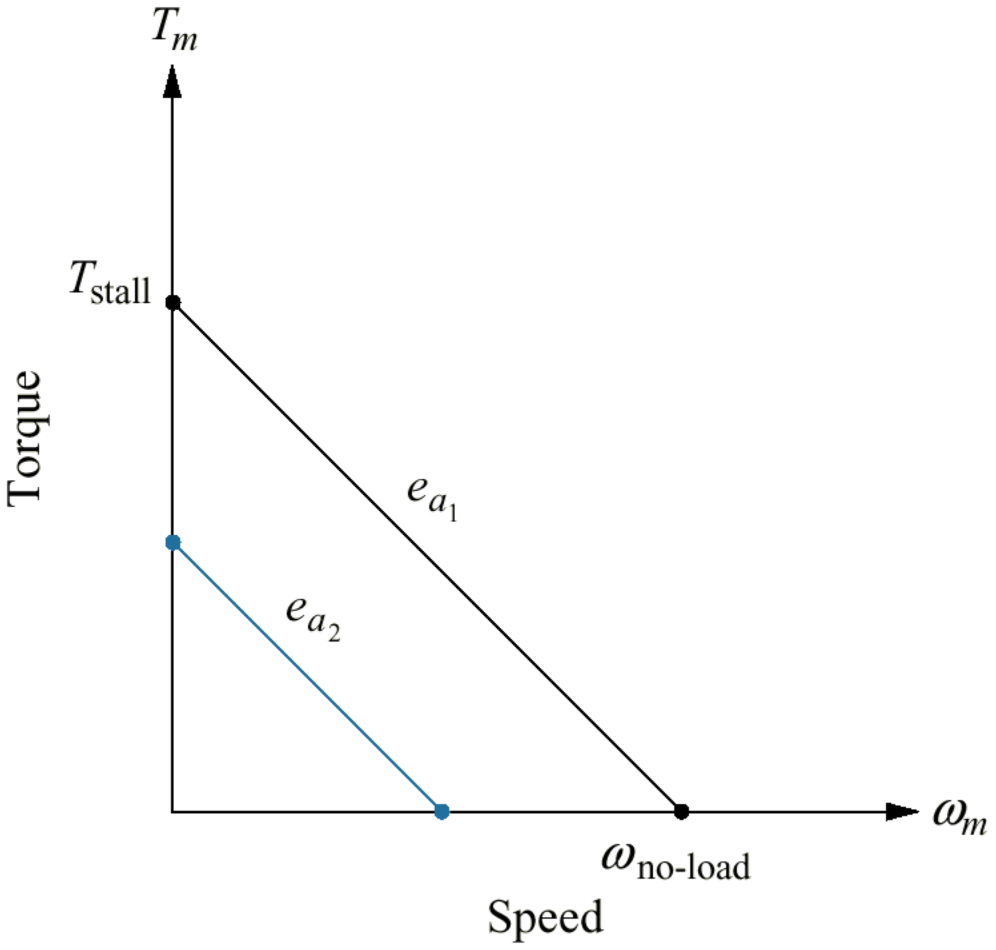
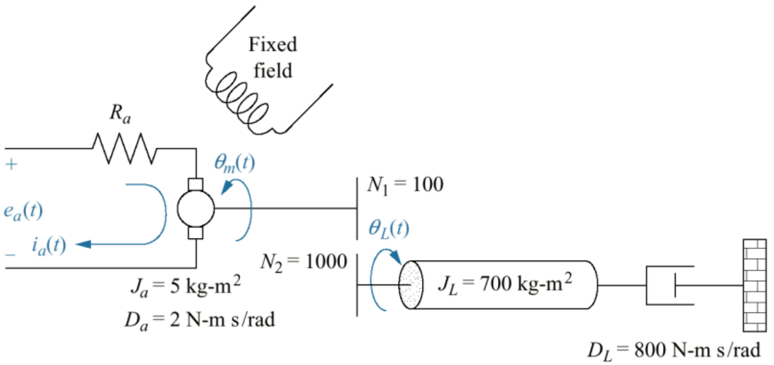


Figure 2.39

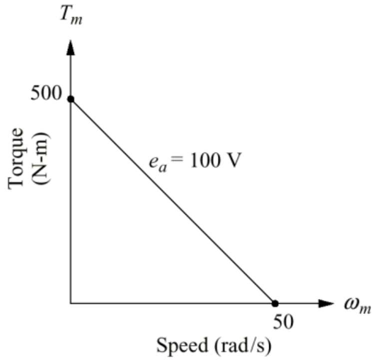
a. DC motor and load;

b. torque-speed curve;

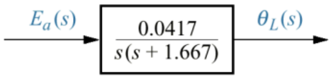
c. block diagram



(a)



(b)



(c)

Figure 2.40
Electromechanical system for
Skill-Assessment Exercise 2.11

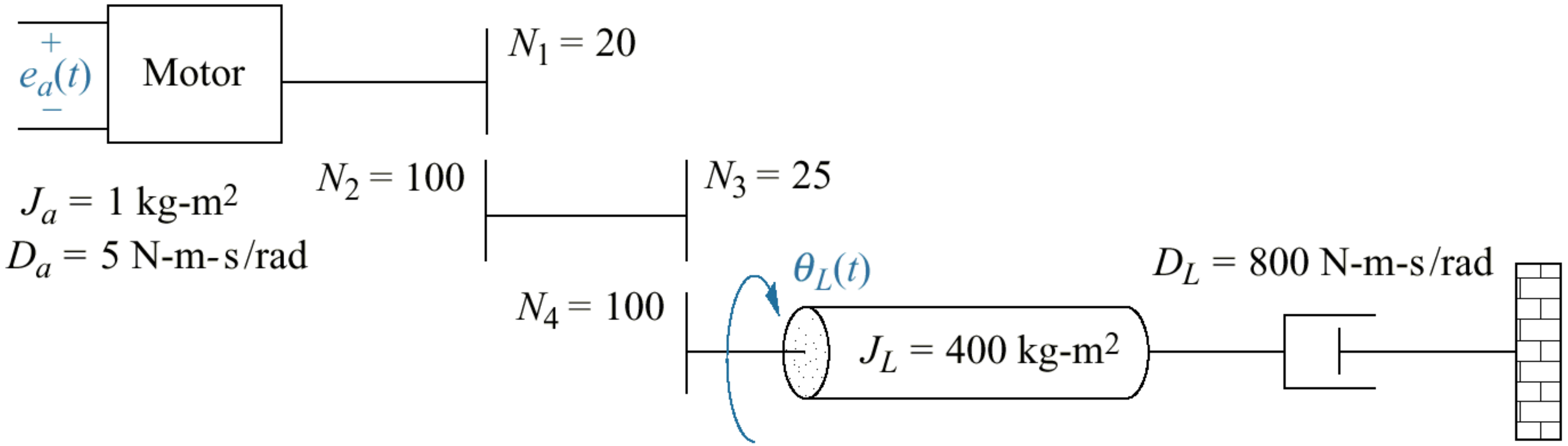


Figure 2.41
Development of series analog:
a. mechanical system;
b. desired electrical representation;
c. series analog;
d. parameters for series analog

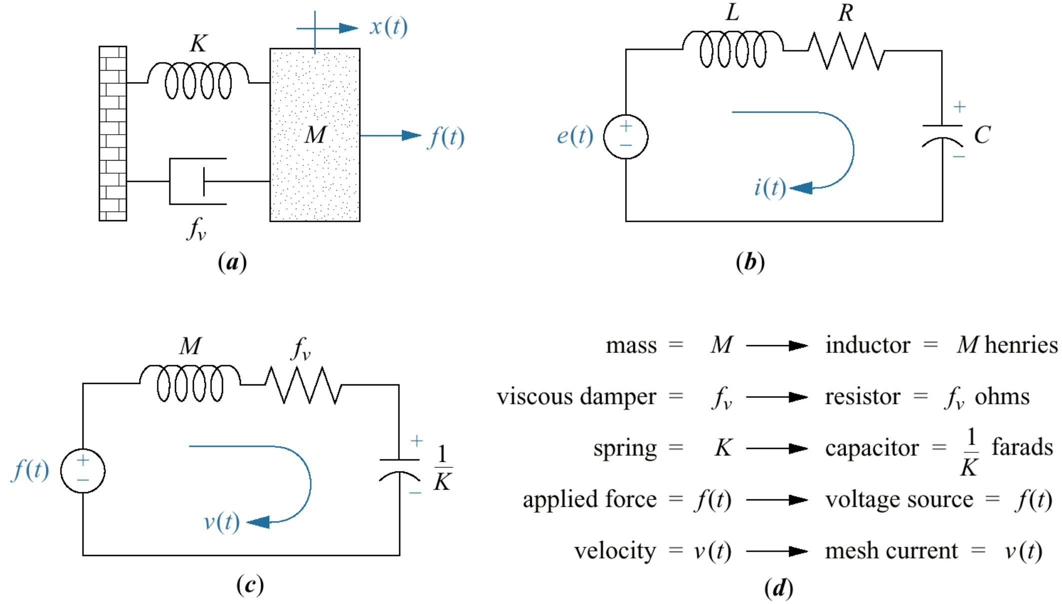


Figure 2.42

Series analog of mechanical system of Figure 2.17(a)

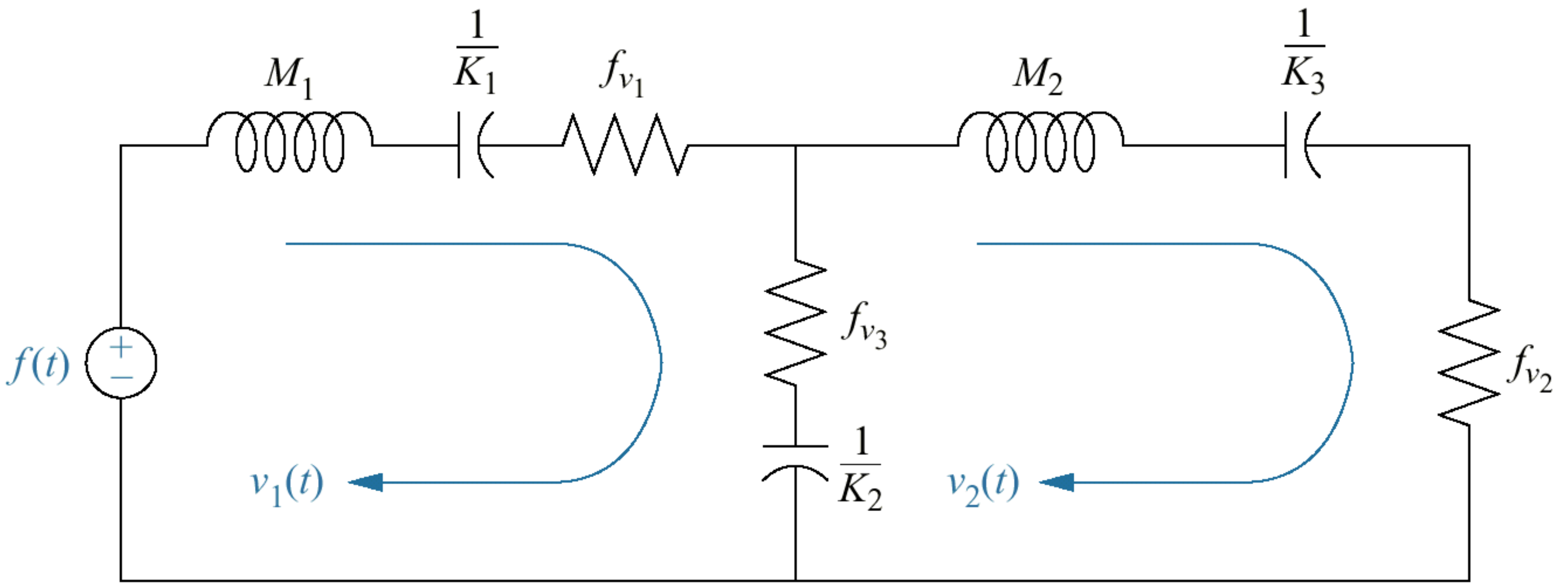


Figure 2.43

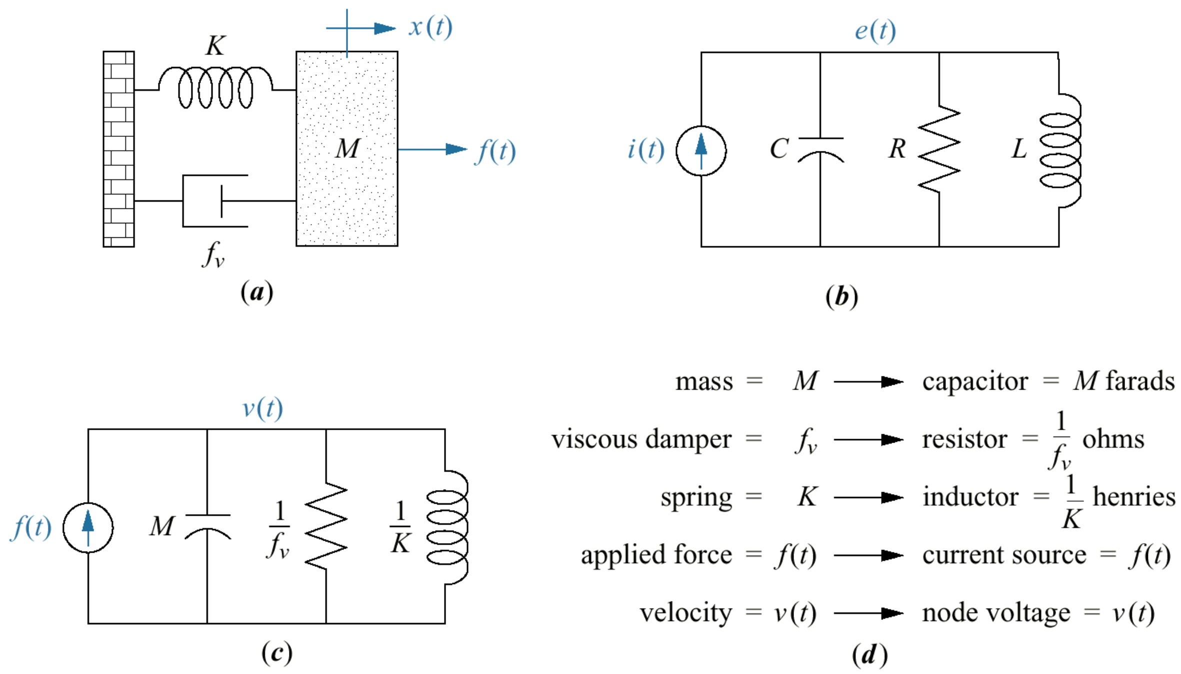
Development of parallel analog:

a. mechanical system;

b. desired electrical representation;

c. parallel analog;

d. parameters for parallel analog



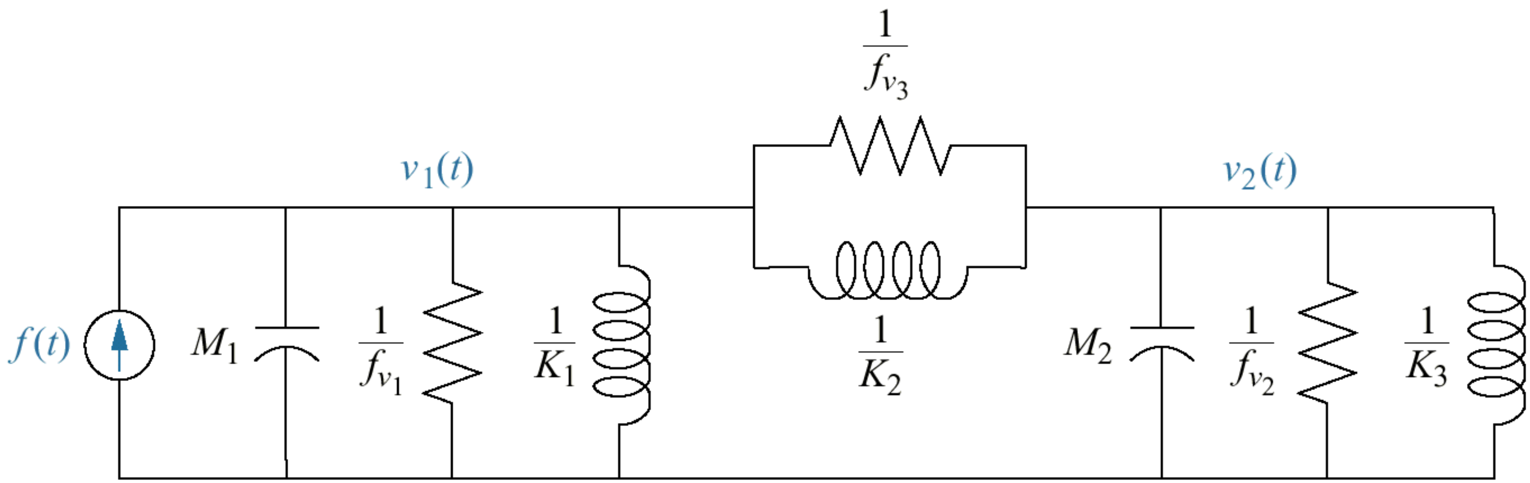


Figure 2.44
Parallel analog of mechanical system of Figure 2.17(a)

Figure 2.45
a. Linear system;
b. nonlinear system

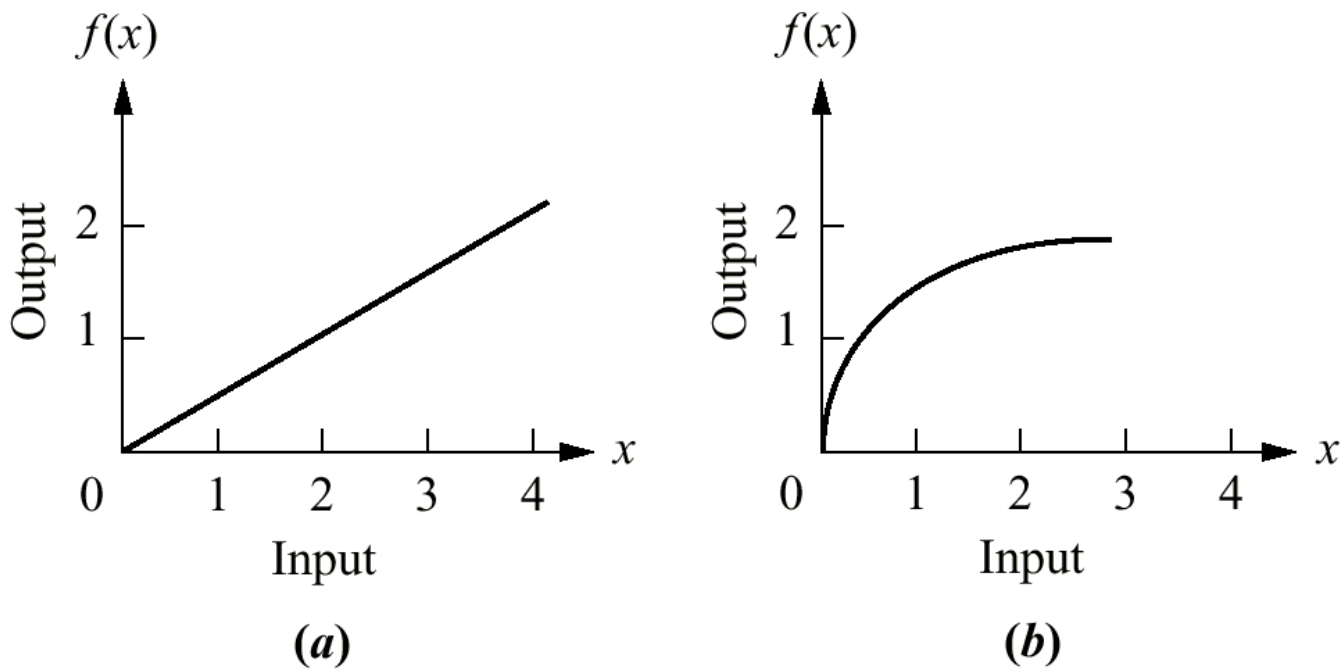


Figure 2.46
Some physical nonlinearities

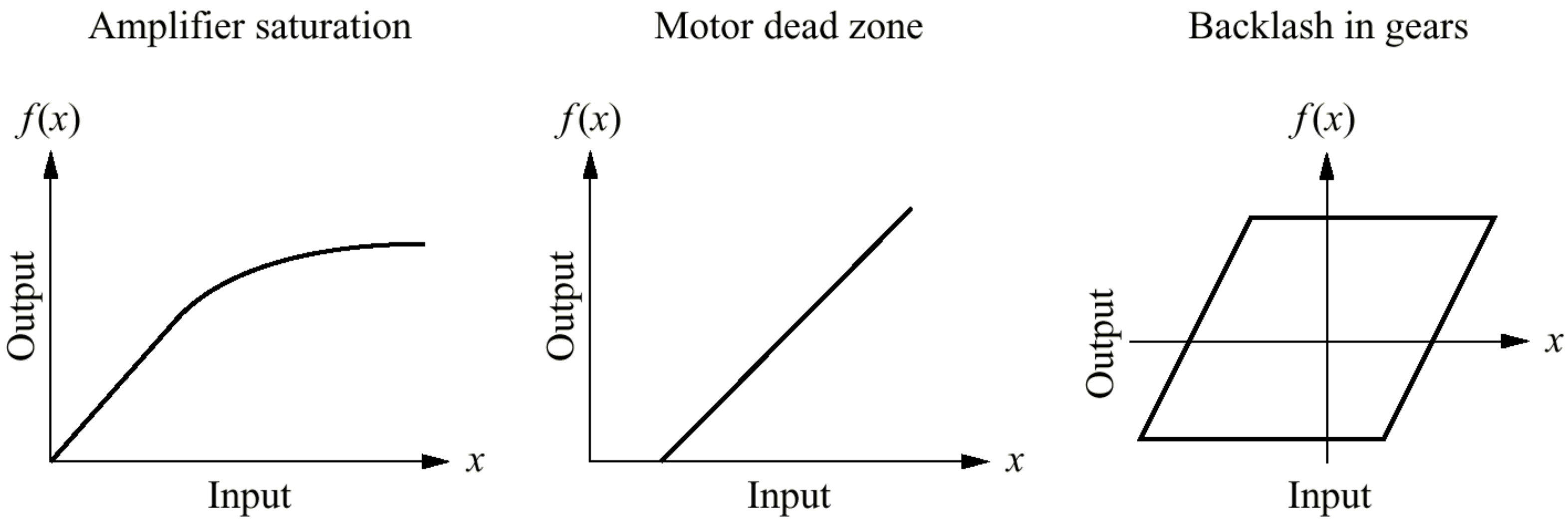
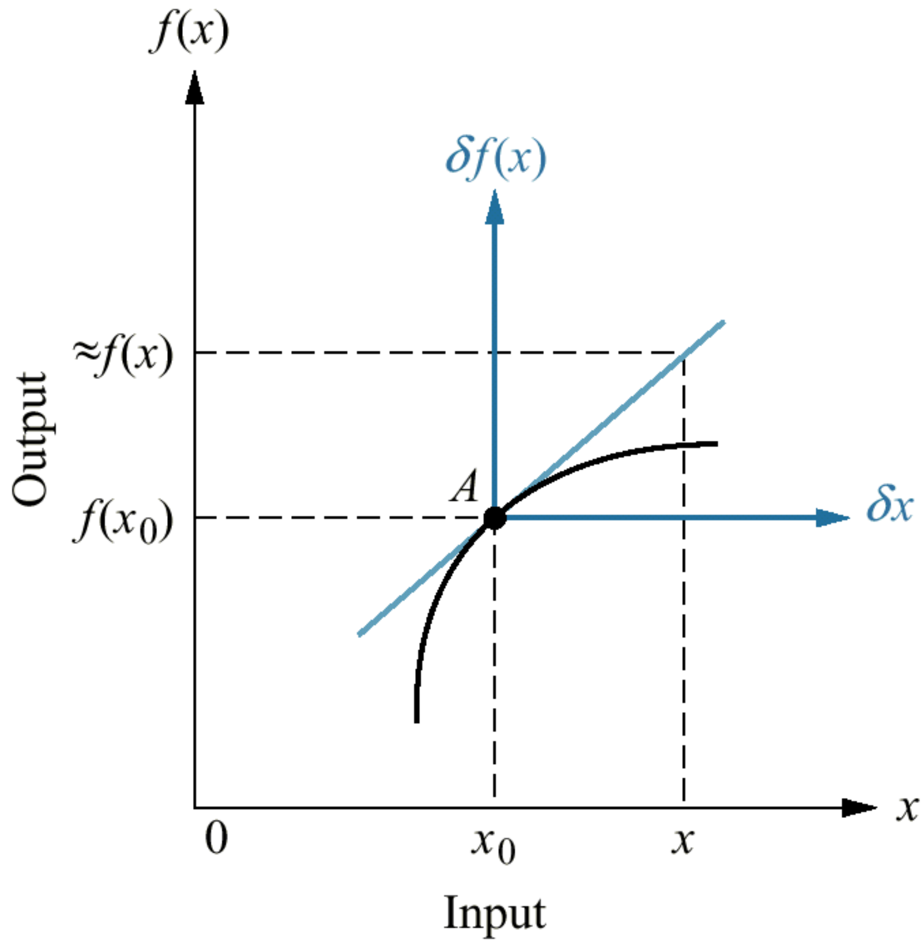


Figure 2.47
Linearization
about a point *A*



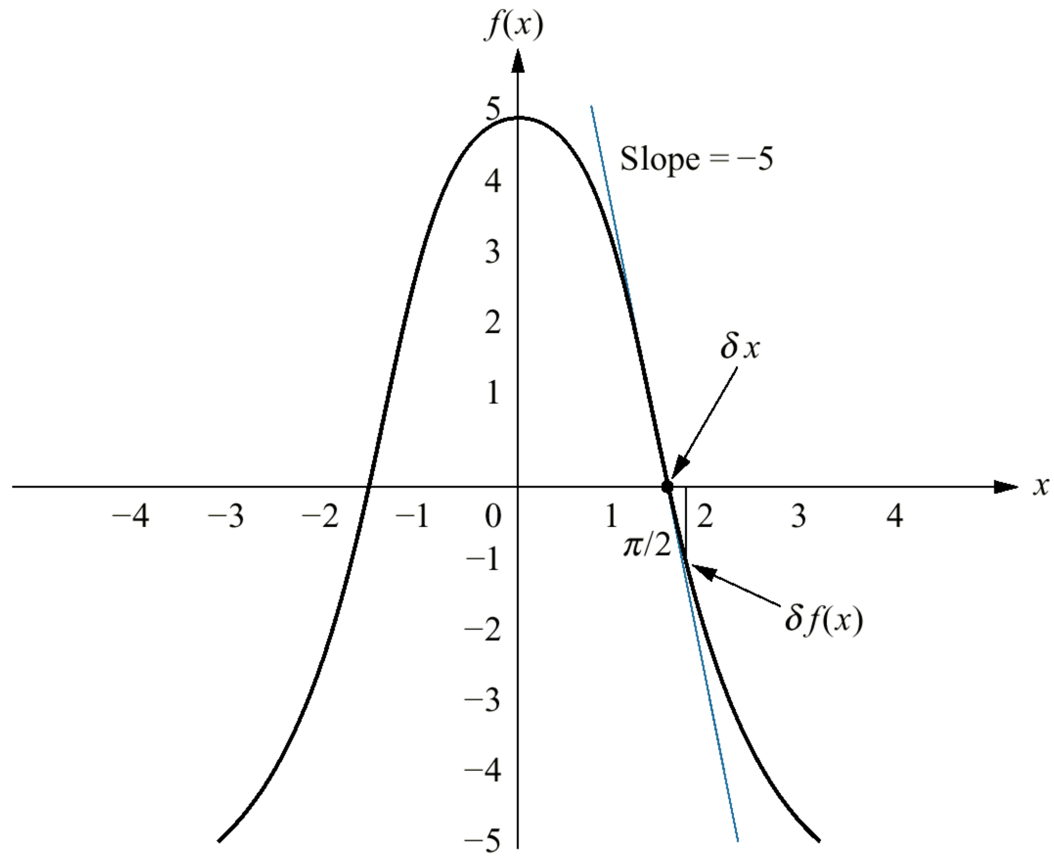


Figure 2.48
Linearization
of 5 cos *x* about
$x = \pi/2$

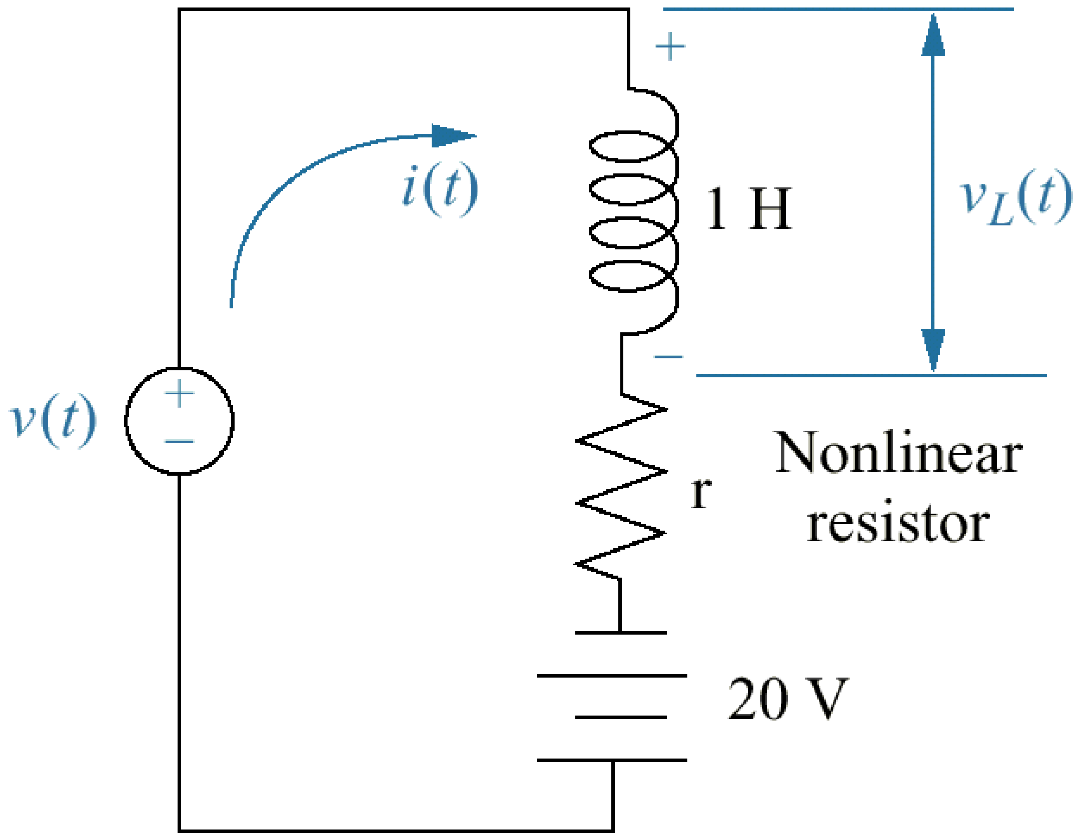


Figure 2.49 Nonlinear electrical network

Figure 2.50

Nonlinear electric circuit for Skill-Assessment Exercise 2.13

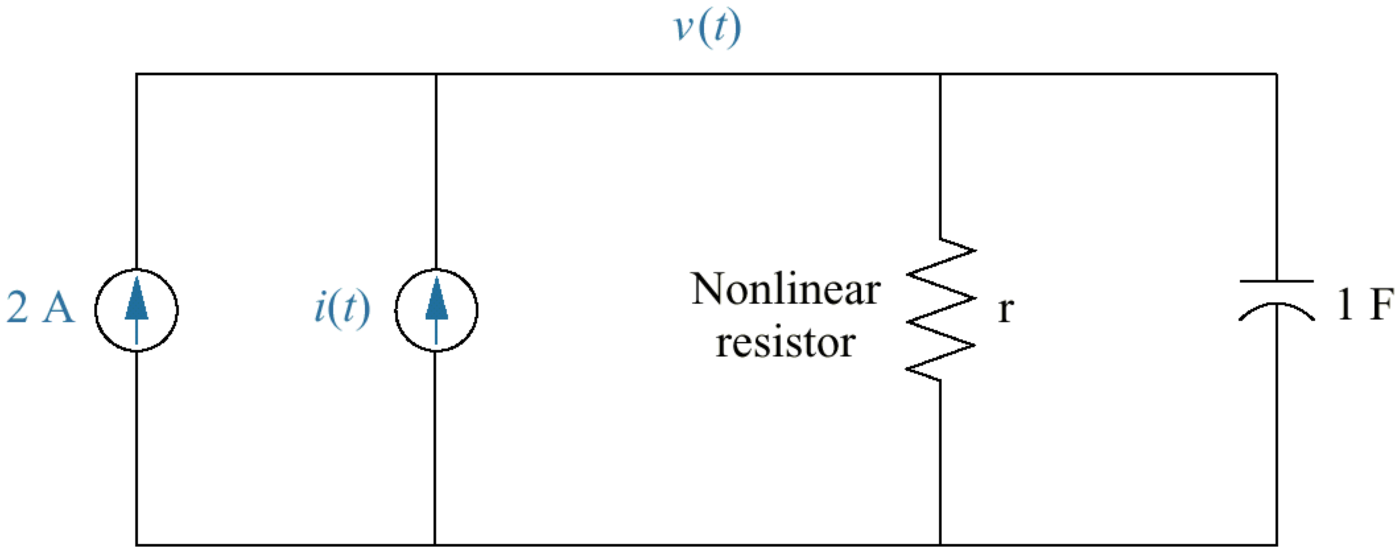


Table 2.6
Subsystems of the antenna azimuth position control system

Subsystem	Input	Output
Input potentiometer	Angular rotation from user $\theta_i(t)$	Voltage to preamp $v_i(t)$
Preamp	Voltage from potentiometers $v_e(t) = v_i(t) - v_o(t)$	Voltage to power amp $v_p(t)$
Power amp	Voltage from preamp $v_p(t)$	Voltage to motor $e_a(t)$
Motor	Voltage from power amp $e_a(t)$	Angular rotation to load $\theta_o(t)$
Output potentiometer	Angular rotation from load $\theta_o(t)$	Voltage to preamp $v_o(t)$

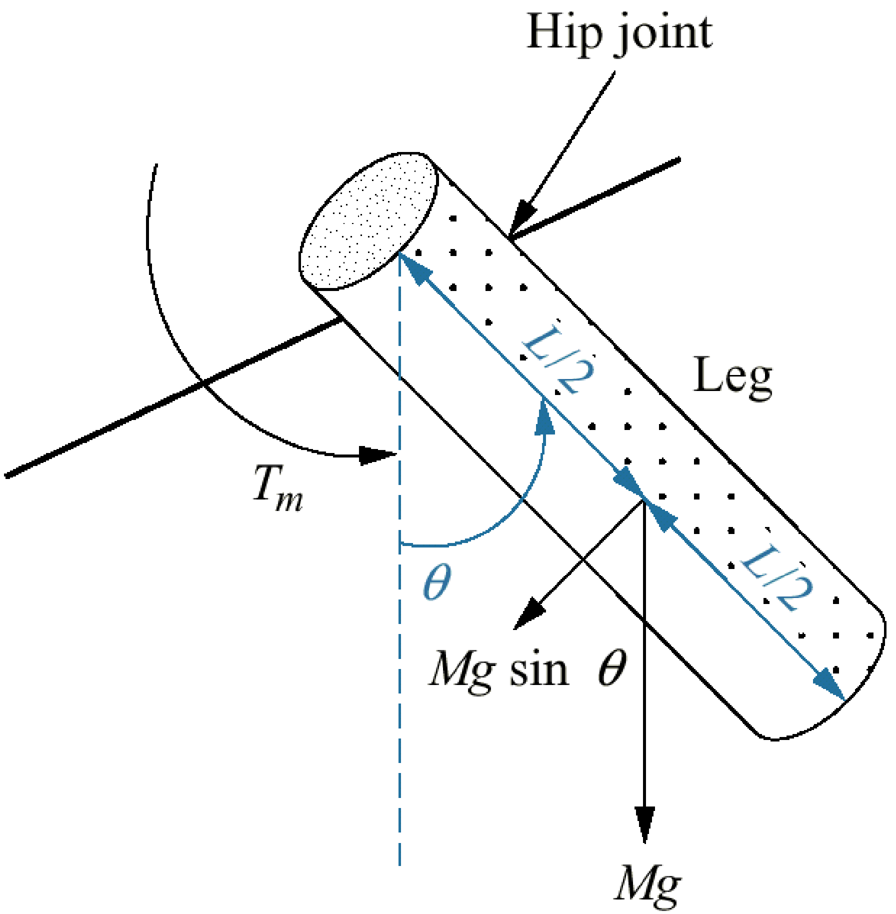


Figure 2.51
Cylinder model of a human leg

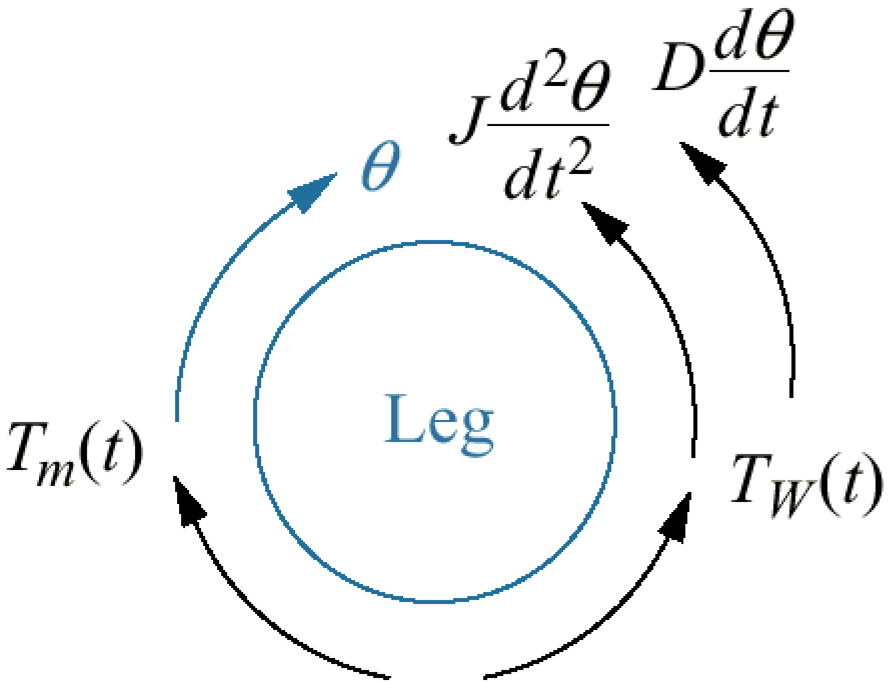


Figure 2.52
Free-body diagram of leg model

Figure 2.53
Nonlinear electric circuit

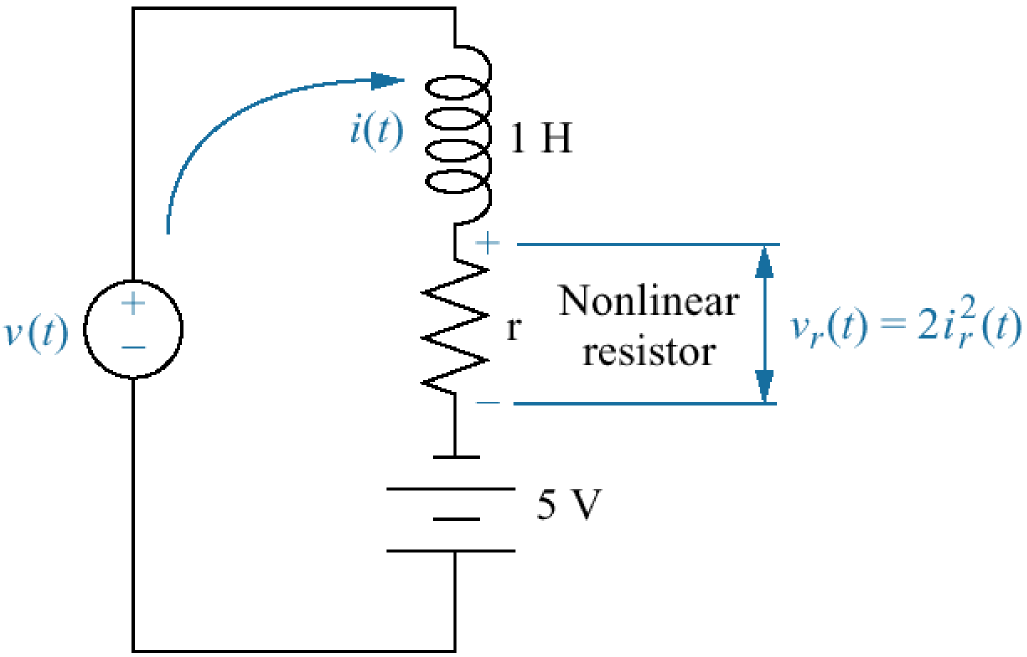


Figure P2.1

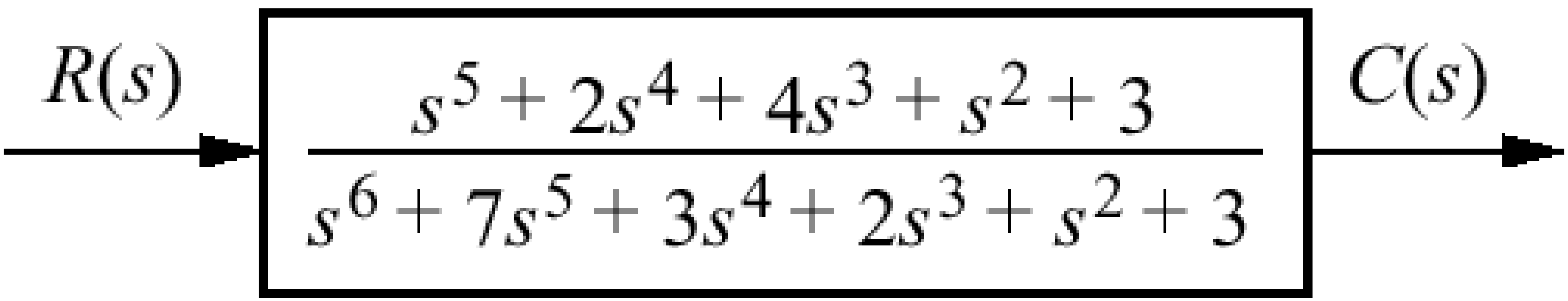
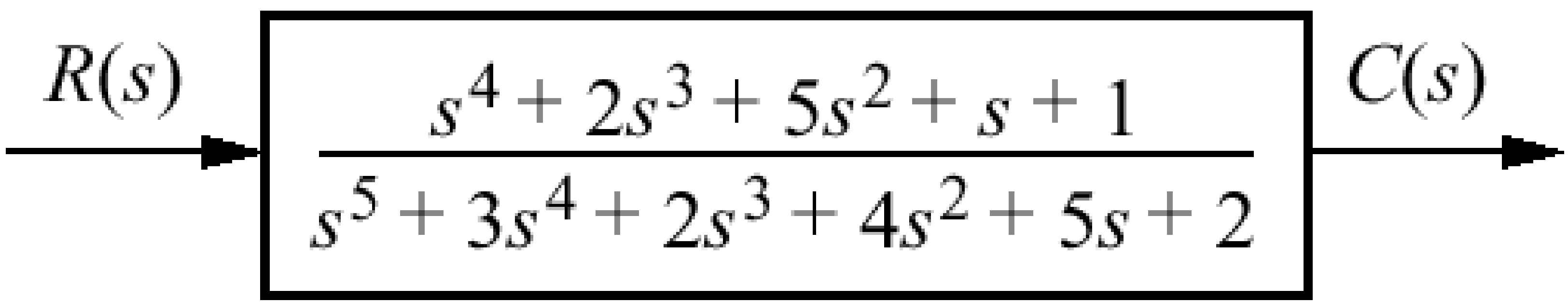


Figure P2.2



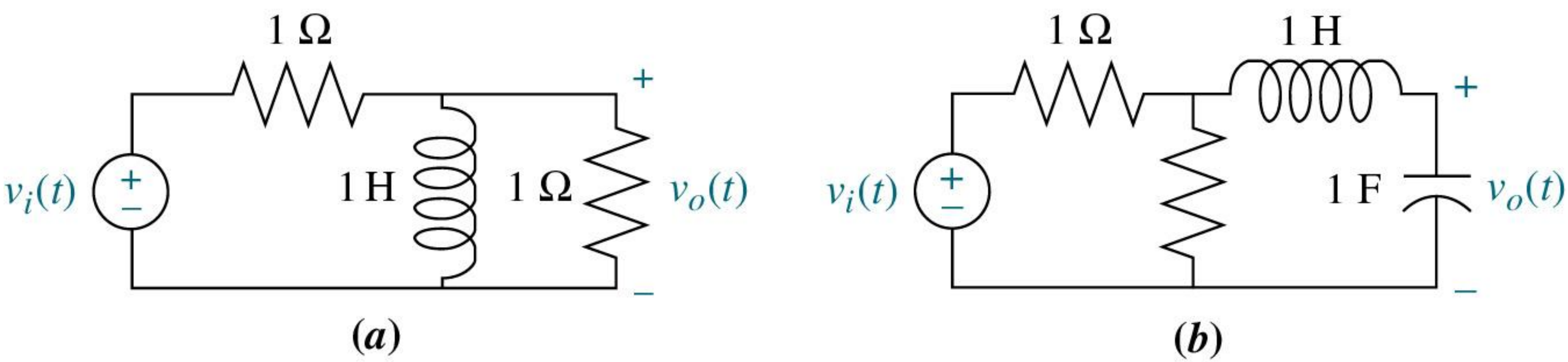
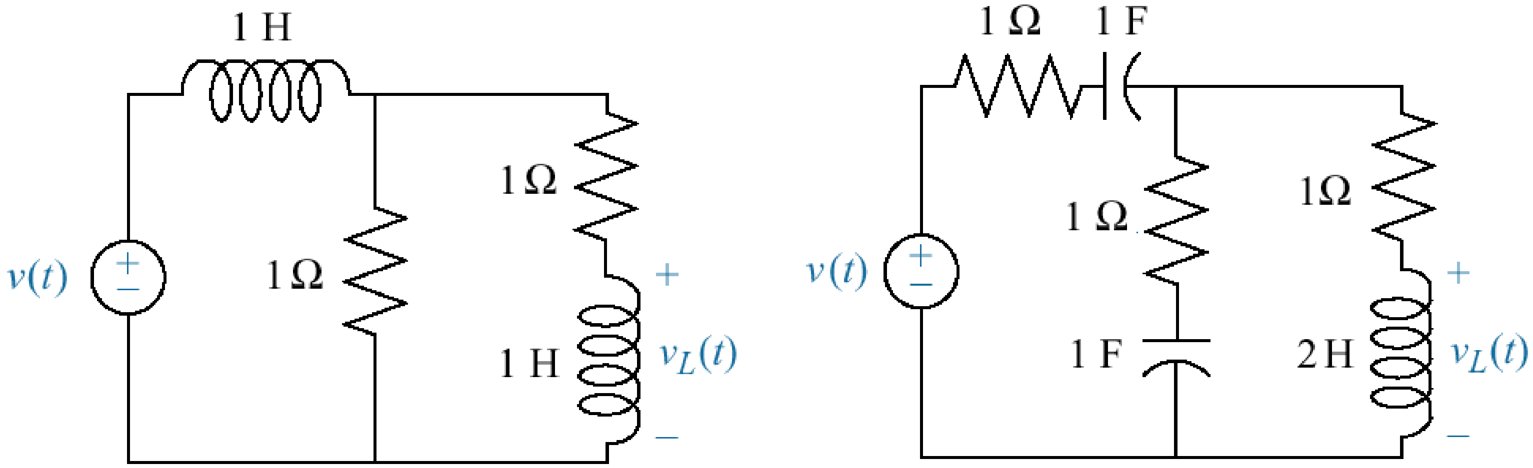


Figure P2-3 (p. 112)

Figure P2.4



(a) (b)

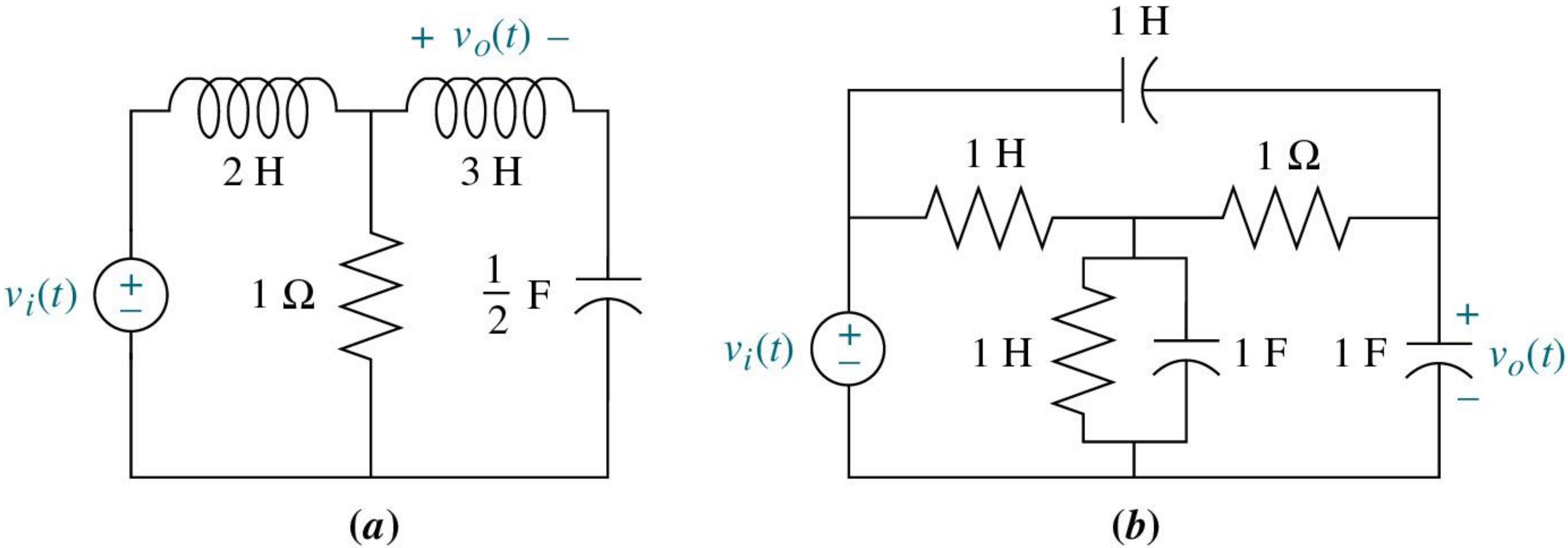


Figure P2-5 (p. 112)

Figure P2.6

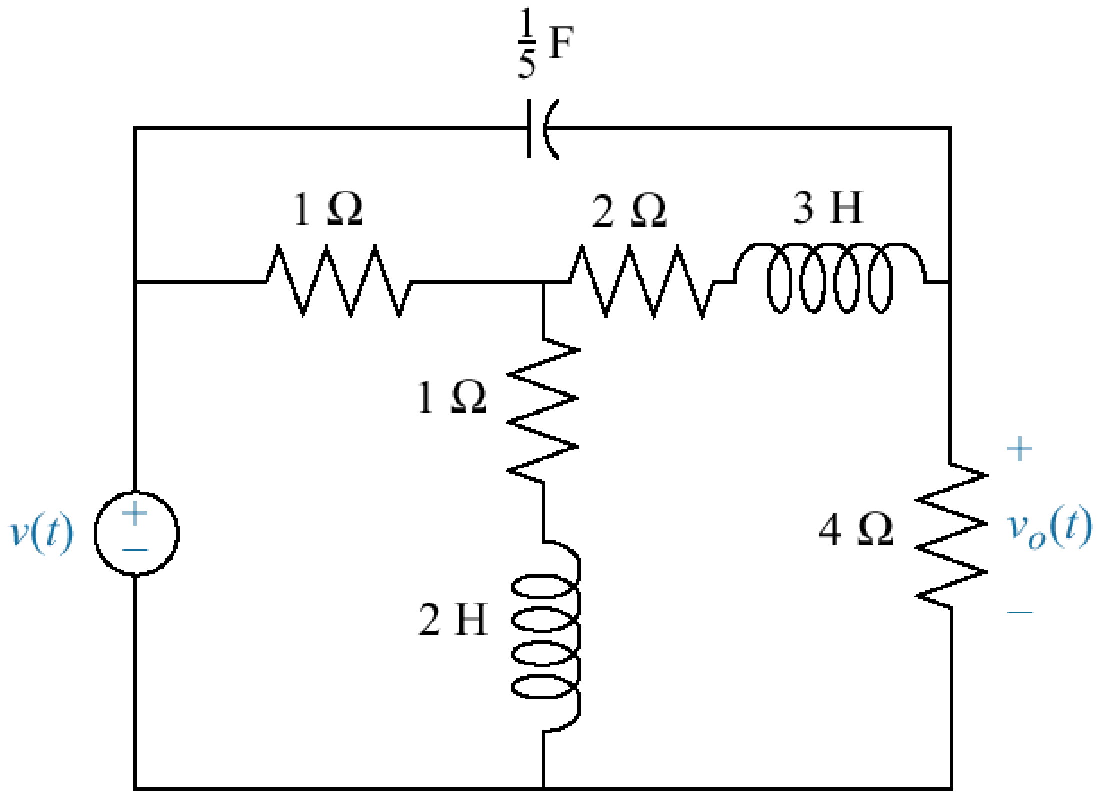
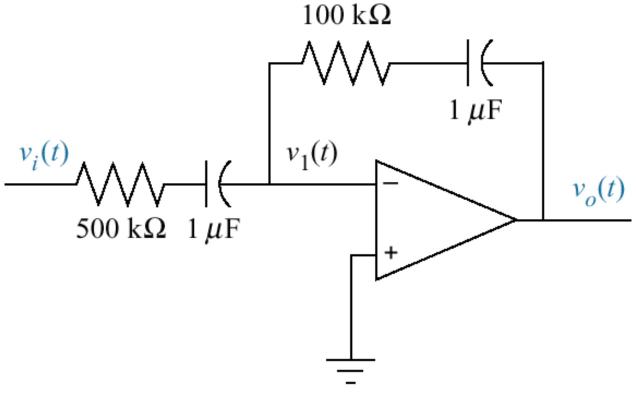
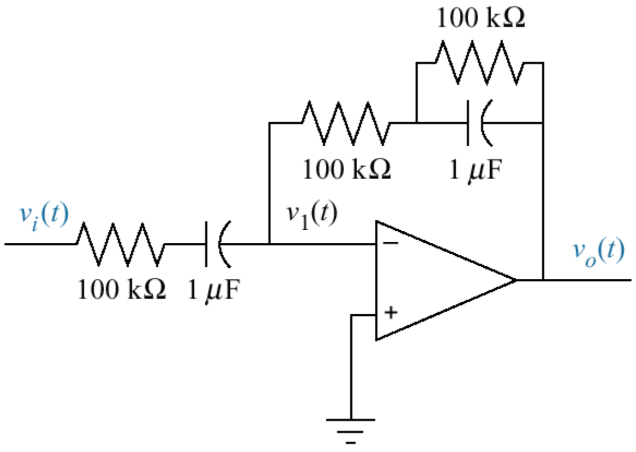


Figure P2.7

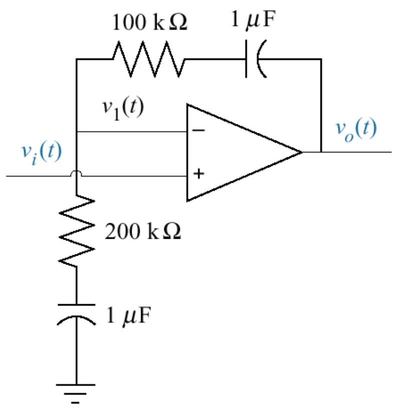


(*a*)

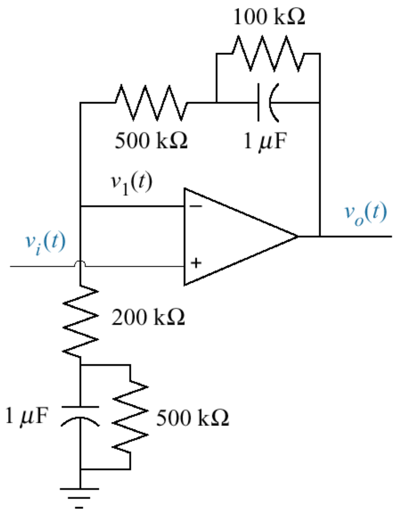


(*b*)

Figure P2.8



(a)



(b)

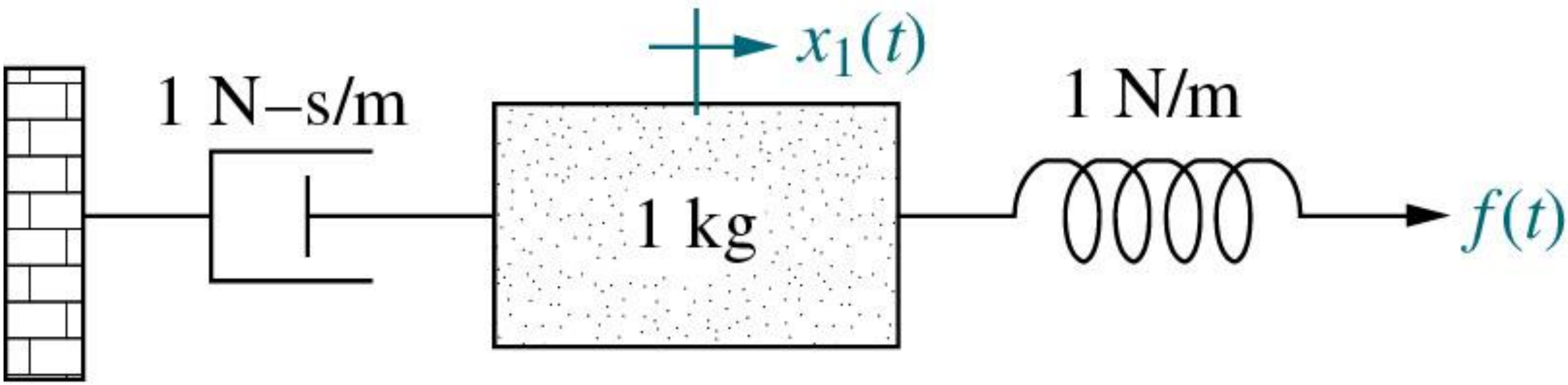


Figure P2-9 (p. 114)

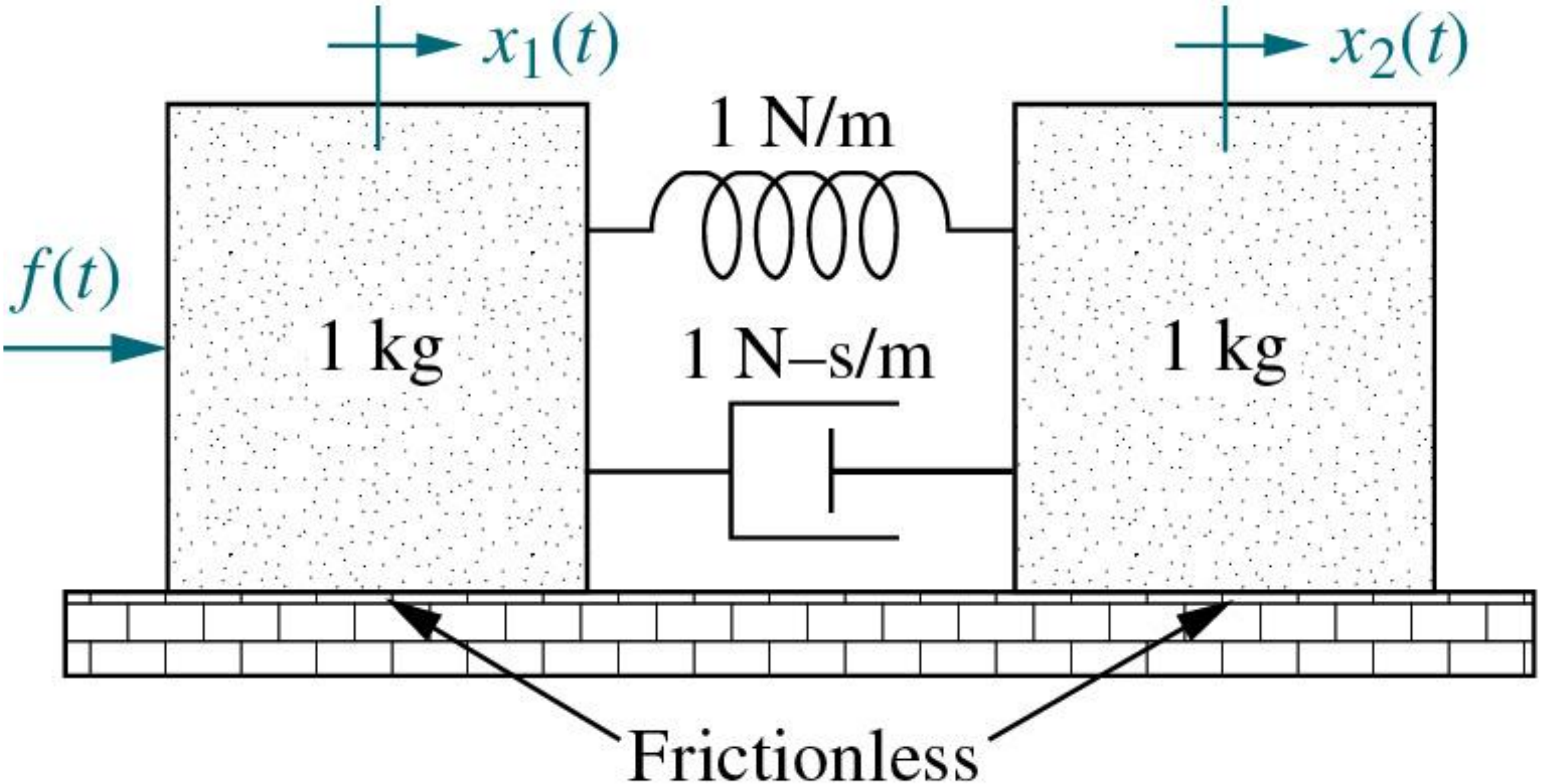


Figure P2-10 (p. 115)

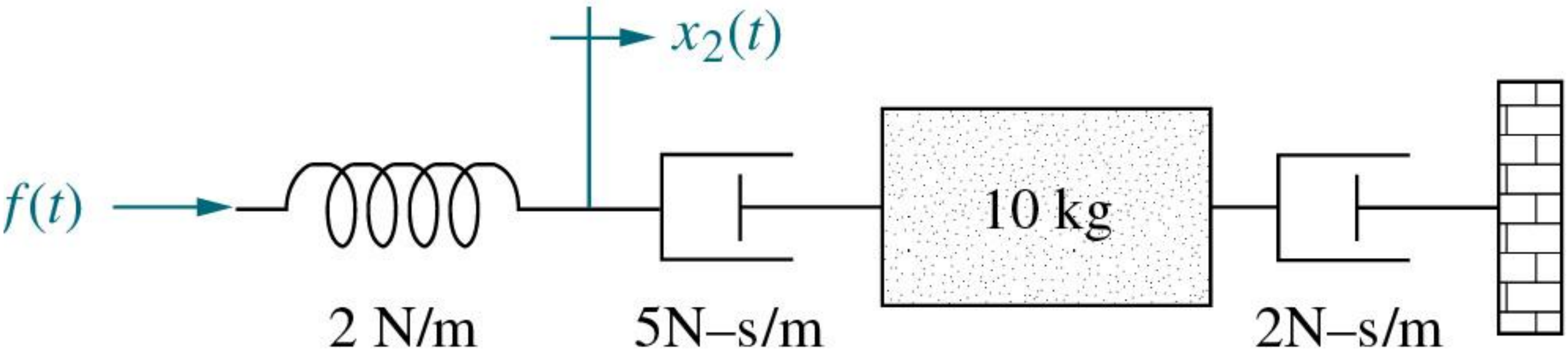


Figure P2-11 (p. 115)

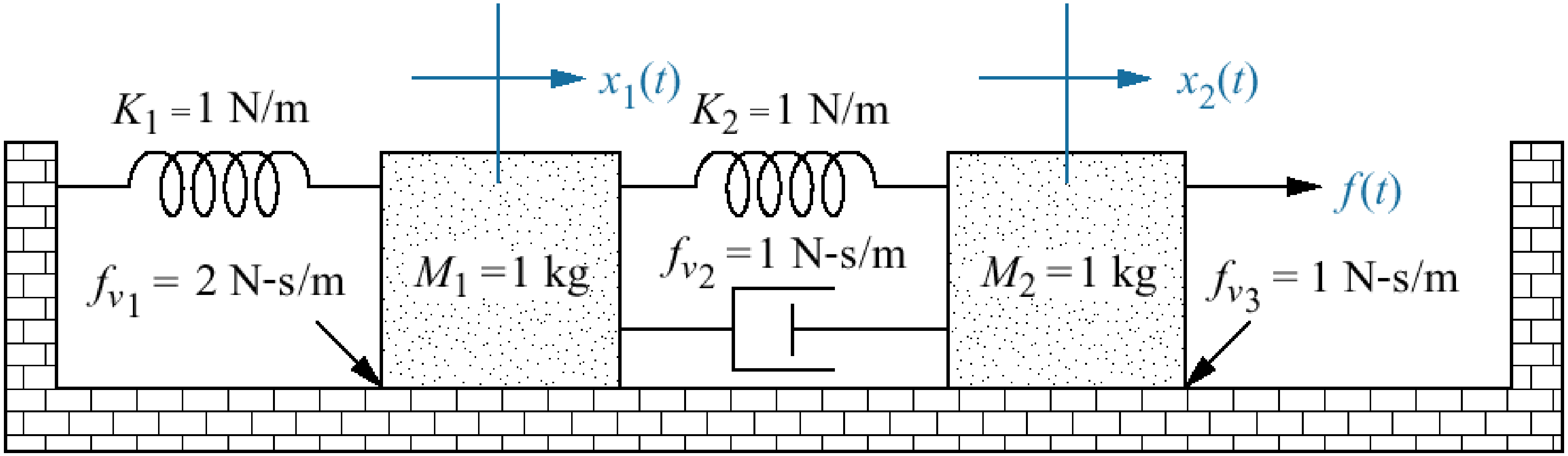


Figure P2.12

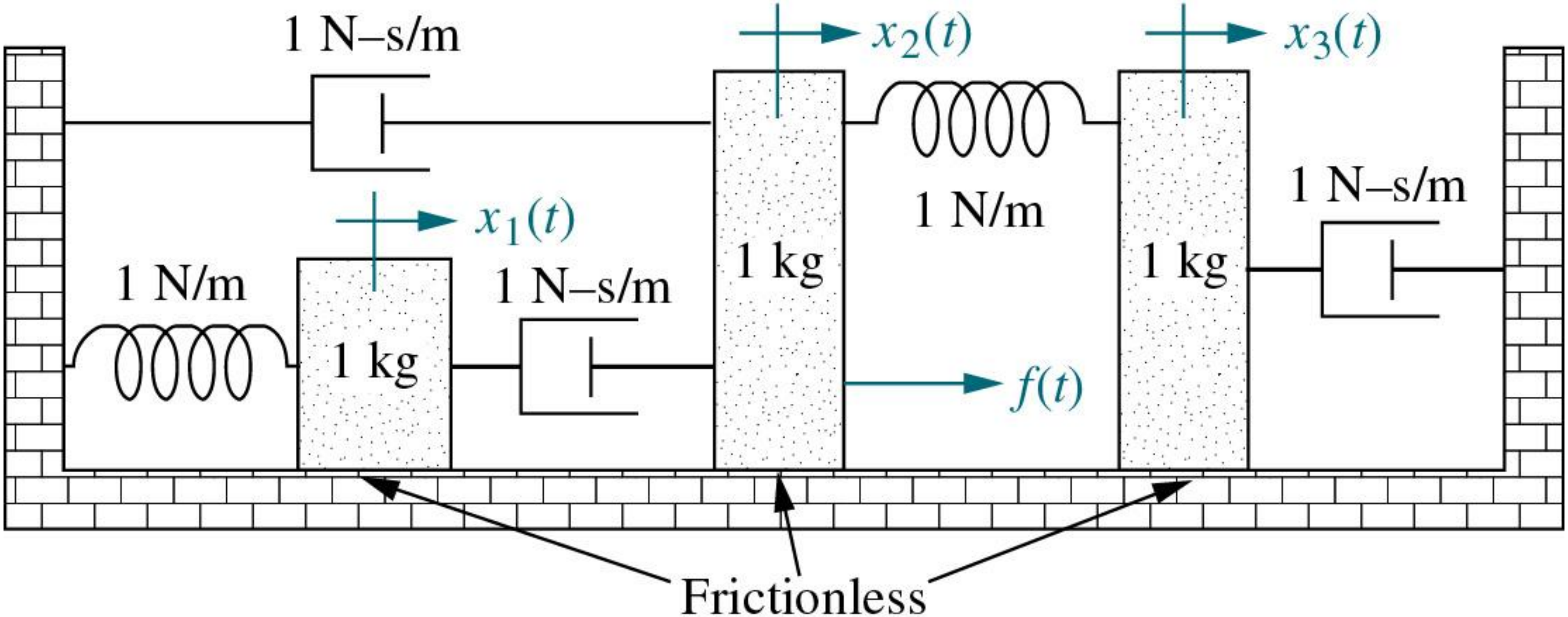
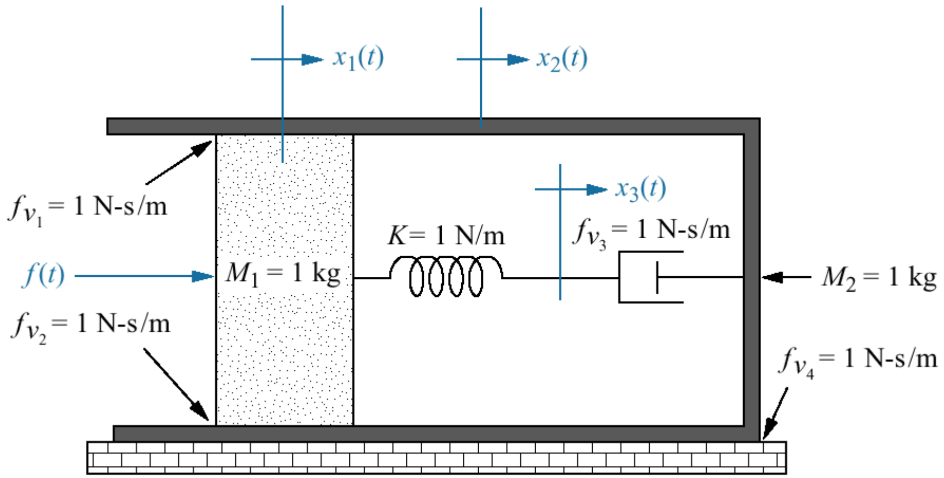
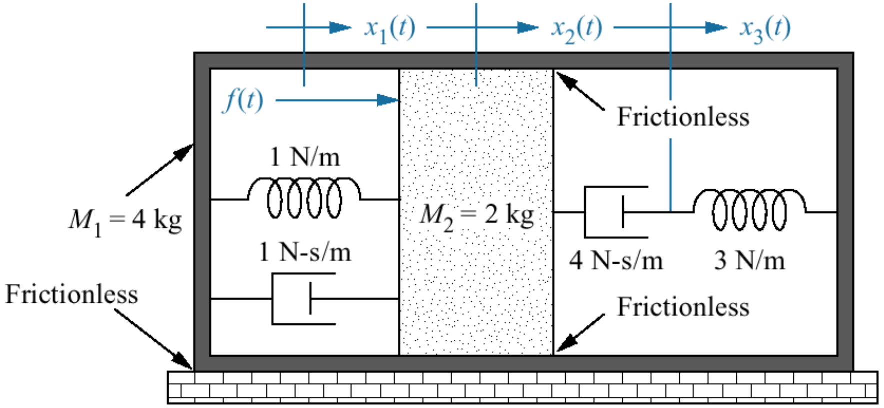


Figure P2-13 (p. 115)

Figure P2.14



(*a*)



(*b*)

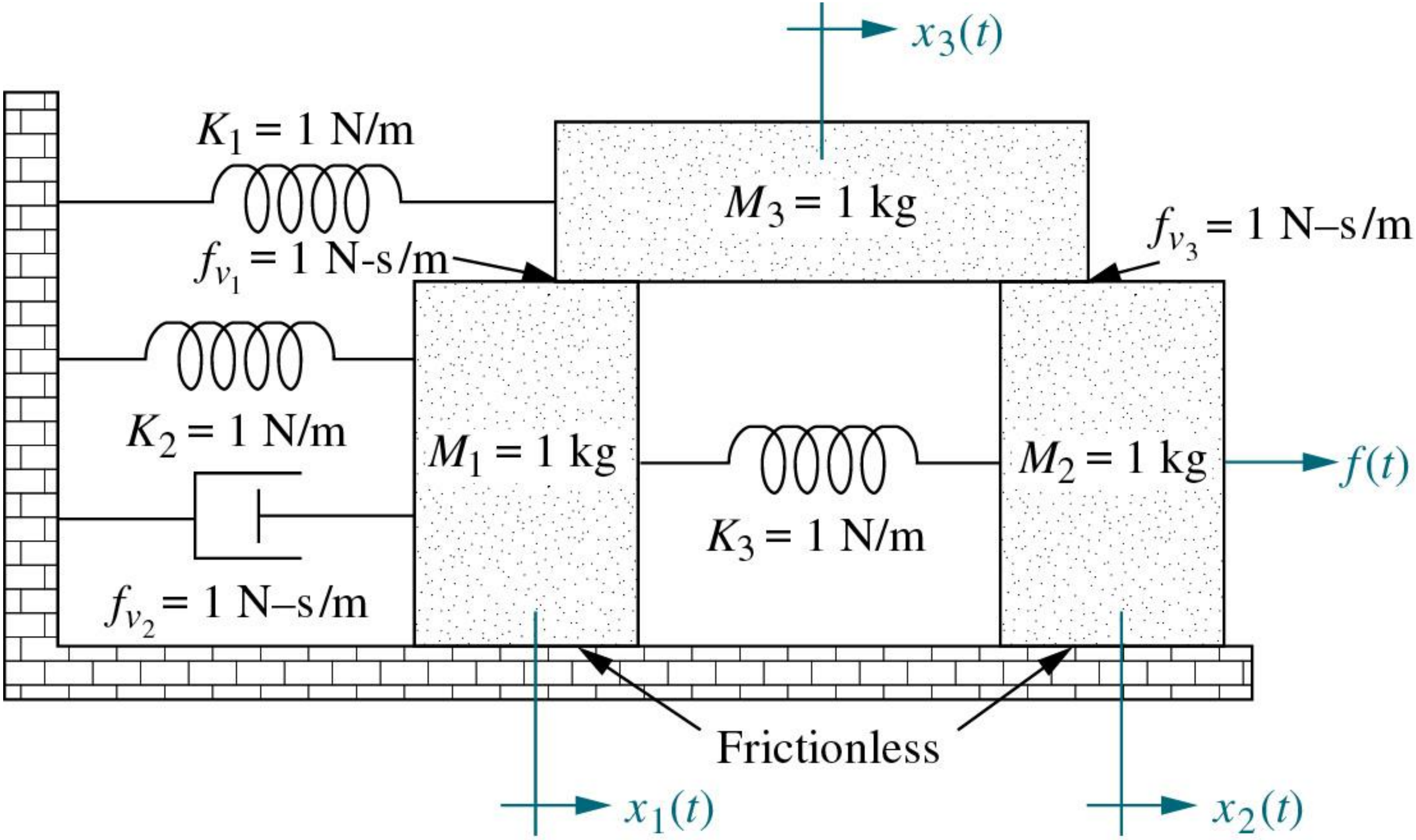


Figure P2-15 (p. 116)

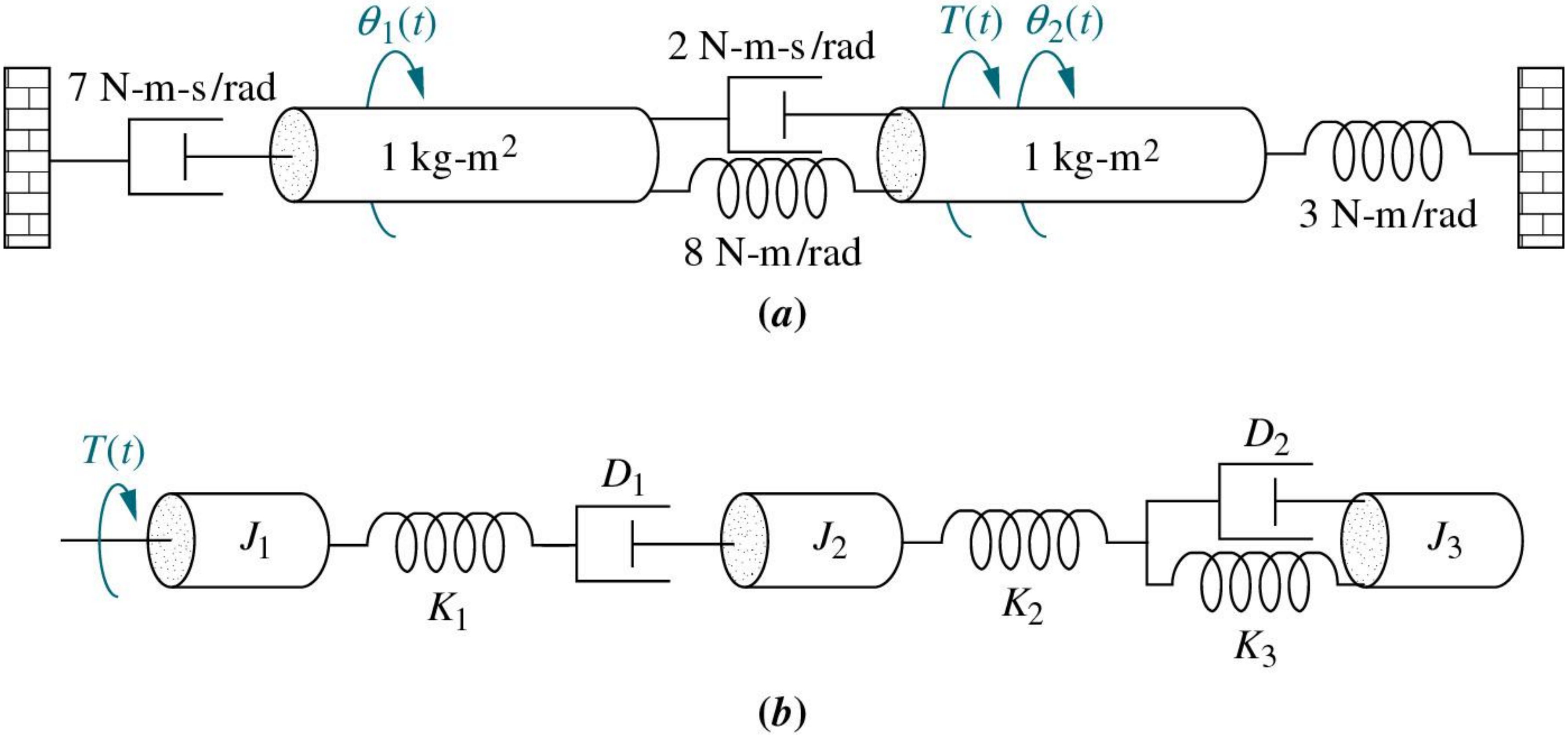
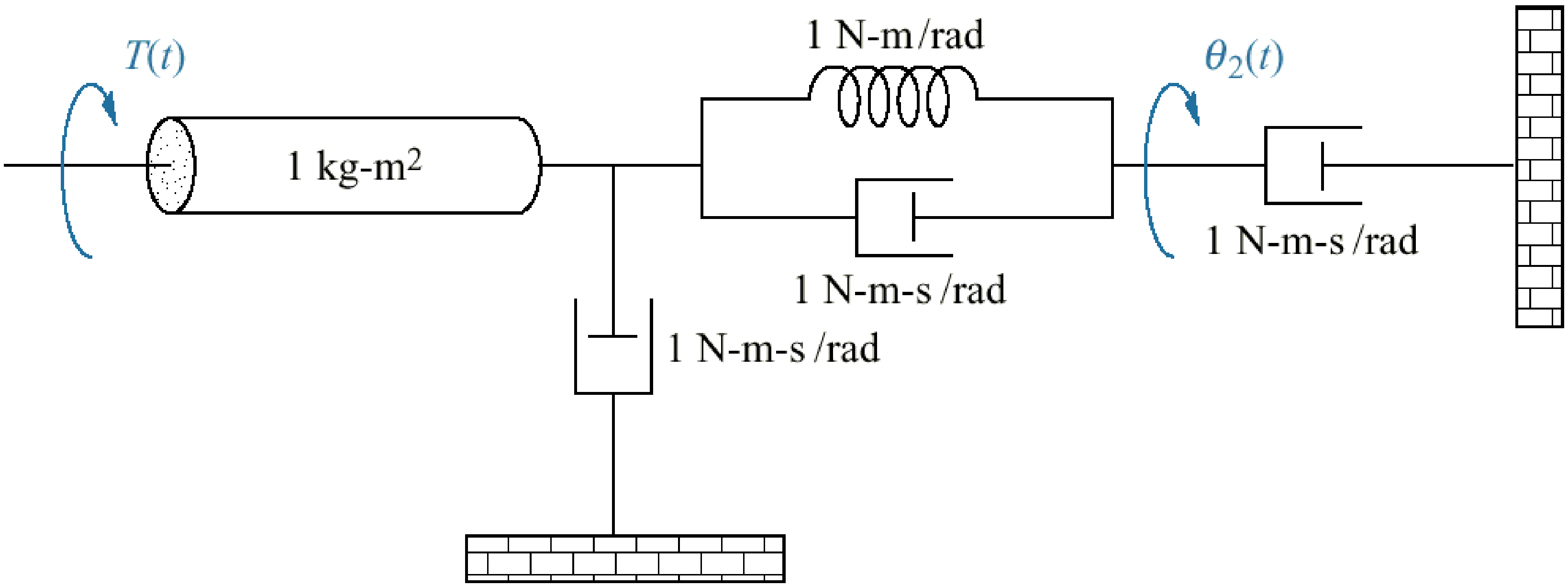


Figure P2-16 (p. 117)

Figure P2.17



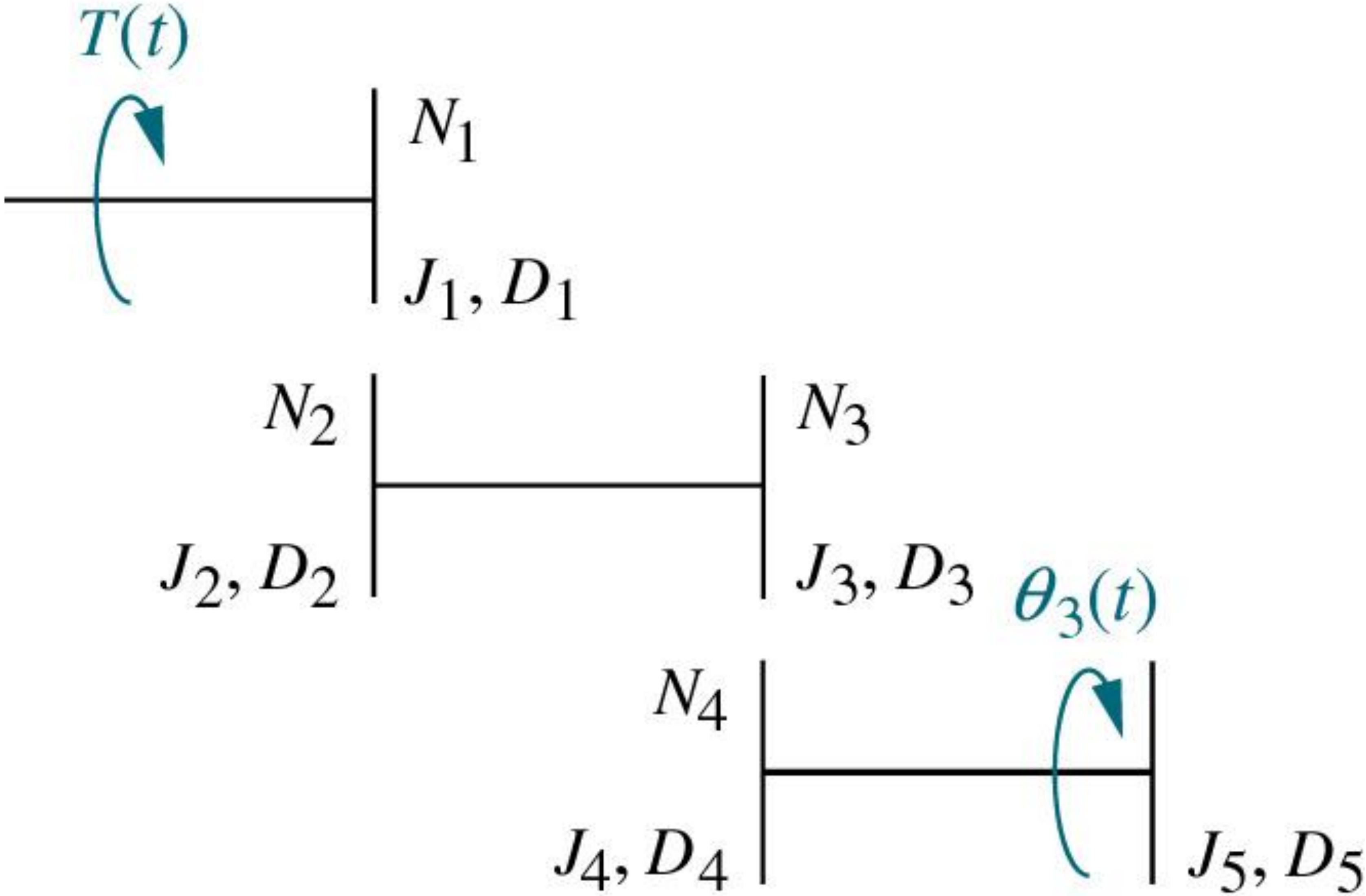
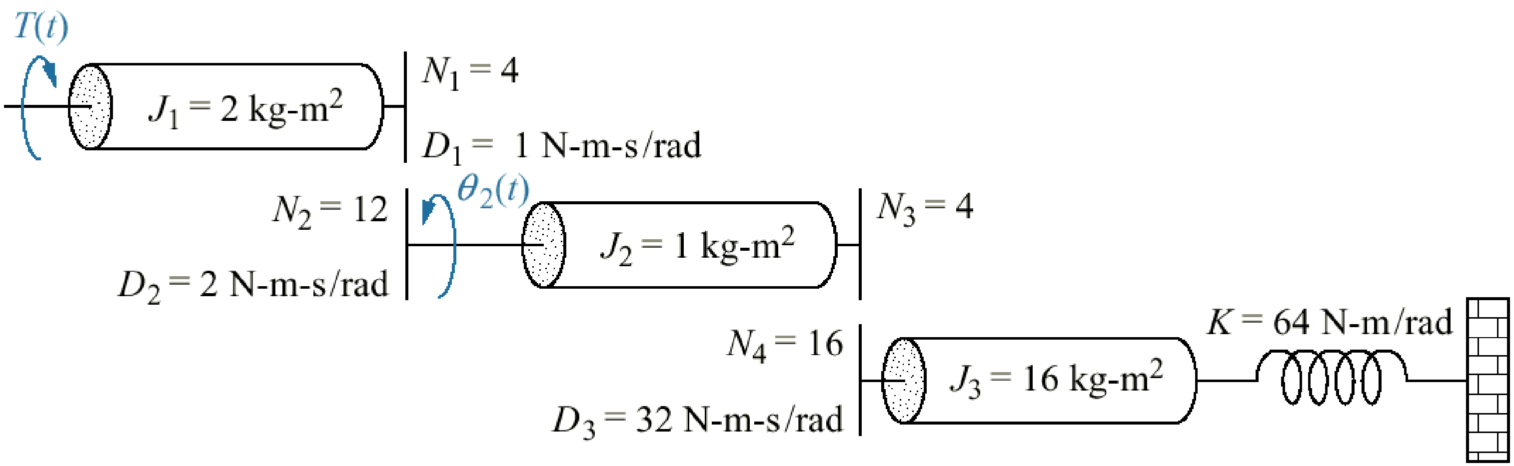


Figure P2-18 (p. 117)

Figure P2.19



T(t)
J1 = 2 kg-m2
N1 = 4
D1 = 1 N-m-s/rad
N2 = 12
D2 = 2 N-m-s/rad
θ2(t)
J2 = 1 kg-m2
N3 = 4
N4 = 16
D3 = 32 N-m-s/rad
J3 = 16 kg-m2
K = 64 N-m/rad

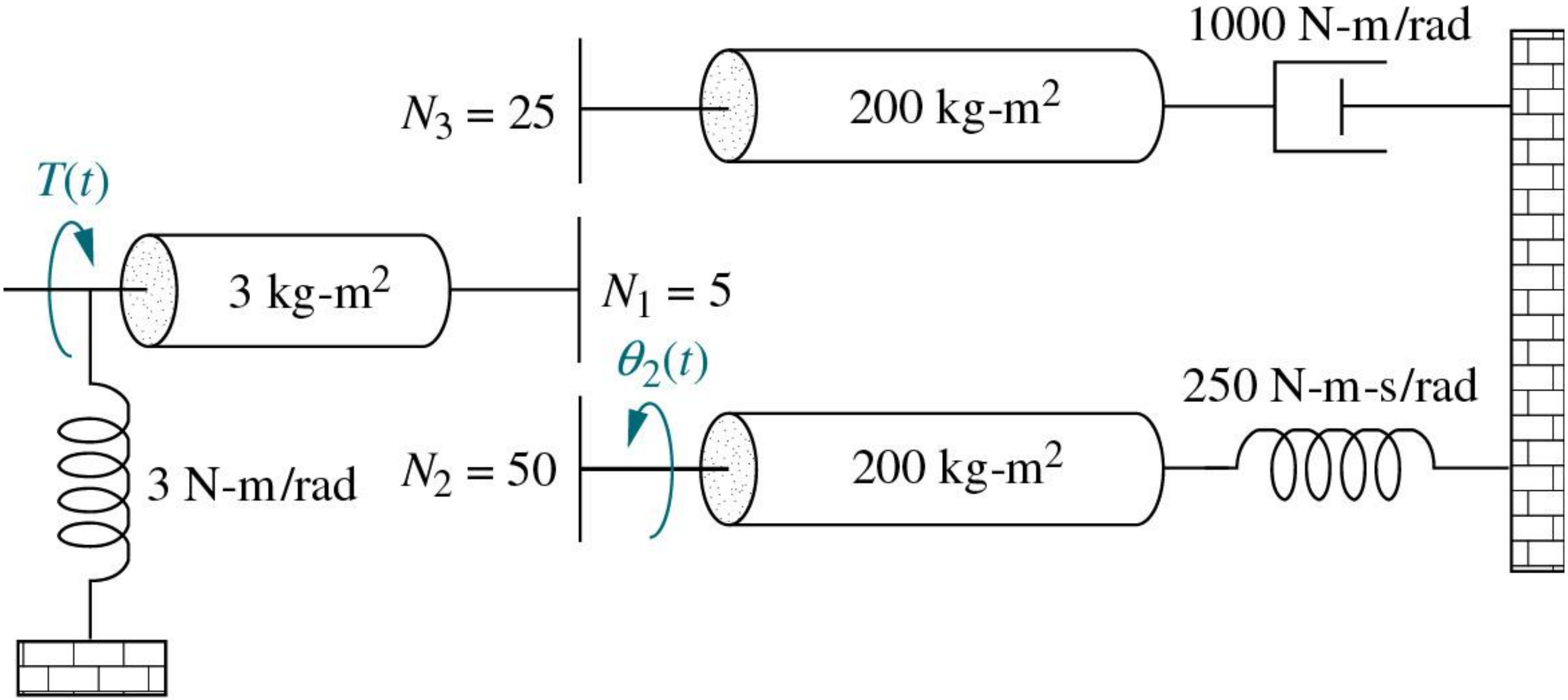
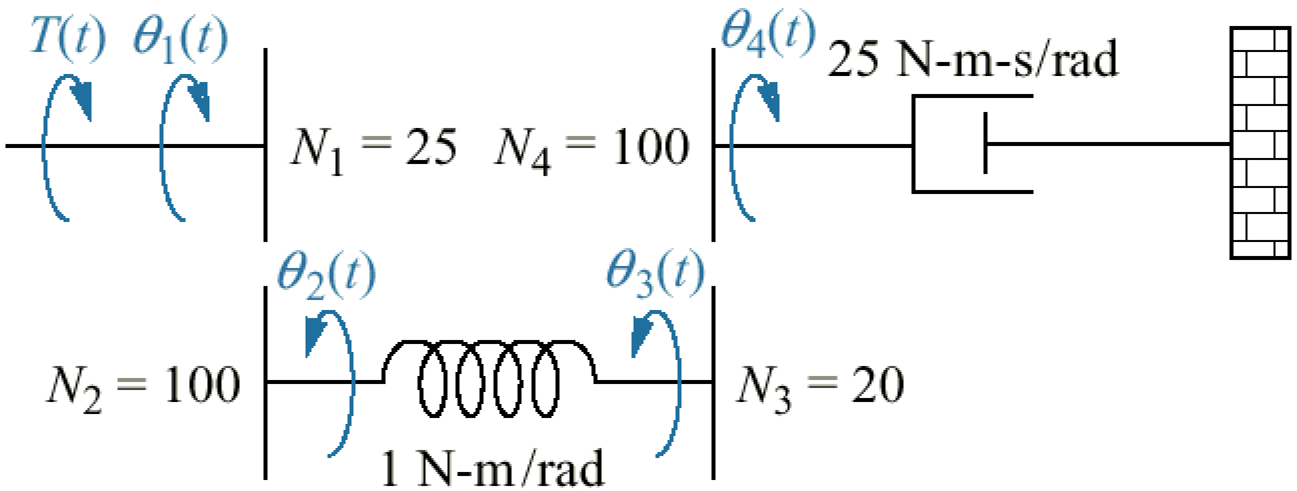


Figure P2-20 (p. 118)

Figure P2.21



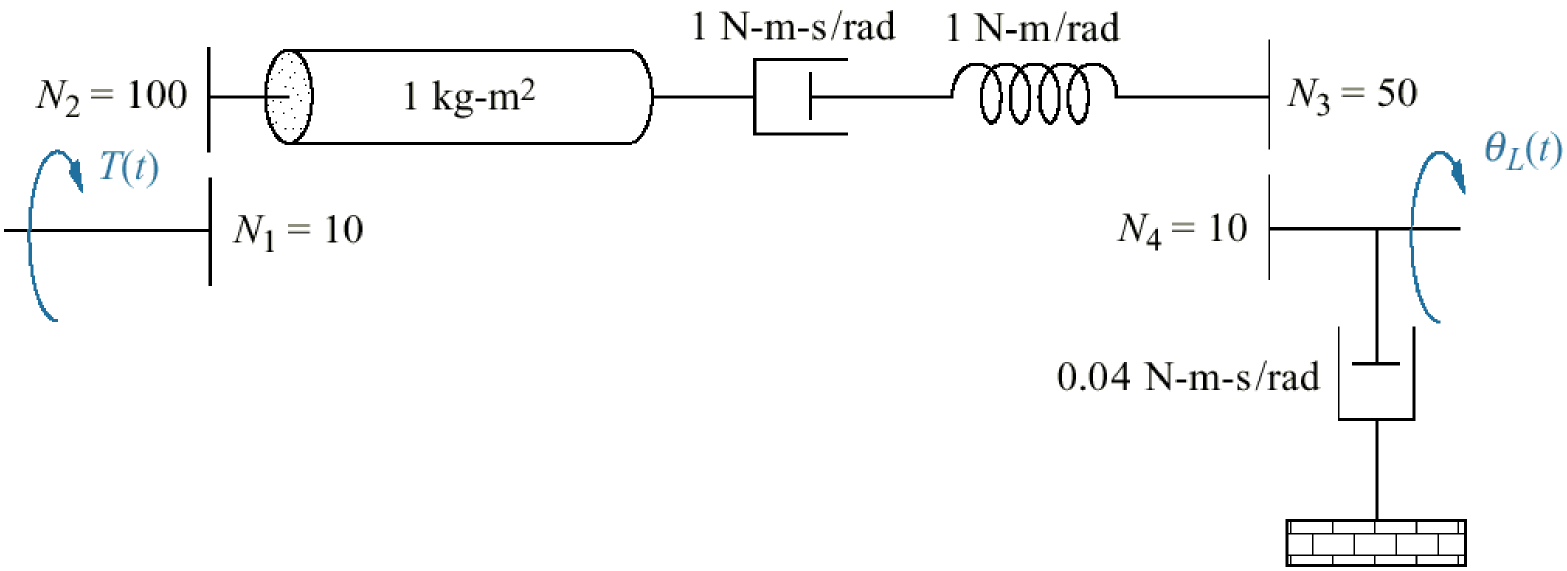


Figure P2.22

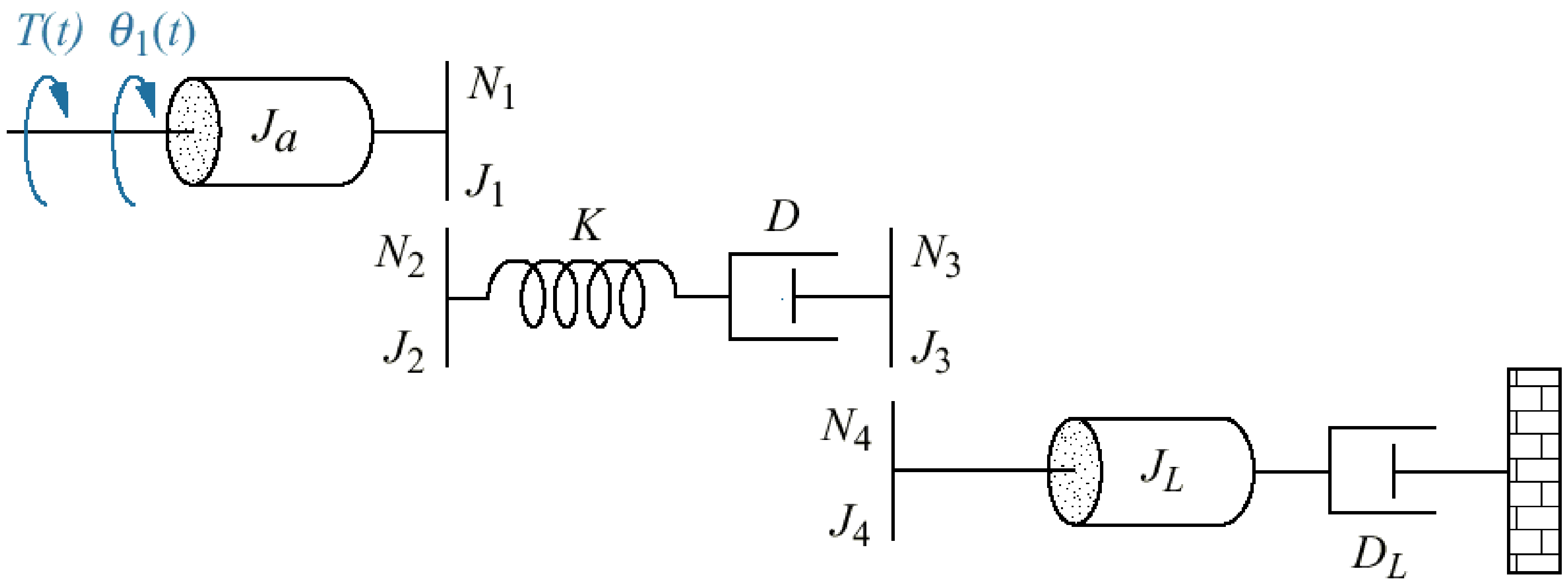


Figure P2.23

Figure P2.24

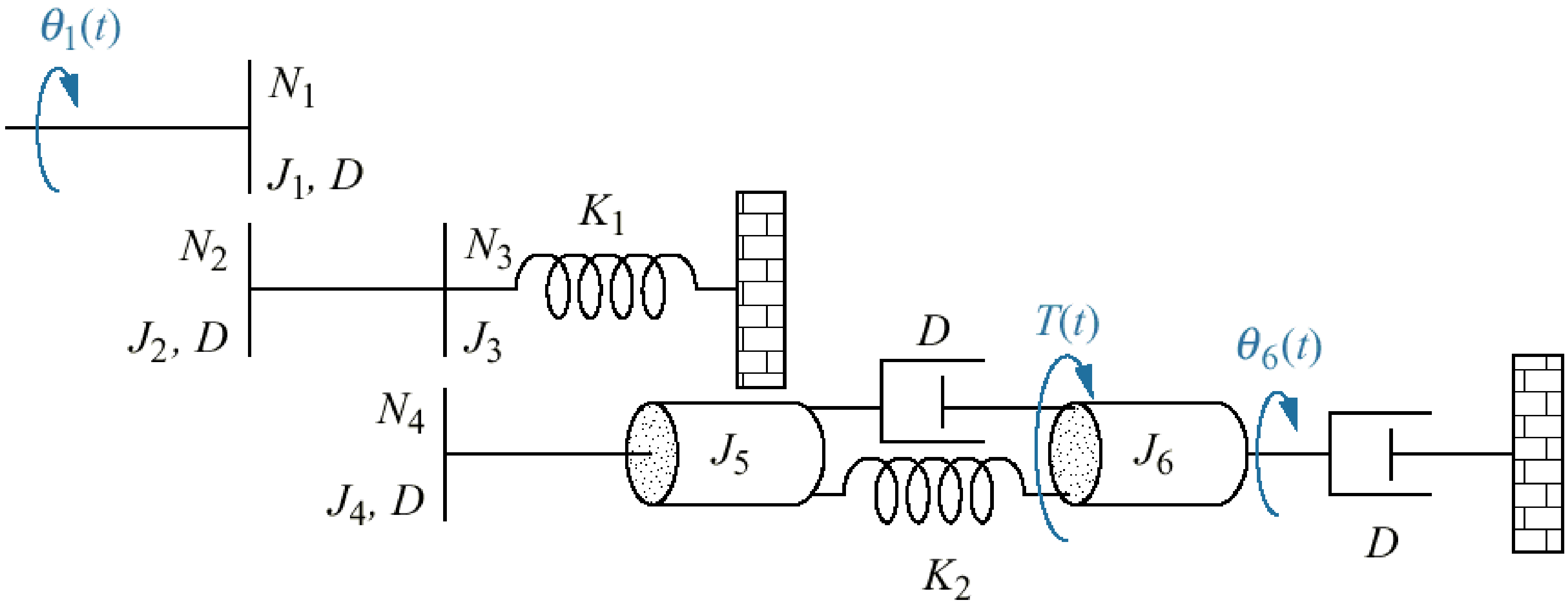
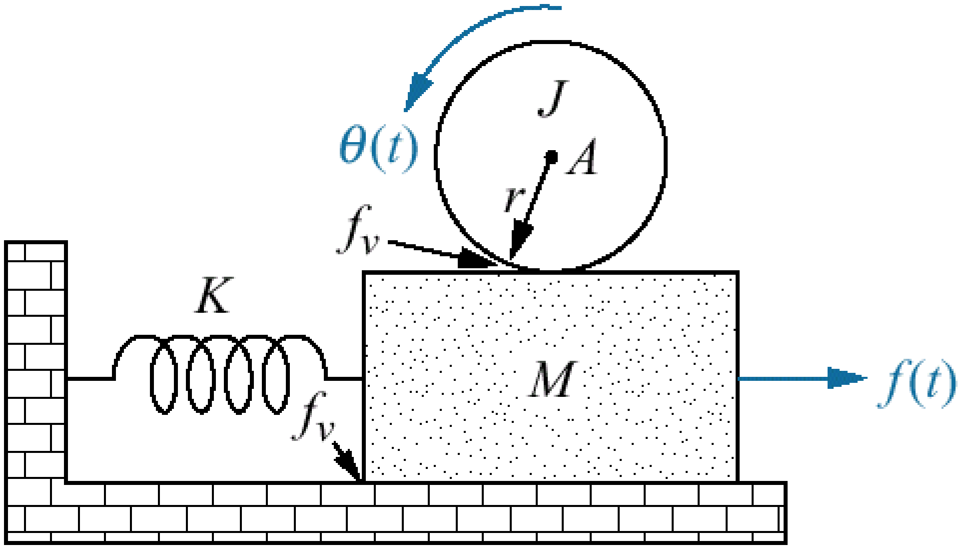
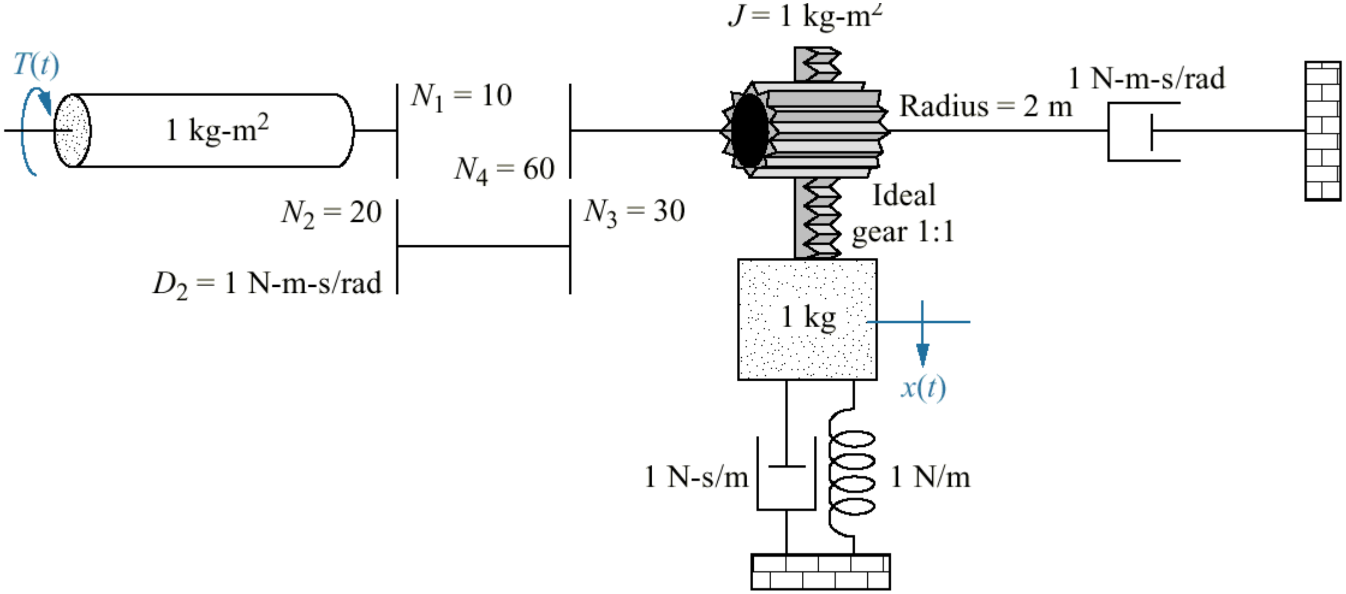


Figure P2.25





T(t)
1 kg-m2
N1 = 10
N4 = 60
N2 = 20
N3 = 30
D2 = 1 N-m-s/rad
J = 1 kg-m2
Radius = 2 m
1 N-m-s/rad
Ideal
gear 1:1
1 kg
x(t)
1 N-s/m
1 N/m

Figure P2.26

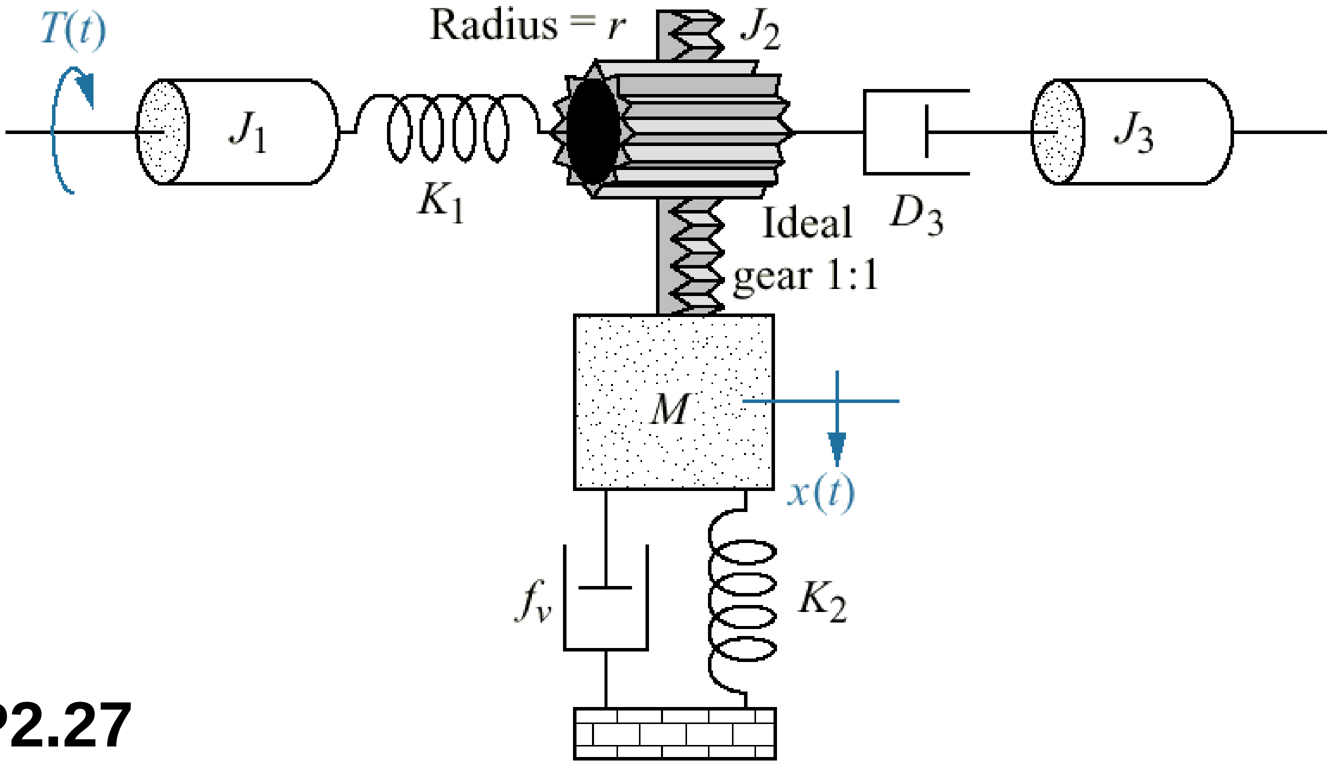
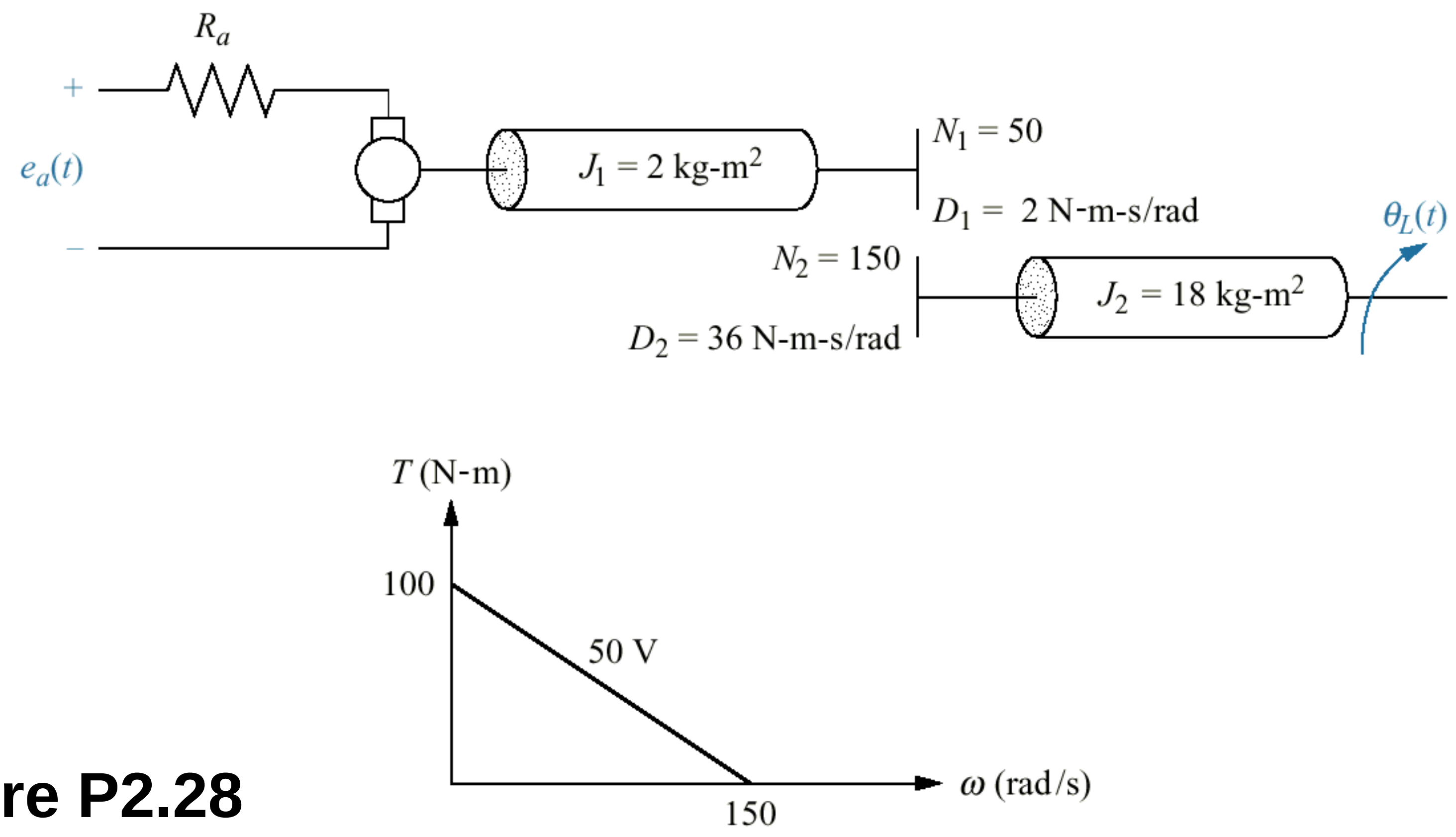
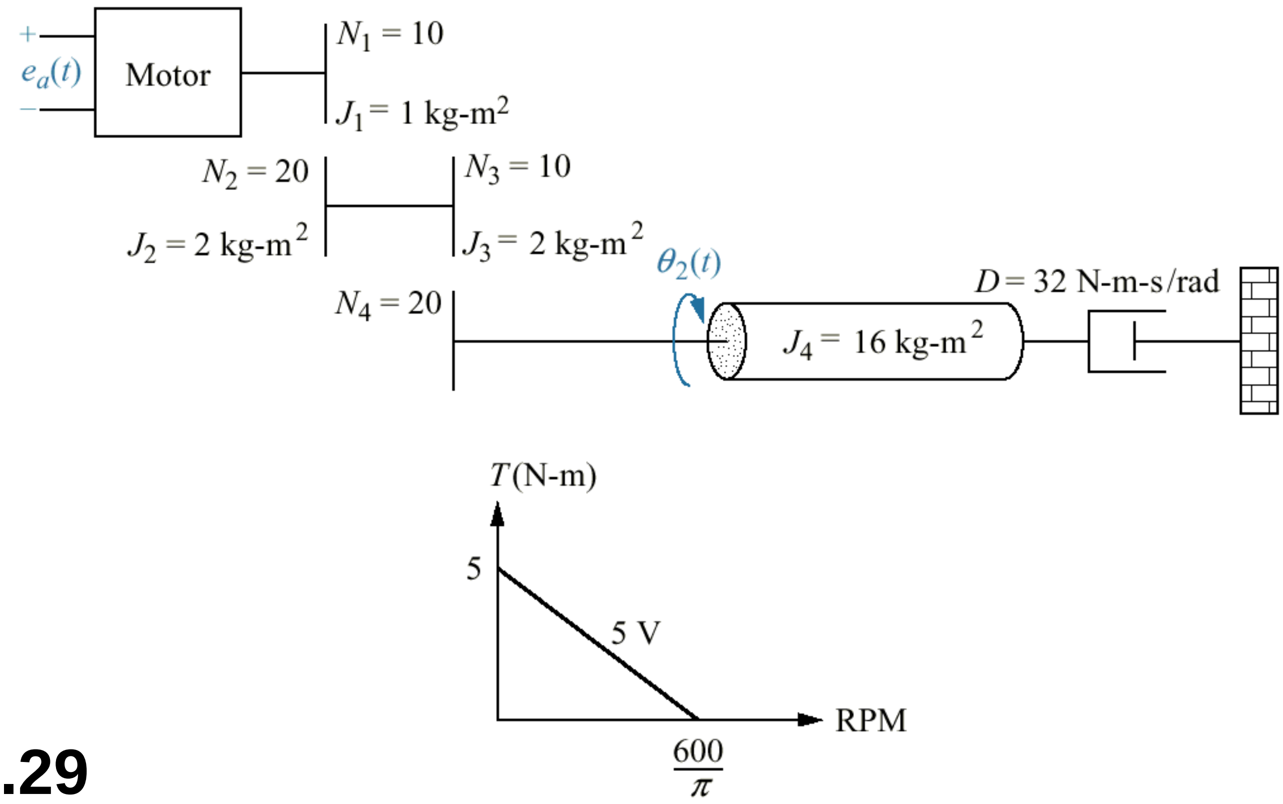


Figure P2.27



R_a
+
$e_a(t)$
−
$J_1 = 2$ kg-m^2
$N_1 = 50$
$D_1 = 2$ N-m-s/rad
$N_2 = 150$
$D_2 = 36$ N-m-s/rad
$J_2 = 18$ kg-m^2
$\theta_L(t)$
T (N-m)
100
50 V
150
ω (rad/s)

Figure P2.28



+
$e_a(t)$
−
Motor
$N_1 = 10$
$J_1 = 1$ kg-m^2
$N_2 = 20$
$J_2 = 2$ kg-m^2
$N_3 = 10$
$J_3 = 2$ kg-m^2
$\theta_2(t)$
$N_4 = 20$
$D = 32$ N-m-s/rad
$J_4 = 16$ kg-m^2
T(N-m)
5
5 V
RPM
$\frac{600}{\pi}$

Figure P2.29

Figure P2.30

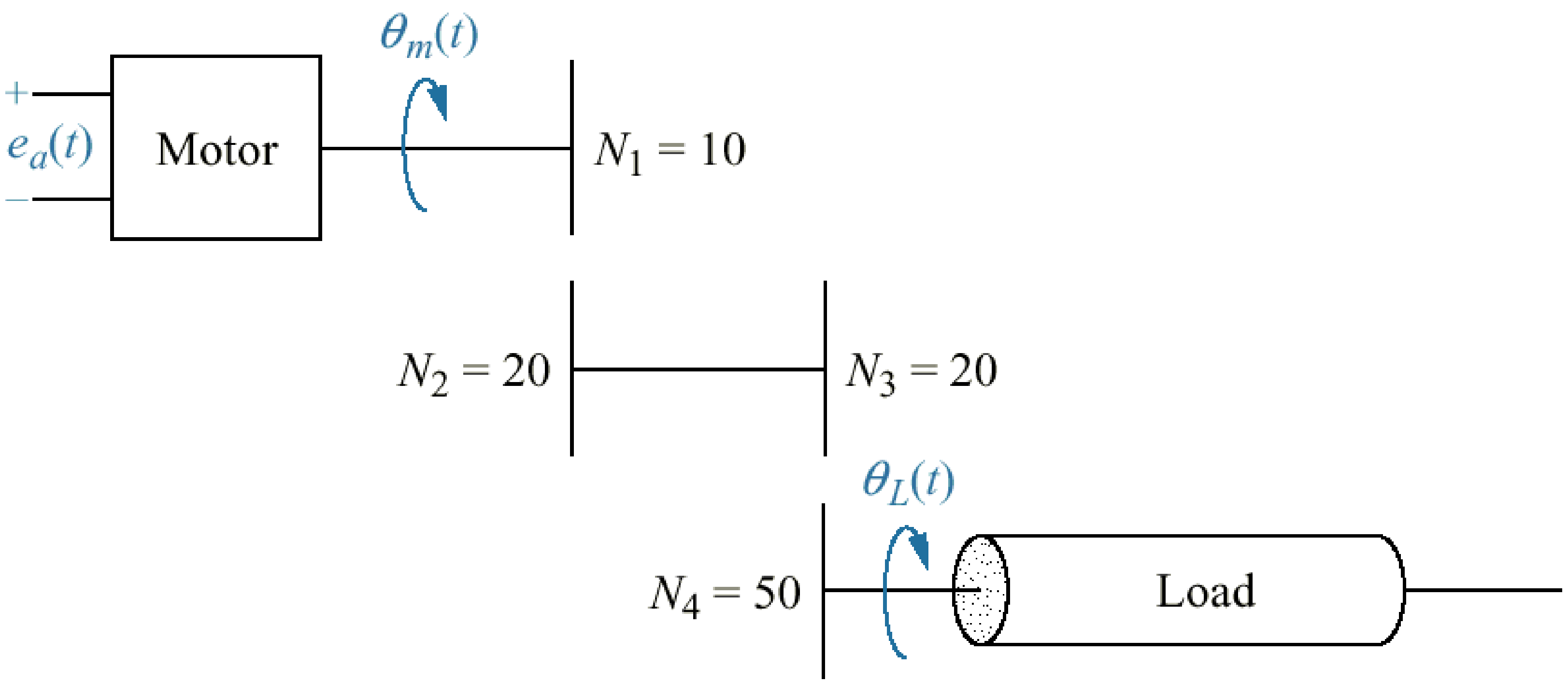
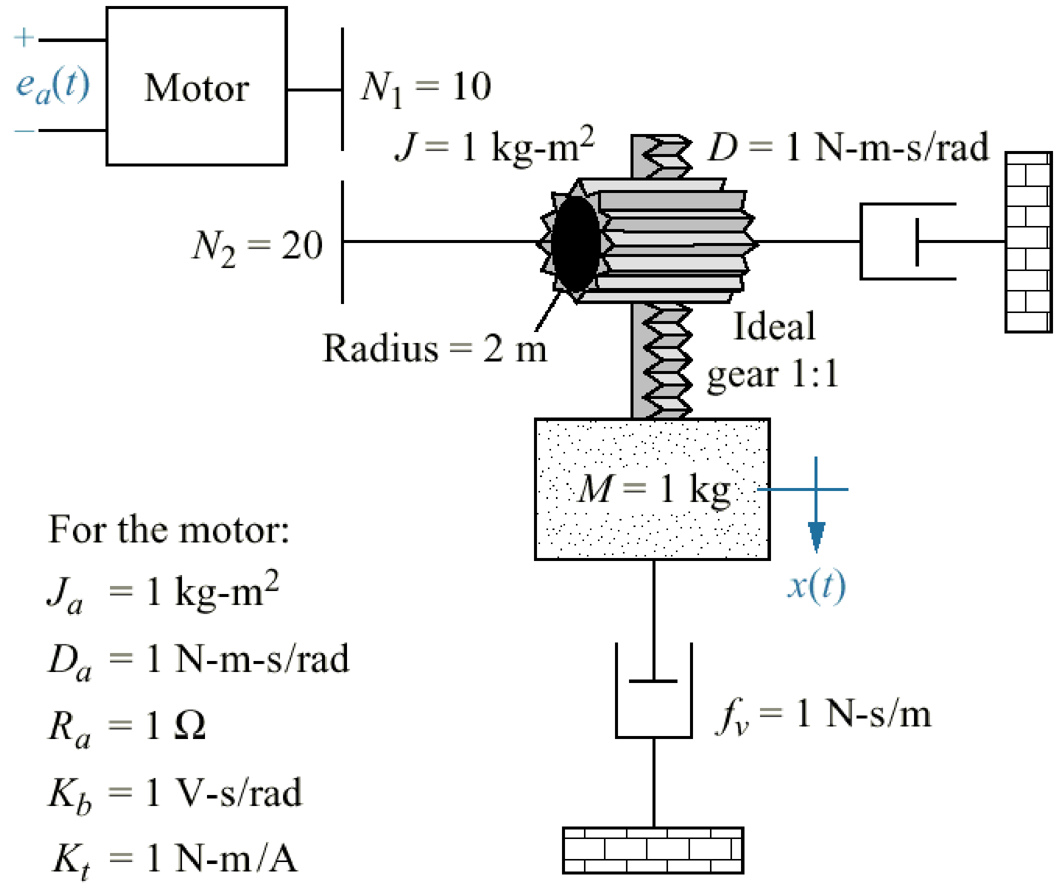


Figure P2.31


+
$e_a(t)$
−
Motor
$N_1 = 10$
$J = 1$ kg-m^2
$D = 1$ N-m-s/rad
$N_2 = 20$
Radius = 2 m
Ideal
gear 1:1
$M = 1$ kg
$x(t)$
$f_v = 1$ N-s/m
For the motor:
$J_a = 1$ kg-m^2
$D_a = 1$ N-m-s/rad
$R_a = 1\ \Omega$
$K_b = 1$ V-s/rad
$K_t = 1$ N-m/A

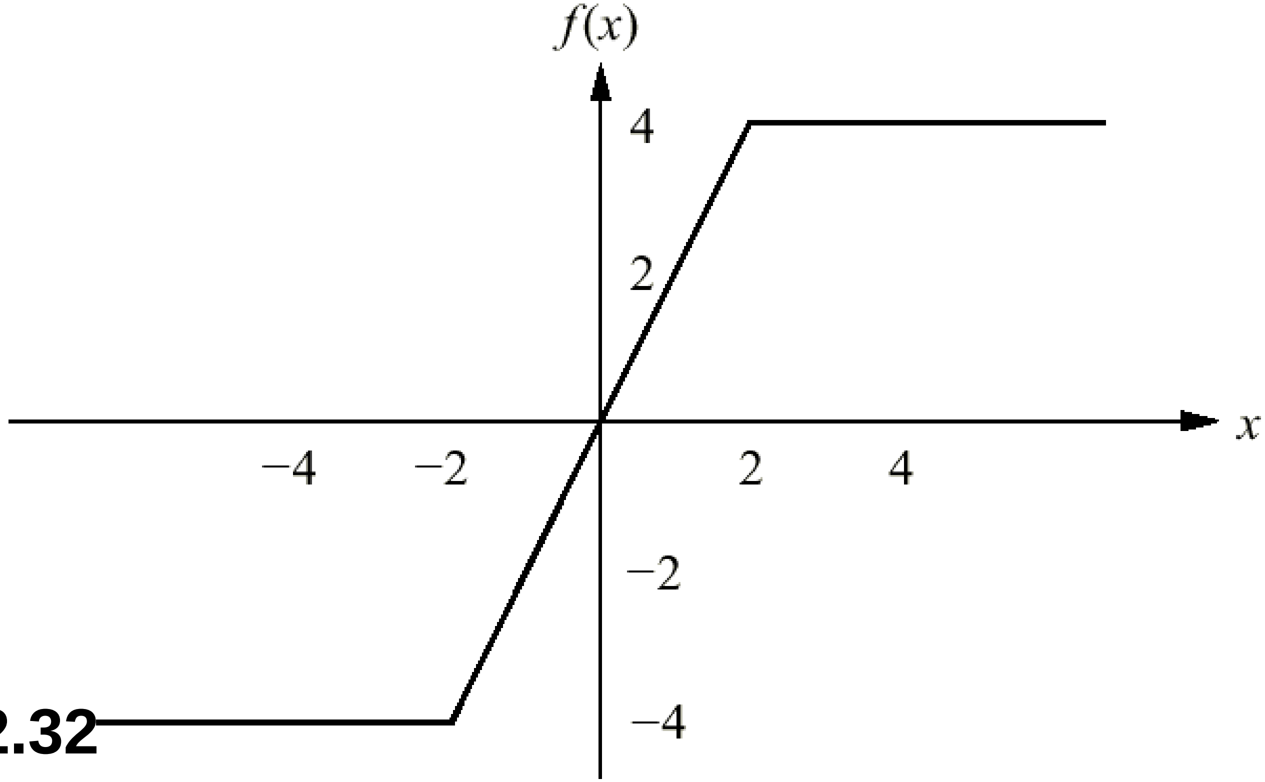


Figure P2.32

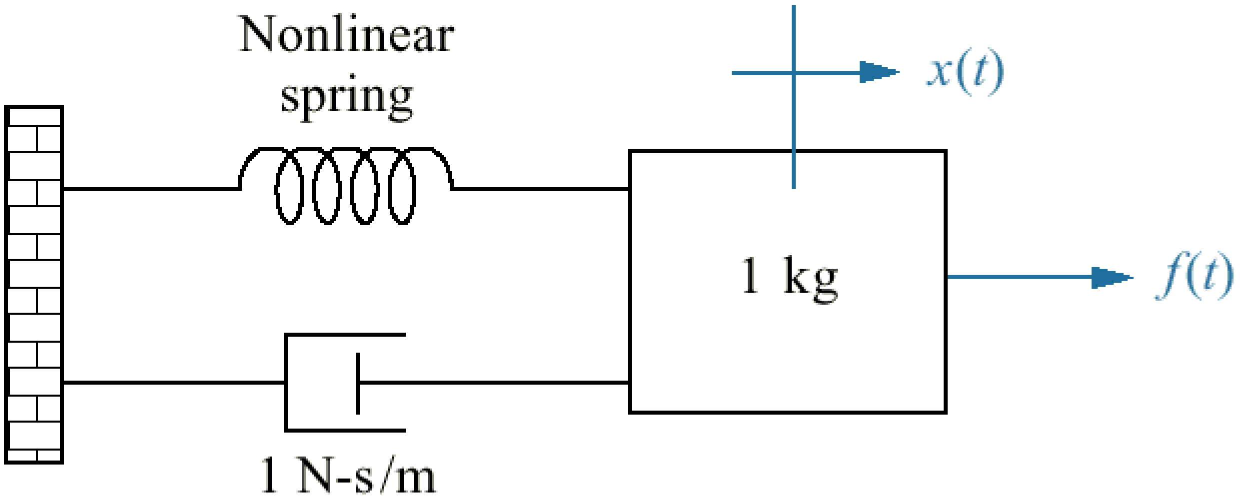


Figure P2.33

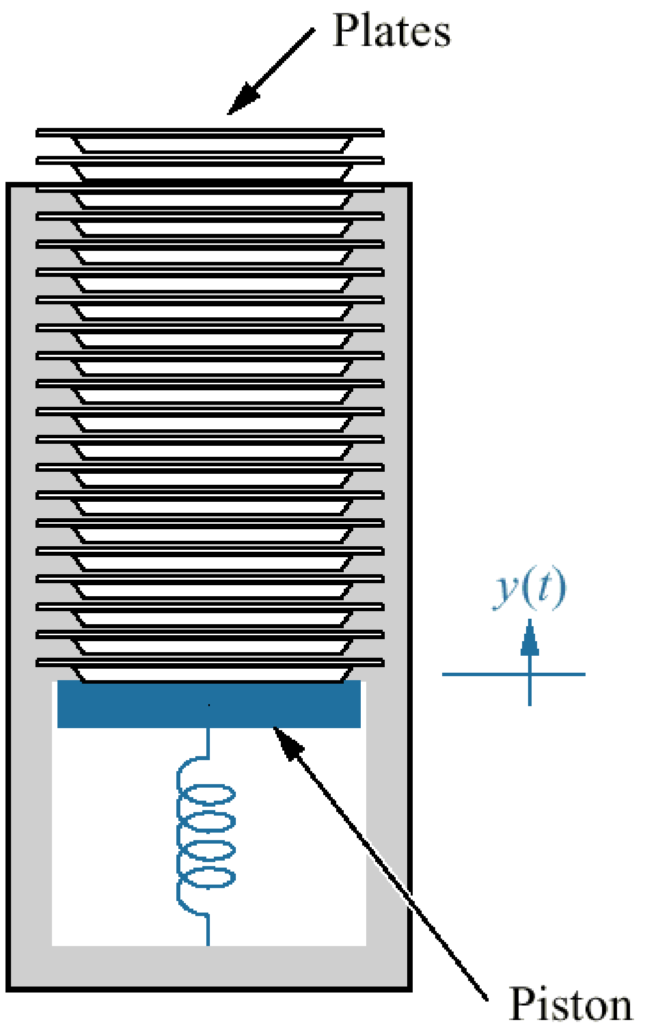


Figure P2.34
Plate dispenser

Figure P2.35
a. Coupling of pantograph and catenary;
b. simplified representation showing the active-control force