**Figure 5.1**
The space shuttle consists of multiple subsystems. Can you identify those that are control systems, or parts of control systems?

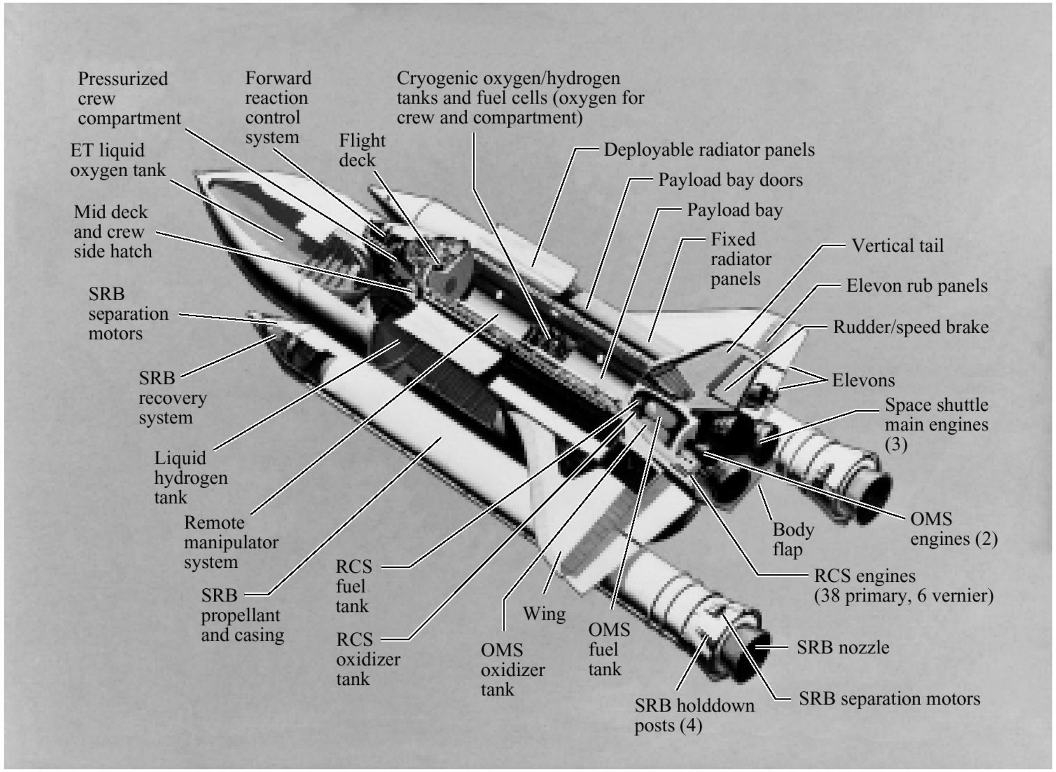


**Figure 5.2**
Components of a block diagram for a linear, time-invariant system

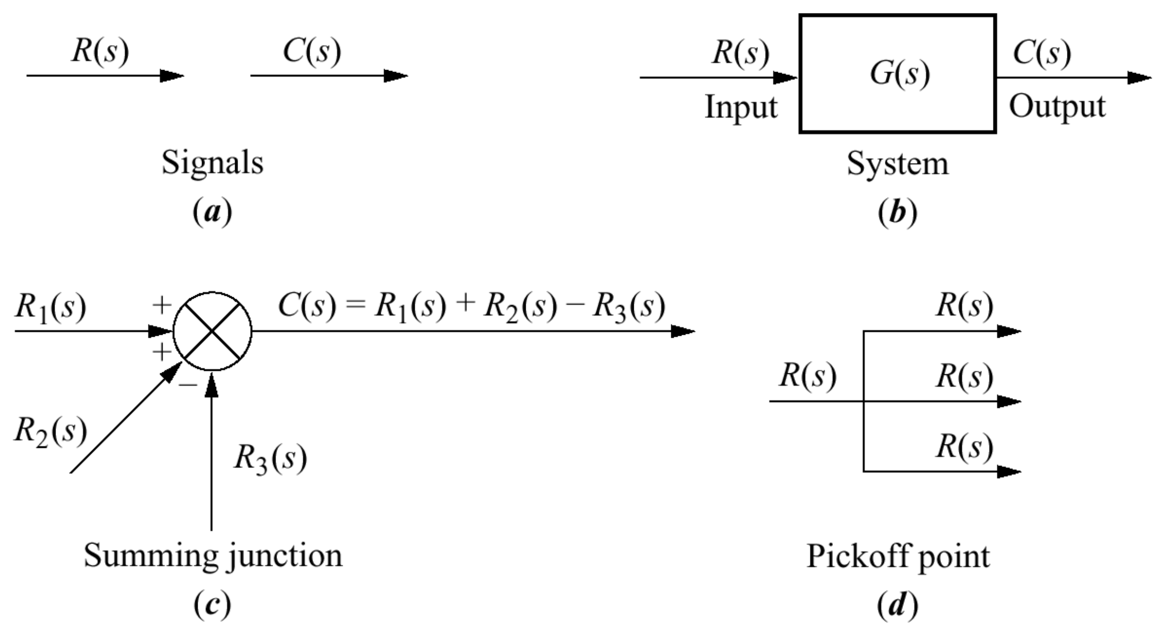


**Figure 5.3**
**a.** Cascaded subsystems;
**b.** equivalent transfer function

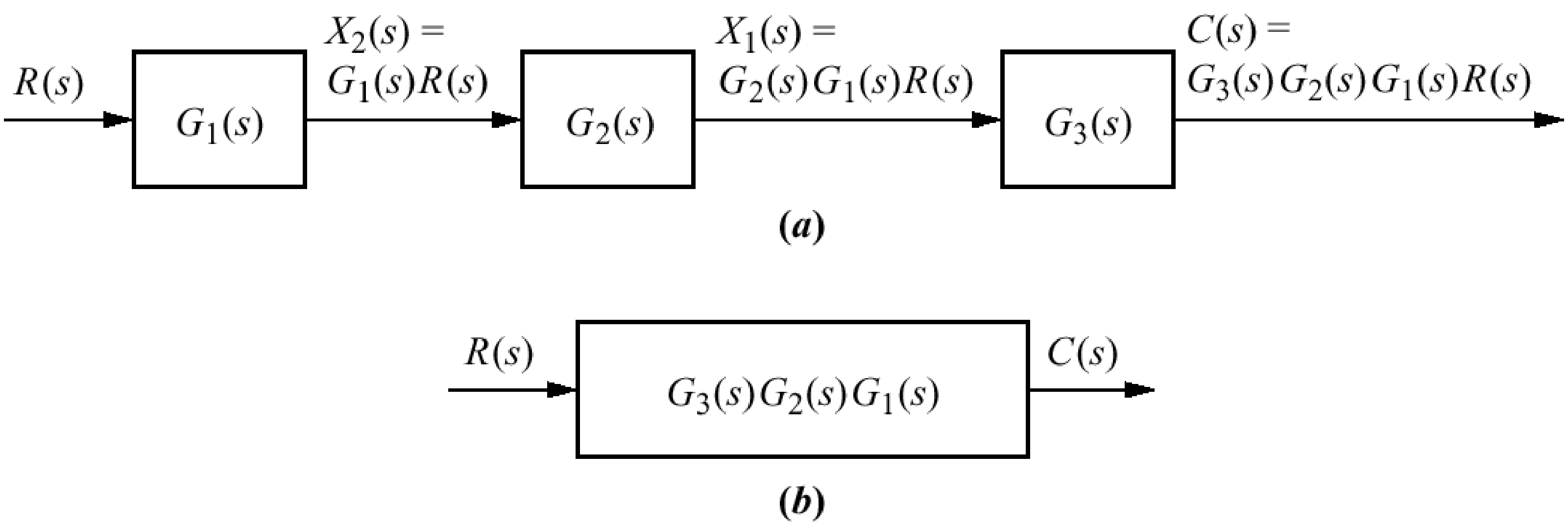


**Figure 5.4** Loading in cascaded systems

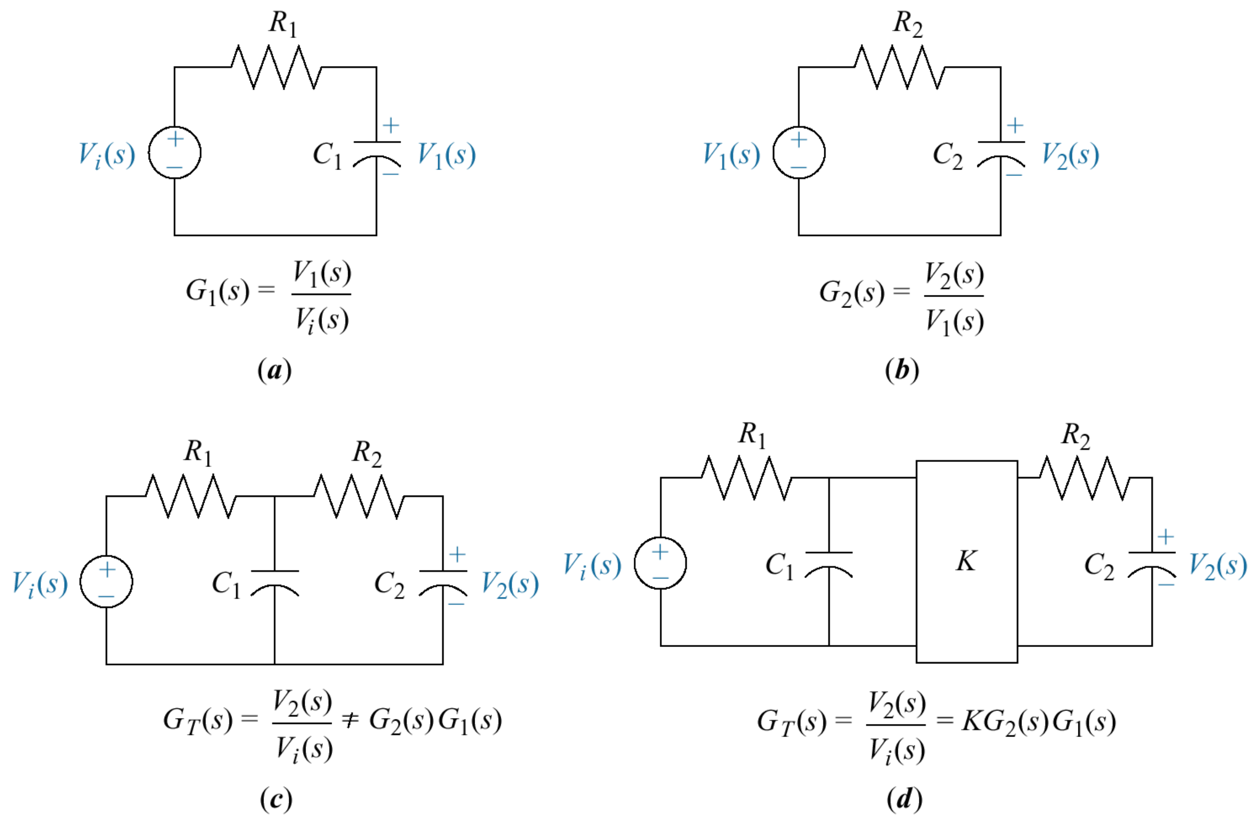
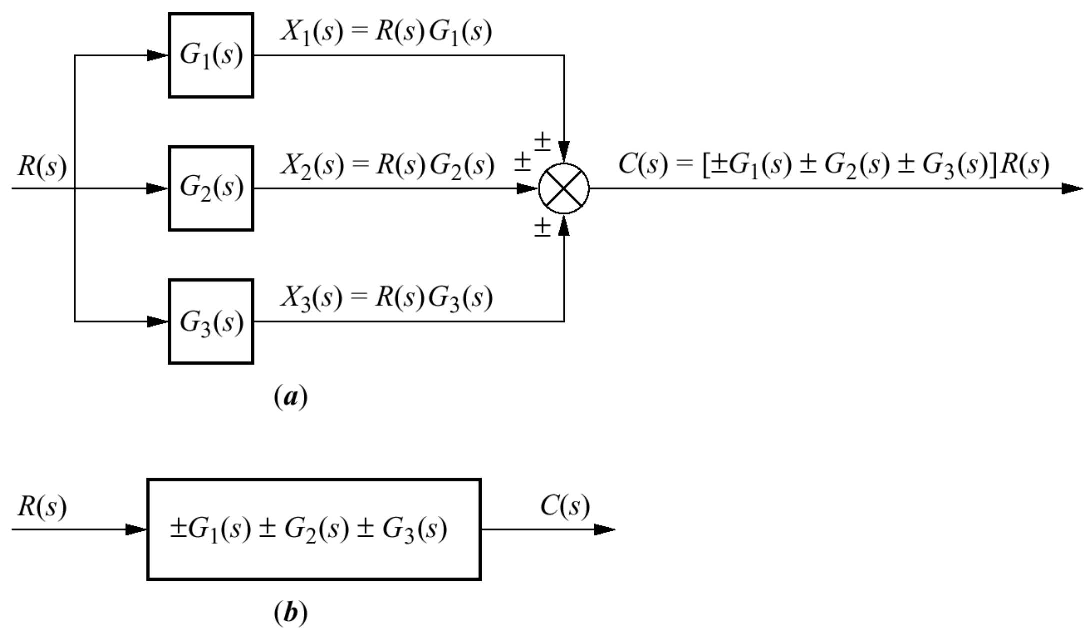


**Figure 5.5**
**a.** Parallel subsystems;
**b.** equivalent transfer function



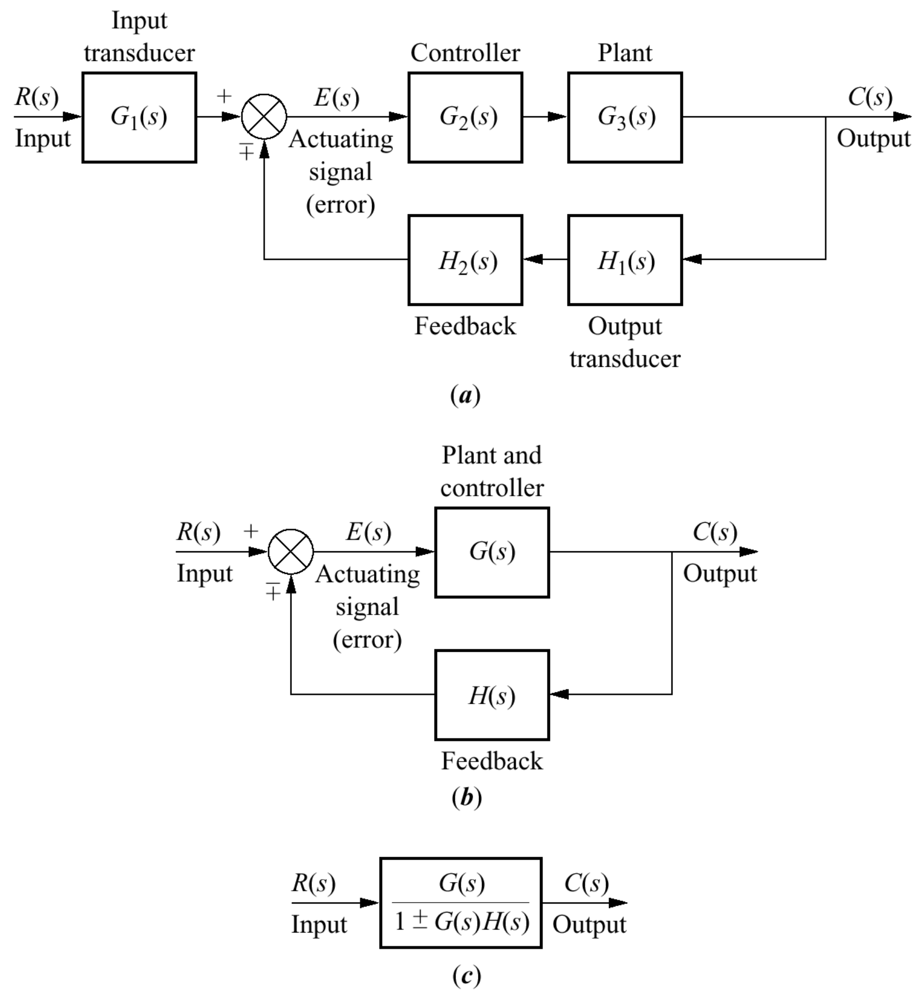



**Figure 5.6**
**a.** Feedback control system;
**b.** simplified model;
**c.** equivalent transfer function

**Figure 5.7**
Block diagram algebra for summing junctions—equivalent forms for moving a block
**a.** to the left past a summing junction;
**b.** to the right past a summing junction

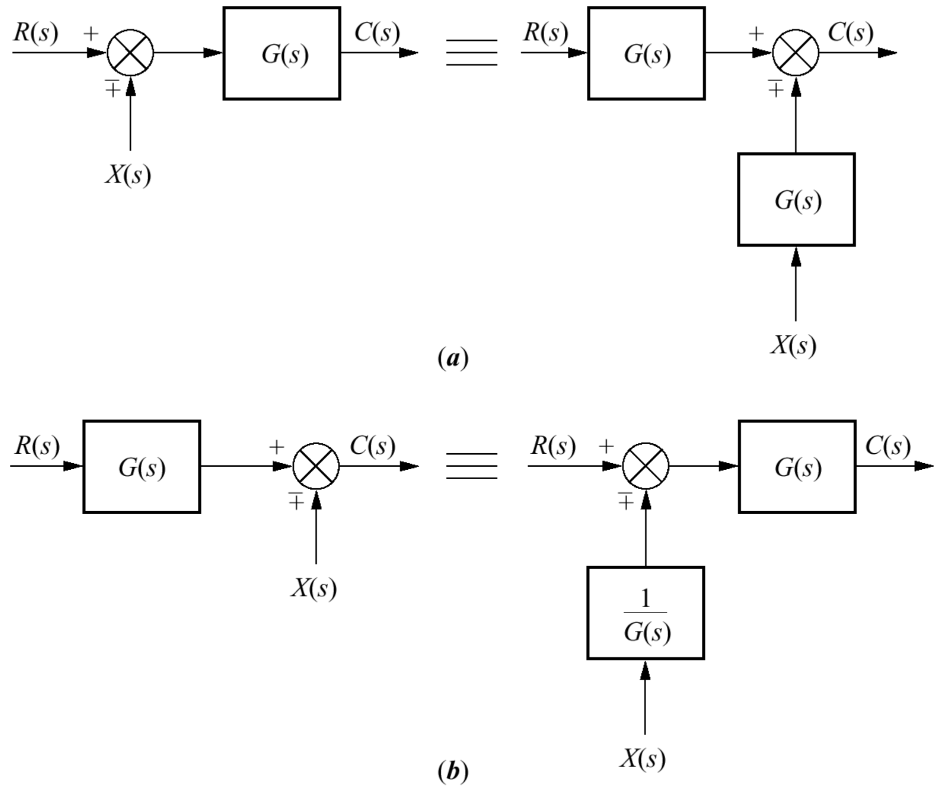


**Figure 5.8**

Block diagram algebra for pickoff points—equivalent forms for moving a block

**a.** to the left past a pickoff point;

**b.** to the right past a pickoff point

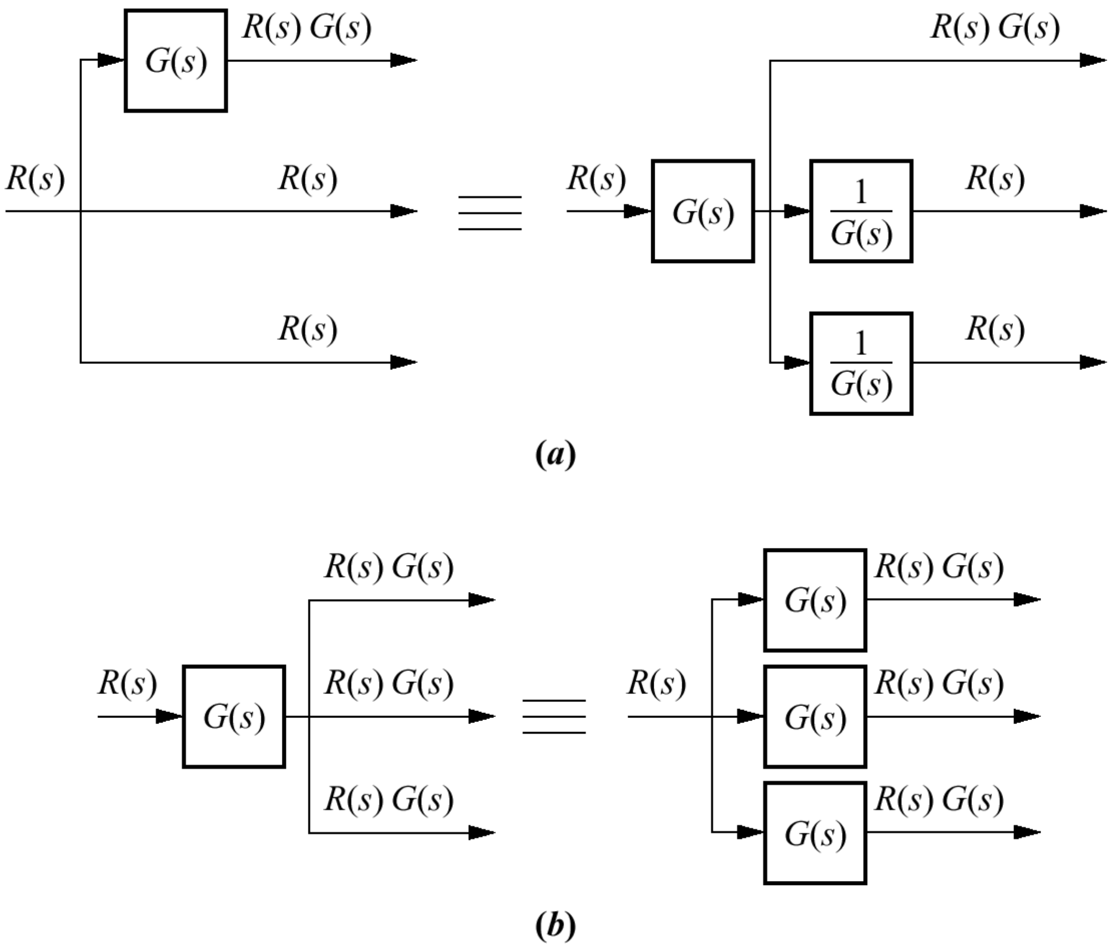
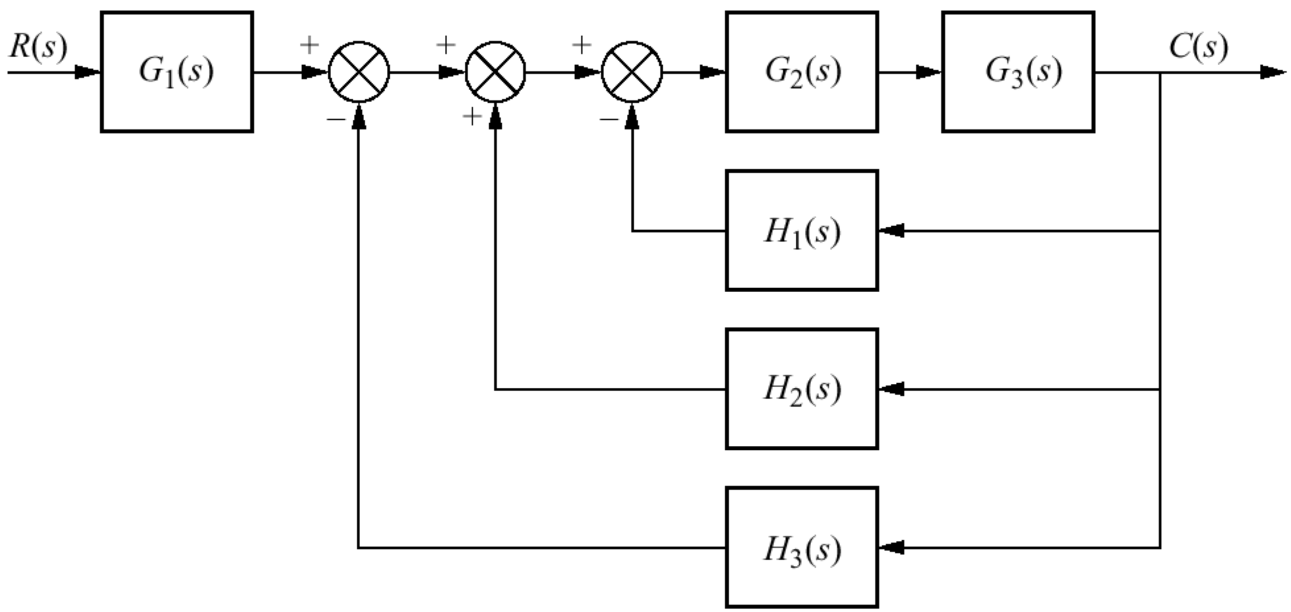
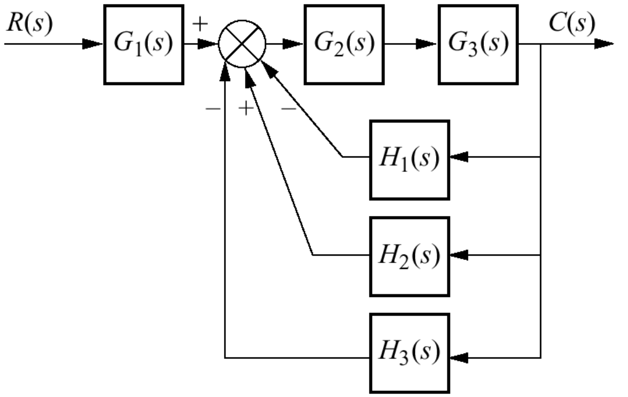


**Figure 5.9**
Block diagram for Example5.1

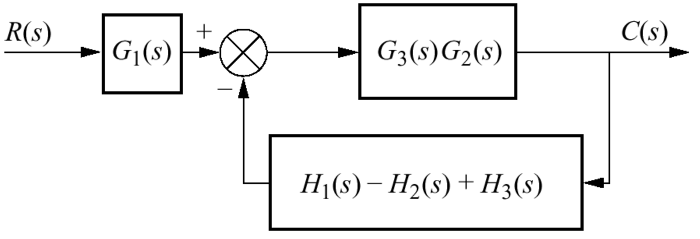


# Figure 5.10

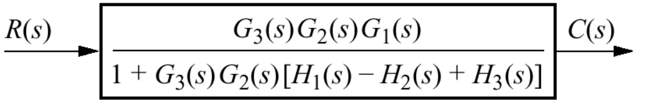
Steps in solving Example 5.1:
**a.** collapse summing junctions;
**b.** form equivalent cascaded system in the forward path and equivalent parallel system in the feedback path;
**c.** form equivalent feedback system and multiply by cascaded $G_1(s)$




(*a*)



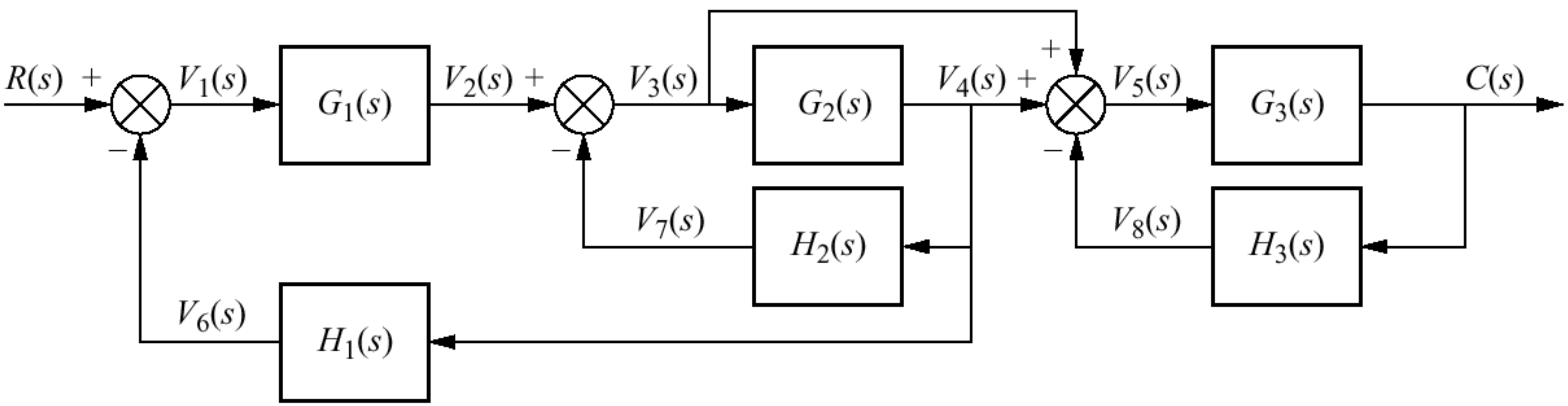

(*b*)




$$\frac{G_3(s)G_2(s)G_1(s)}{1 + G_3(s)G_2(s)[H_1(s) - H_2(s) + H_3(s)]}$$

(*c*)

**Figure 5.11**
Block diagram for
Example 5.2



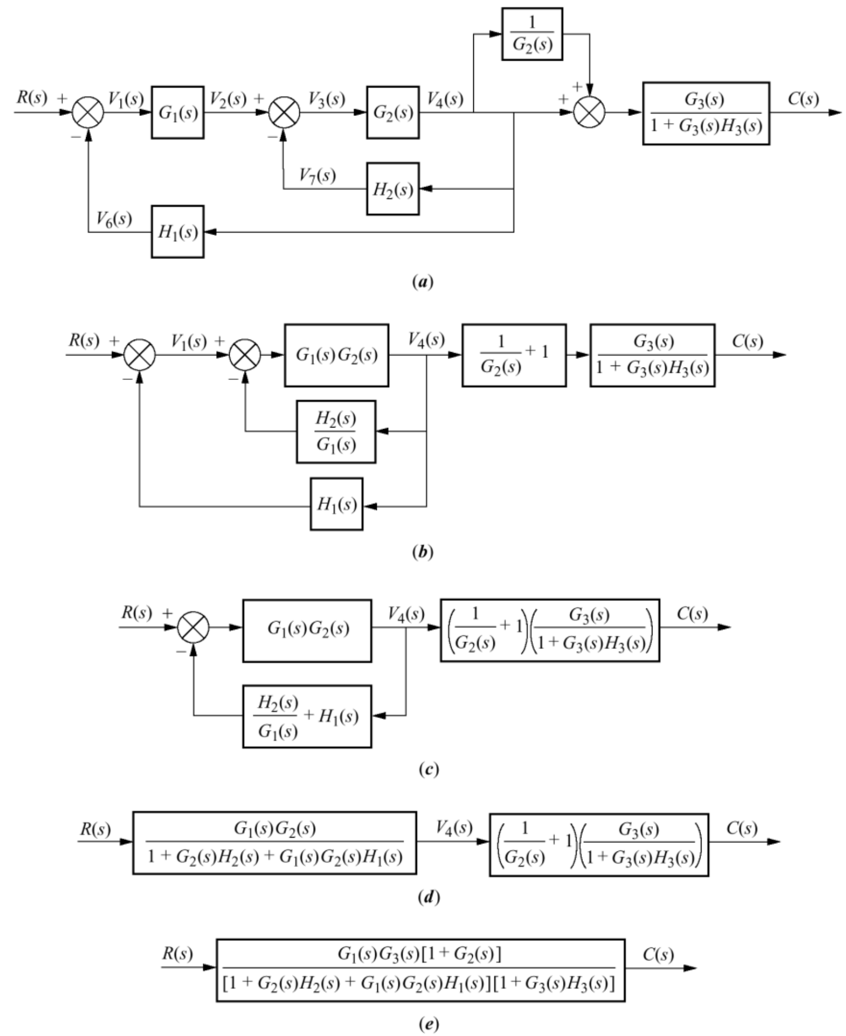



**Figure 5.12**
Steps in the block diagram reduction for Example 5.2

**Figure 5.13**
Block diagram for Skill-Assessment Exercise 5.1

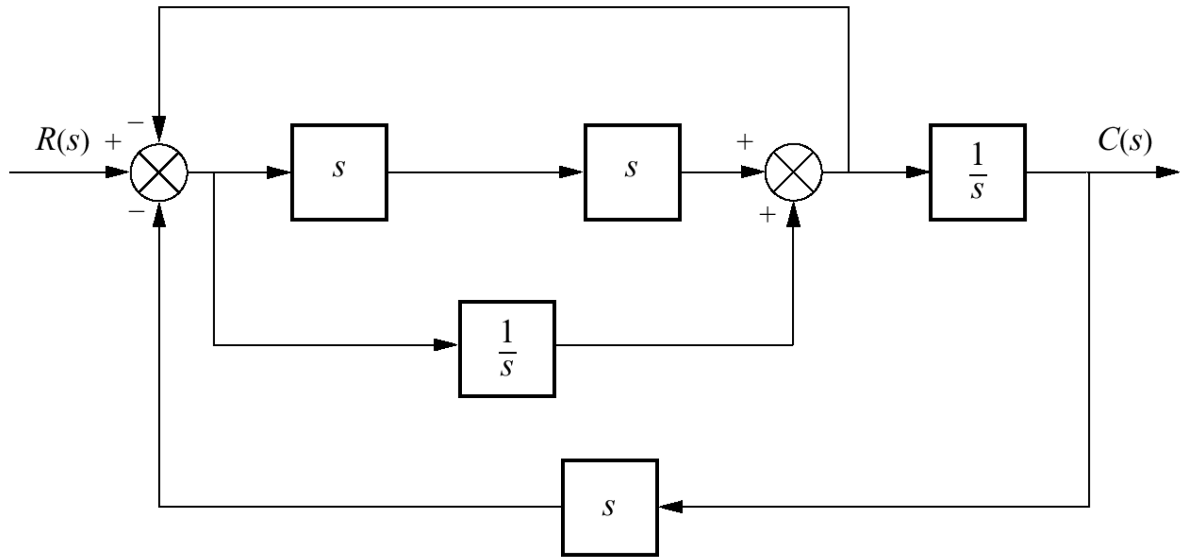


**Figure 5.14**
Second-order feedback control system

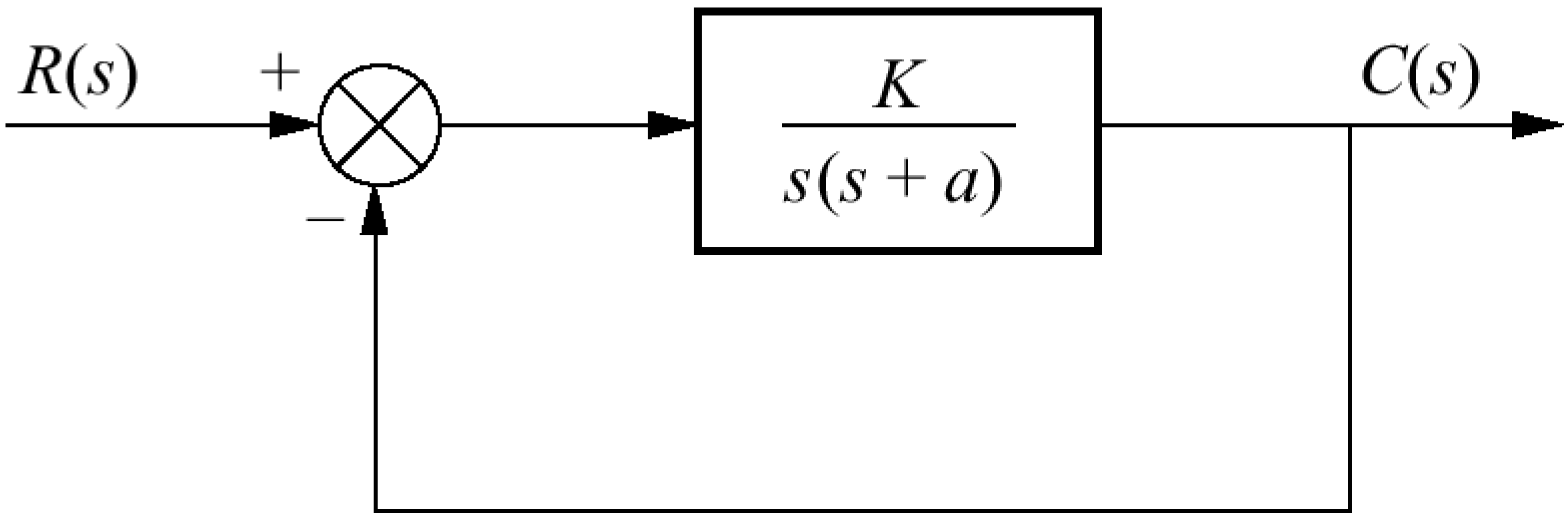


**Figure 5.15**
Feedback system for Example 5.3

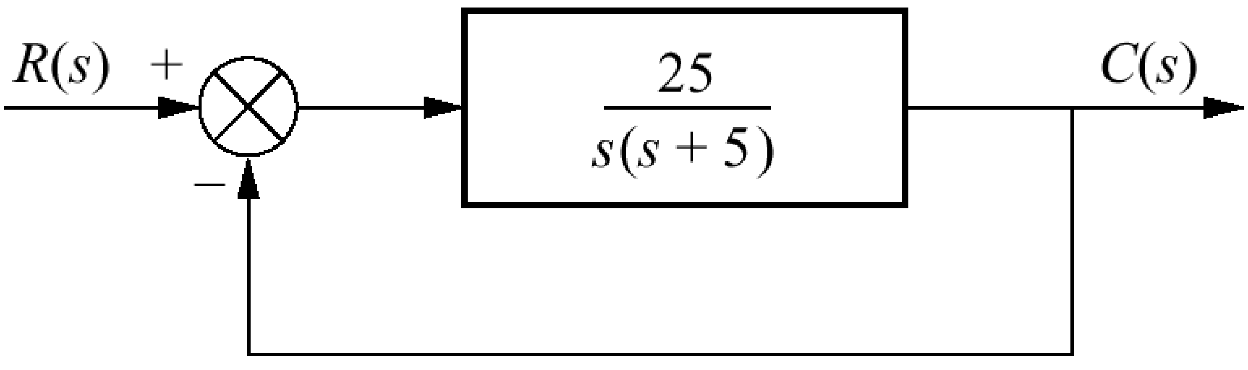


**Figure 5.16**
Feedback system for
Example 5.4

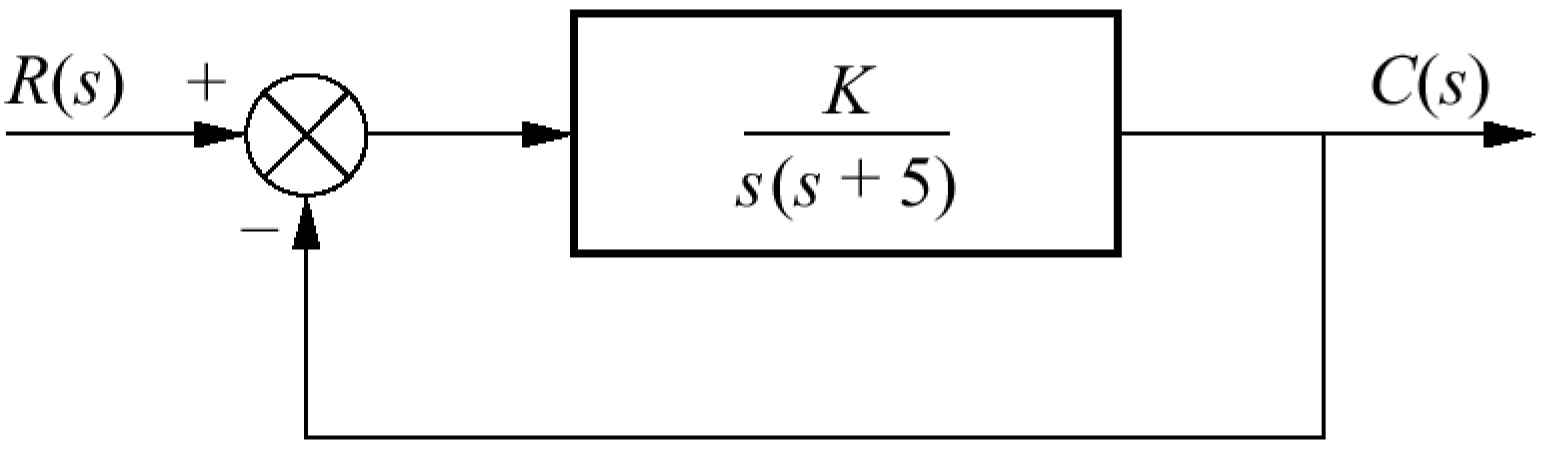
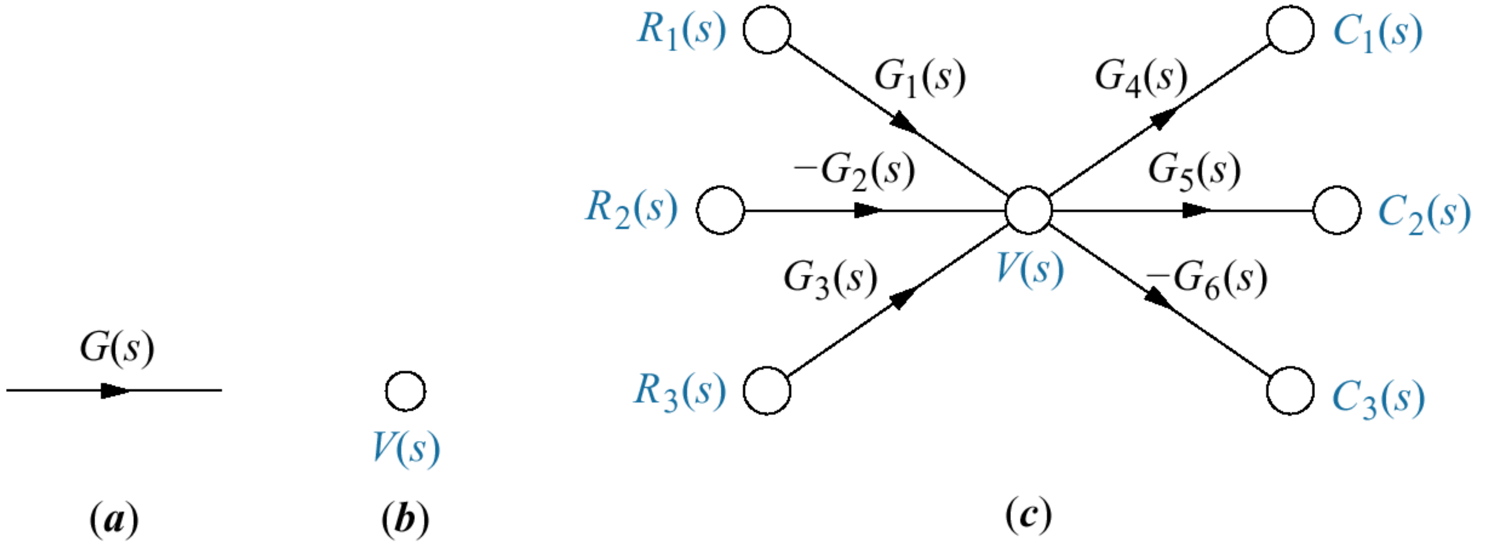


**Figure 5.17**
Signal-flow graph components:
**a.** system;
**b.** signal;
**c.** interconnection of systems and signals



# Figure 5.18

Building signal-flow graphs:
**a.** cascaded system nodes (from Figure 5.3(a));
**b.** cascaded system signal-flow graph;
**c.** parallel system nodes (from Figure 5.5(a));
**d.** parallel system signal-flow graph;
**e.** feedback system nodes (from Figure 5.6(b));
**f.** feedback system signal-flow graph

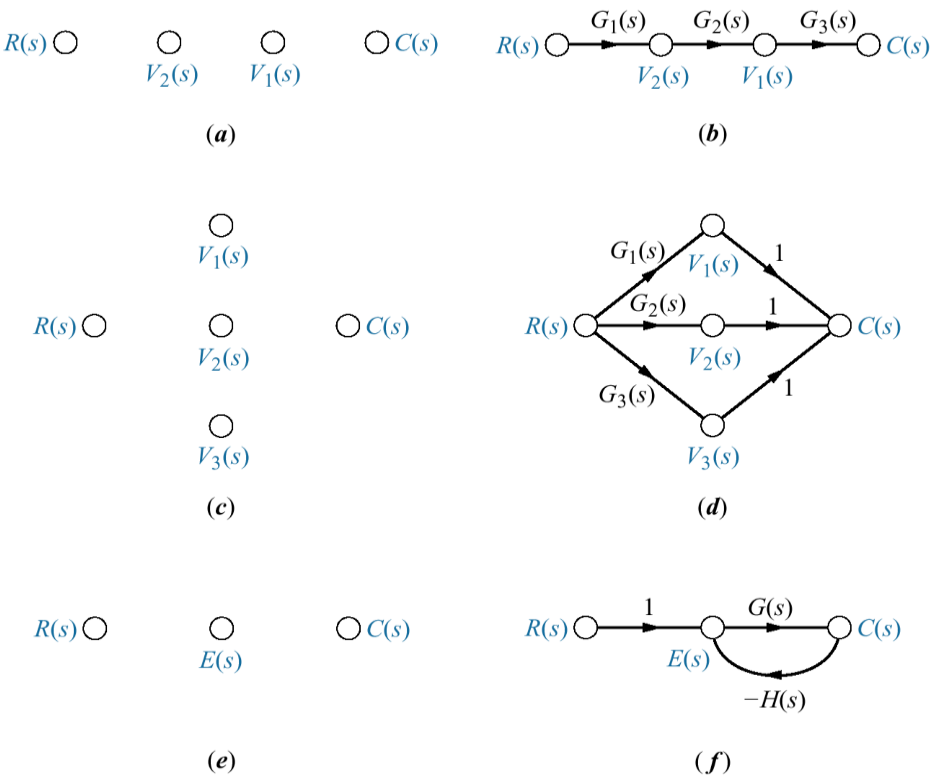


**Figure 5.19**
Signal-flow graph development:
**a.** signal nodes;
**b.** signal-flow graph;
**c.** simplified signal-flow graph

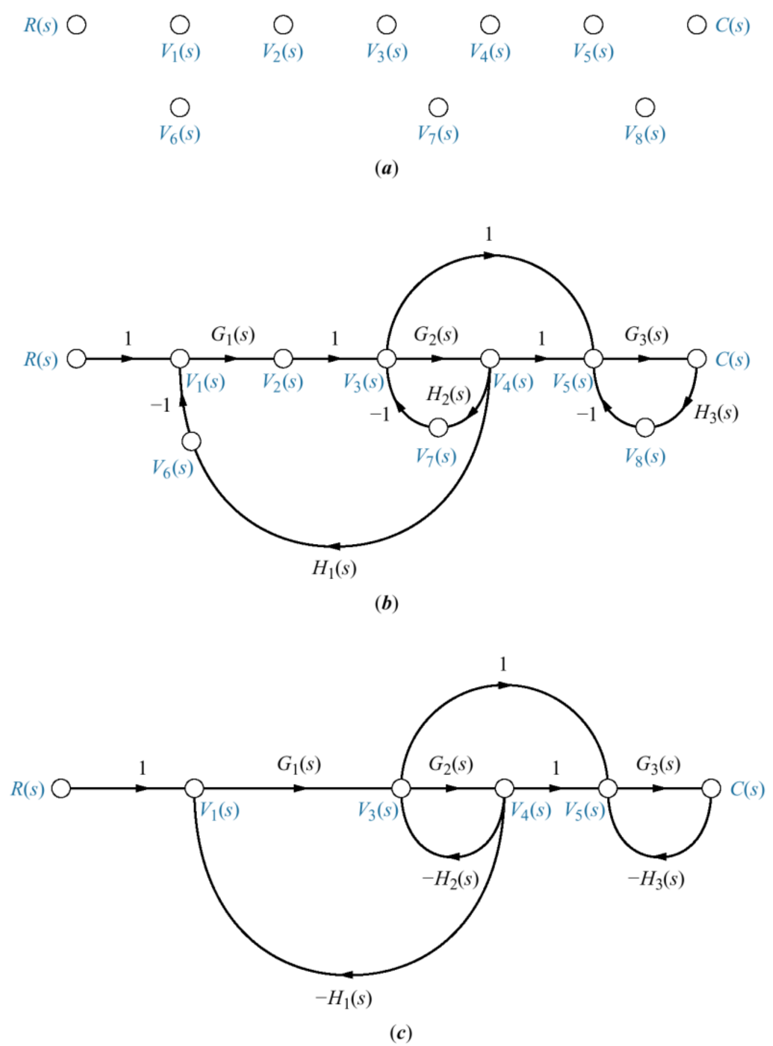


**Figure 5.20**
Signal-flow graph
for demonstrating
Mason’s rule

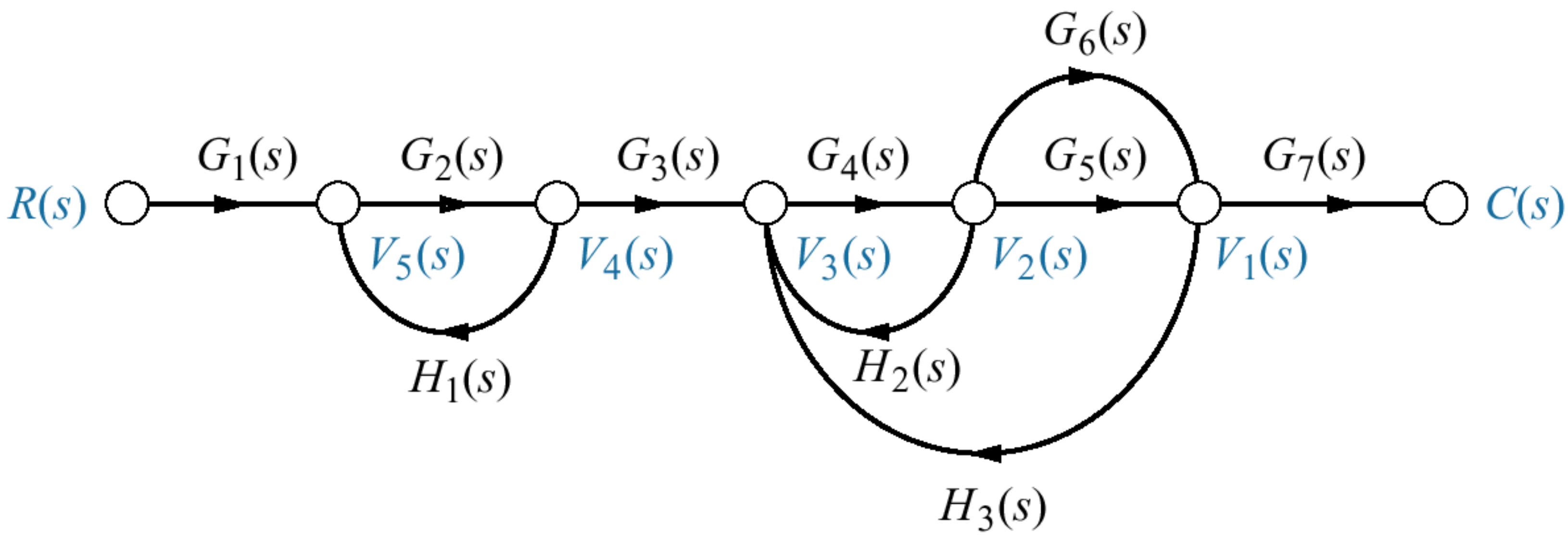
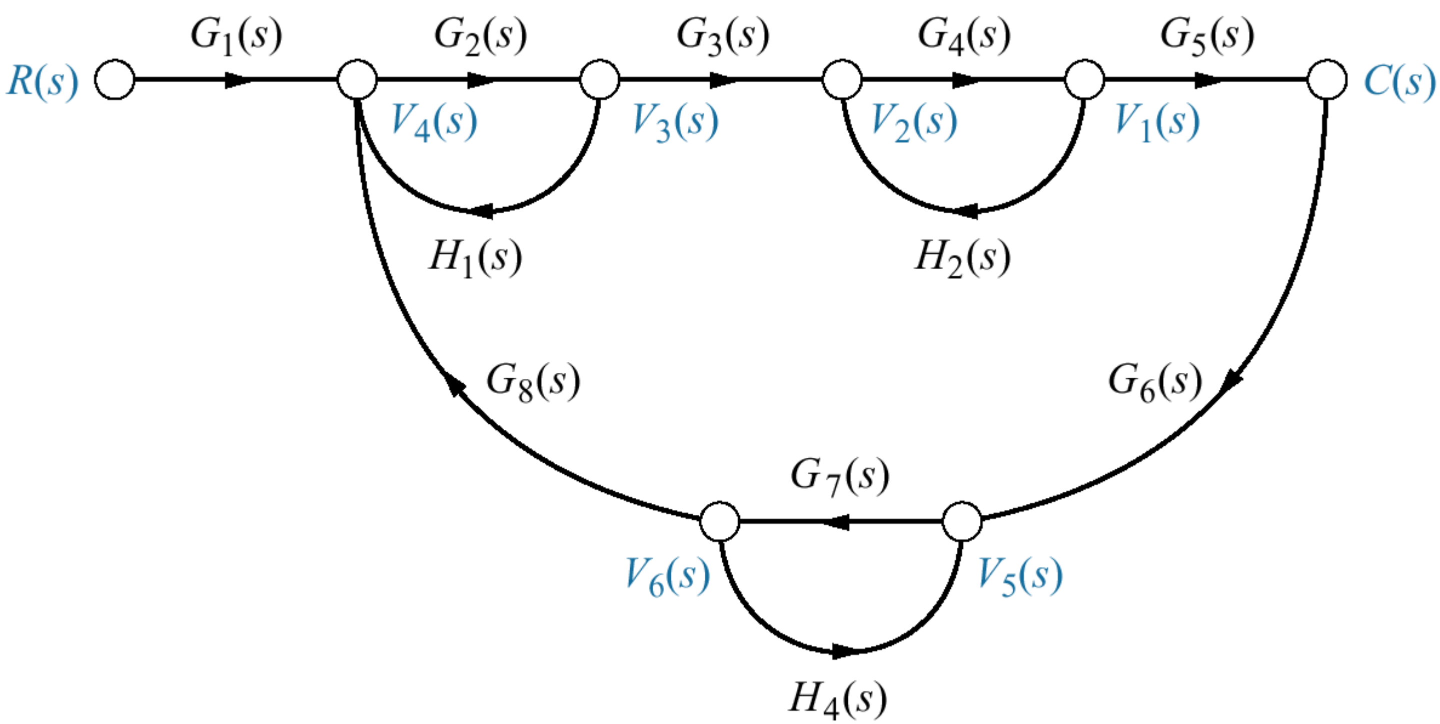
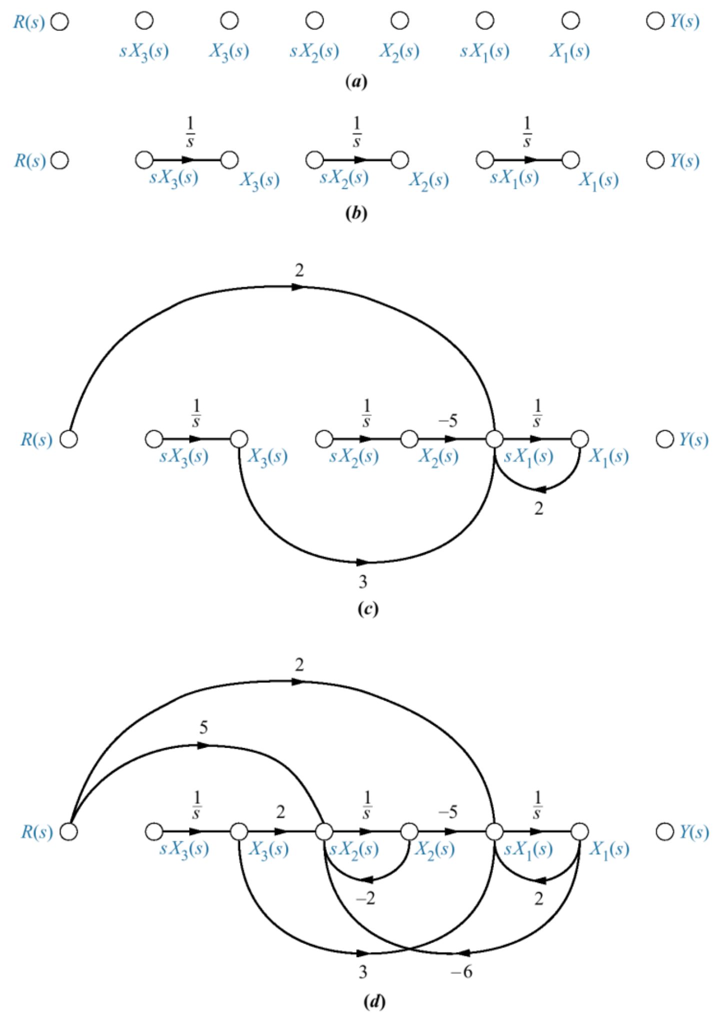


**Figure 5.21**
Signal-flow graph for Example 5.7






# Figure 5.22

Stages of development of a signal-flow graph for the system of Eqs. 5.36:

**a.** place nodes;

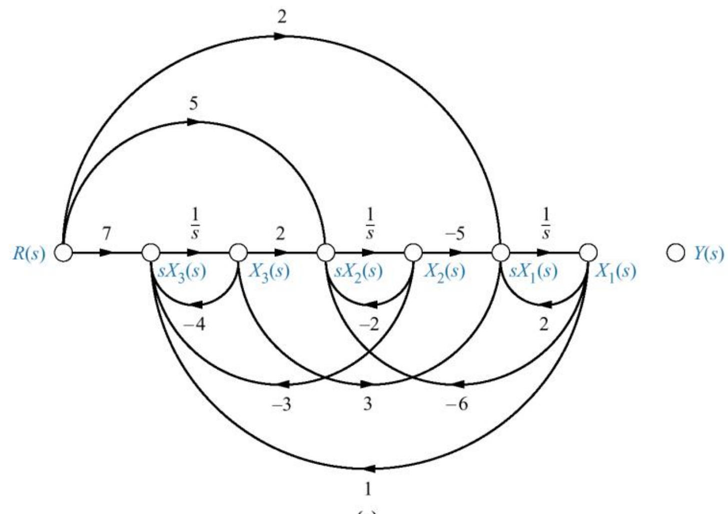
**b.** interconnect state variables and derivatives;

**c.** form $dx_1/dt$ ;

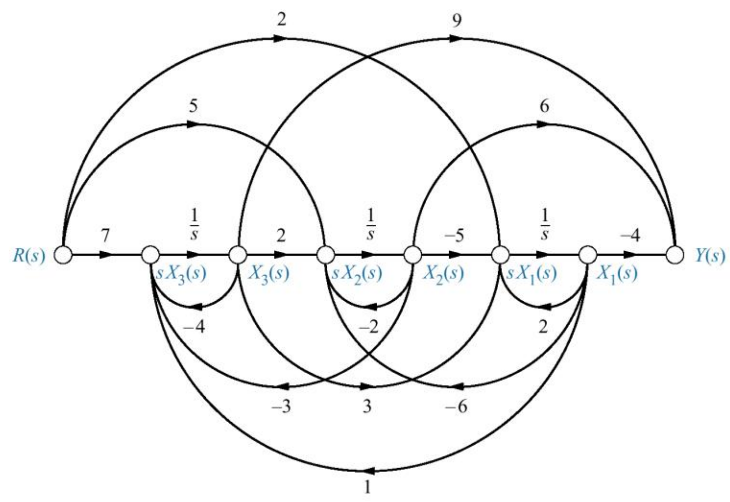
**d.** form $dx_2/dt$

*(figure continues)*

**Figure 5.22**
*(continued)*
**e.** form $dx_3$ /dt;
**f.** form output




(*e*)




(*f*)

**Figure 5.23**
Representation of Figure 3.10 system as cascaded first-order systems

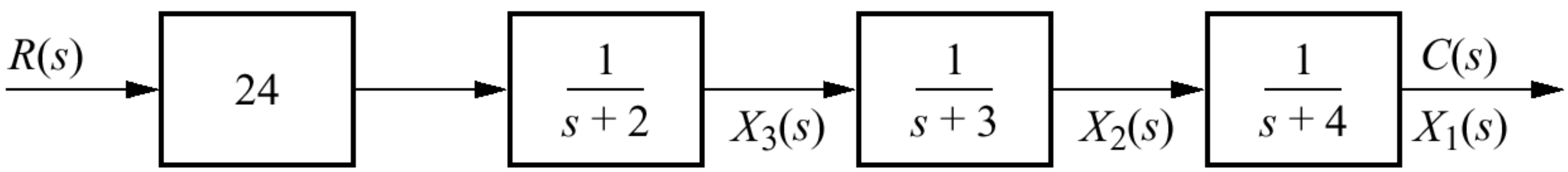


**Figure 5.24**

**a.** First-order subsystem;

**b.** signal-flow graph for Figure 5.23 system

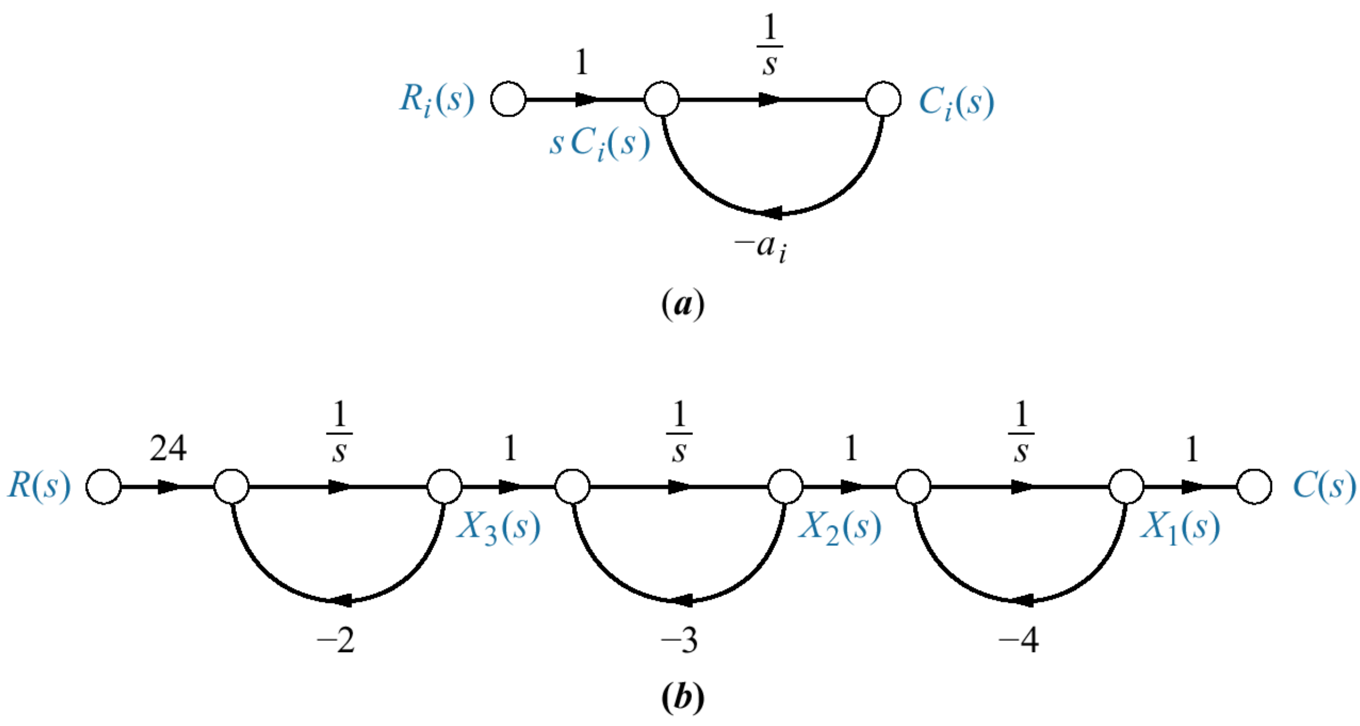


**Figure 5.25** Signal-flow representation of Eq. (5.45)

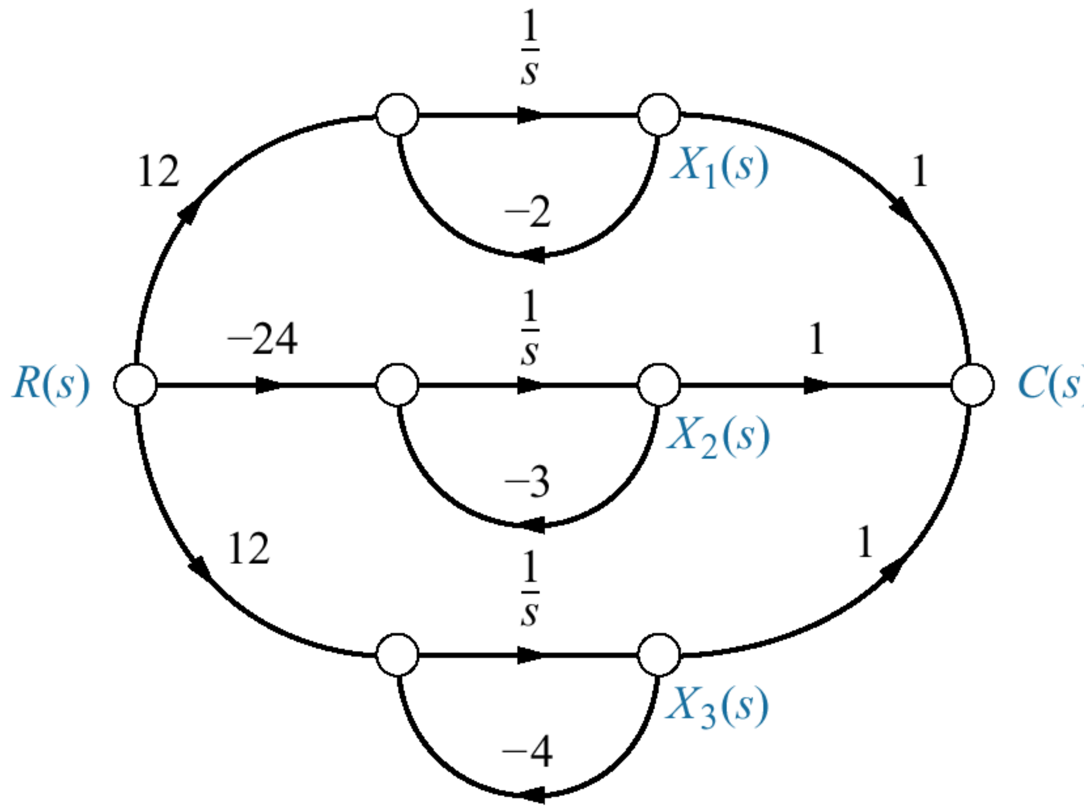


**Figure 5.26**
Signal-flow representation of Eq. (5.52)

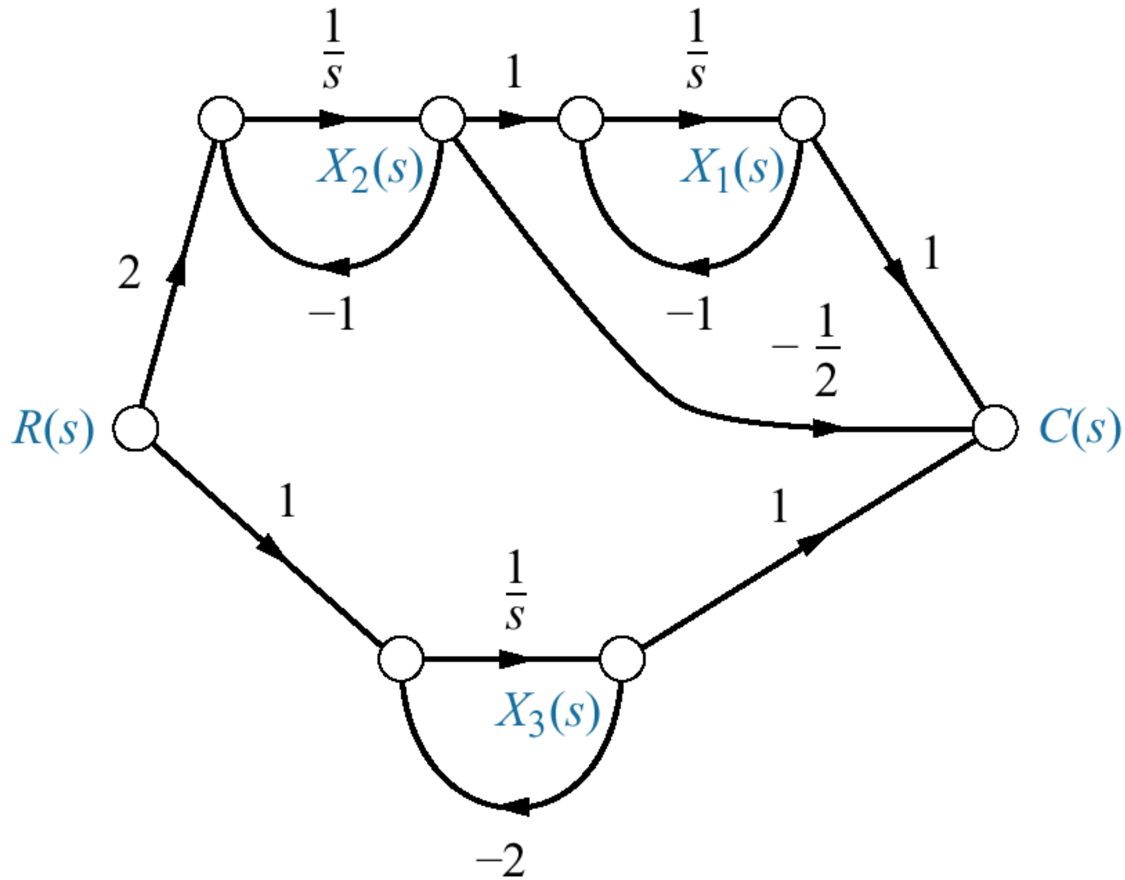


**Figure 5.27**

Signal-flow graphs for obtaining forms for
$G(s) = C(s)/R(s) = (s^2 + 7s + 2)/(s^3 + 9s^2 + 26s + 24)$:

**a.** phase-variable form;

**b.** controller canonical form

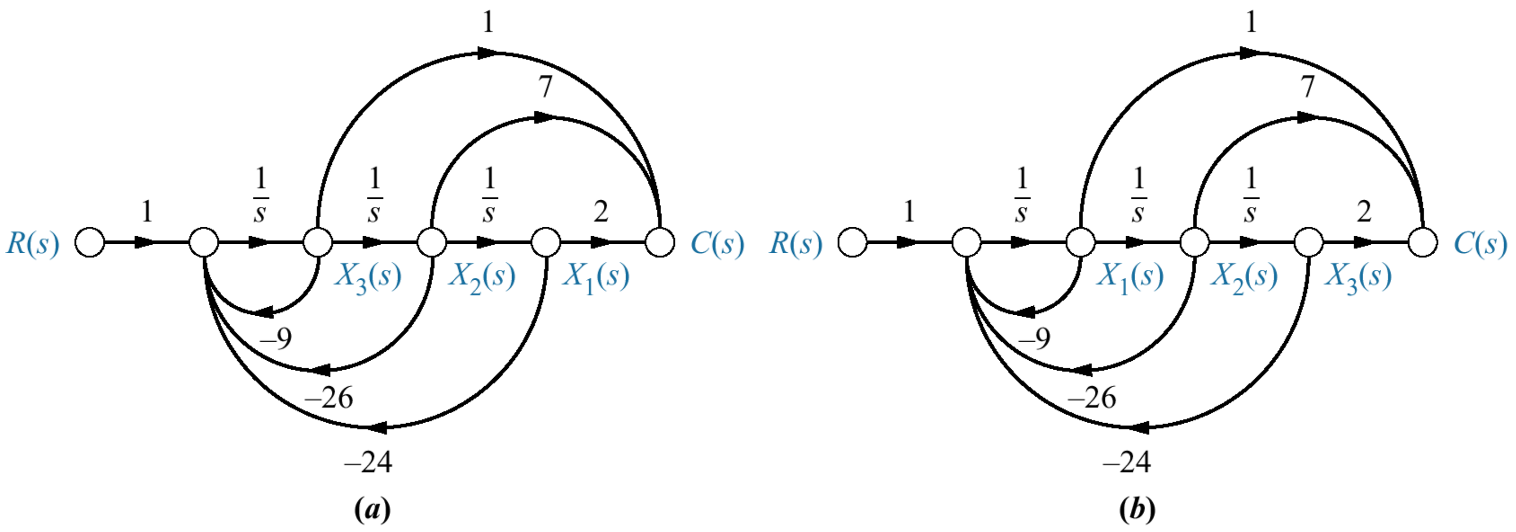


**Figure 5.28**
Signal-flow graph for observer canonical form variables:
**a.** planning;
**b.** implementation

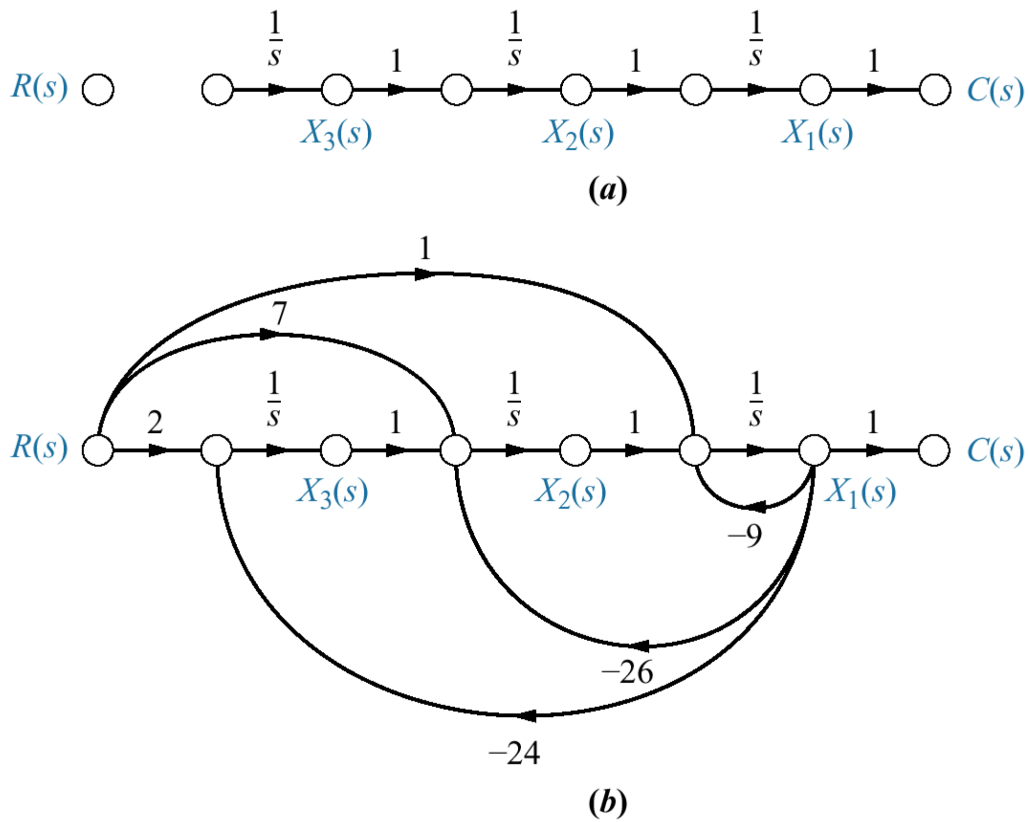


**Figure 5.29**
Feedback
control system
for Example 5.8

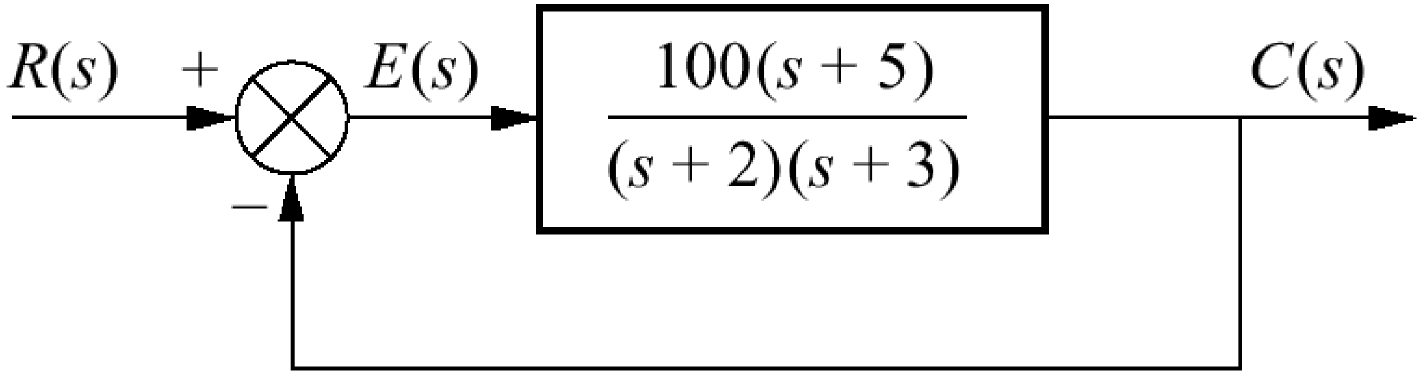


**Figure 5.30**
Creating a signal-
flow
graph for the
Figure 5.29
system:
**a.** forward
transfer
function;
**b.** complete
system

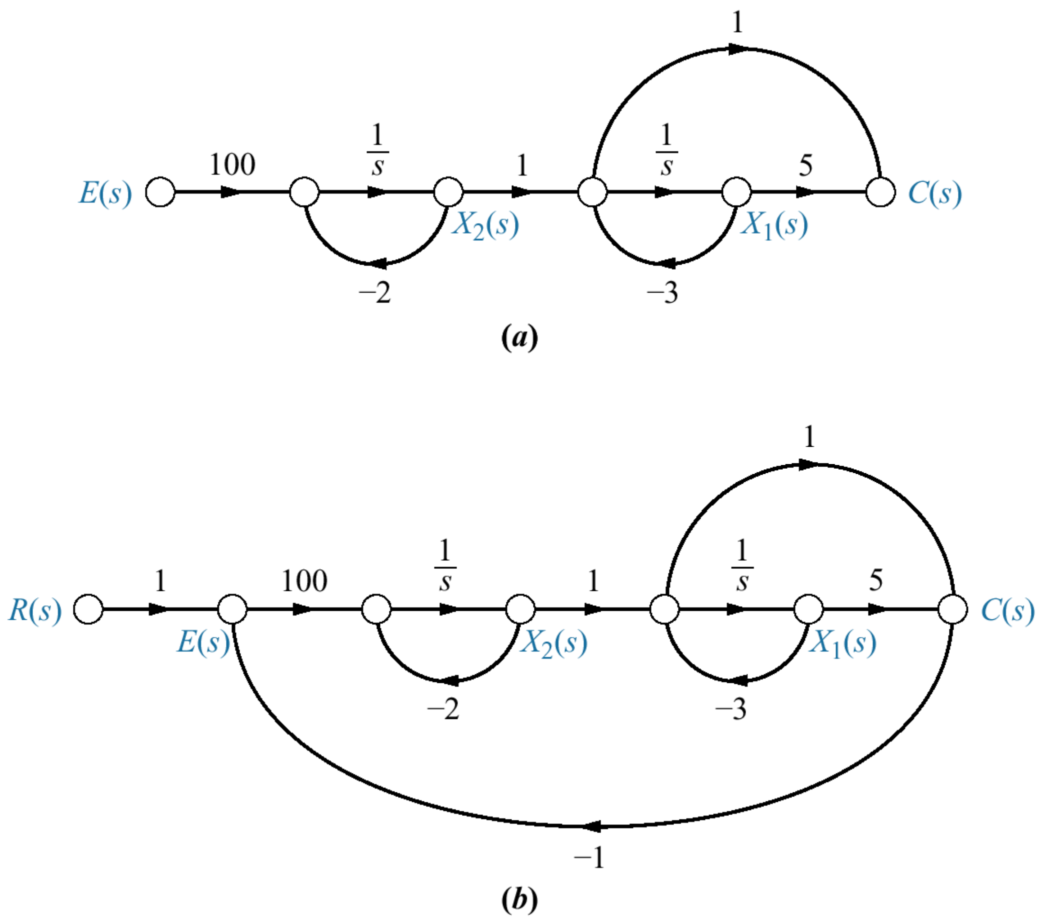


**Figure 5.31**
State-space forms for
$C(s)/R(s) =$
$(s+3)/[(s+4)$
$(s+6)]$.
Note: $y = c(t)$

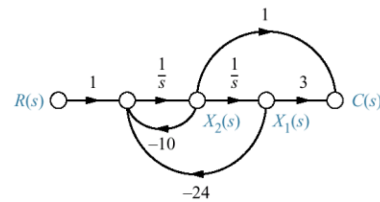
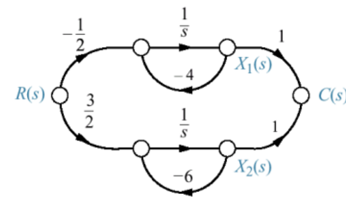
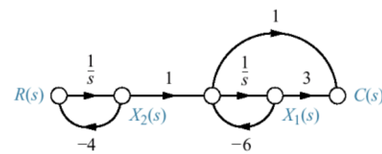
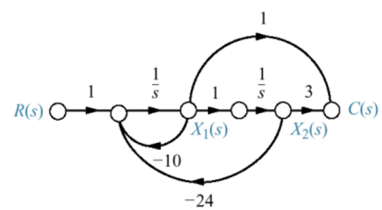
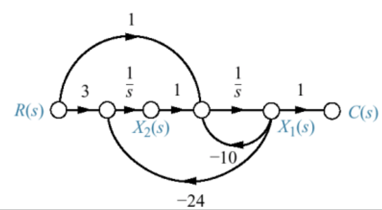
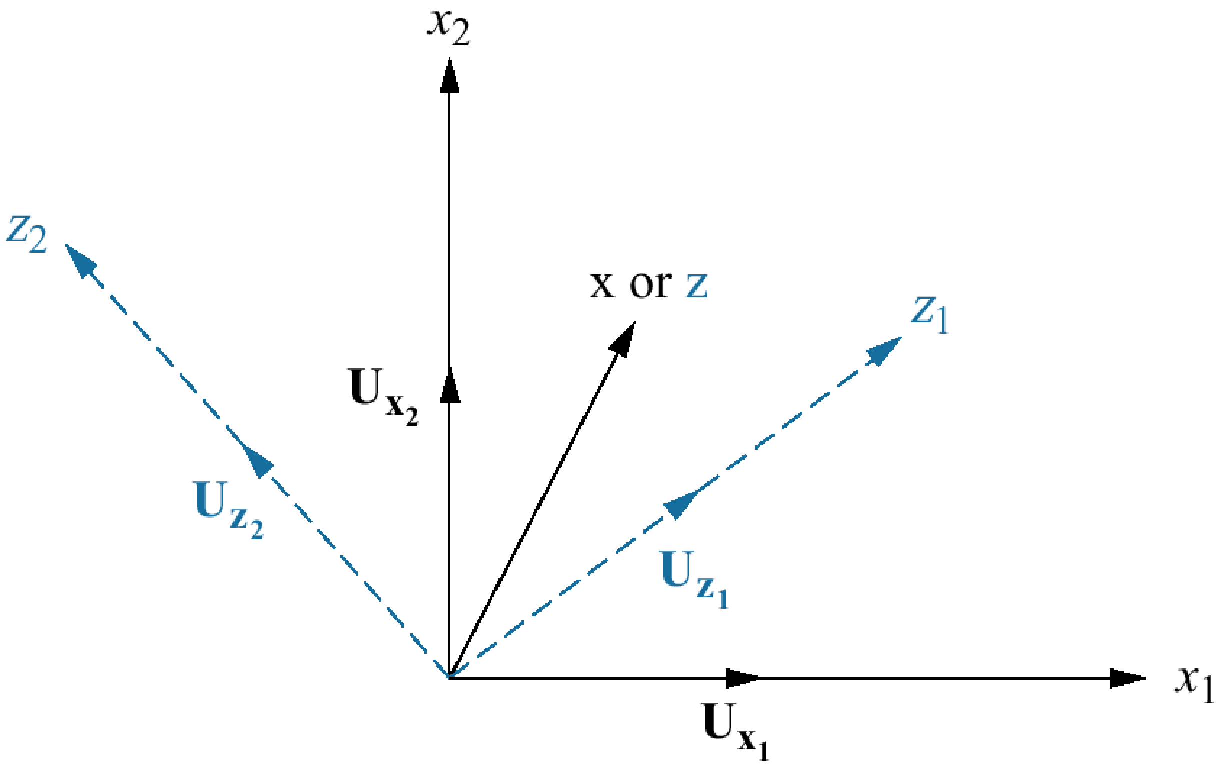
| Form | Transfer Function | Signal-Flow Diagram | State Equations |
|---|---|---|---|
| Phase variable | $\frac{1}{(s^2+10s+24)} * (s+3)$ |  | $\dot{\mathbf{x}} = \begin{bmatrix} 0 & 1 \\ -24 & -10 \end{bmatrix}\mathbf{x} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r$ <br> $y = [3 \quad 1]\mathbf{x}$ |
| Parallel | $\frac{-1/2}{(s+4)} + \frac{3/2}{s+6}$ |  | $\dot{\mathbf{x}} = \begin{bmatrix} -4 & 0 \\ 0 & -6 \end{bmatrix}\mathbf{x} + \begin{bmatrix} -\frac{1}{2} \\ \frac{3}{2} \end{bmatrix} r$ <br> $y = [1 \quad 1]\mathbf{x}$ |
| Cascade | $\frac{1}{(s+4)} * \frac{(s+3)}{(s+6)}$ |  | $\dot{\mathbf{x}} = \begin{bmatrix} -6 & 1 \\ 0 & -4 \end{bmatrix}\mathbf{x} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r$ <br> $y = [-3 \quad 1]\mathbf{x}$ |
| Controller canonical | $\frac{1}{(s^2+10s+24)} * (s+3)$ |  | $\dot{\mathbf{x}} = \begin{bmatrix} -10 & -24 \\ 1 & 0 \end{bmatrix}\mathbf{x} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} r$ <br> $y = [1 \quad 3]\mathbf{x}$ |
| Observer canonical | $\frac{\frac{1}{s} + \frac{3}{s^2}}{1 + \frac{10}{s} + \frac{24}{s^2}}$ |  | $\dot{\mathbf{x}} = \begin{bmatrix} -10 & 1 \\ -24 & 0 \end{bmatrix}\mathbf{x} + \begin{bmatrix} 1 \\ 3 \end{bmatrix} r$ <br> $y = [1 \quad 0]\mathbf{x}$ |

**Figure 5.32**
State-space transformations



# Figure 5.33

To be an eigenvector, the transformation **Ax** must be collinear with **x**; thus in (*a*), **x** is not an eigenvector; in (*b*), it is.

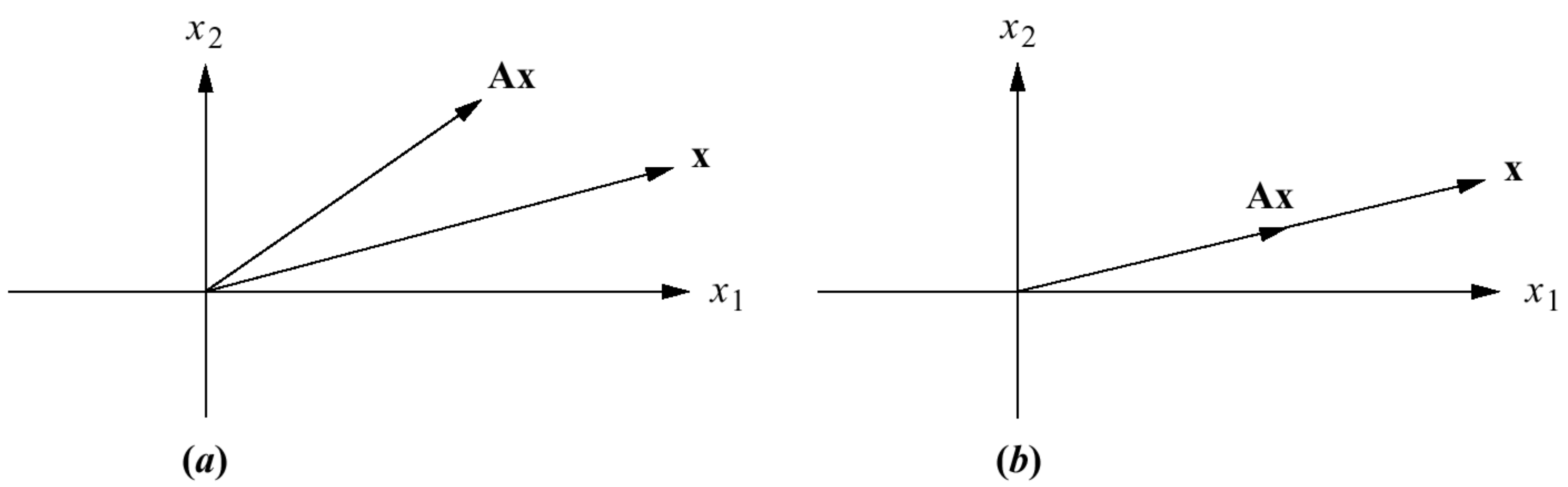
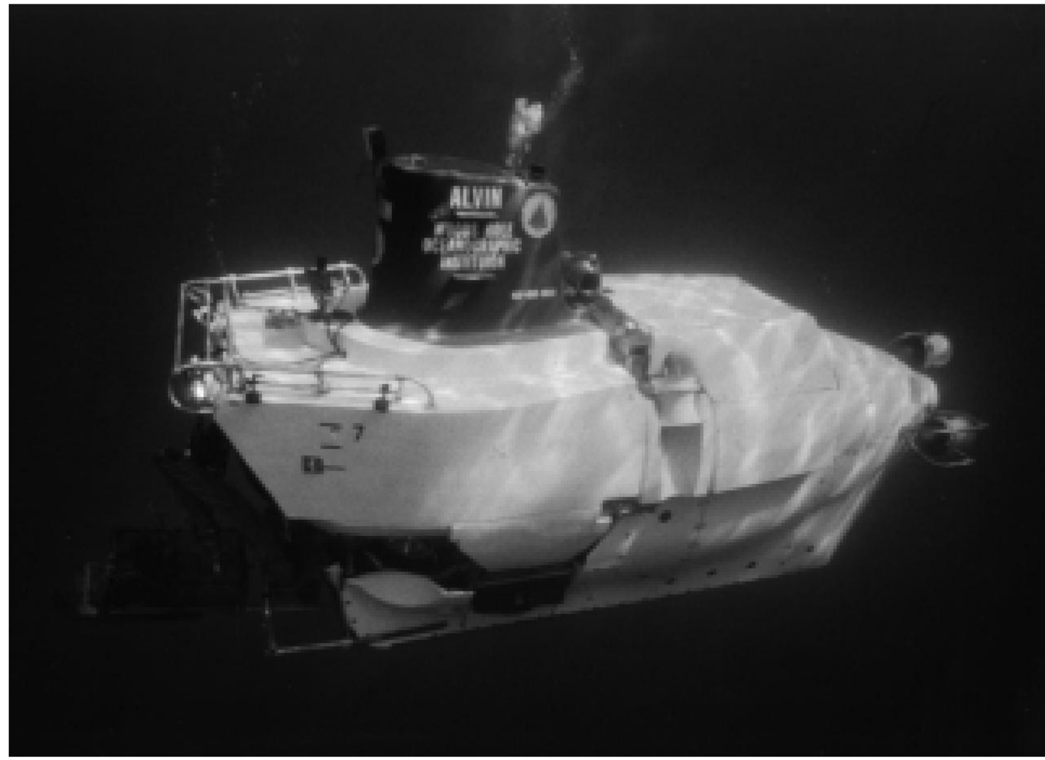


**Figure 5.34**
*Alvin*, a manned submersible, explored the wreckage of the*Titanic* with a tethered robot, *Jason Junior.*



# Figure 5.35

Block diagram reduction for the antenna azimuth position control system:
**a.** original;
**b.** pushing input potentiometer to the right past the summing junction;
**c.** showing equivalent forward transfer function;
**d.** final closed-loop transfer function

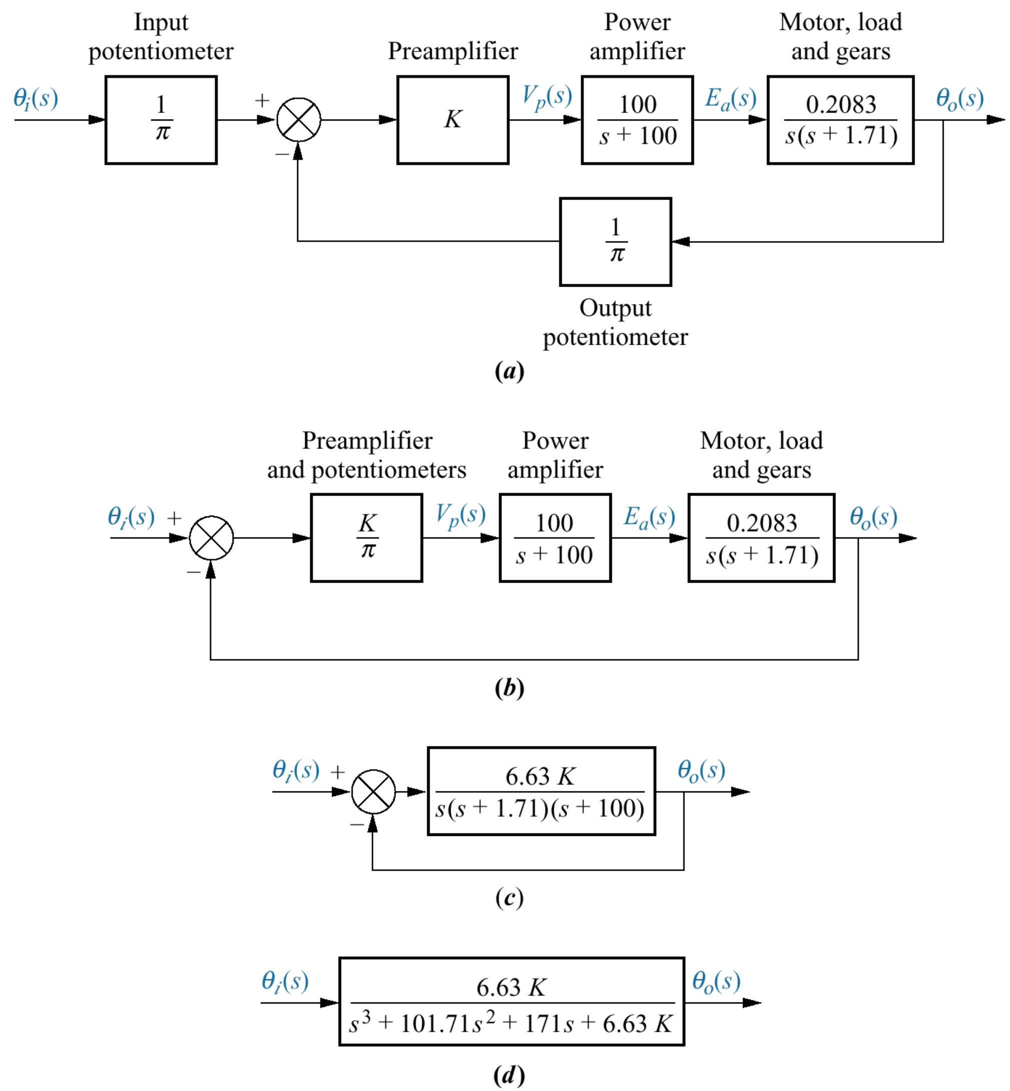


**Figure 5.36**
Signal-flow graph for the antenna azimuth position control system

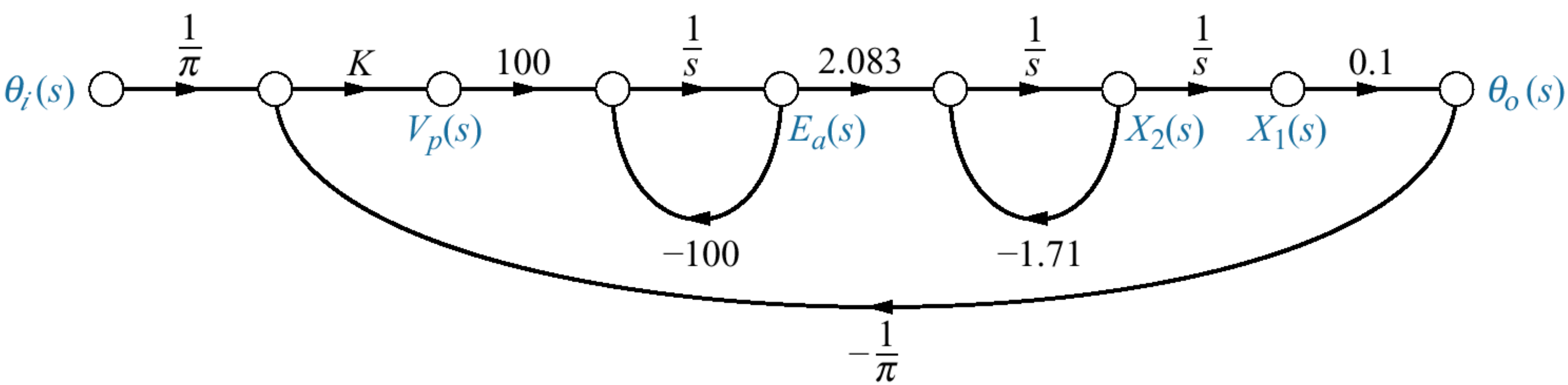
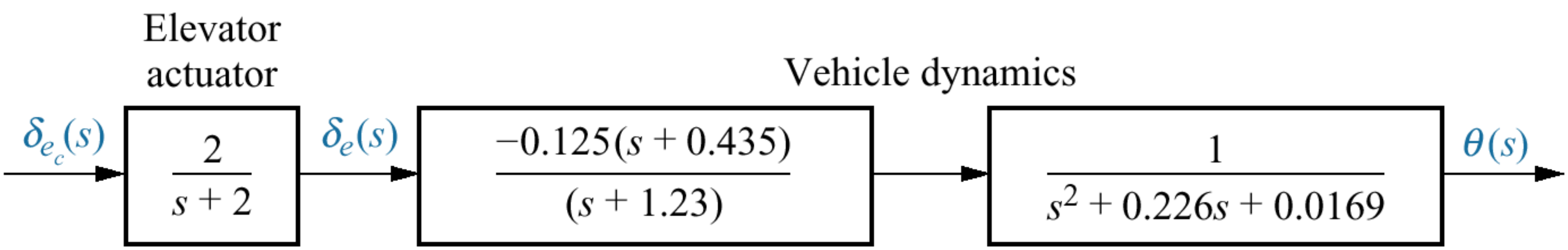


**Figure 5.37**
Block diagram of the UFSS vehicle's elevator and vehicle dynamics, from which a signal-flow graph can be drawn



# Figure 5.38

Signal-flow graph representation of the UFSS vehicle's pitch-control system:

**a.** without position and rate feedback;

**b.** with position and rate feedback

(Note: Explicitly required variables are: $x_1 = \theta$, $x_2 = d\theta/dt$, and $x_4 = \delta_e$)

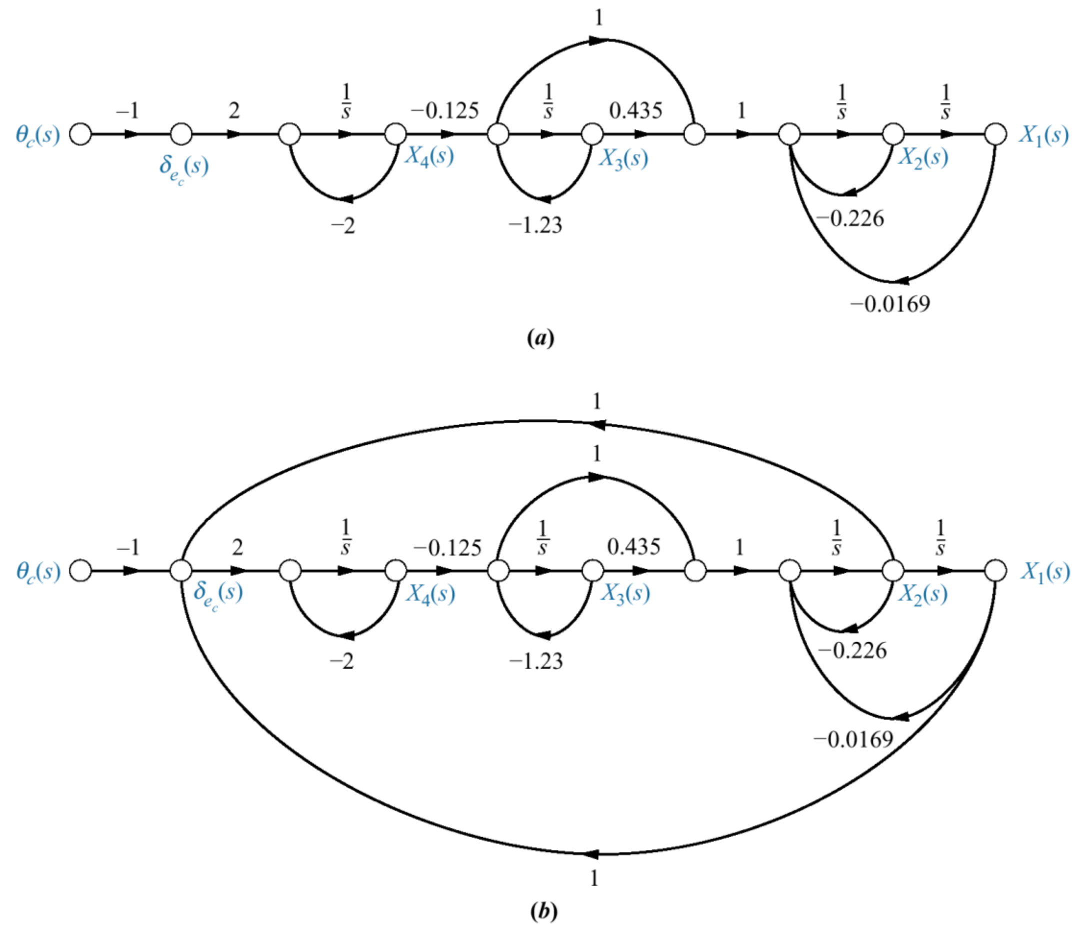
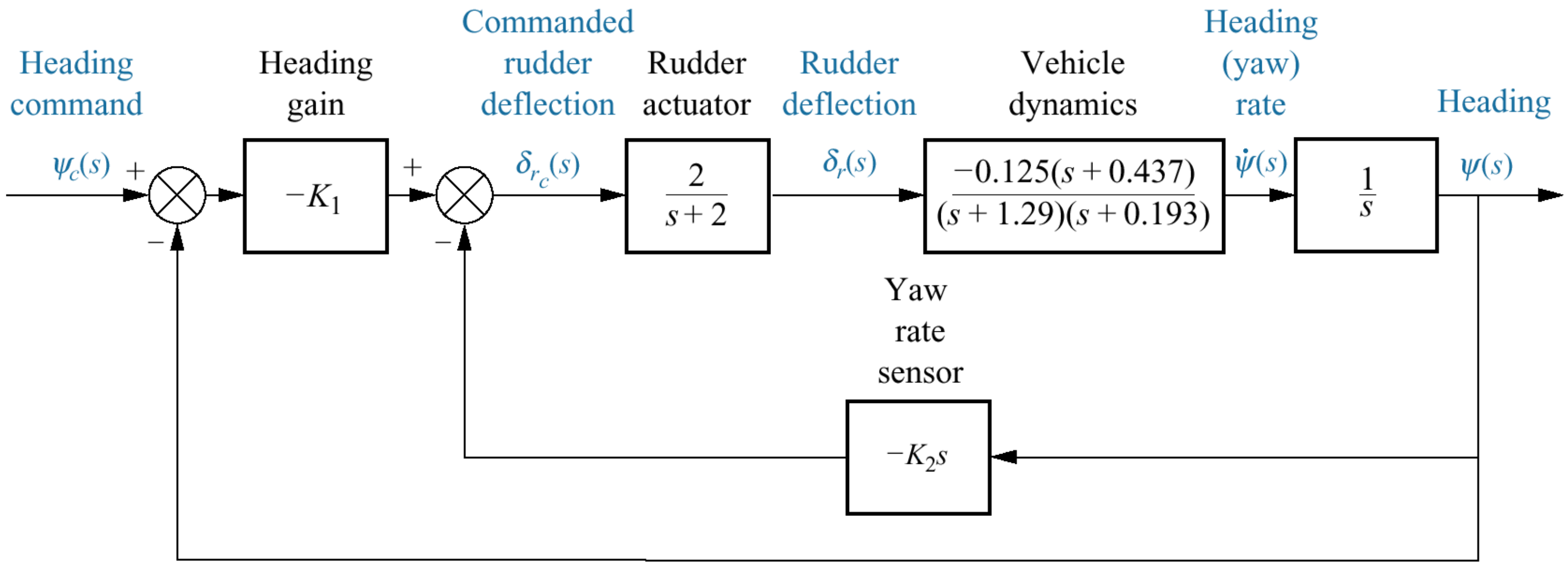
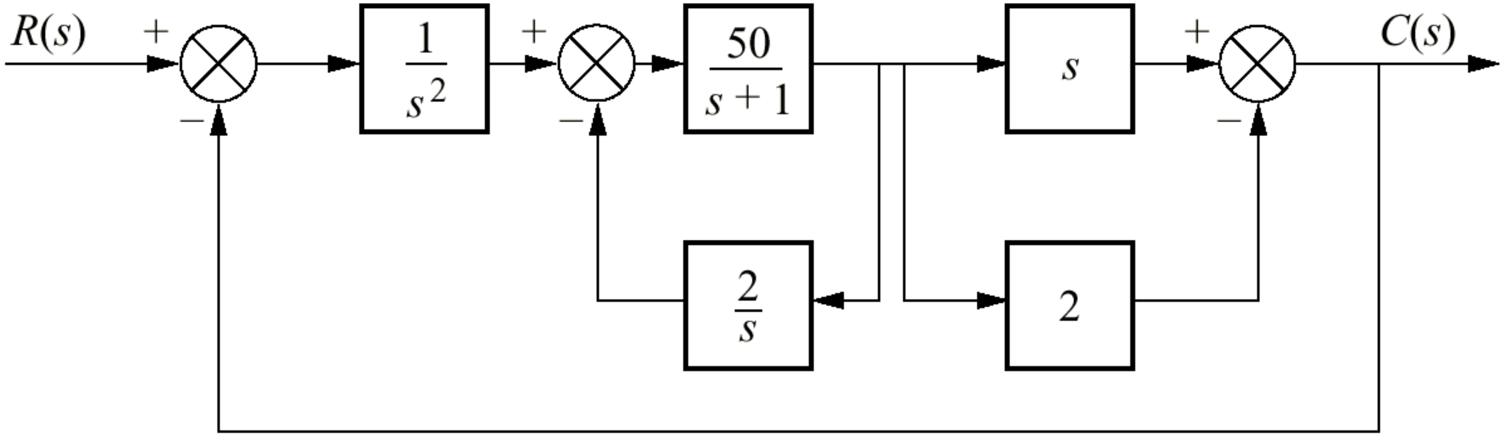


**Figure 5.39**

Block diagram of the heading control system for the UFSS vehicle



# Figure P5.1



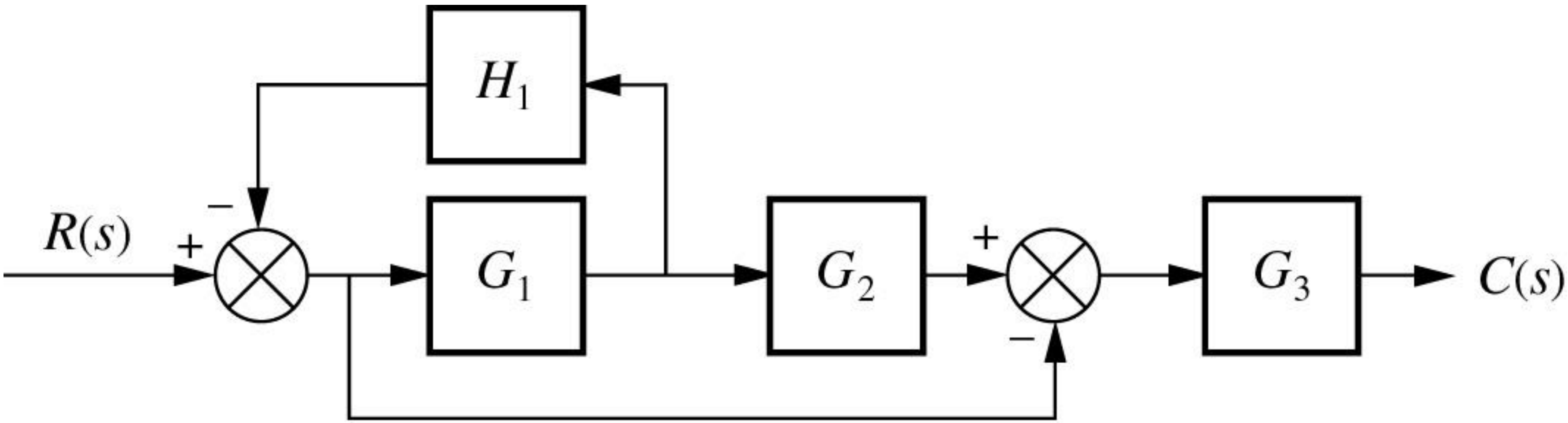
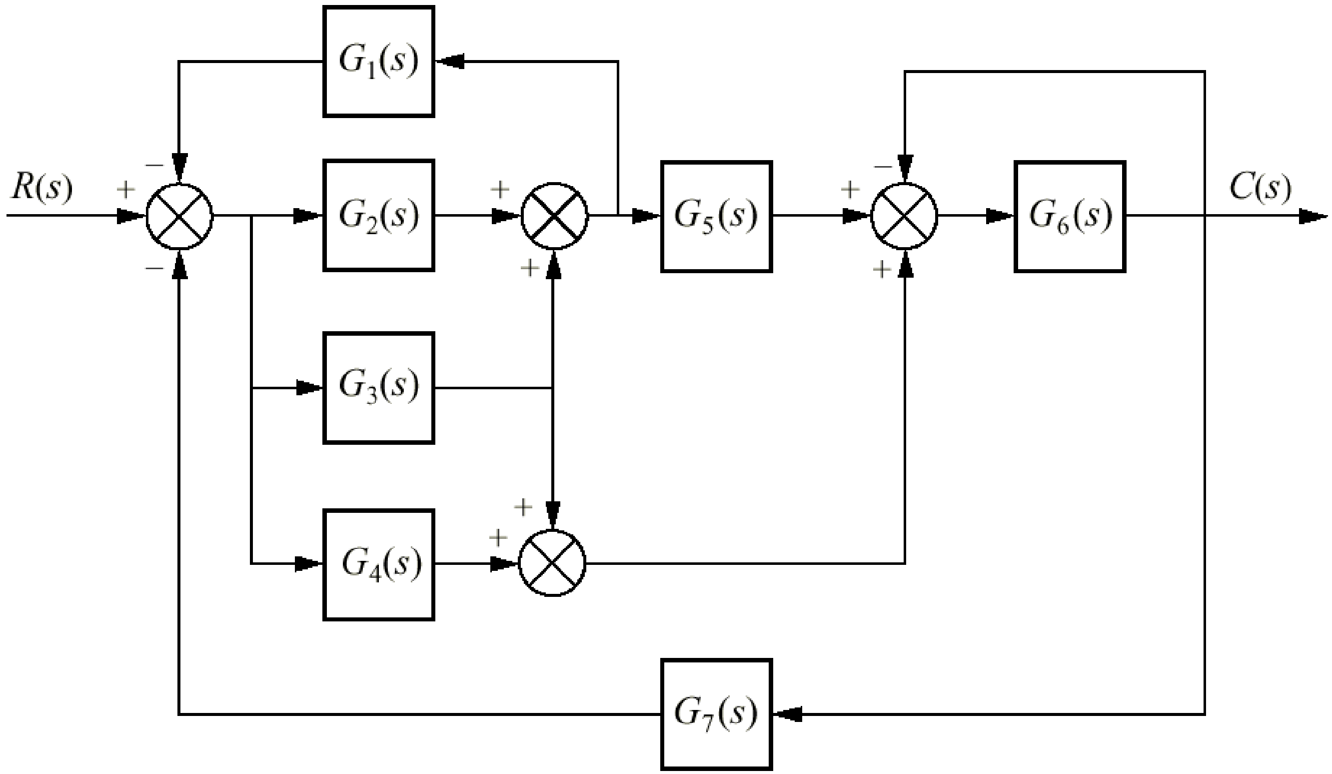



**Figure P5-2  (p. 301)**

# Figure P5.3



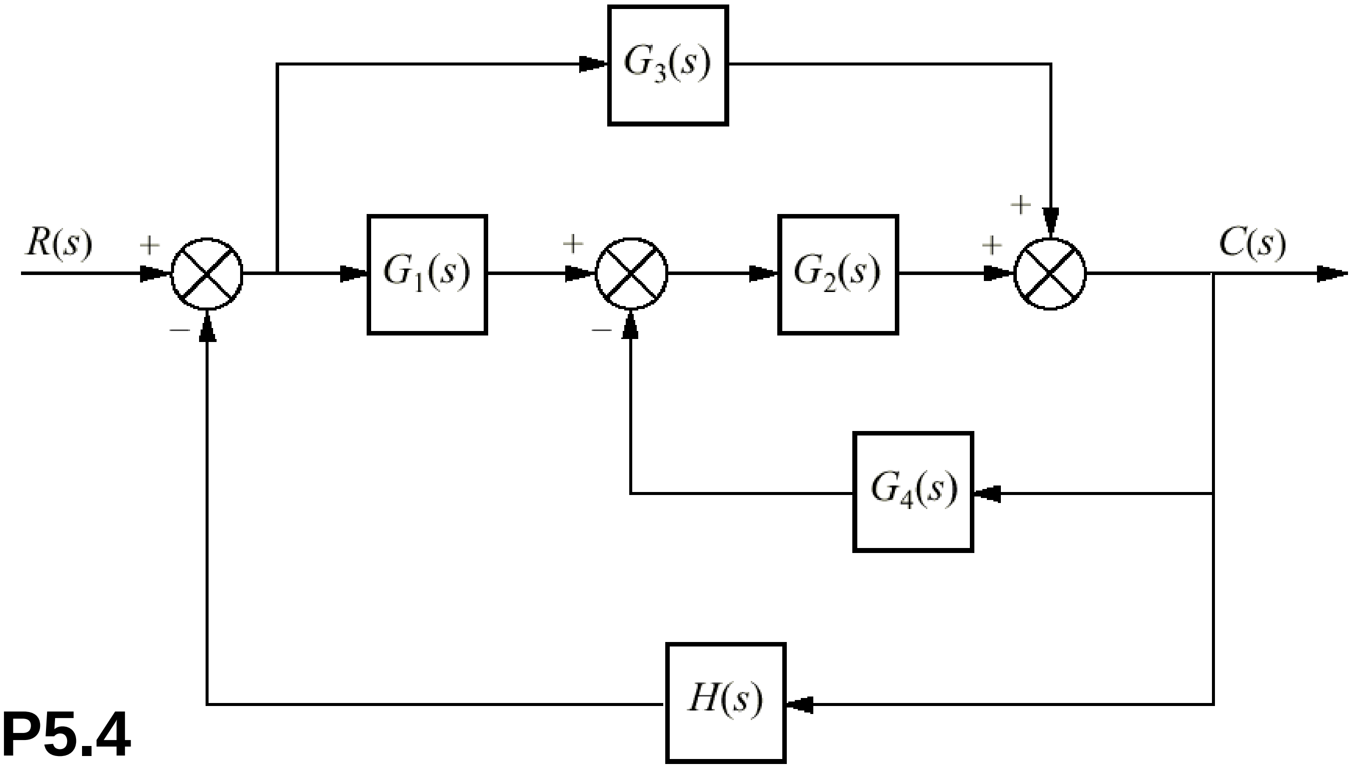



**Figure P5.4**

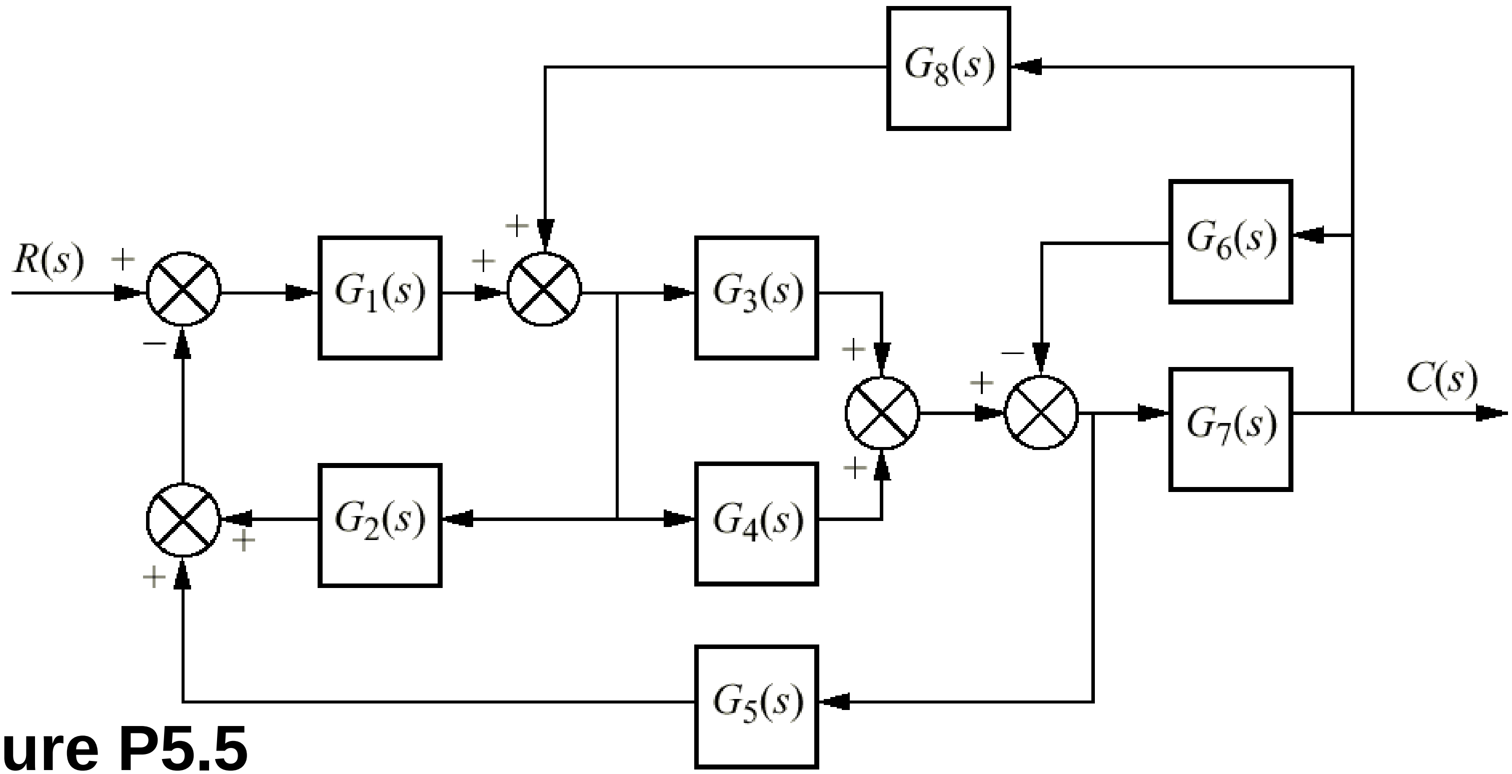
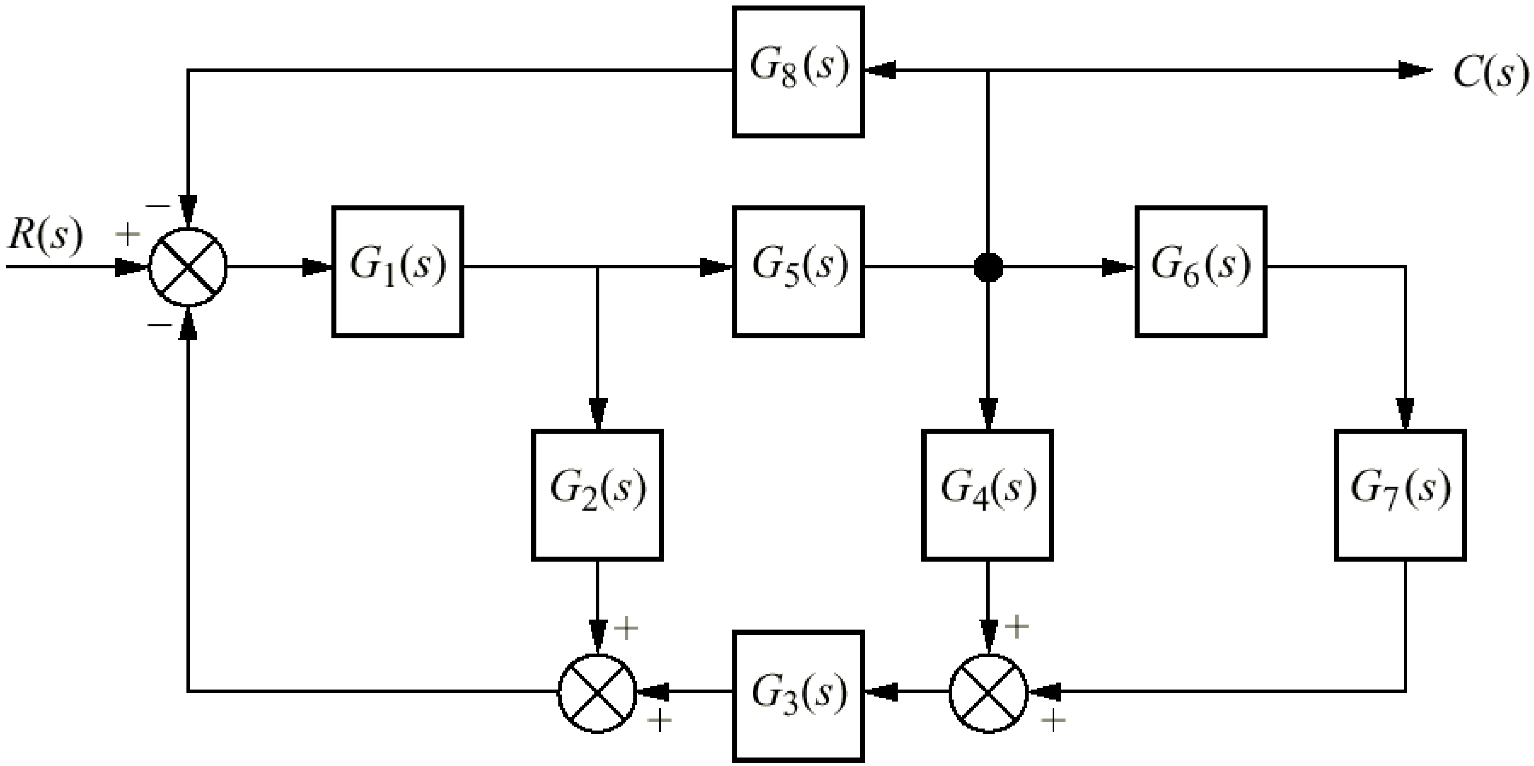



**Figure P5.5**

# Figure P5.6



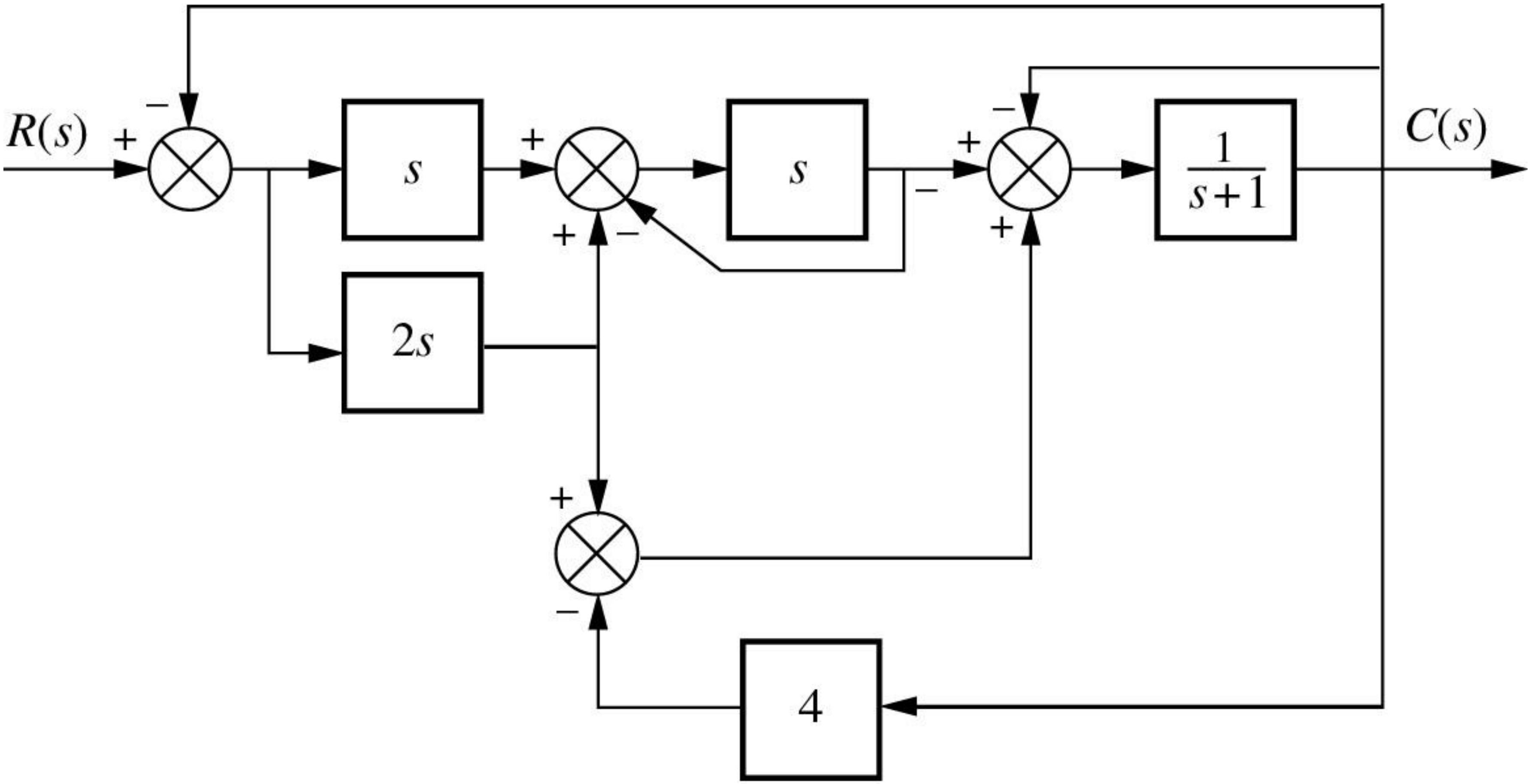
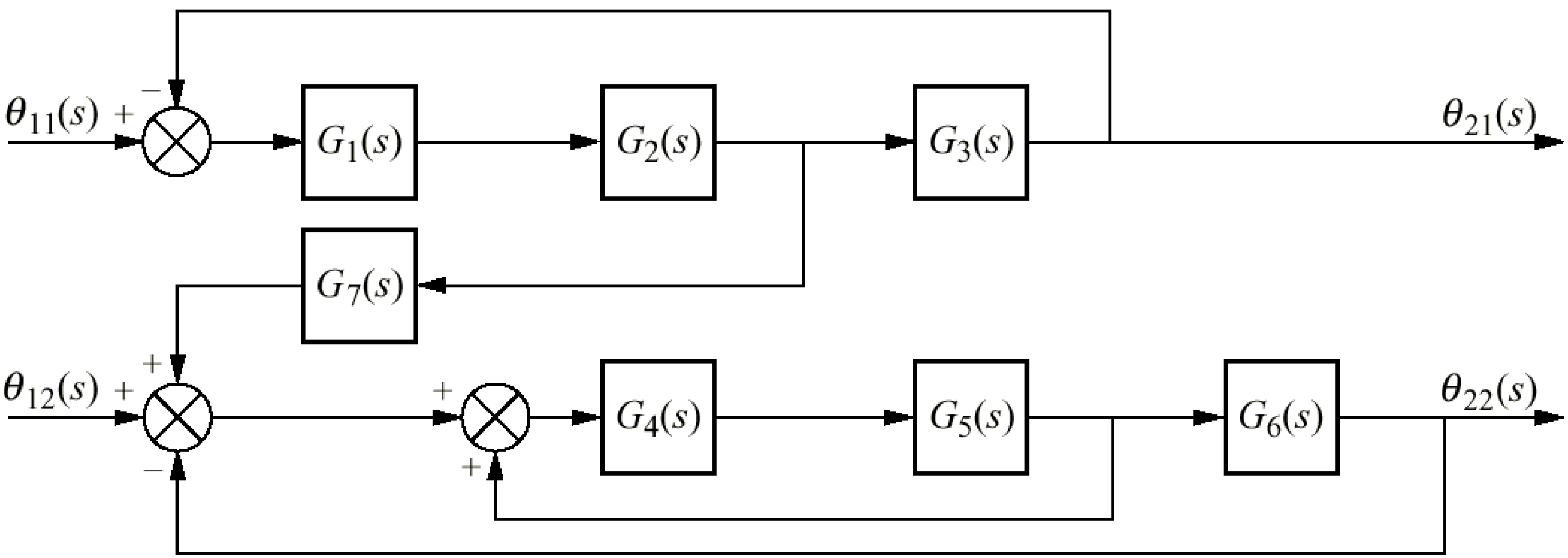


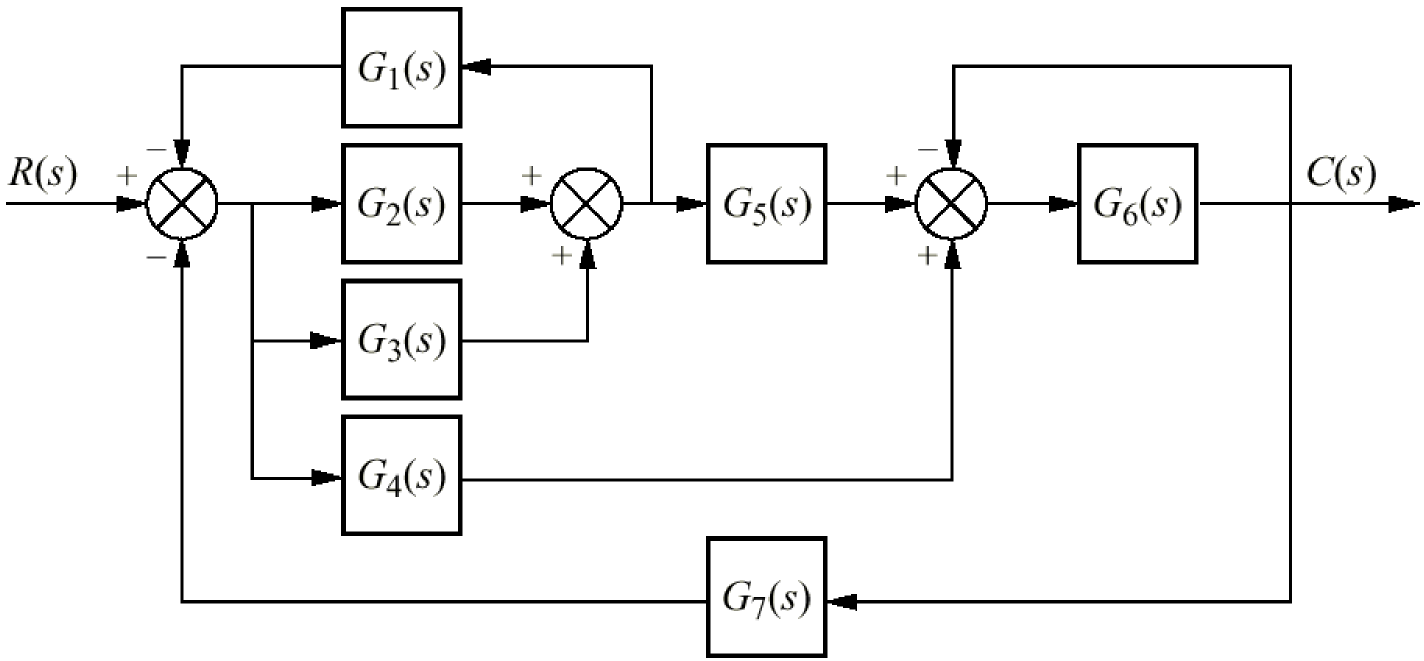

**Figure P5-7  (p. 303)**

# Figure P5.8



$\theta_{11}(s)$
+
−
$G_1(s)$
$G_2(s)$
$G_3(s)$
$\theta_{21}(s)$
$G_7(s)$
$\theta_{12}(s)$
+
+
−
+
+
$G_4(s)$
$G_5(s)$
$G_6(s)$
$\theta_{22}(s)$

# Figure P5.9



# Figure P5.10

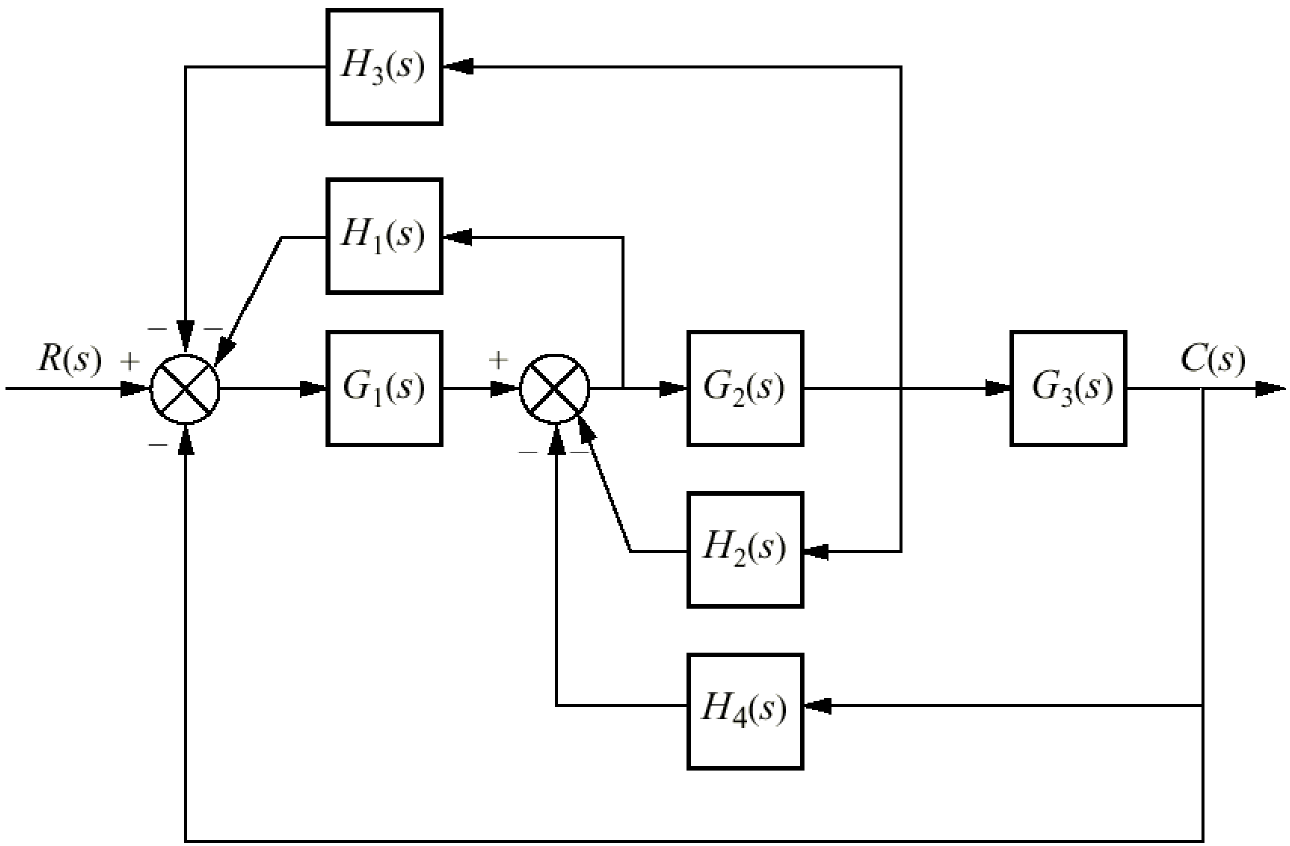
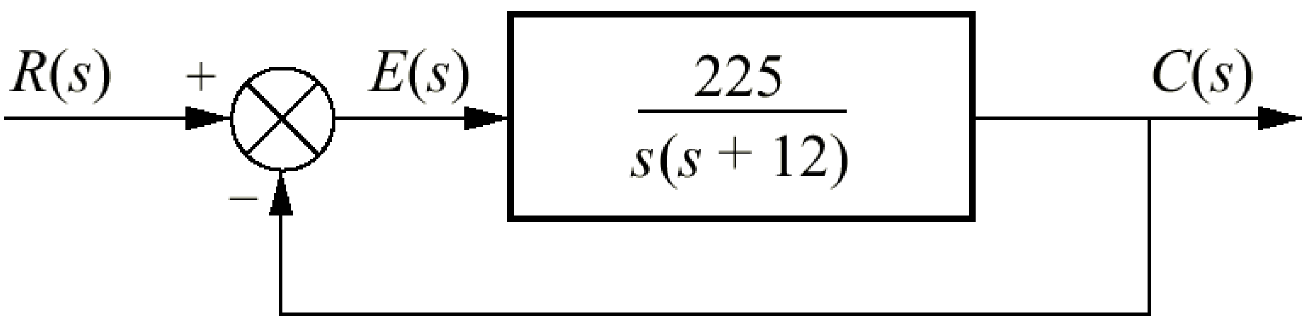


**Figure P5.11**



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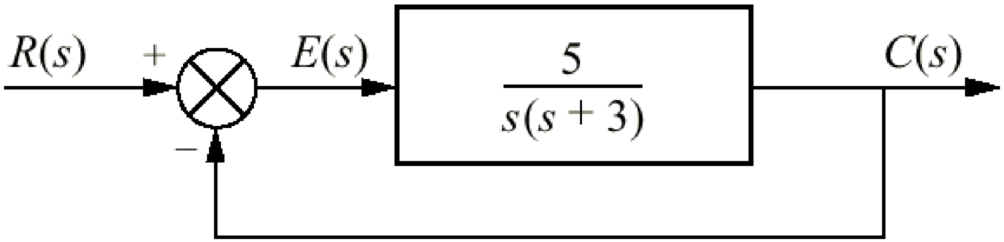

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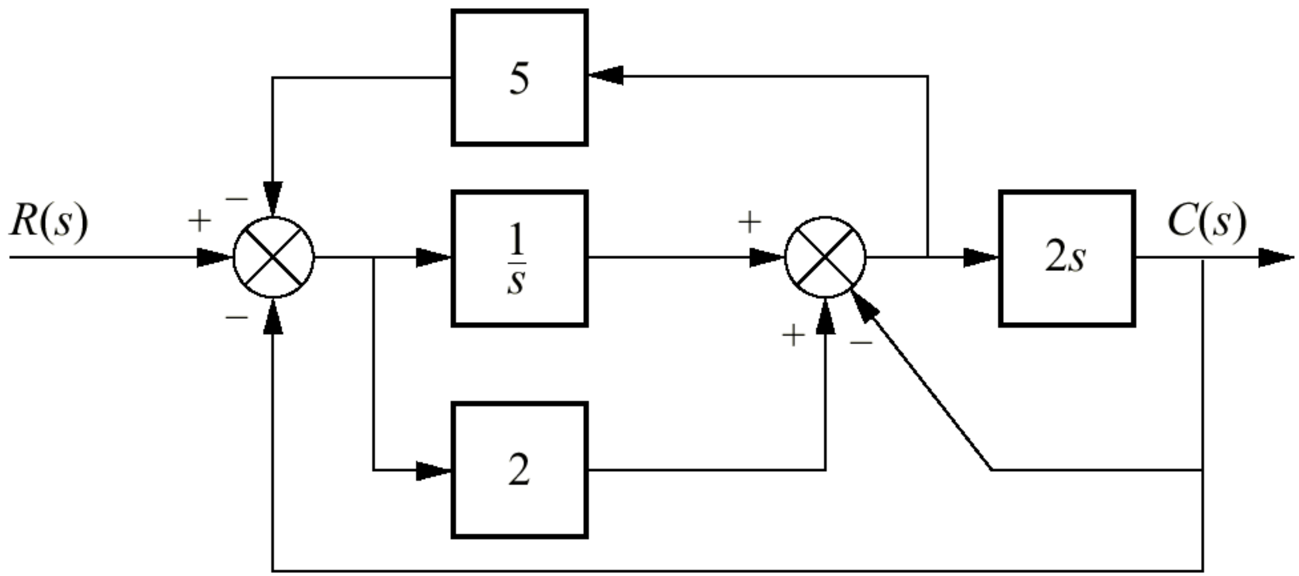


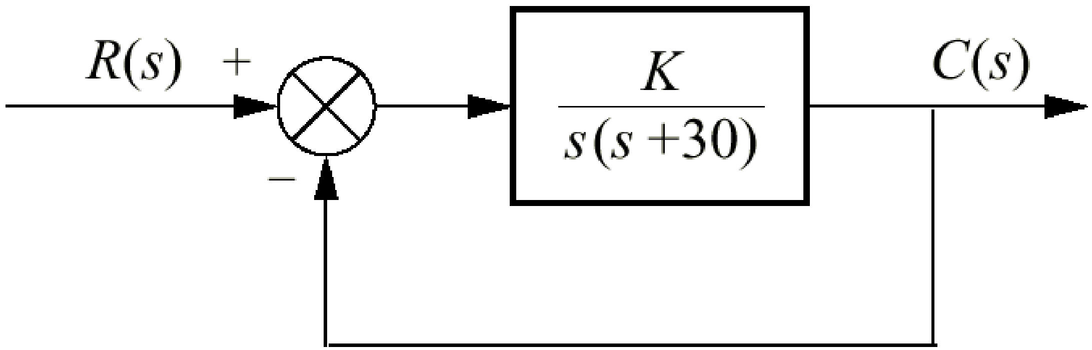
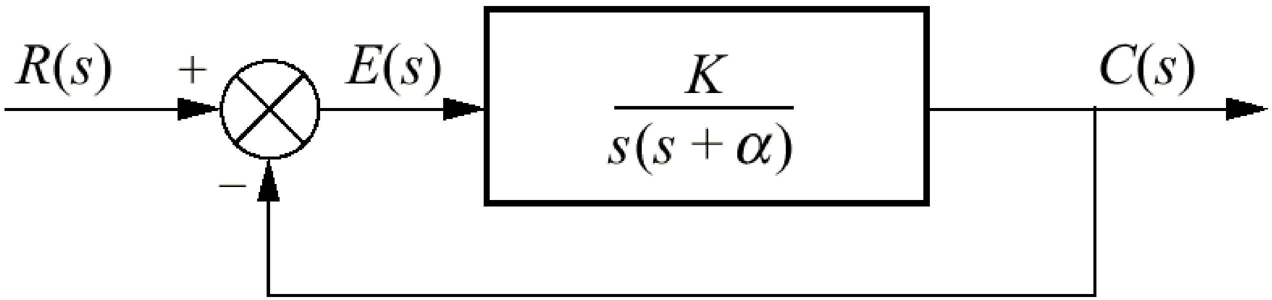



**Figure P5.14**

## Figure P5.15



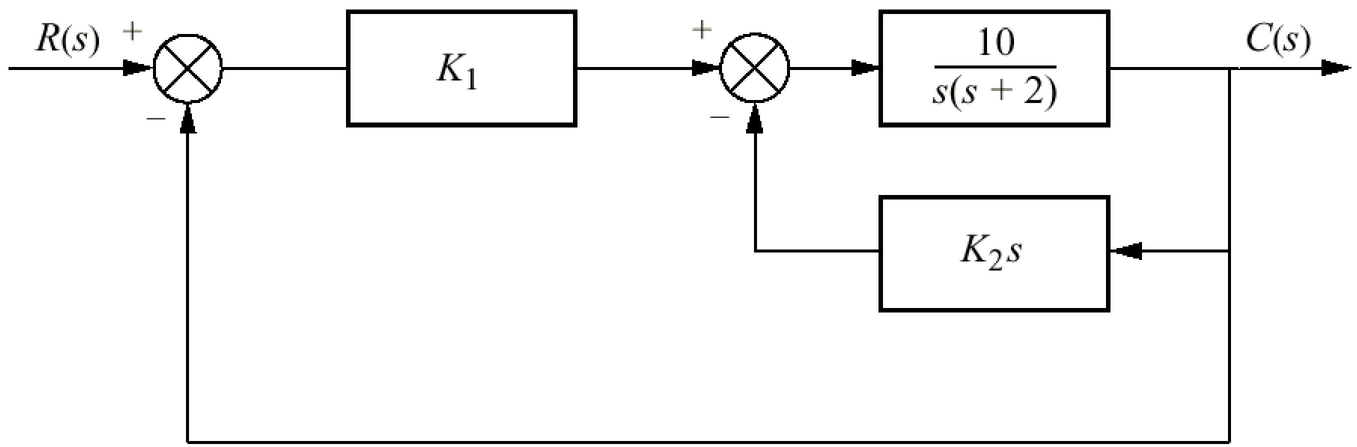
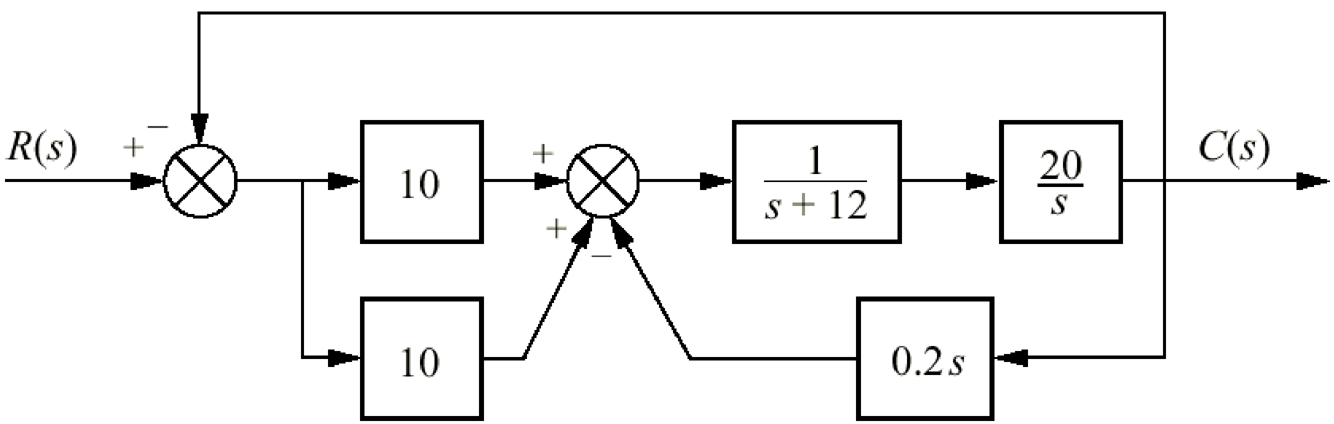
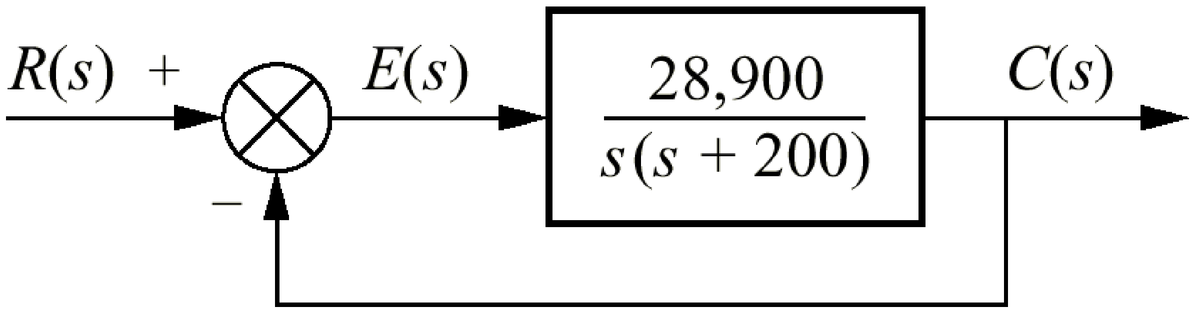



**Figure P5.16**

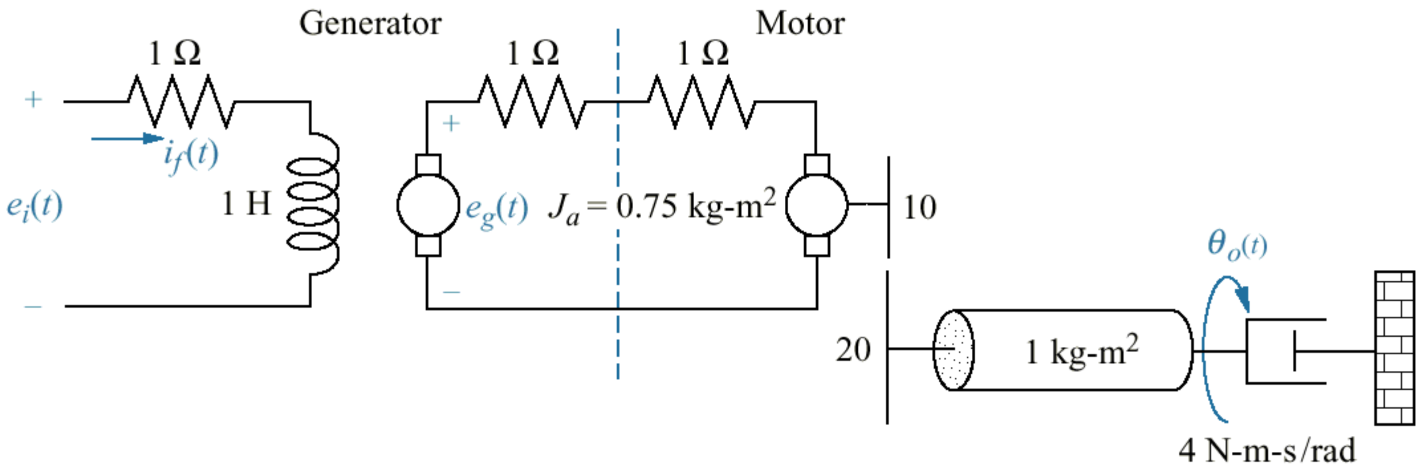
## Figure P5.17



## Figure P5.18



# Figure P5.19



Generator
Motor
1 Ω
1 Ω
1 Ω
+
−
$i_f(t)$
$e_i(t)$
1 H
+
−
$e_g(t)$
$J_a = 0.75$ kg-m²
10
20
$\theta_o(t)$
1 kg-m²
4 N-m-s/rad

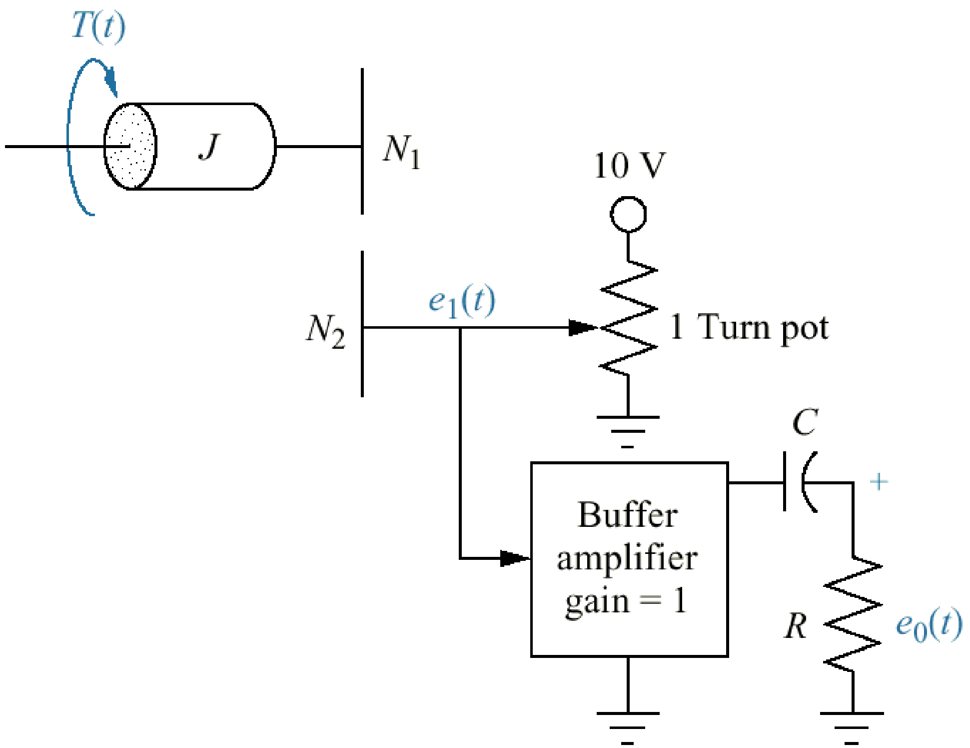



Figure P5.20

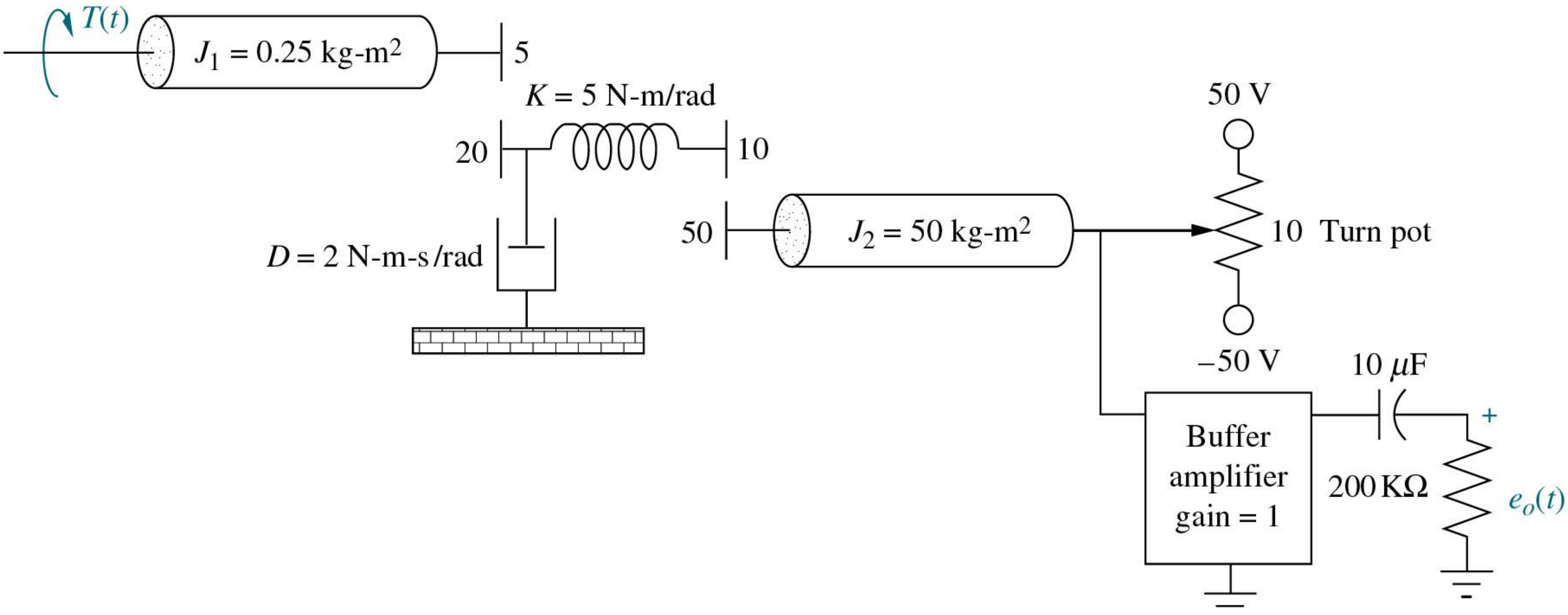
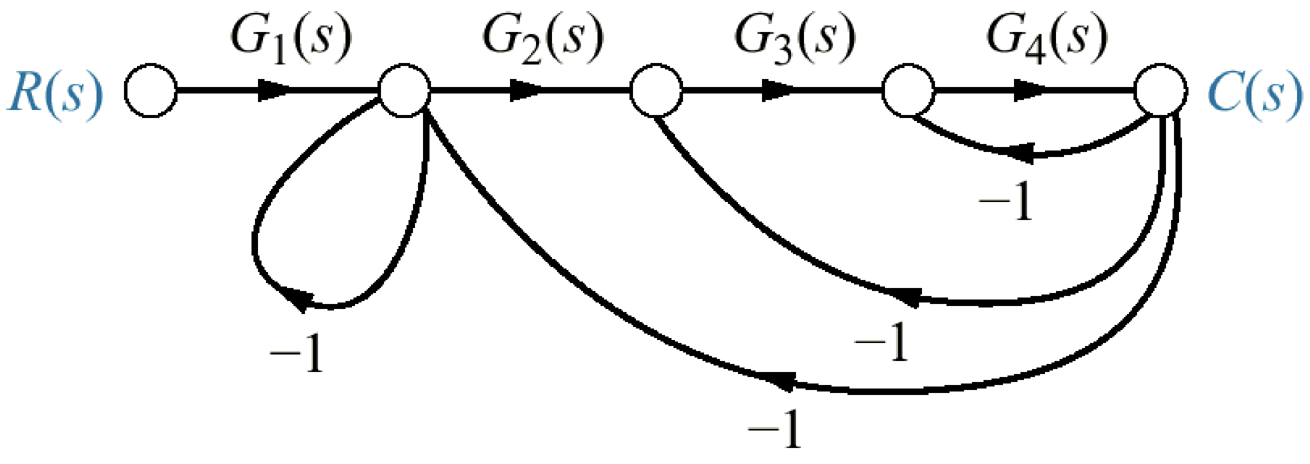



**Figure P5-21 (p. 307)**

## Figure P5.22



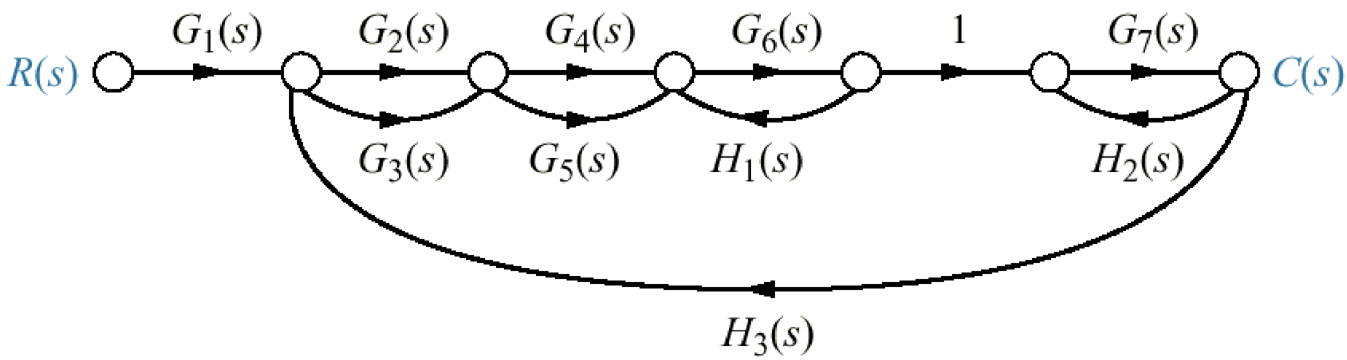
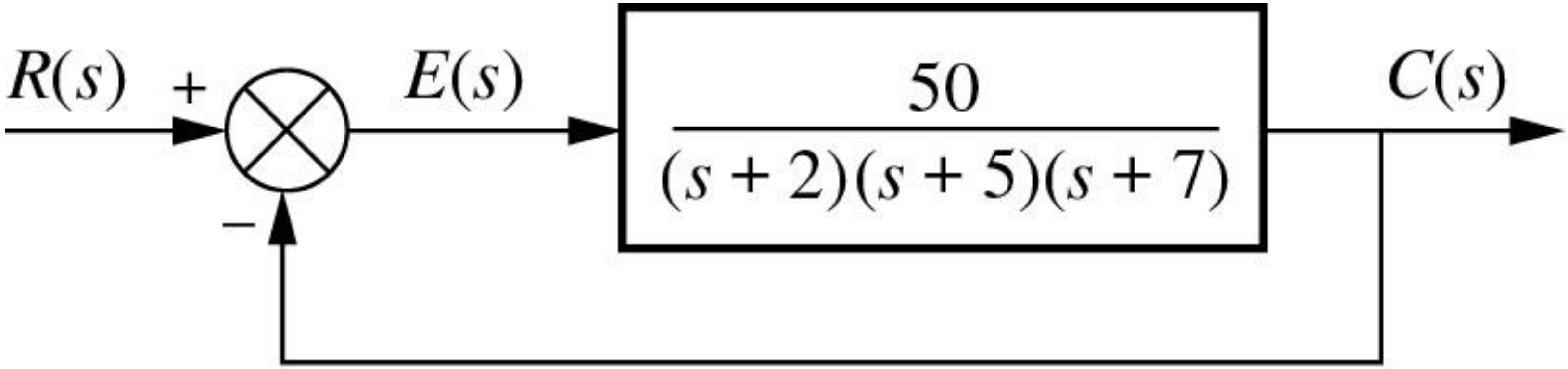
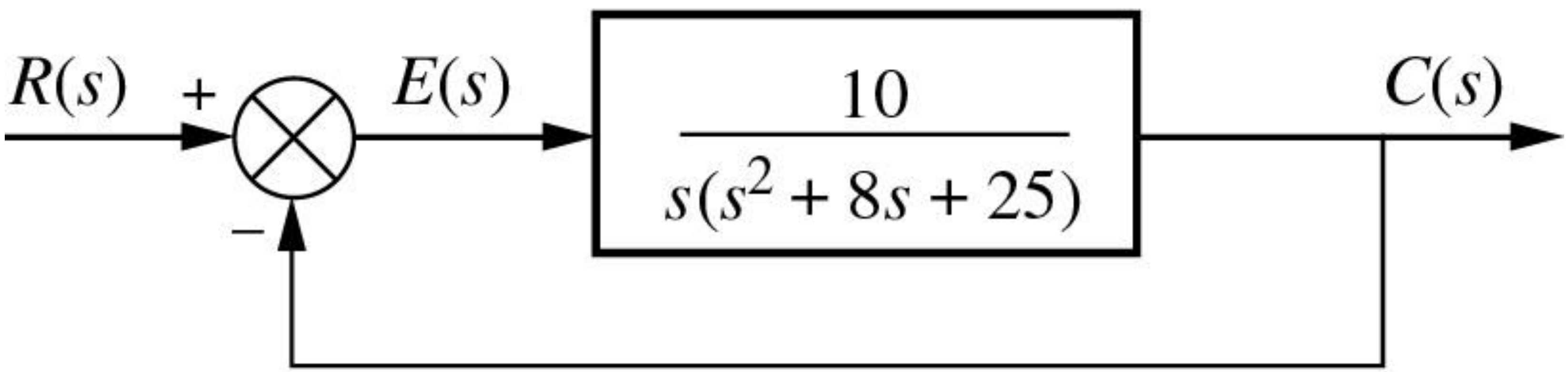



**Figure P5.23**

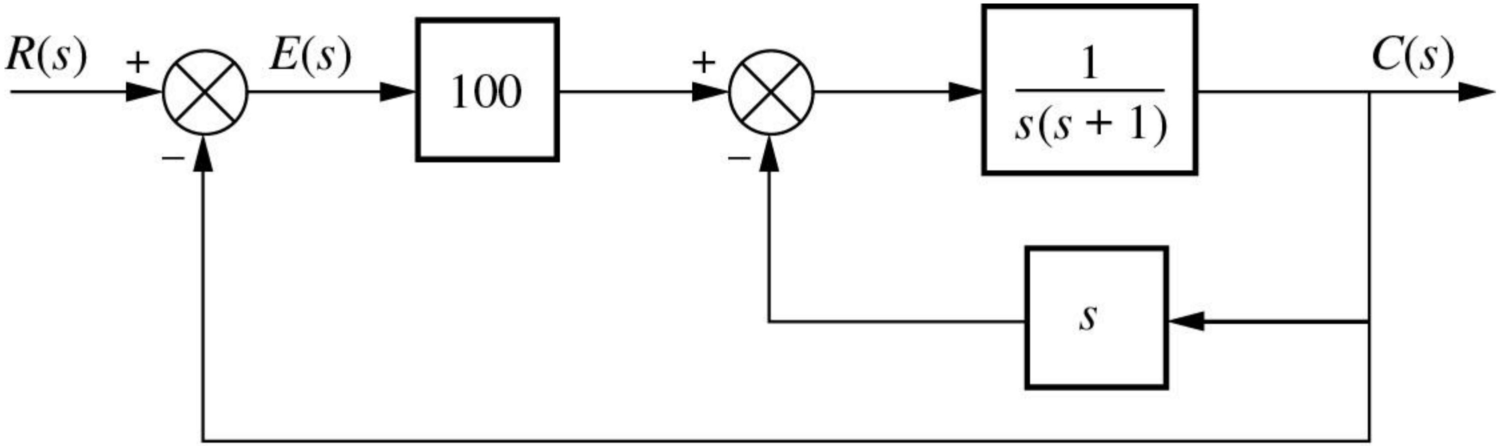



(a)

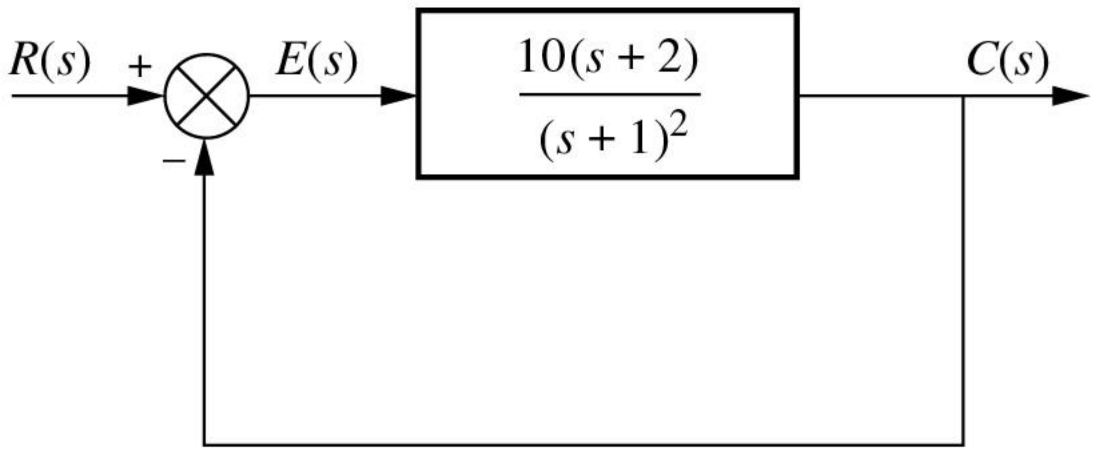



(b)

**Figure P5-24a (p. 309)**



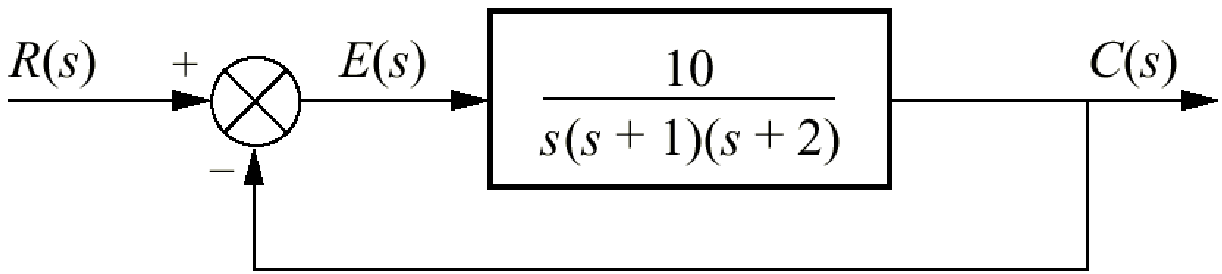

(c)



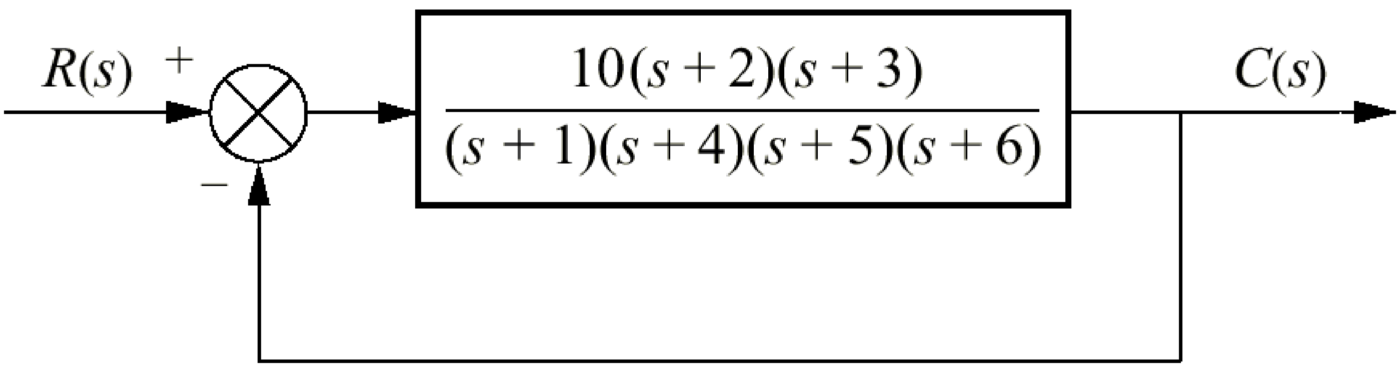

(d)

**Figure P5-24b (p. 310)**

# Figure P5.25



# Figure P5.26



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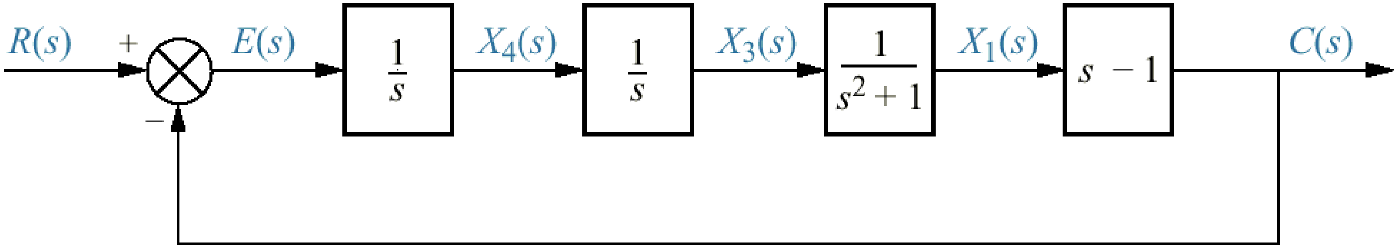
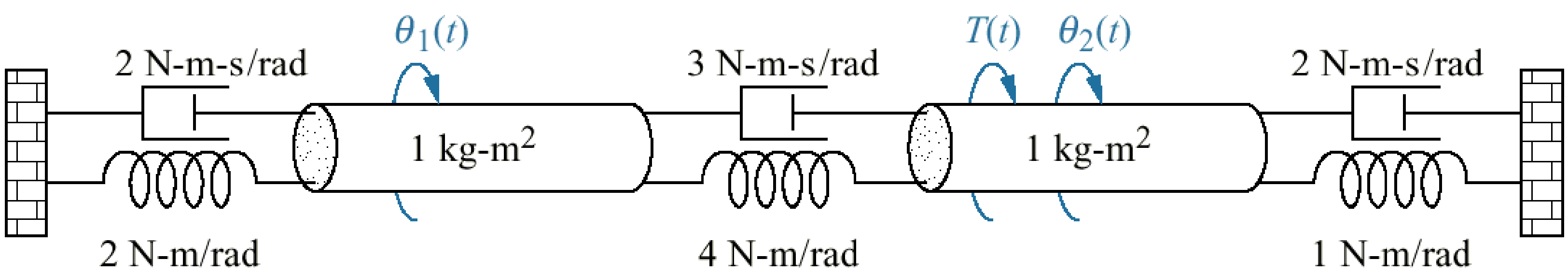
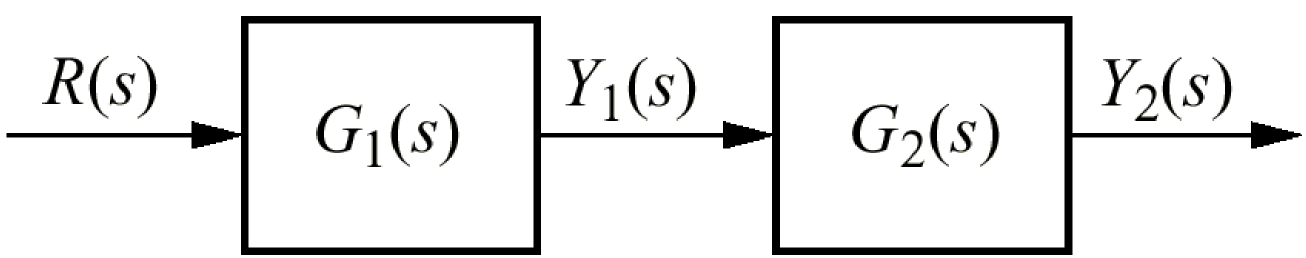




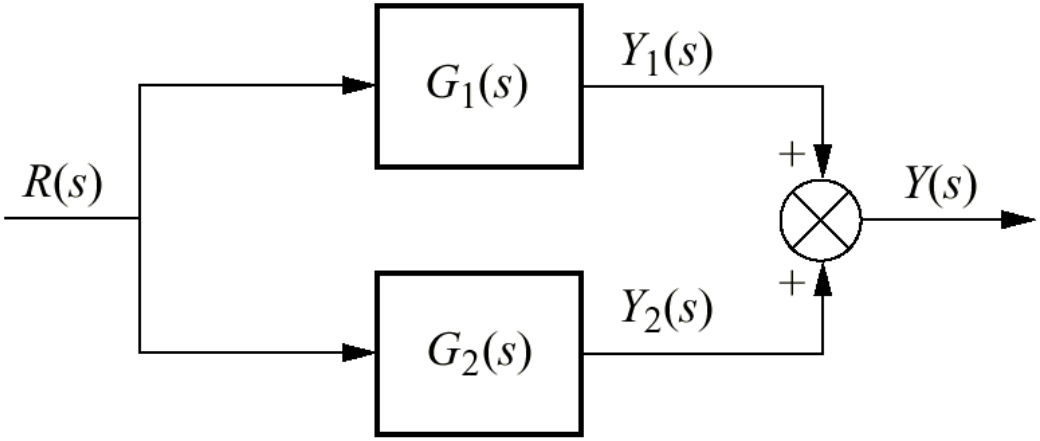
$\theta_1(t)$
$T(t)$
$\theta_2(t)$
2 N-m-s/rad
3 N-m-s/rad
2 N-m-s/rad
1 kg-m$^2$
1 kg-m$^2$
2 N-m/rad
4 N-m/rad
1 N-m/rad


**Figure P5.28**

**Figure P5.29**



# Figure P5.30



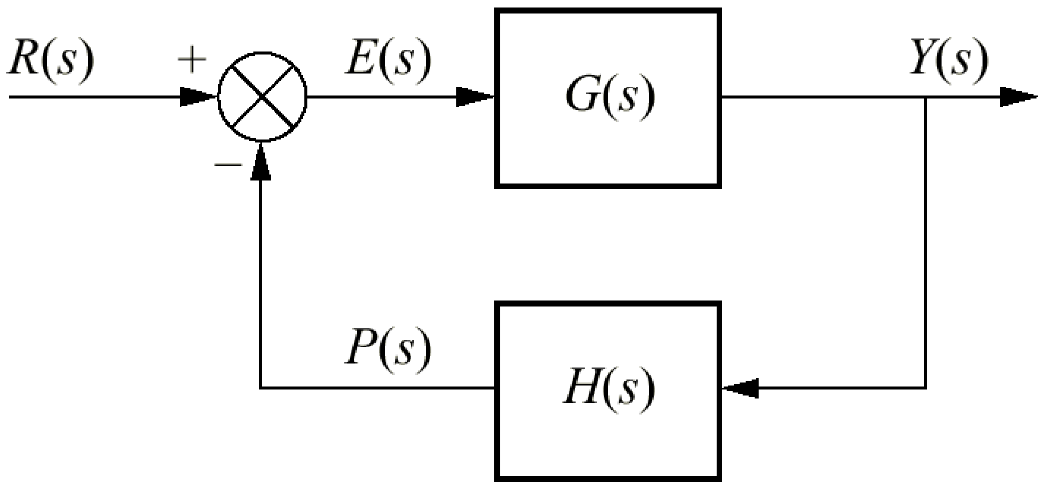
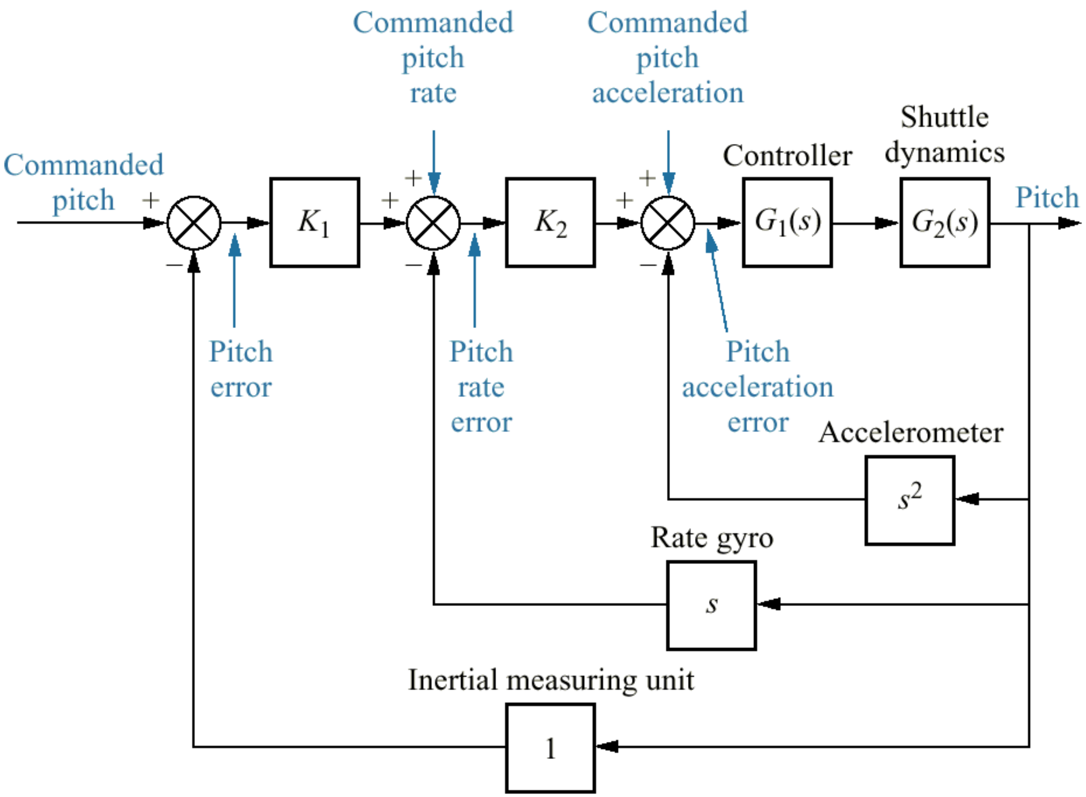



**Figure P5.31**

**Figure P5.32**
Space shuttle pitch control system (simplified)



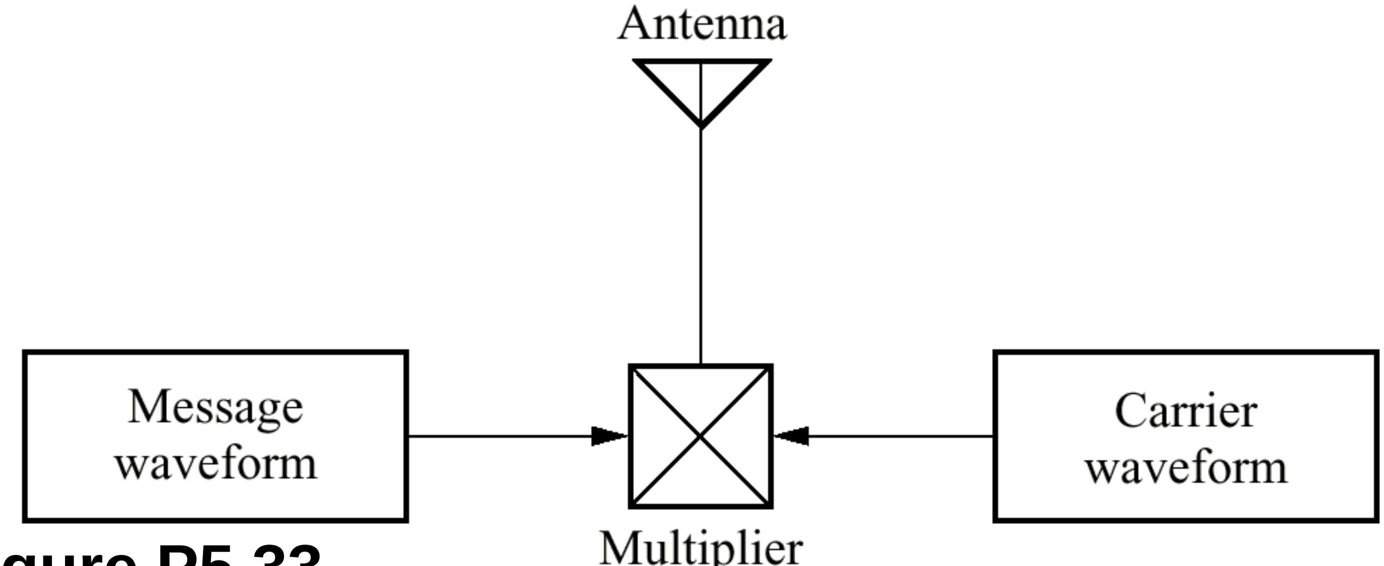



**Figure P5.33**
AM modulator

**Figure P5.34**

Feedback control system representing human eye movement

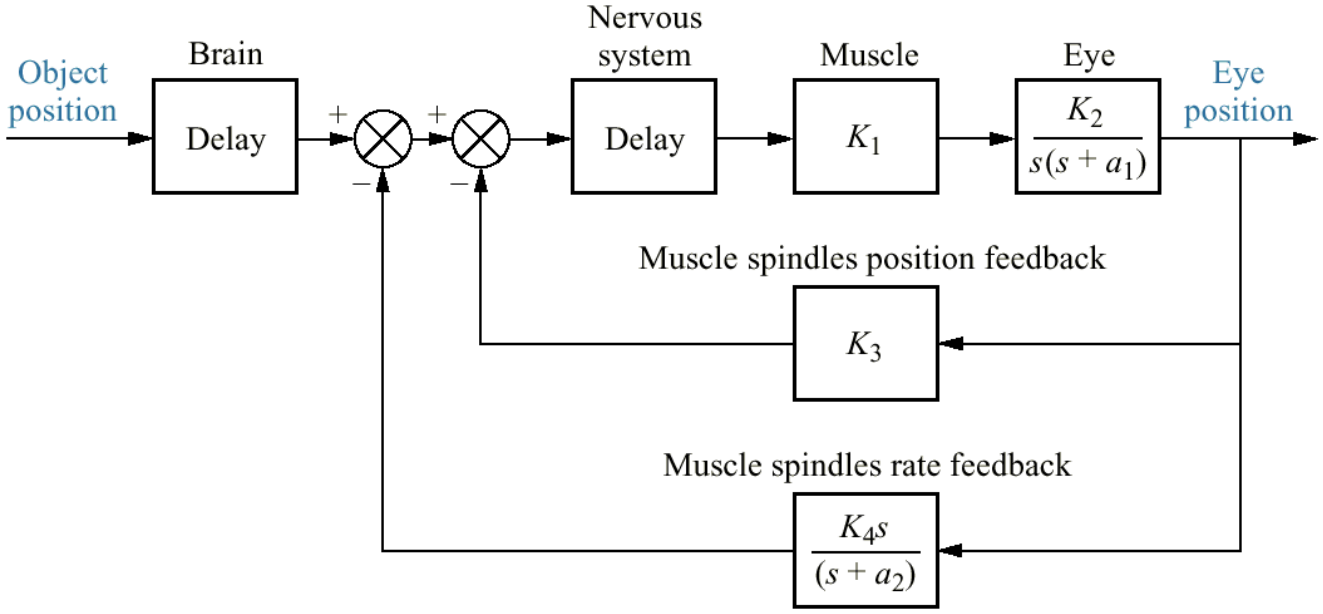
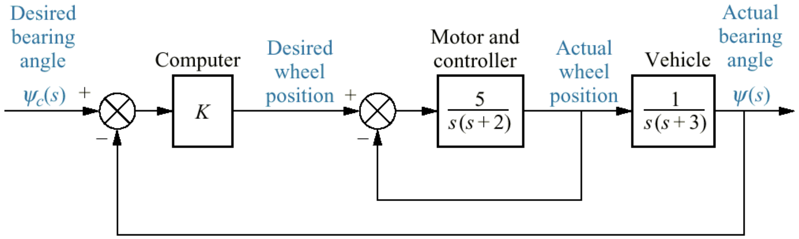


**Figure P5.35**
**a.** HelpMate robot used for in-hospital deliveries;
**b.** simplified block diagram for bearing angle control

Courtesy of Hank Morgan/Rainbow/PNI.

(*a*)




(*b*)

**Figure P5.36**
**a.** Load tester (© 1992 IEEE);
**b.** approximate block diagram

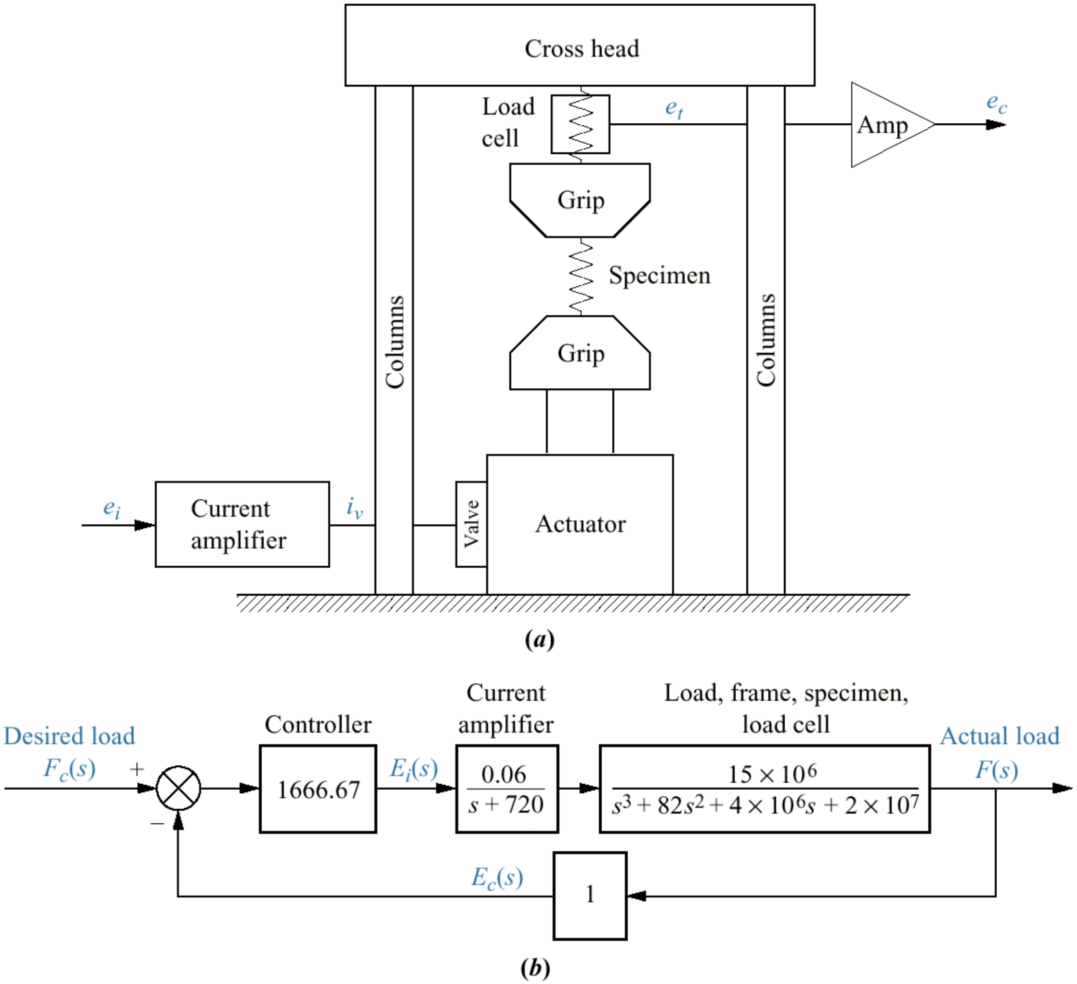


**Figure P5.37**
Solenoid coil circuit

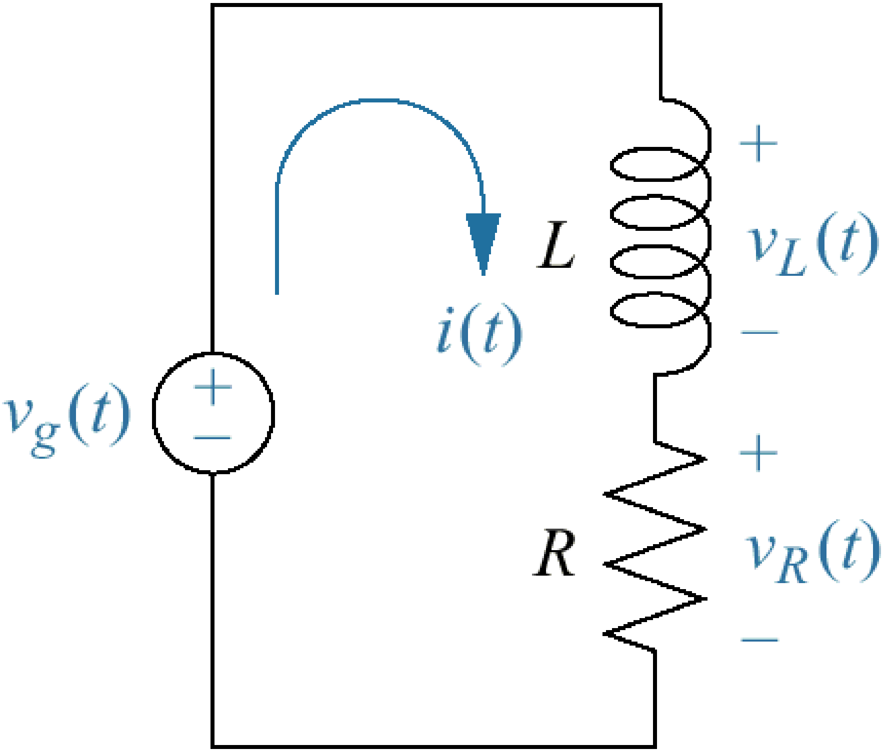


**Figure P5.38**
**a.** Position control: motor and load;
**b.** block diagram

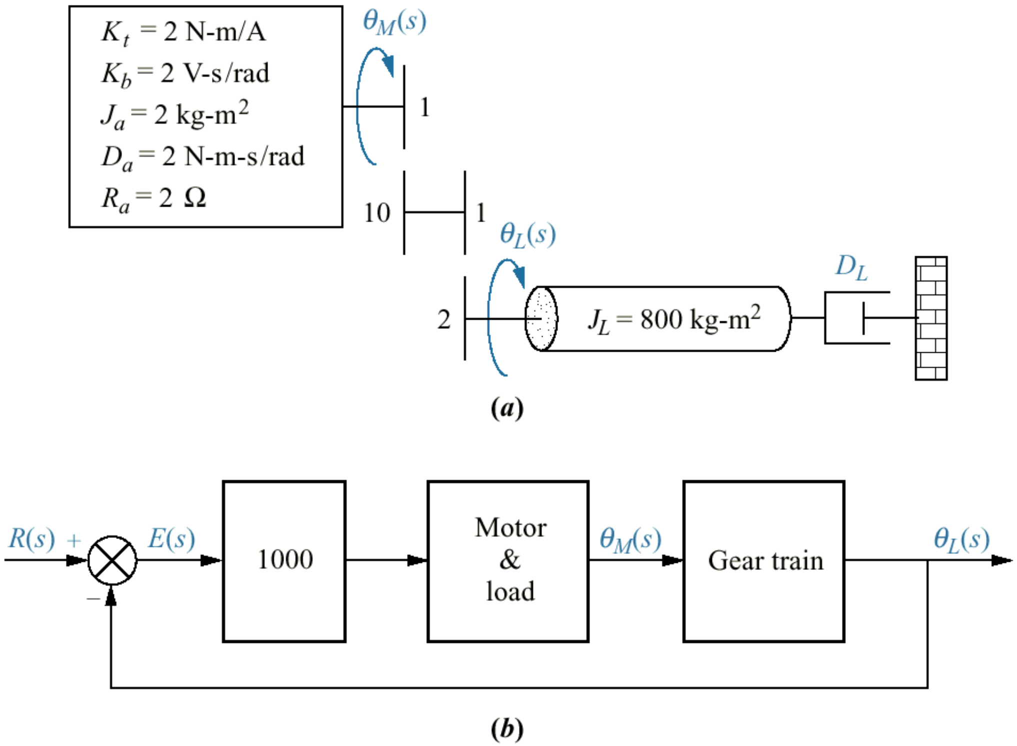


**Figure P5.39**
**a.** Position control;
**b.** position control with tachometer

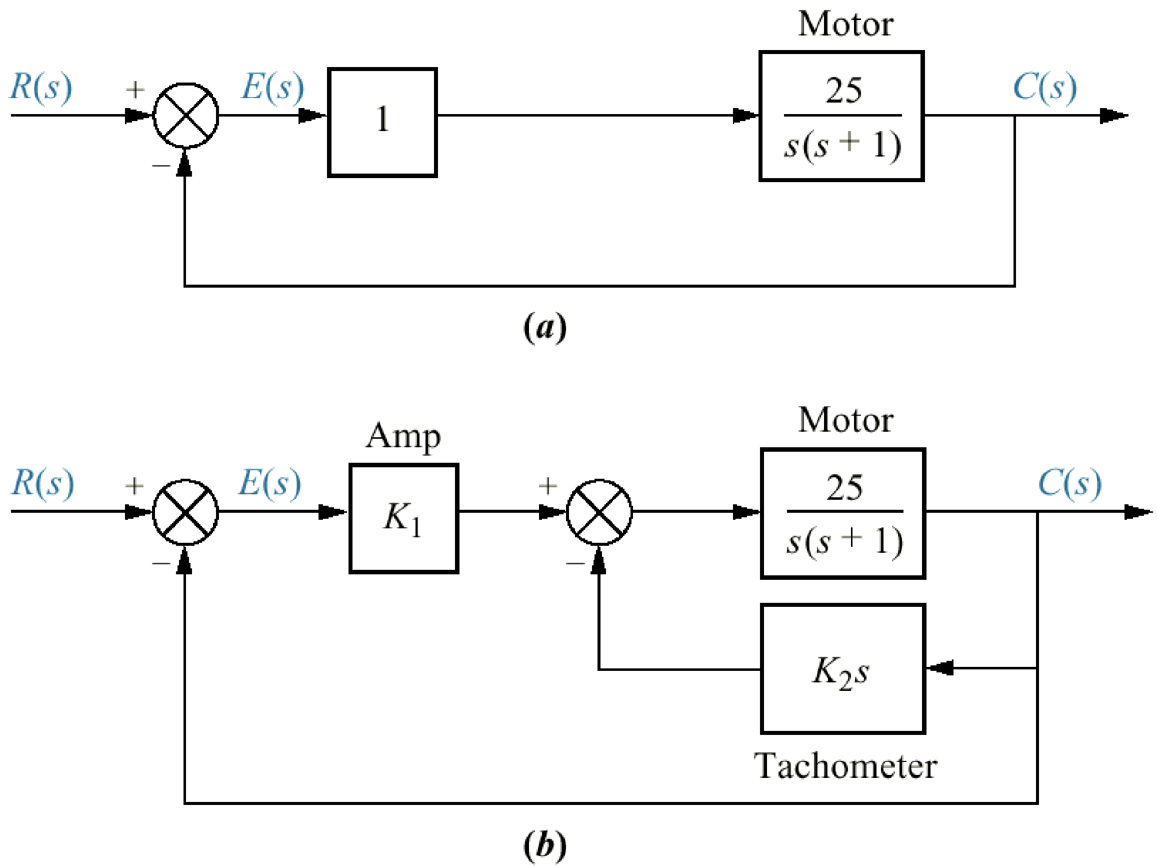


**Figure P5.40**

Position control

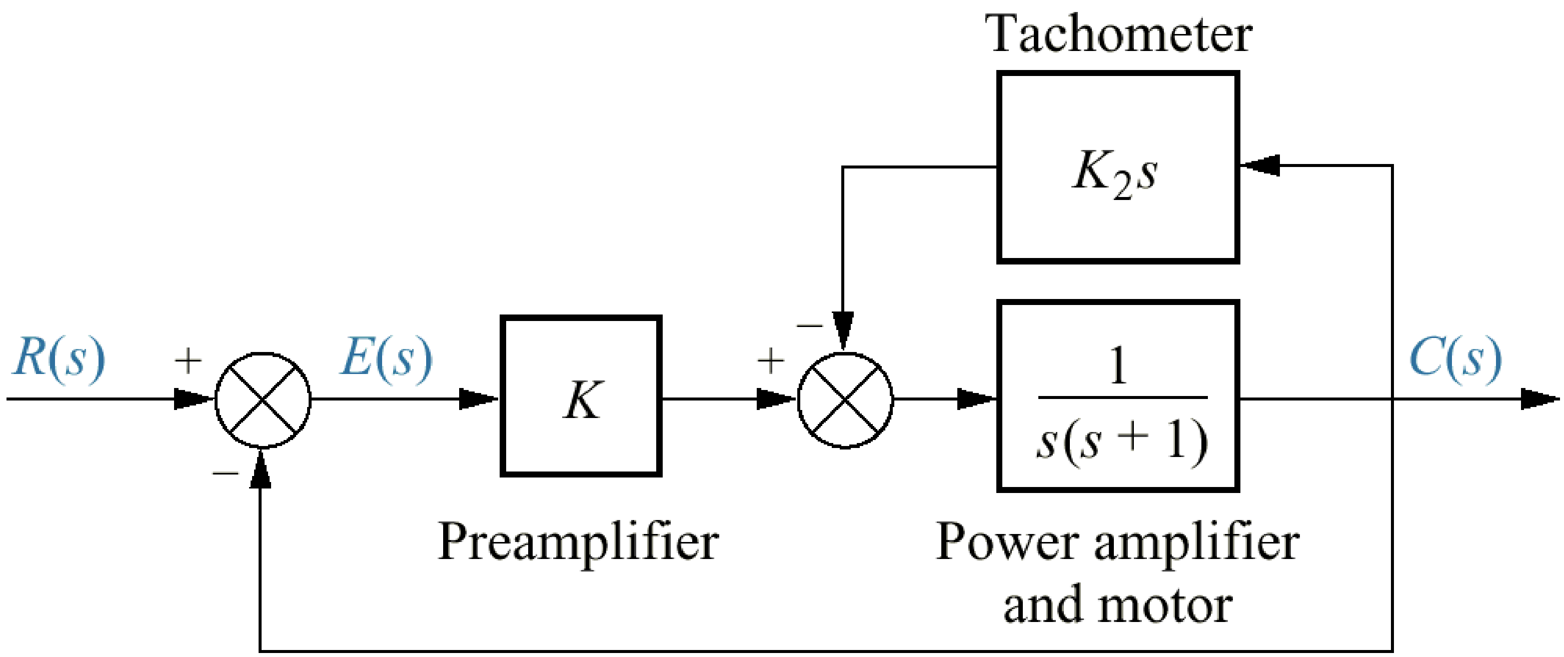


**Figure P5.41**

**a.** Motor and load;

**b.** Motor and load in feedback system