E10.8 A unity feedback system has a plant

$$G(s) = \frac{2257}{s(\tau s + 1)},$$

where $\tau = 2.8$ ms. Select a compensator

$$G_c(s) = K_P + K_I/s,$$

so that the dominant roots of the characteristic equation have damping ratio equal to $\zeta = 1/\sqrt{2}$. Plot $y(t)$ for a step input.

E10.9 A control system with a controller is shown in Figure E10.9. Select K_P and K_I so that the percent overshoot to a step input is $P.O. = 5\%$ and the velocity constant K_v is equal to 5. Verify the results of your design.

E10.10 A control system with a controller is shown in Figure E10.10. Select $K_I = 2$ in order to provide a reasonable steady-state error to a step [8]. Find K_P to obtain a phase margin of $P.M. = 60°$. Find the peak time and percent overshoot of this system.

E10.11 A unity feedback system has

$$G(s) = \frac{1350}{s(s+2)(s+30)}.$$

A lead network is selected so that

$$G_c(s) = \frac{1 + 0.25s}{1 + 0.025s}.$$

Determine the peak magnitude and the bandwidth of the closed-loop frequency response using (a) the Nichols chart, and (b) a plot of the closed-loop frequency response.

Answer: $M_{pw} = 2.3$ dB, $\omega_B = 22$

E10.12 The control of an automobile ignition system has unity feedback and a loop transfer function $L(s) = G_c(s)G(s)$, where

$$G(s) = \frac{K}{s(s+5)} \quad \text{and} \quad G_c(s) = K_P + K_I/s.$$

Let $K_I/K_P = 0.5$ and determine KK_P so that the complex roots have a damping ratio of $\zeta = 1/\sqrt{2}$.

E10.13 The design of Example 10.3 determined a lead network in order to obtain desirable dominant root locations using a cascade compensator $G_c(s)$ in the system configuration shown in Figure 10.1(a). The same lead network would be obtained if we used the feedback compensation configuration of Figure 10.1(b). Determine the closed-loop transfer function $T(s) = Y(s)/R(s)$ of both the cascade and feedback configurations, and show how the transfer function of each configuration differs. Explain how the response to a step $R(s)$ will be different for each system.

E10.14 A robot will be operated by NASA to build a permanent lunar station. The unity feedback position control system for the gripper tool has the process transfer function

$$G(s) = \frac{5}{s(s+1)(0.25s+1)}.$$

Determine a phase-lag compensator $G_c(s)$ that will provide a phase margin of $P.M. = 45°$.

Answer: $G_c(s) = \dfrac{1 + 7.5s}{1 + 110s}$

E10.15 A unity feedback control system has a plant transfer function

$$G(s) = \frac{40}{s(s+2)}.$$

We desire to attain a steady-state error to a ramp $r(t) = At$ of less than $0.05A$ and a phase margin of $P.M. = 30°$. We desire to have a crossover frequency $\omega_c = 10$ rad/s. Determine whether a phase-lead or a phase-lag compensator is required.

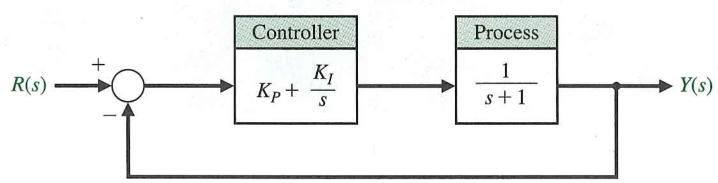


FIGURE E10.9 Design of a controller.

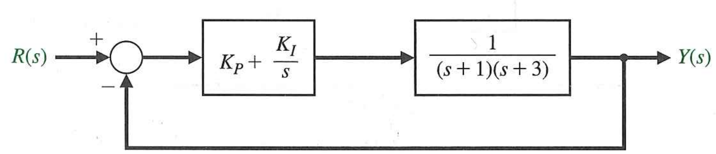


FIGURE E10.10 Design of a PI controller.

E10.16 Consider again the system and specifications of Exercise E10.15 when the required crossover frequency is $\omega_c = 2$ rad/s.

E10.17 Consider again the system of Exercise 10.9. Select K_P and K_I so that the step response is deadbeat and the settling time (with a 2% criterion) is $T_s \le 2$ s.

E10.18 The nonunity feedback control system shown in Figure E10.18 has the transfer functions

$$G(s) = \frac{1}{s - 20} \quad \text{and} \quad H(s) = 10.$$

Design a compensator $G_c(s)$ and prefilter $G_p(s)$ so that the closed-loop system is stable and meets the following specifications: (i) a percent overshoot to a unit step input of $P.O. \le 10\%$, (ii) a settling time of $T_s \le 2$ s, and (iii) zero steady-state tracking error to a unit step.

E10.19 A unity feedback control system has the plant transfer function

$$G(s) = \frac{1}{s(s-5)}.$$

Design a PID controller of the form

$$G_c(s) = K_p + K_D s + \frac{K_I}{s}$$

so that the closed-loop system has a settling time of $T_s \le 1$ s to a unit step input.

E10.20 Consider the system shown in Figure E10.20. Design the proportional-derivative controller $G_c(s)$ such that the system has a phase margin of $40° \le P.M. \le 60°$.

E10.21 Consider the unity feedback system shown in Figure E10.21. Design the controller gain, K, such that the maximum value of the output $y(t)$ in response to a unit step disturbance $T_d(s) = 1/s$ is less than 0.1.

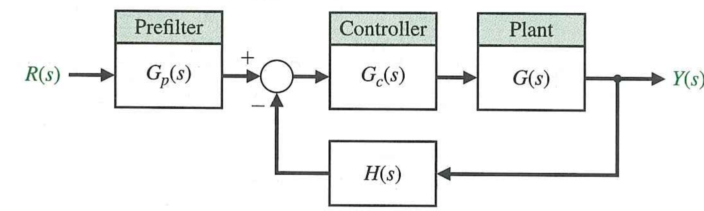


FIGURE E10.18 Nonunity feedback system with a prefilter.

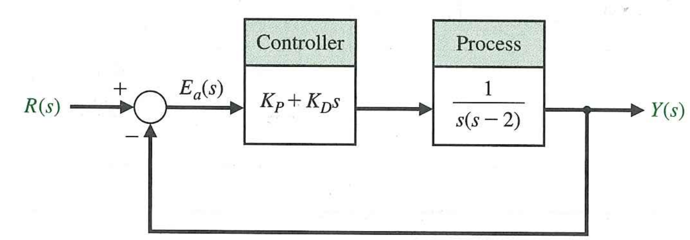


FIGURE E10.20 Unity feedback system with PD controller.

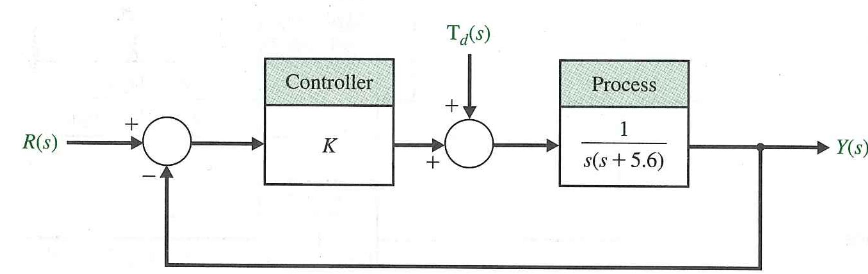


FIGURE E10.21 Closed-loop feedback system with a disturbance input.

PROBLEMS

P10.1 The design of a lunar excursion module is an interesting control problem. The attitude control system for the lunar vehicle is shown in Figure P10.1. The vehicle damping is negligible, and the attitude is controlled by gas jets. The torque, as a first approximation, will be considered to be proportional to the signal $V(s)$ so that $T(s) = K_2V(s)$. The loop gain may be selected by the designer in order to provide a suitable damping. A damping ratio of $\zeta = 0.6$ with a settling time (with a 2% criterion) of less than 2.5 seconds is required. Using a lead network compensation, select the necessary compensator $G_c(s)$ by using (a) frequency response techniques and (b) root locus methods.

P10.2 A magnetic tape recorder transport for modern computers requires a high-accuracy, rapid-response control system. The requirements for a specific transport are as follows: (1) The tape must stop or start in 10 ms, and (2) it must be possible to read 45,000 characters per second. This system is illustrated in Figure P10.2. We will use a tachometer in this case and set $K_a = 50{,}000$ and $K_2 = 1$. To provide a suitable performance, a compensator $G_c(s)$ is inserted immediately following the photocell transducer. Select a compensator $G_c(s)$ so that the percent overshoot of the system for a step input is $P.O. \leq 25\%$. We assume that $\tau_1 = 0.1$ ms, $\tau_a = 0.1$ ms, $K_1 = 2$, $R/L = 0.5$ ms, $K_b = 0.4$, $r = 0.2$, $K_T/LJ = 2.0$ and $K_p = 1$.

P10.3 A simplified version of the attitude rate control for a supersonic aircraft is shown in Figure P10.3. When the vehicle is flying at four times the speed of sound (Mach 4) at an altitude of 100,000 ft, the parameters are [26]

$$\tau_a = 1.0, \qquad K_1 = 0.8,$$
$$\zeta\omega_a = 1.0, \quad \text{and} \quad \omega_a = 5.$$

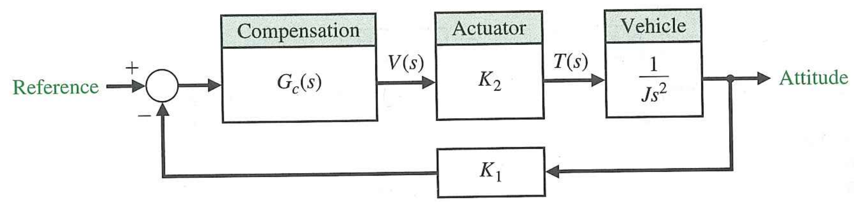


FIGURE P10.1 Attitude control system for a lunar excursion module.

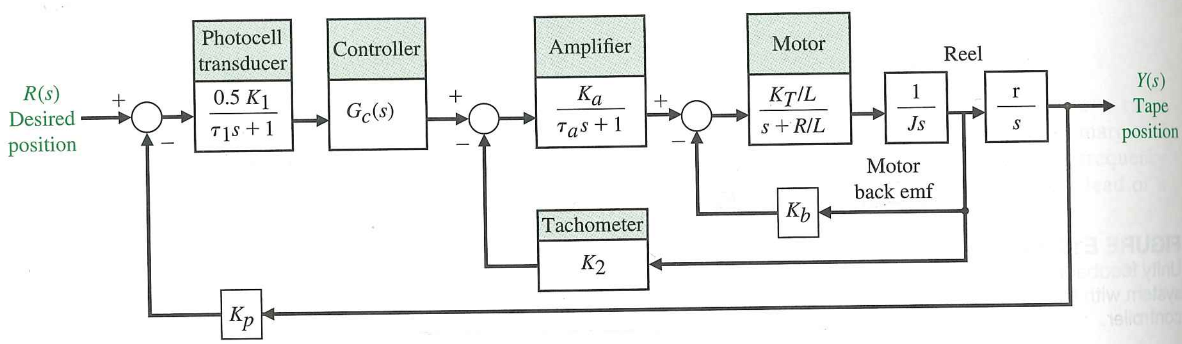


FIGURE P10.2 Block diagram of a tape control system.

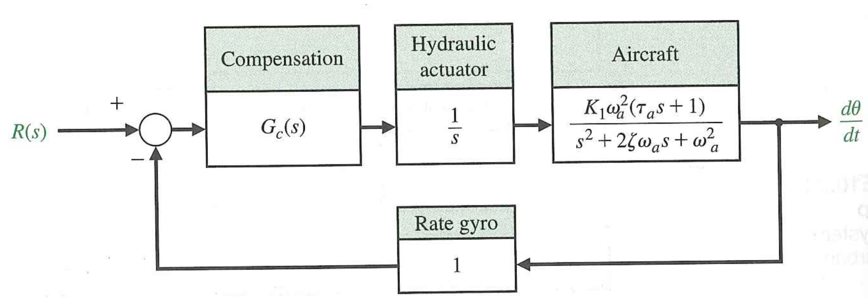


FIGURE P10.3 Aircraft attitude control.

Design a compensator $G_c(s)$ so that the response to a step input has a percent overshoot of $P.O. \leq 5\%$ and a settling time (with a 2% criterion) of $T_s \leq 5$ s.

P10.4 Magnetic particle clutches are useful actuator devices for high power requirements because they can typically provide a 200-W mechanical power output. The particle clutches provide a high torque-to-inertia ratio and fast time-constant response. A particle clutch positioning system for nuclear reactor rods is shown in Figure P10.4. The motor drives two counter-rotating clutch housings. The clutch housings are geared through parallel gear trains, and the direction of the servo output is dependent on the clutch that is energized. The time constant of a 200-W clutch is $\tau = 1/40$ s. The constants are such that $K_Tn/J = 1$. We want the maximum percent overshoot for a step input to be in the range of $10\% \leq P.O. \leq 20\%$. Design a compensator so that the system is adequately stabilized. The settling time (with a 2% criterion) of the system should be $T_s \leq 2$ s.

P10.5 A stabilized precision rate table uses a precision tachometer and a DC direct-drive torque motor, as shown in Figure P10.5. We want to maintain a high steady-state accuracy for the speed control. To obtain a zero steady-state error for a step command design, select a proportional plus integral compensator. Select the appropriate gain constants so that the system has a percent overshoot of $P.O. = 10\%$ and a settling time (with a 2% criterion) of $T_s \leq 1.5$ s.

P10.6 Repeat Problem P10.5 by using a phase-lead compensator and compare the results.

P10.7 A chemical reactor process whose production rate is a function of catalyst addition is shown in block diagram form in Figure P10.7 [10]. The time delay is $T = 50$ s, and the time constant τ is approximately 40 s. The gain of the process is $K = 1$. Design a compensator using Bode plot methods in order to provide a suitable system response. We want to have a steady-state error less than $0.10A$ for a step input $R(s) = A/s$. For the system with the compensation added, estimate the settling time of the system.

P10.8 A numerical path-controlled machine turret lathe is an interesting problem in attaining sufficient accuracy [2, 23]. A block diagram of a turret lathe control system is shown in Figure P10.8. The gear ratio is

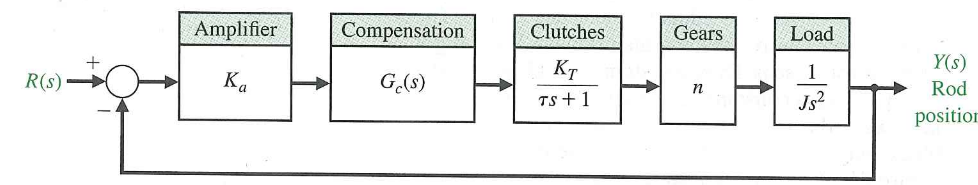


FIGURE P10.4 Nuclear reactor rod control.

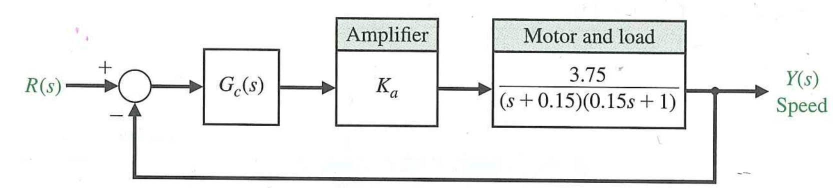


FIGURE P10.5 Stabilized rate table.

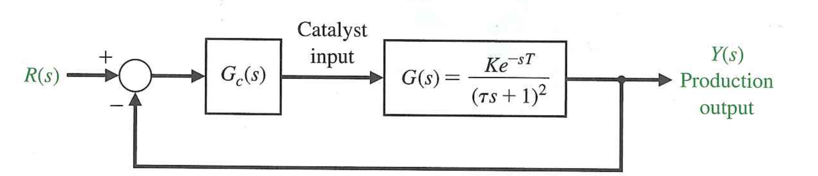


FIGURE P10.7 Chemical reactor control.

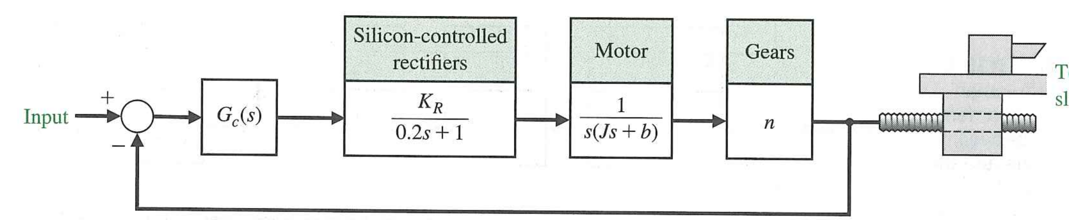


FIGURE P10.8 Path-controlled turret lathe.

$n = 0.2$, $J = 10^{-3}$, and $b = 2.0 \times 10^{-2}$. It is necessary to attain an accuracy of 5×10^{-4} in., and therefore a steady-state position accuracy of 2.5% is specified for a ramp input. Design a cascade compensator to be inserted before the silicon-controlled rectifiers in order to provide a response to a step command with a percent overshoot of $P.O. \leq 5\%$. A suitable damping ratio for this system is $\zeta = 0.7$. The gain of the silicon-controlled rectifiers is $K_R = 5$. Design a suitable phase-lag compensator.

P10.9 The Avemar ferry, shown in Figure P10.9(a), is a large 670-ton ferry hydrofoil built for Mediterranean ferry service. It is capable of 45 knots (52 mph) [29]. The boat's appearance, like its performance, derives from the innovative design of the narrow "wavepiercing" hulls which move through the water like racing shells. Between the hulls is a third quasihull which gives additional buoyancy in rough seas. Loaded with 900 passengers and crew, and a mix of cars, buses, and freight cars trucks, one of the boats can carry almost its own weight. The Avemar is capable of operating in seas with waves up to 8 ft in amplitude at a speed of 40 knots as a result of an automatic stabilization control system. Stabilization is achieved by means of flaps on the main foils and the adjustment of the aft foil. The stabilization control system maintains a level flight through rough seas. Thus, a system that minimizes deviations from a constant lift force or, equivalently, that minimizes the pitch angle $\theta(t)$ has been designed. A block diagram of the lift control system is shown in Figure P10.9(b). The desired response of the system to wave disturbance is a constant-level travel of the craft. Establish a set of reasonable specifications and design a compensator $G_c(s)$ so that the performance of the system is suitable. Assume that the disturbance is due to waves with a frequency $\omega = 6$ rad/s.

P10.10 A unity feedback system has the loop transfer function

$$L(s) = G_c(s)G(s) = G_c(s)\frac{5}{s(s^2 + 5s + 12)}.$$

(a) Determine the step response when $G_c(s) = 1$, and calculate the settling time and steady state for a ramp input $r(t) = t, t > 0$. (b) Design a phase-lag compensator using the root locus method so that the velocity constant is increased to 10. Determine the settling time (with a 2% criterion) of the compensated system.

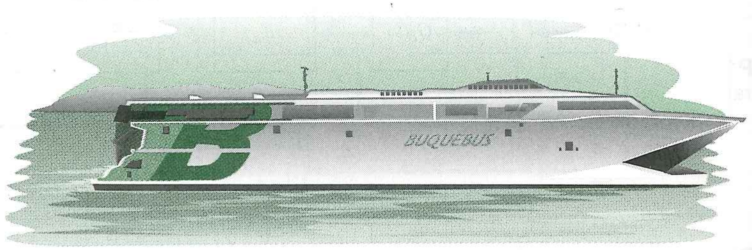
P10.11 A unity feedback control system has the loop transfer function

$$L(s) = G_c(s)G(s) = G_c(s)\frac{160}{s^2}.$$

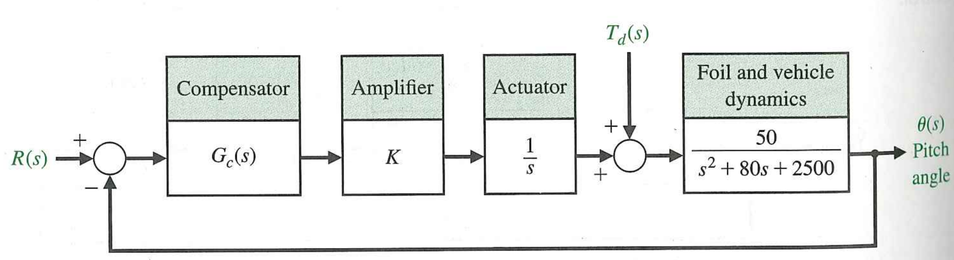
Select a lead-lag compensator so that the percent overshoot for a step input is $P.O. \leq 5\%$ and the settling time (with a 2% criterion) is $T_s \leq 1$ s. It also is desired that the acceleration constant K_a be greater than 7500.

P10.12 A unity feedback system has a plant

$$G(s) = \frac{20}{s(1 + 0.1s)(1 + 0.05s)}.$$



(a)



(b)

FIGURE P10.9 (a) The Avemar ferry built for ferry service between Barcelona and the Balearic Islands. (b) A block diagram of the lift control system.

Select a compensator $G_c(s)$ so that the phase margin is $P.M. \geq 75°$. Use a two-stage lead compensator

$$G_c(s) = \frac{K(1 + s/\omega_1)(1 + s/\omega_3)}{(1 + s/\omega_2)(1 + s/\omega_4)}.$$

It is required that the error for a ramp input be 0.5% of the magnitude of the ramp input ($K_v = 200$).

P10.13 Materials testing requires the design of control systems that can faithfully reproduce normal specimen operating environments over a range of specimen parameters [23]. From the control system design viewpoint, a materials-testing machine system can be considered a servomechanism in which we want to have the load waveform track the reference signal. The system is shown in Figure P10.13.

(a) Determine the phase margin of the system with $G_c(s) = K$, choosing K so that a phase margin of $P.M. = 50°$ is achieved. Determine the system bandwidth for this design.

(b) The additional requirement introduced is that the velocity constant K_v be equal to 2.0. Design a lag compensator so that the phase margin is $P.M. = 50°$ and $K_v = 2$.

P10.14 For the system described in Problem P10.13, the goal is to achieve a phase margin of $P.M. = 50°$ with the additional requirement that the time to settle (to within 2% of the final value) is $T_s \leq 4$ s. Design a phase-lead compensator to meet the specifications. As before, we require $K_v = 2$.

P10.15 A robot with an extended arm has a heavy load, whose effect is a disturbance, as shown in Figure P10.15 [22]. Let $R(s) = 0$ and design $G_c(s)$ so that the effect of the disturbance is less than 20% of the open-loop system effect.

P10.16 A driver and car may be represented by the simplified model shown in Figure P10.16 [17]. The goal is to have the speed adjust to a step input with a percent overshoot of $P.O. \leq 10\%$ and a settling time (with a 2% criterion) of $T_s = 1$ s. Select a proportional plus integral (PI) controller to yield these specifications. For the selected controller, determine the actual response (a) for $G_p(s) = 1$ and (b) with a prefilter $G_p(s)$ that removes the zero from the closed-loop transfer function $T(s)$.

P10.17 A unity feedback control system for a robot submarine has a plant with a third-order transfer function [20]:

$$G(s) = \frac{K}{s(s + 10)(s + 50)}.$$

We want the percent overshoot to be $P.O. = 7.5\%$ for a step input and the settling time (with a 2% criterion) of the system be $T_s = 400$ ms. Find a suitable lead compensator by using root locus methods. Let the

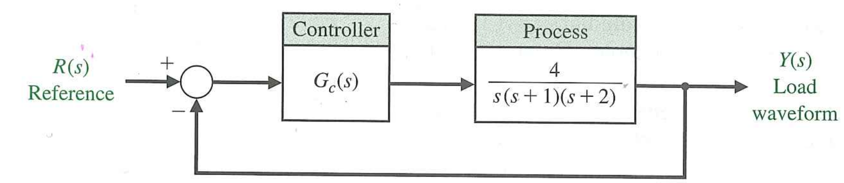


FIGURE P10.13 Materials testing machine system.

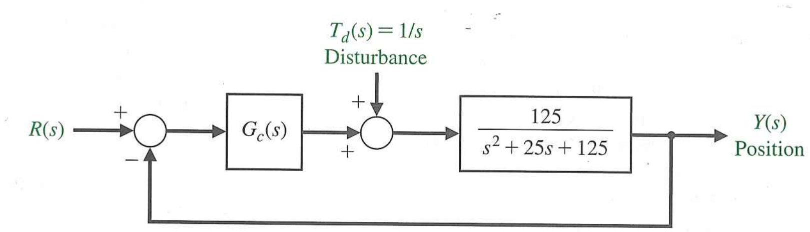


FIGURE P10.15 Robot control.

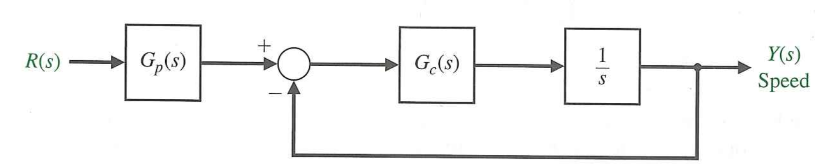


FIGURE P10.16 Speed control of an automobile.