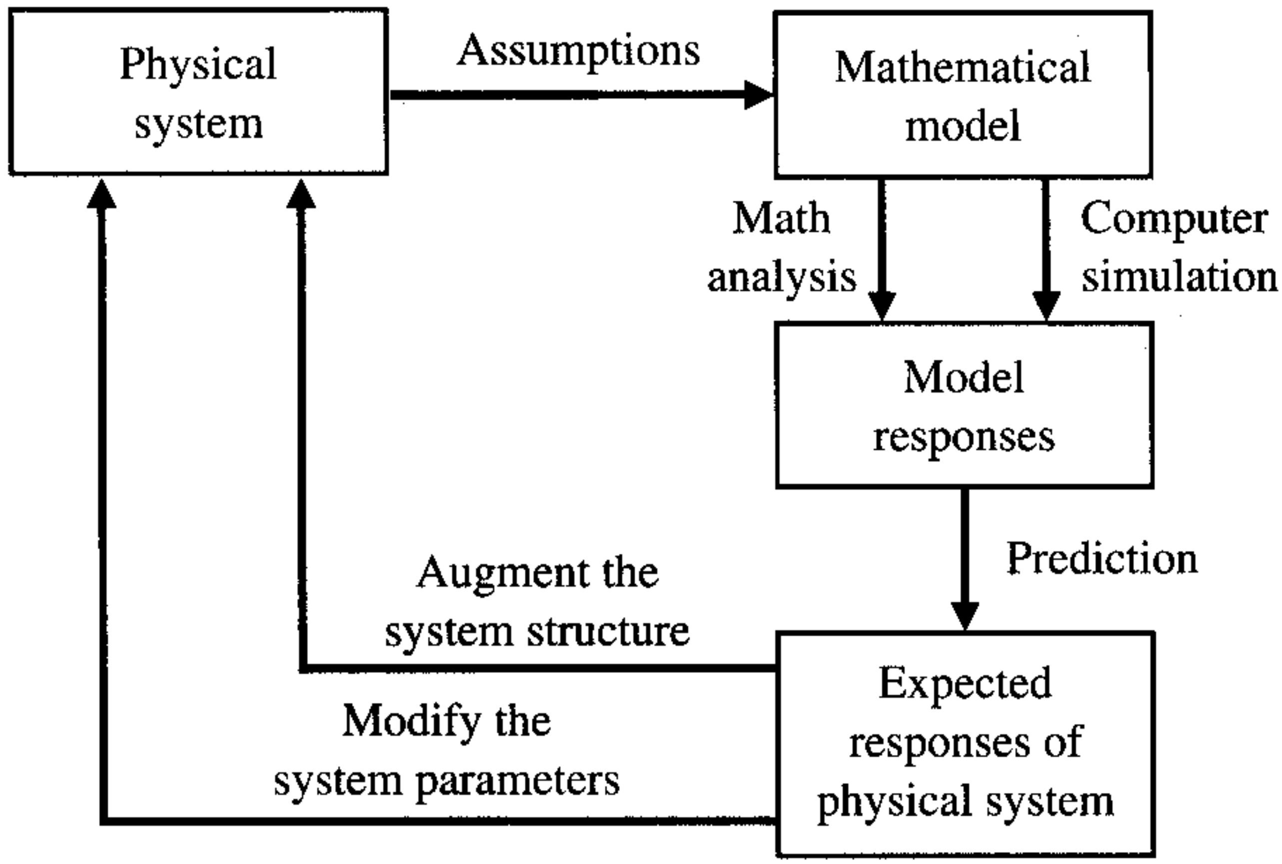


Assuming that a model and the simulation are reliably accurate, computer simulation has the following advantages [14]:

1. System performance can be observed under all conceivable conditions.
2. Results of field-system performance can be extrapolated with a simulation model for prediction purposes.
3. Decisions concerning future systems presently in a conceptual stage can be examined.
4. Trials of systems under test can be accomplished in a much reduced period of time.
5. Simulation results can be obtained at lower cost than real experimentation.
6. Study of hypothetical situations can be achieved even when the hypothetical situation would be unrealizable in actual life at the present time.
7. Computer modeling and simulation is often the only feasible or safe technique to analyze and evaluate a system.

TABLE Summary of Through- and Across-Variables for Physical Systems

System	Variable Through Element	Integrated Through Variable	Variable Across Element	Integrated Across Variable
Electrical	Current, i	Charge, q	Voltage difference, v_{21}	Flux linkage, λ_{21}
Mechanical translational	Force, F	Translational momentum, P	Velocity difference, v_{21}	Displacement difference, y_{21}
Mechanical rotational	Torque, T	Angular momentum, h	Angular velocity difference, ω_{21}	Angular displacement difference, θ_{21}
Fluid	Fluid volumetric rate of flow, Q	Volume, V	Pressure difference, P_{21}	Pressure momentum, γ_{21}
Thermal	Heat flow rate, q	Heat energy, H	Temperature difference, T_{21}	

TABLE 2.4 Summary of Describing Differential Equations for Ideal Elements

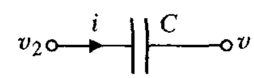
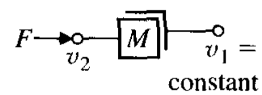
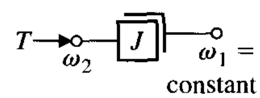
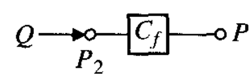
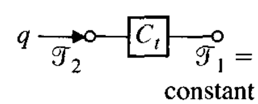
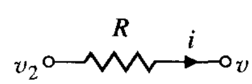
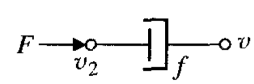
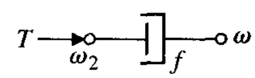
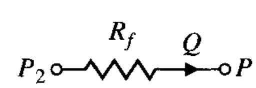
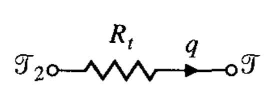
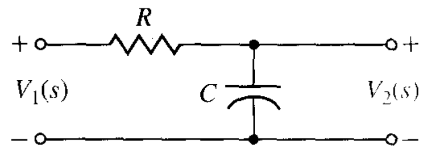
Type of Element	Physical Element	Describing Equation	Energy E or Power $\mathcal{P}$	Symbol
	Electrical inductance	$v_{21} = L \dfrac{di}{dt}$	$E = \dfrac{1}{2} Li^2$	
Inductive storage	Translational spring	$v_{21} = \dfrac{1}{K} \dfrac{dF}{dt}$	$E = \dfrac{1}{2} \dfrac{F^2}{K}$	
	Rotational spring	$\omega_{21} = \dfrac{1}{K} \dfrac{dT}{dt}$	$E = \dfrac{1}{2} \dfrac{T^2}{K}$	
	Fluid inertia	$P_{21} = I \dfrac{dQ}{dt}$	$E = \dfrac{1}{2} IQ^2$	
	Electrical capacitance	$i = C \dfrac{dv_{21}}{dt}$	$E = \dfrac{1}{2} Cv_{21}^2$	
	Translational mass	$F = M \dfrac{dv_2}{dt}$	$E = \dfrac{1}{2} Mv_2^2$	
Capacitive storage	Rotational mass	$T = J \dfrac{d\omega_2}{dt}$	$E = \dfrac{1}{2} J\omega_2^2$	
	Fluid capacitance	$Q = C_f \dfrac{dP_{21}}{dt}$	$E = \dfrac{1}{2} C_f P_{21}^2$	
	Thermal capacitance	$q = C_t \dfrac{d\tau_2}{dt}$	$E = C_t \tau_2$	
	Electrical resistance	$i = \dfrac{1}{R} v_{21}$	$\mathcal{P} = \dfrac{1}{R} v_{21}^2$	
	Translational damper	$F = fv_{21}$	$\mathcal{P} = fv_{21}^2$	
Energy dissipators	Rotational damper	$T = f\omega_{21}$	$\mathcal{P} = f\omega_{21}^2$	
	Fluid resistance	$Q = \dfrac{1}{R_f} P_{21}$	$\mathcal{P} = \dfrac{1}{R_f} P_{21}^2$	
	Thermal resistance	$q = \dfrac{1}{R_t} \mathrm{T}_{21}$	$\mathcal{P} = \dfrac{1}{R_t} \mathrm{T}_{21}$	

TABLE 2.7 Transfer Functions of Dynamic Elements and Networks

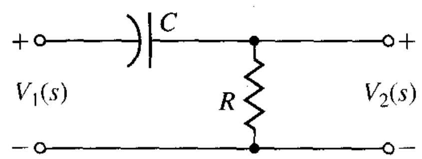
Element or System | ***G(s)***

1. Integrating circuit, filter



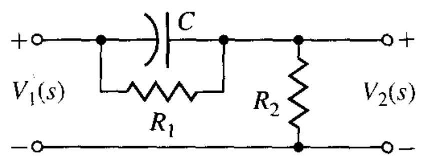
$$\frac{V_2(s)}{V_1(s)} = \frac{1}{RCs + 1}$$

2. Differentiating circuit



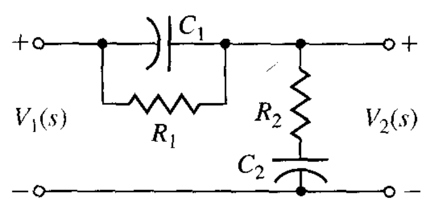
$$\frac{V_2(s)}{V_1(s)} = \frac{RCs}{RCs + 1}$$

3. Differentiating circuit



$$\frac{V_2(s)}{V_1(s)} = \frac{s + 1/R_1 C}{s + (R_1 + R_2)/R_1 R_2 C}$$

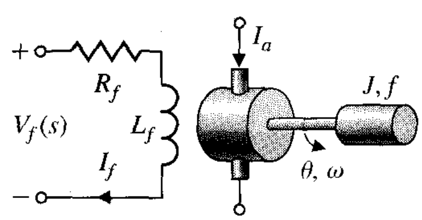
4. Lead-lag filter circuit



$$\tau_a = R_1 C_1$$
$$\tau_b = R_2 C_2$$
$$\tau_{ab} = R_1 C_2$$
$$\tau_1 \tau_2 = \tau_a \tau_b$$
$$\tau_1 + \tau_2 = \tau_a + \tau_b + \tau_{ab}$$

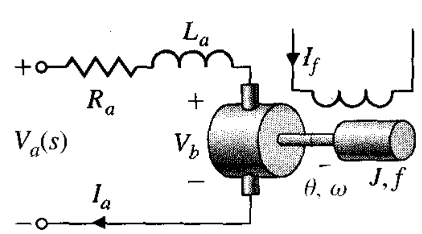
$$\frac{V_2(s)}{V_1(s)} = \frac{(1 + s\tau_a)(1 + s\tau_b)}{\tau_a \tau_b s^2 + (\tau_a + \tau_b + \tau_{ab})s + 1} = \frac{(1 + s\tau_a)(1 + s\tau_b)}{(1 + s\tau_1)(1 + s\tau_2)}$$

5. dc motor, field-controlled, rotational actuator



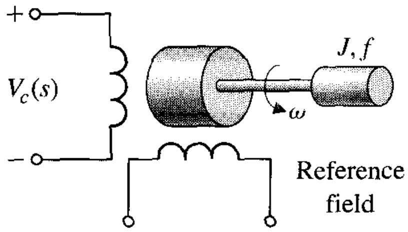
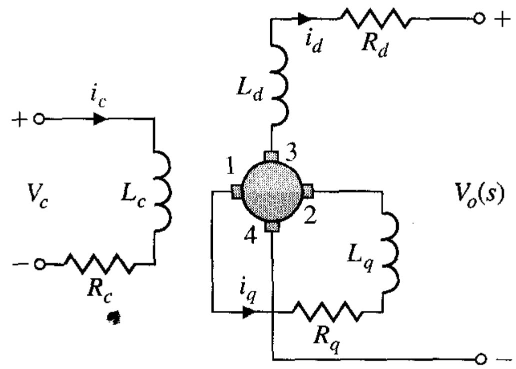
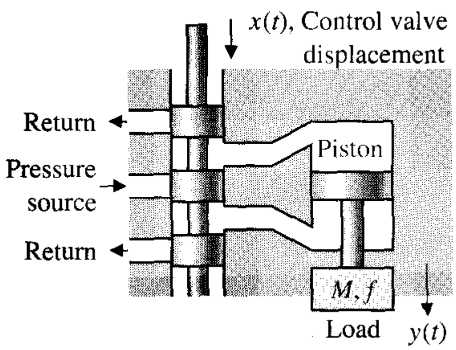
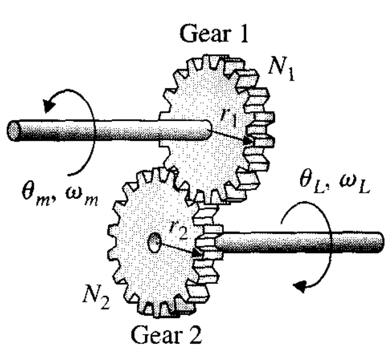
$$\frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js + f)(L_f s + R_f)}$$

6. dc motor, armature-controlled, rotational actuator



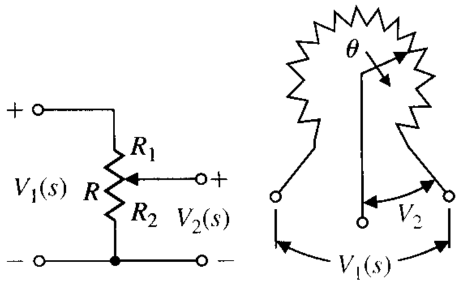
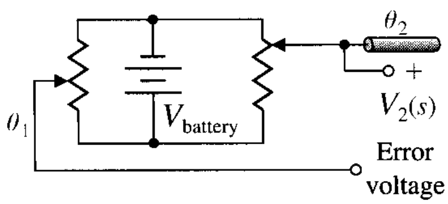
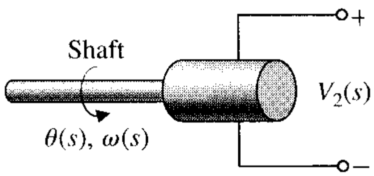
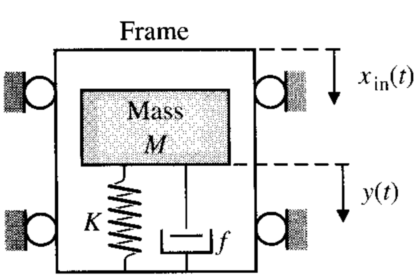
$$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{s[(R_a + L_a s)(Js + f) + K_b K_m]}$$

(continued)

<table>
<tr><th>Element or System</th><th>G(s)</th></tr>
<tr><td>7. ac motor, two-phase control field, rotational actuator

</td><td>$$\frac{\theta(s)}{V_c(s)} = \frac{K_m}{s(\tau s + 1)}$$
$\tau = J/(f - m)$
m = slope of linearized torque-speed curve (normally negative)</td></tr>
<tr><td>8. Amplidyne, voltage and power amplifier

</td><td>$$\frac{V_o(s)}{V_c(s)} = \frac{(K/R_c R_q)}{(s\tau_c + 1)(s\tau_q + 1)}$$
$\tau_c = L_c/R_c, \quad \tau_q = L_q/R_q$
For the unloaded case, $i_d \simeq 0$, $\tau_c \simeq \tau_q$, $0.05\ \text{s} < \tau_c < 0.5\ \text{s}$
$V_{12} = V_q$, $V_{34} = V_d$</td></tr>
<tr><td>9. Hydraulic actuator

</td><td>$$\frac{Y(s)}{X(s)} = \frac{K}{s(Ms + B)}$$
$$K = \frac{Ak_x}{k_p}, \quad B = \left(f + \frac{A^2}{k_p}\right)$$
$$k_x = \left.\frac{\partial g}{\partial x}\right|_{x_0}, \quad k_p = \left.\frac{\partial g}{\partial P}\right|_{P_0},$$
$g = g(x, P) = \text{flow}$
A = area of piston</td></tr>
<tr><td>10. Gear train, rotational transformer

</td><td>$$\text{Gear ratio} = n = \frac{N_1}{N_2}$$
$N_2\theta_L = N_1\theta_m, \quad \theta_L = n\theta_m$
$\omega_L = n\omega_m$</td></tr>
</table>

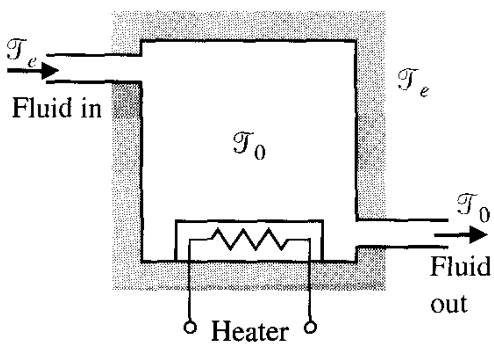
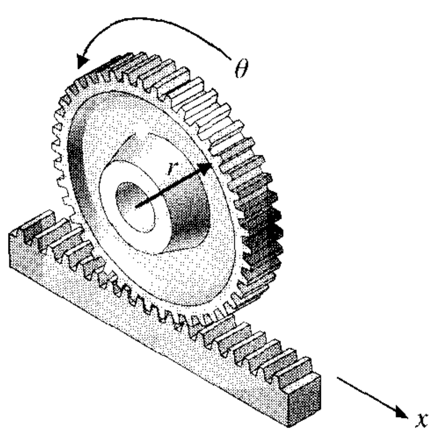
(continued)

TABLE 2.7 *Continued*

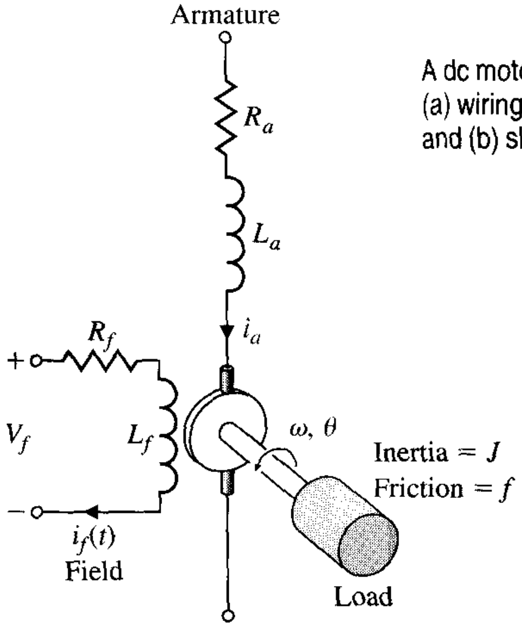
Element or System	G(s)
11. Potentiometer, voltage control 	$\dfrac{V_2(s)}{V_1(s)} = \dfrac{R_2}{R} = \dfrac{R_2}{R_1 + R_2}$ $\dfrac{R_2}{R} = \dfrac{\theta}{\theta_{max}}$
12. Potentiometer error detector bridge 	$V_2(s) = k_s(\theta_1(s) - \theta_2(s))$ $V_2(s) = k_s\theta_{error}(s)$ $k_s = \dfrac{V_{battery}}{\theta_{max}}$
13. Tachometer, velocity sensor 	$V_2(s) = K_t\omega(s) = K_t s\theta(s)$; K_t = constant
14. dc amplifier 	$\dfrac{V_2(s)}{V_1(s)} = \dfrac{k_a}{s\tau + 1}$ R_o = output resistance C_o = output capacitance $\tau = R_oC_o$, $\tau \ll 1$ and is often negligible for servomechanism amplifier
15. Accelerometer, acceleration sensor 	$x_o(t) = y(t) - x_{in}(t)$, $\dfrac{X_o(s)}{X_{in}(s)} = \dfrac{-s^2}{s^2 + (f/M)s + K/M}$ For low-frequency oscillations, where $\omega < \omega_n$, $\dfrac{X_o(j\omega)}{X_{in}(j\omega)} \simeq \dfrac{\omega^2}{K/M}$

(continued)

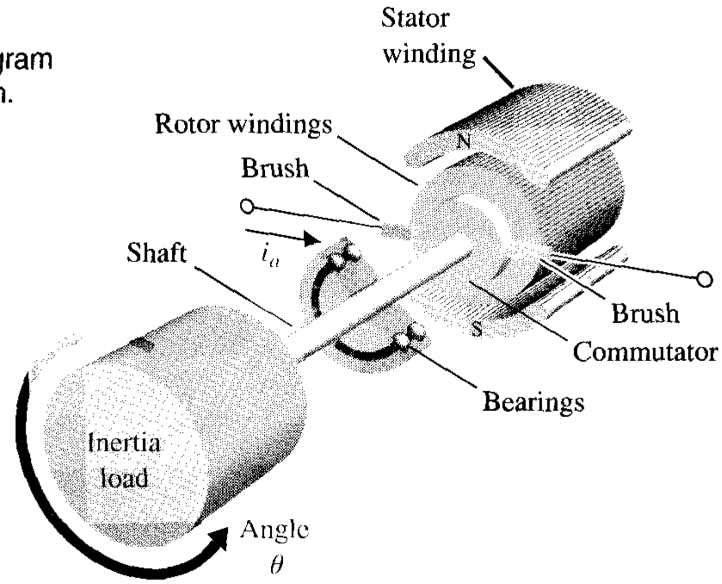
TABLE 2.7 *Continued*

Element or System	$G(s)$
16. Thermal heating system 	$\dfrac{\mathrm{T}(s)}{q(s)} = \dfrac{1}{C_t s + (QS + 1/R)}$, where $\tau = \tau_o - \tau_e =$ temperature difference due to thermal process $C_t =$ thermal capacitance $Q =$ fluid flow rate $=$ constant $S =$ specific heat of water $R_t =$ thermal resistance of insulation $q(s) =$ rate of heat flow of heating element
17. Rack and pinion 	$x = r\theta$ converts radial motion to linear motion

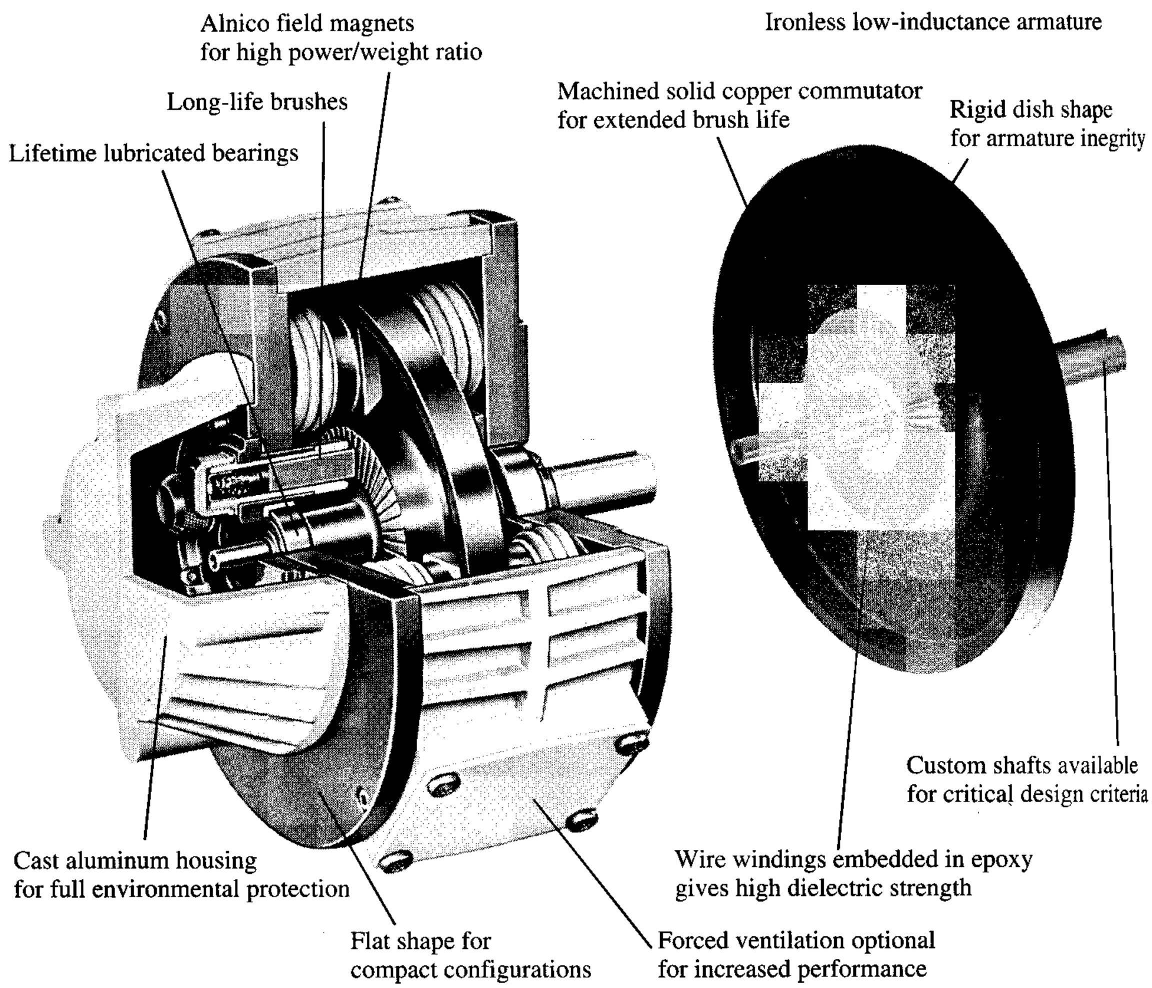
A dc motor
(a) wiring diagram
and (b) sketch.



(a)



(b)



A pancake dc motor with a flat wound armature and a permanent magnet rotor. These motors are capable of providing high torque with a low rotor inertia. A typical mechanical time constant is in the range of 15 ms. (Courtesy of Mavilor Motors.)