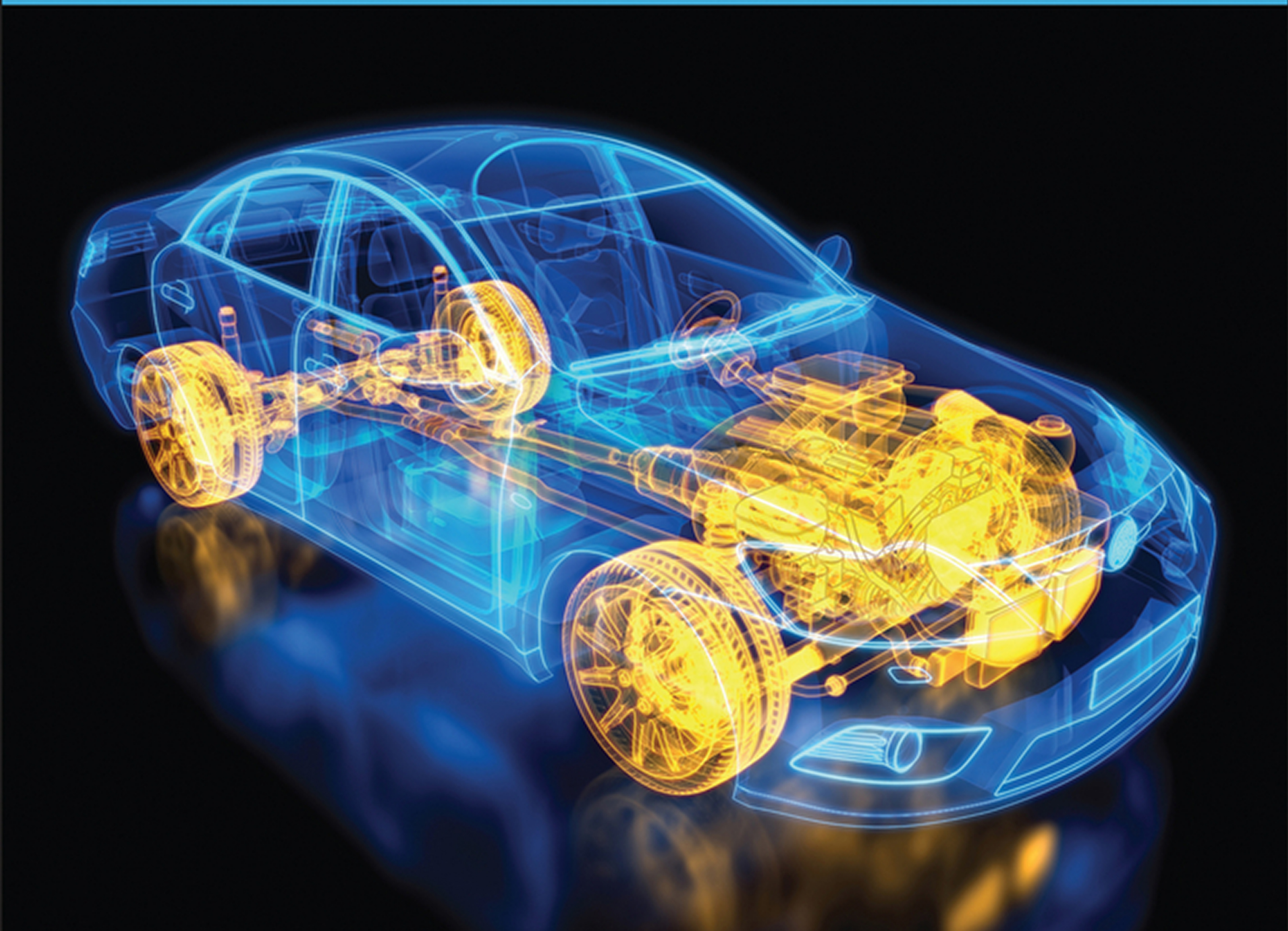
ROBERT C. JUVINALL • KURT M. MARSHEK

Fundamentals of Machine Component Design

Seventh Edition



WILEY

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PREFACE

This book is intended as a text for first courses in Mechanical Engineering Design and as a reference for practicing engineers. It is assumed that the user has had basic courses in Mechanics, Strength of Materials, and Materials Properties. However, the first nine chapters of the book (Part I) serve to review as well as extend this basic background. The remaining chapters (Part II) deal with the application of these fundamentals to specific machine components.

Part I—FUNDAMENTALS

Although much of Part I of the text is a review of earlier courses, we would like to call attention to several particular sections.

- Sections 1.2, 1.3, and 1.4 deal with three of the broadest aspects of engineering—safety, ecology, and social significance. These are concerns to which today's students are particularly responsive.
- Section 1.7 presents a methodology for solving machine component problems. Embodied in this methodology is a sample problem format that includes a restatement, solution, and comments for the problem under the headings: known, find, schematic, decisions, assumptions, analysis, and comments. *Decisions* are choices made by the designer. Since design is an iterative decision-making process of synthesis, whenever the heading "decisions" is utilized, a design problem is presented. If a solution is presented without decisions being made, the problem is one of analysis. The inclusion of the category "decisions" allows the student to see clearly the difference between design and analysis. Once appropriate decisions have been made, analysis can follow. *Assumptions*, which are used in solving a problem, are statements about beliefs; for example, the material is homogeneous throughout. The design engineer and the student need to understand what assumptions are made in solving a problem. The listing of assumptions provides more opportunities for students of machine design to "think before doing." *Comments* present key aspects of the solution and discuss how better results might be obtained by making different design decisions, relaxing certain assumptions, and so on.
- Sections 1.8, 1.9, and 1.10 review fundamental energy relationships. Most students at this level need to gain insight and understanding concerning such basic matters as the relationship between work input to a rotating camshaft and work output at a translating follower, and the relationship between engine power, vehicle speed, and fuel consumption.
- Most teachers of Mechanical Engineering Design lament the weakness of their students in the area of free-body diagram analysis of loads. Unless the loading on a machine component is properly established, subsequent design or analysis is of little value. Section 2.2 is directed toward helping relieve this common deficiency and its associated problems.
- References are often an invaluable resource for the student as they provide in depth coverage of topics to which the text may only be able to devote a single paragraph. As such, *MIL-HDBK-5J* and *MIL-HDBK-17* are introduced to the student in Chapter 3. These two references provide a wealth of pragmatic engineering knowledge regarding engineering materials and composites.

The use of these volumes, along with the chapter references, has the ability to dramatically enhance a student's knowledge base.

- An elementary treatment of residual stresses is included in Chapter 4. An understanding of the basic concepts involved is vital to modern stress analysis, particularly when fatigue is present.
- Castigliano's method for determining elastic deflections and redundant reactions is included in Chapter 5. This method permits a ready solution to many problems not amenable to traditional elementary methods.
- Chapter 6 on Failure Theories, Safety Factors, Stress Intensity Factors, and Reliability includes introductory treatments of fracture mechanics and interference theory of statistical reliability prediction.
- Chapter 7 focuses on impact, which is also called shock, sudden, or impulsive loading.
- Chapter 8 contains a simplified, condensed, and introductory version of Fatigue Design and Fatigue Crack Growth. This chapter is particularly important, and represents primarily new material for most students.
- Chapter 9 deals with the various kinds of surface deterioration experienced by machine components. This is of great importance because more machine parts "fail" (cease to be suitable for performing their intended function) because of surface damage than from actual breakage.

Part II—APPLICATIONS

Part II is concerned with the application of the fundamentals to specific machine components. In engineering practice, problems involving the design, analysis, or application of machine members can seldom be solved by applying the fundamentals alone. As critically important as a knowledge of the underlying sciences is, it is seldom sufficient. Almost always some empirical information must be used, and good engineering judgment brought to bear. Actual engineering design problems seldom have only one correct answer. For example, engineering staffs of competing companies arrive at different product designs as solutions to the same problem. And these solutions change as new technology, new materials, new manufacturing methods, and new marketing conditions prevail. For many students, the course based on this text will provide their first experience in dealing with these kinds of professional engineering problems.

Most engineers find that this aspect of engineering adds to the interest and excitement of their profession. There is a close parallel between engineers and medical doctors in this respect: Both must solve real-life problems *now*, making full use of the best available scientific information. Engineers must design engines and build electronic apparatus even though scientists are still seeking a more complete knowledge of combustion and electricity. Similarly, medical doctors cannot tell their patients to await treatment until more research has been completed.

Even though the fundamentals treated in Part I are seldom *sufficient* for solving engineering problems relating to machine components, it is important that they be applied fully and consistently. In particular, a special effort has been made in Part II to deal with fatigue and surface considerations in a manner consistent with the treatment given in Chapters 8 and 9. This sometimes results in the development of procedures that vary in detail from those given in the specialized literature, but this discrepancy is not of major importance. What *is* of major importance is helping the student learn to approach engineering problems by applying the fundamentals and other scientific knowledge as extensively as possible, and then supplementing these with empirical data and judgment as required to get good solutions within available time limitations.

Few engineering schools allot sufficient time to cover all the machine components treated in Part II. In addition, many components are not treated in the book, and even more are not yet in existence. For these reasons, each component is treated not only as an end in itself, but also as a representative example of applying basic fundamentals and necessary empirical information to solve practical engineering problems.

Throughout Part II, the reader will find numerous instances in which ingenuity, insight, and imagination are called for in order to deal effectively with engineering problems associated with an individual machine component. The next step in the study of Mechanical Engineering Design usually involves the conception and design of a complete machine. As an introduction to this next step, the final two chapters of the book (Chapters 21 and 22), present (1) a case study of the design of the first commercially successful automotive automatic transmission, and (2) a case study of the design of the mechanical systems for a remote control vehicle. Here, as with numerous other designs of complete machines, one cannot help being impressed and inspired by the insights, ingenuity, and imagination (as well as the prolonged diligent effort) displayed by engineers and engineering students. Also illustrated in these case studies is the way that the design of any one component is often influenced by the design of related parts.

Because engineers will inevitably need to continue to deal with SI, British gravitational, and English engineering units, all three systems are used in the text and problems. Recalling the NASA/JPL Mars Climate Orbiter, where the root cause of the loss of the Orbiter spacecraft was the failed translation of English units into metric units in a segment of ground-base, navigation-related mission software, should help to remind the student just how important it is to understand and apply units properly.

Robert C. Juvinall
Kurt M. Marshek

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CONTENTS

OC Content available in eBook

SS Student solution available in interactive e-text

SYMBOLS

A	area, cross-sectional area, arm of planetary gear
A	point A
A_0	original unloaded cross-sectional area
a	influence coefficient
a, a	acceleration
a	crack depth, radius of contact area of two spheres
A_c	effective clamped area
a_{cr}	critical crack depth
A_f	final area
A_r	area reduction
A_t	tensile stress area, tensile stress area of the thread
$\overline{B}$	actual backlash
b	section width, half width of contact area measured perpendicular to axes of two parallel contacting cylinders, gear face width, band width
C	spring index, overall heat transfer coefficient, rated load capacity, heat transfer coefficient, constant (material property)
C	specific heat
c	distance from the neutral axis to the extreme fiber, half of crack length, radial clearance, center distance, distance between shafts, crack length
$\bar{c}$	distance from the centroidal axis to the extreme inner fiber, actual distance between gear and pinion centers
c_{cr}	critical crack length
CR	contact ratio
$\overline{CR}$	actual contact ratio
CG	center of gravity
C_G	gradient factor or gradient constant
c_i	distance from the neutral axis to the extreme inner fiber
C_L	load factor
C_{Li}	life factor
c_o	distance from the neutral axis to the extreme outer fiber
CP	center of aerodynamic pressure
C_p	elastic coefficient
C_R	reliability factor
c_ρ	volumetric specific heat
C_{req}	required value of C
C_s	surface factor
D	diameter, mean coil diameter, velocity factor
d	diameter, major diameter, nominal diameter, wire diameter
d_{av}	average diameter
d_b	diameter of base circle
d_c	collar (or bearing) diameter
dc/dN	crack propagation rate
$(dc/dN)_o$	crack propagation rate at $(\Delta K)_o$
d_g	pitch diameter of gear
d_i	minor diameter of the internal thread
d_m	mean diameter
d_p	pitch diameter, pitch diameter of pinion
d_r	root (or minor) diameter
E	modulus of elasticity, elastic proportionality constant, tensile elastic modulus
E	modulus of elasticity (tension)
E_p	plastic strain
e	distance between the neutral axis and the centroidal axis, efficiency, eccentricity, train value, edge distance for joint, percent elongation at break
e/D	edge margin
E_b	Young's modulus for the bolt
E_c	Young's modulus for clamped member, compression modulus of elasticity
E_s	secant modulus
E_t	tangent modulus
F	force, compressive force between the surfaces
f	relative hardenability effectiveness, coefficient of friction
$\mathbf{F}$, F	force
F_a	axial force
F_b	bolt axial load
F_{bru}	bearing ultimate strength
F_{bry}	bearing yield strength
F_c	clamping force
f_c	collar (or bearing) coefficient of friction
F_d	drag force, dynamic load

F_{cy}	compression yield strength
F_e	equivalent radial load, equivalent static force, external force
$\mathbf{F}_{ext}$	external force vector applied on a member
F_{ga}	gear axial force
F_{gr}	gear radial force
F_{gt}	gear tangential force
F_i	initial tensile force, initial clamping force
$\mathbf{F}_{int}$	internal force vector at a cross-section
F_n	normal force
f_n	natural frequency
F_r	radial load, radial force
F_s	strength capacity
F_{solid}	force when solid
F_{su}	shear ultimate strength
F_t	thrust force, tendon force, tangential force, thrust load
F_{tu}	tensile ultimate strength
F_{ty}	tensile yield strength
F_w	wear capacity
F_{wa}	worm axial force
F_{wr}	worm radial force
F_{wt}	worm tangential force
G	torsional or shear modulus of elasticity
g	gravitational acceleration or acceleration of gravity, grip length
g_c	constant of proportionality, $32.2\ \text{lbm-ft/lb-s}^2$
H	surface hardness, time rate of heat dissipation
h	section depth, height of fall, leg length, weld size, film thickness, height
h_0	minimum film thickness
H_B	Brinell hardness number
I	polar moment of inertia, moment of inertia, geometry factor, stress invariant
i	integer
I_x	moment of inertia about x-axis
J	polar moment of inertia, spur gear geometry factor
K	curvature factor, spring rate for angular deflection, stress intensity factor, wear coefficient
k	spring rate, thermal conductivity, spring rate for linear deflection, number of standard deviations, shaft spring rate
K	thermal conductivity
K'	section property
K_{I}	stress intensity factor for tensile loading (mode I)
$K_{\mathrm{I}c}$	critical stress intensity factor for tensile loading (mode I)
K_a	application factor
K_B	constant of proportionality
k_b	spring constant for the bolt
K_c	fracture toughness or critical stress intensity factor
k_c	spring constant for clamped members
KE	kinetic energy
K_f	fatigue stress concentration factor
K_i	curvature factor for inner fiber, effective stress concentration factor for impact loading, constant used for calculating initial bolt-tightening force
K_m	mounting factor
K_{max}	stress intensity factor at σ_{max}
K_{min}	stress intensity factor at σ_{min}
k_{ms}	mean stress factor
K_o	curvature factor for outer fiber, overload factor, critical stress intensity factor for infinite plate with central crack in uniaxial tension
K_r	life adjustment reliability factor
k_r	reliability factor
K_s	stress concentration factor for static loading
K_t	theoretical or geometric stress concentration factor
k_t	temperature factor
K_v	velocity or dynamic factor
K_w	Wahl factor, material and geometry factor
L	length, contact length measured parallel to the axis of contacting cylinder, lead, length of weld, life corresponding to radial load F_r, or life required by the application, pitch cone length
L_0	original unloaded length
L_e	equivalent length
L_f	final length, free length
L_R	life corresponding to rated capacity
L_s	solid height
L, ST, LT	longitudinal direction, short transverse direction, long transverse direction
M	moment, internal bending moment, bending moment
M_0	redundant moment
m	mass, strain-hardening exponent, module (used only with SI or metric units)
m'	mass per unit length of belt
$\mathbf{M}_{ext}$	external moment vector applied on a member
M_f	moment of friction forces

$\mathbf{M}_{\text{int}}$ generalized internal moment vector at a cross-section
M_n moment of normal forces
N fatigue life, total normal load, number of active coil turns, number of teeth, number of friction interfaces, number of cycles
n rotating speed, number of cycles, normal force, number of equally spaced planet gears, index (subscript), Ramberg-Osgood parameter
N' virtual number of teeth
N.A. neutral axis
n_c critical speed
N_e number of teeth
N_t total number of turns, number of teeth in the sprocket
P load, cumulative probability of failure, bearing unit load, average film pressure, radial load per unit of projected bearing area, pitch point, diametral pitch (used only with English units), diameter or number of teeth of planet, band force, load (force), uniform load
$\overline{P}$ actual pitch
p frequency of occurrence, probability of failure, surface interface pressure, pitch, film pressure, circular pitch, uniform level of interface pressure, pressure
$\overline{p}$ actual circular pitch
p_0 maximum contact pressure
p_a axial pitch
p_b base pitch
P_c tension created by centrifugal force
P_{cr} critical load
PE potential energy
$p_{\max}$ allowable pressure, maximum normal pressure
p_n circular pitch measured in a plane normal to the teeth
Q heat energy transferred to the system, load, total tangential force, flow rate, mass flow rate
q number of revolutions, notch sensitivity factor, tangential force
Q_f volume of lubricant per-unit time flowing across
Q_s side leakage rate
R radius, transmission speed ratio, area ratio, radius of curvature, diameter or number of teeth of ring or annulus gear, ratio of gear and pinion diameter, load ratio, fatigue cycle stress ratio
r radius, reliability
$\overline{r}$ radial distance to the centroidal axis
$r_{a(\max)}$ maximum noninterfering addendum circle radius of pinion or gear
$r_{\text{ag}}^{\max}$ maximum allowable addendum radius on the gear to avoid interference
$r_{\text{ap}}^{\max}$ maximum allowable addendum radius on the pinion to avoid interference
$r_{\text{ap}}, r_{\text{ag}}$ addendum radii of the mating pinion and gear
r_b base circle radius, back cone radius
$r_{\text{bp}}, r_{\text{bg}}$ base circle radii of the mating pinion and gear
r_c chordal radius
r_f friction radius
$\overline{r}_g$ actual pitch radius of gear
r_i inner radius
$\overline{r}_p$ actual pitch radius of pinion
R_m modulus of resilience
r_n radial distance to the neutral axis
r_o outer radius
S linear displacement, total rubbing distance, Saybolt viscometer measurement in seconds, bearing characteristic number or Sommerfeld variable, diameter or number of teeth of sun gear, slip
S_{cr} critical unit load
S_e elastic limit
S_{eq} equivalent stress—see Table F.4
SF safety factor
S_{fe} surface fatigue strength
S_H surface endurance strength
S–N fatigue stress versus cycles
$S_{\max}$ maximum fatigue cycle stress—see Table F.4
S_n endurance limit
S_n' standard fatigue strength for rotating bending
S_p proof load (strength)
S_{sy} shear yield strength
S_u ultimate strength, ultimate tensile strength
S_{uc} ultimate strength in compression
S_{us} ultimate shear strength, ultimate torsional shear strength
S_{ut} ultimate strength in tension
S_y yield strength
S_{yc} yield strength in compression
S_{yt} yield strength in tension
T torque, brake torque, band brake torque
t time, thickness, nut thickness, throat length
T_a alternating torque
t_a air temperature, ambient air temperature
T_e equivalent static torque

T_f friction torque
T_m modulus of toughness, mean torque
t_o average oil film temperature, oil temperature
t_s average temperature of heat-dissipating surfaces
U stored elastic energy, impact kinetic energy, laminar flow velocity
U' complementary energy
V internal transverse shear force, shear force, volume
$\mathbf{V}, V$ linear velocity, gear pitch line velocity
v velocity at impact, sliding velocity
V_{60} cutting speed in feet per minute for 60-min tool life under standard cutting conditions
V_{av} average velocity
V_g gear tangential velocity, pitch line velocity of the gear
V_{gt} velocity of gear at contact point in tangent direction
V_{pt} velocity of pinion at contact point in tangent direction
V_{gn} velocity of gear at contact point in normal direction
V_{pn} velocity of pinion at contact point in normal direction
V_s sliding velocity
V_w worm tangential velocity
W work done, weight, volume of material worn away, total axial load
$\dot{W}$ power
w load, load intensity, gravitational force, width
Y Lewis form factor based on diametral pitch or module, configuration factor
y distance from the neutral axis, Lewis form factor
Y_{cr} configuration factor at critical crack size
Z section modulus

Greek Letters

α angular acceleration, coefficient of thermal expansion, angles measured clockwise positive from the 0° gage to the principal strain axes numbers 1 and 2, factor by which the compressive strength is reduced through buckling tendencies, thread angle, contact angle, cone angle, normalized crack size
α_{cr} normalized critical crack size
α_1 normalized crack size at c_1
α_2 normalized crack size at c_2
α_n thread angle measured in the normal plane
Δ deflection, material parameter important in computing contact stress
δ, δ deflection
δ linear deflection, wear depth
ΔA change in area
ΔE change in total energy of the system
$\Delta \mathrm{KE}$ change in kinetic energy of the system
ΔK stress intensity range
ΔK_o stress intensity range at the point o
ΔL change in length
$\Delta \mathrm{PE}$ change in gravitational potential energy of the system
ΔN_{12} number of cycles during crack growth from c_1 to c_2
δ_s solid deflection
δ_{st} deflection caused by static loading (static deflection)
ΔT temperature change
ΔU change in internal energy of the system
λ lead angle, helix angle, ratio of actual to ideal distance between gear and pinion centers
ϕ angle between the principal axes and the x- and y-axes, angle giving position of minimum film thickness, pressure angle, angle of wrap
ϕ_n pressure angle measured in a plane normal to the teeth
$\overline{\phi}$ actual pressure angle
γ pitch cone angle
$\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ shear strains
μ mean, viscosity
μ Poisson's ratio—see Appendix F
ν Poisson's ratio
ϵ normal strain
$\epsilon_1, \epsilon_2, \epsilon_3$ principal strains
ϵ_f strain at fracture
ϵ_p plastic strain
ϵ_T "true" normal strain
ϵ_{Tf} true normal strain at fracture
$\epsilon_x, \epsilon_y, \epsilon_z$ normal strains
θ angular displacement, angular deflection, slope
$\theta_{P_{\max}}$ position of maximum film pressure
ρ mass density, radial distance
σ normal stress, standard deviation, uniform uniaxial tensile stress

$\sigma_1, \sigma_2, \sigma_3$	principal stresses in 1, 2, and 3 directions
σ_0	square root of strain-strengthening proportionality constant
σ_a	alternating stress (or stress amplitude)
σ_e	equivalent stress
σ_{ea}	equivalent alternating bending stress
σ_{em}	equivalent mean bending stress
σ_{eq}	equivalent stress
σ_g	gross-section tensile stress
σ_H	surface fatigue stress
σ_i	maximum normal stress in the inner surface
σ_m	mean stress
$\sigma_{\max}$	maximum normal stress
$\sigma_{\min}$	minimum normal stress
σ_{nom}	nominal normal stress
σ_o	maximum normal stress in the outer surface
σ_T	“true” normal stress
σ_x	normal stress acting along x-axis
σ_y	normal stress acting along y-axis
τ	shear stress, natural period of vibration
τ_a	alternating shear stress
τ_{av}	average shear stress
τ_{initial}	initial shear stress
τ_m	mean shear stress
$\tau_{\max}$	maximum shear stress
τ_{nom}	nominal shear stress
τ_{solid}	shear stress when solid
τ_{xy}	shear stress acting on an x face in the y direction
υ	kinematic viscosity
ω	angular velocity, impact angular velocity
ω_g	angular velocity of gear
ω_n	natural frequency
ω_p	angular velocity of pinion
ψ	helix angle, spiral angle

Chapter 1 Problems

SS Student solution available in interactive e-text.

Sections 1.1–1.5

SS **1.1** The Segway two-wheeled, self-balancing electric vehicle invented by Dean Kamen and used for short distance personal transportation reportedly travels at 12.5 mph. The vehicle is controlled and powered with computers and electric motors. Lean forward, you move forward. Lean back and you go backward. Lean the handlebars to the left or right and you turn in that direction—see www.youtube.com for a video. When you need to brake, the motor acts as a dynamometer. Review the design of the Segway and address the question as to whether the Segway® conceptually is a "reasonable safe design" using the following categories:

(a) The *usefulness and desirability* of the product

(b) The *availability* of other and safer products to meet the same or similar needs

(c) The *likelihood* of injury and its probable seriousness

(d) The *obviousness* of the danger

(e) Common *knowledge and normal public expectation* of the danger (particularly for established products)

(f) The *avoidability* of injury by care in use of the product (including the effect of instructions and warnings)

(g) The ability to *eliminate* the danger without seriously impairing the usefulness of the product or making it unduly expensive

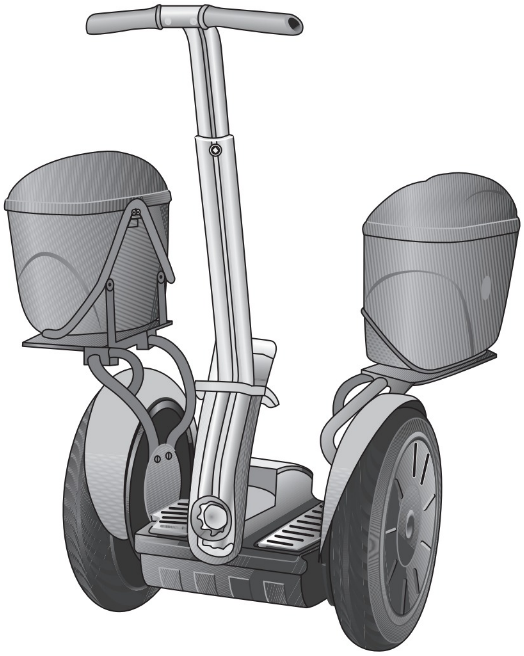

FIGURE P1.1

SS **1.2** Search online at http://www.osha.gov and from 29 CFR 1910.211 *Definitions*, define the following power press terms: *brake, clutch, two-hand control device, die, foot pedal, pinch point, point of operation*. Regulations for power presses are presented in 29 CFR 1910.217. Show a power press and identify the location of each item.

SS **1.3** Search online at http://www.osha.gov and print a copy of 29 CFR 1910.212, *General requirements for all machines*. With these requirements in mind, identify a machine you have used that had a machine guard to protect the operator or other person in the machine area from hazards. Sketch the machine and label the guarding device, power source, point of operation, and danger zone.

SS **1.4** An incident occurred at the residence of an older man wherein he was injured when he reportedly applied sandpaper to a rotating drive belt while attempting to repair an exercise treadmill. The incident treadmill was powered by a 2-hp DC motor and was being “operated” by the man while he was attempting to repair the machine by applying sandpaper to the motor drive V-belt at the time of the accident.

Indeed, he decided to remove the treadmill motor guard so he could better access the underside of the treadbelt. He noticed that the motor drive belt had a “sheen.” He then took a roll of sandpaper, started the 2-hp electric motor, and attempted to apply—in the area of an in-running nip point—the sandpaper to the drive belt to remove the “sheen” while the treadmill motor and tread belt was powered and running. His middle finger on his right hand was reportedly drawn with the sandpaper into the motor belt and rotating drive pulley. He sustained injury to his finger as a result of the accident. From your viewpoint, address the issue of whether the incident treadmill was reasonably safe. Also, list possible causes of the accident.

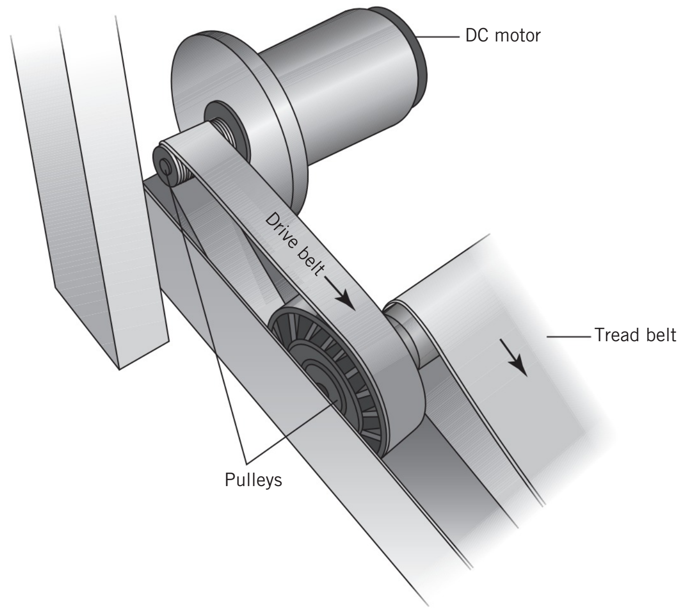

FIGURE P1.4

SS **1.5** Design a danger sign and a caution sign for a power press. For specifications, search online at http://www.osha.gov for 29 CFR 1910.145 entitled *Specifications for accident prevention signs and tags*. Describe the difference between a danger sign and a caution sign. When is the signal word “Warning” used?

SS **1.6** From your own experience and observation, describe briefly (perhaps one or two typed pages, double-spaced) a specific example of mechanical engineering design that you regard as *excellent* from a *safety*, *ecological*, and *sociological* standpoint. (Preferably, choose an example reflecting your own observation and consciousness rather than one featured in the news media.) Your write-up should reflect the professional appearance expected of an engineer. Use illustrations if and where appropriate.

SS **1.7** Parking blocks prevent the forward movement of cars and other vehicles by acting like a "curb." Unfortunately, for elderly persons or others with poor vision, they are sometimes difficult to "see" as they project only 4 to 8 in. off the ground. An ASTM standard recommends that parking blocks not be used in parking lots and parking garages. On the other hand, the Americans for Disabilities Act (ADA) shows the use of parking blocks in the design of parking spaces for persons with disabilities. What are the advantages and disadvantages of parking blocks? What is your opinion as to whether the utility outweighs the risk of harm of using parking blocks? Are there certain places where parking blocks should not be used? Are there parking garages that do not use parking blocks?

SS **1.8** Stairways—*and mechanical engineers sometimes design stairways*—have certain geometric requirements for their design, for example, stairway steps shall be uniform with respect to rise and run. Review local and/or uniform building codes for stairways and steps and record the requirements for rise and run. Also address and answer the question, why are building codes such as those for stairways required?

Sections 1.6 and 1.7

SS **1.9** An object has a mass of 10 kg at a location where the acceleration of gravity is 9.81 m/s^2. Determine its weight in (a) English Engineering units, (b) British Gravitational units, and (c) SI units.

SS **1.10** A truck weighs 3300 lb. What is the magnitude of the net force (lb) required to accelerate it at a constant rate of 5 ft/s^2? The acceleration of gravity is $g = 32.2$ ft/s^2.

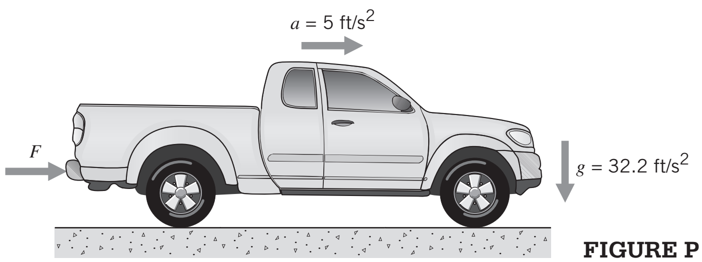

FIGURE P1.10

Sections 1.8–1.10

SS **1.11** A block weighing 3000-lb slides on a flat surface at an initial velocity of 88 ft/s where the coefficient of friction is 0.7. Determine the friction force causing the block to slow. How far does the block travel in slowing to a stop? How many seconds does it take for the block to come to rest? How much work was done to stop the block? What was the initial kinetic energy of the block?

SS **1.12** A car weighing 3000 lb, traveling at 60 mph, decelerates at 0.70 g after the brakes are applied. Determine the force applied to slow the car. How far does the car travel in slowing to a stop? How many seconds does it take for the car to stop?

SS **1.13** What is the rate of work output of a press that delivers 120 strokes per minute, each stroke providing a force of 8000 N throughout a distance of 18 mm? If the press efficiency is 90%, what average torque must be provided by a 1750-rpm driving motor?

Mechanical Engineering Design in Broad Perspective

1

1.1 An Overview of the Subject

The essence of engineering is *the* utilization of the resources and laws of nature to benefit humanity. Engineering is an applied science in the sense that it is concerned with understanding scientific principles and applying them to achieve a designated goal. Mechanical engineering design is a major segment of engineering; it deals with the conception, design, development, refinement, and application of machines and mechanical apparatus of all kinds.

For many students, mechanical engineering design is one of their first *professional engineering courses*—as distinguished from background courses in science and mathematics. Professional engineering is concerned with obtaining *solutions* to practical problems. These solutions must reflect an understanding of the underlying sciences, but usually this understanding is not enough; empirical knowledge and "engineering judgment" are also involved. For example, scientists do not completely understand electricity, but this does not prevent electrical engineers from developing highly useful electrical devices. Similarly, scientists do not completely understand combustion processes or metal fatigue, but mechanical engineers use the understanding available to develop highly useful combustion engines. As more scientific understanding becomes available, engineers are able to devise better solutions to practical problems. Moreover, the engineering process of solving problems often highlights areas particularly appropriate for more intensive scientific research. There is a strong analogy between the engineer and the physician. Neither is a scientist whose primary concern is with uncovering basic knowledge, but both *use* scientific knowledge—supplemented by empirical information and professional judgment—in solving immediate and pressing problems.

Because of the professional nature of the subject, most problems in mechanical engineering design do not have a *single* right answer. Consider, for example, the problem of designing a household refrigerator. There is a nearly endless number of workable designs, none of which could be called an "incorrect" answer. But of the "correct" answers, some are obviously *better* than others because they reflect a more sophisticated knowledge of the underlying technology, a more ingenious concept of basic design, a more effective and economical utilization of existing production technology, a more pleasing aesthetic appearance, and so on. It is precisely at this point, of course, that one finds the challenge and excitement of modern engineering. Engineers today are concerned with the design and development of products for a society different from any that existed previously, and they have more knowledge available to them than did engineers in the past. Hence, they are able to produce distinctly *better* solutions to meet today's needs. How much better depends on their ingenuity, imagination, depth of understanding of the need involved, and of the technology that bears on the solutions, and so on.

This book is primarily concerned with the design of specific *components* of machines or mechanical systems. Competence in this area is basic to the consideration and synthesis of complete machines and systems in subsequent courses and in professional practice. It will be seen that even in the design of a single bolt or spring, the engineer must use the best available scientific understanding together with empirical information, good judgment, and often a degree of ingenuity, in order to produce the best product for today's society.

The technical considerations of mechanical component design are largely centered around two main areas of concern: (1) stress–strain–strength relationships involving the *bulk* of a solid member and (2) surface phenomena including friction, lubrication, wear, and environmental deterioration. Part One of the book is concerned with the fundamentals involved and Part Two with applications to specific machine components. The components chosen are widely used and will be somewhat familiar to the student. It is not feasible or desirable for the student to study the detailed design considerations associated with *all* machine elements. Hence, the emphasis in treating those selected here is on the *methods* and *procedures* used so that the student will gain competence in applying these methods and procedures to mechanical components in general.

When considering a complete machine, the engineer invariably finds that the requirements and constraints of the various components are interrelated. The design of an automotive engine valve spring, for example, depends on the space available for the spring. This, in turn, represents a compromise with the space requirements for the valve ports, coolant passages, spark plug clearance, and so on. This situation adds a whole new dimension to the imagination and ingenuity required of engineers as they seek to determine an optimum design for a combination of related components. This aspect of mechanical engineering design is illustrated by a "case study" in Chapter 21 of the book.

In addition to the traditional technological and economic considerations fundamental to the design and development of mechanical components and systems, the modern engineer has become increasingly concerned with the broader considerations of safety, ecology, and overall "quality of life." These topics are discussed briefly in the following sections.

1.2 Safety Considerations

It is natural that, in the past, engineers gave first consideration to the functional and economic aspects of new devices. After all, unless devices can be made to function usefully, they are of no further engineering interest. Furthermore, if a new device cannot be produced for a cost that is affordable by contemporary society, it is a waste of engineering time to pursue it further. But the engineers who have gone before us have succeeded in developing a multitude of products that do function usefully and that can be produced economically. Partly because of this, increasing engineering effort is now being devoted to broader considerations relating to the influence of engineered products on people and on the environment.

Personnel safety is a consideration that engineers have always kept in mind but now demands increasing emphasis. In comparison with such relatively straightforward computations as stress and deflection, determination of safety is likely to be an elusive and indefinite matter, complicated by psychological and sociological factors. But this should only add to the appeal of the task for an engineer. It challenges him or her to assemble all pertinent facts, and then to make good decisions reflecting understanding, imagination, ingenuity, and judgment.

The important first step in developing engineering competence in the safety area is cultivating an *awareness* of its importance. Product safety is of great concern to legislators, attorneys, judges, jurors, insurance executives, and so forth. But none of these individuals can contribute directly to the safety of a product; they can only underscore the urgency of giving appropriate emphasis to safety in the *engineering development* of a product. It is the *engineer* who must carry out the development of safe products.

Safety is inherently a *relative* matter, and value judgments must be made regarding trade-offs between safety, cost, weight, and so on. Some years ago the first author was associated with a particularly safety-conscious company and was in the position of frequently admonishing the staff safety engineer to reduce further the inevitable hazards associated with the company's equipment.

When pushed a little too far one day, this engineer responded, "Look, I have made this model foolproof, but I can never make it *damn* foolproof! If someone tries hard enough, he can hurt himself with this machine!" The next day this gentleman inadvertently proved his point when he accidentally dropped the new model prototype on his foot and broke a toe! But the point to be made here is that when society makes decisions relative to safety requirements, engineers should contribute important input.

1.2.1 Imagination and Ingenuity

Following awareness, the second main point of safety engineering is *ingenuity*. The engineer must be imaginative and ingenious enough to *anticipate* potentially hazardous situations relating to a product. The old maxim that anything that *can* happen probably *will* happen sooner or later is relevant. The following are four cases in point, all involving costly liability suits.

1. A large open area with a high ceiling was to be heated and cooled with three cubical units, each suspended from the ceiling by long steel rods at four corners. The cubicles were being fitted with heat exchangers, blowers, and filters by workers inside and on top of the enclosures. The flexibility of the long support rods permitted the cubicles to swing back and forth, and the workers sometimes enjoyed getting their cubicle swinging with considerable amplitude. Fatigue failure of a support rod caused the death of one worker. Since large steam pipes (not yet installed at the time of the accident) prevented significant sway of the completed units, and the rods were designed with a safety factor of 17 (based on static weight of the completed cubicles), no further thought was given to safety. No one responsible for the design and installation of the units had reviewed the installation sequence with the imagination and ingenuity needed to foresee this hazard.
2. A boy was seriously injured by collision with a car when the brakes on his new bicycle failed to respond in an emergency. The cause was discovered to be interference between a fitting on the three-speed shift mechanism and a sharp edge on the caliper brake handle. Both the shift control mechanism and the brake handle were of unusual design. Both were safe within themselves and were safe when used in combination with a conventional design of the other member. But when these two unusual members were used together, it was easy for them to be mounted on the handlebar in such a position that the travel of the brake handle was limited, thereby preventing full application of the brake. Again, no one responsible for the overall design of the bicycle foresaw this hazardous situation.
3. A worker lost a hand in a 400-ton punch press despite wearing safety cuffs that were cam-actuated to pull the hands out of the danger zone before the ram came down. The cause was a loosened setscrew that permitted the cam to rotate with respect to its supporting shaft, thereby delaying hand retraction until *after* the ram came down. This case illustrates the old adage that "A chain is no stronger than its weakest link." Here, an otherwise very positive and strong safety device was nullified because of the inexcusably weak link of the setscrew. A very little imagination and ingenuity on the part of the engineer responsible for this design would have brought this hazard to light before the unit was released for production.
4. A crawling infant lost the ends of three fingers as he attempted to climb up an "exercycle" being ridden by an older sister. When placed on the bottom chain, the infant's hand was immediately drawn into the crank sprocket. In order to minimize cost, the exercycle was very properly designed to take advantage of many high-production, low-cost parts used on a standard bicycle. Unfortunately, however, the chain guard, which provides adequate protection for a bicycle, is totally inadequate for the exercycle. Was it too much to expect that the engineer responsible for this design would have enough imagination to foresee this hazard?

Should he or she not have been sufficiently ingenious to devise an alternative guard design that would be economically and otherwise feasible? Should it be necessary for this kind of imagination and ingenuity to be forced upon the engineer by legislation devised and enacted by nonengineers?

1.2.2 Techniques and Guidelines

Once the engineer is sufficiently *aware* of safety considerations and accepts this challenge to his or her *imagination and ingenuity*, there are certain techniques and guidelines that are often helpful. Six of these are suggested in the following:

1. *Review the total life cycle* of the product from initial production to final disposal, with an eye toward uncovering significant hazards. Ask yourself what kinds of situations can reasonably develop during the various stages of manufacturing, transporting, storing, installing, using, servicing, and so on.

2. Be sure that the safety provisions represent a *balanced approach*. Do not accept a dollar penalty to eliminate one hazard and overlook a twenty-cent possibility for eliminating an equal hazard. And, like the punch press example just given, do not focus attention on how strong the wrist cuffs are while overlooking how weak the cam attachment is.

3. *Make safety an integral feature* of the basic design wherever possible, rather than "adding on" safety devices after the basic design has been completed. An example of this was the development of an electrostatic hand-operated paint gun. Earlier stationary-mounted electrostatic paint guns had metal atomizing heads operating at 100,000 volts. A handgun version, incorporating elaborate guards and shields, was quickly recognized as impractical. Instead, a fundamentally new electric circuit design combined with a nonmetallic head was developed so that even if the operator came in contact with the high-voltage head, he or she would receive no shock; the voltage automatically dropped as a hand approached the head, and the head itself had a low enough capacitance to avoid significant discharge to the operator.

4. Use a *"fail-safe" design* where feasible. The philosophy here is that precaution is taken to avoid failure, but if failure *does* occur, the design is such that the product is still "safe"; that is, the failure will not be catastrophic. For example, the first commercial jet aircraft were the British Comets. Some of these experienced catastrophic failure when fatigue cracks started in the outer aluminum "skin" at the corners of the windows (caused by alternately pressurizing the cabin at high altitude and relieving the pressurizing stresses at ground level). Soon after the cracks were initiated, the fuselage skin ripped disastrously (somewhat like a toy rubber balloon). After the cause of the crashes was determined, subsequent commercial jet aircraft incorporated the fail-safe feature of bonding the outer panels to the longitudinal and circumferential frame members of the fuselage. Thus, even if a crack does start, it can propagate only to the nearest bonded seam. The relatively short cracks in no way impair the safety of the aircraft. (This particular fail-safe feature can be illustrated by ripping an old shirt. Once a tear has been started, it is easily propagated to a seam, but it is extremely difficult to propagate the tear through the seam, or "tear stopper.") Fail-safe designs often incorporate *redundant* members so that if one load-carrying member fails, a second member is able to assume the full load. This is sometimes known as the "belt *and* suspenders" design philosophy. (In extreme cases, a "safety pin" may be employed as a third member.)

5. Check *government and industry standards* (such as OSHA and ANSI) and the pertinent technical literature to be sure that legal requirements are complied with, and that advantage is taken of the relevant safety experience of others. The OSHA regulations may be

downloaded from the government's website at http://www.osha.gov. A search for specific titles of ANSI standards can be conducted at http://www.ansi.org. For regional, national, foreign, and international standards and regulatory documents, see http://www.nssn.org.

6. Provide *warnings* of all significant hazards that remain after the design has been made as safe as reasonably possible. The engineers who developed the product are in the best position to identify these hazards. The warnings should be designed to bring the information to the attention of the persons in jeopardy in the most positive manner feasible. Conspicuous warning signs attached permanently to the machine itself are usually best. There are OSHA and ANSI standards pertaining to warning signs. More complete warning information is often appropriately included in an instruction or operating manual that accompanies the machine.

To apply these techniques and guidelines in an alternative procedural form, consider the following list from [9]:

1. Delineate the scope of product uses.
2. Identify the environments within which the product will be used.
3. Describe the user population.
4. Postulate all possible hazards, including estimates of probability of occurrence and seriousness of resulting harm.
5. Delineate alternative design features or production techniques, including warnings and instructions, that can be expected to effectively mitigate or eliminate the hazards.
6. Evaluate such alternatives relative to the expected performance standards of the product, including the following:
   - **a.** Other hazards that may be introduced by the alternatives
   - **b.** Their effect on the subsequent usefulness of the product
   - **c.** Their effect on the ultimate cost of the product
   - **d.** A comparison to similar products
7. Decide which features to include in the final design.

The National Safety Council (see www.nsc.org) publishes a hierarchy of design that sets guidelines for designing equipment that will minimize injuries. The order of design priority is [10][1]:

1. *Design to eliminate hazards and minimize risk.* From the very beginning, the top priority should be to eliminate hazards in the design process.
2. *Incorporate safety devices.* If hazards cannot be eliminated or the risks adequately reduced through design selection, the next step is to reduce the risks to an acceptable level. This can be achieved with the use of guarding or other safety devices.
3. *Provide warning devices.* In some cases, identified hazards cannot be eliminated or their risks reduced to an acceptable level through initial design decisions or through the incorporated safety devices. Warnings are a potential solution.
4. *Develop and implement safe operating procedures and employee safety training programs.* Safe operating procedures and training are essential in minimizing injuries

[1] Bracketed numbers in the text correspond to numbered references at the end of the chapter.

when it is impractical to eliminate hazards or reduce their risks to an acceptable level through design selection, incorporating safety devices, or with warning devices.

5. *Use personal protective equipment.* When all other techniques cannot eliminate or control a hazard, employees should be given personal protective equipment to prevent injuries and illnesses.

1.2.3 Documentation of a Product Design

The documentation of a product design is costly yet necessary to support possible litigation. Such documentation has been categorized [11] as in the following table.

Design Documentation Categories

Category	Description
Hazard and risk data	Historical, field, and/or laboratory testing, causation analyses
Design safety formulation	Fault-tree, failure modes, hazard analyses
Warnings and instruction formulations	Methodology for development and selection
Standards	The use of in-house, voluntary, and mandated design or performance requirements
Quality assurance program	Methodology for procedure selection and production records
Product performance	Reporting procedures, complaint file, follow-up data acquisition and analysis, recall, retrofit, instruction, and warning modification
Decision making	The "how," "who," and "why" of the process

By documenting a design during the process, a safer product is generally produced. Also, imagination and ingenuity can sometimes be stimulated by requiring documentation of a product design.

1.2.4 Nontechnical Aspects

Safety engineering inherently includes important *nontechnical aspects* that are related to the *individuals* involved. Engineers must be aware of these if their safety-related efforts are to be effective. Three specific points within this category are suggested.

1. *Capabilities* and *characteristics* of individuals, both physiological and psychological. When the device is used or serviced, the strength, reach, and endurance requirements must be well within the physiological limitations of the personnel involved. The arrangement of instruments and controls, and the nature of the mental operating requirements, must be compatible with psychological factors. Where the possibility of accident cannot be eliminated, the design should be geared to limiting personnel accident-imposed loads to values minimizing the severity of injury.

2. *Communication*. Engineers must communicate to others the rationale and operation of the safety provisions incorporated in their designs, and in many situations they must involve themselves in "*selling*" the proper use of these safety provisions. What good does it do, for example, to develop an effective motorcycle helmet if it is not used? Or to provide a punch

press with safety switches for both hands if the operator blocks one of the switches closed in order to have a hand free for smoking? Unfortunately, even the most effective communication does not always guarantee intelligent use by the operator. This unresponsiveness may cause controversies, such as that surrounding the requirement that air bags be installed in cars, because a significant segment of the public cannot be persuaded to use seat belts voluntarily. Resolution of such controversies requires intelligent input from many quarters, one of which is certainly the engineering profession.

3. *Cooperation*. The controversy just mentioned illustrates the need for engineers to cooperate effectively with members of other disciplines—government, management, sales, service, legal, and so on—in order that joint safety-directed efforts may prove effective.

1.3 Ecological Considerations

People inherently depend on their environment for air, water, food, and materials for clothing and shelter. In primitive society, human-made wastes were naturally recycled for repeated use. When open sewers and dumps were introduced, nature became unable to reclaim and recycle these wastes within normal time periods, thus interrupting natural ecological cycles. Traditional economic systems enable products to be mass-produced and sold at prices that often do not reflect the true cost to society in terms of resource consumption and ecological damage. Now that society is becoming more generally aware of this problem, legislative requirements and more realistic “total” cost provisions are having increasing impact upon engineering design. Certainly, it is important that the best available engineering input go into societal decisions involving these matters.

We can perhaps state the basic ecological objectives of mechanical engineering design rather simply (1) to utilize materials so that they are economically recyclable within reasonable time periods without causing objectionable air, ground, and water pollution and (2) to minimize the rate of consumption of nonrecycled energy sources (such as fossil fuels) both to conserve these resources and to minimize thermal pollution. In some instances, the minimization of noise pollution is also a factor to be considered.

As with safety considerations, ecological factors are much more difficult for the engineer to tie down than are such matters as stress and deflection. The following is a suggested list of points to be considered:

1. Consider all aspects of the *basic design objective* involved, to be sure that it is sound. For example, questions are raised about the overall merits of some major dam constructions. Are there ecological side effects that might make it preferable to follow an alternative approach? Before undertaking the design of an expanded highway system or a specific mass-transit system, the engineer must determine whether the best available knowledge and judgment indicate that the proposed project represents the best alternative.

2. After accepting the basic design objective, the next step is a review of the *overall concepts* to be embodied into the proposed design. For example, a modular concept may be appropriate, wherein specific components or modules most likely to wear out or become obsolete can be replaced with updated modules that are interchangeable with the originals. The motor and transmission assembly of a domestic automatic washing machine might be an example for which this approach would be appropriate. Another example is the provision of replaceable exterior trim panels on major kitchen appliances that permit the exterior surfaces to be changed to match a new decorating scheme without replacing the entire appliance.

3. An important consideration is *designing for recycling*. At the outset of a new design, it is becoming increasingly important that the engineer consider the full ecological cycle

including the disposal and reuse of the entire device and its components. Consider an automobile. Parts appropriate for reuse (either with or without rebuilding) should be made so that they can be easily removed from a "junk" car. Dismantling and sorting of parts by material should be made as easy and economical as possible. It has been somewhat facetiously suggested that cars be made so that all fasteners break when dropping a junk car from, say, a height of 30 ft. Automatic devices would then sort the pieces by material for reprocessing. A more realistic proposal is that of attaching the wiring harness so that it can be quickly ripped out in one piece for easy salvaging of the copper.

In developing recycling procedures along these lines it is obviously desirable that the costs to a company for recycling versus costs for abandoning the old parts and using virgin materials reflect total real costs to society. No individual company could stay in business if it magnanimously undertook a costly recycling program in order to conserve virgin materials and reduce processing pollution if its competitors could utilize inexpensive new materials obtained at a price that did not reflect these total costs.

4. Select *materials* with ecological factors in mind. Of importance here are the known availability in nature of the required raw materials, processing energy requirements, processing pollution problems (air, water, land, thermal, and noise), and recyclability. Ideally, all these factors would be appropriately reflected within the pricing structure, and this will more likely happen in the future than it has in the past.

   Another factor to be considered is the relative durability of alternative materials for use in a perishable part. For example, consider the great reduction in the number of razor blades required (and in the number of scrap razor blades) made by changing the material to stainless steel. (But would it be better, overall, to devise a convenient and effective way to resharpen the blades rather than throwing them away?)

   The engineer should also consider the *compatibility* of materials with respect to recycling. For example, zinc die castings deteriorate the quality of the scrap obtained when present junked cars are melted.

5. Consider ecological factors when specifying *processing*. Important here are pollution of all kinds, energy consumption, and efficiency of material usage. For example, forming operations such as rolling and forging use less material (and generate less scrap) than cutting operations. There may also be important differences in energy consumption.

6. *Packaging* is an important area for resource conservation and pollution reduction. Reusable cartons and the use of recycled materials for packaging are two areas receiving increasing attention. Perhaps the ultimate in ecologically desirable packaging is that commonly used ice cream container, the cone.

The matter of protecting our environment is a deadly serious one. As the late Adlai Stevenson once said, "We travel together, passengers on a little space ship, dependent on its vulnerable supplies of air and soil … preserved from annihilation only by the care, the work, and I will say the love, we give our fragile craft."

1.4 Societal Considerations

As the reader well knows, the solution to any engineering problem begins with its clear definition. Accordingly, let us define, in the broadest terms, the problem to be addressed when undertaking mechanical engineering design. The opening sentence in this chapter suggests a definition: The basic objective of any engineering design is to provide a machine or device that will benefit humanity. In order to apply this definition, it is necessary to think in more specific terms. Just how does an individual benefit humanity? What "yardstick" (meterstick?) can be used to measure such benefits? The formulation of precise definitions of problem objectives, and the devising of means for measuring results, *fall within the special province of the engineer*.

The writer has suggested [2] that the basic objective of engineering design as well as other human pursuits is to improve the quality of life within our society, and that this might be measured in terms of a life quality index (LQI). This index is in some ways similar to the familiar "gross national product," but very much broader. Judgments about the proper composition of the LQI would, of course, vary somewhat in the many segments of society and also with time.

To illustrate the LQI concept, Table 1.1 lists some of the important factors most people would agree should be included. Perhaps we might arbitrarily assign a value of 100 to the factor deemed most important, with other factors being weighed accordingly. Each factor might then be multiplied by the same fraction so that the total would add up to 100.

The list in the table is admittedly a very rough and oversimplified indication of the direction of thought that would be involved in arriving at an LQI for a given segment of society at a given time. But this *kind* of thinking must be done in order to provide a sound basis for judgment with respect to the fulfillment of the engineering mission of service to humanity.

The professional contribution of engineers engaged in the broad area of engineering design and development plays a major role in determining the LQI of a population. Figure 1.1 depicts the societal relationships involving engineered products. A major segment of the population works within organizations whose function is to do one or more of the following: research, design, develop, manufacture, market, and service engineered products. The efforts of these people, together with appropriate natural resources, go into production systems that yield useful products, waste materials, and experience. The experience is of two kinds: (1) direct working experience of the individuals, which is hopefully constructive and satisfying, and (2) empirical knowledge gained about the effectiveness of the overall system, with implications for its future improvement.

Table 1.1 Preliminary List of Factors Constituting the Life Quality Index (LQI)

1. *Physical health*
2. *Material well-being*
3. *Safety* (crime and accident rates)
4. *Environment* (air, water, land, and natural resource management)
5. *Cultural–educational* (literacy rate, public school quality, college attendance among those qualified, adult educational opportunities, library and museum facilities, etc.)
6. *Treatment of disadvantaged groups* (physically and mentally handicapped, aged, etc.)
7. *Equality of opportunity* (and stimulation of initiative to use opportunities)
8. *Personal freedom*
9. *Population control*

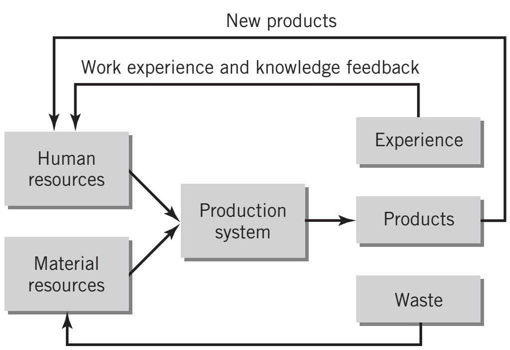

FIGURE 1.1 Societal relationships involving engineered products.