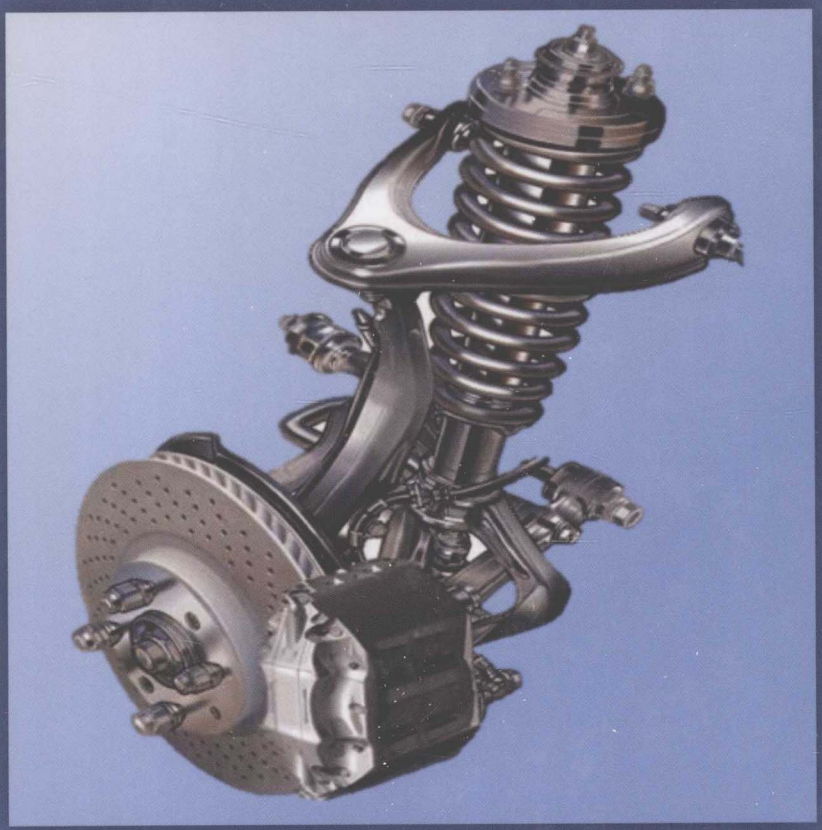
MECHANICAL DESIGN of Machine Components

SECOND EDITION



ANSEL C. UGURAL

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Preface

Introduction

This book developed from classroom notes prepared in connection with junior–senior undergraduate and first-year graduate courses in mechanical design, machine design, mechanical engineering design, and engineering design and analysis. The scope of this book is wider than any other book on the subject. In addition to its applicability to *mechanical engineering*, and to some extent, aerospace, agricultural, and nuclear engineering and applied engineering mechanics curricula, I have endeavored to make the book useful to *practicing engineers* as well. The book offers a simple, comprehensive, and methodical presentation of the fundamental concepts and principles in the design and analysis of machine components and basic structural members. The coverage presumes knowledge of the mechanics of materials and material properties. However, topics that are particularly significant to understanding the subject are reviewed as they are taken up. Special effort has been made to present a book that is as self-explanatory as possible, thereby reducing the work of the instructor.

The presentation of the material in this book strikes a balance between the theory necessary to gain insight into mechanics and the design methods. I, therefore, attempt to stress those aspects of theory and application that prepare a student for more advanced study or professional practice in design. Above all, I have made an effort to provide a visual interpretation of equations and present the material in a form useful to a diverse audience. The analysis presented should facilitate the use of computers and programmable calculators. The commonality of the analytical methods needed to design a wide variety of elements and the use of computer-aided engineering as an approach to design are emphasized.

Mechanical Design of Machine Components provides unlimited opportunities for the use of computer graphics. Computer solutions are usually preferred because the evaluation of design changes and "what-if" analyses require only a few keystrokes. Hence, many examples, case studies, and problems in the book are discussed with the aid of a computer. Generally, solid modeling serves as a design tool that can be used to create finite element (*FE*) models for analysis and dynamic simulation. Instructors may use a simple PC-based *FE* program to give students exposure to the method applied to stress concentration and axisymmetrically loaded and plane stress problems. The website for the book (see Optional Media Supplements) allows the user to treat problems more realistically and demonstrates the elements of good computational practice. The book is *independent* of any software package.

Traditional analysis in design, based on the methods of mechanics of materials, is given full treatment. In some instances, the methods of the applied theory of elasticity are employed. The role of the theory of elasticity in this book is threefold: It places limitations

on the application of the mechanics of materials theory, it is used as the basis of FE formulation, and it provides exact solutions when configurations of loading and component shape are simple. Plates, shells, and structural members are discussed to enable the reader to solve real-life problems and understand interactive case studies. Website addresses of component and equipment manufacturers and open-ended web problems are given in many chapters to provide the reader access to additional information on those topics. Also presented is finite element analysis (FEA) in computer-aided design. The foregoing unified methods of analysis give the reader opportunity to expand his or her ability to perform the design process in a more realistic setting. The book attempts to fill what I believe to be a void in the world of textbooks on machine design.

The book is divided into three sections. The basics of loading, stress, strain, materials, deflection, stiffness, and stability are treated first. Then fracture mechanics, failure criteria, fatigue phenomena, and surface damage of components are dealt with. These are followed by applications to machine and miscellaneous mechanical and structural components. All the sections attempt to provide an integrated approach that links together a variety of topics by means of case studies. Some chapters and sections in the book are also carefully integrated through cross-referencing. Throughout the book, most case studies provide numerous component projects. They present different aspects of the same design or analysis problem in successive chapters. Case studies in the preliminary design of two machines are taken up in the last chapter.

Attention is given to the presentation of the fundamentals and necessary empirical information required to formulate design problems. Important principles and applications are illustrated with numerical examples, and a broad range of practical problems are provided to be solved by students. This book offers numerous worked-out examples and case studies, aspects of which are presented in several sections of the book; many problem sets, most of which are drawn from engineering practice; and a multitude of formulas and tabulations from which design calculations can be made. Most problems can be readily modified for in-class tests. Answers to selected problems and References (identified in *brackets*) are given at the end of the book.

A sign convention consistent with vector mechanics is used throughout for loads, internal forces (with the exception of the shear in beams), and stresses. This convention has been carefully chosen to conform to that used in most classical mechanics of materials, elasticity, and engineering design texts as well as to that most often employed in the numerical analysis of complex machines and structures. Both the international system of units (SI) and the US customary system of units are used, but since in practice the former is replacing the latter, this book places a greater emphasis on SI units.

Text Arrangement

A glance at the table of contents shows the topics covered and the way in which they are organized. Because of the extensive subdivision into a variety of topics and the use of alternative design and analysis methods, the book should provide flexibility in the choice of assignments to cover courses of varying length and content. A discussion of the design process and an overview of the material included in the book are given in Sections 1.1 through 1.4. Most chapters are substantially self-contained. Hence, the order

of presentation can be smoothly altered to meet an instructor's preference. It is suggested, however, that Chapters 1 and 2 be studied first. The sections and chapters marked with an asterisk (*) deal with special or advanced topics. These are optional for a basic course in design and can be skipped without disturbing the continuity of the book.

This book attempts to provide synthesis and analysis that cut through the clutter and save the reader's time. Every effort has been made to eliminate errors. I hope I have maintained a clarity of presentation, as much simplicity as the subject permits, unpretentious depth, an effort to encourage intuitive understanding, and a shunning of the irrelevant. In this context, emphasis is placed on the use of fundamentals to build students' understanding and ability to solve more complex problems throughout.

Features

The following overview highlights key features of this innovative machine design book.

Large Variety of Interesting and Engaging Worked Examples and Homework Problems

Providing fresh, practically based problem content, the text offers *731 homework problems, 185 worked examples, and 11 case studies.*

Consistent Problem-Solving Approach

To provide students a consistent framework for organizing their work, worked examples and case studies use a standard problem-solving format:

1. Problem statement (given)
2. Find
3. Assumptions
4. Solution
5. Comments

Unique Case Studies

Eleven text cases provide additional applications of the use of design processes. Two major case studies—the *crane with winch study* and the *high-speed cutting machine study*—concern system design allowing students to see how the stress and displacement of any one member may be invariably affected by the related parts. These also add to the skill sets they need as practicing engineers. The cases are interesting and relevant with special emphasis on industry uses, material selection, safety considerations, and cost factors.

Three Aspects of Solid Mechanics Emphasized

Equilibrium, material behavior, and geometry of deformation. The book reinforces the importance of these *basic principles of analysis.*

Strong Visual Approach

The book includes about 600 figures and 35 photographs, many with multiple parts, to aid students' comprehension of the concepts. All regular figures include explanatory captions.

Introduction

The author provides solid pedagogical tools and objectives for each chapter, including an excellent summary at the beginning.

Additional Features

Free-body diagrams, review of key stress analysis concepts, material properties and applications, rational design procedure, role of analysis in design, FEA in design.

This Edition Promise

Text Accuracy

The author, a proof reader, and a production editor checked all final pages for accuracy.

Solution Accuracy

Fully worked-out solutions written and class-tested by the author. An accuracy checker independently checked all final solutions.

Reliability

Over the last three decades, Ansel Ugural has written best-selling books on advanced mechanics of materials, elasticity, mechanics of materials, beams, plates and shells, and mechanical design.

Time-Saving Support Material

Available on the companion site at http://www.physicalpropertiesofmaterials.com/book/?isbn=9781439866511.

Meeting ABET Criteria

This book addresses the following ABET criteria:

1. An ability to apply knowledge of mathematics, science, and engineering
2. An ability to design and conduct experiments, as well as to analyze and interpret data
3. An ability to design a system, a component, or a process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
4. An ability to identify, formulate, and solve engineering problems
5. An understanding of professional and ethical responsibilities
6. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

Optional Media Supplements

Supplements: A Solutions Manual is available upon request to instructors in printed form. Written and class-tested by the author, it features complete solutions to problems in the text. Additional material is available from the CRC Web site: http://www.crcpress.com/product/isbn/9781439887806. This includes solutions using MATLAB® for a variety of examples and case studies of practical importance presented in the text.

MATLAB® is a registered trademark of The MathWorks, Inc. For product information, please contact:

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Executive Editor Jonathan Plant made extraordinary efforts in developing this edition of the book. Also, production was managed and handled efficiently by the staff of CRC Press and Spi Global – Content Solutions. I thank them for their professional help. Accuracy checking of the problems, typing of solutions manual, proof reading, and solutions of MATLAB® problems on the website were done by my former student, Dr. Youngjin Chung. In addition, contributing considerably to this volume with computer work, typing new inserts, assisting with some figures, and cover design was Errol A. Ugural. Their work is much appreciated. Lastly, I deeply appreciate the understanding and encouragement of my wife, Nora, daughter, Aileen, and son, Errol, during the preparation of the text.

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Author

Ansel C. Ugural is a visiting professor of mechanical engineering at the New Jersey Institute of Technology, Newark, New Jersey. He has been a National Science Foundation fellow and has taught at the University of Wisconsin. He has held faculty positions at Fairleigh Dickinson University, where he has served for two decades as a professor and chairman of the mechanical engineering department. He has had considerable and diverse industrial experience in both full-time and consulting capacities as a design, development, and research engineer.

Professor Ugural earned his MS in mechanical engineering and PhD in engineering mechanics from the University of Wisconsin–Madison. He has been a member of the American Society of Mechanical Engineers and the American Society of Engineering Education. He is also listed in *Who's Who in Engineering.*

Professor Ugural is the author of several books, including *Mechanical Design: An Integrated Approach* (McGraw-Hill, 2004); *Stresses in Plates and Shells* (McGraw-Hill, 1999); *Stresses in Beams, Plates, and Shells* (CRC Press, 3rd ed., 2010); *Mechanics of Materials* (McGraw-Hill, 1990); and *Mechanics of Materials* (Wiley, 2008). These books have been translated into Korean, Chinese, and Portuguese. Dr. Ugural is also the coauthor (with S.K. Fenster) of *Advanced Mechanics of Materials and Applied Elasticity* (Prentice Hall, 5th ed., 2012). In addition, he has published numerous articles in trade and professional journals.

Symbols

See Sections 11.2, 11.4, 11.9, 11.11, 12.3, 12.5, 12.6, 12.8, and 12.9 for some gearing symbols.

Roman Letters

A	Amplitude ratio, area, coefficient, cross-sectional area
A_e	Effective area of clamped parts, projected area
A_f	Final cross-sectional area
A_o	Original cross-sectional area
A_t	Tensile stress area, tensile stress area of the thread
a	Acceleration, crack depth, distance, radius, radius of the contact area of two spheres
B	Coefficient
b	Distance, width of beam, band, or belt; radius
C	Basic dynamic load rating, bolted-joint constant, centroid, constant, heat transfer coefficient, specific heat, spring index
C_c	Limiting value of column slenderness ratio
C_f	Surface finish factor
C_r	Reliability factor
C_s	Basic static load rating, size factor
c	Distance from neutral axis to the extreme fiber, radial clearance, center distance
D	Diameter, mean coil diameter, plate flexural rigidity $[Et^3/12(1-\nu^2)]$
d	Diameter, distance, pitch diameter, wire diameter
d_{avg}	Average diameter
d_c	Collar (or bearing) diameter
d_m	Mean diameter
d_p	Pitch diameter
d_r	Root diameter
E	Modulus of elasticity
E_b	Modulus of elasticity for the bolt
E_k	Kinetic energy
E_p	Modulus of elasticity for clamped parts, potential energy
e	Dilatation, distance, eccentricity, efficiency
F	Force, tension
F_a	Axial force, actuating force
F_b	Bolt axial force
F_c	Centrifugal force
F_d	Dynamic load
F_i	Initial tensile force or preload
F_n	Normal force
F_p	Clamping force for the parts, proof load
F_r	Radial force
F_t	Tangential force
F_u	Ultimate force
f	Coefficient of friction, frequency
f_c	Collar (or bearing) coefficient of friction

f_n Natural frequency
G Modulus of rigidity
g Acceleration due to gravity
H Time rate of heat dissipation, power
H_B Brinell hardness number (Bhn)
H_V Vickers hardness number
h Cone height, distance, section depth, height of fall, weld size, film thickness
h_f Final length, free length
h_0 Minimum film thickness
h_s Solid height
I Moment of inertia
I_e Equivalent moment of inertia of the spring coil
J Polar moment of inertia, factor
K Bulk modulus of elasticity, constant, impact factor, stress intensity factor, system stiffness
K_c Fracture toughness
K_f Fatigue stress concentration factor
K_r Life adjustment factor
K_s Service factor, shock factor, direct shear factor for the helical spring
K_t Theoretical or geometric stress concentration factor
K_w Wahl factor
k Buckling load factor for the plate, constant, element stiffness, spring index or stiffness
k_b Stiffness for the bolt
k_p Stiffness for the clamped parts
L Grip, length, lead
L_e Equivalent length of the column
L_f Final length
L_0 Original length
L_5 Rating life for reliability greater than 90%
L_{10} Rating life
l Direction cosine, length
M Moment
M_a Alternating moment
M_f Moment of friction forces
M_m Mean moment
M_n Moment of normal forces
m Direction cosine, mass, module, mass
N Normal force, number of friction planes, number of teeth, fatigue life or cycles to failure
N_a Number of active spring coils
N_{cr} Critical load of the plate
N_t Total number of spring coils
N_θ Hoop force
N_ϕ Meridional force
n Constant, direction cosine, factor of safety, modular ratio, number, number of threads, rotational speed
n_{cr} Critical rotational speed
P Force, concentrated load, axial load, equivalent radial load for a roller bearing, radial load per unit projected area

P_a Alternating load
P_{all} Allowable load
P_{cr} Critical load of the column or helical spring
P_m Mean load
p Pitch, pressure, probability
p_{all} Allowable pressure
p_i Internal pressure
p_{max} Maximum pressure
p_{min} Minimum pressure
p_o Outside or external pressure
p_0 Maximum contact pressure
$p(x)$ Probability or frequency function
Q First moment of area, imaginary force, volume, flow rate
Q_S Side leakage rate
q Notch sensitivity factor, shear flow
R Radius, reaction force, reliability, stress ratio
R_B Rockwell hardness in B scale
R_C Rockwell hardness in C scale
r Aspect ratio of the plate, radial distance, radius, radius of gyration
r_{avg} Average radius
r_i Inner radius
r_o Outer radius
S Section modulus, Saybolt viscometer measurement in seconds, Sommerfeld number, strength
S_e Endurance limit of mechanical part
S'_e Endurance limit of specimen
S_{es} Endurance limit in shear
S_f Fracture strength
S_n Endurance strength of mechanical part
S'_n Endurance strength of specimen
S_p Proof strength, proportional limit strength
S_u Ultimate strength in tension
S_{uc} Ultimate strength in compression
S_{us} Ultimate strength in shear
S_y Yield strength in tension
S_{ys} Yield strength in shear
s Distance, sample standard deviation
T Temperature, tension, torque
T_a Alternating torque
T_d Torque to lower the load
T_f Friction torque
T_m Mean torque
T_o Torque of overhauling
T_t Transition temperature
T_u Torque to lift the load
t Temperature, distance, thickness, time
t_a Temperature of surrounding air
t_o Average oil film temperature
U Strain energy, journal surface velocity

U_o Strain energy density
U_{od} Distortional strain energy density
U_{ov} Dilatational strain energy density
U_r Modulus of resilience
U_t Modulus of toughness
U^* Complementary energy
U_o^* Complementary energy density
u Radial displacement, fluid flow velocity
V Linear velocity, a rotational factor, shear force, volume
V_s Sliding velocity
υ Displacement, linear velocity
W Work, load, weight
w Distance, unit load, deflection, displacement
X A radial factor
Y Lewis form factor based on diametral pitch or module, a thrust factor
y Distance from the neutral axis, Lewis form factor based on circular pitch, quantity
$\bar{y}$ Distance locating the neutral axis
Z Curved beam factor, section modulus
z Number of standard deviations

Greek Letters

α Angle, angular acceleration, coefficient, coefficient of thermal expansion, cone angle, form factor for shear, thread angle
α_n Thread angle measured in the normal plane
β Angle, coefficient, half-included angle of the V belt
γ Included angle of the disk clutch or brake, pitch angle of the sprocket, shear strain, weight per unit volume; γ_{xy}, γ_{yz}, and γ_{xz} are shear strains in the xy, yz, and xz planes
γ_{max} Maximum shear strain
Δ Gap, material parameter in computing contact stress
δ Deflection, displacement, elongation, radial interference or shrinking allowance, a virtual infinitesimally small quantity
δ_{max} Maximum or dynamic deflection
δ_s Solid deflection
δ_{st} Static deflection
δ_w Working deflection
ϵ Eccentricity ratio
ε Normal strain; ε_x, ε_y, and ε_z are normal strains in the x, y, and z directions
ε_f Normal strain at fracture
ε_t True normal strain
ε_u Ultimate strain
η Absolute viscosity or viscosity
θ Angle, angular displacement, slope
θ_p Angle to a principal plane or to a principal axis
θ_s Angle to a plane of maximum shear
λ Lead angle, helix angle, material constant
μ Population mean
ν Kinematic viscosity, Poisson's ratio
ρ Mass density

σ	Normal stress; σ_x, σ_y, and σ_z are normal stresses in the x, y, and z planes, standard deviation
σ_a	Alternating stress
σ_{all}	Allowable stress
σ_{cr}	Critical stress
σ_e	Equivalent stress
σ_{ea}	Equivalent alternating stress
σ_{em}	Equivalent mean stress
σ_{max}	Maximum normal stress
σ_{min}	Minimum normal stress
σ_{nom}	Nominal stress
σ_{oct}	Octahedral normal stress
σ_{res}	Residual stress
τ	Shear stress; τ_{xy}, τ_{yz}, and τ_{xz} are shear stresses perpendicular to the x, y, and z axes and parallel to the y, z, and x axes
τ_{avg}	Average shear stress
τ_{all}	Allowable shear stress
τ_d	Direct shear stress
τ_{oct}	Octahedral shear stress
τ_{max}	Maximum shear stress
τ_{min}	Minimum shear stress
τ_{nom}	Nominal shear stress
τ_t	Torsional shear stress
φ	Angle, angle giving the position of minimum film thickness, pressure angle, angle of twist, angle of wrap
φ_{max}	Position of maximum film pressure
ψ	Helix angle, spiral angle
ω	Angular velocity, angular frequency ($\omega = 2\pi f$)
ω_n	Natural angular frequency

Abbreviations

all	Allowable
avg	Average
Bhn	Brinell hardness number
CCW	Counterclockwise
CD	Cold drawn
cr	Critical
CW	Clockwise
fpm	Foot per minute
ft	Foot, feet
h	Hour
HD	Hard drawn
hp	Horsepower
HT	Heat treated
Hz	Hertz (cycles per second)
ID	Inside diameter
in.	Inch, inches
ipm	Inch per minute
ips	Inch per second
J	Joule
kg	Kilogram(s)
kip	Kilopound (1000 lb)
kips	Kilopounds
ksi	Kips per square inch (10^3 psi)
kW	Kilowatt
lb	Pound(s)
ln	Naperian natural logarithm
log	Common logarithm (base 10)
m	Meter
max	Maximum
min	Minimum
mph	Miles per hour
m/s	Meter per second
N	Newton
NA	Neutral axis
OD	Outside diameter
OQ&T	Oil quenched and tempered
OT	Oil tempered
Pa	Pascal
psi	Pounds per square inch
Q&T	Quenched and tempered
R_C	Rockwell hardness, C scale
rad	Radian
req	Required
res	Residual

rpm	Revolutions per minute
rps	Revolutions per second
s	Second
SI	System of international units
st	Static
SUS	Saybolt universal seconds
SUV	Saybolt universal viscosity
VI	Viscosity index
W	Watt
WQ&T	Water quenched and tempered