Machine Elements in Mechanical Design

SIXTH EDITION

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Pearson

MACHINE ELEMENTS IN MECHANICAL DESIGN

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Cover Art: Authors' own
Full-Service Management and Composition: R. Sreemeenakshi/SPi Global
Printer/Binder: LSC Communications, Inc.
Cover Printer: Phoenix Color/ Hagerstown
Text Font: 10/12 Sabon LT Pro Roman

Library of Congress Cataloging-in-Publication Data on File

10 9 8 7 6 5 4 3 2 1

Pearson

ISBN 10: 0-13-444118-4
ISBN 13: 978-0-13-444118-4

CONTENTS

8 Kinematics of Gears 304

9 Spur Gear Design 362

10 Helical Gears, Bevel Gears, and Wormgearing 428

11 Keys, Couplings, and Seals 470

PREFACE

The objective of this book is to provide the concepts, procedures, data, and decision analysis techniques necessary to design machine elements commonly found in mechanical devices and systems. Students completing a course of study using this book should be able to execute original designs for machine elements and integrate the elements into a system composed of several elements.

This process requires a consideration of the performance requirements of an individual element and of the interfaces between elements as they work together to form a system. For example, a gear must be designed to transmit power at a given speed. The design must specify the number of teeth, pitch, tooth form, face width, pitch diameter, material, and method of heat treatment. But the gear design also affects, and is affected by, the mating gear, the shaft carrying the gear, and the environment in which it is to operate. Furthermore, the shaft must be supported by bearings, which must be contained in a housing. Thus, the designer should keep the complete system in mind while designing each individual element. This book will help the student approach design problems in this way.

This text is designed for those interested in practical mechanical design. The emphasis is on the use of readily available materials and processes and appropriate design approaches to achieve a safe, efficient design. It is assumed that the person using the book will be the designer, that is, the person responsible for determining the configuration of a machine or a part of a machine. Where practical, all design equations, data, and procedures needed to make design decisions are specified.

It is expected that students using this book will have a good background in statics, strength of materials, college algebra, and trigonometry. Helpful, but not required, would be knowledge of kinematics, industrial mechanisms, dynamics, materials, and manufacturing processes.

Among the important features of this book are the following:

1. It is designed to be used at the undergraduate level in a first course in machine design.
2. The large list of topics allows the instructor some choice in the design of the course. The format is also appropriate for a two-course sequence and as a reference for mechanical design project courses.
3. Students should be able to extend their efforts into topics not covered in classroom instruction because explanations of principles are straightforward and include many example problems.
4. The practical presentation of the material leads to feasible design decisions and is useful to practicing designers.
5. The text advocates and demonstrates use of computer spreadsheets in cases requiring long, laborious solution procedures. Using spreadsheets allows the designer to make decisions and to modify data at several points within the problem while the computer performs all computations. See Chapter 6 on columns, Chapter 9 on spur gears, Chapter 12 on shafts, Chapter 13 on shrink fits, and Chapter 18 on spring design. Other computer-aided calculation software can also be used.
6. References to other books, standards, and technical papers assist the instructor in presenting alternate approaches or extending the depth or breadth of treatment.
7. Lists of Internet sites pertinent to topics in this book are included at the end of most chapters to assist readers in accessing additional information or data about commercial products.
8. In addition to the emphasis on original design of machine elements, much of the discussion covers commercially available machine elements and devices, since many design projects require an optimum combination of new, uniquely designed parts and purchased components.
9. For some topics the focus is on aiding the designer in selecting commercially available components, such as rolling contact bearings, flexible couplings, ball screws, electric motors, belt drives, chain drives, wire rope, couplings, clutches, and brakes.
10. Computations and problem solutions use both the International System of Units (SI) and the U.S. Customary System (inch-pound-second) approximately equally. The basic reference for the usage of SI units is IEEE/ASTM-SI-10 *American National standard for Metric Practice*. This document is the primary American National Standard on application of the metric system.
11. Extensive appendices are included along with detailed tables in many chapters to help the reader to make real design decisions, using only this text. Several appendix tables feature commercially available structural shapes in both larger and smaller sizes and many in purely metric dimensions are included in this edition to give instructors and students many options for completing design problems.

MECHANICAL DESIGN SOFTWARE

The design of machine elements inherently involves extensive procedures, complex calculations, and many design decisions. Data must be found from numerous charts and tables. Furthermore, design is typically iterative, requiring the designer to try several options for any given element, leading to the repetition of design calculations with new data or new design decisions. This is especially true for complete mechanical devices containing several components as the interfaces between components are considered. Changes to one component often require changes to mating elements. Use of spreadsheets, computational software, and computer-aided mechanical design software can facilitate the design process by performing many of the tasks while leaving the major design decisions to the creativity and judgment of the designer or engineer.

We emphasize that users of computer software must have a solid understanding of the principles of design and stress analysis to ensure that design decisions are based on reliable foundations. We recommend that the software be used only after mastering a given design methodology by careful study and using manual techniques.

The strong movement in the United States and other industrialized countries toward global sourcing of materials and products and the use of multinational design teams makes the use of commercial software highly valuable during the lifelong career of designers and engineers. Furthermore, the specification of commercially available machine components and systems typically involves the use of manufacturers' software built into company Internet sites. This book provides guidance on the use of such sites as an integral part of the machinery design process.

FEATURES OF THE SIXTH EDITION

The practical approach to designing machine elements in the context of complete mechanical designs is retained and refined in this edition. An extensive amount of updating has been accomplished through the inclusion of new photographs of commercially available machine components, new design data for some elements, new or revised standards, new end-of-chapter references, listings of Internet sites, and some completely new elements. Full color has been used for the first time to enhance the visual attractiveness of the book and to highlight prominent features of charts, graphs, and technical illustrations. Numerous, highly detailed, full-color new drawings have been added or have replaced drawings used in previous editions.

The following list summarizes the primary features and the updates.

1. The three-part structure that was introduced in the third edition has been maintained.
   - Part I (Chapters 1–6) focuses on reviewing and upgrading readers' understanding of design philosophies, the principles of strength of materials, the design properties of materials, combined stresses, design for different types of loading, and the analysis and design of columns.
   - Part II (Chapters 7–15) is organized around the concept of the design of a complete power-transmission system, covering some of the primary machine elements such as belt drives, chain drives, wire rope, gears, shafts, keys, couplings, seals, and rolling contact bearings. These topics are tied together to emphasize both their interrelationships and their unique characteristics. Chapter 15, **Completion of the Design of a Power Transmission,** is a guide through detailed design decisions such as the overall layout, detail drawings, tolerances, and fits. Several new, full-color drawings for an example of a gear-type speed reducer have been added to aid students' perception and understanding of how individual machine elements are designed, assembled, and operated together. The representation of the complete single-reduction gear drive at the end of Chapter 15 has been significantly upgraded, aiding students' understanding of how to translate design analysis, decision-making about component details, and commercially available components into a complete assembly.
   - Part III (Chapters 16–22) presents methods of analysis and design of several important machine elements that were not pertinent to the design of a power transmission. These chapters can be covered in any order or can be used as reference material for general design projects. Covered here are plain surface bearings, linear motion elements, fasteners, springs, machine frames, bolted connections, welded joints, electric motors, controls, clutches, and brakes.
2. **The Big Picture, You Are the Designer,** and **Objectives** features introduced in earlier editions are maintained and refined. Feedback about these features from users, both students and instructors, have been enthusiastically favorable. They help readers to draw on their own experiences and to appreciate what competencies they will acquire from the study of each chapter. Constructivist theories of learning espouse this approach.
3. Lists of Internet sites and printed references have been updated and edited in every chapter. Many new entries have been added. The extensive lists of such resources are useful to students, instructors, and practicing engineers to extend their understanding of concepts beyond this book and to access the huge

potential of the Internet as a source of information about practical design methods and commercially available products.

4. Some of the new or updated topics from individual chapters are summarized here.

- In Chapter 1, **The Nature of Mechanical Design,** first ten figures showing a variety of mechanical devices and machinery have been replaced with new, full-color images to enhance students' perceptions of the details of many types of equipment. Two of these new images show production machinery designed by one of the new coauthors of this book.
- Chapter 2, **Materials in Mechanical Design,** continues to emphasize the specification and use of appropriate materials, building on prior courses in metallurgy, materials, and processes. Extensive tables listing materials commonly used in commercially available shapes are included. To serve the global nature of machine design, an extensive table of designations for steel and aluminum alloys from several countries is included. Designations for steel alloys continue to use the SAE numbering system. The discussion of heat treating of steels continues to focus on quenching and tempering along with case hardening to give students an appreciation of the wide range of properties that any given material can have and the importance of being able to specify pertinent heat treatment requirements. Descriptions of white iron, powder metals, aluminum casting and forging alloys, magnesium, nickel-based alloys, titanium alloys, and brasses and bronzes are included. The extensive discussion of advanced engineering composites includes SI data, nanocomposites, and design approaches, continuing to provide students with basic concepts that can lead to novel applications of composite materials to machine design. Materials selection using decision analysis techniques has been refined.
- Chapter 3, **Stress and Deformation Analysis,** has been reorganized with some section titles revised, bringing an improved order of coverage. The objective of the update is to clarify how the external loading, such as direct normal force, direction shear force, torsion/torque, and bending moment can produce normal and shear stresses on a stress element.
- Graphs of stress concentration factors have been returned to the Appendix, allowing students to apply them in most problem-solving exercises in this book. However, information about other print and easily-accessible Internet sources for K_t values remain, giving instructors and students the opportunity to apply a wider scope of design data.
- Chapter 4, **Combined Stresses and Stress Transformation,** has been revised to show that a stress element is always 3-dimensional (3D). Resulting from some loading condition, the stresses on a 3D element, however, can be in 1D or 2D stress state. That is, the values of stress components in certain direction(s) can be zero. This concept is presented to assist readers in analyzing 3D combined loading and combined stress problems. A major change in this chapter is that, while the Mohr's circle technique is used for 1D or 2D stress transformation, the resulting stress element is presented in 3D, having one or two principal stresses equal to zero. The 3D approach can help readers to visualize the stress state of a point (a stress element) at the location of interest.
- The contents of Chapter 5, **Design for Different Types of Loading,** have been reorganized and a brief discussion of failure theories has been added, extending the revisions discussed for Chapters 3 and 4. The design methods for static loading and cyclic loading are now clearly identified in different sections. All stress elements in the Design Examples are 3D elements, while recognizing that some elements are in a 1D or 2D stress state. For failure prediction, a unified approach based on the evaluation of principal stresses against material properties is presented. The 3D approach is also used in mean and alternating stresses calculation when dealing with fatigue failure in cyclic loading condition. Continuing from the 5^{th} edition, are discussions of endurance strength, recommended design and processing approaches under fatigue load, the Smith Diagram approach for showing the effect of mean stress on fatigue, and the damage accumulation method for varying stress amplitudes.
- In Chapter 7, **Belt Drives, Chain Drives, and Wire Rope,** significant new material on synchronous belt drive designs in both SI and U.S. units has been added. Common metric sizes for V-belts, synchronous belts, chains, and sprockets are included. The new section on wire rope complements the former parts of this chapter with information that can be applied to lifting equipment and industrial machinery for which flexible tensile elements are needed.
- Chapter 8, **Kinematics of Gears,** continues to emphasize the geometry of U. S, and metric module-type gearing and has an integrated discussion of spur, helical, bevel, and wormgearing. A useful table for calculating key geometric features of gears and gear teeth aids problem solving and design decisions. Discussions of velocity ratios, train values, and devising gear trains have been refined and new, detailed, color drawings are included.

- Chapter 9, **Spur Gear Design,** continues to be refined in its use of AGMA standards along with the metric module system. The arrangement of sections has been modified for smoother coverage of the various aspects of gear design. Additional example problems illustrate different approaches to the design process. Topics covering gear lubricants and typical viscosity grades are included.
- Chapter 10, **Helical Gears, Bevel Gears, and Wormgearing,** has been updated along similar lines as discussed for Chapter 9 on Spur Gear Design.
- In Chapter 11, **Keys, Couplings, and Seals,** new information is provided for selecting flexible couplings and universal joints.
- In Chapter 12, **Shaft Design,** the highly regarded procedure for the design of a shaft has been continued. Coverage of the torque capacity of selected flexible shaft sizes continues.
- In Chapter 14, **Rolling Contact Bearings,** the bearing selection procedure has been closely tied to the use of manufacturers' data and the specific procedures outlined on their Internet sites, listed at the end of the chapter. This permits the use of a wide variety of sources and types of bearings as is done in practical mechanical design. Sample data are included in the chapter to introduce students to the variables involved in bearing selection and the types of analysis required to specify optimal bearings. An extensive discussion of bearing materials is included for steels, ceramics, Monel, titanium/nickel alloys, and plastics to emphasize the importance of specifying materials that meet application requirements.
- Chapter 16, **Plain Surface Bearings,** includes sample data on *pV factors* for boundary-lubricated bearings and common lubricants, along with the analysis of plain bearing performance under oscillating motion. Coverage of topics such as hydrodynamic and hydrostatic bearings continues. An intriguing new example of the application of boundary lubrication, called the Kugel Fountain, has been added.
- In Chapter 17, **Linear Motion Elements,** new information about high-speed linear actuators has been added to the discussion of power screws and ball screw drives.
- Chapter 18 on **Springs,** Chapter 19 on **Fasteners,** and Chapter 20, **Frames, Bolted Connections, and Welded Joints** provide useful information about components and analysis techniques used in many types of machinery.
- Chapter 21 **Electric Motors and Controls, and** Chapter 22, **Motion Control: Clutches and Brakes,** assist the mechanical designer in specifying electrical drive systems and electrical and mechanical controls for a wide variety of applications.
- **The Appendix** has an extensive set of tables for material properties of steels, cast irons, aluminum alloys, zinc and magnesium alloys, plastics, nickel-based alloys, titanium alloys, bronzes, brasses, and other copper alloys. Several tables of data are included for section properties of commercially available shapes in larger and smaller sizes and in pure metric dimensions to provide a wide array of choices for problem-solving and design. Appendixes for beam deflection formulas, conversion factors, and hardness assist students as they study multiple chapters. Ten charts for stress concentration factors have been returned to the book in a revised order that is related to the manner of loading; tension, bending, and torsion.

INTRODUCING TWO NEW CO-AUTHORS:

For the first five editions of this book, the sole author was Robert L. Mott. For this new 6th edition, two outstanding co-authors have contributed to a great extent in updating and upgrading the content, and enhancing the appearance of the book. Their brief biographies are mentioned below. For those using this book and who may not know Professor Mott, his brief biography follows:

Robert L. Mott is Professor Emeritus of Engineering Technology at the University of Dayton. He is a member of ASEE, SME, and ASME. He is a Fellow of ASEE and a recipient of the ASEE James H. McGraw Award and the Archie Higdon Distinguished Educator Award from the Mechanics Division. He is a recipient of the SME Education Award for his contributions to manufacturing education. He holds the Bachelor of Mechanical Engineering degree from General Motors Institute (Now Kettering University) and the Master of Science in Mechanical Engineering from Purdue University. He has authored three textbooks; *Applied Fluid Mechanics 7th ed.* (2015) and *Machine Elements in Mechanical Design 6th ed.* (2018), published by Pearson; *Applied Strength of Materials 6th ed.* (2017) published by CRC Press. His work experience includes serving as a research engineer for General Motors Corporation, consulting for industrial clients, working for the University of Dayton Research Institute (UDRI), leading the Center for Advanced Manufacturing for UDRI, and serving as an expert witness for accident analysis cases for industrial and automotive accidents. He also served for 12 years as one of the senior personnel for the NSF-sponsored National Center for Manufacturing Education based in Dayton, Ohio.

Edward M. Vavrek is an Associate Professor in Mechanical Engineering Technology at Purdue University Northwest, located at the Westville, IN campus, an extension of Purdue University. He is a member of AGMA, ASME, and ASEE. He received his Bachelor of Science in

Mechanical Engineering from Purdue University Calumet, Masters in Business Administration from Indiana University Northwest, and Masters in Mechanical and Aeronautical Engineering from the Illinois Institute of Technology. He has significant industrial experience in design and development of machinery, using SolidWorks and Inventor, within the printing/converting, shipbuilding, railroad, steel mill, and automotive industries. He has presented multiple papers on his software developed for the area of machine design. He holds one U.S. patent. He also does extensive private consulting in mechanical design that is highly relevant to the content of this book.

Dr. Jyhwen Wang, Ph.D. is a Professor with dual appointment in the departments of Engineering Technology and Industrial Distribution and Mechanical Engineering at Texas A&M University in College Station, TX. He holds the degrees of Ph.D. in Mechanical Engineering and Master of Engineering in Manufacturing Engineering from Northwestern University in Evansville, IL, the M.S. in Industrial Engineering and Operations Research from Syracuse University in Syracuse, NY, and the B.S. in Industrial Engineering from Tunghai University in Taichung, Taiwan. He has significant industrial experience with Weirton Steel Corporation in Weirton, West Virginia along with consulting for several organizations. He has participated in funded research and education projects as PI or Co-PI. He is a Fellow of the American Society of Mechanical Engineers and the Society of Manufacturing Engineers. Professional society memberships include ASME, ASEE, SME, NAMRI/SME (North American Manufacturing Research Institute), and NADDRG (North American Deep Drawing Research Group). He has written book sections for *Manufacturing Processes for Engineering Materials,* (2003) and *Manufacturing Engineering and Technology,* (2001) by Kalpakjian and Schmid published by Pearson.

ACKNOWLEDGMENTS

Our appreciation is extended to all those who provided helpful suggestions for improvements to this book. We thank the editorial staff of Pearson, those who provided illustrations, and the many users of the book, both instructors and students, with whom we have had discussions. Special appreciation goes to our colleagues at the University of Dayton, Purdue University, and Texas A&M University. We would like to thank Amit Banerjee, The Pennsylvania State University; Michael DeVore, Cincinnati State Technical and Community College; Dexter Hulse, University of Cincinnati; Scott Kessler, Colorado Mesa University; and Zhongming Liang, Indiana Purdue University Fort Wayne, for their helpful reviews of this revision. We also thank those who provided thoughtful reviews of prior editions. We especially thank our students—past and present—for their encouragement and positive feedback about this book. All three co-authors extend sincere gratitude to our wives, children, and parents who provided unwavering support, patience, and inspiration as we prepared the new 6th edition of this book.

Robert L. Mott, Edward M. Vavrek, Jyhwen Wang

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PART ONE

PRINCIPLES OF DESIGN AND STRESS ANALYSIS

As you complete the first six chapters of this book, you will gain an understanding of design philosophies, and you will build on earlier-learned principles of strength of materials, materials science, and manufacturing processes. The competencies gained from these chapters are useful throughout the book and in general machine design or product design projects.

Chapter 1: The Nature of Mechanical Design helps you see the big picture of the process of mechanical design. Several examples are shown from different industry sectors: Consumer products, manufacturing systems, construction equipment, agricultural equipment, transportation equipment, ships, and space systems. The responsibilities of designers are discussed, along with an illustration of the iterative nature of the design process. Units and conversions structural shapes, screw threads, and preferred basic sizes complete the chapter.

Chapter 2: Materials in Mechanical Design emphasizes the design properties of materials. Much of this chapter is probably review for you, but it is presented here to emphasize the importance of material selection to the design process and to explain the data for materials presented in the Appendices.

Chapter 3: Stress and Deformation Analysis is a review of the basic principles of stress and deflection analysis. It is essential that you understand the basic concepts summarized here before proceeding with later material. Reviewed are direct tensile, compressive, and shearing stresses; bending stresses; and torsional shear stresses.

Chapter 4: Combined Stresses and Stress Transformations is important because many general design problems and the design of machine elements covered in later chapters of the book involve combined stresses. You may have covered these topics in a course in strength of materials.

Chapter 5: Design for Different Types of Loading is an in-depth discussion of design factors, fatigue, and many of the details of stress analysis as used in this book.

Chapter 6: Columns discusses the long, slender, axially loaded members that tend to fail by buckling rather than by exceeding the yield, ultimate, or shear stress of the material. Special design and analysis methods are reviewed here.

CHAPTER ONE

THE NATURE OF MECHANICAL DESIGN

THE BIG PICTURE — The Nature of Mechanical Design

Discussion Map

- To design mechanical components and devices, you must be competent in the design of individual elements that comprise the system.
- But you must also be able to integrate several components and devices into a coordinated, robust system that meets your customer's needs.

Discover

Think, now, about the many fields in which you can use mechanical design:

What are some of the products of those fields?

What kinds of materials are used in the products?

What are some of the unique features of the products?

How were the components made?

How were the parts of the products assembled?

Consider consumer products, construction equipment, agricultural machinery, manufacturing systems, and transportation systems on the land, in the air, in space, and on and under water.

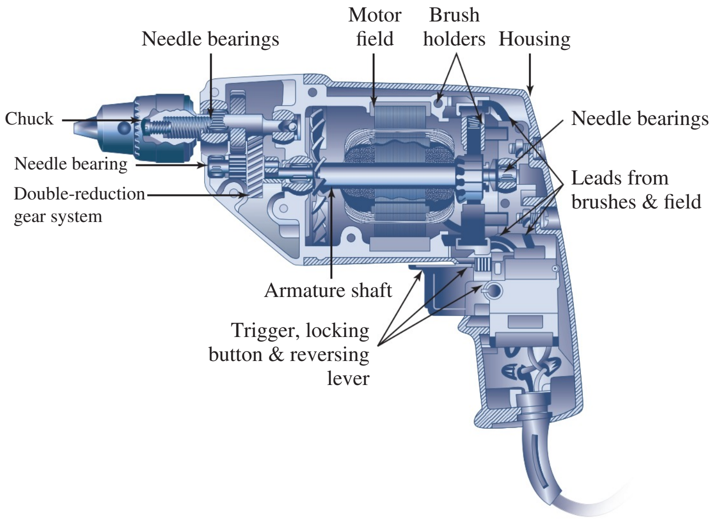
In this book, you, will find the tools to learn the principles of ***Machine Elements in Mechanical Design***.

Design of machine elements is an integral part of the larger and more general field of mechanical design. Designers and design engineers create devices or systems to satisfy specific needs. Mechanical devices typically involve moving parts that transmit power and accomplish specific patterns of motion. Mechanical systems are composed of several mechanical devices.

Therefore, to design mechanical devices and systems, you must be competent in the design of individual machine elements that comprise the system. But you must also be able to integrate several components and devices into a coordinated, robust system that meets your customer's needs. From this logic comes the name of this book, *Machine Elements in Mechanical Design.*

Think about the many fields in which you can use mechanical design. Discuss these fields with your instructor and with your colleagues who are studying with you. Talk with people who are doing mechanical design in local industries. Try to visit their companies if possible, or meet designers and design engineers at meetings of professional societies. Consider the following fields where mechanical products are designed and produced.

(*a*)

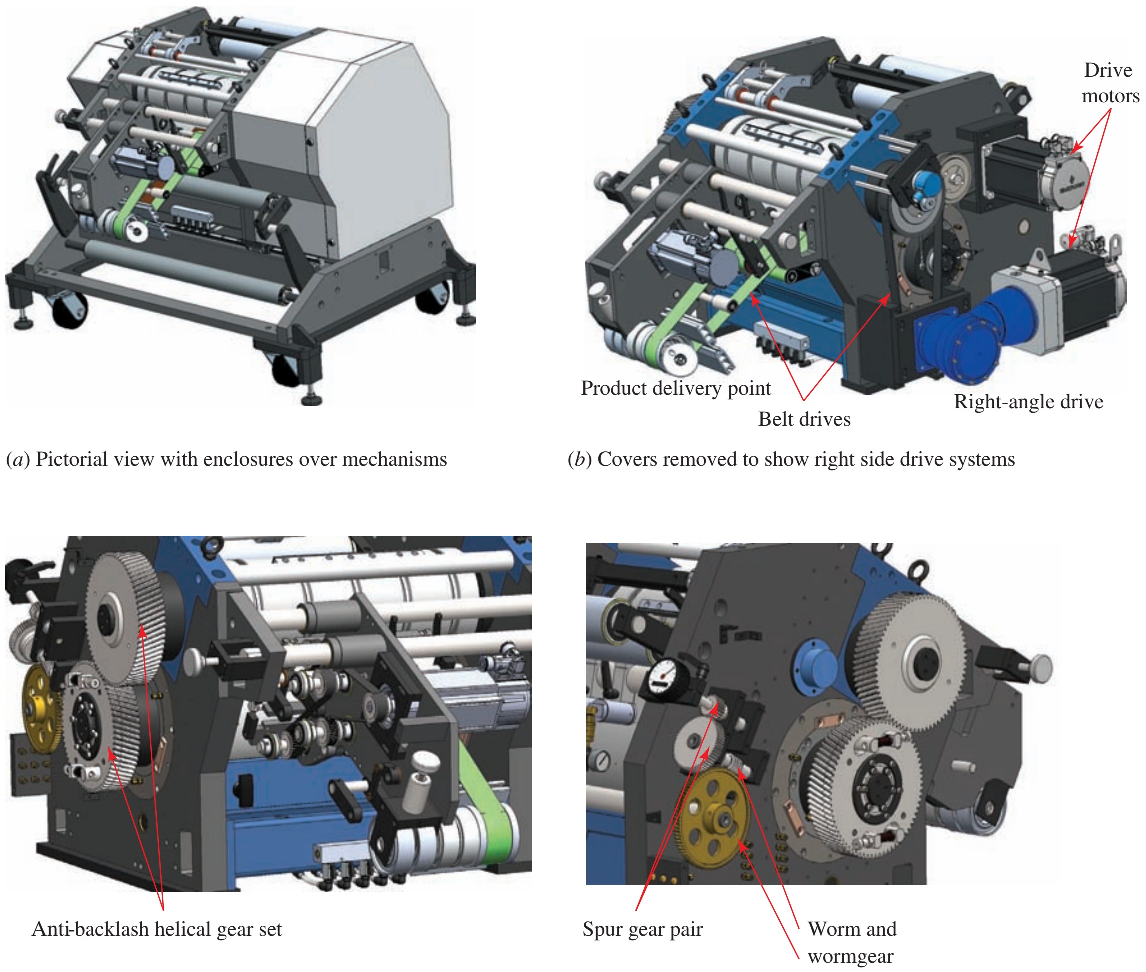


(*b*)

FIGURE 1–1 (a) Hand-held power drill (b) Cutaway view of a hand drill

- ***Consumer products:*** Household appliances (can openers, food processors, mixers, toasters, vacuum cleaners, clothes washers), lawn mowers, chain saws, power tools, garage door openers, air-conditioning systems, and many others. See Figures 1–1 and 1–2 for a few examples of commercially available products.
- ***Manufacturing systems:*** Material handling devices, conveyors, cranes, transfer devices, industrial robots, machine tools, automated assembly systems, special-purpose processing systems, forklift trucks, and packaging equipment. See Figures 1–3 and 1–4.
- ***Construction equipment:*** Tractors with front-end loaders or backhoes, cranes, power shovels, earthmovers, graders, dump trucks, road pavers, concrete mixers, powered nailers and staplers, compressors, and many others. See Figures 1–5 and 1–6.
- ***Agricultural equipment:*** Tractors, harvesters (for corn, wheat, tomatoes, cotton, fruit, and many other crops), rakes, hay balers, plows, disc harrows, cultivators, and conveyors. See Figures 1–6, 1–7, and 1–8.
- ***Transportation equipment:*** (a) Automobiles, trucks, and buses, which include hundreds of mechanical devices such as suspension components (springs, shock absorbers, and struts); door and window operators; windshield wiper mechanisms; steering systems; hood and trunk latches and hinges; clutch and braking systems; transmissions; driveshafts; seat adjusters; and numerous parts of the engine systems. (b) Aircraft, which include retractable landing gear, flap and rudder actuators, cargo-handling devices, seat reclining mechanisms, dozens of latches, structural components, and door operators. See Figures 1–9 and 1–10.

FIGURE 1–2 Chain saw
(Shutterstock)



(*a*) Pictorial view with enclosures over mechanisms
(*b*) Covers removed to show right side drive systems
(*c*) Left side, viewed from front of machine
(*d*) Closer view of gear drives from left-rear

FIGURE 1–3 Closed end mailer for the printing industry
Created by Edward M. Vavrek for The Lettershop Group, Leeks, UK

- ***Ships:*** Winches to haul up the anchor, cargo-handling cranes, rotating radar antennas, rudder steering gear, drive gearing and driveshafts, and the numerous sensors and controls for operating on-board systems.
- ***Space systems:*** Satellite systems, the space shuttle, the space station, and launch systems, which contain numerous mechanical systems such as devices to deploy antennas, hatches, docking systems, robotic arms, vibration control devices, devices to secure cargo, positioning devices for instruments, actuators for thrusters, and propulsion systems.

How many examples of mechanical devices and systems can you add to these lists?

What are some of the unique features of the products in these fields?

What kinds of mechanisms are included?

What kinds of materials are used in the products?

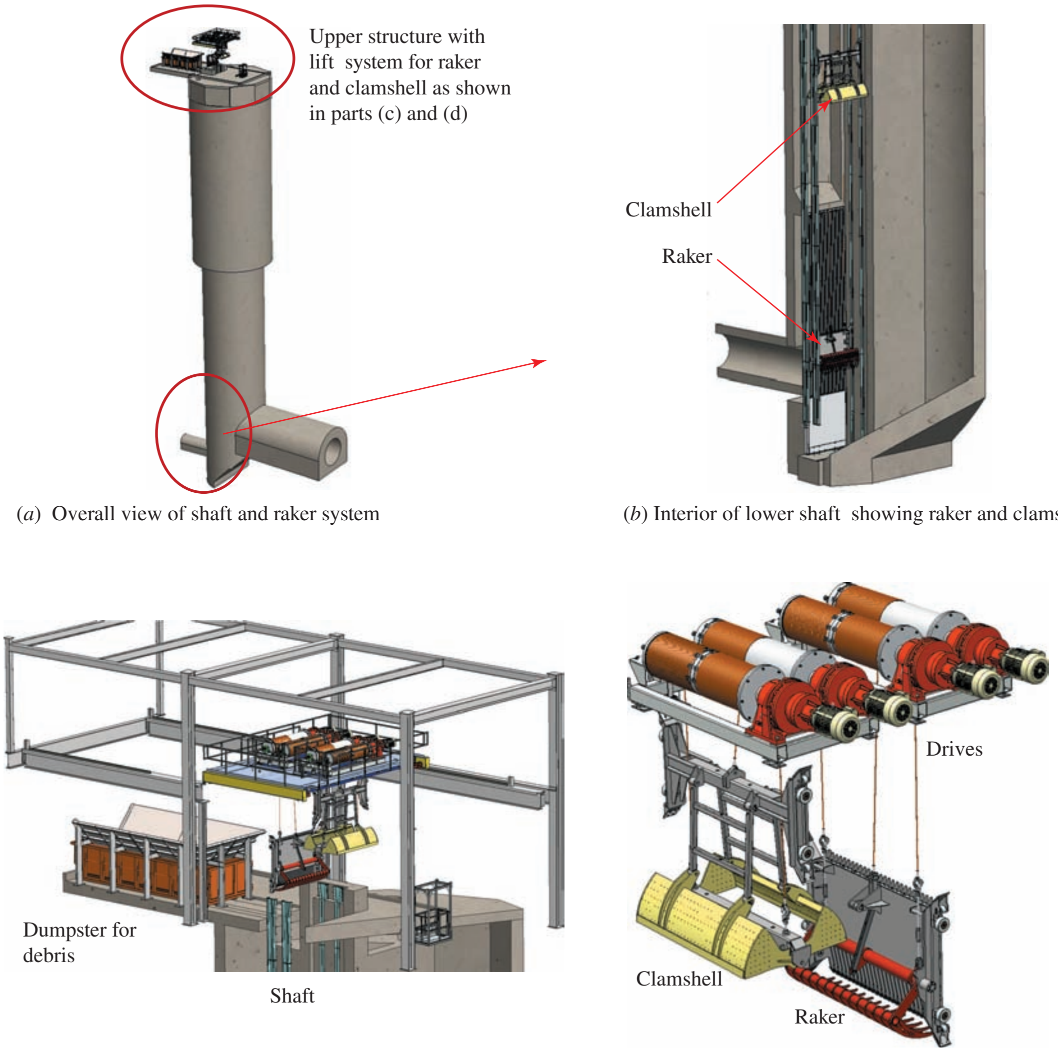
How were the components made?

How were the parts assembled into the complete products?

In this book, you will find the tools to learn the principles of *Machine Elements in Mechanical Design*. In the introduction to each chapter, we include a brief scenario called *You Are the Designer*. The purpose of these scenarios is to stimulate your thinking about the material presented in the chapter and to show examples of realistic situations in which you may apply it.

Let's consider Figures 1–3 and 1–4 more closely to show specific examples of how coverage of machine elements relates directly to mechanical design.

Figure 1–3 shows a *closed end mailer* for the printing industry. It takes in bulk paper, forms it, cuts it, and delivers it to the user. Clearly shown are electric motor drives, a right-angle gearbox, a belt drive to rotate rollers, a helical gear pair, a spur gear pair, a worm/wormgear set, bearings, and several other types



(*a*) Overall view of shaft and raker system

(*b*) Interior of lower shaft showing raker and clamshell

(*c*) Upper structure and lift system

(*d*) Drive system for clamshell and raker lifts

FIGURE 1–4 Raker and clamshell for a deep rock tunnel connector pumping station
Created by Edward M. Vavrek for Fairfield Service Company, Michigan City, IN

FIGURE 1–5 Construction crane on a building site
(Shutterstock)

FIGURE 1–6 Construction backhoe and front-end loader
(Shutterstock)

FIGURE 1–7 Corn harvester on a farm
(Shutterstock)

FIGURE 1–8 Heavy duty tractor for farm, highway construction, and commercial applications
(Shutterstock)

FIGURE 1–9 Aircraft showing open door and steps
(Shutterstock)

FIGURE 1–10 Landing gear for a large aircraft
(Shutterstock)

of mechanisms. Scan the chapter and section titles for this book to see how these topics are presented.

Figure 1–4 shows a huge system called *deep rock tunnel connector pumping system*. The vertical shaft is over 250 ft deep and it is part of a water storage system for a major city. Of most interest to this book is the mechanical drive system on the upper part of the shaft that lifts a raker system that separates debris from a huge screen in the water flow path. The debris falls to the bottom of the shaft and the clamshell device picks it up, raises it to the top of the shaft and then transports it horizontally to dispose it into a specially designed dumpster. The drive systems, wire-rope lifting systems, actuating mechanisms, transfer system, and other components are highly relevant to the topics presented in this book.

YOU ARE THE DESIGNER

Consider, now, that you are the designer responsible for the design of a new consumer product, such as the hand drill for a home workshop shown in Figure 1–1. What kind of technical preparation would you need to complete the design? What steps would you follow? What information would you need? How would you show, by calculation, that the design is safe and that the product will perform its desired function?

The general answers to these questions are presented in this chapter. As you complete the study of this book, you will learn about many design techniques that will aid in your design of a wide variety of machine elements. You will also learn how to integrate several machine elements into a mechanical system by considering the relationships between and among elements. ■

1–1 OBJECTIVES OF THIS CHAPTER

After completing this chapter, you will be able to:

1. Recognize examples of mechanical systems in which the application of the principles discussed in this book is necessary to complete their design.
2. List what design skills are required to perform competent mechanical design.
3. Describe the importance of integrating individual machine elements into a more comprehensive mechanical system.
4. Describe the main elements of the *product realization process*.
5. Write statements of *functions* and *design requirements* for mechanical devices.
6. Establish a set of criteria for evaluating proposed designs.
7. Work with appropriate units in mechanical design calculations both in the U.S. Customary Unit System and in SI metric units.
8. Distinguish between *force* and *mass*, and express them properly in both unit systems.
9. Present design calculations in a professional, neat, and orderly manner that can be understood and evaluated by others knowledgeable in the field of machine design.
10. Become acquainted with section properties of commercially available structural shapes and other tables of data in the Appendix of this book to aid in performing design and analysis tasks throughout the book.

1–2 THE DESIGN PROCESS

The ultimate objective of mechanical design is to produce a useful product that satisfies the needs of a customer and that is safe, efficient, reliable, economical, and practical to manufacture. Think broadly when answering the question, "Who is the customer for the product or system I am about to design?" Consider the following scenarios:

- ***You are designing a can opener for the home market.*** The ultimate customer is the person who will purchase the can opener and use it in the kitchen of a home. Other customers may include the designer of the packaging for the opener, the manufacturing staff who must produce the opener economically, and service personnel who repair the unit.
- ***You are designing a piece of production machinery for a manufacturing operation.*** The customers include the manufacturing engineer who is responsible for the production operation, the operator of the machine, the staff who install the machine, and the maintenance personnel who must service the machine to keep it in good running order.
- ***You are designing a powered system to open a large door on a passenger aircraft.*** The customers include the person who must operate the door in normal service or in emergencies, the people who must pass through the door during use, the personnel who manufacture the opener, the installers, the aircraft structure designers who must accommodate the loads produced by the opener during flight and during operation, the service technicians who maintain the system, and the interior designers who must shield the opener during use while allowing access for installation and maintenance.

It is essential that you know the desires and expectations of all customers before beginning product design. Marketing professionals are often employed to manage the definition of customer expectations, but designers will likely work with them as a part of a product development team.

Numerous approaches are available that guide designers through the complete process of product design and methods for creating new, innovative products. Some are oriented toward large complex products such as aircraft, automobiles, and multifunction machine tools. It is advisable for a company to select one method that is suitable to their particular style of products or to create one that meets their special needs. The following discussion identifies the salient features of some of the approaches and the listed references and Internet sites provide more details. Some of the listed methods are applied in combination.

- ***Axiomatic design.*** See References 14, 15, and 18 and Internet site 8. Axiomatic design methods implement a process where developers think functionally first, followed by the innovative creation of the physical embodiment of a product to meet customer requirements along with the process needed to produce the product.
- ***Quality function deployment (QFD).*** See Reference 8 and Internet sites 9 and 10. QFD is a quality system that espouses understanding customer requirements and uses quality systems thinking to maximize positive quality that adds value. The process also includes use of the "House of Quality" matrix described in Reference 8.
- ***Design for six sigma (DFSS).*** See References 18–20 and Internet sites 11 and 16. The objective of Six Sigma Quality is to reduce output variation that will result in no more than 3.4 defective parts per million (PPM). The term *six sigma or* 6Σ refers to a distribution of performance measures, in which products produced are within upper and lower specification limits that are six process standard deviations from the mean.
- ***TRIZ.*** See References 21–23 and Internet sites 12–15. TRIZ is an acronym for a Russian phrase that translates into English as "Theory of Inventive Problem

Solving." Developed in 1946 in Russia by Genrich Altshuller and colleagues, the process is applied throughout the world to create and to improve products, services, and systems. TRIZ is a problem-solving method based on logic and data, not intuition, which accelerates the project team's ability to solve problems creatively.

- ***Total design.*** See Reference 13. An integrated approach to product engineering using a systematic and disciplined process to create innovative products that satisfy customer needs.
- ***The engineering design process—embodiment design.*** See Reference 26. A comprehensive process involving need identification, concept selection, decision making, detail design, modeling and simulation, design for manufacturing, robust design, and several other elements.
- ***Failure modes and effects analysis (FMEA).*** See Reference 24 and Internet site 17. An analysis technique which facilitates the identification of potential problems in the design of a product by examining the effects of lower level failures. Recommended actions or compensating provisions are made to reduce the likelihood of the problem occurring or mitigating the risk if problems do occur. The process evolved from military and NASA procedures designed to enhance the reliability of products and systems. For many years, MIL STD 1629A defined accepted FMEA methods used in military and commercial industry. Even though that standard was cancelled, it remains the basis for much of the current work related to FMEA. MIL-Handbook-502A Product Support Analysis is now widely used. The prevalent standards in the automotive and aerospace industries are SAE J1739 and SAE TA-STD-0017, Product Support Analysis.
- ***Product design for manufacture and assembly.*** See Reference 27. A product design methodology with a heavy emphasis on how the components and the assembled product are to be manufactured to achieve a low-cost, high-quality design. Included are design for die casting, forging, powder metal processing, sheet metalworking, machining, injection molding, and many other processes.

It is also important to consider how the design process fits with all functions that must happen to deliver a satisfactory product to the customer and to service the product throughout its life cycle. In fact, it is important to consider how the product will be disposed of after it has served its useful life. The total of all such functions that affect the product is sometimes called the *product realization process* or *PRP*. (See References 3 and 10.) Some of the factors included in PRP are as follows:

- Marketing functions to assess customer requirements.
- Research to determine the available technology that can reasonably be used in the product.
- Availability of materials and components that can be incorporated into the product.
- Product design and development.
- Performance testing.
- Documentation of the design.
- Vendor relationships and purchasing functions.
- Consideration of global sourcing of materials and global marketing.
- Work-force skills.
- Physical plant and facilities available.
- Capability of manufacturing systems.
- Production planning and control of production systems.
- Production support systems and personnel.
- Quality systems requirements.
- Operation and maintenance of the physical plant.
- Distribution systems to get products to the customer.
- Sales operations and time schedules.
- Cost targets and other competitive issues.
- Customer service requirements.
- Environmental concerns during manufacture, operation, and disposal of the product.
- Legal requirements.
- Availability of financial capital.

Can you add to this list?

You should be able to see that the design of a product is but one part of a comprehensive process. In this book, we will focus more carefully on the design process itself, but the producibility of your designs must always be considered. This simultaneous consideration of product design and manufacturing process design is often called *concurrent engineering*. Note that this process is a subset of the larger list given previously for the product realization process. Other major books discussing general approaches to mechanical design are listed as References 6, 7, and 12–26.

1–3 SKILLS NEEDED IN MECHANICAL DESIGN

Product engineers and mechanical designers use a wide range of skills and knowledge in their daily work, including the following:

1. Sketching, technical drawing, and 2D and 3D computer-aided design.
2. Properties of materials, materials processing, and manufacturing processes.
3. Applications of chemistry such as corrosion protection, plating, and painting.
4. Statics, dynamics, strength of materials, kinematics, and mechanisms.