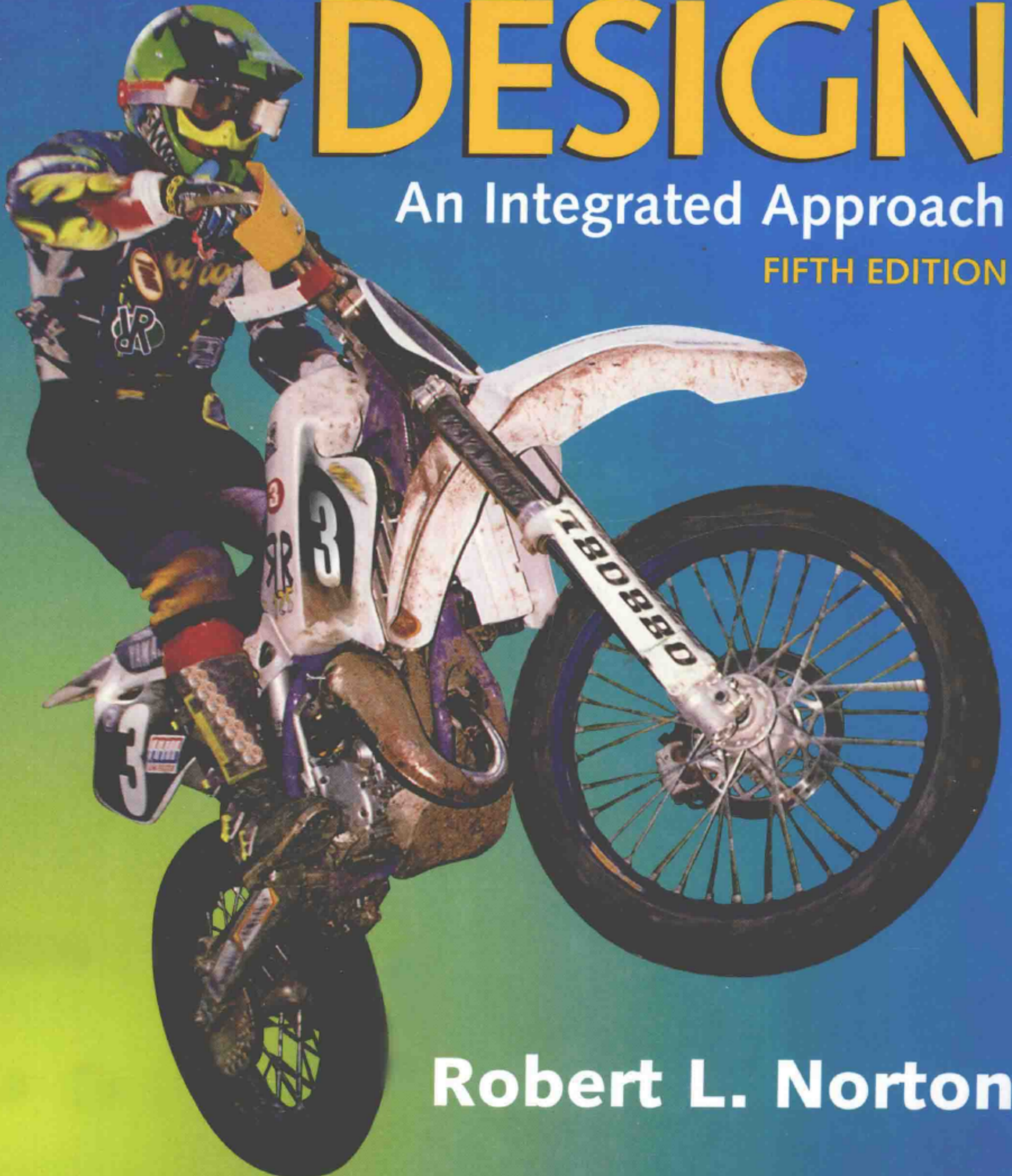


MACHINE DESIGN

An Integrated Approach

FIFTH EDITION



Robert L. Norton

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Robert L. Norton

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The cover photograph by the author is of Tom Norton, seven-time New England Trail Riders Association (NETRA) Hare Scrambles Champion (and the author's son).

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ABOUT THE AUTHOR

Robert L. Norton earned undergraduate degrees in both mechanical engineering and industrial technology at Northeastern University, an MS in engineering design at Tufts University, and was awarded a Doctor of Engineering (h.c.) from Worcester Polytechnic Institute (WPI). He is a registered professional engineer in Massachusetts. He has over 50 years experience in engineering design and manufacturing and over 40 years experience teaching mechanical engineering, engineering design, computer science, and related subjects at Northeastern University, Tufts University, and WPI. Norton has been on the faculty of WPI since 1981, and is currently the Milton P. Higgins II Distinguished Professor Emeritus. He is also the founder and president of Norton Associates Engineering Consultants since 1970.

At Polaroid Corporation for 10 years, he designed cameras, related mechanisms, and high-speed automated machinery. He spent three years at Jet Spray Cooler Inc., designing food-handling machinery and products. For five years he helped develop artificial-heart and noninvasive assisted-circulation devices at the Tufts New England Medical Center and Boston City Hospital. Since leaving industry to join academia in 1974, he has continued as an independent consultant on engineering projects ranging from disposable medical products to high-speed production machinery. He holds thirteen U.S. patents.

He is the author of numerous technical papers and journal articles covering kinematics, dynamics of machinery, cam design and manufacturing, computers in education, engineering education, and of the texts *Design of Machinery*, *Kinematics and Dynamics of Machinery*, *Machine Design: An Integrated Approach*, and the *Cam Design and Manufacturing Handbook*. He is a Fellow of the American Society of Mechanical Engineers and a member of the Society of Automotive Engineers. In 2007, he was selected as a *U. S. Professor of the Year* by the *Council for the Advancement and Support of Education (CASE)* and the *Carnegie Foundation for the Advancement of Teaching*, who jointly present the only national awards for teaching excellence given in the United States of America.

This book is dedicated to the memory of:

Donald N. Zwiep

1924-2012

Provost, Department Head, and Professor Emeritus
Worcester Polytechnic Institute

A gentleman and a leader,
without whose faith and foresight,
this book would never have been written.

of the theory but also attempts to avoid presenting a string of disparate topics in favor of an integrated approach that ties the various topics together via *case studies*.

Most *Elements* texts contain many more topics and more content than can possibly be covered in a one-semester course. Before writing the first edition of this book, a questionnaire was sent to 200 U.S. university instructors of the *Elements* course to solicit their opinions on the relative importance and desirability of the typical set of topics in an *Elements* text. With each revision to second through fifth editions, users were again surveyed to determine what should be changed or added. The responses were analyzed and used to influence the structure and content of this book in all editions. One of the strongest desires originally expressed by the respondents was for *case studies* that present realistic design problems.

We have attempted to accomplish this goal by structuring the text around a series of ten case studies. These case studies present different aspects of the same design problem in successive chapters, for example, defining the static or dynamic loads on the device in Chapter 3, calculating the stresses due to the static loads in Chapter 4, and applying the appropriate failure theory to determine its safety factor in Chapter 5. Later chapters present more complex case studies, with more design content. The case study in Chapter 6 on fatigue design is one such example a real problem taken from the author's consulting practice. Chapter 8 presents FEA analyses of several of these case studies and compares those results to the classical solutions done in prior chapters.

The case studies provide a series of machine design projects throughout the book that contain various combinations of the elements normally dealt with in this type of text. The assemblies contain some collection of elements such as links subjected to combined axial and bending loads, column members, shafts in combined bending and torsion, gearsets under alternating loads, return springs, fasteners under fatigue loading, rolling element bearings, etc. This integrated approach has several advantages. It presents the student with a generic design problem in context rather than as a set of disparate, unrelated entities. The student can then see the interrelationships and the rationales for the design decisions that affect the individual elements. These more comprehensive case studies are in Part II of the text. The case studies in Part I are more limited in scope and directed to the engineering mechanics topics of the chapter. In addition to the case studies, each chapter has a selection of worked-out examples to reinforce particular topics.

Chapter 9, Design Case Studies, is devoted to the setup of three design case studies that are used in the following chapters to reinforce the concepts behind the design and analysis of shafts, springs, gears, fasteners, etc. Not all aspects of these design case studies are addressed as worked-out examples since another purpose is to provide material for student-project assignments. The author has used these case study topics as multi-week or term-long project assignments for groups or individual students with good success. Assigning open-ended project assignments serves to reinforce the design and analysis aspects of the course much better than set-piece homework assignments.

Problem Sets

Most of the 886 problem sets (686, or 77%) are independent within a chapter, responding to requests by users of the first edition to decouple them. The other 23% of the problem sets are built upon in succeeding chapters. These linked problems have the same dash number in each chapter and their problem number is **boldface** to indicate their commonality among chapters. For example, Problem 3-4 asks for a static force analysis of a trailer hitch; Problem 4-4 requests a stress analysis of the same hitch based on the forces calculated in Problem 3-4; Problem 5-4 asks for the static safety factor for the hitch using the stresses calculated in

Problem 4-4; Problem 6-4 requests a fatigue-failure analysis of the same hitch, and Problem 7-4 requires a surface stress analysis. The same trailer hitch is used as an FEA case study in Chapter 8. Thus, the complexity of the underlying design problem is unfolded as new topics are introduced. An instructor who wishes to use this approach can assign problems with the same dash number in succeeding chapters. If one does not want to assign an earlier problem on which a later one is based, the solution manual data from the earlier problem can be provided to the students. Instructors who do not like interlinked problems can avoid them entirely and select from the 686 problems with nonbold problem numbers that are independent within their chapters.

Text Arrangement

Chapter 1 provides an introduction to the design process, problem formulation, safety factors, and units. Material properties are reviewed in Chapter 2 since even the student who has had a first course in material science or metallurgy typically has but a superficial understanding of the wide spectrum of engineering material properties needed for machine design. Chapter 3 presents a discussion of the fundamentals of kinematic linkages and cams. It also provides a review of static and dynamic loading analysis, including beam, vibration, and impact loading, and sets up a series of case studies that are used in later chapters to illustrate the stress and deflection analysis topics with some continuity.

The *Design of Machine Elements* course, at its core, is really an intermediate-level, applied stress-analysis course. Accordingly, a review of the fundamentals of stress and deflection analysis is presented in Chapter 4. Static failure theories are presented in detail in Chapter 5 since the students have typically not yet fully digested these concepts from their first stress-analysis course. Fracture-mechanics analysis for static loads is also introduced.

The *Elements* course is typically the student's first exposure to fatigue analysis since most introductory stress-analysis courses deal only with statically loaded problems. Accordingly, fatigue-failure theory is presented at length in Chapter 6 with the emphasis on stress-life approaches to high-cycle fatigue design, which is commonly used in the design of rotating machinery. Fracture-mechanics theory is further discussed with regard to crack propagation under cyclic loading. Strain-based methods for low-cycle fatigue analysis are not presented but their application and purpose are introduced to the reader and bibliographic references are provided for further study. Residual stresses are also addressed. Chapter 7 presents a thorough discussion of the phenomena of wear mechanisms, surface contact stresses, and surface fatigue.

Chapter 8 provides an introduction to Finite Element Analysis (FEA). Many instructors are using the machine elements course to introduce students to FEA as well as to instruct them in the techniques of machine design. The material presented in Chapter 8 is not intended as a substitute for education in FEA theory. That material is available in many other textbooks devoted to that subject and the student is urged to become familiar with FEA theory through coursework or self-study. Instead, Chapter 8 presents proper techniques for the application of FEA to practical machine design problems. Issues of element selection, mesh refinement, and the definition of proper boundary conditions are developed in some detail. These issues are not usually addressed in books on FEA theory. Many engineers in training today will, in their professional practice, use CAD solid modeling software and commercial finite element analysis code. It is important that they have some knowledge of the limitations and proper application of those tools. This chapter can be taken up earlier in the course if desired, especially if the students are expected to use FEA to solve assigned tasks. It is relatively independent of the other chapters. Many of various chapters' problem assignments have Solidworks models of their geometry provided on the website.

These eight chapters comprise Part I of the text and lay the analytical foundation needed for design of machine elements. They are arranged to be taken up in the order presented and build upon each other with the exception of Chapter 8 on FEA.

Part II of the text presents the design of machine elements in context as parts of a whole machine. The chapters in Part II are essentially independent of one another and can be taken (or skipped) in any order that the instructor desires (except that Chapter 12 on spur gears should be studied before Chapter 13 on helical, bevel, and worm gears). It is unlikely that all topics in the book can be covered in a one-term or one semester course. Uncovered chapters will still serve as a reference for engineers in their professional practice.

Chapter 9 presents a set of design case studies to be used as assignments and as example case studies in the following chapters and also provides a set of suggested design project assignments in addition to the detailed case studies as described above. Chapter 10 investigates shaft design using the fatigue-analysis techniques developed in Chapter 6. Chapter 11 discusses fluid-film and rolling-element bearing theory and application using the theory developed in Chapter 7. Chapter 12 gives a thorough introduction to the kinematics, design and stress analysis of spur gears using the latest AGMA recommended procedures. Chapter 13 extends gear design to helical, bevel, and worm gearing. Chapter 14 covers spring design including helical compression, extension and torsion springs, as well as a thorough treatment of Belleville springs. Chapter 15 deals with screws and fasteners including power screws and preloaded fasteners. Chapter 16 presents an up-to-date treatment of the design of weldments for both static and dynamic loading. Chapter 17 presents an introduction to the design and specification of disk and drum clutches and brakes. The appendices contain material-strength data, beam tables, and stress-concentration factors, as well as answers to selected problems.

Supplements

A **Solutions Manual** is available to instructors from the publisher and **PowerPoint slides** of all figures and tables in the text are available on the publisher's website (password protected) at:

<http://www.pearsonhighered.com/>

To download these resources, choose the **Instructor Support** tab to register as an instructor and follow instructions on the site to obtain the resources provided. Mathcad files for all the problem solutions are available with the solutions manual. This computerized approach to problem solutions has significant advantages to the instructor who can easily change any assigned problem's data and instantly solve it. Thus, an essentially infinite supply of problem sets is available, going far beyond those defined in the text. The instructor also can easily prepare and solve exam problems by changing data in the supplied files.

As errata are discovered they will be posted on the author's personal website at:

<http://www.designofmachinery.com/MD/errata.html>

Professors who adopt the book may register at the author's personal website to obtain additional information relevant to the subject (syllabi, project assignments, etc.) and the text and to download updated software (password protected). Go to:

<http://www.designofmachinery.com/registered/professor.html>

Anyone who purchases the book may register at the author's personal website to request updated software for the current edition (password protected). Go to:

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Since the book's first printing in 1995, several users have kindly pointed out errors and suggested improvements. My thanks go to Professors R. Boudreau of U. Moncton, Canada, V. Glazman of Cal Poly Pomona, John Steele of Colorado School of Mines, Burford J. Furman of San Jose State University, and Michael Ward of California State University, Chico.

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Preface

Introduction

This text is intended for the *Design of Machine Elements* courses typically given in the junior year of most mechanical engineering curricula. The usual prerequisites are a first course in *Statics and Dynamics*, and one in *Strength of Materials*. The purpose of this book is to present the subject matter in an up-to-date manner with a strong design emphasis. The level is aimed at junior-senior mechanical engineering students. A primary goal was to write a text that is very easy to read and that students will enjoy reading despite the inherent dryness of the subject matter.

This textbook is designed to be an improvement over others currently available and to provide methods and techniques that take full advantage of computer-aided analysis. It emphasizes design and synthesis as well as analysis. Example problems, case studies, and solution techniques are spelled out in detail and are self-contained. All the illustrations are done in two colors. Short problems are provided in each chapter and, where appropriate, longer unstructured design-project assignments are given.

The book is independent of any particular computer program. Computer files for the solution of all the examples and case studies written in several different languages (*Mathcad*, *MATLAB*, *Excel*, and *TK Solver*) are provided on the book's website at <http://www.pearsonhighered.com/norton>. Several other programs written by the author are also provided as executable files. These include a Mohr's circle generator (*MOHR.exe*), matrix solver (*MATRIX.exe*) and linkage and cam design programs. An index of the website's content is on the website.

While this book attempts to be thorough and complete on the engineering-mechanics topics of failure theory and analysis, it also emphasizes the synthesis and design aspects of the subject to a greater degree than most other texts in print on this subject. It points out the commonality of the analytical approaches needed to design a wide variety of elements and emphasizes the use of computer-aided engineering as an approach to the design and analysis of these classes of problems. The author's approach to this course is based on 50 years of practical experience in mechanical engineering design, both in industry and as a consultant. He has taught mechanical engineering design at the university level for 40 of those years as well.

What's New in the Fifth Edition?

- New sections covering the fundamentals of kinematics have been added to Chapter 3. These will be of value in those curricula where kinematics has been added to the machine design course syllabus.
- Twenty-one Master Lecture videos on the topics of most chapters are provided on the website. These are taken from the author's live lectures to classes at WPI. The student can watch these videos to review and enhance their understanding of the book's topics.
- Eight short videos are provided on the website in which the author demonstrates various principles of stress analysis and shows examples of common machine parts such as springs, gears, and bearings.
- Six videos that show real machinery in operation are also provided on the website.
- The author's latest programs, *LINKAGES* and *DYNACAM* are included on the website.
- Over 90 problems are added or revised with all being in SI units.

Philosophy

This is often the first course that mechanical engineering students see that presents them with design challenges rather than set-piece problems. Nevertheless, the type of design addressed in this course is that of *detailed design*, which is only one part of the entire design-process spectrum. In detailed design, the general concept, application, and even general shape of the required device are typically known at the outset. We are not trying to invent a new device so much as define the shape, size, and material of a particular machine element such that it will not fail under the loading and environmental conditions expected in service.

The traditional approach to the teaching of the *Elements* course has been to emphasize the design of individual machine parts, or elements, such as gears, springs, shafts, etc. One criticism that is sometimes directed at the *Elements* course (or textbook) is that it can easily become a “cookbook” collection of disparate topics that does not prepare the student to solve other types of problems not found in the recipes presented. There is a risk of this happening. It is relatively easy for the instructor (or author) to allow the course (or text) to degenerate into the mode “Well, it’s Tuesday, let’s design springs—on Friday, we’ll do gears.” If this happens, it may do the student a disservice because it doesn’t necessarily develop a fundamental understanding of the practical application of the underlying theories to design problems.

However, many of the machine elements typically addressed in this course provide superb examples of the underlying theory. If viewed in that light, and if presented in a general context, they can be an excellent vehicle for the development of student understanding of complex and important engineering theories. For example, the topic of preloaded bolts is a perfect vehicle to introduce the concept of prestressing used as a foil against fatigue loading. The student may never be called upon in practice to design a preloaded bolt, but he or she may well utilize the understanding of prestressing gained from the experience. The design of helical gears to withstand time-varying loads provides an excellent vehicle to develop the student’s understanding of combined stresses, Hertzian stresses, and fatigue failure. Thus the *elements* approach is a valid and defensible one as long as the approach taken in the text is sufficiently global. That is, it should not be allowed to degenerate into a collection of apparently unrelated exercises, but rather provide an integrated approach.

Another area in which the author has found existing texts (and *Machine Elements* courses) to be deficient is the lack of connection made between the dynamics of a system and the stress analysis of that system. Typically, these texts present their machine elements with (magically) predefined forces on them. The student is then shown how to determine the stresses and deflections caused by those forces. In real machine design, the forces are not always predefined and can, in large part, be due to the accelerations of the masses of the moving parts. However, the masses cannot be accurately determined until the geometry is defined and a stress analysis done to determine the strength of the assumed part. Thus, an impasse exists that is broken only by iteration, i.e., assume a part geometry and define its geometric and mass properties, calculate the dynamic loads due in part to the material and geometry of the part. Then calculate the stresses and deflections resulting from those forces, find out it fails, redesign, and repeat.

An Integrated Approach

The text is divided into two parts. The first part presents the fundamentals of stress, strain, deflection, materials properties, failure theories, fatigue phenomena, fracture mechanics, FEA, etc. These theoretical aspects are presented in similar fashion to other texts. The second part presents treatments of specific, common design elements used as examples of applications

Thanks are due several people who responded to surveys for the fifth edition and made many good suggestions: Steven J. Covey of St. Cloud State University, Yesh P. Singh of University of Texas at San Antonio, César Augusto Álvarez Vargas of Universidad Autonoma de Manizales, Caldas, Colombia, Ardeshir Kianercy of University of Southern California, Kenneth W. Miller of St. Cloud State University, Yannis Korkolis of University of New Hampshire, J. Alex Thomasson of Texas A&M, Timothy Dewhurst of Cedarville University, Jon Svenninggaard of VIA University College, Horsens, Denmark, John D. Landes of University of Tennessee, Peter Schuster of California Polytechnic State University, Amanuel Haque of Penn State University, J. Brian Jordon of University of Alabama, Yabin Liao of Arizona State University, Raymond K. Yee of San Jose State University, Jean-Michel Dhainaut of Embry-Riddle Aeronautical University, Pal Molian of Iowa State University, and John Strenkowski of North Carolina State University.

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Finally, Nancy Norton, my infinitely patient wife for the past fifty-three years, deserves renewed kudos for her unfailing support and encouragement during many summers of “book widowhood.” I could not have done it without her.

Every effort has been made to eliminate errors from this text. Any that remain are the author’s responsibility. He will greatly appreciate being informed of any errors that still remain so they can be corrected in future printings. An e-mail to norton@wpi.edu will be sufficient.

*Robert L. Norton
Naples, FL
January 1, 2013*

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