世界优秀教材中国版

机械原理（第三版 改编版）

Design of Machinery

(Third Edition)

原著 Robert L. Norton

改编 韩建友

高等教育出版社

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出版说明

为进一步适应高等教育教学改革发展的趋势，加速培养具有国际竞争力的高素质优秀人才，教育部在《关于加强高等学校本科教学工作提高教学质量的若干意见》的通知（教高[2001]4号）中提出："本科教育要创造条件使用英语等外语进行公共基础课和专业课教学。"目前，按照教育部教高[2001]4号文件的精神，我国各类高校都以不同的形式全面展开"双语"教学，教师们在"双语"教学实践中积累了一些经验，同时也对双语教学提出了不同的意见与看法。教材是教学内容与教学方法的知识载体，是教师教学、学生学习的基本工具，也是深化教学改革、提高教学质量的重要保证。因此，一本优秀的"双语"教学教材无疑将对高校开展"双语"教学产生积极的推动作用。许多老师在实践中体会到，没有国外原版教材，"双语"教学犹如无本之木，无源之水，而直接使用国外教材作为"双语"教学的教材在实际授课中也存在诸多弊病。尤其是在机械类课程的教学中，不仅存在着工程标准不同的问题，而且存在着课程内容与课程体系的差异。许多教师在授课过程中采用不同的教材作参考，根据授课的需要将所需的资料拼凑到一起，以解决上述教学中存在的矛盾。因此，由于缺乏合适的双语教材，使双语教学缺乏进入机械类课程课堂教学的基础。

高等教育出版社在发展壮大过程中积极实施国际化的战略，从世界范围内发掘优秀教育资源服务于我国高校的教育教学与人才培养，为我国高等教育的持续发展提供精工细作的食粮。针对我国高校开展"双语"教学的现状，我社积极开展与 Pearson Education，John Wiley & Sons，McGraw-Hill 以及 Thomson Learning 等国外大型教育出版集团合作，以不同的方式将国外优秀教材输送到我国高等教育的第一线。针对机械类课程的特点及我国高校机械类课程开展"双语"教学存在的问题，我社与国内外的专家一道，努力打造适合国内教学的"双语"教学教材。为此，我社积极组织国内外专家，展开了改编国外优秀教材，为我国机械类课程"双语"教学量体裁衣的尝试。

首先，精选教材。我们广泛了解我国高校机械类课程开展"双语"教学的情况，了解广大高校广大师生在开展"双语"教学的过程中对教材的需求。然后，我们与多家国外出版公司进行了广泛接触，经推荐并在国内专家的协助下，精选了涉及机械、材料、能源动力、工程图学等学科专业领域的优秀教材几十种之多。我们聘请了国内高校一线教师、专家学者参与这些原版教材的评介工作，从中遴选出了一批优秀教材进行改编，并组织出版。

这批教材普遍具有以下特点：（1）基本上是近几年出版的，在国际上被广泛使用，在同类教材中具有相当的权威性；（2）高版次，历经多年教学实践检验，内容翔实准确，反映时代要求；（3）各种教学资源配套整齐，为师生提供了极大的便利；（4）插图精美、丰富，图文并茂，与正文相辅相成；（5）语言简练、流畅，可读性强，比较适合非英语国家的学生阅读。

其次，慎选改编者。教材的优劣将直接影响到教学质量的高低，而一位学识渊博、治学严谨的作者必然编写出高水平的精品教材。我们与国内众多高等院校的众多专家学者进行了广泛的接触和细致的协商，几经酝酿，最终确定下来改编者。大多数改编者都是有国外留学背景的中青年学者，他们既有相当高的学术水平，又热爱教学，活跃在教学第一线。他们能够承担此任，

不单是因为他们了解引进版教材的知识结构、表达方式和写作方法，更重要的是他们有精力、有热情，愿意付出，有的甚至付出了比写一本新教材更多的劳动。我们向他们表示最真诚的谢意。

在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作，这套引进改编的教材体现了一定的权威性、系统性、先进性和经济性等特点。

改编国外优秀教材，就是在保留国外原版教材风格的基础上，使之满足国内教学的实际需要，这样，不仅引进了国外优秀教材所包含的先进的科技知识，而且引进了先进的教育理念、教学思想。我们希望这套教材能够为我国高校“双语”教学的教材建设带来启示，同时也对推进我国高校机械类课程“双语”教学有所裨益。

高等教育出版社
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改编版前言

Robert L.Norton 著的《Design of machinery: an introduction to the synthesis and analysis of mechanisms and machines》是美国比较广泛应用的机械原理教材。该书在 2004 年出版了第三版。在我国已经出版了该书第二版的影印本和翻译本。现把该书第三版改编为内容适合我国机械原理教学基本要求的简本，供我国机械原理双语教学使用，也可作为机械原理教学的辅助教材，还可供机械工程方面的专业人员参考。该书内容丰富，大部分内容适合我国机械类本科生的教学要求。原书 858 页，共包括 16 章的内容、参考文献和习题、6 个附录、1 个索引和 1 个光盘目录。其中第 1 章至第 9 章为第一部分（PART Ⅰ），称为**机构运动学**；第 10 章至第 16 章为第二部分（PART Ⅱ），称为**机械动力学**。各章内容见本书原著者第一版序。本书删去了原书第 10、13、14、15、16 章的全部内容以及附录和索引，其内容分别为：**Chapter 10** Dynamics Fundamentals; **Chapter 13** Engine Dynamics; **Chapter 14** Multicylinder Engines; **Chapter 15** Cam Dynamics; **Chapter 16** Engineering Design; **Appendix A** Computer Programs; **Appendix B** Materials Properties; **Appendix C** Geometric Properties; **Appendix D** Spring Data; **Appendix E** Atlas of Geared Fivebar Linkage Coupler Curves; **Appendix F** Answers to Selected Problems; **Index**。从所删除的内容可以看到，这些内容或是与我们的课程关系不大，或是在其他课程里面已学过。保留的各章也做了部分删节，删减原则同上。删减内容在相应章末的简注中都作了说明，这样可使有兴趣的同学和读者查找原著。此外，为缩减篇幅还删除了各章中的全部习题和参考文献。根据四年多双语教学的体会，在各章末尾的简注中对与我国教材内容叙述不同的内容或术语作了说明。

采用该教材可直接了解到美国教材的内容及结构体系，了解到机械理论方面的最新成果，还可使学生学到地道的英语表达方式及习惯，对语言阅读方面能有所提高。

韩建友

2007 年 2 月于北京科技大学

注：韩建友，博士，生于 1956 年。现为北京科技大学机械工程学院教授，博士生导师

ABOUT THE AUTHOR

Robert L. Norton earned undergraduate degrees in both mechanical engineering and industrial technology at Northeastern University and an MS in engineering design at Tufts University. He is a registered professional engineer in Massachusetts. He has extensive industrial experience in engineering design and manufacturing and many years experience teaching mechanical engineering, engineering design, computer science, and related subjects at Northeastern University, Tufts University, and Worcester Polytechnic Institute.

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 (counterpulsation) devices at the Tufts New England Medical Center and Boston City Hospital. Since leaving industry to join academia, he has continued as an independent consultant on engineering projects ranging from disposable medical products to high-speed production machinery. He holds 13 U.S. patents.

Norton has been on the faculty of Worcester Polytechnic Institute since 1981 and is currently professor of mechanical engineering, head of the design group in that department, and the director of the Gillette Project Center at WPI. He teaches undergraduate and graduate courses in mechanical engineering with emphasis on design, kinematics, vibrations, and dynamics of machinery.

He is the author of numerous technical papers and journal articles covering kinematics, dynamics of machinery, cam design and manufacturing, computers in education, and engineering education and of the texts *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. Rumors about the transplantation of a Pentium microprocessor into his brain are decidedly untrue (though he could use some additional RAM). As for the unobtainium ring, well, that's another story.

PREFACE
to the Third Edition

The third time is the charm.
ANONYMOUS

The third edition is an evolutionary improvement over the second edition, which was an extensive revision of the first edition. See the updated *Preface to the First Edition* (overleaf) for more detailed information on the book's purpose and organization. Throughout this third edition many small improvements have been made to the discussion of a variety of topics in every chapter, based largely on user feedback, and all known errors have been corrected. The major change is the addition of 231 new problem sets, a 46% increase over the second edition, bringing the total to 731 problems, plus 88 larger scale project assignments. Many problem figures have been redrawn and enhanced as have some in the text body. All of the problem figures are now included as PDF files on the CD-ROM so that students can easily obtain hard copies to work the solutions on.

Some new material also has been added. An introduction to compliant mechanisms and MEMS is provided in Chapter 2. Chapter 3 adds a section on "Other Useful Linkages" that solve common problems in industry. The treatment of cams in Chapter 8 has been both condensed and enhanced with new material. Chapter 9's discussion of transmissions is enhanced and expanded. The treatment of engine dynamics in Chapters 13 and 14 has been improved.

The third edition is also enhanced by the addition of much new software on the attached CD-ROM. New student versions of the author-written programs, FOURBAR, FIVEBAR, SIXBAR, SLIDER, DYNACAM, ENGINE, and MATRIX have been revised, enhanced, and improved. All now provide larger screens and new features. Some *TKSolver* models also are included, as noted in the text.

The *Working Model* 2D *Version* 5.2 *Textbook Edition* (*WM*) program is still included, free of charge, on the CD-ROM and is a newer version than in the second edition. In addition, Professor Shih-Liang (Sid) Wang of North Carolina A&T has added many models to his included package, *Mechanism Simulation in a Multimedia Environment*, that now contains over 100 *Working Model*

files based on the book's figures and 19 *Matlab*® models for kinematic analysis and animation.

These *WM* models bring the text's figures to life with animation, graphs, and numerical output. For each of Professor Wang's simulations, a video file of the mechanism can be played independently of the *Working Model* program, or the student can open, run, modify, interact with, save, print, and create new *WM* simulation files for any assignment with the provided program. Microsoft Internet Explorer is used to navigate among hyperlinked HTML files that contain text, picture, video, *Matlab*, and *Working Model* files.

Some of the *Matlab* files supplied will analyze fourbar, slider crank, and inverted slider crank linkages and animate their motion. Other *Matlab* files calculate the tooth profile of an involute spur gear, show the geometric generation of an involute and the motion of an elliptic trammel. *Matlab* source code is provided. The *Matlab* program is not. Extensive comments are provided within each *Matlab* file identifying the equations used from the text by number. The student can modify these models for other applications.

ACKNOWLEDGMENTS The sources of photographs and other nonoriginal art used in the text are acknowledged in the captions and opposite the title page, but the author would also like to express his thanks for the cooperation of all those individuals and companies who generously made these items available. The author is indebted to, and would like to thank, a number of users who kindly notified him of errors or suggested improvements. These include: Professors *Eben Cobb* of WPI, *Diego Galuzzi* of University of Buenos Aires, *John R. Hall* of WPI, *Shafik Iskander* of U. Tennessee, *Richard Jakubek* of RPI, *Cheong Gill-Jeong* of Wonkwang Univ., Korea, *Swami Karunamoorthy* of St. Louis University, *Pierre Larochelle* of Florida Tech, *Scott Openshaw* of Iowa State, *Francis H. Raven* of Notre Dame, *Arnold E. Sikkema* of Dordt College, and *Donald A. Smith* of U. Wyoming.

Professors *Melvin R. Corley* of Louisiana Tech, *R. Devashier* of U. Evansville, *Krishna Gupta* of U. Illinois-Chicago, *Michael Keefe* of U. Delaware, *John Steffen* of Valparaiso University, *Douglas Walcerz* of York College, and *Lindsey Wells* of U. Texas at Tyler also provided useful suggestions or corrections. Reviewers of this edition also included: Professors *Kurt Anderson* of RPI, *Steve de Bruyn Kops* of U. Washington, *Marek Kujath* of Dalhousie University, *Mark Nagurka* of Marquette University, *Tim Nye* of McMaster University, and *Bob Williams* of Ohio University. The author also thanks the many others who responded to the survey on the second edition.

Professors *Larry L. Howell* of BYU, *G. K. Ananthasuresh* of U. Penn, and *Yong-Mo Moon* of WPI kindly supplied photographs of compliant mechanisms. Professor *Cosme Furlong* of WPI generously supplied MEMS photos and information.

The author would like to express his special appreciation to Professor *Sid Wang* of NCAT for his efforts in creating the *Working Model* and *Matlab* files on the CD-ROM. Professor *Thomas A. Cook*,

Mercer University (Emeritus) provided most of the new problem sets as well as their solutions in his impressive and voluminous solutions manual and its accompanying *Mathcad®* solution files. The author is most grateful for Dr. Cook's valuable contributions.

If you find any errors or have comments or suggestions for improvement, please email the author at *norton@wpi.edu*. Errata as discovered, and other book information, will be posted on the author's web site at http://www.designofmachinery.com.

Robert L. Norton
Mattapoisett, Mass.
August, 2002

PREFACE

to the First Edition

When I hear, I forget
When I see, I remember
When I do, I understand
ANCIENT CHINESE PROVERB

This text is intended for the kinematics and dynamics of machinery topics which are often given as a single course, or two-course sequence, in the junior year of most mechanical engineering programs. The usual prerequisites are first courses in statics, dynamics, and calculus. Usually, the first semester, or portion, is devoted to kinematics, and the second to dynamics of machinery. These courses are ideal vehicles for introducing the mechanical engineering student to the process of design, since mechanisms tend to be intuitive for the typical mechanical engineering student to visualize and create.

While this text attempts to be thorough and complete on the topics of analysis, it also emphasizes the synthesis and design aspects of the subject to a greater degree than most texts in print on these subjects. Also, it emphasizes the use of computer-aided engineering as an approach to the design and analysis of this class of problems by providing software that can enhance student understanding. While the mathematical level of this text is aimed at second- or third-year university students, it is presented *de novo* and should be understandable to the technical school student as well.

Part I of this text is suitable for a one-semester or one-term course in kinematics. Part II is suitable for a one-semester or one-term course in dynamics of machinery. Alternatively, both topic areas can be covered in one semester with less emphasis on some of the topics covered in the text.

The writing and style of presentation in the text is designed to be clear, informal, and easy to read. Many example problems and solution techniques are presented and spelled out in detail, both verbally and graphically. All the illustrations are done with computer-drawing or drafting programs. Some scanned photographic images are also included. The entire text, including equations and artwork, is printed directly from the author's computer disk by laser typesetting for maximum clarity and quality. Many suggested readings are provided in the bibliography. Short problems, and where appropriate, many longer, unstructured design project assignments are provided at the ends of chapters. These projects provide an opportunity for the students *to do and understand.*

The author's approach to these courses and this text is based on over 40 years' experience in mechanical engineering design, both in industry and as a consultant. He has taught these subjects since 1967, both in evening school to practicing engineers and in day school to younger students. His approach to the course has evolved a great deal in that time, from a traditional approach, emphasizing graphical analysis of many structured problems, through emphasis on algebraic methods as computers became available, through requiring students to write their own computer programs, to the current state described above.

The one constant throughout has been the attempt to convey the art of the design process to the students in order to prepare them to cope with *real* engineering problems in practice. Thus, the author has always promoted design within these courses. Only recently, however, has technology provided a means to more effectively accomplish this goal, in the form of the graphics microcomputer. This text attempts to be an improvement over those currently available by providing up-to-date methods and techniques for analysis and synthesis that take full advantage of the graphics microcomputer, and by emphasizing design as well as analysis. The text also provides a more complete, modern, and thorough treatment of cam design than existing texts in print on the subject.

The author has written seven interactive, student-friendly computer programs for the design and analysis of mechanisms and machines. These programs are designed to enhance the student's understanding of the basic concepts in these courses while simultaneously allowing more comprehensive and realistic problem and project assignments to be done in the limited time available than could ever be done with manual solution techniques, whether graphical or algebraic. Unstructured, realistic design problems which have many valid solutions are assigned. Synthesis and analysis are equally emphasized. The analysis methods presented are up to date, using vector equations and matrix techniques wherever applicable. Manual graphical analysis methods are de-emphasized. The graphics output from the computer programs allows the student to see the results of variation of parameters rapidly and accurately and reinforces learning.

These computer programs are distributed on CD-ROM with this book, which also contains instructions for their use on any IBM compatible, Windows 98/2000/NT capable computer. Programs SLIDER, FOURBAR, FIVEBAR and SIXBAR analyze the kinematics and dynamics of those types of linkages. Program DYNACAM allows the design and dynamic analysis of cam-follower systems. Program ENGINE analyzes the slider-crank linkage as used in the internal combustion engine and provides a complete dynamic analysis of single and multicylinder engine inline, V, and W configurations, allowing the mechanical dynamic design of engines to be done. Program MATRIX is a general purpose linear equation system solver.

All these programs, except MATRIX, provide dynamic, graphical animation of the designed devices. The reader is strongly urged to make use of these programs in order to investigate the results of variation of parameters in these kinematic devices. The programs are designed to enhance and aug-

ment the text rather than be a substitute for it. The converse is also true. Many solutions to the book's examples and to the problem sets are provided on the CD-ROM as files to be opened in these programs. Most of these solutions can be animated on the computer screen for a better demonstration of the concept than is possible on the printed page. The instructor and students are both encouraged to take advantage of the computer programs provided. Instructions for their use are in Appendix A.

The author's intention is that synthesis topics be introduced first to allow the students to work on some simple design tasks early in the term while still mastering the analysis topics. Though this is not the "traditional" approach to the teaching of this material, the author believes that it is a superior method to that of initial concentration on detailed analysis of mechanisms for which the student has no concept of origin or purpose.

Chapters 1 and 2 are introductory. Those instructors wishing to teach analysis before synthesis can leave Chapters 3 and 5 on linkage synthesis for later consumption. Chapters 4, 6, and 7 on position, velocity, and acceleration analysis are sequential and build upon each other. In fact, some of the problem sets are common among these three chapters so that students can use their position solutions to find velocities and then later use both to find the accelerations in the same linkages. Chapter 8 on cams is more extensive and complete than that of other kinematics texts and takes a design approach. Chapter 9 on gear trains is introductory. The dynamic force treatment in Part II uses matrix methods for the solution of the system simultaneous equations. Graphical force analysis is not emphasized. Chapter 10 presents an introduction to dynamic systems modeling. Chapter 11 deals with force analysis of linkages. Balancing of rotating machinery and linkages is covered in Chapter 12. Chapters 13 and 14 use the internal combustion engine as an example to pull together many dynamic concepts in a design context. Chapter 15 presents an introduction to dynamic systems modeling and uses the cam-follower system as the example. Chapters 3, 8, 11, 13, and 14 provide open ended project problems as well as structured problem sets. The assignment and execution of unstructured project problems can greatly enhance the student's understanding of the concepts as described by the proverb in the epigraph to this preface.

ACKNOWLEDGMENTS The sources of photographs and other nonoriginal art used in the text are acknowledged in the captions and opposite the title page, but the author would alsolike to express his thanks for the cooperation of all those individuals and companies who generously made these items available. The author would also like to thank those who reviewed various sections of the first edition of the text and who made many useful suggestions for improvement. Mr. John Titus of the University of Minnesota reviewed Chapter 5 on analytical synthesis and Mr. Dennis Klipp of Klipp Engineering, Waterville, Maine, reviewed Chapter 8 on cam design. Professor William J. Crochetiere and Mr. Homer Eckhardt of Tufts University, Medford, Mass., reviewed Chapter 15. Mr. Eckhardt and Professor Crochetiere of Tufts, and Professor Charles Warren of the University of Alabama

taught from and reviewed Part I. Professor Holly K. Ault of Worcester Polytechnic Institute thoroughly reviewed the entire text while teaching from the pre-publication, class-test versions of the complete book. Professor Michael Keefe of the University of Delaware provided many helpful comments. Sincere thanks also go to the large number of undergraduate students and graduate teaching assistants who caught many typos and errors in the text and in the programs while using the pre-publication versions. Since the book's first printing, Profs. D. Cronin, K. Gupta, P Jensen, and Mr. R. Jantz have written to point out errors or make suggestions that I have incorporated and for which I thank them. The author takes full responsibility for any errors that may remain and invites from all readers their criticisms, suggestions for improvement, and identification of errors in the text or programs, so that both can be improved in future versions. Contact *norton@wpi.edu.*

Robert L. Norton
Mattapoisett, Mass.
August, 1991

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