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机械设计

Design of Machinery

机器和机构综合与分析

An Introduction to the Synthesis and Analysis of Mechanisms and Machines

（英文版·原书第2版）

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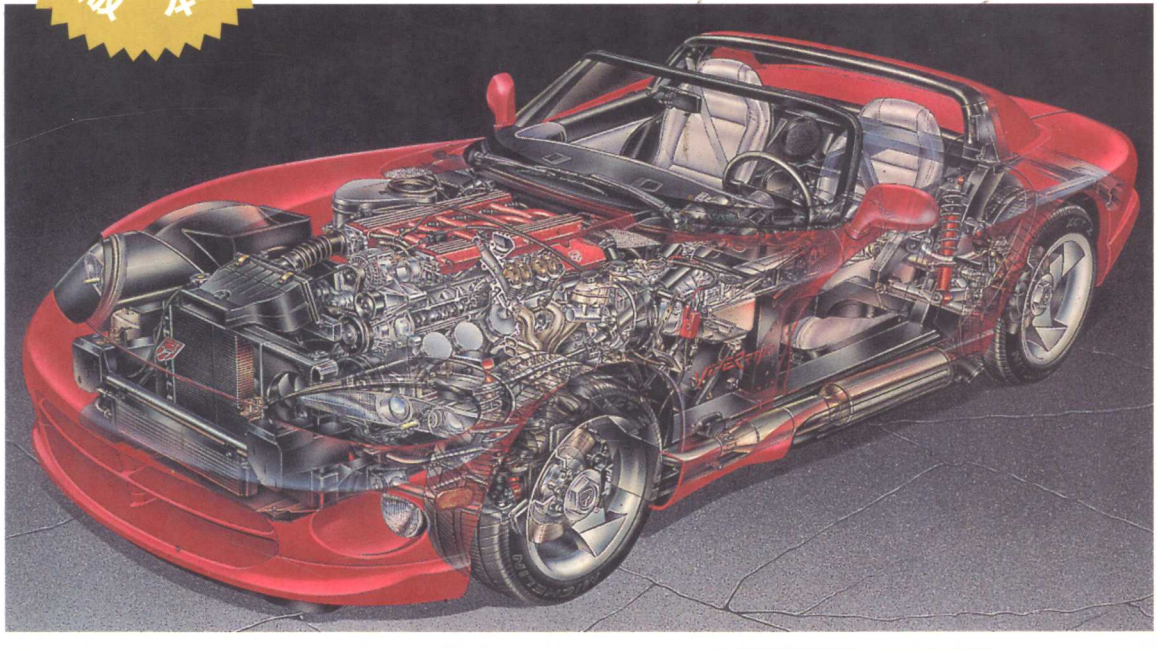

（美）R.L. 诺顿(Robert L. Norton) 著

机械工业出版社
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1 Pound-inch (lb-in)	=	0.0833	Pound-feet (lb-ft)
1 Pound-inch/second (lb-in/s)	=	0.0218	Horsepower (hp)
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出版说明

随着我国加入 WTO，国际间的竞争越来越激烈，而国际间的竞争实际上也就是人才的竞争、教育的竞争。为了加快培养具有国际竞争力的高水平技术人才，加快我国教育改革的步伐，国家教育部近来出台了一系列倡导高校开展双语教学、引进原版教材的政策。以此为契机，机械工业出版社近期推出了一系列国外影印版教材，其内容涉及高等学校公共基础课，以及机、电、信息领域的专业基础课和专业课。

引进国外优秀原版教材，在有条件的学校推动开展英语授课或双语教学，自然也引进了先进的教学思想和教学方法，这对提高我国自编教材的水平，加强学生的英语实际应用能力，使我国的高等教育尽快与国际接轨，必将起到积极的推动作用。

为了做好教材的引进工作，机械工业出版社特别成立了由著名专家组成的国外高校优秀教材审定委员会。这些专家对实施双语教学做了深入细致的调查研究，对引进原版教材提出许多建设性意见，并慎重地对每一本将要引进的原版教材一审再审，精选再精选，确认教材本身的质量水平，以及权威性和先进性，以期所引进的原版教材能适应我国学生的外语水平和学习特点。在引进工作中，审定委员会还结合我国高校教学课程体系的设置和要求，对原版教材的教学思想和方法的先进性、科学性严格把关，同时尽量考虑原版教材的系统性和经济性。

这套教材出版后，我们将根据各高校的双语教学计划，举办原版教材的教师培训，及时地将其推荐给各高校选用。希望高校师生在使用教材后及时反馈意见和建议，使我们更好地为教学改革服务。

机械工业出版社
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序

由美国马萨诸塞州伍斯特工学院 R. L. Norton 教授编著的“Design of Machinery An Introduction to the Synthesis and Analysis of Mechanisms and Machines”一书，第 1 版出版于 1992 年，第 2 版出版于 1999 年，第 2 版的新媒体版本于 2001 年出版。该书是 McGraw-Hill 教育出版公司 2001 年出版的机械工程系列教材之一，是美国大学本科的机构运动学和机械动力学课程的教材。

全书分 2 篇，第 1 篇为机构运动学，主要介绍运动学基础、连杆机构综合图解法和解析法、连杆机构的运动分析、凸轮机构设计、齿轮和轮系设计；第 2 篇为机械动力学，主要介绍动力学基础、动力分析、平衡、发动机动力学、多缸发动机和凸轮机构动力学。

本书与国内外同类教材相比，有以下特点：

1. 以代数法和向量矩阵为基本的数学工具，在机构综合和分析中突出计算机的应用，体现了近年来美国大学本科机构运动学和机械动力学课程改革的经验。

2. 突出机构综合和设计方面的内容。作者希望把设计过程中的技术教给学生，以培养他们将来在实际工作中应对工程问题的能力。

3. 注重应用和实践。作者以其 30 多年从事机械设计和工业界工作的经验编写了许多来自生产和生活的运动装置实例，并增加了有关设计过程和设计案例分析的内容，有助于培养学生的工程意识。

4. 从内容上看，本书与国内有关教材相比，机构运动学方面，连杆机构的内容介绍较多，而大量压缩了齿轮机构的内容；机械动力学方面，还具体介绍了发动机和凸轮机构的动力学问题。

5. 每章都附有大量的计算示例、习题和设计作业题、参考文献和推荐可阅读的参考书目，以利于启发学生的构思。

6. 随书附有 CD-ROM 1 张，包括若干计算机程序、多媒体环境下的机构动画仿真软件包、自学互检题、计算示例和习题解答等。软件具有动画演示、数据和曲线图形输出及观察参数调整的变化结果等各种功能。69 个工作模型除了可演示外，学生还可打开程序、运行、修改、交互、储存、打印，并可创建新的工作模型仿真文件，这将有助于学生自习、课外完成作业，培养其发明创新的意识。

随着我国加入 WTO，教育事业正面临着新的挑战和竞争，加速培养具有国际竞争能力的高级科学技术人才是当务之急。为此需要引进大量国外的优秀原版教材，一方面有利于进行双语教学，另一方面可促进课程体系和教学内容改革更深入地开展。

R. L. Norton 教授编著的“Design of Machinery An Introduction to the Synthesis and Anal-

ysis of Mechanisms and Machines”第2版新媒体版本教材是一本具有改革思想的优秀教材。这次作为优秀原版教材引进影印出版，同时由北京科技大学的陈立周教授等老师全文翻译。原版教材和中译本出版后，可推荐作为机械类专业机械原理课程选用的双语教材或教学参考书，也可供其他专业师生和广大工程技术人员作为参考自学之用。

翁海珊
北京科技大学

PREFACE

to the New Media Version of the Second Edition

The medium is the message.
MARSHALL MCLUHAN

This *New Media Version* of the second edition has been enhanced by the addition of new software on the attached CD-ROM. The Working Model 4.0 2D Homework Edition is still included free of charge on the CD-ROM. In addition, Professor Shih-Liang (Sid) Wang of North Carolina A&T has created the package *Mechanism Simulation in a Multimedia Environment* containing 43 new *Working Model* files based on the book's figures and 6 new *Matlab*® models for kinematic analysis and animation.

In combination with the 20 *Working Model* files previously supplied, these now provide 69 models that 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 *Working Model* simulation files for any assignment with the provided *Working Model* program. Microsoft Internet Explorer is used to navigate among hyperlinked HTML files that contain text, picture, video, *Matlab*, and *Working Model* files.

Some *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.

The supplied student versions of the author-written programs, FOURBAR, FIVEBAR, SIXBAR, SLIDER, DYNACAM, ENGINE, and MATRIX have all been revised, enhanced, and improved. Most now allow Fourier transforms of their variables to be calculated.

Also included is the *FE Exam Interactive Review for Kinematics and Applied Dynamics* by E. Anderson and J. Hashemi. This is a set of interactive review quizzes.

This revision of the second edition has also allowed the text to be updated to match changes made to some problem statements during the creation of the solutions manual. All known errors in the text have been corrected and many suggestions for improvement from users also have been incorporated in this revision. If you find any other errors, 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://me.wpi.edu/norton.htm.

The author would like to express his appreciation to Professor Sid Wang for his efforts in creating the *Working Model* and *Matlab* files. Professor Thomas A. Cook's herculean effort in the creation of the 1 200-page solutions manual and its *Mathcad* ® files is also greatly appreciated. Professors M. Corley of Louisiana Tech, R. Devashier of U. Evansville, K. Gupta of U. Illinois-Chicago, J. Steffen of Valparaiso University, and D. Walcerz of York College all provided useful suggestions or corrections.

Robert L. Norton
Norfolk, Mass.
May, 2000

PREFACE

to the Second Edition

Why is it we never have time to do it right the first time, but always seem to have time to do it over?
ANONYMOUS

The second edition has been revised based on feedback from a large number of users of the book. In general, the material in many chapters has been updated to reflect the latest research findings in the literature. Over 250 problem sets have been added, more than doubling the total number of problems. Some design projects have been added also. All the illustrations have been redrawn, enhanced, and improved.

Coverage of the design process in Chapter 1 has been expanded. The discussions of the Grashof condition and rotatability criteria in Chapter 2 have been strengthened and that of electric motors expanded. A section on the optimum design of approximate straight line linkages has been added to Chapter 3. A discussion of circuits and branches in linkages and a section on the Newton-Raphson method of solution have been added to Chapter 4. A discussion of other methods for analytical and computational solutions to the position synthesis problem has been added to Chapter 5. This reflects the latest publications on this subject and is accompanied by an extensive bibliography.

The chapters formerly devoted to explanations of the accompanying software (old Chapters 8 and 16) have been eliminated. Instead, a new Appendix A has been added to describe the programs FOURBAR, FIVEBAR, SIXBAR, SLIDER, DYNACAM, ENGINE, and MATRIX that are on the attached CD-ROM. These programs have been completely rewritten as *Windows* applications and are much improved. A student version of the simulation program *Working Model* by *Knowledge Revolution,* compatible with both *Macintosh* and *Windows* computers, is also included on CD-ROM along with 20 models of mechanisms from the book done in that package. A user's manual for *Working Model* is also on the CD-ROM.

Chapter 8 on cam design (formerly 9) has been shortened without reducing the scope of its coverage. Chapter 9 on gear trains (formerly 10) has been significantly expanded and enhanced, especially in respect to the design of compound and epicyclic trains and their efficiency. Chapter 10 on dynamics fundamentals has been augmented with material formerly in Chapter 17 to give a more coherent treatment of dynamic modeling. Chapter 12 on balancing (formerly 13) has been expanded to include discussion of moment balancing of linkages.

The author would like to express his appreciation to all the users and reviewers who have made suggestions for improvement and pointed out errors, especially those who responded to the survey about the first edition. There are too many to list here, so rather than risk offense by omitting anyone, let me simply extend my sincerest thanks to you all for your efforts.

Robert L. Norton
Mattapoisett, Mass.
August, 1997

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 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 35 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 which 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 3.1 or Windows 95/98/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 augment 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 read into 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 also like 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 which 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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