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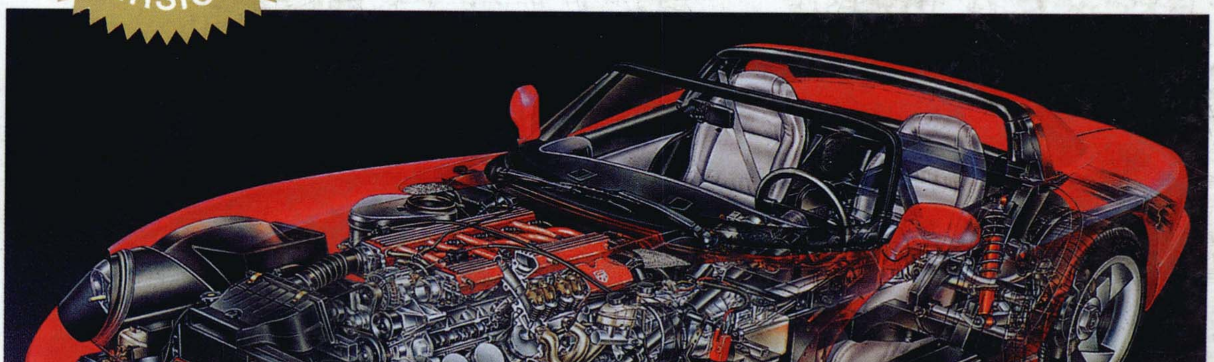
DESIGN OF MACHINERY

An Introduction to the Synthesis and Analysis of Mechanisms and Machines

NEW MEDIA VERSION

SECOND EDITION



ROBERT L. NORTON

INTERNATIONAL EDITION

DESIGN OF MACHINERY

AN INTRODUCTION TO THE SYNTHESIS AND ANALYSIS OF MECHANISMS AND MACHINES

Second Edition

New Media Version

Robert L. Norton

Worcester Polytechnic Institute

Worcester, Massachusetts

McGraw Hill

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International Edition 2002

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From U.S. Customary Units to Metric Units

1 Blob (bl)	=	175.127	Kilograms (kg)
1 Cubic inch (in^3)	=	16.387	Cubic centimeters (cc)
1 Foot (ft)	=	0.3048	Meters (m)
1 Horsepower (hp)	=	745.699	Watts (W)
1 Inch (in)	=	0.0254	Meters (m)
1 Mile, U. S. statute (mi)	=	1609.344	Meters (m)
1 Pound force (lb)	=	4.4482	Newtons (N)
	=	444,822.2	Dynes
1 Pound mass (lbm)	=	0.4536	Kilograms (kg)
1 Pound-foot (lb-ft)	=	1.3558	Newton-meters (N-m)
	=	1.3558	Joules (J)
1 Pound-foot/second (lb-ft/s)	=	1.3558	Watts (W)
1 Pound-inch (lb-in)	=	0.1128	Newton-meters (N-m)
	=	0.1128	Joules (J)
1 Pound-inch/second (lb-in/s)	=	0.1128	Watts (W)
1 Pound/foot^2 (lb/ft^2)	=	47.8803	Pascals (Pa)
1 Pound/inch^2 (lb/in^2), (psi)	=	6894.757	Pascals (Pa)
1 Revolution/minute (rpm)	=	0.1047	Radians/second (rad/sec)
1 Slug (sl)	=	14.5939	Kilograms (kg)
1 Ton, short (2000 lbm)	=	907.1847	Kilograms (kg)

Between U.S. Customary Units

1 Blob (bl)	=	12	Slugs (sl)
1 Foot (ft)	=	12	Inches (in)
1 Horsepower (hp)	=	550	Pound-feet/second (lb-ft/s)
1 Knot	=	1.1515	Miles/hour (mph)
1 Mile, U. S. statute (mi)	=	5280	Feet (ft)
1 Mile/hour	=	1.4667	Feet/sec (ft/s)
1 Pound force (lb)	=	16	Ounces (oz)
1 Pound mass (lbm)	=	0.0311	Slugs (sl)
1 Pound-foot (lb-ft)	=	12	Pound-inches (lb-in)
1 Pound-foot/second (lb-ft/s)	=	0.001818	Horsepower (hp)
1 Pound-inch (lb-in)	=	0.0833	Pound-feet (lb-ft)
1 Pound-inch/second (lb-in/s)	=	0.0218	Horsepower (hp)
1 Pound/inch^2 (lb/in^2), (psi)	=	144	Pounds/foot^2 (lb/ft^2)
1 Radian/second (rad/sec)	=	9.549	Revolutions/minute (rpm)
1 Slug (sl)	=	32.174	Pounds mass (lbm)
1 Ton, short	=	2000	Pounds mass (lbm)

DESIGN OF MACHINERY

AN INTRODUCTION TO THE SYNTHESIS AND ANALYSIS OF MECHANISMS AND MACHINES

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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, the Russell G. Searle Distinguished Instructor, and head of the design group in that department. 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 text *Machine Design: An Integrated Approach*. 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.

* See Index.

This book is dedicated to the memory of my father,

Harry J. Norton, Sr.

who sparked a young boy's interest in engineering;

to the memory of my mother,

Kathryn W. Norton

who made it all possible;

to my wife,

Nancy Norton

who provides unflagging patience and support;

and to my children,

Robert, Mary, and Thomas,

who make it all worthwhile.

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

Take to Kinematics. It will repay you. It is more fecund than geometry; it adds a fourth dimension to space.

CHEBYSCHEV TO SYLVESTER, 1873

PART I

KINEMATICS OF MECHANISMS

CONTENTS