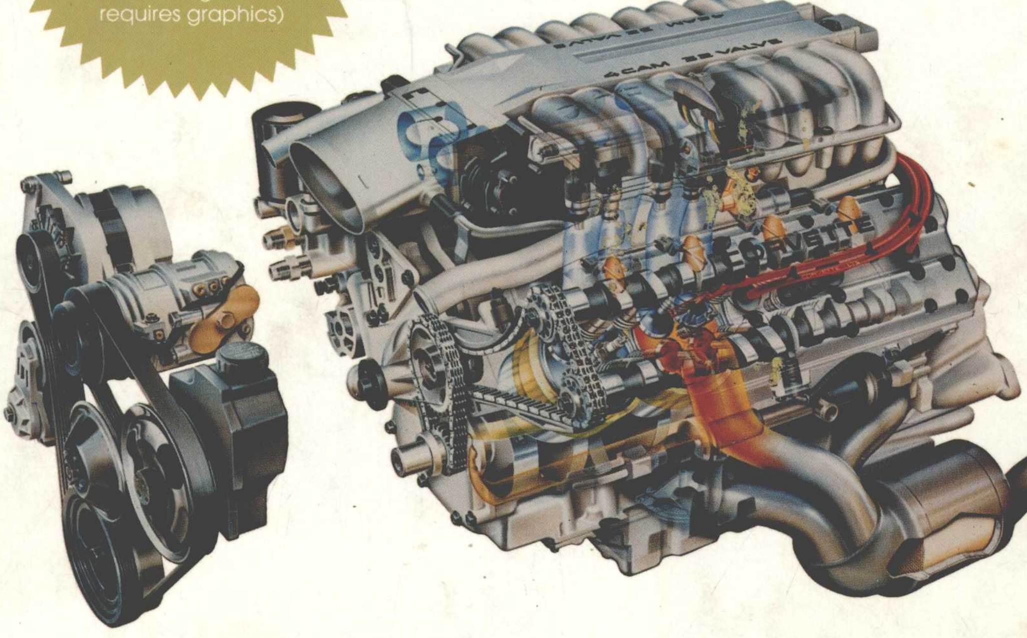
DESIGN OF MACHINERY

An Introduction to the Synthesis and Analysis of Mechanisms and Machines

SIMULATION / MODELING SOFTWARE ENCLOSED

For use with IBM PC™ and compatibles. (3 1/2" high density disk, 640K RAM, DOS 3.0 and higher, requires graphics)



ROBERT L. NORTON

DESIGN OF MACHINERY

AN INTRODUCTION TO THE SYNTHESIS AND ANALYSIS OF MECHANISMS AND MACHINES

Robert L. Norton

Worcester Polytechnic Institute

Worcester, Massachusetts

McGraw-Hill, Inc.

New York St. Louis San Francisco Auckland Bogotá Caracas
Hamburg Lisbon London Madrid Mexico Milan Montreal New Dehli
Paris San Juan São Paulo Singapore Sydney Tokyo Toronto

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1 2 3 4 5 6 7 8 9 0 DOC DOC 9 0 9 8 7 6 5 4 3 2 1

P/N 047799-X
PART OF
ISBN 0-07-909702-2

The editor was John J. Corrigan;
the production supervisor was Friederich W. Schulte;
the book design was done by Wanda Siedlecka.
The body text was set in Palatino, and headings set in Avant Garde.
Comp Associates, Worcester, Mass., made the color separations.
R. R. Donnelley & Sons was printer and binder.

All text, drawings, and equations in this book were prepared and typeset electronically, by the author, on a *Macintosh*® IIx computer using Microsoft *Word*®, Adobe *Illustrator*®, *PowerDraw*® by Engineered Software, *MathType*® by Design Science, and Aldus *Pagemaker*® desktop publishing software. Printer's film color separations were made on a *Varityper* 4300 laser typesetter directly from the author's disks using Aldus *PrePrint*. All *clip art* illustrations are courtesy of *Dubl-Click Software Inc.*, 18201 Gresham St., Northridge, CA, 91325, reprinted from their *Industrial Revolution* and *Old Earth Almanac* series with their permission (and with the author's thanks).

Library of Congress Cataloging-in-Publication Data

Norton, Robert L.
Design of machinery: an introduction to the synthesis and analysis of mechanisms and machines / Robert L. Norton.
p. cm. —(McGraw-Hill series in mechanical engineering)
Includes bibliographical references and index.
ISBN 0-07-909702-2 (set)
1. Machinery—Design. 2. Machinery, Kinematics. 3. Machinery, Dynamics of. I. Title. II. Series.
TJ230.N63 1992
621.8'15—dc20 91-7510

PREFACE

When I hear, I forget
When I see, I remember
When I do, I understand
CALVIN COOLIDGE

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 30 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 several menu driven, 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 a floppy disk, with this book which also contains instructions for their use on any IBM compatible, MS DOS computer. Programs FOURBAR, FIVEBAR and SIXBAR analyze the kinematics of those types of linkages. Program DYNAFOUR does a complete dynamic analysis of the fourbar linkage in addition to its kinematics. 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 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 program disk as files to be read into these programs. Many 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.

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 pursue the traditional approach of teaching 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 9 on cams is more extensive and complete than that of other kinematics texts and takes a design approach. Chapter 10 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. Balancing of rotating machinery and linkages is covered in Chapter 13. Chapters 14 and 15 use the internal combustion engine as an example to pull together many dynamic concepts in a design context. Chapter 17 presents an introduction to dynamic systems modelling and uses the cam-follower system as the example. Chapters 3, 9, 12, 14, and 15 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 Mr. Coolidge 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 have reviewed various sections 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 Keyes Fiber Corp., Waterville, Maine, reviewed Chapter 9 on cam design. Professor William J. Crochetiere and Mr. Homer Eckhardt of Tufts University, Medford, Mass., reviewed Chapter 17. 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. Special thanks go to Professor John Sullivan of Worcester Polytechnic Institute for the use of an Apple scanner. 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. 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.

Robert L. Norton

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 and New Hampshire. 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 ten years, he designed cameras, related mechanisms, and high-speed automated machinery. He spent three years at Jet Spray Cooler Inc., Waltham, Mass., 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 thirteen U.S. patents.

Norton has been on the faculty of Worcester Polytechnic Institute since 1981, and is currently Professor of Mechanical Engineering and head of the design group in that department. He teaches undergraduate and graduate courses in mechanical engineering with emphasis on design, kinematics, and dynamics of machinery. He also directs the operation of several general-purpose and computer-aided-design laboratories. 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. He is a member of the American Society of Mechanical Engineers and the American Society of Engineering Education. Rumors about the transplantation of a 68040 microprocesssor 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 Warren 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,

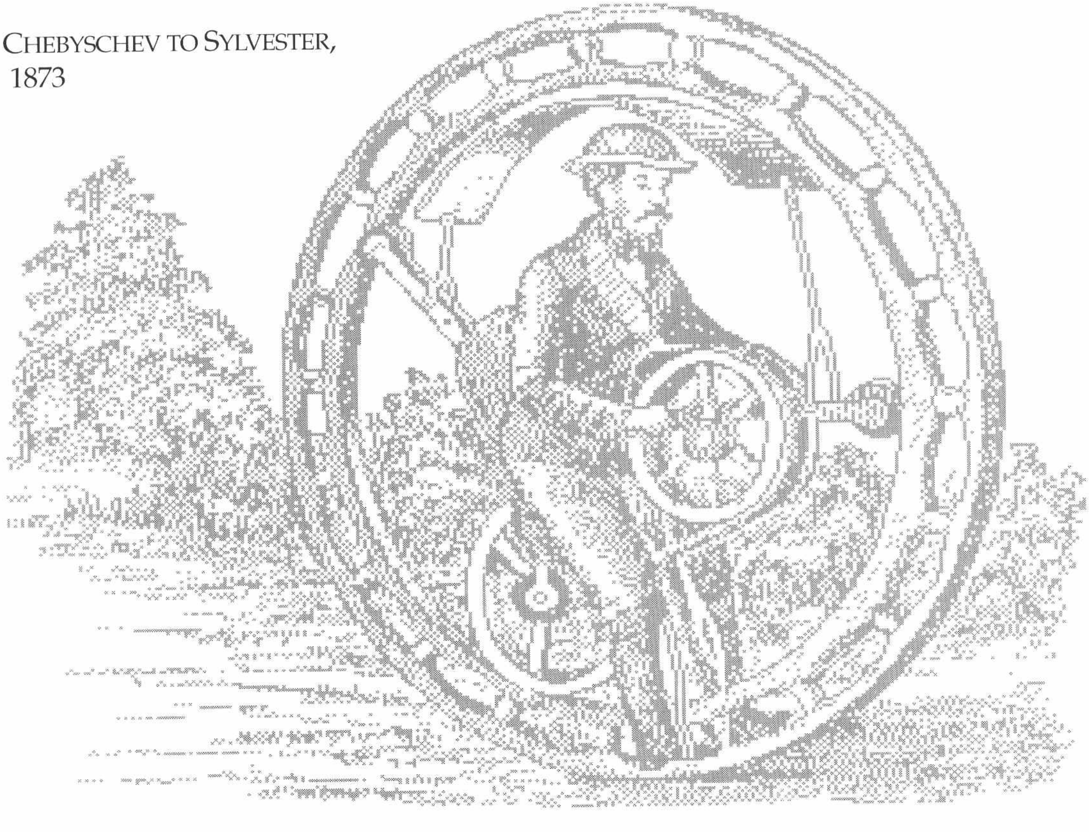
who make it all worthwhile.

CONTENTS

PART I

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

CHEBYSCHEV TO SYLVESTER,
1873



KINEMATICS OF MECHANISMS