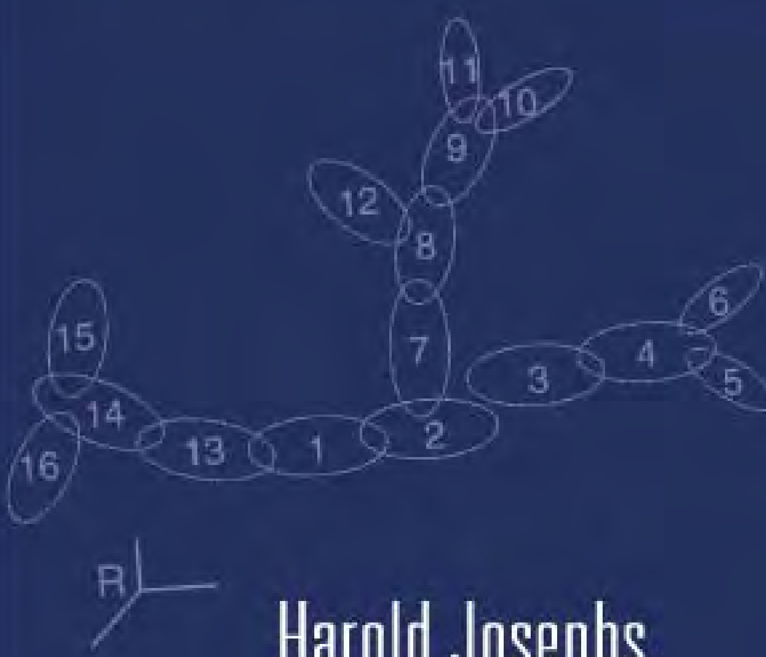
DYNAMICS of MECHANICAL SYSTEMS



Harold Josephs
Ronald L. Huston

CRC PRESS

DYNAMICS of MECHANICAL SYSTEMS

DYNAMICS of MECHANICAL SYSTEMS

Harold Josephs
Ronald L. Huston

CRC PRESS

Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Josephs, Harold.
Dynamics of mechanical systems / by Harold Josephs and Ronald L. Huston.
p. ; cm.
Includes bibliographical references and index.
ISBN 0-8493-0593-4 (alk. paper)
1. Mechanical engineering. I. Huston, Ronald L., 1937- II. Title.

TJ145 .J67 2002.
621—dc21 2002276809
CIP

Direct all inquiries to CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

International Standard Book Number 0-8493-0593-4
Library of Congress Card Number 2002276809
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Preface

This is a textbook intended for mid- to upper-level undergraduate students in engineering and physics. The objective of the book is to give readers a working knowledge of dynamics, enabling them to analyze mechanical systems ranging from elementary and fundamental systems such as planar mechanisms to more advanced systems such as robots, space mechanisms, and human body models. The emphasis of the book is upon the fundamental procedures underlying these dynamic analyses. Readers are expected to obtain skills ranging from the ability to perform insightful hand analyses to the ability to develop algorithms for numerical/computer analyses. In this latter regard, the book is also intended to serve as an independent study text and as a reference book for beginning graduate students and for practicing engineers.

Mechanical systems are becoming increasingly sophisticated, with applications requiring greater precision, improved reliability, and extended life. These enhanced requirements are spurred by a demand for advanced land, air, and space vehicles; by a corresponding demand for advanced mechanisms, manipulators, and robotics systems; and by a need to have a better understanding of the dynamics of biosystems. The book is intended to enable its readers to make engineering advances in each of these areas. The authors believe that the skills needed to make such advances are best obtained by illustratively studying fundamental mechanical components such as pendulums, gears, cams, and mechanisms while reviewing the principles of vibrations, stability, and balancing. The study of these subjects is facilitated by a knowledge of kinematics and skill in the use of Newton's laws, energy methods, Lagrange's equations, and Kane's equations. The book is intended to provide a means for mastering all of these concepts.

The book is written to be readily accessible to students and readers having a background in elementary physics, mathematics through calculus and differential equations, and elementary mechanics. The book itself is divided into 20 chapters, with the first two chapters providing introductory remarks and a review of vector algebra. The next three chapters are devoted to kinematics, with the last of these focusing upon planar kinematics. Chapter 6 discusses forces and force systems, and Chapter 7 provides a comprehensive review of inertia including inertia dyadics and procedures for obtaining the principal moments of inertia and the corresponding principal axes of inertia.

Fundamental principles of dynamics (Newton's laws and d'Alembert's principle) are presented in Chapter 8, and the use of impulse–momentum and work–energy principles is presented in the next two chapters with application to accident reconstruction. Chapters 11 and 12 introduce generalized dynamics and the use of Lagrange's equation and Kane's equations with application to multiple rod pendulum problems. The next five chapters are devoted to applications that involve the study of vibration, stability, balancing, cams, and gears, including procedures for studying nonlinear vibrations and engine balancing. The last three chapters present an introduction to multibody dynamics with application to robotics and biosystems.

Application and illustrative examples are discussed and presented in each chapter, and exercises and problems are provided at the end of each chapter. In addition, each chapter has its own list of references for additional study. Although the earlier chapters provide the basis for the latter chapters, each chapter is written to be as self-contained as possible, with excerpts from earlier chapters provided as needed.

Acknowledgments

The book is an outgrowth of notes the authors have compiled over the past three decades in teaching various courses using the subject material. These notes, in turn, are based upon information contained in various texts used in these courses and upon the authors' independent study and research.

The authors acknowledge the inspiration for a clearly defined procedural study of dynamics by Professor T. R. Kane at the University of Pennsylvania, now nearly 50 years ago. The authors particularly acknowledge the administrative support and assistance of Charlotte Better in typing and preparing the entire text through several revisions. The work of Xiaobo Liu and Doug Provine for preparation of many of the figures is also acknowledged.

The Authors

Harold Josephs, Ph.D., P.E., has been a professor in the Department of Mechanical Engineering at Lawrence Technological University in Southfield, MI, since 1984, subsequent to working in industry for General Electric and Ford Motor Company. Dr. Josephs is the author of numerous publications, holds nine patents, and has presented numerous seminars to industry in the field of safety, bolting, and joining. Dr. Josephs maintains an active consultant practice in safety, ergonomics, and accident reconstruction. His research interests are in fastening and joining, human factors, ergonomics, and safety. Dr. Josephs received his B.S. degree from the University of Pennsylvania, his M.S. degree from Villanova University, and his Ph.D. from the Union Institute. He is a licensed Professional Engineer, Certified Safety Professional, Certified Professional Ergonomist, Certified Quality Engineer, Fellow of the Michigan Society of Engineers, and a Fellow of the National Academy of Forensic Engineers.

Ronald L. Huston, Ph.D., P.E., is distinguished research professor and professor of mechanics in the Department of Mechanical, Industrial, and Nuclear Engineering at the University of Cincinnati. He is also a Herman Schneider chair professor. Dr. Huston has been at the University of Cincinnati since 1962. In 1978, he served as a visiting professor at Stanford University, and from 1979 to 1980 he was division director of civil and mechanical engineering at the National Science Foundation. From 1990 to 1996, Dr. Huston was a director of the Monarch Research Foundation. He is the author of over 140 journal articles, 142 conference papers, 4 books, and 65 book reviews and is a technical editor of *Applied Mechanics Reviews*, and book review editor of the *International Journal of Industrial Engineering*. Dr. Huston is an active consultant in safety, biomechanics, and accident reconstruction. His research interests are in multibody dynamics, human factors, biomechanics, and ergonomics and safety. Dr. Huston received his B.S. degree (1959), M.S. degree (1961), and Ph.D. (1962) from the University of Pennsylvania, Philadelphia. He is a Licensed Professional Engineer and a Fellow of the American Society of Mechanical Engineers.

Contents

1

Introduction

1.1 Approach to the Subject

This book presents an introduction to the dynamics of mechanical systems; it is based upon the principles of elementary mechanics. Although the book is intended to be self-contained, with minimal prerequisites, readers are assumed to have a working knowledge of fundamental mechanics' principles and a familiarity with vector and matrix methods. The readers are also assumed to have knowledge of elementary physics and calculus. In this introductory chapter, we will review some basic assumptions and axioms and other preliminary considerations. We will also begin a review of vector methods, which we will continue and expand in Chapter 2.

Our procedure throughout the book will be to develop a general methodology which we will then simplify and specialize to topics of interest. We will attempt to illustrate the concepts through examples and exercise problems. The reader is encouraged to solve as many problems as possible. Indeed, it is our belief that a basic understanding of the concepts and an intuitive grasp of the subject are best obtained through solving the exercise problems.

1.2 Subject Matter

Dynamics is a subject in the general field of mechanics, which in turn is a discipline of classical physics. Mechanics can be divided into two divisions: solid mechanics and fluid mechanics. Solid mechanics may be further divided into flexible mechanics and rigid mechanics. Flexible mechanics includes such subjects as strength of materials, elasticity, viscoelasticity, plasticity, and continuum mechanics. Alternatively, aside from statics, dynamics is the essence of rigid mechanics. Figure 1.2.1 contains a chart showing these subjects and their relations to one another.

Statics is a study of the behavior of rigid body systems when there is no motion. Statics is concerned primarily with the analysis of forces and force systems and the determination of equilibrium configurations. In contrast, *dynamics* is a study of the behavior of moving rigid body systems. As seen in Figure 1.2.1, dynamics may be subdivided into three sub-subjects: kinematics, inertia, and kinetics.