WILLIAM L. CLEGHORN
NIKOLAI DECHEV

MECHANICS OF MACHINES

INTERNATIONAL
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WILLIAM L. CLEGHORN and NIKOLAI DECHEV

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PREFACE

This book is intended mainly for use as an undergraduate text. It contains topics and material sufficient for a one-half-year course. It may also be useful to practicing engineers.

Conventional notation is employed throughout, primarily using the International System set of units. Approximately one-quarter of the examples employ the U.S. Customary System.

Many examples included in each chapter relate to situations of practical significance. Problems of varying length and difficulty are included at the end of each chapter. In addition, twenty-six computer design projects are supplied in Appendix A. It is suggested that these be completed using the software Working Model 2D.

The companion website for this textbook (www.oup.com/cleghorn-xse) has numerous files of 3D animations, mechanisms, video clips of real mechanical systems in operation. These images have been stored in the MPEG(*.mp4) format and may be viewed through the web browser with appropriate movie plug-ins installed (Windows Media Player or Quicktime player). Within the text, each of these files is identified either in boldface in square brackets (e.g., [**Video1.1**]) or within a textbox located in the margin as shown here.

Video 1.1
Single Cylinder
Piston Engine

The companion website also contains interactive 2D models based on Working Model 2D, and requiring a file player of that software. To open and use these models, Working Model 2D must be downloaded and installed on the computer. A link to acquire this software is provided on the website. Within the text, each of these files is identified either in boldface in square brackets (e.g., [**Model 1.14A**]) or within a textbox located in the margin as shown here. Appendix D lists all models and animations and video segments.

Video 1.14A,
1.14B
Model 1.14A,
1.14B
Four-Bar with
Coupler Point

The companion website also contains more than ten Mathcad files for use with a select set of problems dealing with the analysis and synthesis of mechanisms. The problems for which the Mathcad files may be applied are identified in the statements associated with end-of-chapter problems.

Graphical and analytical methods of analysis are included for the kinematic and kinetic analyses of mechanisms. Graphical methods may be applied in situations where analysis for only one position of a mechanism is required. They often require a scaled drawing in the configuration for which an analysis is required. For several of the end-of-chapter problems, a scaled drawing may be obtained from the companion website. Such problems are identified by the icon shown in the margin. Analytical solutions are useful in instances when solutions are required for a series of mechanism configurations.

Chapter 1 covers basic concepts, including linkage classification by motion characteristics, as well as degrees of freedom of the planar joints of mechanisms. Some common examples of mechanisms, along with their associated animations, are provided.

Chapter 2 provides the background material required to carry out static and dynamic analyses of planar mechanical systems. Expressions for relative velocity and acceleration in the radial-transverse coordinate system are covered. The instantaneous centre of velocity of a body is presented. Equations for the kinetics of a rigid body and associated commonly employed sets of units are also provided. The concept of mechanical advantage is covered along with its determination using the instantaneous centres of velocity of the mechanism.

Chapter 3 covers traditional graphical analysis of planar mechanisms. Both velocity and acceleration analyses are presented using vector polygons for one position of the mechanism. Velocity analyses implementing the method of instantaneous centres of velocity are also covered.

Chapter 4 presents an analytical method based on complex numbers for the kinematic analysis of a planar mechanism. The equations generated using this technique may be programmed on a computer for completing an analysis in a series of positions.

Chapter 5 gives a comprehensive synopsis of gears. This includes many common types of gears and related animations of the gears in meshing action. This chapter also includes some of the common methods of gear manufacture.

Chapter 6 presents an analysis of gear trains. For analysis of planetary gear trains, an algorithm suited for computer implementation is provided.

Chapter 7 presents design procedures of cam mechanisms. Both graphical and analytical methods are covered. In addition, the computer program Cam Design is included on the companion website. This program can synthesize a wide variety of disc cams. For a given set of input parameters and prescribed motion of the follower, all pertinent kinematic parameters are provided as a function of input motion.

Chapter 8 covers graphical force analyses of planar mechanisms. Each graphical analysis may be applied for one configuration of a mechanism—for either static or dynamic conditions.

Chapter 9 covers analytical force analysis of planar mechanisms. The governing equations of motion are derived for an arbitrary configuration of a mechanism and may be programmed on a computer to determine results for multiple configurations. Means to balance a four-bar mechanism and a slider crank mechanism are also provided.

Chapter 10 covers the analysis and design of flywheels. This includes determining the size of a flywheel required to keep speed fluctuations within a desired tolerance.

Chapter 11 presents some common methods for the synthesis of mechanisms. This includes graphical and analytical techniques for function synthesis and rigid-body guidance synthesis of four-bar and slider crank mechanisms.

Chapter 12 introduces and describes the design process methodology as it applies to mechanisms and machines. The complete design process is described, including problem formulation, conceptualization, preliminary design, detailed design, embodiment, testing, and documentation/reporting. Various examples are provided throughout the chapter for each stage of the process.

Chapter 13 presents an extensive set of case studies in the design of mechanisms and machines. The case studies allow the reader to follow along in the problem formulation stage, whereby a structured set of design goals and design objectives is developed. Next, one or more possible design solutions that satisfy the design goal and objectives are described. These are solutions that are commonly used in the field; description of their operation is included as well. Finally, a design summary and a set of recommendations highlight the strength and limitations of the proposed design solutions.

Appendix A includes a set of design projects. They can be ideally solved using the Working Model 2D software. Appendix B provides background reference material related to scalars and vectors. Appendix C gives a brief review of mechanics, which is the basis of much of the material presented in this textbook. Appendix D lists the files included on the companion website.

William L. Cleghorn
Nikolai Dechev

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CHAPTER 1

INTRODUCTION

1.1 PRELIMINARY REMARKS

Mechanics is a science that predicts the conditions of a system either at rest or in motion, when under the action of forces and moments. Within mechanics, the study can involve stationary systems at rest (statics) or systems in motion (dynamics). In statics, the motion of the parts in a system is zero (or insignificant), so the analysis is about the forces that act between the parts. In dynamics, the analysis is concerned with the forces that arise in a system of moving parts.

A *machine* is defined as an apparatus that transmits energy through its parts to perform desired tasks. This definition does not restrict the form of energy transmitted, nor does it restrict the size and rigidity of the parts. It therefore encompasses a vast array of mechanical and electrical devices, many of which have a profound effect on our lives. One of the simplest types of machines is the lever. The lever works by transforming a small force with large motion into a high force with short motion. In this way, the small force available from human effort can be magnified into high force for various farming or construction activities. An example of a more complex and recent machine is the automobile. An automobile is a machine that transfers energy from the engine into the drive shaft and onto the wheels, to provide motion. In fact, we can also say the engine is a machine that transfers the energy from the fuel (gasoline) into the drive shaft.

This textbook, entitled *Mechanics of Machines,* deals with the statics and dynamics of various mechanical systems that transmit energy through their parts. The wheel and the lever were among the earliest inventions of machines. Engineers have since designed numerous ingenious machines for the advancement of society. Machines are widely used in all aspects of our society, such as transportation, farming, manufacturing, medicine, war, sports, and many others. For example, doctors employ machines to treat patients, or they can prescribe machines such as prosthetic hands, arms and legs to replace natural limbs. In recent years, robotic machines have had a significant influence in manufacturing methods. Some are able to rapidly perform repetitive tasks in a reliable and accurate manner and can be used to work in hostile and dangerous environments.

Some machines are a combination of mechanical, electrical, and hydraulic components. An automobile is composed of mechanical parts of the drive train, suspension, and steering systems, along with electrical parts used to ignite the air–fuel mixture in the engine and to provide lighting and sensory feedback for the driver.

Machines having electrical components usually incorporate at least some mechanical parts. The hard drive within a computer has electric motors with rotating shafts for spinning the disc that holds the data. It also has a mechanical arm carrying a magnetic sensor head that swings above the disc to store and access data. The keyboard may be considered a machine with mechanical parts. Printers and scanners have machine components such as gears and lever arms to handle the paper. Many electronic watches have hands operated by miniature ratchet wheels that are pushed around one tooth at a time.

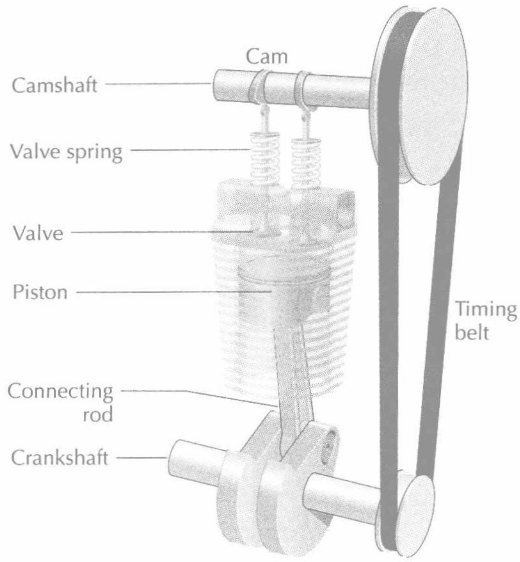

Figure 1.1 Single-cylinder piston engine [Model 1.1].

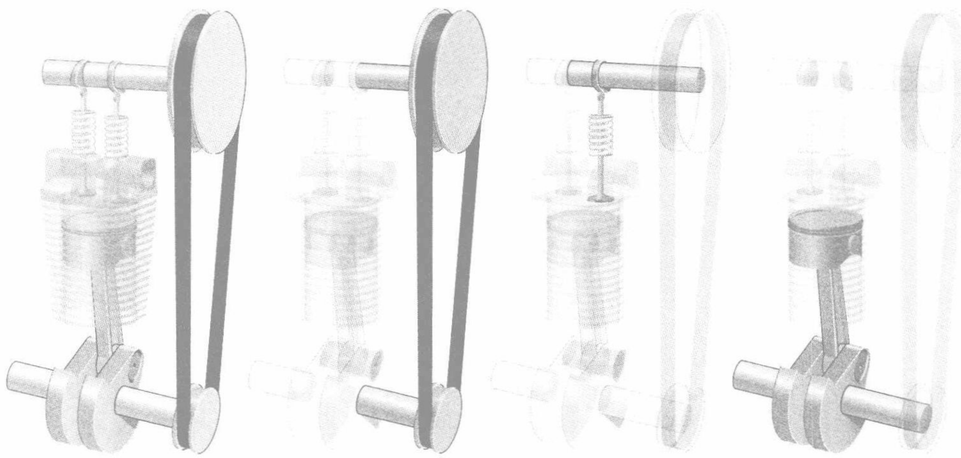

Figure 1.2 Mechanisms in a single-cylinder piston engine: (a) Engine. (b) Timing belt drive. (c) Cam mechanism. (d) Slider crank mechanism.

This textbook will consider only the mechanical parts of machines, along with their analysis. To conduct such analyses, it is usually convenient to divide a machine into subsystems, referred to as *mechanisms* (or *linkages*), rather than attempting to analyse all parts of a machine simultaneously. They may be either moving or stationary. Even with this restriction, there are countless types of machine.

A well-known example of a machine is the single-cylinder internal combustion piston engine, as illustrated in Figure 1.1. This machine serves as a good example, since it contains mechanisms within itself, which are described later in this text. In particular, it highlights three mechanisms such as a *timing belt drive*, a *cam mechanism*, and a *slider crank mechanism*, which are illustrated in Figures 1.2(b), 1.2(c), and 1.2(d), respectively. An animation of this machine is provided by [**Video 1.1: Single-Cylinder Piston Engine**], included on the companion website. A detailed description of the operation of this machine is given in Chapter 13, Section 13.2.1.

Video 1.1
Single-Cylinder Piston Engine

A simple machine may also be considered as a single mechanism. For instance, the tongs shown in Figure 1.3(a) can be considered either as a machine or as a mechanism. Figure 1.3(b) shows a free-body diagram of the system used to analyse the manual force required to generate sufficient gripping force.

Mechanisms are widely used in applications where precise relative movement and transmission of force are required. Motions may be continuous or intermittent, linear, and/or angular. Examples