1

Introductory Concepts

1.1 Introduction to Machines

1.1.1 Brief History of Machines

In our modern world, we are surrounded by machines, and they have become an integral part of our daily lives. We know that high-tech machines of today were not always in existence, but it is hard to imagine what it would be like without them because our lives would be drastically different. It is difficult to say when the first machine was developed. Knowledge of very early machines comes from archeology, but this work is difficult. The difficulty is partly due to the fact that it is rare to discover intact machines, but it is more common to discover early machine components. Over time machines developed from very crude to extremely elaborate, and often that development moved in parallel with the development of human culture.

In the very early years, machine development was difficult and slow. Sometimes advancements in technology were driven by military needs, and other times advancements were required for survival. Primitive man devised simple tools made of wood, stone, or bone that were essential for survival. Machines were developed to produce fire, and simple mechanisms were developed to trap animals for food. Numerous machines from different cultures were also developed to extract water. Archimedes (287–212 BC) developed a method for water extraction using a spiral screw, such as the one illustrated in Figure 1.1. Machines such as levers and inclined planes were used by the Egyptians to build numerous monuments such as the pyramids.

One important class of mechanisms developed through the ages is those used to measure time. Many machines were devised for measurement of the phases of the moon, but one particularly interesting device was discovered in a shipwreck in 1900. The Antikythera mechanism, which is schematically shown in Figure 1.2, is estimated to have been fabricated around 100 BC from a bronze alloy. This complex gear mechanism contains at least 30 gears and acts as an analog computer to calculate astronomical positions. The device likely was used to predict solar and lunar eclipses as well as display positions of the five known planets of the time.

A major contributor to machine inventions was Leonardo da Vinci (1452–1519). He recorded ideas and observations in thousands of pages of notebooks, mostly in the form of drawings. He was fascinated with nature and was way ahead of his time in understanding fluid flow and turbulence. In his study of human anatomy, he recognized mechanical function such as the joints acting as hinges. Leonardo used principles of engineering statics to analyze

Machine Analysis with Computer Applications for Mechanical Engineers, First Edition. James Doane.

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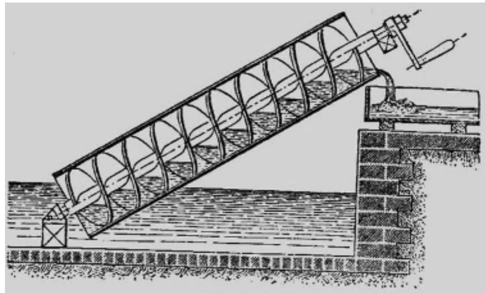


Figure 1.1 Archimedes' screw. Source: Wikimedia [http://commons.wikimedia.org/wiki/File:Brockhaus_and_Efron_Encyclopedic_Dictionary_b3_020-4.jpg]

the mechanics of biomaterials such as bones and muscle. His knowledge of mechanics was also applied to machines, and Leonardo is believed to be responsible for dissecting machines into basic machine elements. Among his many machine designs was a water-powered milling machine that utilized primitive gears to transmit motion. He also developed concepts for converting rotary crank motion into reciprocating motion. He designed hoist systems to lift heavy loads using gears. He recognized the high level of friction in machines and designed multiple devices, such as bearings, to reduce friction. Leonardo's interest in anatomy and mechanics also led to his work to design a flying machine, as shown in Figure 1.3.

Galileo (1564–1642) investigated the behavior of pendulums, and he discovered that the period of pendulum is not affected by amplitude of motion. Christiaan Huygens (1629–1695)

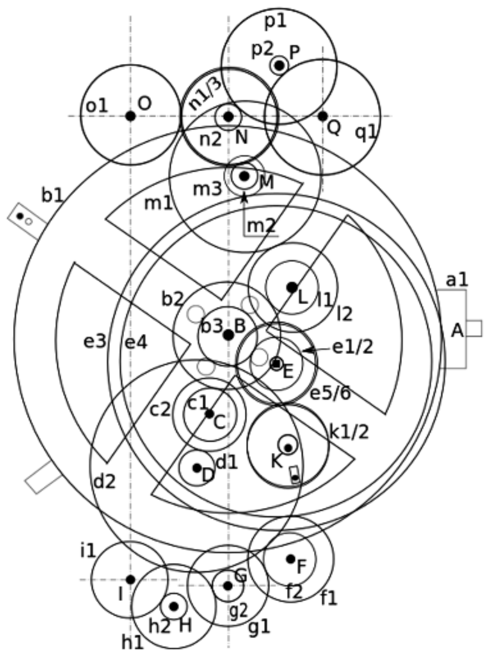


Figure 1.2 Schematic of the Antikythera mechanism. Source: Wikimedia [http://commons.wikimedia.org/wiki/File:Antikythera_mechanism_-_labelled.svg]

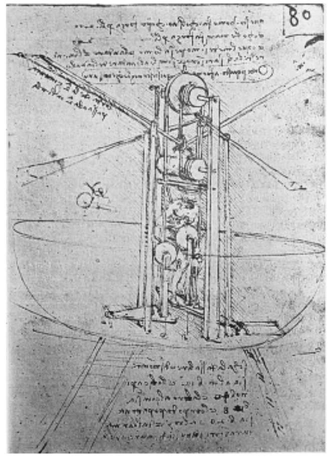


Figure 1.3 Sketch of flying machine by Leonardo da Vinci. Source: Wikimedia [http://commons.wikimedia.org/wiki/File:Leonardo_da_vinci,_Flying_machine.jpg]

was a Dutch scientist who worked in areas of mathematics, physics, astronomy, and horology (the science of measuring time). Huygens worked with clocks to make them more accurate, and he patented the first pendulum clock in 1656. Figure 1.4 shows a pendulum clock invented by Huygens and built around 1673.

Leonhard Euler (1707–1783) was a great mathematician of the eighteenth century. His contributions to mathematics and science were numerous and cover a breadth of topics. As an engineering student, you will see references to Euler in numerous classes. A very important contribution of Euler was the Euler–Bernoulli beam equation, which is extensively used to calculate deflection of beams. Euler introduced a rotating coordinate system critical for describing three-dimensional orientation of rigid bodies, which is vital to describing complex three-dimensional motion of mechanisms.

It is impossible to think of advancements in machines without discussing the development of steam engines. Steam engines, such as that shown in Figure 1.5, replaced the use of horses to generate power and allowed for operation of factories in cities.

James Watt (1736–1819), a Scottish engineer, experimented with steam and made improvements to the steam engine designed by Thomas Newcomen in the early 1700s. The Watt steam engine has several ingenious inventions that make it a vast improvement. Watt recognized that a great amount of energy was wasted in the Newcomen engine. While repairing a Newcomen engine, he realized that the cylinder (for the piston) was heated and cooled repeatedly. Watt thought that if the condensing step could be moved, the condenser could be kept cold at all times while the cylinder remained hot. One of Watt's inventions was to separate the condensing step to reduce wasted energy and it greatly improved efficiency. Watt developed a mechanism known as a straight line mechanism, which is a linkage mechanism that generates a straight line path to move pistons (see Section 1.5.5 for additional information on straight line mechanisms). Watt also utilized a governor mechanism as an early feedback system to regulate rotation speed. Lighter engines were of course later developed, such as Nikolaus Otto's four-stroke engine developed in the late 1800s. The sun gear mechanism used by Watt will be discussed in Chapter 8.

Gears are a vital part of many machines. Though crude gear designs allow for transfer of power, they are not well suited for higher speed operation. Robert Willis (1800–1875) made

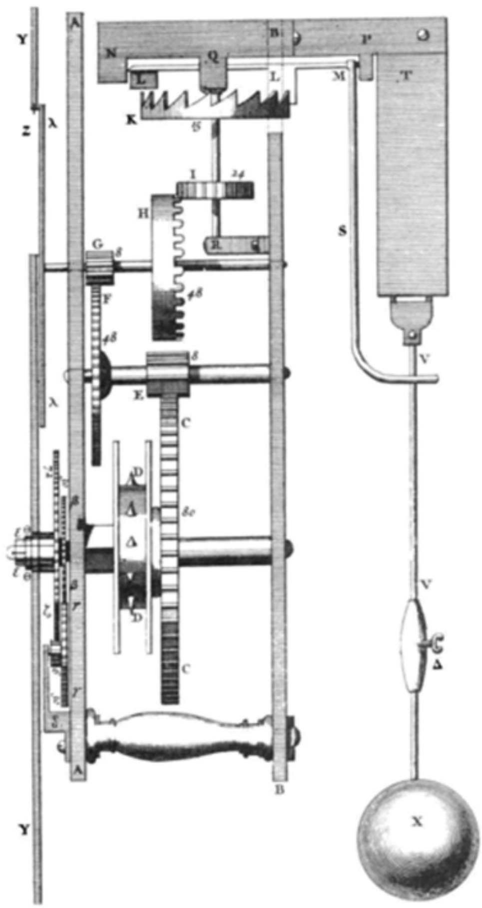


Figure 1.4 Huygens pendulum clock. Source: Wikimedia [http://commons.wikimedia.org/wiki/File:Huygens_clock.png]

significant contributions to the standardization and design of gears and gear teeth. Willis showed that involute curves (curves used for gear teeth – see Chapter 7 for details) allow for interaction of gears with different diameters without angular acceleration. Willis developed the use of a constant pressure angle to standardize gear manufacturing. A brief historical timeline of gear development is provided in Chapter 7.

German engineer Franz Reuleaux (1829–1905) is often noted as one of the greatest minds in machine theory of the nineteenth century and the father of kinematics. His extensive work in kinematics was published as a book in 1875, which was quickly translated into English as the title *The Kinematics of Machinery: Outlines of a Theory of Machines*. Both Willis and Reuleaux developed ideas that mechanisms are formed as kinematic chains, which can be analyzed by examining relative motion of element pairs. Reuleaux expanded on existing ideas of instant centers of rotation by calculation of centrodes, or paths of the instant center. Reuleaux developed ideas that mechanical motion was controlled by interactions and connections between the individual moving members of the machine.

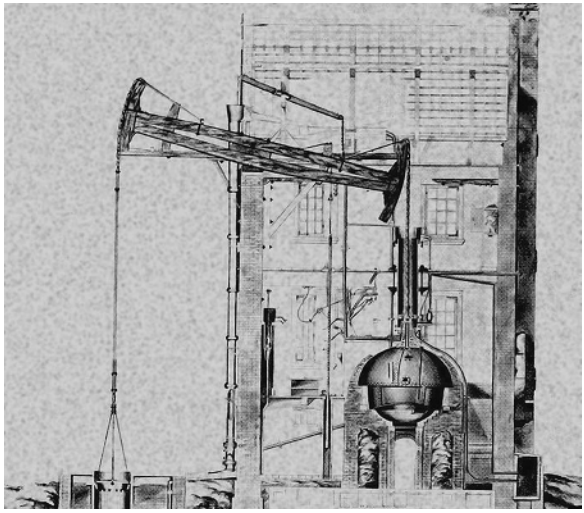


Figure 1.5 Newcomen steam engine. Source: Wikimedia [http://commons.wikimedia.org/wiki/File:Newcomen_steam_engine_at_landgoed_groenedaal.jpg]

Ferdinand Freudenstein (1926–2006) is often referred to as the father of modern kinematics. He began making major contributions to machine analysis early in his career. The Freudenstein equation, which will be discussed and used in several sections relating to linkages, was actually developed in his Ph.D. dissertation. The equation is very useful in position analysis of linkage mechanisms as well as linkage design.

1.1.2 Why Study Machine Analysis?

It would be very rare to go through a day without the use of some type of machine. Today's machines come in many forms. Some machines are rather basic such as a bicycle or simple hand tools while others, such as cars and automated manufacturing equipment, can be very complex. Recent advancements in technology allow for machines to be automated and run at very high speeds. High-speed operations of machines offer many advantages but can add complications in design.

Mechanical engineers responsible for designing machines must have a strong understanding of machine kinematics and kinetics. Poor understanding of the kinematics and kinetics of machines can lead to unsatisfactory performance or even catastrophic failure of components. Acceleration analysis, as an example, must be performed for all portions of a machine's cycle to determine maximum values. Though this acceleration analysis is typically complicated, it is required to determine force values, which are then used to design machine elements based on allowable stress values or allowable deformations.

This text will examine the core subjects of kinematics and kinetics of machines. The primary focus will be to build a strong foundation of machine analysis; therefore, many advanced topics are outside the scope and will not be presented. Readers interested in exploring the more advanced topics, or more information about the core topics of this text, should review the bibliography sections at the end of each chapter for suggested resources.

1.1.3 Differences between Machine Analysis and Machine Design

It is fairly common in a 4-year mechanical engineering curriculum to take machine analysis and machine design as two separate courses. Both courses are important, but the content differs. It is somewhat common for students to confuse the two courses or be unclear why both courses are needed.

Machine analysis focuses on the kinematics and kinetics of mechanisms. Course material builds on concepts learned in engineering dynamics. The most common machine components covered in a machine analysis course include linkages, gears, and cams though others can be included. Machine analysis covers methods of designing the geometry of linkage mechanisms to perform specific tasks, as well as analyzing the kinematics of an existing linkage mechanism. Deflection of the machine members is often considered negligible, so they are commonly treated as rigid bodies. Analysis of gears focuses mostly on the interaction of teeth and behavior of gear trains. The focus on cams is developing the geometry of the cam to perform the desired motion. Though topics in machine analysis include forces, things such as deflection, stress, fatigue, and wear are not discussed.

The focus of machine design revolves more around designing machine elements for strength and rigidity. Much of the material covered in machine design will build on previous knowledge of mechanics of materials, such as combined loading conditions, failure criteria, curved beams, deflection of complex systems, and pressurized cylinders. Gears are studied to develop understanding of contact stresses and bending stresses to avoid failure. Concepts of shaft design are covered, including stress concentrations, fatigue stress, and deflection. Other machine elements often discussed in machine design include bearings, clutches, brakes, fasteners, and springs.

Though the two topic areas are different, they work in parallel. An engineer's first focus will be the motion of the machine. The fundamental requirement is often focused around the idea of proper displacements. Once the displacement has been developed, the resulting acceleration can be determined. Using the accelerations, the study moves to kinetics to determine forces. Design work then moves to analysis of developed stresses and deformations. This design process is often iterative. Machine analysis is a phase of machine design. Therefore, one must often use knowledge of machine analysis and machine design through multiple iterations to develop the final design.

1.2 Units

1.2.1 Importance of Units

Engineering students get introduced and reintroduced to systems of units throughout their college lives. Nearly every engineering text, regardless of the subject, offers at least a short section devoted to units. However, most engineering students still get confused by the details of the different systems of units. That confusion, unfortunately, commonly continues past graduation and can cause serious (sometimes catastrophic) problems. In 1983, a Boeing 767 ran out of fuel at 41 000 feet because of an error when manually converting between kilograms and liters to determine the required amount of fuel. NASA lost a Mars orbiter due to a mismatch in unit systems. From these quick examples alone, you can determine that it is extremely important for engineering students to understand unit systems and unit conversions.

1.2.2 Unit Systems

Throughout this text, both the International System of units (SI from Systeme International) and the US customary unit system (inherited from the British Imperial System) will be used.

Table 1.1 Summary of unit systems

Quantity	SI unit (symbol)	US customary unit (symbol)
Time	Second (s)	Second (s)
Length	Meter (m)	Foot (ft)
Mass	Kilogram (kg)	Slug
Force	Newton (N)	Pound (lb)

Where applicable, figures will give dimensions in both sets of units. Example problems will include a sample from each system, and end-of-chapter problems will do the same. It is recommended to work problems from each category to become proficient at both. Regardless of individual preference, a mechanical engineering student needs to become fluent in both systems. Typically, a person will have better intuitive sense for one system compared with the other. As an example, a person raised using the US units will have a good sense for a distance in miles but may not even approximately determine a distance in kilometers. A general summary of the units is given in Table 1.1.

The base units for the SI system are time, mass, and length. Units for force are then defined using Newton's second law. A newton is the force required to give a one kilogram mass an acceleration of one meter per second squared.

$$1\ \mathrm{N} = 1\ \mathrm{kg} \cdot 1\ \mathrm{m/s^2} \tag{1.1}$$

Therefore, a newton will have units of $\mathrm{kg} \cdot \mathrm{m/s^2}$. In US customary units, the base units are length, time, and force. A slug (32.174 pounds mass) will accelerate at a rate of one foot per second squared if it has an applied force of one pound.

$$1\ \mathrm{lb} = 1\ \mathrm{slug} \cdot 1\ \mathrm{ft/s^2} \tag{1.2}$$

Manipulation of the equation will show that a slug will have units of $\mathrm{lb} \cdot \mathrm{s^2/ft}$. In some cases, you may see yet another unit for mass known as a blob. The blob is simply the inch version of a slug: $\mathrm{lb} \cdot \mathrm{s^2/in}$. Therefore, one blob is equal to 12 slugs. It is often convenient to express values in the SI system using prefixes. The common prefixes are given in Table 1.2.

Table 1.2 SI unit prefixes

Amount	Multiple	Prefix	Symbol
1 000 000 000 000	10^{12}	Tera	T
1 000 000 000	10^{9}	Giga	G
1 000 000	10^{6}	Mega	M
1 000	10^{3}	Kilo	k
100	10^{2}	Hecto	h
10	10	Deka	da
0.1	10^{-1}	Deci	d
0.01	10^{-2}	Centi	c
0.001	10^{-3}	Milli	m
0.000 001	10^{-6}	Micro	μ
0.000 000 001	10^{-9}	Nano	n
0.000 000 000 001	10^{-12}	Pico	p

1.2.3 Units of Angular Motion

For some students, a common source of confusion comes from units for angular dimensions. The common units of angular measure used in mathematics are the degree and the radian. A degree (°) is equal to 1/360 of a full revolution. In other words, there are 360° in a complete revolution. To define a radian, consider the concept of arc length. In a circle of radius r, if θ is expressed in radians, the arc length is defined by $s = r\theta$. Therefore, a radian is the central angle that will cause the arc length to equal the radius. There are 2π radians in a complete revolution.

$$1 \text{ revolution} = 2\pi \text{ radians} = 360^\circ \tag{1.3}$$

It is also important to note that radians are a ratio. By simply rearranging the arc length equation, radians will be in terms of arc length over radius, both of which are length terms.

It is fairly common for students to have a better understanding of degrees, which leads to the tendency to use degrees as a default. However, a mistake of using the incorrect unit can cause very large error because a radian is considerably larger than a degree (1 radian is approximately 57.296 degrees). Much of the material in machine analysis will rely on a complete understanding of when to use degrees versus when to use radians. In general, radians have geometrical meaning (such as circumference of a circle) and are far more convenient to use in mathematics. Degrees are rather artificial and do not directly tie into geometry. The idea to use 360 increments seems rather arbitrary, but it actually dates back to the Babylonians who used a sexagesimal system, which is a base 60 system passed down to the Babylonians by the ancient Sumerians. The sexagesimal system is also still used today to measure time (60 minutes in an hour and 60 seconds in a minute).

1.2.4 Force and Mass

Another common source of confusion comes from trying to distinguish between mass and force (or weight), especially in the English system of units. The terms mass and weight are often misused, but they are not the same. The basic relationship between mass and force was discovered by Isaac Newton and is known as Newton's second law given in Equation 1.4.

$$F = ma \tag{1.4}$$

Using SI units of kilogram for mass and meter per second squared for acceleration, the units for force will be $\mathrm{kg} \cdot \mathrm{m/s^2}$, which was previously defined as a newton. For US customary units, force would be defined as pounds (or more appropriately pound force that has the symbol $\mathrm{lb_f}$) and the acceleration would have units of feet per second squared. This would cause the units of mass to be $\mathrm{lb_f} \cdot \mathrm{s^2/ft}$, which was previously defined as a slug.

The English Engineering system uses pound mass ($\mathrm{lb_m}$) as the unit of mass. The relationship between pound force and pound mass is defined using

$$1\ \mathrm{lb_f} = 32.17 \frac{\mathrm{lb_m} \cdot \mathrm{ft}}{\mathrm{s^2}} \tag{1.5}$$

Using our definition of a slug, we can also write

$$1 \text{ slug} = 32.17\ \mathrm{lb_m} \tag{1.6}$$

Weight is a force caused by gravity acting on a mass. Newton's second law can be transformed to give the relationship between weight and mass:

$$W = mg \tag{1.7}$$

where g is the acceleration due to gravity. In SI units, the acceleration due to gravity is 9.81 m/s^2 and in US customary units it is 32.17 ft/s^2.

It is sometimes convenient to use a proportionality constant g_c and rewrite Newton's second law as

$$F = \frac{ma}{g_c} \tag{1.8}$$

where

$$g_c = 1\,\frac{\text{kg}\cdot\text{m/s}^2}{\text{N}} \qquad \text{(SI units)} \tag{1.9a}$$

$$g_c = 1\,\frac{\text{slug}\cdot\text{ft/s}^2}{\text{lb}_\text{f}} \qquad \text{(US customary units)} \tag{1.9b}$$

$$g_c = 32.17\,\frac{\text{lb}_\text{m}\cdot\text{ft/s}^2}{\text{lb}_\text{f}} \qquad \text{(English Engineering units)} \tag{1.9c}$$

Note that it is not required to use the proportionality constant as long as you are thorough in keeping track of all units. The usefulness of the proportionality constant will be illustrated in a few quick examples.

Example Problem 1.1

What is the weight in pound force of an object that has a mass of 75 pounds mass?

Solution: For this problem, we will use the proportionality constant for English Engineering units. The weight is calculated using

$$W = \frac{ma}{g_c} = \frac{75\ \text{lb}_\text{m}\cdot 32.17\,\dfrac{\text{ft}}{\text{s}^2}}{32.17\,\dfrac{\text{lb}_\text{m}\cdot\text{ft/s}^2}{\text{lb}_\text{f}}}$$

Answer: $W = 75\ \text{lb}_\text{f}$

Example Problem 1.2

What is the weight in newtons of an object that has a mass of 65 kilograms?

Solution: For this problem, we will use the proportionality constant for SI units. The weight is calculated using

$$W = \frac{ma}{g_c} = \frac{65\ \text{kg}\cdot 9.81\,\dfrac{\text{m}}{\text{s}^2}}{1\,\dfrac{\text{kg}\cdot\text{m/s}^2}{\text{N}}}$$

Answer: $W = 637.65\ \text{N}$

Example Problem 1.3

What is the weight in pound force of an object that has a mass of 4 slugs?

***Solution*:** For this problem, we will use the proportionality constant for US customary units. The weight is calculated using

$$W = \frac{ma}{g_c} = \frac{4\ \text{slug} \cdot 32.17\,\dfrac{\text{ft}}{\text{s}^2}}{1\,\dfrac{\text{slug} \cdot \text{ft/s}^2}{\text{lb}_\text{f}}}$$

Answer: $W = 128.68\ \text{lb}_\text{f}$

1.3 Machines and Mechanisms

1.3.1 Machine versus Mechanism

Before we jump into the concepts of machine analysis, we must first understand the idea of machines versus mechanisms. You may think that there is no real difference between a machine and a mechanism, and you may use the two terms interchangeably. In fact, it can be difficult to properly define a machine or mechanism because there is not really a clear division between the two. A general definition of a mechanism is that it is a fundamental device (or assembly of parts) to produce, transform, or control motion. For example, a mechanism can transform rotary motion to linear motion. Mechanisms will typically develop low forces. A machine can be thought of as a combination or assembly of mechanisms to do work, provide force, or transmit power. Machines have the primary purpose of completing work. A milling machine, as an example, is a manufacturing tool that uses a rotating cutter to remove material. The machine does work, and must provide large amounts of power to cut high-strength alloys. There are numerous mechanisms, or machine elements, within the milling machine. Lead screws, as an example, are machine elements used to transmit rotary motion to linear motion to move the table of the milling machine. The rotary cutter is powered by belts or gears, which allow for variations in operating speed.

1.3.2 Simple Machines

You most likely have been introduced to the simple machines: lever, wheel, pulley, inclined plane, and screw. The only reason to briefly discuss some of them here is to start the foundation of machines and mechanisms. A lot of more complex machines build off these fundamental simple machines. Probably, the most basic machine of all is the lever. A lever is simply a rigid member that rotates about a fulcrum (pivot point) to transmit force to another point. There are three classes of levers. First class levers, as shown in Figure 1.6a, have the fulcrum located between the applied force and the load. They are typically used to provide a mechanical advantage. Pulling a nail with a hammer is an example of first class levers. Second class levers, as shown in Figure 1.6b, have the load located between the fulcrum and the applied force. These levers are again used to provide a mechanical advantage. Every time you use a wheelbarrow, you are taking advantage of a second class lever. If the force is applied between the fulcrum and the load, as shown in Figure 1.6c, it is a third class lever. Third class levers actually lose the mechanical advantage, but they allow for large movement at the load. Third class levers occur frequently in the human body to provide large range of motion.

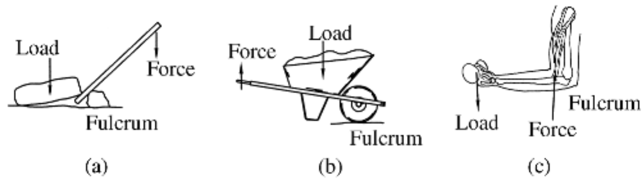


Figure 1.6 Three classes of levers: (a) first class; (b) second class; (c) third class

Though levers can give large mechanical advantage, compound levers can be used to generate the same mechanical advantage in a more compact design. The benefits of compound levers will be illustrated by comparing a simple lever arrangement in Example Problem 1.4 with the modified compound lever arrangement in Example Problem 1.5.

Another simple machine is the inclined plane, as shown in Figure 1.7a. The force required to push the body up the inclined plane will depend on the slope of the inclined plane. The portion of the total load multiplied by the ratio of rise to length of the slope will give the force required. As an example, if the slope length is five times the rise, the force needed will be one-fifth the load. One variation of an inclined plane is a wedge. Wedges do their job by moving, unlike stationary inclined planes. Chisels and hatchets are other common examples of wedges. It will be shown later in this chapter that cam mechanisms utilize the principles of inclined planes and wedges.

If we take the inclined plane and wrap it around a cylinder, we get the basic principle of a screw. There are a wide variety of uses for screw mechanisms. Archimedes used screws to raise water, and screw feeders are still commonly used in material handling. In plastics manufacturing, injection molding machines use a large screw to feed the plastic pellets to the dies. Screw mechanisms are used in tools such as clamps, drills, and presses. A common application in machine analysis is a worm gear, as illustrated in Figure 1.7b. The worm has an inclined plane wrapped in the form of a helix. As the worm spins about its central axis, the mating worm gear turns.

1.3.3 Static Machine Analysis

This text will obviously focus on machines in motion. However, before focusing on the kinematics and kinetics of machines in motion, let us look at how to analyze static forces in machines. The goal is to calculate output forces based on a given set of input forces. Static force analysis is presented here as a brief review and as a means of preparation for dynamic force analysis. It will be seen in Chapter 11 that dynamic force analysis builds off of the concepts of static force analysis. For complex machines, it is necessary to disassemble the machine and create multiple free body diagrams. Because this method is likely review from statics,

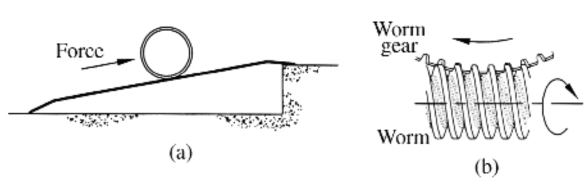


Figure 1.7 (a) Inclined plane. (b) Example of helical inclined plane

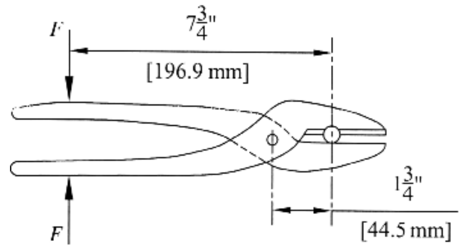


Figure 1.8

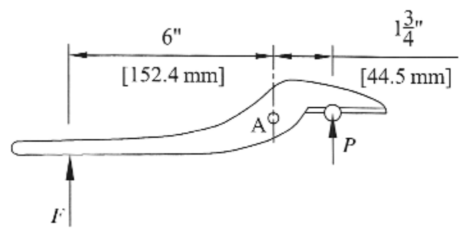


Figure 1.9

the process will be demonstrated in examples. Interested readers can reference engineering statics textbooks for more examples.

Example Problem 1.4

Force is applied to the handles of cutting shears in the location shown in Figure 1.8. Determine the magnitude of cutting force.

***Solution*:** To determine the cutting force, we need to isolate one portion of the cutting shears and draw a free body diagram as shown in Figure 1.9.
Summation of moments about point A gives

$$\sum M_A = 0$$

$$F(6) - P(1.75) = 0$$

$$P = \frac{6}{1.75} F$$

Answer: $P = 3.43F$

Example Problem 1.5

The cutting shears from Example Problem 1.4 are modified using compound levers as shown in Figure 1.10. Determine the magnitude of the cutting force for the applied force shown.

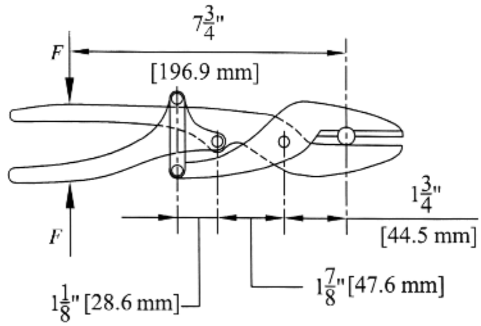


Figure 1.10

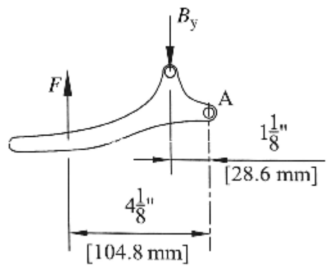


Figure 1.11

***Solution*:** We again separate the mechanism and construct free body diagrams of individual components. Starting with the lower handle shown in Figure 1.11, the summation of moments gives

$$\sum M_A = 0$$

$$F(4.125) - B_y(1.125) = 0$$

$$B_y = \frac{4.125}{1.125}F = 3.67F$$

The force B_y is directed through the two-force member to the upper cutter. From the free body diagram shown in Figure 1.12,

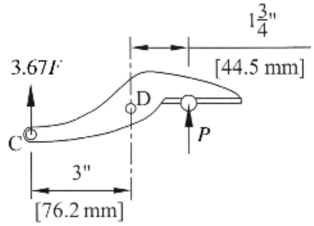


Figure 1.12

$$\sum M_D = 0$$
$$3.67F(3) - P(1.75) = 0$$
$$P = \frac{3.67F(3)}{1.75}$$

Answer: $P = 6.29F$

The previous examples show the benefit of compound linkage mechanisms. Notice that the distance from the applied force to the cutting location remained the same for both examples. The modification to a compound linkage nearly doubled the cutting force.

1.3.4 Other Types of Machines

Obviously, the machines of today utilize more than the simple machines. Many different types of more complex machines exist, but this text will focus on only a few common machine elements. Sections to follow will briefly introduce the basic types of mechanisms covered in this text. Chapters to follow will provide further details needed for analysis and design of such mechanisms. The primary types of mechanisms covered are linkages, gears, and cams. While reading the sections to follow, try to think of actual examples of machines that use these types of mechanisms. The better you can understand the basic uses of these mechanisms, the better start you will have to being able to analyze them in future chapters.

1.4 Linkage Mechanisms

1.4.1 Introduction to Linkage Mechanisms

The first category of mechanism we will examine is linkage mechanisms. Linkage mechanisms will be introduced in this chapter, but Chapters 3–6 focus on the details of linkage mechanisms. In some forms, a linkage mechanism is a set of connected levers (or compound levers) used to provide a specific motion. A link is simply an individual rigid body, which is then interconnected in pairs to form a linkage mechanism. A joint is a point where pairs of links are connected. The complete assembly of links is known as a linkage mechanism or kinematic chain. This text will focus primarily on planar linkage mechanisms, which are mechanisms in which all links in the system move in parallel planes. Another classification would be spatial mechanisms, where the links are not all in parallel planes.

1.4.2 Types of Links

Links are numbered sequentially beginning with one for the stationary link, which typically represents the frame of the mechanism. The stationary link is commonly called the ground link. The driving link is numbered as link 2, and all remaining links are numbered in order. Points of rest are designated with the letter O. For example, in a four-bar linkage mechanism O_2 and O_4 are points of attachment for links 2 and 4, respectively. Link numbering is illustrated in Figure 1.13.

There are different ways to classify link types, but a common method is to classify by the number of connection points (or nodes) it contains. A link with two connection points is referred to as a binary link. Similarly, a ternary link will have three connection points and a quaternary link will have four. Figure 1.14 shows examples of each link type described.

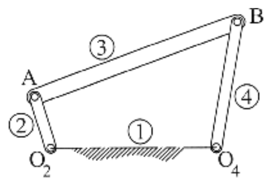


Figure 1.13 Numbering system for a linkage mechanism

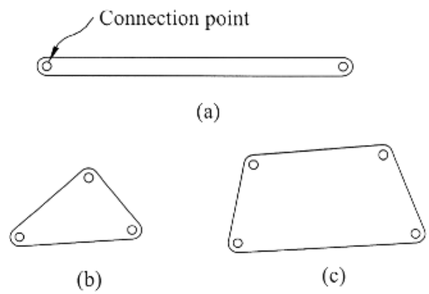


Figure 1.14 Link classification by number of nodes: (a) binary link; (b) ternary link; (c) quaternary link

Links can also be classified by their actual function. Examples of this type of classification will be presented in Section 1.5 during the discussion of common types of linkage mechanisms.

1.4.3 Types of Joints

Now that we have developed a general understanding of links, we can move on to types of joints, which are connections between links. Joints serve the function of controlling relative motion of connected links. Typically, joints, which are also referred to as kinematic pairs, are more confusing to students due to the layers of terminology. Classification of joints is also more confusing than that of links. Joints can be classified by the type of contact, the number of links connected, the method of maintaining joint contact, and the general motion of the joint. One thing to note is that there are several types of joints, but only a few of those are applicable in planar mechanisms. Since this text will focus extensively on planar mechanisms, this section will focus more on the joint types that relate to planar motion. This does not indicate that the others are not important. The other types will be only briefly discussed here (in an attempt to reduce confusion).

Joint types are separated into two major categories known as lower pairs and higher pairs. Lower pairs are joints with surface contact, and higher pairs are joints with point or line contact. Of the six lower pairs, only two apply to planar mechanisms. Figure 1.15 illustrates the two lower pairs significant for planar mechanisms. The first is known as a revolute joint, which is commonly designated by the symbol R. A revolute joint, as shown in Figure 1.15a, can be thought of as a basic hinge joint or pin joint. The second lower pair that applies to planar mechanisms is the prismatic pair, designated by the symbol P. A prismatic pair, as shown in Figure 1.15b, is a sliding joint constrained to move in one linear direction without rotation.

The remaining four lower pairs, which are illustrated in Figure 1.16, do not apply to planar mechanisms due to the fact that the resulting motion is three dimensional. The helical joint

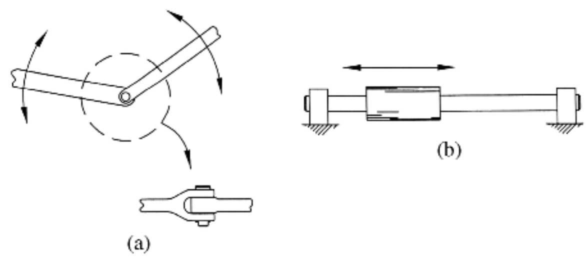


Figure 1.15 Lower pairs usable in planar mechanisms: (a) revolute joint; (b) prismatic joint

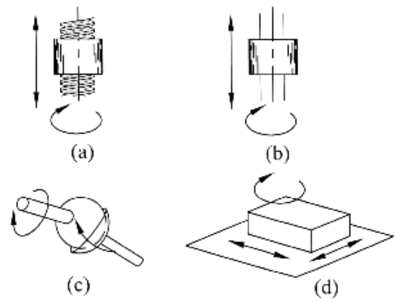


Figure 1.16 Lower pairs for spatial mechanisms: (a) helical joint; (b) cylindrical joint; (c) spherical joint; (d) planar joint

shown in Figure 1.16a is a linear screw allowing rotation and linear translation (yet the two motions are constrained by the pitch of the screw). A cylindrical joint, as shown in Figure 1.16b, is allowed to translate in a linear direction and rotate about its axis. Figure 1.16c shows a spherical joint, which is a ball and socket joint. A planar joint, as illustrated in Figure 1.16d, is like a block moving freely on a plane and allows motion in the Cartesian x–y plane and rotation about the z-axis.

The lower pairs for planar mechanisms shown in Figure 1.15 are both one-degree-of-freedom joints. Revolute joints only allow one angular rotation and prismatic joints only allow translation in one axial direction. Although the helical joint is not a joint used in planar mechanisms, it also is a one-degree-of-freedom joint because the angular motion and translation are constrained by the pitch of the helix. The cylindrical joint is a two-degree-of-freedom joint allowing independent rotation and translation. The spherical joint and planar joint are both three-degree-of-freedom joints.

1.5 Common Types of Linkage Mechanisms

The number of possible arrangements of links in a linkage mechanism is only limited by the imagination. However, many common applications can be achieved with basic four-bar linkage mechanism (the four bars are the fixed ground link and three moving links). More complicated linkage mechanisms are commonly built using a four-bar mechanism to drive others. Some mechanisms that have a physical form different from a typical four-bar mechanism can be modeled as an equivalent four-bar mechanism. Because of their frequent use and wide variety of applications, discussion of linkage mechanisms in this text will focus heavily on four-bar

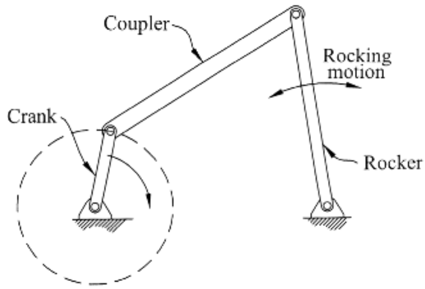


Figure 1.17 Crank–rocker mechanism

mechanisms. Some special configurations of four-bar mechanisms have been given names because they occur so frequently. Some of those common configurations will be briefly defined here, though more detail will be given in future chapters.

1.5.1 Crank–Rocker Mechanisms

The general four-bar mechanism can have many configurations. However, different names exist for the configurations based on the range of motion of links 2 and 4. Chapter 3 will further examine the different configurations. The configuration we will examine in this section is known as a crank–rocker mechanism, which is shown in Figure 1.17. The title of this mechanism comes from the fact that the driving link (link 2) is called a crank and the output link (link 4) is called a rocker. Link 3 is a floating link that connects the driver to the output and is commonly called the coupler. The term crank signifies that the driving link will complete a full revolution relative to the ground link. Typically, the crank will move in a continuous rotating motion at a constant rotational speed. The term rocker signifies that the output link oscillates in a rocking motion and is unable to complete a full revolution.

Crank–rocker mechanisms have many common applications. One very common application would be the mechanism used to move windshield wipers. The wipers are driven by a motor that causes the crank to continually rotate. The blade then moves with the output link in a rocking motion.

1.5.2 Slider–Crank Mechanisms

The next category of linkage mechanisms discussed is a slider–crank mechanism, which is shown in Figure 1.18. A slider–crank mechanism is a special case of a four-bar mechanism. The input link (link 2) is again a crank and moves in a continuous rotation. The output is now a sliding block, called a slider or piston, and is constrained to oscillate in a pure straight line

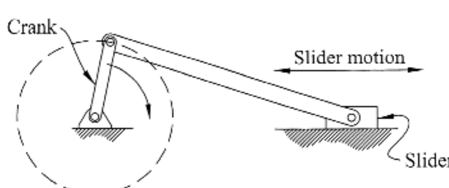


Figure 1.18 Slider–crank mechanism

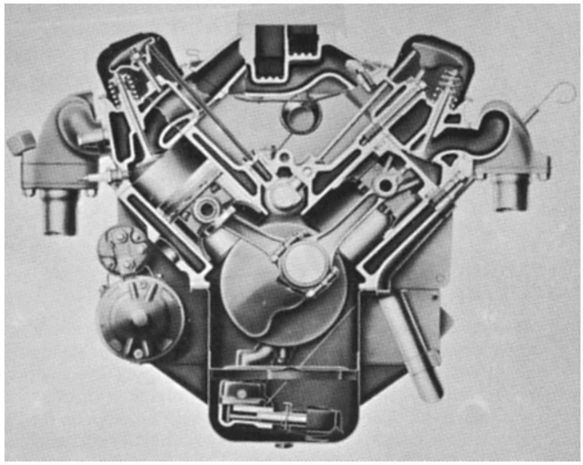


Figure 1.19 Chevrolet V8 engine showing slider–crank mechanism. Reproduced from Mabie and Reinholtz, Mechanisms and Dynamics of Machinery, 4th edition, John Wiley & Sons. © 1987

motion. The link connecting the crank to the slider (link 3) is commonly known as the connecting rod but the name often changes depending on the application.

Common applications of slider–crank mechanisms include reciprocating engines and compressors. Figure 1.19 shows slider–crank mechanisms in a V8 engine.

1.5.3 Toggle Mechanisms

Toggle mechanisms generate large forces through a short distance and are commonly used in clamps and crushers. The toggle mechanism shown in Figure 1.20a is a multilink mechanism

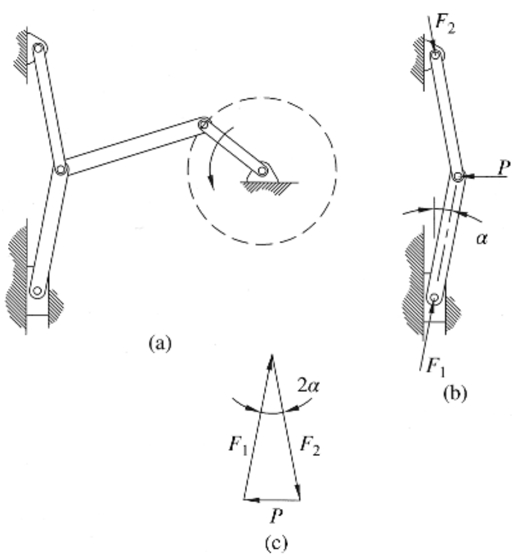


Figure 1.20 (a) Toggle mechanism. (b) Forces. (c) Force polygon

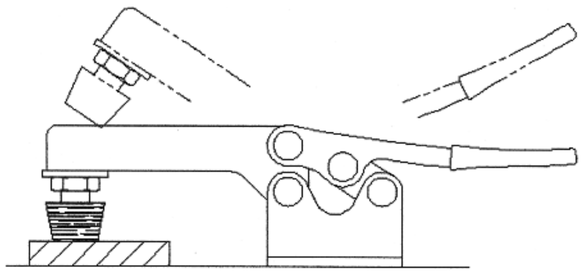


Figure 1.21 Toggle clamp

combining the four-bar crank–rocker mechanism and the slider–crank mechanism. The slider–crank portion is shown separated in Figure 1.20b to better illustrate the force magnification. A force P applied as shown will cause reaction forces F_1 and F_2. Figure 1.20c shows a force polygon.

From the force polygon, it can be seen that

$$\sin\alpha = \frac{P/2}{F_1}$$

$$F_1 = \frac{P}{2\sin\alpha} \tag{1.10}$$

From Equation 1.10, it can be seen that as α approaches zero the force F_1 approaches infinity. Therefore, toggle mechanisms can generate a large output force for a relatively small input force. A very common application of a toggle mechanism is a toggle clamp, such as the one shown in Figure 1.21.

1.5.4 Quick Return Mechanisms

Quick return mechanisms come in many forms, but all have the same fundamental goal. Commonly, mechanisms are developed to do work, and the cycle of motion can be separated into a working stroke and a return stroke. Mechanisms can be designed such that the time required for the working stroke equals that of the return stroke. Quick return mechanisms, as the name implies, are mechanisms that have a return stroke that is faster (takes less time) than the working stroke. The faster return occurs due to the geometry of the mechanism and occurs even with a constant input speed. The time ratio is the ratio of input displacement during the work stroke to the input displacement during the return stroke.

Several mechanism types can have a quick return. A slight adjustment to the slider–crank mechanism shown in Figure 1.18 such that the crank center of rotation is offset from the centerline of the slider (known as an offset slider–crank mechanism) will make a quick return mechanism. Offset slider–crank mechanisms and other types of quick return mechanisms will be explored further in Chapter 5.

1.5.5 Straight Line Mechanisms

The next class of linkage mechanism is in which a point on the mechanism generates a straight line motion, which sounds like a very simple task. A mechanism that converts rotary motion

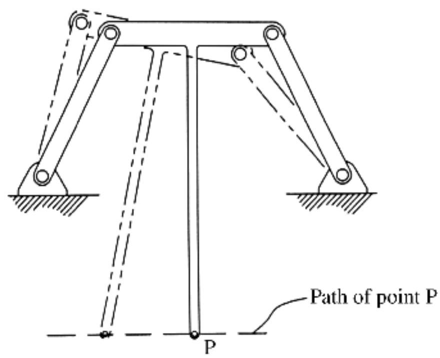


Figure 1.22 Straight line mechanism

to a straight line motion (over a limited interval) is known as a straight line mechanism. Developing a machine to generate a straight line is rather complex, and they developed throughout history. In early development of the steam engine, it was required for parts, such as piston rods, to move in a straight line. Many configurations have been developed and most only generate an approximate straight line due to the fact that exact straight line mechanisms are very complicated to design. Figure 1.22 shows one example of a straight line mechanism in which point P moves along the straight line path shown.

1.5.6 Scotch Yoke Mechanism

A scotch yoke mechanism, as shown in Figure 1.23, has the same fundamental objective of the slider–crank mechanism discussed in Section 1.5.2. The scotch yoke is a basic mechanism that converts rotary motion into reciprocating linear motion using a pin in a moving slot.

An application for this mechanism is to open and close valves. The crank is connected to the slider by the pin, and as the crank turns the pin it moves the slider. Though the goal of the slider–crank and scotch yoke mechanisms is the same, their performance differs slightly. The scotch yoke mechanism will generate perfect simple harmonic motion (sine wave), whereas the slider–crank mechanism will produce a slightly distorted sine wave. Because the output is simple harmonic motion, the scotch yoke mechanism is commonly used in testing equipment to simulate simple harmonic vibration. A major disadvantage to a scotch yoke mechanism is the high contact pressure and wear.

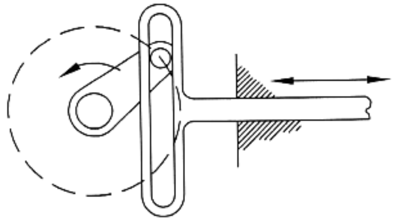


Figure 1.23 Scotch yoke mechanism

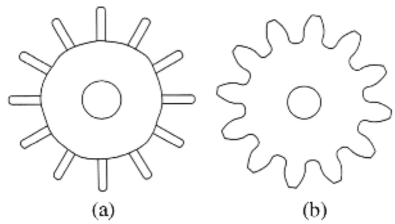


Figure 1.24 (a) Early gears with peg teeth. (b) Modern gears with involute teeth

1.6 Gears

1.6.1 Introduction to Gears

From its first discovery, very primitive man made many uses of the wheel. Eventually, wheels developed to more efficient forms including a solid wheel with a separate axle. Many other ideas, such as gears, sparked from the basic concepts of a wheel and axle. In very early development of gears, they were simply wheels with peg teeth, such as those shown in Figure 1.24a. Though the peg teeth served a useful purpose, these early gears did not operate smoothly due to nonuniform velocity transmission. Other tooth shapes were eventually developed to improve the performance of gears. Modern gears have a gear tooth shape of a complex involute curve, such as the one shown in Figure 1.24b. Chapter 7 will cover development of the involute curve as well as the interaction between mating gears.

The most basic definition of gears would be that they are toothed wheels used to transmit power. However, gears can accomplish much more. Gear sets have numerous applications, including automotive, aircraft, agricultural equipment, marine equipment, and manufacturing. Gear sets vary drastically in size. High-power applications, such as the gearbox shown in Figure 1.25, require very large gear sets. Smaller sets are used in hand tools, such as the one shown in Figure 1.26, to change speed.

Gears will be discussed in detail in Chapters 7 and 8. Chapter 7 will focus on gear geometry and terminology, while Chapter 8 will focus on combining gears into gear trains. There are

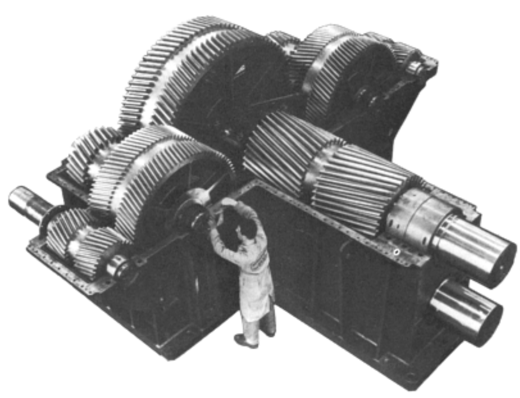


Figure 1.25 Example of a large power transmission gear unit. Reproduced from Michalec, Precision Gearing Theory and Practice, John Wiley & Sons, © 1966

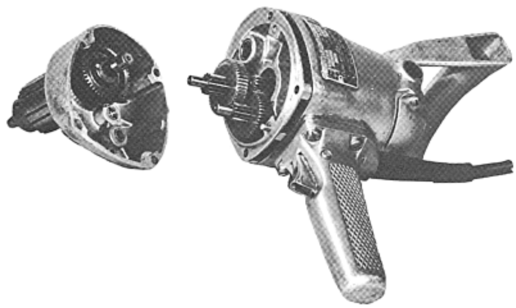


Figure 1.26 Gear application. Reproduced from Michalec, Precision Gearing Theory and Practice, John Wiley & Sons, © 1966

several types of gears, but one major factor for choosing the appropriate gear would be the relative shaft positions. The two major shaft arrangements would be parallel and intersecting; though intersecting should be further divided into perpendicular and skewed.

1.6.2 Spur Gears

The first type of gear to be discussed will be spur gears. Spur gears are very common and have the simplest geometry. The easiest way to think of the function of two spur gears in contact is to think of two rolling cylinders in contact, as shown in Figure 1.27a. One cylinder would turn and drive the mating cylinder. If the cylinders have different diameters, there would be a speed difference between the two cylinders. One major disadvantage of having two rolling cylinders in contact would be the large potential of slipping between the two cylinders. Adding teeth to the cylinders will create spur gears, as shown in Figure 1.27b. The teeth eliminate this slip problem causing positive rolling contact. The driving gear, often called the pinion, will rotate in the opposite direction of the driven gear. The ratio of speeds of the two gears will depend on the number of teeth on the two gears, which will be discussed in detail in Chapter 7.

Spur gears have teeth that are parallel to the axis of rotation and they connect parallel shafts. Properly aligned spur gears will not produce end thrust. The pinion and gear will rotate in opposite directions if both have external teeth, or will rotate in the same direction if the gear has internal teeth.

Gears are standardized, which allows for interchangeability and less expensive manufacturing. Hobbing, which is illustrated in Figure 1.28, is a common process for producing spur gears. The cylindrical cutter (hob), as shown in Figure 1.28a, cuts the teeth in the gear blank. Figure 1.28b shows a hobbing operation, which is a special milling operation to progressively cut the gear teeth.

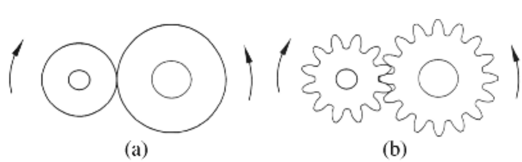
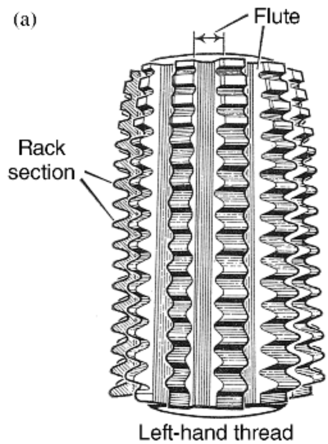


Figure 1.27 (a) Rolling cylinders. (b) Spur gears



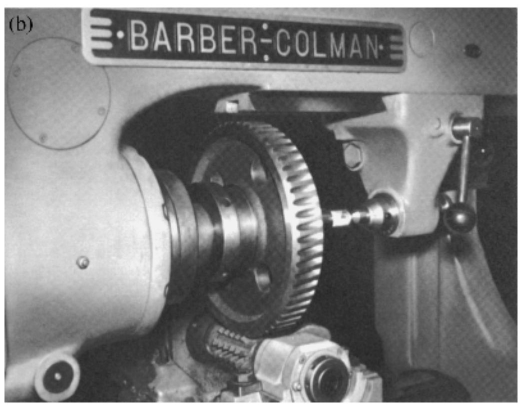


Figure 1.28 (a) Cutting hob. (b) Hobbing a spur gear. Reproduced from Mabie and Reinholtz, Mechanisms and Dynamics of Machinery, 4th edition, John Wiley & Sons, © 1987

1.6.3 Helical Gears

Though spur gears are very useful, they do have limitations. Spur gears will tend to be noisy due to the abrupt contact of the gear teeth. An improvement could be made by staggering the teeth, such as the layout shown in Figure 1.29b. A helical gear is developed as the individual spur gears within the staggered set approach zero thickness.

Helical gears are similar to spur gears in overall function. Unlike spur gears, the teeth on helical gears are cut at an angle to the gear's axis of rotation. Though the details will be presented in later chapters, the angled teeth allow for smoother operation and higher speeds. The trade-off for better performance is higher manufacturing costs.

Helical gears are extremely versatile and can be used in parallel or intersecting shaft arrangements. A parallel arrangement is shown in Figure 1.29a and an intersecting shaft arrangement is shown in Figure 1.29d. Helical gears tend to push apart, or exert a side thrust. One method of compensating for the side thrust is to combine two helical gears with opposite helical angles. Such a gear is known as a herringbone and is shown in Figure 1.29c. The hobbing process for a helical gear is shown in Figure 1.30.

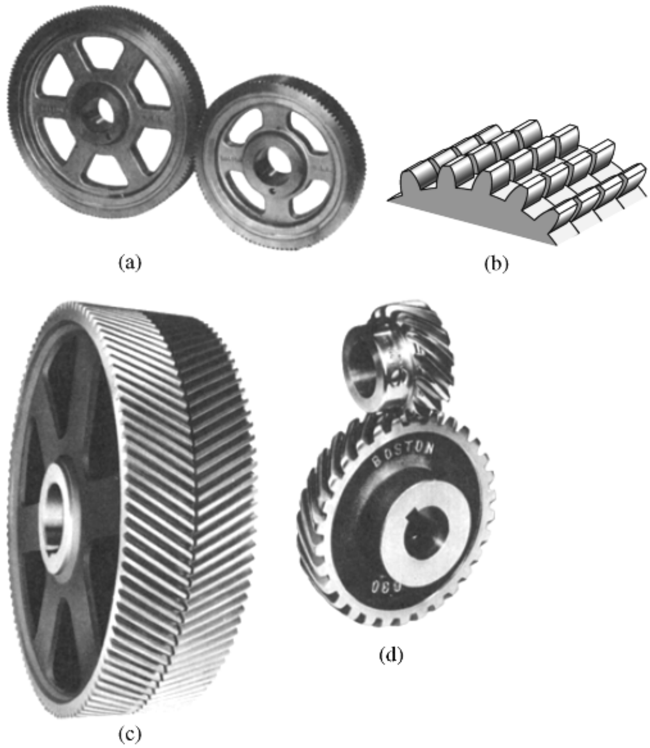


Figure 1.29 Types of helical gears: (a) mounted on parallel shafts (most common type), gears have helices of opposite hand; (b) rotated spur gear laminations approach a helical gear as laminations approach zero thickness; (c) double helical or herringbone gears may or may not have a center space, depending on manufacturing method; (d) when mounted on nonparallel shafts, they are crossed helical gears, and usually have the same hand. ((a, d) Courtesy Boston Gear; (c) courtesy Horsburgh & Scott.) Reproduced from Juvinall and Marshek, Machine Component Design, 5th edition, John Wiley & Sons, © 2011

1.6.4 Bevel Gears

Bevel gears are an efficient means of transmitting power in intersecting shaft arrangements. Bevel gears connect shafts typically intersecting at 90° angles, although other angles are possible. The simplest way to visualize the interaction of bevel gears is to consider two cones in contact.

There are three types of bevel gears, as illustrated in Figure 1.31. The simplest type is a straight bevel, shown in Figure 1.31a. Spiral bevels, shown in Figure 1.31c, have curved teeth and allow for higher speeds. Spiral bevel gears have two or more teeth in contact at all times, which lowers tooth loading. The teeth engage more gradually than straight bevel gears, which cause quieter operation. Hypoid bevel gears, such as the set shown in Figure 1.31e, keep the benefits of spiral bevels but allow the drive shaft to be set lower.

Bevel gears can be used for speed reduction, but sometimes they are used to simply transmit power between intersecting shafts. Therefore, a 1 : 1 ratio is fairly common. Figure 1.31b shows a bevel gear set with no change in speed.

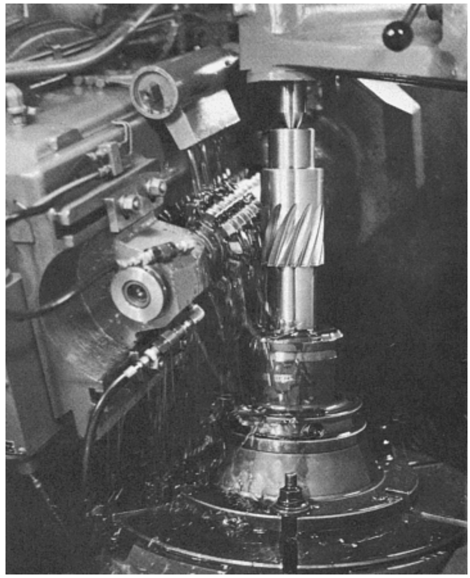


Figure 1.30 Hobbing a helical gear. Reproduced from Mabie and Reinholtz, Mechanisms and Dynamics of Machinery, 4th edition, John Wiley & Sons, © 1987

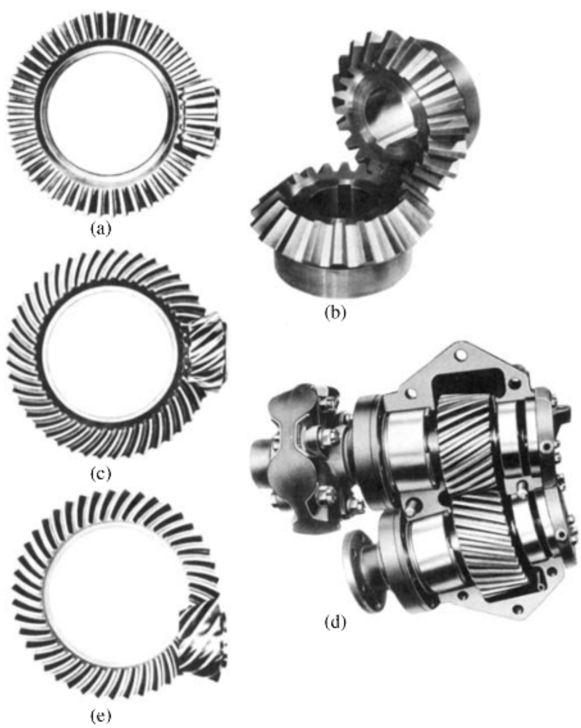


Figure 1.31 Types of bevel gears: (a) straight-tooth bevel gears; (b) straight-tooth bevel gears; special case of miter gears (1:1 ratio); (c) spiral bevel gears; (d) bevel gears mounted on nonperpendicular shafts; (e) hypoid gears. ((a, c, d, e) Courtesy Gleason Machine Division; (b) courtesy Horsburgh & Scott.) Reproduced from Juvinall and Marshek, Machine Component Design, 5th edition, John Wiley & Sons, © 2011

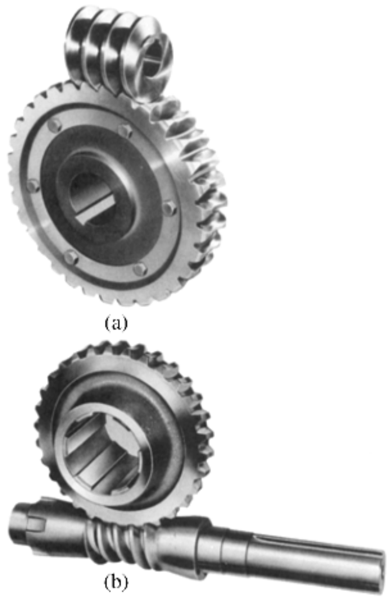


Figure 1.32 Worm gear sets: (a) single enveloping; (b) double enveloping. ((a) Courtesy Horsburgh & Scott; (b) courtesy Ex-Cell-O Corporation, Cone Drive Operations.) Reproduced from Juvinall and Marshek, Machine Component Design, 5th edition, John Wiley & Sons, © 2011

1.6.5 Worm Gears

Another common gearing for right angle shaft arrangements is worm gears. Worm gears allow for very high reduction ratios compared with other gearing systems. A worm gear set, such as those shown in Figure 1.32, consists of a worm meshing with a worm gear. The worm is essentially a threaded screw, and the worm gear can be thought of as a special helical gear.

Worm gear sets are commonly used in speed reducers, as shown in Figure 1.33, because they can have very large reductions in speed. A large concern with worm gear sets would be heat generation. The speed reducer shown also has fins to increase heat transfer.

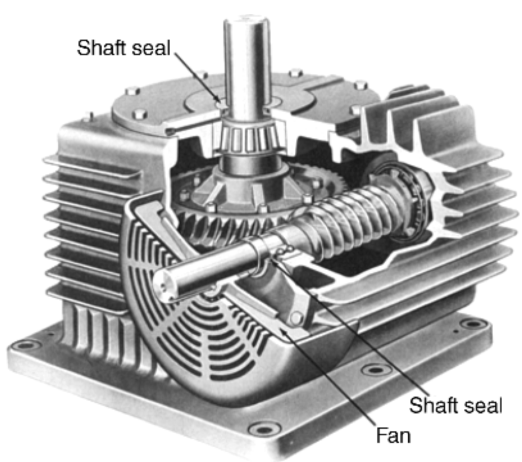


Figure 1.33 Worm gear speed reducer. (Courtesy Cleveland Gear Company.) Reproduced from Juvinall and Marshek, Machine Component Design, 5th edition, John Wiley & Sons, © 2011

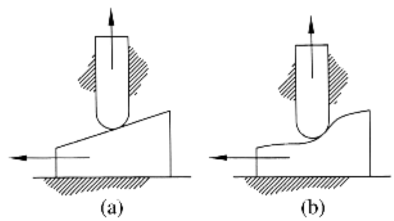


Figure 1.34 Basic concept of a cam: (a) simple wedge; (b) complex wedge

1.7 Cams

1.7.1 Introduction to Cams

Cam mechanisms are another major class of mechanisms and are used to develop nonuniform motion. In its basic form, a cam can be thought of as a specifically shaped wheel that causes a defined motion of a follower. Most commonly, cams are used to cause follower motion that is complex and accurately timed. As will be seen in later chapters, cam design often requires specific constraints on velocity and accelerations, which become more critical at high-speed operation.

In their most basic form, cams can be thought of as a specialized wedge. Figure 1.34a shows a simple wedge being moved horizontally along a flat surface. As the wedge moves to the left, it will push the rod above it upward. The surface of the wedge could be more complex, such as that shown in Figure 1.34b, so that the motion of the rod is in a very specific fashion. In the language of cam mechanisms, the wedge is the cam and the rod is a follower. The cam surface will typically describe a mathematical function so that the follower moves in the required fashion.

For practical purposes, cams will not be simple wedges. Cam mechanisms come in a wide variety of shapes, but a couple of the most common types are introduced below.

1.7.2 Disk Cams

Probably, the most common type of cam in use would be disk cams (sometimes called radial cams). To get a general understanding of a disk cam, we will continue the basic wedge concept from Figure 1.34. The wedge shown in Figure 1.35a has a similar concept but it now causes

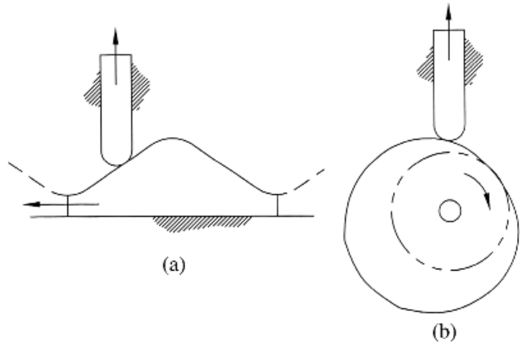


Figure 1.35 (a) Wedge for a rise and fall motion. (b) Wedge profile wrapped around a circle

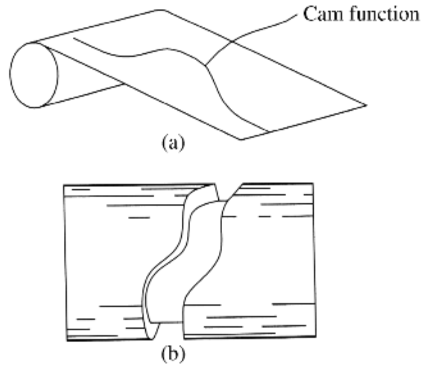


Figure 1.36 (a) Wrapping the cam function around the cylinder. (b) Drum cam

a very specific type of motion. If the wedge were moved to the left, it would cause the follower to rise and then fall back to its original position. We could have that motion continue by constantly moving the wedge to the left and right, though that is not very convenient, or by having several wedges lined up in a row (as shown). To make the continuous motion more practical, we take the top profile of the wedge and wrap it around a circle as shown in Figure 1.35b. That circular disk, known as a disk cam, can now rotate at a constant speed and cause the desired continuous rise and fall of the follower.

Obviously, the wedge profile can become far more complex to get nearly any desired motion of the follower. The profile is generally defined by a mathematical expression. The mathematical expression must be carefully picked to ensure proper follower motion as well as safe acceleration values. Chapter 9 will cover many common mathematical functions used in cam design and describe procedures for "wrapping" that function around the circle to create the disk cam geometry.

1.7.3 Cylindrical Cams

The basic structure of a cylindrical cam (also called a drum cam or barrel cam) uses a groove cut around the periphery of a cylinder. Figure 1.36a shows the idea of wrapping the mathematical cam function around a cylinder. The figure shows the cam function, which would be rolled around the cylinder. The result is a cylindrical cam such as the one shown in Figure 1.36b. The layout design process for a cylindrical cam is generally simple compared with disk cams because the cam function can theoretically be drawn on a paper template and rolled around a cylinder. The transfer of the cam function onto a disk cam is more complex and causes distortion. Figure 1.37 shows the process of cutting a cylindrical cam.

1.8 Solution Methods

Throughout the text several methods will be introduced for analyzing machine elements. Each method will provide specific advantages and disadvantages. Often a designer will utilize more than one method within a particular design process, so it is important to be familiar with several solution methods. The three common methods for this text will be graphical, analytical, and computer solution methods.

Figure 1.37 Cutting a cylindrical cam

1.8.1 Graphical Techniques

Graphical techniques often have the advantage of being quick and simple, especially for developing initial designs. As an example, it is often desired to design a linkage mechanism to perform a very specific task. Graphical techniques can be utilized easily to develop several possible configurations. Once an arrangement has been designed, it may be desirable to move to other solution methods to refine the mechanism.

Velocity and acceleration analysis can often be done graphically with the use of vector polygons. If drawn by hand, the polygons can provide a quick solution at a lower level of accuracy. Polygons can also be generated in CAD software at a higher level of accuracy.

Graphical techniques offer other advantages. One is that most machine analysis work will require creating drawings of the machine elements. Graphical techniques can often be done in conjunction with the drawing process. Another advantage is that graphical techniques are very visual, which can aid in understanding the solution.

1.8.2 Analytical Methods

Analytical methods require the development and solution of equations, making them the most familiar to engineering students. An obvious advantage of analytical methods over graphical methods would be improved accuracy. There are instances, however, when analytical methods are tedious or excessively complex. It can often be beneficial to use a combination of graphical and analytical methods.

1.8.3 Computer Solutions

The last solution method discussed includes the use of computer software. Machine analysis problems often become repetitive. Development of a simple computer code can greatly aid in the repetitive calculations. It is often desired to have solutions for several positions of a mechanism, and developing these solutions analytically can be very time consuming. Therefore, it is common to use computers to solve for velocity, acceleration, and forces in a mechanism through the complete range of motion for that mechanism.

Even though commercial software is available, it is fairly straightforward for an individual to develop solutions in spreadsheets or computer programs such as MathCAD or MATLAB®. Because of the major advantages of utilizing computers for mechanism analysis, this book will focus on not only the underlying theory but also how to develop computer code to solve for a wide variety of mechanisms. Chapter 6, as an example, will focus almost entirely on computer solution methods for linkage mechanisms.

It would be of limited use to develop a computer code to solve only one mechanism arrangement. For example, developing a computer code that only analyzes slider–crank linkage mechanisms would be less useful than a code to solve any arrangement of a four-bar linkage mechanism. To make computer code more versatile, the methodology for solving kinematics of mechanisms using computers is often quite different from the methods for solving kinematics analytically. Computer methods often take advantage of numerical optimization methods.

1.9 Methods of Problem Solving

1.9.1 Step 1: Carefully Read the Problem Statement

Most students do not like story problems. In essence, all engineering problems are just story problems. The critical first step is to carefully read the problem statement and completely understand the problem. Read the problem statement two or three times if necessary, but do not move on to step 2 until you completely understand the problem statement.

1.9.2 Step 2: Plan Your Solution

It is very important to think about the solution process required for the problem. Do not just start writing down equations aimlessly looking for one that may work. One of the biggest mistakes students make is that they memorize solution steps to certain styles of problems. Do not memorize solution procedures! Instead, understand how to plan the solution to any type of problem. Memorizing solution procedures may make you successful on homework problems, but it is most likely setting you up for failure on exams. Most professors will not write exam questions that are extremely similar to homework problems. You must be able to plan a solution to any style of problem to be really successful.

1.9.3 Step 3: Solve the Problem

Obviously, this is a critical step. However, it is important to understand that you need to solve the problem in a way to help ensure success. Solve the problem neatly and following your solution plan developed in step 2. Keep your work as organized as possible. Well-organized work will help you review problems later and will help your professor understand your thought process. Draw figures when necessary (as neatly as possible) because figures will definitely help you visualize the problem.

1.9.4 Step 4: Read the Problem Statement Again

This is a very important step that is often ignored. Once the problem is solved, read the problem statement again. The main purpose would be to verify that you solved everything asked for in the problem statement. This is also a good time to make sure that you included the proper units on you answers.

1.10 Review and Summary

This chapter served as a general introduction into the field of machine analysis and to illustrate the importance of machine analysis. Machines are continually becoming more complex requiring a deeper knowledge of machine theory. The remaining chapters will be discussing details of the different types of mechanisms introduced in this chapter. Therefore, a primary purpose of this chapter was to develop the common terms and basic types of mechanisms.

Problems

P1.1 Make a list of machines you use during the next week. Write a brief description of the machine.

P1.2 Human factors engineering, which focuses on aspects of the interface between man and machines, is an important aspect of machine design. Discuss issues such as safety, comfort, and efficiency that must be considered in machine design. Give specific examples of machines with good and poor human factors engineering.

P1.3 Research a topic of interest related to a machine failure. Discuss the cause(s) of the failure. How could the design have been changed to reduce the risk of the failure?

P1.4 For each of the linkage mechanisms shown in Figure 1.38, identify all missing link numbers and attachment points. Label each link by the number of connection points (binary, ternary, or quaternary).

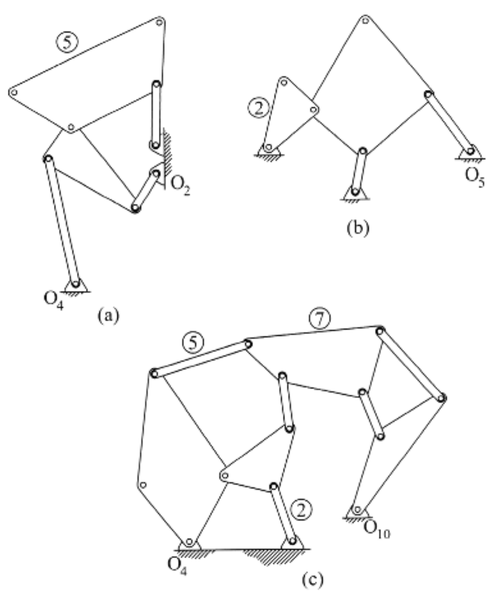


Figure 1.38

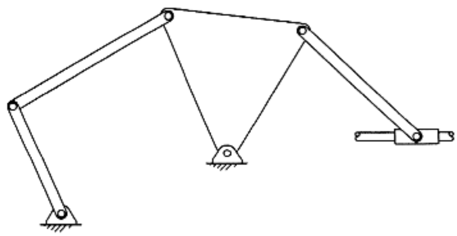


Figure 1.39

P1.5 For the linkage mechanism shown in Figure 1.39, identify all revolute and prismatic joints.

P1.6 Find four applications of a crank–rocker mechanism. Describe the application of each and draw a simplified diagram of each mechanism.

P1.7 Research slider–crank mechanisms and scotch yoke mechanisms. Discuss the similarities and differences between each.

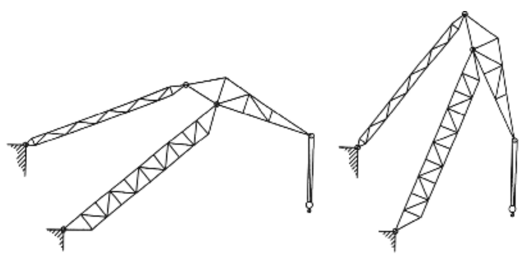


Figure 1.40

P1.8 Figure 1.40 shows a level luffing crane, which is an application of an approximate straight line four-bar mechanism. The crane allows for horizontal motion of the hook while it maintains an approximately constant elevation. Research the function of the level luffing crane and summarize your findings.

P1.9 Research different types of straight line mechanisms, such as Watt's mechanism and Robert's mechanism. Discuss the advantages and disadvantages of each type.

P1.10 Research applications of the different gear systems discussed in this chapter. Write a summary of your findings.

P1.11 Explain why helical gears provide smoother motion compared with spur gears.

P1.12 Research applications of the different cam systems discussed in this chapter. Write a summary of your findings.

P1.13 The two mechanisms shown in Figure 1.41 both convert rotary motion to linear oscillating motion of slider B. Figure 1.41a shows a traditional slider–crank

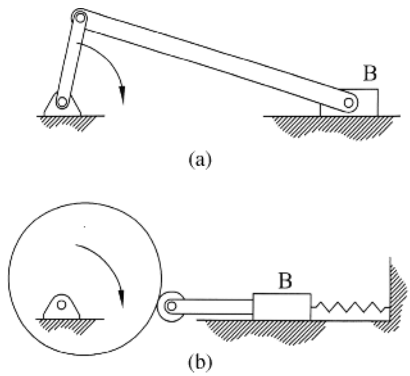


Figure 1.41

mechanism and Figure 1.41b uses an eccentric cam. Discuss similarities and differences of the motion of slider B for each arrangement.

Further Reading

Paz, E.B., Ceccarelli, M., Otero, J.E., and Sanz, J.M. (2010) *A Brief Illustrated History of Machines and Mechanisms*, Springer, New York.