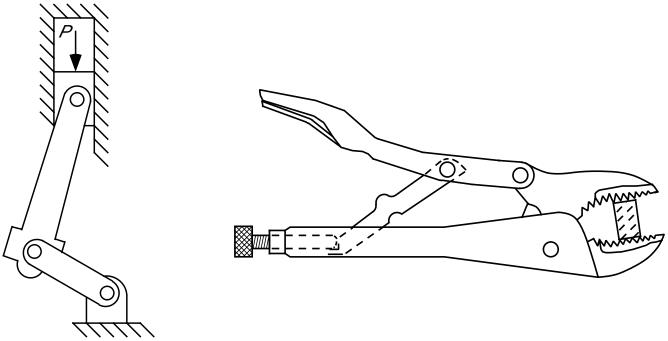
CHAPTER 1

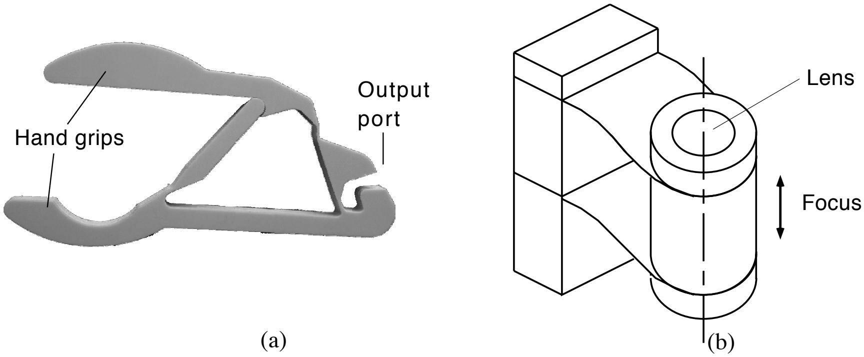
INTRODUCTION

A mechanism is a mechanical device used to transfer or transform motion, force, or energy [1, 2]. Traditional rigid-body mechanisms consist of rigid links connected at movable joints; the section of a reciprocating engine shown in Figure 1.1a is an example. The linear input is transformed to an output rotation, and the input force is transformed to an output torque. As another example, consider the Vise Grip pliers shown in Figure 1.1b. This mechanism transfers energy from the input to the output. Since energy is conserved between the input and output (neglecting friction losses), the output force may be much larger than the input force, but the output displacement is much smaller than the input displacement. Like mechanisms, structures may also consist of rigid links connected at joints, but relative rigid-body motion is not allowed between the links.



(a) (b)

Figure 1.1. Examples of rigid-link mechanisms: (a) part of a reciprocating engine, and (b) Vise Grip.



(a) (b)

Figure 1.2. Examples of compliant mechanisms: (a) crimping mechanism (from [3]), and (b) parallel-guiding mechanism.

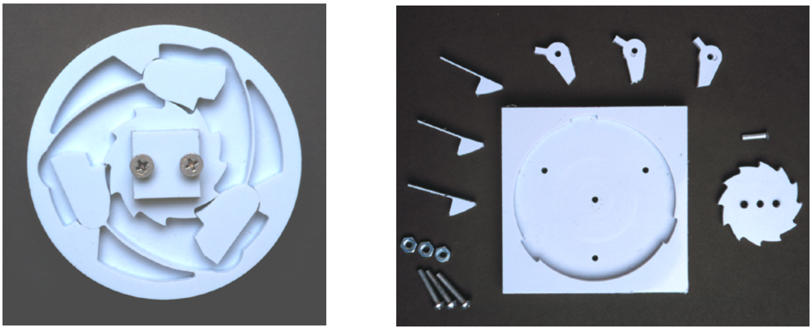
A compliant mechanism also transfers or transforms motion, force, or energy. Unlike rigid-link mechanisms, however, compliant mechanisms gain at least some of their mobility from the deflection of flexible members rather than from movable joints only. An example of a compliant crimping mechanism is shown in Figure 1.2a. The input force is transferred to the output port, much like the Vise Grip, only now some energy is stored in the form of strain energy in the flexible members. Note that if the entire device were rigid, it would have no mobility and would therefore be a structure. Figure 1.2b shows a device that also requires compliant members to focus a lens [4, 5].

1.1 ADVANTAGES OF COMPLIANT MECHANISMS

Compliant mechanisms may be considered for use in a particular application for a variety of reasons. The advantages of compliant mechanisms are considered in two categories: cost reduction (part-count reduction, reduced assembly time, and simplified manufacturing processes) and increased performance (increased precision, increased reliability, reduced wear, reduced weight, and reduced maintenance).

An advantage of compliant mechanisms is the potential for a dramatic reduction in the total number of parts required to accomplish a specified task. Some mechanisms may be manufactured from an injection-moldable material and be constructed of one piece. For example, consider the compliant overrunning clutch shown in Figure 1.3a [6, 7] and its rigid-body counterpart shown in Figure 1.3b. Considerably fewer components are required for the compliant mechanism than for the rigid mechanism. The reduction in part count may reduce manufacturing and assembly time and cost. The compliant crimping mechanism and its rigid-body counterpart illustrated in Figure 1.4 are other examples of part reduction.

Compliant mechanisms also have fewer movable joints, such as pin (turning) and sliding joints. This results in reduced wear and need for lubrication. These are valuable characteristics for applications in which the mechanism is not easily accessible, or for operation in harsh environments that may adversely affect joints.



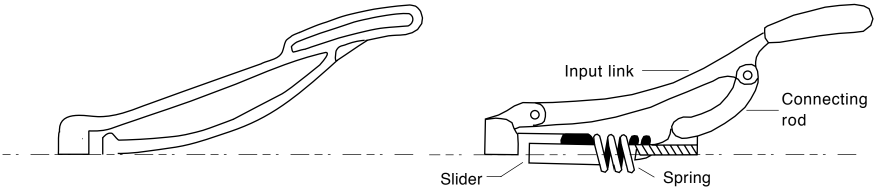
(a) (b)

Figure 1.3. (a) Compliant overrunning clutch, and (b) its rigid-body counterpart shown disassembled. (From [6] and [7].)

Reducing the number of joints can also increase mechanism precision, because backlash may be reduced or eliminated. This has been a factor in the design of high-precision instrumentation [8, 9]. An example of a high-precision compliant mechanism is shown in Figure 1.5. Because the motion is obtained from deflection rather than by adjoining parts rubbing against each other, vibration and noise may also be reduced.

An example of a compliant mechanism designed for harsh environments is shown in Figure 1.6. This simple gripping device holds a die (such as a computer chip) during processing. The die must be transported between several different chemicals without becoming damaged. Made of Teflon—inert to the chemicals in which it is placed—the gripper holds the die without external force.

Because compliant mechanisms rely on the deflection of flexible members, energy is stored in the form of strain energy in the flexible members. This stored energy is similar to the strain energy in a deflected spring, and the effects of springs may be integrated into a compliant mechanism's design. In this manner, energy can easily be stored or transformed, to be released at a later time or in a different manner. A bow-and-arrow system is a simple example. Energy is stored in the limbs as the archer draws the bow; strain energy is then transformed to the kinetic energy of



(a) (b)

Figure 1.4. (a) Compliant crimping mechanism developed by AMP Inc., and (b) its rigid-body counterpart . Because of symmetry, only half the mechanism is shown. (From [4].)

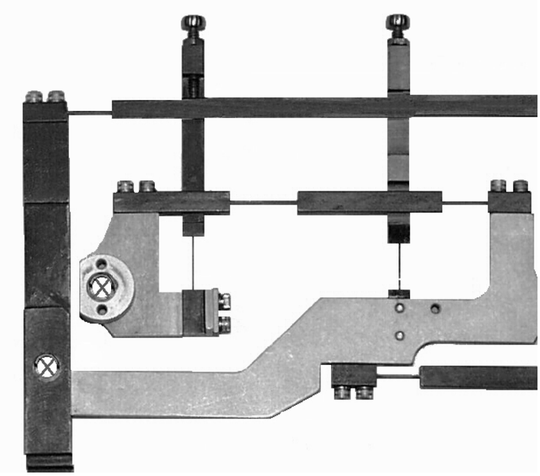


Figure 1.5. Example of a high-precision compliant mechanism.

the arrow. These energy storage characteristics may also be used to design mechanisms that have specific force–deflection properties, or to cause a mechanism to tend to particular positions. For example, the mechanism shown in Figure 1.7 is a robot end effector that was designed to have a constant output force regardless of the input displacement.

It is possible to realize a significant reduction in weight by using compliant mechanisms rather than their rigid-body counterparts. This may be a significant factor in aerospace and other applications. Compliant mechanisms have also benefited companies by reducing the weight and shipping costs of consumer products.

Figure 1.6. Compliant die grippers used to hold a die during process in several different harsh chemicals.

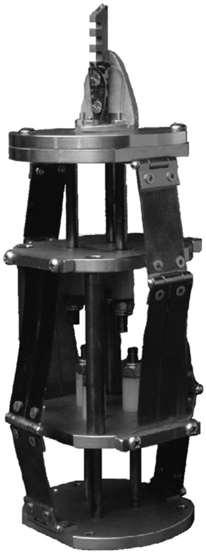


Figure 1.7. Compliant constant-force robot end effector.

Another advantage of compliant mechanisms is the ease with which they are miniaturized [10–19]. Simple microstructures, actuators, and sensors are seeing wide usage, and many other microelectromechanical systems (MEMS) show great promise. The reduction in the total number of parts and joints offered by compliant mechanisms is a significant advantage in the fabrication of micromechanisms. Compliant micromechanisms may be fabricated using technology and materials similar to those used in the fabrication of integrated circuits. MEMS are discussed in more detail in Section 1.6.

The compliant fishhook pliers (Compliers) illustrated in Figure 1.8 demonstrate several of the advantages discussed above. Part-count reduction is evident in that they are injection molded as a single piece. They are in a fairly harsh environment

Figure 1.8. Compliant pliers, or Compliers, fishhook removal pliers.

Figure 1.9. Compliant parallel motion bicycle brakes.

where pin joints may rust and require more maintenance. They are also lightweight and are not only easy to carry, but will float if the angler drops them in water.

The high-performance bicycle brakes shown in Figure 1.9 are another example of a compliant mechanism that demonstrates several advantages of compliant mechanisms. Unlike traditional cantilever-type brakes, these brake pads do not rotate in their motion. The first brakes that had such motion used a traditional parallelogram four-bar linkage to achieve the desired motion, and a return spring was necessary to ensure that the brakes would disengage when the rider let go of the handle. The compliant brakes shown have a reduced part count because two pin joints and the return spring are integrated into a single flexible strip of titanium or stainless steel. The manufacturer claims that the manufacturing cost is approximately one-third of that for the other style of parallel motion brakes. The reliability is increased because of the reduced number of parts to fail, and the spring that was causing consumer complaints was eliminated. The reduced joints also make it more reliable in dirty environments, such as mountain biking, because foreign material has a lower probability of getting in joints. A number of common devices that are compliant mechanisms are shown in Figure 1.10.

1.2 CHALLENGES OF COMPLIANT MECHANISMS

Although offering a number of advantages, compliant mechanisms present several challenges and disadvantages in some applications. Perhaps the largest challenge is the relative difficulty in analyzing and designing compliant mechanisms. Knowledge of mechanism analysis and synthesis methods and the deflection of flexible members is required. The combination of the two bodies of knowledge in compliant mechanisms requires not only an understanding of both, but also an understanding of their interactions in a complex situation. Since many of the flexible members undergo large deflections, linearized beam equations are no longer valid. Nonlinear

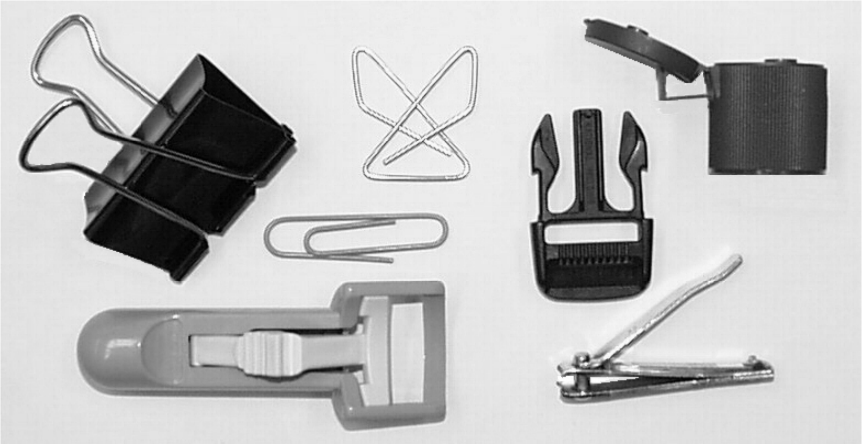


Figure 1.10. Common compliant devices. A binder clip, paper clips, backpack latch, lid eyelash curler, and nail clippers are shown.

equations that account for the geometric nonlinearities caused by large deflections must be used. Because of these difficulties, many compliant mechanisms in the past were designed by trial and error. Such methods apply only to very simple systems that perform relatively simple tasks and are often not cost-efficient for many potential applications. Theory has been developed to simplify the analysis and design of compliant mechanisms, and the limitations are not as great as they once were. Even considering these advances, however, analysis and design of compliant mechanisms are typically more difficult than for rigid-body mechanisms.

Energy stored in flexible elements has been discussed as an advantage, since it can be used to simplify mechanisms that incorporate springs, obtain specified force–deflection relationships, and store energy that is transferred or transformed by the mechanism. However, in some applications, having energy stored in flexible members is a disadvantage. For example, if a mechanism's function is to transfer energy from the input to an output, not all of the energy is transferred, but some is stored in the mechanism.

Fatigue analysis is typically a more vital issue for compliant mechanisms than for their rigid-body counterparts. Since compliant members are often loaded cyclically when a compliant mechanism is used, it is important to design those members so they have sufficient fatigue life to perform their prescribed functions.

The motion from the deflection of compliant links is also limited by the strength of the deflecting members. Furthermore, a compliant link cannot produce a continuous rotational motion such as is possible with a pin joint.

Compliant links that remain under stress for long periods of time or at high temperatures may experience stress relaxation or creep. For example, an electric motor may use the force caused by a deflected cantilever beam to hold brushes in place. With time, this holding force may decrease and the motor will no longer function properly.

The developments in this book present ways to address or overcome these challenges, but it is important to understand the difficulties and limitations of compliant mechanisms. Such knowledge is helpful in determining which applications will benefit most by use of compliant mechanism technology.

1.3 HISTORICAL BACKGROUND

The concept of using flexible members to store energy and create motion has been used for millennia. Archaeological evidence suggests that bows have been in use since before 8000 B.C. and were the primary weapon and hunting tool in most cultures [20]. Consider the longbow illustrated in Figure 1.11. Early bows were constructed of relatively flexible materials such as wood and animal sinew. Strain energy in the bow is transformed to kinetic energy of the arrow.

Catapults are another example of the early use of compliant members used by the Greeks as early as the fourth century B.C. [21]. Early catapults were constructed of wooden members that were deflected to store energy and then release it to propel a projectile. Figure 1.12 is a sketch of a compliant catapult by Leonardo da Vinci.

Flexible members have also been used to simulate the motion of turning joints. The flexural hinges of book covers, for example, have been constructed by changing the material composition and thickness at the desired point of flexure to obtain the desired motion. Other methods were developed early in the twentieth century to obtain this type of motion for other applications. The single-axis cross-flexure pivot [23] (Figure 1.13a) and Bendix Corporation's flexural (Free-Flex) pivots (Figure

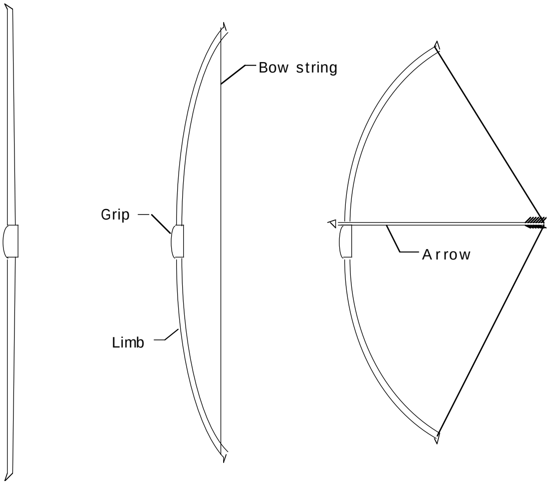


Figure 1.11. Longbow in its unstrung, strung, and drawn positions.

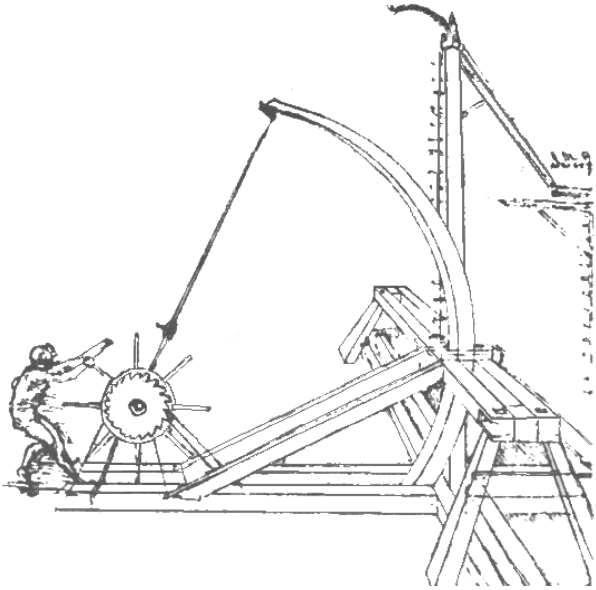
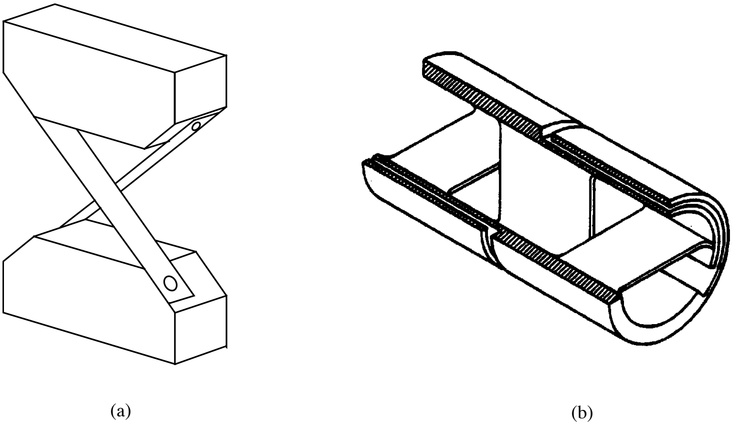


Figure 1.12. Leonardo da Vinci's sketch of a compliant catapult. (From [22].)

1.13b) are examples. The use of flexural or living hinges has been particularly important in products fabricated of injection-molded plastics [24, 25].

Flexible elements have also been used extensively in measurement instruments [8, 9]. Examples include high-accuracy load cells (Figure 1.14) for force measurement, and Bourdon tubes for pressure measurement.

The number of products that rely on flexible members to perform their functions has increased significantly over the last few decades, thanks in part to the develop-



(a) (b)

Figure 1.13. (a) Single-axis cross-flexure pivot, and (b) Bendix Corporation flexural pivot.

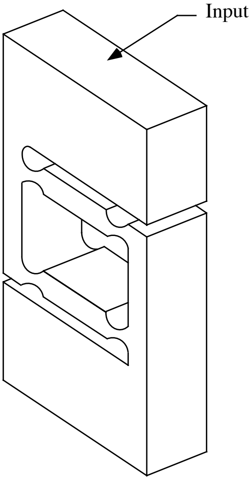


Figure 1.14. Load cell for force measurement.

ment of stronger and more reliable materials. The use of compliant mechanisms will probably continue to increase with time as materials and design methodologies are improved. The demand for increased product quality and decreased cost also pressures manufacturers to implement compliant mechanisms.

University and industry research has played an important role in the development of compliant mechanism theory and application [26–85]. Appendix A lists a number of important publications in the area.

1.4 COMPLIANT MECHANISMS AND NATURE*

Humans and nature often have differing philosophies on mechanical design. Stiff structures are usually preferred by humans because for many, stiffness means strength. Devices that must be capable of motion are constructed of multiple stiff structures assembled in such a manner as to allow motion (e.g., door hinges, linkages, and roller bearings). However, stiffness and strength cannot be equated—stiffness is a measure of how much something deflects under load, whereas strength is how much load can be endured before failure. Despite human tendencies, it is possible to make things that are flexible *and* strong. Nature uses stiff structures where needed—tree trunks, bones, teeth, and claws—but in living organisms, it more often relies on flexibility in living organisms. Bee wings (Figure 1.15), bird wings,

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*See [26], [81], and [83].

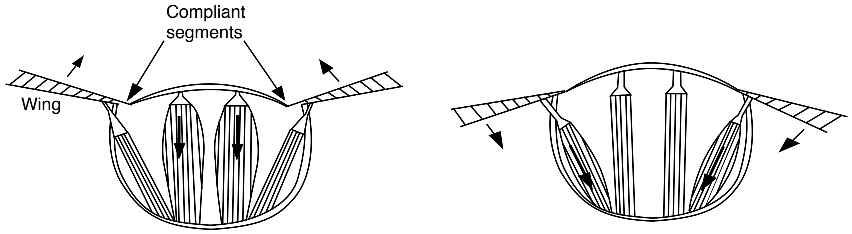

Figure 1.15. Bee wings demonstrate the use of compliance in nature.

tree branches, leaf stems, fish (Figure 1.16), and single-celled organisms are only a few examples of creations that use compliance to their advantage. Nature also has the advantage of *growing* living things, and no assembly is required [81].

The contrast between nature and human design is easily identifiable when humans try to replace one of nature's products. For example, a human heart valve is a compliant one-way valve that is capable of sustaining billions of cycles without failure. However, most current artificial heart valves use a number of assembled stiff parts with pin joints to obtain motion. They also have a comparatively short life, cause difficulty in blood flow, and often damage blood cells.

In many mechanical systems, stiff structures are a necessity. It would be quite disconcerting to feel a floor deflect as one walked across a room or to see a building sway in the wind. However, much can be learned from nature, and many devices may be made flexible and strong in order to gain some of the same advantages seen in living organisms, including increased life of some components and reduced assembly. Compliant mechanisms are one way that flexibility may be used to obtain some of these advantages in mechanical design.

1.5 NOMENCLATURE AND DIAGRAMS*

Nomenclature and skeleton diagrams are important tools in communicating mechanism design information. The following nomenclature for compliant mechanisms is

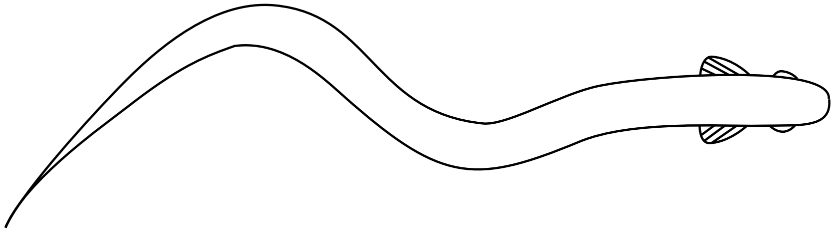

Figure 1.16. An eel uses its compliance to swim.

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*The text and figures of this section are summarized from [38], [58], and [70].

consistent with rigid-body mechanism nomenclature, but allows for further description and identification of compliant mechanisms.

1.5.1 Compliant Mechanisms versus Compliant Structures

To illustrate the difference between a compliant mechanism and a compliant structure, consider the flexible cantilever beams shown in Figure 1.17. The diving board shown in Figure 1.17a transforms the kinetic energy of the falling diver to strain energy in the beam, and then transforms it again to kinetic energy as the diver springs off the board. Using the definition of a mechanism as a device that transfers or transforms motion or energy, the diving board qualifies as a mechanism. The same function could be performed by using a more complicated rigid-body mechanism consisting of rigid links and a spring.

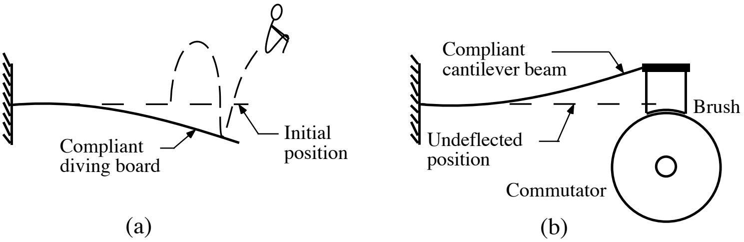
The compliant cantilever shown in Figure 1.17b is used in an electric motor to maintain contact between the brush and commutator. Since this device performs its function without transferring or transforming motion or energy, it is classified as a compliant structure.

Note that the two examples in Figure 1.17 both consist of compliant cantilever beams; however, their classification as a structure or mechanism depends on their function. Many of the analysis and design methods presented here apply to both structures and mechanisms.

1.5.2 Nomenclature

Rigid-body mechanisms are constructed of rigid links joined with kinematic pairs, such as pin joints and sliders. These components are easily identified and characterized. Since compliant mechanisms gain at least some of their motion from the deflection of flexible members, components such as links and joints are not as easily distinguished. Identification of such components is useful to allow the accurate communication of design and analysis information.

Link Identification. A link is defined as the continuum connecting the mating surfaces of one or more kinematic pairs. Revolute (pin or turning) joints and



(a) (b)

Figure 1.17. (a) Compliant diving board, and (b) compliant cantilever beam.

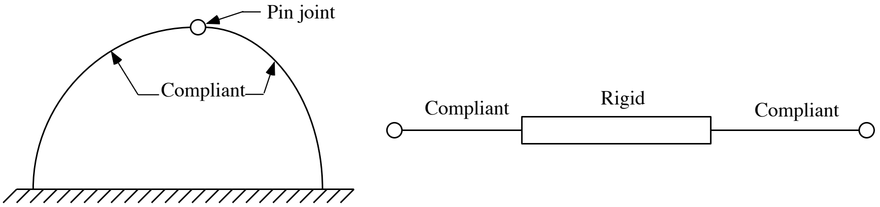
prismatic (sliding) joints are examples of kinematic pairs. Links can be identified by disassembling the mechanism at the joints and counting the resulting links. For example, if the Vise Grip shown in Figure 1.1b is disassembled at the four pin joints, then there are four links. Consider the compliant device with one pin joint shown in Figure 1.18a. It is shown disassembled in Figure 1.18b. Note that it consists of one link. The mechanisms shown in Figures 1.2a and 1.3a each consist of one link and one kinematic pair.

Note that the mechanism illustrated in Figure 1.2b has no traditional joints, and therefore has zero links. Such mechanisms are termed *fully compliant mechanisms*, since all their motion is obtained from the deflection of compliant members. Compliant mechanisms that contain one or more traditional kinematic pairs along with compliant members are called *partially compliant mechanisms*.

For a rigid link, the distances between joints are fixed, and the shape of the link is kinematically unimportant regardless of the forces applied. The motion of a compliant link, however, is dependent on link geometry and the location and magnitude of applied forces. Because of this difference, a compliant link is described by its *structural type* and its *functional type*.

The structural type is determined when no external forces are applied and is similar to the identification of rigid links. A rigid link that has two pin joints is termed a *binary link*. A rigid link with three or four pin joints is a *ternary* or a *quaternary link*, respectively. A compliant link with two pin joints has the same structure as a binary link and is called a *structurally binary link*, and so on for other types of links.

A link's functional type takes into account the structural type and the number of *pseudo joints*. Pseudo joints occur where a load is applied to a compliant segment, as shown in Figure 1.19. If a force is applied on a compliant link somewhere other than at the joints, its behavior may change dramatically. A structurally binary link with force or moment loads only at the joints is termed *functionally binary*. A compliant link with three pin joints is *structurally ternary*, and if loads are applied only at the joints, it is also *functionally ternary*. The same applies for quaternary links. If a link has two pin joint connections and also has a force on a compliant segment, it is structurally binary and functionally ternary, due to the added pseudo joint caused by the force. This is illustrated for binary and ternary links in Figure 1.19.



(a) (b)

Figure 1.18. One-link compliant mechanism.

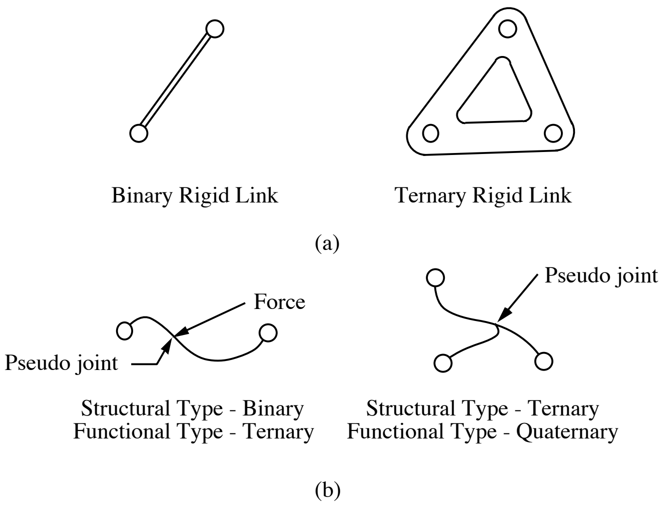


Figure 1.19. Examples of link types.

Segment Identification. While the definition of a link used above is consistent with that for rigid-body kinematics, it is not very descriptive of a compliant link. The application of a force or moment to a compliant link affects the deformation of the link, and therefore, its contribution to the mechanism's motion. Link characteristics that influence its deformation include cross-sectional properties, material properties, and magnitude and placement of applied loads and displacements. Thus a compliant link is further characterized into segments.

A link may be composed of one or more segments. The distinction between segments is a matter of judgment and may depend on the structure, function, or loading of the mechanism. Discontinuities in material or geometric properties often represent the endpoints of segments. The link shown in Figure 1.18 consists of three segments, one of which is rigid and two compliant. Since the distance between the endpoints of a rigid segment remains constant, it is considered a single segment, regardless of its size or shape.

Segment and Link Characteristics. The characteristics of individual segments and links may also be described, as shown in Figures 1.20a and b. A segment may be either rigid or compliant. This is referred to as a segment's *kind.* A compliant segment may be further classified by its *category* of either simple or compound. A simple segment is one that is initially straight, has constant material properties, and a constant cross section. All other segments are compound.

A link may be either rigid or compliant (its kind) and may consist of one or more segments. A rigid link needs no more characterization. A compliant link may

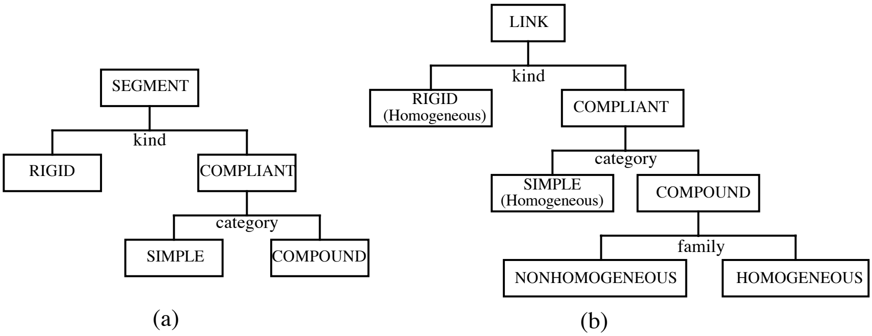


Figure 1.20. Component characteristics of (a) segments, and (b) links.

be either simple or compound (its category). A simple compliant link consists of one simple compliant segment; all others are compound links. A compound link may be either homogeneous or nonhomogeneous. This is its *family*. A homogeneous link is one that consists of all rigid segments or all compliant segments. Therefore, rigid links and simple compliant links are special cases of homogeneous links. Nonhomogeneous links contain both rigid and flexible segments.

1.5.3 Diagrams

Skeleton diagrams are often used to facilitate the description of the structure of rigid-body mechanisms. Similar diagrams for compliant mechanisms must distinguish between rigid and compliant links and segments. Symbols that represent individual joints or segments are shown in Figure 1.21. A compliant segment is shown as a single line and a rigid segment as two parallel lines. Additional information may be included in the diagram to show its categorization as a simple or compound segment. An axially compliant segment is one that is allowed to compress or extend. An extension spring is an example of an axially compliant segment.

Diagrams for the mechanisms illustrated in Figures 1.2a, b, 1.3a, and 1.11 are shown in Figures 1.22a, b, c, and d, respectively.

1.6 COMPLIANT MEMS

Microelectromechanical systems (MEMS) integrate mechanical and electrical components with feature sizes ranging from micrometers to millimeters. They may be fabricated using methods similar to those used to construct integrated circuits.

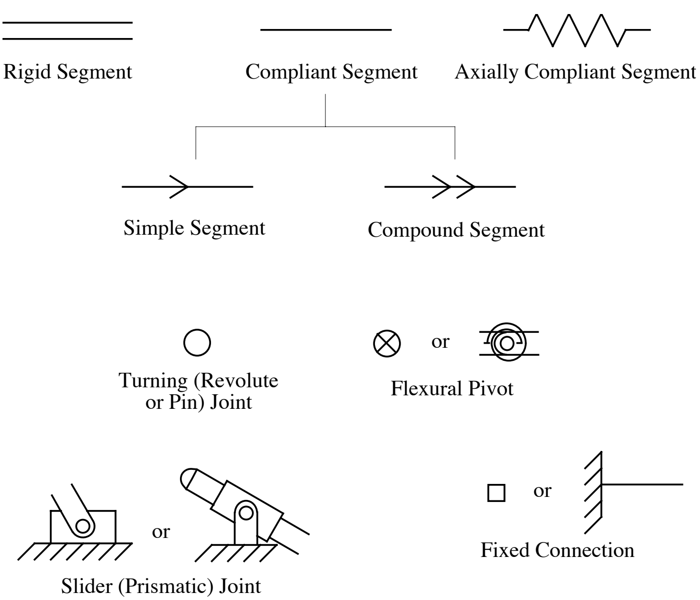


Figure 1.21. Symbol convention for compliant mechanism diagrams.

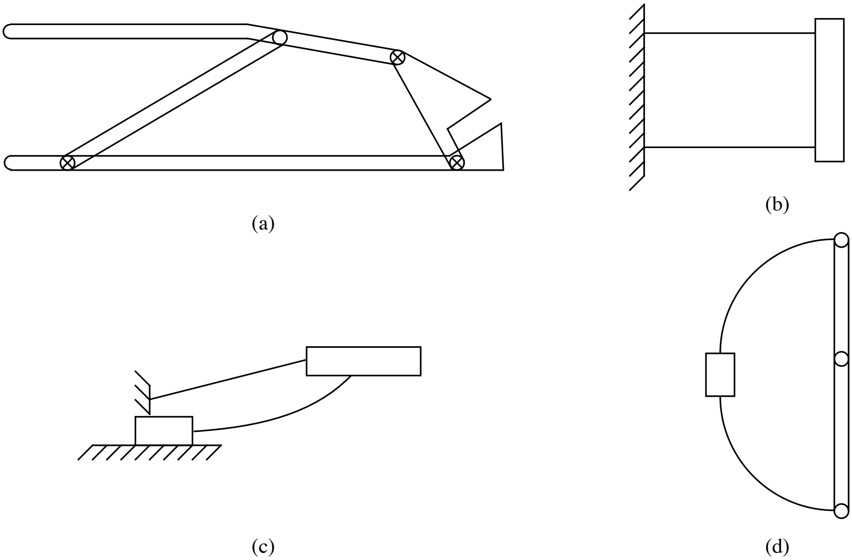


Figure 1.22. Diagrams representing the compliant mechanisms in (a) Figure 1.2a, (b) Figure 1.2b, (c) Figure 1.4a, and (d) Figure 1.11.

MEMS have the great potential of providing significant cost advantages when batch fabricated. Their size also makes it possible to integrate them into a wide range of systems. Microsensors (e.g., accelerometers for automobile crash detection and pressure sensors for biomedical applications) and microactuators (e.g., for moving arrays of micromirrors in projection systems) are examples of commercial applications of MEMS. This field is expected to grow dramatically over time.

The most common methods for MEMS fabrication use planar layers of material. Surface micromachining uses multiple layers of material that are deposited, then patterned using planar lithography. Possibly the most common material for surface micromachining is polycrystalline silicon, or polysilicon, on a silicon wafer. Bulk micromachining involves selectively etching the wafer substrate to create cavities and structures. LIGA (a German acronym which stands for lithography, electroforming, injection molding) uses x-rays to construct high-aspect-ratio structures in a single layer of material. More detail on the fabrication methods used in MEMS can be found in a number of sources, including [86].

The constraints introduced by the planar nature of MEMS fabrication and the scale (which makes assembly of parts difficult) introduce a number of challenges in constructing mechanical devices at the micro level. Compliant mechanisms present solutions to many of these problems. The advantages at the micro level are that compliant mechanisms [87]:

- Can be fabricated in a plane
- Require no assembly
- Require less space and are less complex
- Have less need for lubrication
- Have reduced friction and wear
- Have less clearance due to pin joints, resulting in higher precision
- Integrate energy storage elements (springs) with the other components

There are also some challenges associated with designing compliant MEMS. The performance is highly dependent on the material properties, yet the design is limited to a few materials that are compatible with the fabrication methods. The material properties are not always well known at this scale, and there can often be significant scatter in material property data because device sizes are often on the order of the material grain size. Tests have demonstrated that compliant components can be very robust at the micro level and often last longer than do components that use pin joints or other elements that induce wear.

An example of a compliant micro device, a micro compliant bistable mechanism, is shown in the scanning electron microscope (SEM) photo in Figure 1.23. An example of a compliant member as part of a Sandia National Laboratories microengine is shown in the SEM photo in Figure 1.24a. This type of microengine uses a number of flexible components, and a view of the overall mechanism is shown in Figure 1.24b.

The compliant mechanism theory presented in this book applies for the analysis and design of micro and macro devices. Examples of micro compliant mechanisms

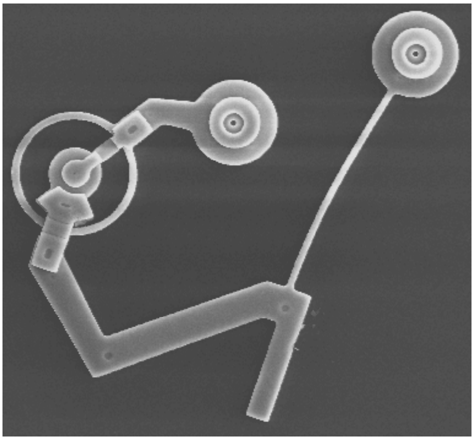


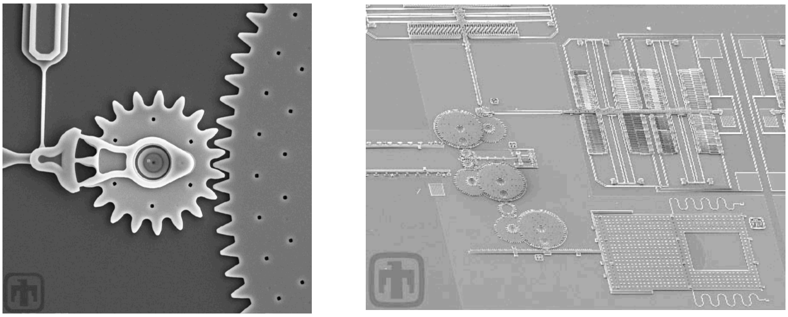
Figure 1.23. Scanning electron micrograph of a microcompliant bistable mechanism.

are provided throughout the following chapters. The cgs (centimeter–gram–second) system of units is often used to ensure a consistent set of units. The unit of force in this system of units is the dyne (g-cm/s^2). The length unit of micrometer, (μm, 1 X 10^{-6} m) is often used to describe the dimensions of various components. When performing calculations, this unit is converted to meters when using the meter–kilogram–second (mks) system or to centimeters for the cgs system.

PROBLEMS

1.1 List several possible advantages of compliant mechanisms.

1.2 List possible challenges or disadvantages associated with compliant mechanisms.



(a) (b)

Figure 1.24. (a) Compliant member in a microengine, and (b) microengine that uses several compliant members. (Courtesy of Sandia National Laboratories, www.sandia.gov.)

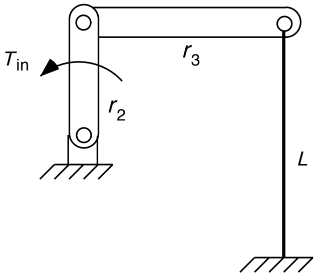


Figure P1.4. Figure for Problem 1.4.

1.3 What is the difference between a compliant mechanism and a compliant structure?

1.4 Consider the flapper mechanism shown in its undeflected position in Figure P1.4. How many links does this mechanism have? Identify the segments for the compliant link.

1.5 Consider the compliant mechanism shown in Figure P1.5.
   (a) How many links does this mechanism have?
   (b) How many compliant segments are in this mechanism? Rigid segments? (Include ground.)
   (c) Is this a partially compliant mechanism, a fully compliant mechanism, or a rigid-body mechanism?

1.6 Consider the compliant mechanism illustrated in Figure P1.6. How many links does it have? How many rigid segments does this mechanism have? Compliant segments? Identify and label the segments of each link. Is this a fully compliant or a partially compliant mechanism?

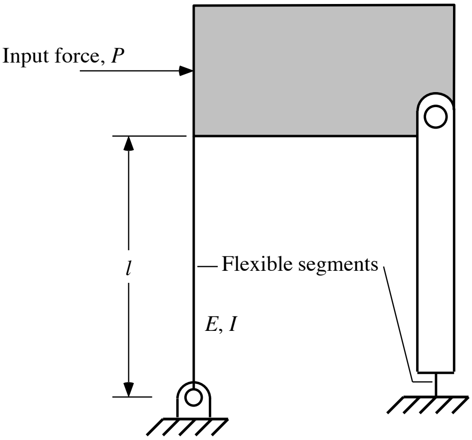


Figure P1.5. Figure for Problem 1.5.

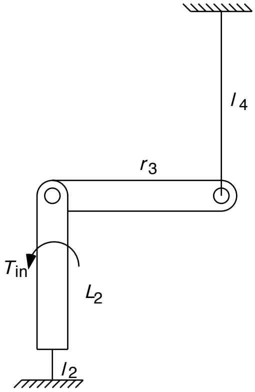


Figure P1.6. Figure for Problem 1.6.

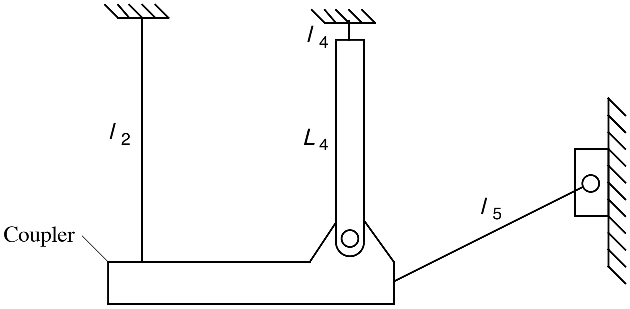


Figure P1.7. Figure for Problem 1.7.

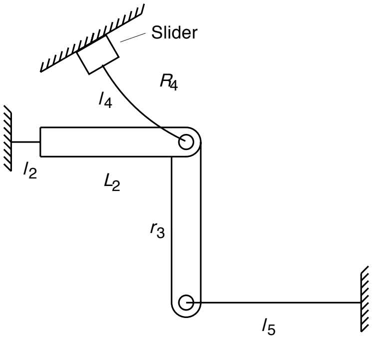


Figure P1.8. Figure for Problem 1.8.

1.7 Consider the mechanism illustrated in Figure P1.7. How many links does it have? How many rigid segments does this mechanism have? Compliant segments? Identify and label the segments of each link.

1.8 Consider the mechanism illustrated in Figure P1.8. How many links does it have? How many rigid segments does this mechanism have? Compliant segments? Identify and label the segments of each link.