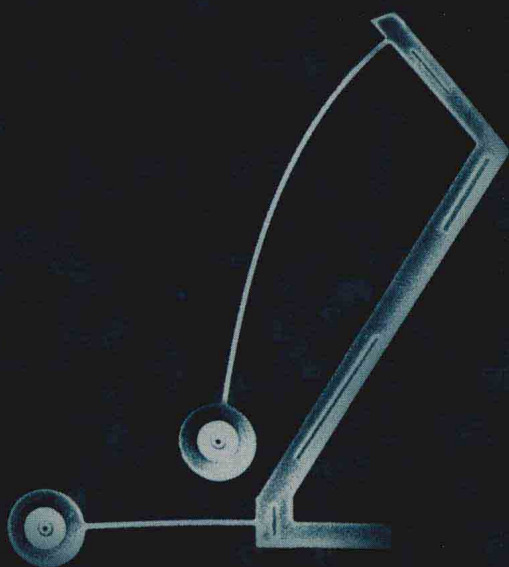
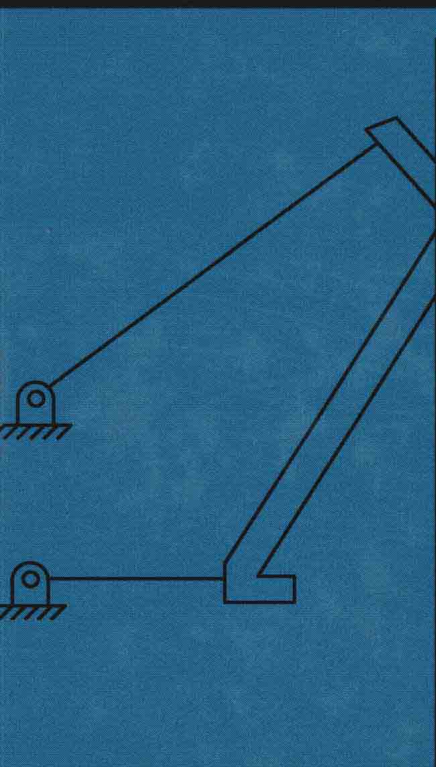


# Compliant Mechanisms



Larry L. Howell

This book is printed on acid-free paper. ∞

Copyright © 2001 by John Wiley & Sons, Inc. All rights reserved.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4744. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012, (212) 850-6011, fax (212) 850-6008, E-Mail: PERMREQ @ WILEY.COM.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold with the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional person should be sought.

***Library of Congress Cataloging-in-Publication Data:***

Howell, Larry L.

Compliant mechanisms/Larry L. Howell

p. cm.

ISBN 0-471-38478-X (cloth : alk. paper)

1. Mechanical movements. 2. Machinery, Kinematics of. I. Title

TJ181 .H89 2002

621.8'11—dc21

2001026196

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

# COMPLIANT MECHANISMS

To my wife

**Peggy**

and my children

**Angela, Travis, Nathan, and Matthew**

# PREFACE

---

Compliant mechanisms offer great promise in providing new and better solutions to many mechanical-design problems. Since much research in the theory of compliant mechanisms has been done in the last few years, it is important that the abundant information be presented to the engineering community in a concise, understandable, and useful form. The purpose of this book is to fulfill this need for students, practicing engineers, and researchers.

The book presents methods for the analysis and design of compliant mechanisms and illustrates them with examples. The materials in the book provide ideas for engineers to employ the advantages of compliant mechanisms in ways that otherwise may not be possible. The analysis of small deflection devices is addressed, but emphasis is given to compliant mechanisms that undergo large, nonlinear deflections. The pseudo-rigid-body model is introduced as a method which simplifies the analysis of compliant mechanisms that undergo large deflections by modeling them with elements common to traditional mechanisms. This simplification makes it possible to design compliant mechanisms for many types of tasks. The advantages of compliant mechanisms in the emerging area of microelectromechanical systems (MEMS) are also addressed, and several MEMS examples are provided throughout the book.

The chapters are organized to flow from simple to more complex concepts; the book then concludes with the application of the previous materials to specific types of devices. This is done by organizing the chapters into major sections of introduction, fundamentals, analysis, design, and special-purpose mechanisms. In a similar way, simple examples facilitate understanding, followed by more complicated examples that demonstrate how the material can be used in applications.

Review of essential topics in strength of materials, machine design, and kinematics is provided to create a self-contained book that does not require a lot of additional references to solve compliant-mechanism problems. These reviews can help emphasize important topics the reader has studied previously, or they can be used as a resource for those from other disciplines who are working in the area of MEMS or related areas. The appendixes provide a resource for quick reference to important equations presented in the book.

The area of compliant mechanisms exists thanks to the vision and insight of Professor Ashok Midha. Many have contributed to the knowledge of compliant mechanisms, but Professor Midha may be considered the father of modern compliant mechanisms. His insight and vision have had a profound effect on the field and on those with whom he has associated. I have greatly benefited from both his work in compliant mechanisms and his example and mentorship, and I am grateful for his influence.

The earlier versions of this book were used as notes in compliant mechanisms courses offered at Brigham Young University, Purdue University, and the University of Missouri, Rolla. Students made many helpful comments to improve the quality of the notes.

Several colleagues have graciously volunteered their time and expertise by contributing parts of the book. Professor G. K. Ananthasuresh at the University of Pennsylvania and Professor Mary I. Frecker at Pennsylvania State University wrote Chapter 9. Dr. Morgan D. Murphy of Delphi Automotive Systems contributed Appendix G. Chapter 11 relies heavily on graduate work completed by Brian Jensen when he was at Brigham Young University.

Some of the text and figures in this book are summarized from previous writings, including a number of papers coauthored with graduate students and colleagues and published by the American Society of Mechanical Engineers (ASME) in various conference proceedings and in the *Journal of Mechanical Design*. Work from a number of graduate student theses has also been included. Grateful thanks is extended to all those who have participated in this work: James Derderian, Patrick Opdahl, Brian Edwards, John Parise, and Brian Jensen have generously contributed sections of this book. The contributions of Scott Lyon, Brent Weight, and Greg Roach are also greatly appreciated, as are the efforts of many other students that have made this possible. The valuable assistance of Megan Poppitz is also gratefully acknowledged.

The Mechanical Engineering Department at Brigham Young University has been very supportive of this project and has provided many resources to assist in its completion. The College of Engineering and the administration of Brigham Young University have also supported the author's efforts in many ways.

In addition to the many students who have provided recommendations and encouragement for this work, others are thanked for their helpful reviews and comments to improve the manuscript. Special thanks to Professor G. K. Ananthasuresh, Dr. Morgan D. Murphy, Professor Kenneth W. Chase, and Professor Don Norton of Brigham Young University's English Department, and the university editing service for valuable reviews and comments on the manuscript.

Much of the fundamental work in compliant mechanisms has been funded by the National Science Foundation (NSF). The resources provided were a wise investment and will have a far-reaching impact for many years to come. The following NSF grants have supported the author's work in the area of compliant mechanisms: DMI-9624574 (CAREER Award), CMS-9978737, ECS-9528238, and DMI-9980835. The Utah Center of Excellence Program is also acknowledged for support of commercialization of compliant mechanism theory through funding of the Center of Excellence in Compliant Mechanisms.

I express my love and gratitude to my wife and children for their continued love, support, and companionship. And my eternal thanks to my parents, for their love and sacrifice. Finally, I humbly acknowledge the gifts from God, for which no words could ever adequately express my gratitude.

LARRY L. HOWELL

*Provo, Utah*

# CONTENTS

---

<b>PREFACE</b>	<b>XV</b>
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 Advantages of Compliant Mechanisms	2
1.2 Challenges of Compliant Mechanisms	6
1.3 Historical Background	8
1.4 Compliant Mechanisms and Nature	10
1.5 Nomenclature and Diagrams	11
1.5.1 Compliant Mechanisms versus Compliant Structures	12
1.5.2 Nomenclature	12
1.5.3 Diagrams	15
1.6 Compliant MEMS	15
Problems	18
<b>2 FLEXIBILITY AND DEFLECTION</b>	<b>21</b>
2.1 Linear versus Nonlinear Deflections	21
2.2 Stiffness and Strength	22
2.3 Flexibility	23
2.4 Displacement versus Force Loads	26
2.5 Material Considerations	28
2.5.1 Maximum Deflection for a Flexible Beam	28

2.5.2	Ratio of Strength to Young's Modulus . . . . .	29
2.5.3	Other Material Selection Criteria . . . . .	30
2.5.4	Creep and Stress Relaxation . . . . .	32
2.6	Linear Elastic Deflections . . . . .	34
2.7	Energy Storage . . . . .	38
2.8	Stress Stiffening . . . . .	41
2.9	Large-Deflection Analysis . . . . .	42
2.9.1	Beam with Moment End Load . . . . .	43
2.9.2	Elliptic-Integral Solutions . . . . .	45
2.9.3	Numerical Methods . . . . .	55
	Problems . . . . .	55
<b>3</b>	<b>FAILURE PREVENTION . . . . .</b>	<b>61</b>
3.1	Stress . . . . .	61
3.1.1	Principal Stresses . . . . .	62
3.1.2	Stress Concentrations . . . . .	67
3.2	Static Failure . . . . .	67
3.2.1	Ductile Materials . . . . .	68
3.2.2	Brittle Materials . . . . .	73
3.3	Fatigue Failure . . . . .	77
3.3.1	Fatigue Basics . . . . .	78
3.3.2	Fatigue Failure Prediction . . . . .	79
3.3.3	Estimating Endurance Limit and Fatigue Strength . . . . .	82
3.3.4	Endurance Limit and Fatigue Strength Modification Factors . . . . .	83
3.3.5	Surface Factor . . . . .	84
3.3.6	Size Factor . . . . .	84
3.3.7	Load Factor . . . . .	85
3.3.8	Reliability . . . . .	86
3.3.9	Miscellaneous Effects . . . . .	86
3.3.10	Completely Reversed Loading . . . . .	88
3.3.11	Fluctuating Stresses . . . . .	93
3.3.12	Fatigue of Polymers . . . . .	98
3.3.13	Testing . . . . .	102
	Problems . . . . .	104
<b>4</b>	<b>RIGID-LINK MECHANISMS . . . . .</b>	<b>111</b>
4.1	Introduction . . . . .	111
4.1.1	Mobility . . . . .	111
4.1.2	Kinematic Chains and Inversions . . . . .	112
4.1.3	Classification of Four-Bar Mechanisms . . . . .	113
4.1.4	Mechanical Advantage . . . . .	113
4.2	Position Analysis . . . . .	115
4.2.1	Four-Bar Mechanism: Closed-Form Equations . . . . .	116
4.2.2	Slider-Crank Mechanism: Closed-Form Equations . . . . .	117
4.2.3	Complex Number Method . . . . .	118

4.3	Velocity and Acceleration . . . . .	123
4.4	Kinematic Coefficients. . . . .	125
4.4.1	Four-Bar Kinematic Coefficients . . . . .	125
4.4.2	Slider–Crank Kinematic Coefficients . . . . .	126
4.5	Mechanism Synthesis. . . . .	126
4.5.1	Function Generation . . . . .	127
4.5.2	Path Generation . . . . .	129
4.5.3	Motion Generation . . . . .	130
	Problems. . . . .	131
<b>5</b>	<b>PSEUDO-RIGID-BODY MODEL . . . . .</b>	<b>135</b>
5.1	Small-Length Flexural Pivots. . . . .	136
5.1.1	Active and Passive Forces . . . . .	140
5.1.2	Stress . . . . .	141
5.1.3	Living Hinges . . . . .	144
5.2	Cantilever Beam with a Force at the Free End (Fixed–Pinned). . . . .	145
5.2.1	Parametric Approximation of the Beam’s Deflection Path. . . . .	147
5.2.2	Characteristic Radius Factor. . . . .	148
5.2.3	Coordinates of Beam End. . . . .	150
5.2.4	Rule of Thumb for Characteristic Radius Factor. . . . .	151
5.2.5	Angular Deflection Approximation. . . . .	152
5.2.6	Stiffness Coefficient . . . . .	152
5.2.7	Torsional Spring Constant. . . . .	156
5.2.8	Stress . . . . .	157
5.2.9	Practical Implementation of Fixed–Pinned Segments . . . . .	160
5.3	Fixed–Guided Flexible Segment . . . . .	162
5.4	End-Moment Loading . . . . .	165
5.5	Initially Curved Cantilever Beam . . . . .	166
5.5.1	Stiffness Coefficient for Initially Curved Beams . . . . .	169
5.5.2	Stress for Initially Curved Beams . . . . .	170
5.6	Pinned–Pinned Segment . . . . .	170
5.6.1	Initially Curved Pinned–Pinned Segments . . . . .	172
5.7	Segment with Force and Moment (Fixed–Fixed) . . . . .	175
5.7.1	Loading Cases . . . . .	175
5.8	Other Methods of Pin Joint Simulation . . . . .	180
5.8.1	Living Hinges . . . . .	181
5.8.2	Passive Joints. . . . .	183
5.8.3	Q-Joints . . . . .	185
5.8.4	Cross-Axis Flexural Pivots . . . . .	189
5.8.5	Torsional Hinges . . . . .	190
5.8.6	Split-Tube Flexures . . . . .	193
5.9	Modeling of Mechanisms. . . . .	194
5.9.1	Examples . . . . .	195
5.10	Use of Commercial Mechanism Analysis Software . . . . .	205
	Problems. . . . .	209

<b>6</b>	<b>FORCE–DEFLECTION RELATIONSHIPS . . . . .</b>	<b>219</b>
6.1	Free-Body Diagram Approach . . . . .	220
6.2	Generalized Coordinates . . . . .	225
6.3	Work and Energy . . . . .	226
6.4	Virtual Displacements and Virtual Work . . . . .	228
6.5	Principle of Virtual Work . . . . .	230
6.6	Application of the Principle of Virtual Work . . . . .	231
6.7	Spring Function for Fixed–Pinned Members . . . . .	237
6.8	Pseudo-Rigid-Body Four-Bar Mechanism . . . . .	239
6.9	Pseudo-Rigid-Body Slider Mechanism . . . . .	248
6.10	Multi-Degree-of-Freedom Mechanisms . . . . .	254
6.11	Conclusions . . . . .	256
	Problems . . . . .	256
<b>7</b>	<b>NUMERICAL METHODS . . . . .</b>	<b>259</b>
7.1	Finite Element Analysis . . . . .	260
7.2	Chain Algorithm . . . . .	261
	7.2.1 Shooting Method . . . . .	268
<b>8</b>	<b>COMPLIANT MECHANISM SYNTHESIS . . . . .</b>	<b>275</b>
8.1	Rigid-Body Replacement (Kinematic) Synthesis . . . . .	275
	8.1.1 Loop Closure Equations . . . . .	280
8.2	Synthesis with Compliance: Kinetostatic Synthesis . . . . .	286
	8.2.1 Additional Equations and Unknowns . . . . .	287
	8.2.2 Coupling of Equations . . . . .	288
	8.2.3 Design Constraints . . . . .	290
	8.2.4 Special Case of $\theta_o = \theta_j$ . . . . .	292
8.3	Other Synthesis Methods . . . . .	297
	8.3.1 Burmester Theory for Finite Displacements . . . . .	297
	8.3.2 Infinitesimal Displacements . . . . .	298
	8.3.3 Optimization of Pseudo-Rigid-Body Model . . . . .	298
	8.3.4 Optimization . . . . .	299
8.4	Problems . . . . .	299
<b>9</b>	<b>OPTIMAL SYNTHESIS WITH CONTINUUM MODELS. . . .</b>	<b>301</b>
	Ananthasuresh, G. K., and Frecker, M. I.	
9.1	Introduction . . . . .	301
	9.1.1 Distributed Compliance . . . . .	303
	9.1.2 Continuum Models . . . . .	303

- 9.1.3 Elastostatic Analysis Using the Finite Element Method . . . . . 304
  - 9.1.4 Structural Optimization . . . . . 305
- 9.2 Formulation of the Optimization Problem . . . . . 306
  - 9.2.1 Objective Function, Constraints, and Design Variables . . . . . 306
  - 9.2.2 Measures of Stiffness and Flexibility . . . . . 308
  - 9.2.3 Multicriteria Formulations . . . . . 310
- 9.3 Size, Shape, and Topology Optimization . . . . . 312
  - 9.3.1 Size Optimization . . . . . 312
  - 9.3.2 Shape Optimization . . . . . 319
  - 9.3.3 Topology Optimization . . . . . 319
- 9.4 Computational Aspects . . . . . 323
  - 9.4.1 Optimization Algorithms . . . . . 324
  - 9.4.2 Sensitivity Analysis . . . . . 325
- 9.5 Optimality Criteria Methods . . . . . 327
  - 9.5.1 Derivation of the Optimality Criterion . . . . . 327
  - 9.5.2 Solution Procedure . . . . . 329
  - 9.5.3 Examples . . . . . 329
- 9.6 Conclusion . . . . . 332
- 9.7 Acknowledgments . . . . . 332
- Problems . . . . . 332

**10 SPECIAL-PURPOSE MECHANISMS 337**

- 10.1 Compliant Constant-Force Mechanisms . . . . . 337
  - 10.1.1 Pseudo-Rigid-Body Model of Compliant Slider Mechanisms . . 338
  - 10.1.2 Dimensional Synthesis . . . . . 339
  - 10.1.3 Determination of Force Magnitude . . . . . 342
  - 10.1.4 Examples . . . . . 343
  - 10.1.5 Estimation of Flexural Pivot Stress . . . . . 344
  - 10.1.6 Examples . . . . . 345
- 10.2 Parallel Mechanisms . . . . . 346
  - 10.2.1 Compliant Parallel-Guiding Mechanisms . . . . . 347
  - 10.2.2 Applications . . . . . 347
  - 10.2.3 Pseudo-Rigid-Body Model . . . . . 350
  - 10.2.4 Additional Design Considerations . . . . . 352
- Problems . . . . . 353

**11 BISTABLE MECHANISMS . . . . . 355**

- 11.1 Stability . . . . . 355
- 11.2 Compliant Bistable Mechanisms . . . . . 357
- 11.3 Four-Link Mechanisms . . . . . 359
  - 11.3.1 Energy Equations . . . . . 360
  - 11.3.2 Requirements for Bistable Behavior . . . . . 362
  - 11.3.3 Young Bistable Mechanisms . . . . . 367

- 11.4 Slider–Crank or Slider–Rocker Mechanisms. . . . . 372
  - 11.4.1 Energy Equations . . . . . 373
  - 11.4.2 Requirements for Bistable Behavior . . . . . 374
  - 11.4.3 Examples for Various Spring Positions . . . . . 374
- 11.5 Double-Slider Mechanisms . . . . . 377
  - 11.5.1 Double-Slider Mechanisms with a Pin Joining the Sliders . . . 377
  - 11.5.2 Double-Slider Mechanisms with a Link Joining the Sliders . . 379
  - 11.5.3 Requirements for Bistable Behavior . . . . . 381
- 11.6 Snap-Through Buckled Beams . . . . . 382
- 11.7 Bistable Cam Mechanisms. . . . . 382
  - Problems. . . . . 383
- A REFERENCES . . . . . 385**
- B PROPERTIES OF SECTIONS . . . . . 399**
  - B.1 Rectangle . . . . . 399
  - B.2 Circle . . . . . 399
  - B.3 Hollow Circle . . . . . 400
  - B.4 Solid Semicircle . . . . . 400
  - B.5 Right Triangle . . . . . 400
  - B.6 I Beam with Equal Flanges . . . . . 400
- C MATERIAL PROPERTIES . . . . . 401**
- D LINEAR ELASTIC BEAM DEFLECTIONS . . . . . 407**
  - D.1 Cantilever Beam with a Force at the Free End. . . . . 407
  - D.2 Cantilever Beam with a Force Along the Length. . . . . 407
  - D.3 Cantilever Beam with a Uniformly Distributed Load . . . . . 408
  - D.4 Cantilever Beam with a Moment at the Free End . . . . . 408
  - D.5 Simply Supported Beam with a Force at the Center . . . . . 408
  - D.6 Simply Supported Beam with a Force Along the Length . . . . . 409
  - D.7 Simply Supported Beam with a Uniformly Distributed Load . . . . . 409
  - D.8 Beam with One End Fixed and the Other End Simply Supported. . . 409
  - D.9 Beam with Fixed Ends and a Center Load. . . . . 410
  - D.10 Beam with Fixed Ends and a Uniformly Distributed Load . . . . . 410
  - D.11 Beam with One End Fixed and the Other End Guided . . . . . 410

**E PSEUDO-RIGID-BODY MODELS . . . . . 411**

E.1 Small-Length Flexural Pivot . . . . . 411

E.2 Vertical Force at the Free End of a Cantilever Beam . . . . . 412

E.3 Cantilever Beam with a Force at the Free End . . . . . 413

E.4 Fixed–Guided Beam . . . . . 415

E.5 Cantilever Beam with an Applied Moment at the Free End . . . . . 416

E.6 Initially Curved Cantilever Beam . . . . . 417

E.7 Pinned–Pinned Segments . . . . . 418

    E.7.1 Initially Curved Pinned–Pinned Segments . . . . . 418

E.8 Combined Force–Moment End Loading . . . . . 420

**F EVALUATION OF ELLIPTIC INTEGRALS . . . . . 421**

**G TYPE SYNTHESIS OF COMPLIANT MECHANISMS . . 425**

Murphy, M. D.

G.1 Matrix Representation for Rigid-Link Mechanisms . . . . . 425

G.2 Compliant Mechanism Matrices . . . . . 426

    G.2.1 Segment-Type Designation . . . . . 428

    G.2.2 Connection-Type Designation . . . . . 428

    G.2.3 Examples . . . . . 429

G.3 Determination of Isomorphic Mechanisms . . . . . 429

    G.3.1 Rigid-Body Isomorphic Detection Techniques . . . . . 431

    G.3.2 Isomorphism Detection for Compliant Mechanisms . . . . . 431

G.4 Type Synthesis . . . . . 433

G.5 Determination of Design Requirements . . . . . 434

G.6 Topological Synthesis of Compliant Mechanisms . . . . . 435

    G.6.1 Segment-Type Enumeration . . . . . 436

    G.6.2 Connection-Type Enumeration . . . . . 437

    G.6.3 Combined Segment and Connection-Type Results . . . . . 438

    G.6.4 Formation of Compliant Mechanisms . . . . . 441

G.7 Examples . . . . . 442

    G.7.1 Discussion . . . . . 449

**INDEX . . . . . 451**

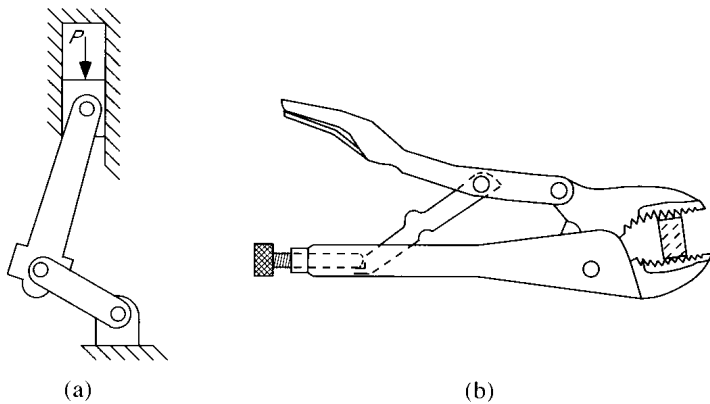
# CHAPTER 1

---

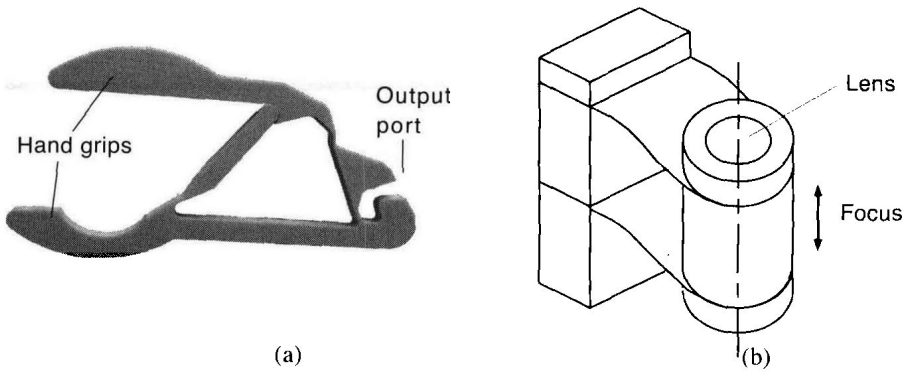
## INTRODUCTION

---

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.



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



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

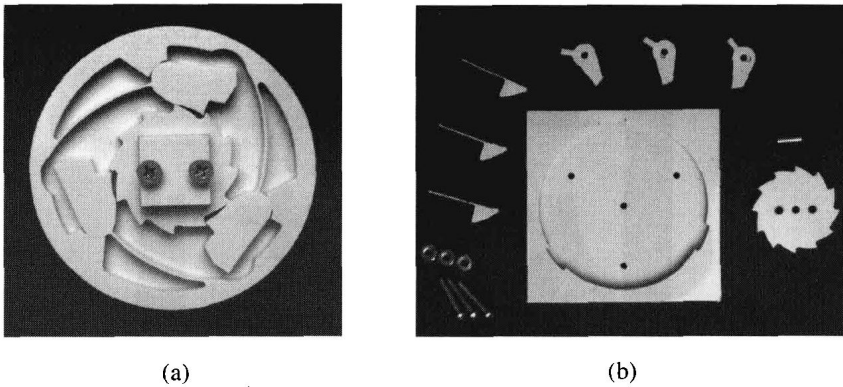
A compliant mechanism also transfers or transforms motion, force, or energy. Unlike rigid-link mechanisms, however, compliant mechanisms gain at least some of their mobility from the deflection of flexible members rather than from movable joints only. An example of a compliant crimping mechanism is shown 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.

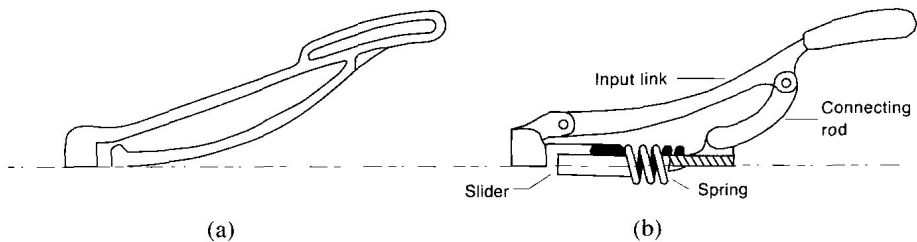


**Figure 1.3.** (a) Compliant overrunning clutch, and (b) its rigid-body counterpart shown disassembled. (From [6] and [7].)

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



**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].)