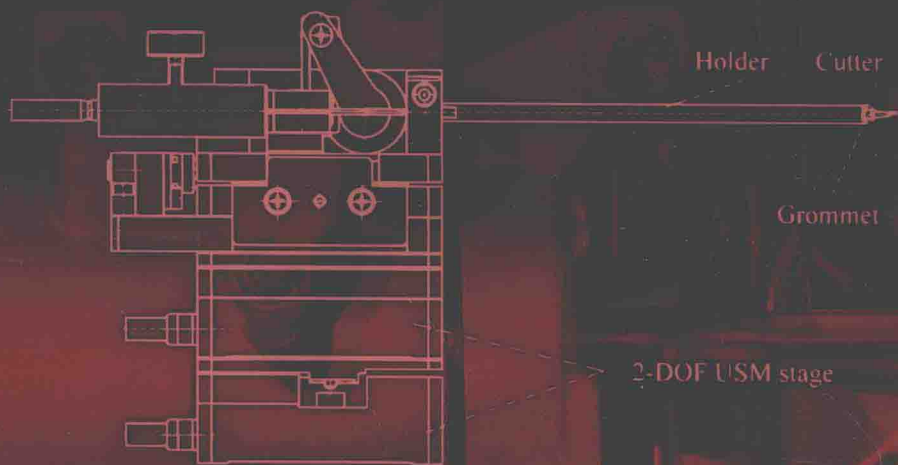




CRC Press
Taylor & Francis Group

Modeling and Control of Precision Actuators

Tan Kok Kiong • Huang Sunan



Modeling and Control of Precision Actuators

Tan Kok Kiong • Huang Sunan



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

MATLAB® is a trademark of The MathWorks, Inc. and is used with permission. The MathWorks does not warrant the accuracy of the text or exercises in this book. This book's use or discussion of MATLAB® software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB® software.

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2014 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper
Version Date: 20131003

International Standard Book Number-13: 978-1-4665-5644-7 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Preface

Much fundamental research, technologies, and applications are now moving toward achieving high-precision positioning and higher specifications in production, thus achievable with the requirements of precision motion control up to the order of the submicrometer or nanometer level. This is driven by the emergence of current technologies, such as high-precision manufacturing processes, machines, biotechnology, and nanotechnology. From the early 1980s, semiconductor and biomedical industries demanded high-precision actuators to execute more precise positioning and manufacturing in their processes, and the move toward ever-higher precision has continued to now. Requirements pertaining to the precision of motion vary substantially. As such, high-precision actuators are now in high demand, and are expected to perform various types of movements, from rotation to translation, high torque capability, wide speed range, etc. The application areas of high-precision actuators are diverse in aerospace, microelectronics, biomedical engineering, and nanotechnology.

This book is a result of several years of work in the realization of precise actuators. The primary intent of this book is to report new technologies in the area of precision motion control, which can ultimately be applied in industry. It covers dynamical analysis of precise actuators and strategies of design for various control applications. The book consists of eight chapters treating different topics. The content is suitable for graduate students and engineers in precision engineering.

In what follows, the contents of the book are briefly reviewed.

Chapter 1 introduces the driving forces behind precise actuators, several typical types of the actuators, as well as their applications. Chapter 2 describes nonlinear dynamics of precise actuators and their mathematical forms, including hysteresis, creep, friction, and force ripples.

Chapter 3 presents control strategies for precise actuators based on the Preisach model as well as creep dynamics. The identification algorithm is first proposed to estimate Preisach model parameters, and then the inversion feedforward controller is designed for hysteresis compensation. This strategy is mainly for low frequency. For the case where precise actuators work at high bandwidth relative to the resonant frequencies, another identification and compensation strategy is designed. The proposed methods are illustrated by experimental results.

Chapter 4 develops relay feedback techniques for identifying nonlinearities such as friction and force ripples. By converting the closed-loop system into

a multiple-relay feedback system, switching conditions of a stable limit cycle are obtained. Hence, friction and force ripples are identified by numerically solving a set of equations. Simulation and real-time experiments show the practical appeal of the proposed method.

Model predictive control (MPC) has become an attractive feedback strategy, especially for linear systems. MPC solves an online optimization to determine inputs, taking into account the current conditions of the plant, any disturbances affecting operation, and imposed safety and physical constraints. Over the last several decades, MPC technology has reached a mature stage. In Chapter 5, we present an MPC approach based on piecewise affine models that emulate the frictional effects in a precise actuator. Specially, an integral MPC design imposes robustness on a model-plant mismatch near zero speed. Implementation of the real-time control is handled by a gain scheduling table so that the complexity is comparable to the traditional feedforward proportional-integral-derivative (PID).

Chapter 6 presents the concepts of air bearing stages with the corresponding control method. A linear air bearing stage is first considered. Since it is a floating object, eddy current braking is introduced into the system. A nonlinear control with proportional-integral (PI) control is designed for dealing with nonlinear terms. Subsequently, a multi-DOF (degrees of freedom) spherical air bearing stage is presented. An adaptive noise filter and a controller for angular positioning are proposed to achieve high performance. Finally, experimental results are given to show the effectiveness of the proposed control algorithm.

Chapter 7 presents a set of schemes suitable for fault detection and accommodation control of mechanical systems. The basic idea of designing a fault detection scheme is to use the information provided by a model-based nonlinear observer to find failure occurrences. The fault detection decision is carried out by comparing the observer outputs with their signatures. After a fault is detected, the controller is reconfigured by incorporating neural networks that are used to capture the nonlinear characteristics of unknown faults. The designed schemes can achieve the automated fault detection and accommodation control using a dead-zone operator.

Chapter 8 is intended to provide readers with a bridge between the design methods of the previous chapters and their applications. With this purpose in mind, the chapter emphasizes the key issues involved and how to implement the precision motion control tasks in a practical system. These issues are demonstrated by three case studies. The first case study describes a robust adaptive control method for positioning piezoelectric actuators (ultrasonic motor) to achieve highly precise motion. Real-time experimental results are provided to verify the effectiveness of the proposed scheme when applied to high-precision motion trajectory tracking, such as intracytoplasmic sperm injection (ICSI). The second case study is focused on a motion control for a two-dimensional stage that is used to treat a common disease called otitis media with effusion (OME), involving a surgeon inserting a grommet in

the eardrum to bypass the Eustachian tube to drain fluid when medication fails. The third application is a vision-based real-time temperature monitoring system, where an object recognition and tracking algorithm will be applied to guide a temperature sensor to monitor the temperature of the working tool while it is carrying out operations.

Tan Kok Kiong
Huang Sunan

MATLAB[®] is a registered trademark of The MathWorks, Inc. For product information, please contact:

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098 USA
Tel: 508 647 7000
Fax: 508-647-7001
E-mail: info@mathworks.com
Web: www.mathworks.com <<http://www.mathworks.com>>

Acknowledgments

The first author is thankful to his PhD students for their research leading to the contents of the book. They include Liu Lei, Chen Silu, Nguyen Hoang Tuan Minh, Liang Wenyu, and Zhang Yi.

The authors thank Dr. Teo Chek Sing and Tan Chee Siong for their assistance in the writing of the book. They also thank the National University of Singapore and Singapore Institute of Manufacturing Technology for their funding support. The editing process would not have been as smooth without the generous assistance of Laurie Schlags, Robin Lloyd-Starkes and Li Ming Leong.

Finally, the authors thank their families for their love and support.

**Tan Kok Kiong
Huang Sunan**

About the Authors

Tan Kok Kiong earned his B.Eng. in electrical engineering with honors in 1992 and PhD in 1995 from the National University of Singapore.

Dr. Kiong is currently an associate professor with the Department of Electrical and Computer Engineering, National University of Singapore. His current research interests are in the areas of advanced control and autotuning, precision instrumentation and control, and general industrial automation. He has produced more than 160 journal papers to date and has written 5 books, all resulting from research in these areas. He has so far attracted research funding in excess of S\$7 million and has won several teaching and research awards.

Huang Sunan earned his PhD degree from Shanghai Jiao Tong University, Shanghai, China, in 1994. Currently, he is a research fellow in the Singapore Institute of Neurotechnology, National University of Singapore. His research interests include error compensation of high-precision machines, adaptive control, neural network control, and rehabilitation robot control.

Contents

Preface	xi
Acknowledgments	xv
About the Authors	xvii
1. Introduction	1
1.1 Growing Interest in Precise Actuators	1
1.2 Types of Precise Actuators	3
1.2.1 Piezoelectric Actuator	3
1.2.1.1 Stack Actuator	3
1.2.1.2 Piezoelectric Shear Actuator	3
1.2.1.3 Piezoelectric Bending Actuator	4
1.2.2 Linear Motor	5
1.2.2.1 Permanent Magnet Linear Motor	5
1.2.2.2 Linear Piezo Stage	7
1.2.2.3 Linear Air Bearing Stage	8
1.3 Applications of Precise Actuators	9
References	10
2. Nonlinear Dynamics and Modeling	11
2.1 Hysteresis	11
2.2 Creep	14
2.3 Friction	15
2.4 Force Ripples	17
References	19
3. Identification and Compensation of Preisach Hysteresis in Piezoelectric Actuators	21
3.1 SVD-Based Identification and Compensation of Preisach Hysteresis	23
3.1.1 Parameter Identification of Preisach Hysteresis	23
3.1.1.1 Least-Squares Estimation by SVD	23
3.1.1.2 Identification Revision Using SVD Updating	25
3.1.1.3 Simulation Study of Proposed Identification Approach	27

3.1.2	Compensation Strategy of Preisach Hysteresis	27
3.1.2.1	Preisach-Based Inversion Compensation	27
3.1.2.2	Proposed Composite Control Strategy	30
3.1.2.3	Simulation Study of Proposed Compensation Strategy	31
3.1.3	Experimental Studies	31
3.1.3.1	Experimental Setup	32
3.1.3.2	Hysteresis Identification at Low Frequencies	32
3.1.3.3	Performance of Proposed Composite Controller at Low Frequencies	33
3.1.3.4	Performance of Proposed Composite Controller at Higher Frequencies	38
3.1.4	Discussions	38
3.2	High-Bandwidth Identification and Compensation of Hysteretic Dynamics in Piezoelectric Actuators	40
3.2.1	Proposed Model Identification Strategy	42
3.2.1.1	Model of PA Systems	42
3.2.1.2	Identification of Quasi-Static Hysteresis	43
3.2.2	Proposed Composite Controller	45
3.2.2.1	Analysis of Feedforward and Feedback Controllers at High Frequencies	45
3.2.2.2	Design of Feedforward Controller	47
3.2.2.3	Design of Feedback Controller	48
3.2.3	Experimental Studies	50
3.2.3.1	Identification of Quasi-Static Hysteresis	50
3.2.3.2	Drift Suppression	50
3.2.3.3	Preisach Hysteresis Identification	50
3.2.3.4	Identification of Nonhysteretic Dynamics	52
3.2.3.5	Controller Design	54
3.2.3.6	Performance Evaluation	54
3.2.4	Discussions	58
3.3	Concluding Remarks	60
	References	60
4.	Identification and Compensation of Friction and Ripple Force	63
4.1	Relay Feedback Techniques for Precision Motion Control	63
4.2	Identification and Compensation of Friction Model	64
4.2.1	System Model	64
4.2.2	DCR Feedback System	66
4.2.3	Friction Modeling Using DCR Feedback	69
4.2.3.1	Low-Velocity Mode: Static Friction Identification	69
4.2.3.2	High-Velocity Mode: Coulomb and Viscous Friction Identification	69

4.2.3.3	Estimating the Boundary Lubrication Velocity by Optimization	71
4.2.4	Simulation	72
4.2.4.1	Limit Cycle Variation with Relay Gains	72
4.2.4.2	Phase 1: Low-Velocity Mode	73
4.2.4.3	Phase 2: High-Velocity Mode	74
4.2.4.4	Estimation of δ via Optimization	74
4.2.5	Real-Time Experiments	76
4.3	Modeling and Compensation of Ripples and Friction in Permanent Magnet Linear Motors	81
4.3.1	Overall PMLM Model	81
4.3.2	Model Identification	82
4.3.2.1	Dual-Input Describing Function (DIDF) for Nonlinear Portion of PMLM Model	83
4.3.2.2	Parameter Estimation from Harmonic Balance	86
4.3.2.3	Extraction of Frequency Components from DFT	87
4.3.3	Simulation	88
4.3.4	Real-Time Experiments	89
4.3.4.1	Identification of the Spatial Cogging Frequency	89
4.3.4.2	Parameter Estimation	91
4.3.4.3	Model Compensation	92
	References	97
5.	Model Predictive Control of Precise Actuators	99
5.1	Model Predictive Control Concepts for Motion Tracking	101
5.1.1	Prediction and Optimization	102
5.1.2	Offset-Free and Robust MPC	103
5.1.2.1	Offset-Free Tracking	104
5.1.2.2	Robust Formulation	107
5.2	Hybrid MPC for Ultrasonic Motors	108
5.2.1	Piecewise Affine Model of Motion	108
5.2.2	Model Predictive Control for PWA Model	111
5.2.2.1	Terminal Gain	112
5.2.2.2	Terminal Cost	112
5.2.2.3	Terminal Set	112
5.3	From Parametric MPC to PID Gain Scheduling Controllers	113
5.4	Simulation Study and Experiment Results	114
5.4.1	Simulation Studies	114
5.4.2	Experiment	117
5.5	Concluding Remarks	118
	References	119

6. Modeling and Control of Air Bearing Stages	123
6.1 Problem Statements	124
6.2 Control of Linear Air Bearing Stage	124
6.3 Controller Design for the System	127
6.4 Experimental Results	133
6.5 Control of Spherical Air Bearing Stage	137
6.5.1 Mechanical Structure	137
6.5.1.1 Voice Coil Actuators	138
6.5.1.2 Pneumatic System	141
6.5.2 Control System	142
6.5.2.1 Hardware of Control System	142
6.5.2.2 Modeling of Air Bearing Stage	146
6.5.2.3 Parameter Identification	146
6.5.2.4 Noise Filter	147
6.5.2.5 Model-Based Controller Design	149
6.6 Performance Analysis of Spherical Air Bearing System	150
6.6.1 Model Identification	151
6.6.2 Noise Filter	151
6.6.3 Control Results	154
6.7 Concluding Remarks	155
References	156
7. Fault Detection and Accommodation in Actuators	157
7.1 Problem Statements	158
7.2 Types of Failure	159
7.2.1 Examples of Actuator Failure	159
7.2.2 Sensor Failure	160
7.3 Fault Diagnosis Scheme	161
7.3.1 Fault Detection	161
7.3.2 Fault Isolation	161
7.3.3 Fault Identification	162
7.4 Control of the System under No-Fault Condition	163
7.5 Accommodation Control after Fault Detection	164
7.6 Extension to Output Feedback Control Design	165
7.6.1 Fault Diagnosis Scheme	165
7.6.1.1 Fault Detection	165
7.6.1.2 Fault Isolation	166
7.6.2 Robust Control for the System under No-Fault Condition	167
7.6.3 Accommodation Control after Fault Detection	168
7.7 Experimental Tests	168
7.8 Concluding Remarks	172
References	175

8. Case Studies of Precise Actuator Applications	177
8.1 Robust Adaptive Control of Piezoelectric Actuators with an Application to Intracytoplasmic Sperm Injection	178
8.1.1 Modeling of the Piezoelectric Actuator	179
8.1.2 Robust Adaptive Control	181
8.1.3 Experimental Results	185
8.1.4 Biomedical Application	191
8.1.4.1 Instruments	191
8.1.4.2 The Structure of Oocytes	192
8.1.4.3 ICSI Process	194
8.1.4.4 Results	194
8.2 Control of a 2-DOF Ultrasonic Piezomotor Stage for Grommet Insertion	196
8.2.1 Background	197
8.2.1.1 Control Objectives	199
8.2.2 System Modeling	200
8.2.2.1 Model of Single-Axis USM Stage	200
8.2.2.2 Model of 2-DOF USM Stage	201
8.2.2.3 Parameter Estimation	203
8.2.3 Controller Design	206
8.2.3.1 LQR-Assisted PID Control	206
8.2.3.2 Nonlinear Compensation	207
8.2.3.3 Control of 2-DOF USM Stage	208
8.2.4 Experimental Results	210
8.3 Vision-Based Tracking and Thermal Monitoring of Nonstationary Targets	214
8.3.1 Computer Imaging Technologies	215
8.3.2 Decoupled Tracking and Thermal Monitoring	216
8.3.2.1 Overall System Configuration	217
8.3.2.2 Vision and Image Processing System	220
8.3.2.3 Noncontact Temperature Measurement System	225
8.3.2.4 Tracking Control of Linear Motor	226
8.3.2.5 Practical Issues	228
8.3.2.6 Experimental Results	231
References	239
Index	243

1

Introduction

In a wide range of industries, many applications require much higher precision over a high bandwidth and speed than traditional actuators can deliver. This increase in demand for higher-precision motion control has led to many new innovations, including high-speed Maglev transportation systems, robotics machines, micromanipulation systems, semiconductors, and the use of piezo-electric materials to create motion. Precise actuators are the motion enablers of the motion control system. They utilize a physical interaction to convert an electrical energy into mechanical motion to achieve high speed and high accuracy resolution. Developments of such precise actuators and their control technologies will have an impact on a wide range of industries, from medical technology to precision tooling machines and 3D printing. The purpose of this chapter is to discuss the drivers of precise actuators, main types of precise actuators, challenges in their control, and precision applications.

1.1 Growing Interest in Precise Actuators

In recent years, electronic control and machine control have become more efficient as new microprocessors, digital signal processors (DSPs), and other electronics chips are providing the control platform with tremendous computing and processing power. Advances in actuators, such as direct drive motors, piezo motors, coil motors, air bearing motors, linear motors, and brushless motors are reducing traditional issues such as backlash, hysteresis, friction, and parasitic system dynamics. The technical field of precision actuators has expanded significantly over the past 30 years to include design method, error compensation, control, actuator, sensor, fault failure, software platform, and design methodology.

Frequently used actuators in the domain of precision and ultraprecision are piezoelectric actuator (PA) and linear motors. For example, PAs have been applied to products such as a piezoelectric buzzer, a printer head, and ultrasonic motors. In precision engineering applications, PAs have been increasingly

employed, such as in modern micro- and nanofabrication, dynamic imaging with scanning probe microscopes (SPMs), and advanced spacecrafts with sensitive optical instruments. With the development of ultra-accurate applications, more stringent requirements are presented [1], which lay out the scope of current techniques.

- High bandwidth: In SPMs, the PAs are required to track at very high rates, which may exceed the resonant frequencies of PAs. Currently, most PAs operate at frequencies less than 10% of the resonant frequencies.
- High accuracy: In addition to high-bandwidth requirements, high accuracy is another requirement for PAs. Moreover, both high bandwidth and high accuracy are current requirements in which the precision tracking is required at rates possibly beyond the resonant frequencies.
- Feedforward control: Feedback control is validated at normal working frequency, but it is limited at frequencies higher than the resonant frequencies due to the measurement noise at high frequencies. The model-based inversion feedforward compensation, which relies on the model identification, is a useful technology to increase the tracking rates and enhance the trajectory tracking accuracy at high frequencies, because the feedforward controller is effective for avoiding the measurement noise that is more serious at high frequencies.

The 2009 global market for piezoelectric-operated actuators and motors was estimated to be 6.6 billion, and the market is estimated to reach 12.3 billion by 2014, showing an average annual growth rate of 13.2% per year [2]. Due to the demand from the consumer electronics market beyond computers, hard disk drive (HDD) demand has been experiencing continual growth over the past decade. It was reported in 2007 that 516.2 million hard disk drives were sold [3]. Meanwhile, the linear motor is gaining attention in precision manufacturing. The main driver of linear motor technology is the ever-increasing performance demand in incremental positioning applications [4]. Unlike rotary machines, linear motors require no indirect coupling mechanisms as in gear boxes, chains, and screws coupling. This greatly reduces the effects of contact-type nonlinearities and disturbances, such as backlash and frictional forces. In addition to precise actuator design, the control of precision systems also has a wide range of applications in high-speed and high-accuracy automation. The growth of nanotechnology and nanoscale manufacturing has further raised the positioning requirements for machine and controller design. The performance of such systems depends on the application of advanced feedback control due to the large-scale system of controlled variables and the uncertainties that might affect the system significantly.

1.2 Types of Precise Actuators

In this book, we will focus mainly on two common types of actuation technology used to achieve linear motion: piezoelectric actuator and linear motor.

1.2.1 Piezoelectric Actuator

The piezoelectric actuator (PA) has become an increasingly popular candidate as a precise actuator in industry, due to its ability to achieve high precision and its versatility to be implemented in various applications. More specifically, the PA can provide very precise positioning (of the order of nanometer) and produce forces from low force (a few grams) to high force (up to a few thousand Newtons). This is because PAs have the following appealing properties:

- High bandwidth (at rates of kHz)
- Small displacement (typically several microns)
- High accuracy (typically subnanometer accuracy)
- High force
- Friction-free (flexible joints are commonly used to avoid generating the friction)
- Minimal static energy consumption
- Small size

The increasingly widespread industrial applications of the PA in various optical fiber alignments, mask alignment, and medical micromanipulation surgical robots are self-evident testimonies of the effectiveness of the PA in these application domains. To obtain maximum performance from PAs, various types have been designed.

1.2.1.1 Stack Actuator

The most popular design for PAs is a stack of ceramic layers separated by thin metallic electrodes, called stack actuator (see Figure 1.1). The stack actuator changes its dimension or size when an electric field with a power supply is applied to it. Such change is very small and produces linear motion. This implies that the stack actuator can achieve high-precision displacements (typically 20 nm). The actuator can also produce different forces according to supply voltage. Commercial products for such stack actuators are available from Physik Instrumente, Kinetic Ceramics, and NEC, which can provide precise positioning in microns or at the nanometer level.

1.2.1.2 Piezoelectric Shear Actuator

Piezoelectric shear actuators are also very common, as shown in Figure 1.2. Compared with linear PAs, shear actuators are adapted for small transverse

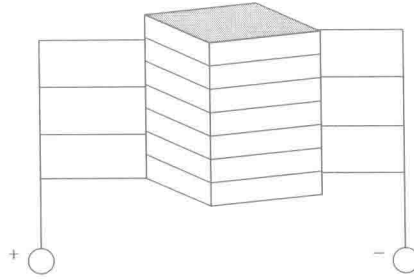


FIGURE 1.1
Piezoelectric stack actuator.

displacements where space is a constraint. They offer very fast response times. The main advantage of the shear actuators is their suitability for a bipolar operational source, whereby the mid-position corresponds to a drive voltage of 0 V. It should be noticed that in a shear actuator, the electric field is applied perpendicular to the polarization direction, which is different from the other types of actuators.

1.2.1.3 Piezoelectric Bending Actuator

In addition to the stack and shear actuators, piezoelectric bending actuators (these actuators are often referred to as benders, piezoelectric cantilevers, or piezoelectric bimorphs) are another important PA. The working principle is that the application of an electric field across the two-layer element produces curvature when one layer expands while the other layer contracts. Typical movement for this kind of actuator is on the micrometer level (from hundreds to thousands of microns), while the bender force generated is small (from tens to hundreds of grams). Figures 1.3 and 1.4 show two common bending configurations that are often used in various applications. The first configuration, as shown in Figure 1.3, is called serial bender and has two piezoelectric layers with two electrodes and an antiparallel polarization connected to each other. The second configuration, as shown in Figure 1.4, is

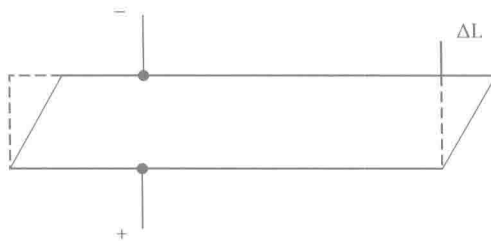


FIGURE 1.2
Piezoelectric shear actuator.