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Andrew J. Fleming
Kam K. Leang

Design, Modeling and Control of Nanopositioning Systems

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Andrew J. Fleming · Kam K. Leang

Design, Modeling and Control of Nanopositioning Systems

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Andrew J. Fleming
School of Engineering and Computer Science
University of Newcastle
Callaghan, NSW
Australia

Kam K. Leang
Mechanical Engineering
University of Nevada, Reno
Reno, NV
USA

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To my family

Andrew J. Fleming

To Allyson, Norie, Phirin, the Newcomer
and The Squeaker

Kam K. Leang

Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline, such as new theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies…, new challenges. Much of this development work resides in industrial reports, feasibility study papers, and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

The range of monographs that appear in the *Advances in Industrial Control* series is very wide and from time to time the Editors are able to welcome into the series a monograph that seems destined to become a definitive text for its field. This monograph, *Design, Modeling and Control of Nanopositioning Systems* by Andrew J. Fleming and Kam K. Leang is such an example. The monograph is a comprehensive treatise on designing and implementing control systems for nanopositioning systems. Such control modules are found in devices like the atomic force microscope. To give context to the monograph, a nanometer (nm) is the unit 1×10^{-9} m and an atomic force microscope has a resolution of 0.01 nm. Thus, for example, with the diameter of iron atoms at 0.28 nm, gallium atoms at 0.26 nm, and gold atoms at 0.27 nm, an atomic force microscope can explore the atomic topography of samples.

The narrative trajectory of the monograph assigns the first five chapters to the physical components used in nanopositioning systems, including piezoelectric transducers and position sensors. These five chapters are followed by four chapters on control topics. The control chapters cover: shunt control, feedback control, force-feedback control, and feedforward control. The concluding five chapters of the monograph report issues that affect the application and implementation of the control systems designed. Consequently these chapters cover command signal design, how to compensate for hysteresis effects, the use of charge drives, the nature of noise in nanopositioning systems, and finally the electrical issues raised by the use of piezoelectric transducers.

The authorial team has worked with these systems for some years now and is able to write from a wealth of experience. Dr. Andrew J. Fleming is an Australian

Research Fellow and a Senior Lecturer at the University of Newcastle, NSW, Australia. He is a noted expert on piezoelectric applications, and with S.O. Reza Moheimani co-authored the well received *Advances in Industrial Control* monograph, *Piezoelectric Transducers for Vibration Control and Damping* (ISBN 978-1-84628-331-4, 2006). Author Dr. Kam K. Leang is an Associate Professor at the University of Nevada, Reno, USA. With a background in Mechatronics, Dr. Leang has research interests in iterative learning control and piezo-based nanopositioning systems and applications.

In the introductory chapter, there is a useful Book Summary (Sect. 1.6) that gives the reader an indication of the level of prior knowledge the authors expect the reader to have to benefit fully from the monograph. The reader, new to nanopositioning systems, will find the monograph well structured and accessible for self-learning purposes. The control chapters are very readable and involve an interesting variety of PID control and the more advanced methods. A notable feature of the monograph is the way theory is supported by experimental assessments and case studies. The industrial control engineer will find plenty of useful explanation and discussion of the physical reasons for system design and control choices. The monograph also contains reports on aspects of control design that are often glossed over in many texts. One striking example is the work and chapter on the interplay between control design and the noise present in nanopositioning systems. The breadth and thoroughness of the material presented and the way chapters are so very well focussed should make this monograph a valuable resource for lecture and short courses in the nanopositioning field. Although the text has a strong control focus, it is thought that readers outside of the control community, for example, physicists and scientists, will also find the text accessible and interesting.

In conclusion, the monograph presents a thorough and engaging exposition of the state of the art in nanopositioning and is a valuable and welcome contribution to the literature and to the *Advances in Industrial Control* series.

Glasgow, Scotland, UK

M. J. Grimble
M. A. Johnson

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Chapter 1
Introduction

This chapter provides an introduction to the design, applications, and characteristics of piezoelectric nanopositioning systems. Particular attention is paid to the characteristics that limit speed and resolution. The performance limitations are then discussed followed by an overview of control techniques to improve performance.

1.1 Introduction to Nanotechnology

On December 29, 1959, physicist Richard Feynman gave a talk entitled "There's Plenty of Room at the Bottom" at an American Physical Society meeting at the California Institute of Technology (CalTech). Feyman's talk sparked interest in ideas and concepts behind nanoscience and nanotechnology. In his talk, Feynman described a process in which scientists would be able to manipulate and control individual atoms and molecules. Over a decade later, the term nanotechnology was coined by Professor Norio Taniguchi through his work on ultraprecision machining. Modern nanotechnology began in 1981 with the development of the scanning tunneling microscope (STM) (Binnig et al. 1982), a type of scanning probe microscope. The STM gave scientists the ability to "see" individual atoms.

The National Nanotechnology Initiative (NNI) defines nanotechnology as the manipulation of matter at the nanoscale, or more specifically at least one dimension sized from 1 to 100 nm (http://www.nano.gov/). One nanometer is one billionth of a meter, and on a comparative scale, if a marble were a nanometer, then one meter would be the size of Earth. Research and development in nanotechnology encompasses many fields, such as surface science, organic chemistry, molecular biology, semiconductor physics, and microfabrication. In general, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.

What attracts scientists and engineers to work at the nanoscale is matter such as gases, liquids, and solids can exhibit unusual physical, chemical, and biological properties at the nanoscale. Therefore, scientists and engineers can develop

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novel nanostructured materials that are stronger or have different physical properties compared to other forms or sizes of the same material. For example, some materials can be developed that are better at conducting heat or electricity, or become more chemically reactive or reflect light better or change color as their size or structure is altered. Other applications of nanotechnology are equally diverse, ranging from extensions of conventional device physics to completely new approaches based upon molecular self-assembly, from developing new materials with dimensions on the nanoscale to direct control of matter on the atomic scale. Over the last several decades, billions of dollars have been invested in nanotechnology because of the variety of potential industrial and military applications.

Scanning probe microscopes such as the STM and the atomic force microscope (AFM) were invented in the 1980s to allow scientists to see and manipulate matter at the nanoscale (see Sect. 1.3 for detailed discussion). For example, the AFM uses a small microfabricated cantilever with a sharp tip (probe) located at its distal end to interact with and “feel” the sample surface (Binnig and Quate 1986; Leang et al. 2009). The tool can obtain high-resolution topographical images, and it also has the ability to directly measure various properties of a specimen. For example, the structural and mechanical properties of biological specimens such as cells and DNA have been investigated by the tool.

In addition to imaging and investigating the surface of a sample at the nanoscale, scanning probe-based tools can be exploited for manufacturing at the nanoscale, a process also known as nanomanufacturing. Nanomanufacturing involves scaled-up, reliable, and cost-effective manufacturing of nanoscale materials, structures, devices, and systems. Nanomanufacturing also includes research, development, and integration of top-down processes and increasingly complex bottom-up or self-assembly processes. Some techniques to create nanosize features and devices include photolithography, nanoimprint, self-assembly, and the use of probe-based tools to physically shape or modify the surface of a sample.

One critical tool in nanotechnology is the nanopositioning system. Nanopositioning systems are used extensively in scanning probe microscopy and in applications that require subnanometer precision motion control. Nanopositioning systems are introduced next.

1.2 Introduction to Nanopositioning

Nanopositioning stages are mechanical positioning devices capable of developing displacements with nanometer scale resolution. A simple nanopositioning stage is illustrated in Fig. 1.1. The moving platform is centrally suspended by four leaf flexures. These flexures are designed to *flex* and deflect freely in the direction of travel but resist motion in other directions. Their purpose is to guide the motion of the platform and to provide a preloading force on the actuator.

Most nanopositioning systems employ piezoelectric stack actuators for developing force and displacement. The actuators elongate by around 0.1 % when the

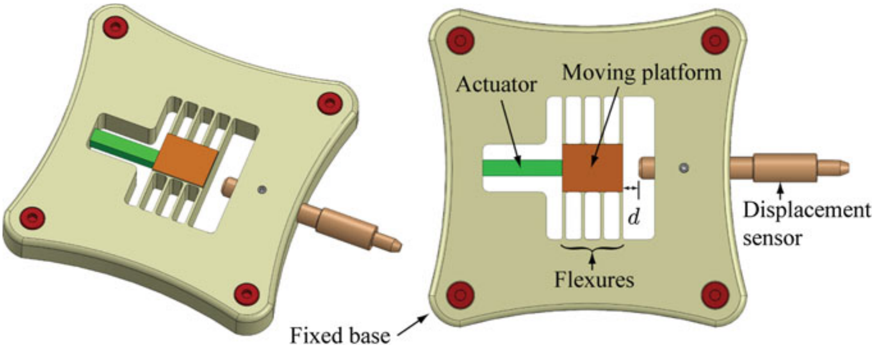

Fig. 1.1 A single degree-of-freedom positioning stage. The actuator expansion causes the platform to displace laterally. The resulting displacement d is measured by the position sensor

maximum voltage of between 60 and 200 V is applied. In Fig. 1.1, the actuator drives the moving platform through a flexure that permits only lateral deflection. This is necessary to avoid transmitting any bending or torsional forces that may be produced by the actuator. Further information on piezoelectric actuators can be found in Chap. 2.

Sources of positioning error in a nanopositioning stage include actuator nonlinearity and creep, structural vibration, and thermal drift. To eliminate these errors, a position sensor is incorporated into the stage and used within a feedback control loop to regulate the position. Figure 1.1 illustrates a position sensor that directly measures the position of the moving platform relative to the frame. The feedback controller works to equate the measured position to the command reference, thereby eliminating errors due to actuator nonlinearity, thermal drift, and other sources of disturbance.

Nanopositioning systems come in a variety of forms and are widely applied in a diverse range of scientific and industrial applications. Some examples include: fiber aligners (Wang et al. 2007), beam scanners (Potsaid et al. 2007), and lateral positioning platforms (Devasia et al. 2007). Among other applications in nanotechnology (Bhushan 2004), nanopositioning platforms are used widely in scanning probe microscopy (Salapaka and Salapaka 2008; Abramovitch et al. 2007; Meyer et al. 2004) and nanofabrication systems (Tseng et al. 2005, 2008; Tseng 2008). Examples of some commercial nanopositioning stages are pictured in Fig. 1.2. Other examples are described in Chap. 3.

1.3 Scanning Probe Microscopy

A common application of nanopositioners is in the lateral and vertical positioning stages of scanning probe microscopes (SPMs) such as the AFM. Unlike a traditional optical microscope that uses light for imaging, an AFM image is formed by scanning a microcantilever probe over the surface, as illustrated in Fig. 1.3. The AFM is one

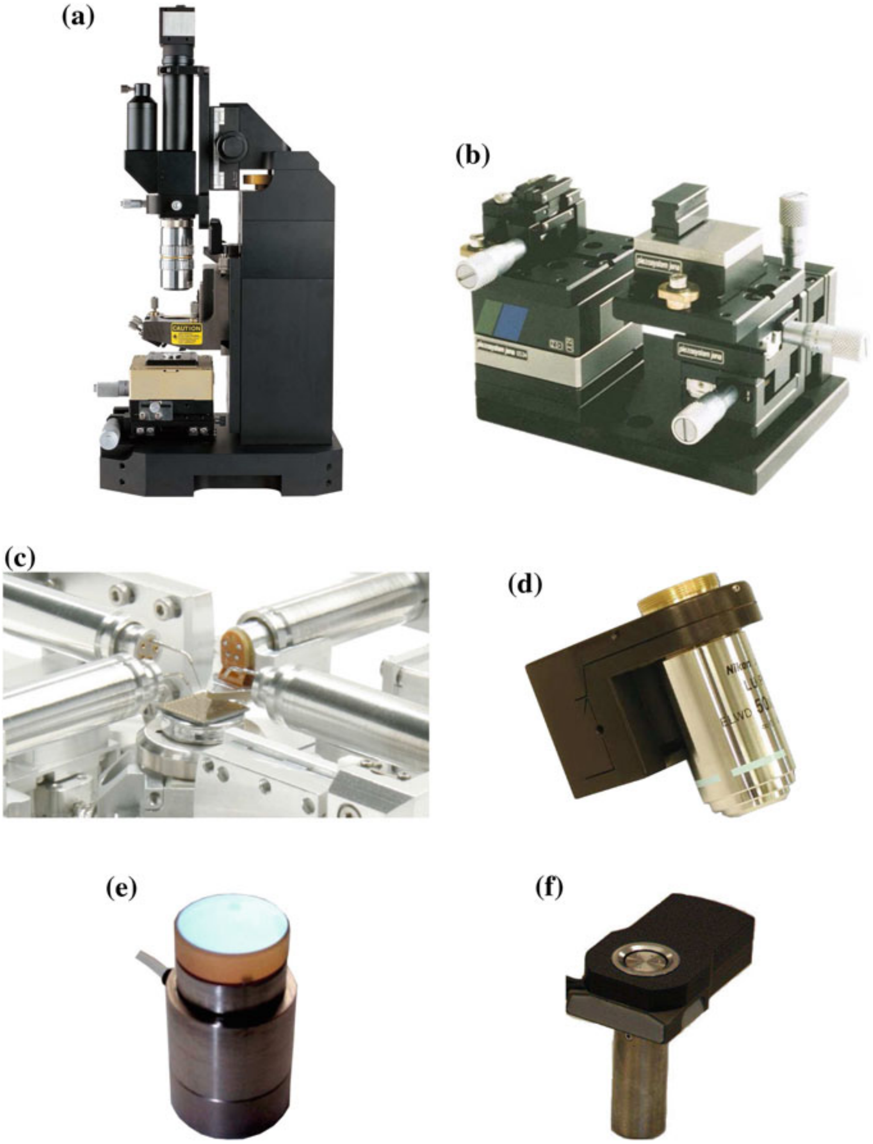

Fig. 1.2 Examples of commercial nanopositioning systems. **a** Park Systems Corp. (Korea) atomic force microscope with 2-axis sample nanopositioner. **b** Piezosystem Jena GmbH (Germany) fiber alignment system with 3-axis nanopositioner. **c** Zyvex Instruments (USA) probe station with four piezoelectric tube nanopositioners. **d** Madcity Labs Inc. (USA) microscope objective nanopositioner. **e** Queensgate Instruments Ltd. (UK) mirror tilting stage. **f** NT-MDT Co. (Russia) piezoelectric tube nanopositioner for scanning probe microscopy

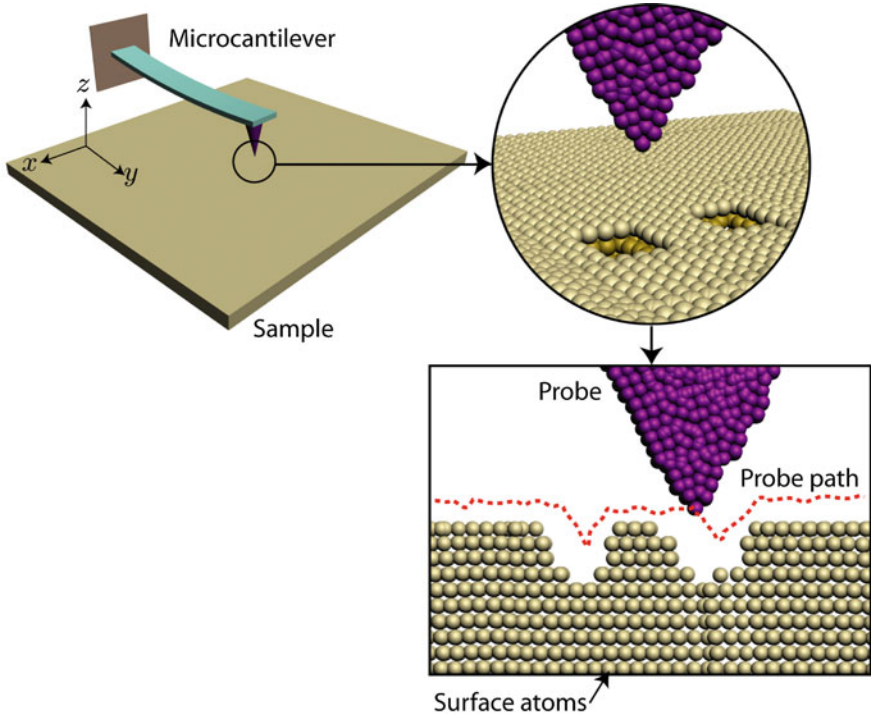

Fig. 1.3 The operation of an atomic force microscope

of the most versatile microscopes due to its ability to work with conducting and nonconducting samples in a vacuum, air, or in water (Binnig and Quate 1986). The probe is a micro-machined cantilever with a sharp tip protruding toward the sample surface. When the probe is brought into contact with the surface, the tip-to-sample interaction causes the cantilever to deflect vertically. This deflection is measured and used to construct an image of the sample. The AFM essentially "feels" the surface with a tiny, finger-like cantilever. In a vacuum, resolution of an AFM is on the order of 0.01 nm. With such high resolution, an AFM can generate topographical images of atoms, as well as to control, manipulate, and alter the properties of matter at the nanoscale (Salapaka and Salapaka 2008).

The positioning of the probe tip relative to the sample can be achieved with two basic configurations: (a) scan-by-sample or (b) scan-by-probe as shown in Fig. 1.4. In the scan-by-sample configuration, the nanopositioner, flexure-based design shown equipped with three piezo stacks, moves the sample relative to a fixed probe. The x and y axis piezos position the sample along the lateral direction (parallel to the sample surface) and a z axis stack moves the sample vertically. The deflection of the cantilever is measured optically, by reflecting a laser beam off the end of the cantilever onto a nearby photodetector. Alternatively, in the scan-by-probe arrangement shown in Fig. 1.4b, a nanopositioner moves the probe relative to a fixed sample both laterally

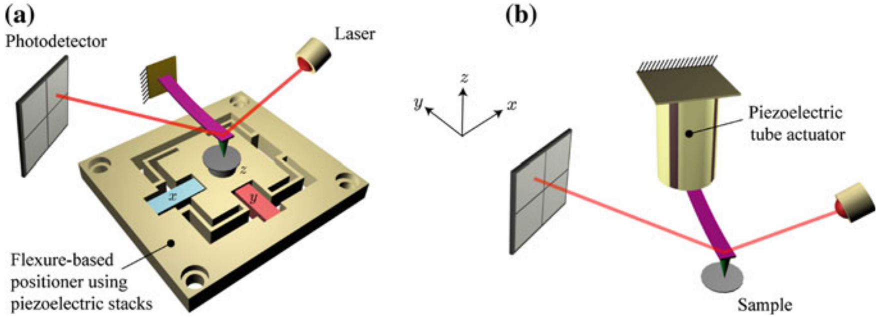

Fig. 1.4 Two positioning schemes for SPMs: **a** scan-by-sample and **b** scan-by-probe

and vertically. In scan-by-probe systems, the laser and photodector are required to move with the cantilever; however, this can be avoided by incorporating sensing elements into the cantilever itself, such as using piezoresistive, piezoelectric, or capacitive elements.

There are three basic operating modes of an AFM: contact, noncontact, and tapping mode. In contact mode, the probe interacts with the sample at very close range where the dominant force on the tip is repulsive. In this mode, the deflection of the AFM cantilever is sensed and a feedback controller is used to maintain a desired deflection. The spring constant of a contact mode AFM cantilever varies between 0.001 and 10 N/m.

Soft samples such as living cells have a contact stiffness comparable to, or less than, the cantilever stiffness, therefore, they may be deformed or damaged during contact mode operation. Noncontact mode avoids direct sample contact by exploiting attractive Van der Waals forces. In this mode, the AFM tip is hovered above the surface (at approximately 50–150 Å). By oscillating the tip, the effective stiffness of the microcantilever is effected by the force gradient of the attractive forces. The effective stiffness can be related to the sample topography by measuring or regulating the amplitude, phase, or resonance frequency of the probe. In general, noncontact mode AFM provides lower resolution than contact mode but does not pollute or damage the sample. Noncontact mode can also be used to measure long range forces such as magnetic or electric fields in samples such as hard disk media or charged insulators.

For high-resolution imaging of soft samples such as living cells, polymers, and gells, tapping mode AFM is the preferred method. In this mode, the AFM cantilever is oscillated near its resonance frequency (50 kHz–1 MHz) using a piezoelectric actuator. As the AFM tip is brought into contact with the surface, the tip lightly touches or taps the surface. When the cantilever intermittently contacts the surface, the oscillating behavior is altered by the energy loss during the tip-to-sample interaction. The change in energy is monitored and used to construct an image of the surface.

Precision positioning is needed in many AFM applications. In particular, precise position control in both the lateral and vertical directions is needed to hold the probe at a desired location or to track a desired motion trajectory. For instance, when the AFM is used to create quantum dots (2–80 nm in size), accurate position control of the indenter tip is needed as the probe position directly affects the size, spacing, and distribution of the nanofeatures. Even 2–4 nm variation in size and spacing of the nanofeatures can drastically alter their properties (Leonard et al. 1993). Additionally, high-speed control of the probe's movement is needed for high throughput fabrication, imaging, and metrology. Without accurate motion control along a specific trajectory at high speed, oscillations can cause the tip to collide with nearby features, leading to excessive tip-to-sample forces and imaging artifacts. Large forces can damage the probe tip or soft specimens such as cells. Thus, accurate position control is critical in an AFM.

1.4 Challenges with Nanopositioning Systems

Due to their effectively infinite resolution, piezoelectric actuators are universally employed in nanopositioning applications. However, the positioning accuracy of piezoelectric actuators is limited by hysteresis over large displacements, creep, and thermal drift which is present at low-frequencies. Another major problem with nanopositioning systems is the presence of lightly damped mechanical resonances. These dynamics can result in large oscillations, particularly when step-changes or high frequency inputs are involved. The impact of these detrimental phenomena are discussed below.

1.4.1 Hysteresis

When employed in an actuating role, piezoelectric transducers display a significant hysteresis in the transfer function from the applied voltage to the resulting strain or displacement (Adriaens et al. 2000). A typical hysteresis response is plotted in Fig. 1.5. In dynamic applications, hysteresis is considered the foremost limitation to performance. It leads to poor positioning accuracy, poor repeatability, and mixing of harmonic content into the displacement response.

1.4.2 Creep

When a piezoelectric transducer is commanded by a step change in voltage, the response speed is limited only by the mechanical resonance of the host structure or transducer. Creep, illustrated in Fig. 1.6, is the phenomenon where actuator deflection slowly "creeps" upward after an increase in applied voltage. The time constant is typically a few minutes. Creep severely degrades the low-frequency and static positioning ability of piezoelectric actuators.

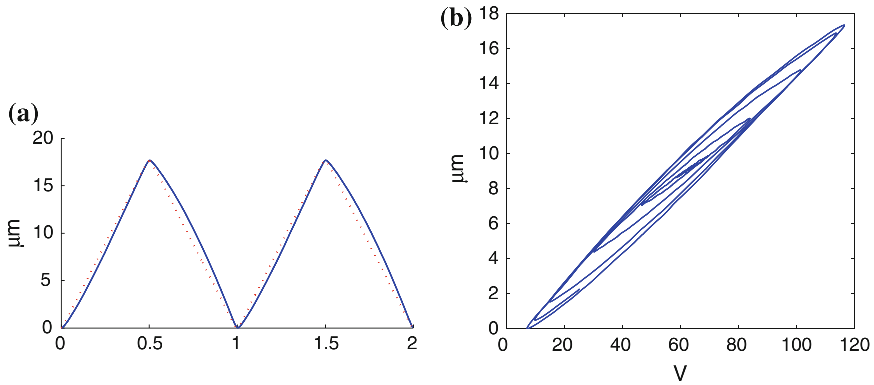

Fig. 1.5 Displacement hysteresis exhibited by the P-733 nanopositioner described in Sect. 3.2.2. **a** *Triangle input* The displacement in µm is plotted against time in seconds. **b** XY plot of displacement versus spplied voltage with an increasing amplitude sine wave input

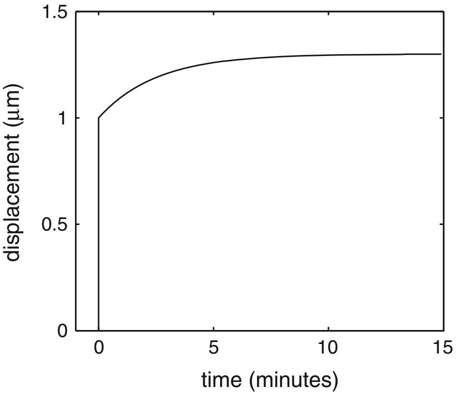

Fig. 1.6 An example of piezoelectric creep. The response to a step change in voltage is plotted over a period of 15 min

1.4.3 Thermal Drift

The properties of piezoelectric materials are highly temperature dependent. Figure 1.7 shows a 20 % increase in displacement sensitivity over a range of 50 °C. In the worst case, this would result in a drift of 0.4 % of the full range per degree of temperature drift. This is vastly more significant than the drift due to mechanical thermal drift. Such temperature dependence limits the use of piezoelectric transducers as calibrated force or displacement actuators.

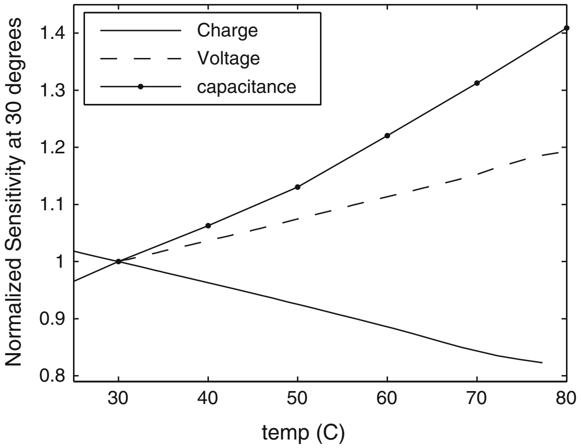

Fig. 1.7 The normalized displacement sensitivity to temperature variation of the piezoelectric tube described in Sect. 3.1.1

1.4.4 Mechanical Resonance

The greatest speed limitation of a nanopositioner is the mechanical resonances that arises from the platform mass interacting with the stiffness of the support flexures, mechanical linkages, and actuators. Since the lowest resonance frequency is typically of greatest interest, the dynamics of a nanopositioner may be approximated by a unity-gain second-order low-pass system

$$G(s) = \frac{\omega_r^2}{s + 2\omega_r \zeta s + \omega_r^2}, \tag{1.1}$$

where ω_r and ζ are the resonance frequency and damping ratio. The magnitude and phase responses of this system are plotted in Fig. 1.9. To avoid excitation of the mechanical resonance, the frequency of driving signals is limited to around 1–10 % of the resonance frequency. In applications where scan frequency is the foremost performance limitation, for example in high-speed atomic force microscopy (Ando et al. 2005; Schitter et al. 2007; Humphris 2005; Rost et al. 2005), the nanopositioner is operated in open-loop with driving signals that are shaped to reduce harmonic content. Although such techniques, reviewed in (Fleming and Wills 2008), can provide a fast response, they are not accurate as nonlinearity and disturbance remain uncontrolled.

The transient response of a nanopositioning stage can be vastly improved by actively damping the first resonance mode. This can reduce the settling time by greater than 90 % and allow a proportional increase in the scan speed. Systems with active damping also facilitate greater tracking performance as the controller gain can be significantly increased, as discussed in the following subsection.

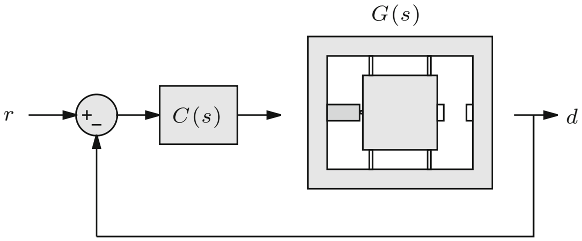

Fig. 1.8 A nanopositioner G in a displacement feedback control loop

1.5 Control of Nanopositioning Systems

1.5.1 Feedback Control

The most popular technique for control of commercial nanopositioning systems is sensor-based feedback control (Fig. 1.8) using integral or proportional-integral control (P Instruments 2009). Such controllers are simple, robust to modeling error, and effectively reduce piezoelectric nonlinearity at low-frequencies. However, the bandwidth of integral tracking controllers is severely limited by the presence of highly resonant modes. The cause of such limited closed-loop bandwidth can be explained by examining the loop gain $|CG|$ in Fig. 1.9. Here, the resonant system G is controlled by an integral controller C with gain α. The factor limiting the maximum feedback gain and closed-loop bandwidth is gain margin.

At the resonance frequency ω_r the phase lag exceeds π so the loop gain must be less than 1 or 0 dB for stability in closed-loop. The condition for closed-loop stability is

$$\frac{\alpha}{\omega_r} \times \frac{1}{2\zeta} < 1, \text{ or } \alpha < 2\omega_r\zeta. \tag{1.2}$$

As the system G is unity gain, the feedback gain α is also the closed-loop bandwidth ω_{cl} (in radians per second). Thus, the maximum closed-loop bandwidth is proportional to the product of damping ratio ζ and resonance frequency ω_r, that is,

$$\text{max. closed-loop bandwidth} < 2\omega_r\zeta. \tag{1.3}$$

This is a severe limitation as the damping ratio is typically on the order of 0.01, so the maximum closed-loop bandwidth is less than 1 % of the resonance frequency. The maximum closed-loop bandwidth can also be estimated directly from the frequency response by replacing the factor 2ζ with $1/P$, where P is the linear magnitude of the resonance peak divided by the DC gain, that is

$$\text{max. closed-loop bandwidth} < \frac{\omega_r}{P}, \tag{1.4}$$

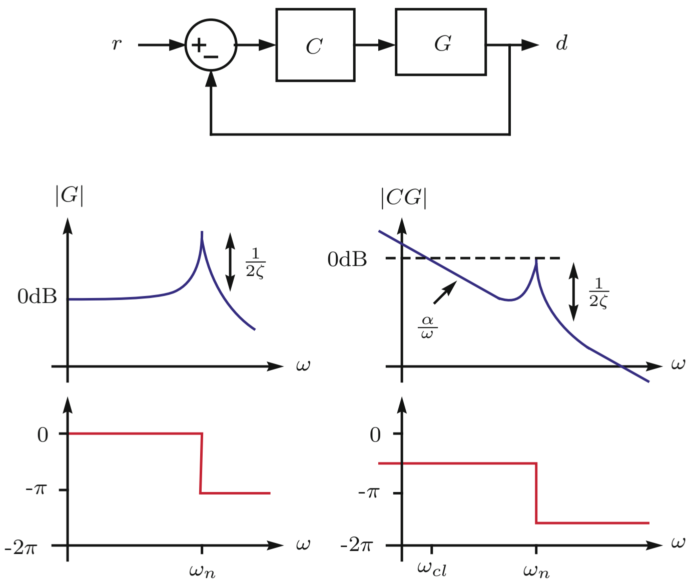

Fig. 1.9 A nanopositioning system G controlled by an integral controller $C = \alpha/s$. The frequency response of G and the system loop gain CG are plotted on the *left-hand side* and *right-hand side*, respectively

Techniques aimed at improving the closed-loop bandwidth are based on either inverting the resonance using a notch filter (Abramovitch et al. 2008) or damping the resonance with a damping controller (Aphale et al. 2008). Other feedback-based approaches include state-feedback (Okazaki 1990), gain scheduling (Merry et al. 2009), robust control (Korson and Helmicki 1995; Salapaka et al. 2002), and repetitive control (Aridogan et al. 2009; Merry et al. 2011; Shan and Leang 2012).

Inversion techniques are popular as they are simple to implement and can provide excellent closed-loop bandwidth, up to or greater than the resonance frequency (Abramovitch et al. 2008). The major disadvantage of inversion-based techniques is the requirement for an accurate system model. If the system resonance frequency shifts by only 1 %, a high-gain inversion-based feedback controller can become unstable. In most applications this is unacceptable as the load mass and resonance frequency can vary significantly during service. As a result of this sensitivity, high-performance inversion-based controllers are applied in applications where the resonance frequency is stable, or when the feedback controller can be continually recalibrated (Abramovitch et al. 2008).

Damping control is an alternative method for reducing the bandwidth limitations imposed by mechanical resonance. Damping control uses a feedback loop to artificially increase the damping ratio ζ of a system. Due to Eq. (1.2), an increase in ζ allows a proportional increase in the feedback gain and closed-loop bandwidth. Although damping controllers alone cannot increase the closed-loop bandwidth to beyond the resonance frequency, they have the advantage of being insensitive to variations in resonance frequency. In addition, as damping controllers suppress, rather than invert, the mechanical resonance, they provide better rejection of external disturbances than inversion-based systems (Devasia et al. 2007).

A number of techniques for damping control have been demonstrated successfully in the literature, these include Positive Position Feedback (PPF) (Fanson and Caughey 1990), polynomial-based control (Aphale et al. 2008), shunt control (Fleming and Moheimani 2006), resonant control (Sebastian et al. 2008) and Integral Resonance Control (IRC) (Aphale et al. 2007, 2008). These techniques can successfully damp a system resonance with modest insensitivity to variations in resonance frequency. However, like all feedback control systems, the tracking controller gain is still limited by stability margins and the positioning resolution is still dominated by sensor-induced noise.

To demonstrate the limitations imposed by sensor noise, consider a nanopositioner with feedback control derived from a high performance capacitive sensor with a range of $\pm 100\ \mu\text{m}$ and root-mean-square (RMS) noise of $20\,\text{pm}/\sqrt{\text{Hz}}$. An estimate of the RMS positioning noise can be found by multiplying noise density by the square-root of closed-loop bandwidth. i.e.,

$$\text{RMS Noise} = \sqrt{\text{Bandwidth}} \times \text{Noise Density}. \tag{1.5}$$

For example, with a closed-loop bandwidth of 100 Hz, the positioning noise is 0.2 nm RMS or approximately 1.2 nm peak-to-peak (if the noise is normally distributed). For atomic resolution, the closed-loop bandwidth must be reduced to below 1 Hz, which is a severe limitation.

1.5.2 Feedforward Control

Feedforward or inversion-based control is commonly applied to both open- and closed-loop nanopositioning systems that require improved performance (Devasia et al. 2007; Butterworth et al. 2008). Good reference tracking can be achieved if the plant model or its frequency response are known with high accuracy. In addition to improved performance, other attractive characteristics of inversion-based control are the lack of additive sensor noise and the ease of implementation, particularly in high-speed applications (Schitter and Stemmer 2004).

The foremost difficulty with inversion-based control is the lack of robustness to variations in plant dynamics, especially if the system is resonant (Devasia 2002; Butterworth et al. 2008). However, this problem only exists with static feedforward controllers. More recently, iterative techniques have been reported that eliminate both vibration and nonlinearity in systems with periodic inputs (Wu and Zou 2007). Although such techniques originally required a reference model (Wu and Zou 2007), in 2008, both Kim and Zou (2008), Li and Bechhoefer (2008) presented techniques that operate without any prior system knowledge. Both techniques achieve essentially perfect tracking of periodic references regardless of nonlinearity or dynamics. A feedback-based repetitive controller has been designed for tracking periodic reference trajectories (Aridogan et al. 2009; Shan and Leang 2012, 2013). Unfortunately iterative feedforward and repetitive control approaches are restricted to applications with periodic references. A digital signal processor is also required.

1.6 Book Summary

This book aims to provide a practical introduction to the design and control of nanopositioning systems. It includes introductory content for the beginner and more advanced topics for achieving the maximum performance from piezoelectric nanopositioning systems.

1.6.1 Assumed Knowledge

Approximately half of the content in this book is introductory and will suit readers from diverse backgrounds in physics, electrical engineering, and mechanical engineering. The more advanced concepts such as hysteresis inversion and command shaping are targeted at control engineers aiming to achieve maximum performance from nanopositioning systems; however, an introduction to these concepts is also provided for those without a background in control theory.

It is assumed that the reader is familiar with basic linear systems and control theory, for example: transfer functions, state space systems, frequency response analysis, transient response analysis, and stability. The chapters on Hysteresis and Command Shaping will also require a working knowledge of linear algebra and optimal control theory. An understanding of electronics and circuit theory is required for the chapters on Shunt Control, Charge Drives, and Electrical Considerations. The chapter on Mechanical Design assumes basic knowledge of solid mechanics including: stress, strain, bending moments, etc.

1.6.2 Content Summary

For a newcomer to the field of piezoelectric nanopositioning, the chapters are designed by be read in order. The concepts of piezoelectricity, nanopositioning, and mechanics are introduced in Chaps. 2, 3 and 4. These chapters are followed by an introduction to position sensor technology in Chap. 5 and basic control techniques in Chap. 7.

The advanced topics begin with Shunt Control in Chap. 6 and Force Feedback control in Chap. 8. Both of these methods improve the controllability of a nanopositioner by reducing or eliminating the mechanical resonances. The servo bandwidth can also be improved by the Feedforward and Command Shaping techniques described in Chaps. 9 and 10, respectively.

The modeling and inversion of piezoelectric hysteresis is considered in Chap. 11. This is followed by an introduction to charge amplifiers in Chap. 12 which can be an effective way of reducing hysteresis in dynamic applications. This book concludes with a detailed analysis of positioning noise in Chap. 13 and an introduction to the electrical limitations in Chap. 14.

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