Piezoelectric stack actuateds nanopositioners engineering essay

Engineering

CopyrightbyUgolo Efetobore EbibodeHIDDEN TEXT: Optional—If you do not include a copyright page, delete entire page and the following page break. The Thesis Committee for University of AberdeenCertifies that this is the approved version of the following thesis: Resonance damping of a nanopositioner via closed-loop controlAPPROVED BYSUPERVISING COMMITTEE: Sumeet S. AphaleResonance damping of a nanopositioner via closed-loop controlbyUGOLO EFETOBORE EBIBODEThesisSubmitted as part of the requirement for the MEng. degree in EngineeringMASTER DEGREE OF ENGINEERING IN ELECTRICAL & ELECTRONIC ENGINEERINGhttp://www. tauracing. com/images/spons/University%20of%20Aberdeen. jpgSchool of Engineering, University of AberdeenMay, 2013DedicationThis thesis is dedicated to God almighty and my family. AcknowledgementsI wish to acknowledge the support of my academic supervisor, Dr. Sumeet S. Aphale for his advice and guidance while carrying out this project. I will also like to thank my family for their constant love and support which gave me the confidence and drive to pursue and realise my dreams. AbstractHidden text: The abstract may be included at the discretion of the supervisor. Piezoelectric-stack-actuated nanopositioners are used in Scanning Probe Microscopes. These systems are found in a lot of industrial applications and are resonant in nature. They are characterized by a lightly damped resonant mode which dominates their frequency response thus leading to extreme limitation in their overall positioning bandwidth. Also, positioning errors can be introduced from the higher order harmonics of the triangular waveform typically used to excite these systems. These shortcomings have limited the performance of these systems with reference to the continuous and growing demand for higher engineering precision accuracy in the fields they are employed. Consequently, various open loop and close loop control damping strategies have been employed, modified and are been researched to alleviate and possibly eliminate the problems limiting the performance of the nanopositioners. The main objective of this thesis is therefore to carry out a review of the available damping strategies with a view to design and simulate the performance of a preferred strategy suitable for high speed, accurate nanoscale positioning applications and with good tracking performance. This follows a short review of the applications, designs, problems and remedies of nanopositioners. Table of ContentsHIDDENT TEXT: If you choose to place the chapter number (" Chapter 1") and the chapter title (" Introduction") on different lines, the automatically generated table of contents will reflect that format. After creating a new table of contents, set them on the same line by deleting the page number and paragraph marker at the end of each chapter number line.

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List of AbbreviationsSPM – Scanning Probe MicroscopeSTM – Scanning Tunnel MicroscopeAFM – Atomic Force MicroscopePZT – Lead zirconium titanateMEMS – Micro-electromechanical systemsNEMS – Nano-electromechanical systemsPPF – Positive Position FeedbackPVPF – Positive Velocity and Position FeedbackIRC – Integral Resonant Control

INTRODUCTION

Piezoelectric stack actuated nanopositioners are widely used in the design of the Scanning Probe Microscope (SPM). This successful application of Nanotechnology is characterised by a lightly damped resonance mode which limits the accuracy of the scanners’ performance. Other problems which considerably limit the performance of the system are hysteresis; creeps; cross coupling; thermal drift and uncertainties which results mainly due to the nonlinearity nature of the device. Over the past 20years, engineers have employed various control strategies to improve the performance of the SPM. Both passive and active damping control strategies have been successfully employed, with records of substantial damping and improvement in the performance of SPM, with reference to the growing ultra –high precision positioning requirements of various science fields. Control strategies employed, aim at damping the resonance mode of the system primarily, but also reduce the effect of other associated problems with the system by its' robustness to system uncertainties, thereby improving the precision of the scanning probe, making it possible for higher resolutions and improved scanning bandwidth. This project will review the available open loop and close loop damping strategies with the aim of designing and simulating a preferred choice to show damped resonance with improved system performance and robustness to system uncertainties.

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Objectives

The objective of this project includes the following; A review of nanopositioners with respect to their applications, design, problems and remedies. Derive models for the two axes of the nanopositioner for which frequency response data was made available; match frequency response of both given and derived models to confirm correct modelling technique and finally, simulate the open-loop raster scanning performance of the nanopositioner using SIMULINK. A review of the existing open - loop and close- loop damping schemes for resonant systems, comparing their advantages and disadvantages. With supportive argument for a chosen control strategy, design the closed-loop damping controller and simulate the performance for the damped system using SIMULINK. Compare the performance of the open-loop system to the closed-loop system and comment on the findings. Identifying if the technique is robust to plant uncertainties such as change of resonant frequency by applying a change of 10% to the resonant frequency and comparing performance with earlier performance. Implementation of a suitable tracking controller and compare performance.

Thesis structure

This thesis comprises 6 chapters, with chapter 1 presenting an introduction to the project, setting out the background to the work, its objectives, methodology and broad structure. Chapter 2 provides a more detailed overview of nanopositioners, focussing particular on their applications, designs, problems and remedies. Chapter 3 deals with the modelling of an open-loop nanopositioner and simulation of its raster scanning performance. Chapter 4 contains a review of existing open - loop and close- loop damping schemes with regards deciding on a preferred control strategyChapter 5 presents the design and simulation of the preferred resonance control scheme, showing improved damping of the system and its robustness to plant uncertainties. Also presented in this chapter is the design and simulation of a suitable tracking controller for the damped system. Chapter 6 is the concluding section with recommendations for further research work to develop the proposed strategy.

OVERVIEW OF NANOTECHNOLOGY AND NANOPOSITIONERS

Brief History of Nanotechnology

The development of micro-technology can be placed at about sixty years with reference to the period of the invention of semiconductor transistor. However, the practical development of nanotechnology started with the invention of Scanning Tunnelling Microscope (STM) in the early1980s by

Gerd Binning and Heinrich Roher [1]. The Atomic Force Microscope (AFM) was invented in 1986 by C. F. Quate, G. Binning and Ch. Gerber [2]. These equipments enabled the visualization and manipulation of matter with Nano-scale requirements.

Nanopositioning

This involves precision control and manipulation of devices at nanoscale. A nanopositioner can easily be described as a mechanical device made of a movable component in a rigid frame used for nanopositioning. Controlled nanopositioning systems consist of four main elements: Piezo actuators for motionStage (mechanism of mechanical translation)Sensor for positioning measurementController to maintain desired positionThe word Piezo is derived from a Greek word " piezein", which means to squeeze or press. Piezoelectric actuators are characterised by quite a small change in dimension when an electric field is applied (e. g. 0. 1%) [3]. However, the following properties listed below makes these materials ideal for applications which involves positioning at nanometer sensitivity: It has the capacity of providing repeatable motion at nanometer scale. Do not suffer from wear and tear and do not have backlash. Have fast response time and can generate large forces. Operational in a wide temperature range and barely needs maintenance. They are not affected by magnetic fields. A commonly used piezoelectric material is lead zirconium titanate (PZT). A Piezoelectric stack actuator is a multilayer of stack PZT thin films which are connected electrically in parallel. The thinner the individual film, the lower the voltage required to obtain maximum expansion of the general stack. These materials can be designed for effectively any application for which electromechanical transducer are used for [4]. At present these devices are been employed in a wide range of engineering motion applications such as movement in all three translational axes, angular, rotation and tilting requirements where emphasis on accuracy with nanometer precision are required for success [5]. However, Scanning Probe Microscopes made from piezoelectric material suffer high mechanical resonance and some inherent nonlinear properties such as [5]; hysteresis, creep, thermal drift, etc. Two main types of piezoelectric device have been successful used in the manufacturing of the Scanning Probe Microscopes. These are the piezoelectric tube and the piezoelectric stack actuator.

Piezoelectric tube

These actuators are made out of monolithic ceramics and provide good flexibility in applications under conditions such as high vacuum and high temperatures. Depending on the applied voltage to the ceramic tube, the length and the diameter of the tube may contract or expands. Applications requiring three axes motion can be achieved by multi-electrode configurations. The inside surface of the piezoelectric tubes is generally poled as positive. Positive supply is thus achieved when the applied field is same with the original poling direction. Bending deflection in segmented tubes is achieved when one segment is biased similarly to the original poling direction and the other segment is biased opposite to the original poling direction [1, 6]. Figure 2. 1: Side view and top view of a piezoelectric tube scanner with quartered external electrodes and a continuous inner electrode [1]The equations below can be used to calculate change in linear dimension, change in diameter and mean diameter change respectively:$\Delta L = D31 \times L \times$

(V/t)(1)$\Delta D = D33 \times V$(2)$DM = (OD + ID)/ 2$(3)Where, L = Tube Length; ΔL = Change in length[m]; ΔD = Diameter change [m], t = Wall thickness of the tube; DM = mean diameter [m]; ID = Inner Diameter [m]; OD = Outer Diameter [m]; V = Applied voltage [V]; $D31$ = strain coefficient (relating the displacement to the polarization direction) [m/V]; $D33$ = strain coefficient (relating the field and displacement to the polarization direction) [m/V],

Piezoelectric stack actuator

They are made of two or several linear actuators glued together. The purpose of the stacking is to obtain more displacement than can be achieved by a single linear actuator. Stack actuators achieve relatively higher displacement of up to 0. 2 % compared to that of the piezoelectric tube which is about 0. 1%. Similar to the piezoelectric tubes, displacement in piezoelectric actuators is a relative to the actuator length, the applied electric field and the piezoelectric material properties. The material properties are described by the piezoelectric strain coefficients. Figure 2. 2: Basic principle of a piezoelectric stack actuatorThe equation below can be used to calculate the change in length of a single-layer piezo actuator:$\Delta L = S \times L0 \approx \pm E \times d33 \times L0$ (4)Where, S is the strain (dimensionless), $L0$ is the original length [m], E is the electric field strength [V/m], $d33$ is the piezoelectric coefficient of material [m/V], with $d33$ and $d31$ usually referred to as " piezo gain". Piezoelectric tube scanners are still widely used in Scanning Probe Microscopes but are now being overtaken by piezoelectric stack-actuated nanopositioning platforms, due to their larger range of motion, greater mechanical robustness, and lower cross coupling between the axes. [3]When scanning with an SPM, the piezoelectric tube or piezo electric stack actuator is actuated in a raster pattern. Precision and speed is required for good scan results [1]. To successful achieve precise positioning at nanometer levels, requires a careful design and optimization of the positioning sensor, the mechanical design of the system and motion controller.

Types of Actuators

An actuator can broadly be defined as a device that produces motion from a source of power. Piezoelectric actuators converts electrical signal into physical displacement or a useable force when displacement is prevented. Below is a review of some types and their usage in the field of nanotechnology.

Piezo Actuators

Piezoelectric actuators as mentioned earlier, converts an electrical signal into a physical displacement. Based on these characteristics, it is employed in the design of nanopositioners. These devices have applications in areas where a precision controlled displacement is required e. g. to finely adjust precision machining tools, lenses, mirrors, hydraulic valves etc. [7].

Piezoelectric Generators

Piezoelectric generators with the right amount of force are capable of producing voltages which is sufficient to cause a spark across an electrode gap, thus they are used as ignitors in small lighters, welding equipment, gas cookers, etc. Piezoelectric ignition systems are generally small and simple [8].

Piezoelectric Sensors

Piezoelectric sensors are capable of converting a physical parameter, such as system pressure or system acceleration to an electrical signal. This may involve the physical parameter acting directly on the piezoelectric element or an audio signal capable of establishing vibrations in the element maybe employed. The vibrations are then converted into an electrical signal [9]. They are widely employed as sensors for physical parameters in controlled systems.

Piezoelectric Transducers

Piezoelectric transducers have a dual effect. They can convert electrical energy into vibrational mechanical energy and also can convert mechanical vibrations into an electrical signal [10]. A single piezoelectric transducer can be used in the design of devices for measuring flow rates, distances, or fluid levels, incorporate both the signal sending and receiving roles. Other designs can incorporate two transducers and separate the roles.

Review of Application Areas of Nanotechnology

Researches in fields such as Micro-Electromechanical Systems (MEMS), Nano-Electromechanical Systems (NEMS) and other Micro-Nanotechnologies have led to a wide area of technological development. Below is a review of the main area of interest with regards this project and a brief view into other areas and how these researches have or will improve modern technological application.

Scanning probe microscopy

Scanning probe microscopy (SPM) refers to a family of instruments which enables us to study and manipulate materials over dimensions of several 100 mm to 10 pm. These devices are capable of interrogating and when required, altering the surface profile of a sample at the molecular and atomic levels. The two most widely used SPMs are Scanning Tunnelling Microscopes (STMs) and Atomic Force Microscopes (AFMs). Scanning Tunnel Microscopes: These devices operate with the principle of quantum tunnelling. It consist of a sharp probe tip which when brought very close to a conducting surface which is to be examined, allows electrons to tunnel through the vacuum between the probe tip and the surface of the material . Once a tunnelling current is established, the probe is moved in a raster pattern (i. e. a scanning pattern in which a surface area is scanned from side to side in lines from top to bottom) in the x-y plane over the surface. This enables information acquisition which can be used to generate image of the surface with atomic resolution. During the scanning process, due to the nonlinear nature of material surfaces at nanometer range, good quality resolutions will require regulating of the distance between the probe tip and the surface to ensure effective scanning [1]. Atomic Force Microscopes: This device, like the STM, relies on a scanning approach to generate images of material surfaces. With the AFM, measurement of ultra-small forces in the order of 1 nN or less, which is obtained by measuring the motion of a very flexible micro cantilever with a very small mass, placed between the probe tip and the surface to be examined is used to generate the image. This process enabled the investigation of non-conducting surfaces which was a major restriction for the STM [1].

Medical Science/Biology

Nanotechnology has brought about advances in nanofabrication techniques. This has opened a wider area of highly sophisticated biomedical applications for magnetic nanoparticles for experimental use, both in vitro and in vivo research and applications. In vitro applications, several biotechnological approaches have been developed in the past using magnetic nanoparticles. A molecular biological diagnostic procedure which has become more and more important is bio magnetic separation. This process involves using magnetic nanoparticles bounded to antibodies to target cells, DNA or bacteria. After binding of the ligands the targets can be separated by the use of an external magnetic field. Another successful medical approach which employs nanotechnology is magnetic cell separation for in vitro diagnosis in cancer patients. Scattered tumour cells in the peripheral blood of cancer patients are detected with the use of super paramagnetic nanospheres. For in vivo application, magnetic nanoparticles are either incorporated or coated by different materials to enable biocompatibility. Delivery of therapeutic agents to specific body compartments without harming healthy tissue has been achieved. This approach uses carriers like magnetic microparticles, magnetoliposomes or magnetic iron oxide nanoparticles to increases the concentration of drugs in the region of interest [5] as well as in tissue engineering [11].

Aerospace/space

Nanotechnology development from a space system perspective promises and has enabled high capability devices and systems with low mass and low power consumption. Successes in the aerospace technology includes areas such as vibration control and cancellation, thrusters, structural monitoring, fuel injection systems, valve control, adaptive coating and corrosion protection for aluminium alloys, solar power generation and utilization as well as energy storage devices.[12]

Agriculture

The application of nanotechnology in agriculture mainly involves food packaging and enhancement of food products. The main focus is directed towards enhanced uptake but making available nanosized substances rich in nutrients for consumption. Other benefits, such as improvement in taste, longer shelf life, safer packaging, better traceability of food products, consistency, stability, texture and healthier food can also be achieved [13].

Problems associated with nanopositioning

The efficiency of nanopositioners in nanopositing applications as earlier pointed is affected by quite a number of nonlinear factors besides its lightly damped resonant mode. Below is a brief review of the nonlinear factors which considerably affect the performance of SPM.

Hysteresis

Hysteresis is the main form of nonlinearity in piezoelectric actuators. The original meaning of the word refers to " lagging behind" or " coming after". In other words, it describes situations when the consequences or effect of an input are experienced with a certain delay or lag time. The level of hysteretic distortion in a piezoelectric actuator varies depending on either the maximum value of the input voltage being applied, the frequency of the input signal or both [1, 14].

Creep

Creep is defined as the deformation tendency of a solid material under the influence of stresses. The rate of deformation in materials is usually a function of the properties of the material, operational temperature, operational time and the applied force or structural load. This is a common undesirable property associated with piezoelectric actuators and can result in significant loss in precision when positioning is required over extended operational periods. In particular, during slow operation of SPMs, creep can result in significant distortions in the image generated [15].

Thermal Drift

This effect arises as a result of the thermal expansion or contraction of the mechanical components used in making the nanopositioner. In a typical SPM, operated in ambient temperature, a 1° change in temperature can cause a 50 nm drift of the actuator. Although this effect can be suppressed in low temperature experiments, in applications that involve interrogation and manipulation of the matter in ambient temperature it amounts to a substantial hurdle. [1, 14]

Cross coupling

Cross-coupling effect is one of the main complications associated with scanning applications. It refers to the positioning error along one axis generated while the nanopositioner moves in other axis, such as the stage's response in the X axis when the stage is driven in the Y axis. It is often assumed to be negligible. However, it has been shown that such effects could become significant if the actuator is used in a high-speed scanning process [14, 15].

Remedies

Scanning probe microscopes are successfully used in the industry today. The quality of image resolutions is dependent on the design of the scanner used with regards to its robustness to uncertainties and the nonlinearity factors of the system which affect its’ performance. Below are some design techniques employed in ensuring high quality scanning is achieved when manufacturing SPM.

Open loop / Close loop control system:

In open-loop control system of a nanopositioner, a voltage signal is applied as input for motion control. But due to the nonlinearity nature of the piezo-actuators, and the possibility of having system uncertainties, positioning errors may occur in the system. In closed-loop control system a position sensor is employed to monitor the position of the stage. Errors in system performance is fed-back to the controller for correction. This cause the nanopositioner to reach its precise commanded position [14].

Flexure stages

This involves the use of flexure bearing or hinges to link a static base to a moveable platform of a system. The movement of the platform when an electric field is applied is guided by the flexure mechanism. This guided motion is generated by the elastic deformation of the flexure material. It causes the linkage to be friction free, resulting in smooth motion. Flexure design mechanism results provides stiffness and neutralizes errors, such as unplanned motions, crosstalk and titling. They are not affected by frictional wear and tear thus eliminating the need for routine maintenance. This ensure that performance remains consistent for the operational lifetime of the stage [16].

Kinematic mounting

Kinematic mounting helps to eliminate the distortion effect caused by the movement of the piezo-actuator to the frame of the stage. The use of kinematic mounting also reduces the effect of temperature variations on the drift of the stage.