

博士学位论文

面向原子力显微镜高通量测量的
纳米定位技术研究

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NANOPOSITIONING FOR HIGH-THROUGHPUT
ATOMIC FORCE MICROSCOPY

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摘 要

原子力显微镜(atomic force microscope, AFM)是纳米科技领域的重要发明,它以XYZ三个自由度的纳米定位技术为核心,保证了探针与样品间极高的相对运动精度,具有原子级水平的超高分辨力,成为了物质科学、生命科学和纳米制造技术发展不可替代的工具。近年来,除了精度外,各前沿领域纷纷对AFM提出了高通量测量,即兼具大范围和高速率的要求。这对纳米定位技术提出了前所未有的挑战——其必须同时具备大行程与高控制带宽。然而,在目前普遍采用的直驱范式下,纳米定位技术存在行程和带宽之间的矛盾这一核心瓶颈。因此,现有AFM要么在范围与速率之间平衡,获得中庸的性能;要么以牺牲一个指标为代价,换取另一个指标的提升。如何使AFM兼具大范围和高速测量能力是纳米技术领域亟待解决的公开难题。

本学位论文提出基于法应力电磁直驱、粘滑压电致动原理设计新型AFM定位器,克服传统致动方式无法兼顾行程和带宽的学术思想。针对所面临的电磁致动器-柔顺机构间的电-磁-机耦合、粘滑平台跨尺度高通量纳米精度运动生成等难题,从理论建模、传动机制、构型设计、测控方法、应用验证五个方面开展基础理论与关键技术研究,主要研究成果如下:

发展了考虑致动器负刚度特性影响的法应力电磁致动纳米定位器电-磁-机耦合理论,揭示了电流、致动力、刚度、位移、能量等多物理量间的映射关系,建立了基于等效磁路法、有限元方法和拉格朗日法的法应力电磁致动纳米定位器的电磁-机械耦合动力学模型。进而,在考虑定位器在实际制造和操作过程中所受到的各种约束的前提下,以定位行程与谐振频率乘积最大化为目标,对定位器样机进行了基于耦合模型的优化设计,通过有限元仿真验证了模型描述各电磁参数、机械参数影响的准确性。制作样机并开展性能测试,实验结果验证了所提出的模型在性能预测精度上的优势。

针对AFM栅格扫描测量对 X 轴 $\approx Y$ 轴 $\gg Z$ 轴的行程需求和 Z 轴 $\gg X$ 轴 $\gg Y$ 轴的带宽需求,提出了以兼顾大行程和高谐振频率的 X 轴为重点、将各轴性能需求分而治之的串联式电磁(XY)-压电(Z)混合致动三轴AFM纳米定位器构型,设计了内嵌式柔顺机构-电磁致动器一体化 X 轴拓扑结构,破解了现有法应力电磁致动平台柔顺机构体积大、质量大对实现高谐振频率的制约。利用电磁-机械耦合动力学模型确定机构参数并制作样机,实验结果验证了 X 轴在实现 $212.7\mu\text{m}$ 行程的同时具有 1313.2Hz 的谐振频率,将文献中 $200\mu\text{m}$ 级纳米定位器的谐振频率记录提升了3倍。进一步开发

了基于该定位器的 AFM 测量系统，并通过在高度校准标准样品上开展高通量测量实验证明了所提出的系统的先进性和有效性。

提出了一种通过电流产生偏置磁通进而产生可调节负刚度的电磁弹簧，探明了电磁弹簧可调负刚度特性对纳米定位器定位行程与谐振频率等关键性能指标的影响机制，并进一步研制了将负刚度电磁弹簧与法应力电磁致动纳米定位器相结合的可调刚度纳米定位器。实验结果表明，所提出的定位器在 3.24 倍的范围内实现了无级、快速的刚度调节，具备针对不同应用场景中不同性能需求而优化调整的能力，并可在各刚度设置下保证纳米级的运动精度。进一步作为 Z 轴，构建了 AFM 集成系统，实现了高刚度设置下清晰的纳米尺度成像和低刚度设置下连续的大范围成像。

提出了应用粘滑压电致动原理的、高速宏动步进与高通量微动扫描相结合的跨尺度纳米定位新方式，将直驱纳米定位的高带宽控制思想引入到粘滑定位器的扫描模式运动控制中，以级联线性动力学与摩擦模型的动力学模型为基础探明了粘滑压电定位器从扫描到步进模式转变的边界条件，定义了可扫轨迹集，即边界条件约束下各扫描频率下的最大扫描范围的集合，并提出以轨迹峰值加速度和定位器摩擦界面启动摩擦力为约束的可扫轨迹集辨识方法，实现了对扫描任务的可控性评估，使定位器的高通量扫描潜力得以充分发挥。在典型粘滑定位器上开展了高通量跨尺度纳米定位实验，实现了在 1.2 cm 内的任意宏观位置下 $3000 \mu\text{m}\cdot\text{Hz}$ 的扫描通量，较现有文献中粘滑定位器的扫描通量提升了 1-2 个数量级。

将粘滑跨尺度高通量超精密运动生成拓展至 XY 平面，发明了具有串联构型的、XY 两轴基于粘滑致动原理的 AFM 纳米定位器，提出了使用环绕状态积分反馈控制器进行过渡渐进的“高速步进+过渡渐进+高带宽扫描”三阶段控制算法，解决了步进与扫描运动高效融合、多轴跨尺度运动的轴间耦合抑制等控制难题。进一步构建了 AFM 集成系统，提出了基于粘滑压电致动纳米定位的 AFM 跨尺度抽样测量方法并在毫米级范围内开展了测量实验验证，实现了比传统毫米级 AFM 提高了 1-2 个数量级的测量通量。

以上成果可以分别满足 AFM 面向单一连续兴趣区域的高通量测量、适应带宽和行程不同需求切换的多功能测量、面向多个分散兴趣区域的高通量测量等应用场景对纳米定位器提出的新需求。

关键词：原子力显微镜，纳米定位，柔顺机构，高通量，运动控制，法应力电磁致动，可调刚度技术，粘滑压电致动

Abstract

Atomic force microscope (AFM) is a significant invention in the field of nanotechnology. At its core lies a three-degree-of-freedom (*XYZ*) nanopositioning system, which ensures extremely high relative motion accuracy between the probe and the sample, enabling atomic-level ultra-high resolution. This has made AFM an indispensable tool in the advancement of materials science, life sciences, and nanomanufacturing technologies. In recent years, beyond the pursuit of precision, emerging research fields have begun to demand high-throughput AFM measurements—that is, simultaneous requirements for long motion ranges and high scanning speed. This poses unprecedented challenges for nanopositioning technology, which must now provide both long positioning range and high control bandwidth. However, under the widely adopted direct-drive paradigm, nanopositioning faces a fundamental trade-off between travel range and bandwidth. As a result, existing AFM systems must either compromise both aspects for balanced performance or sacrifice one to enhance the other. How to achieve both large-range and high-speed AFM measurement capabilities remains an urgent and open problem in the field of nanotechnology.

This dissertation proposes novel AFM nanopositioners based on normal-stressed electromagnetic actuation and stick-slip piezoelectric actuation principles, aiming to overcome the long-standing trade-off between range and bandwidth found in conventional actuation methods. In response to key challenges—such as electro-magneto-mechanical coupling between electromagnetic actuators and compliant mechanisms, and cross-scale, high-throughput nano-precision motion generation in stick-slip systems—this work conducts fundamental theoretical and technical research in five main areas: theoretical modeling, transmission mechanisms, structural design, measurement and control methods, and application verification. The main contributions are as follows:

A theoretical framework for electro-magneto-mechanical coupling in normal-stress electromagnetic-actuated nanopositioners was developed, accounting for the actuator's negative stiffness characteristics. This model reveals the mapping relationships among multiple physical quantities, including current, actuation force, stiffness, displacement, and energy. A coupled dynamic model was constructed using equivalent magnetic circuit

methods, finite element method, and Lagrangian method. Based on this model, and under practical manufacturing and operating constraints, the design of the nanopositioner prototype was optimized with the goal of maximizing the product of range and resonant frequency. The model's accuracy in predicting electromagnetic and mechanical parameter impacts was validated through finite element simulations. A prototype was fabricated and tested, and the experimental results verified the model's predictive performance.

In response to AFM raster scanning needs—requiring $X \approx Y \gg Z$ in range and $Z \gg X \gg Y$ in bandwidth—a hybrid electromagnetic (XY)-piezoelectric (Z) nanopositioner was proposed. The design focuses on maximizing both the travel range and resonance frequency of the X -axis, decoupling the performance demands of each axis. An integrated topology of a compliant mechanism and electromagnetic actuator was developed for the X -axis, overcoming the limitations of bulky and heavy compliant mechanisms that hinder high resonance frequency in conventional systems. The coupled model was used to determine the design parameters, and a prototype achieves a 212.7 μm travel range and 1313.2 Hz resonance frequency—tripling the frequency record for nanopositioners with similar travel ranges in existing literature. An integrated AFM measurement system was built on this basis, and high-throughput tests on height calibration samples demonstrate its superiority and effectiveness.

A novel electromagnetic spring with adjustable negative stiffness was proposed, where bias magnetic flux is generated by current. The mechanism by which tunable negative stiffness influences key performance indicators—such as positioning range and resonance frequency—was elucidated. A variable-stiffness nanopositioner combining this electromagnetic spring with a normal-stress electromagnetic actuator was developed. Experiments showed that the stiffness could be continuously and rapidly adjusted over a $3.24\times$ range, enabling optimization for different application scenarios while maintaining nanometer-level motion precision across all stiffness settings. When used as the Z -axis in an AFM integrated system, it enabled both high-resolution imaging under high stiffness and continuous long-range imaging under low stiffness.

A new paradigm of cross-scale nanopositioning based on stick-slip piezoelectric actuation was proposed, combining high-speed macro stepping and high-throughput micro scanning. The high-bandwidth control philosophy of direct-drive nanopositioners was

introduced into the scanning control of stick-slip systems. Using a cascaded linear dynamic-friction model, the boundary conditions for transitions between scanning and stepping modes were established. The scannable trajectory set—defining the maximum scanning range under varying frequencies within given boundary conditions—was formulated. A method for identifying this set based on peak acceleration and interfacial friction constraints was developed, enabling controllability assessments of scanning tasks and fully exploiting the scanning potential of stick-slip positioning. Cross-scale high-throughput nanopositioning experiments were conducted, achieving a scan throughput of $3000\text{ }\mu\text{m}\cdot\text{Hz}$ at arbitrary macroscopic positions within 1.2 cm —improving the throughput of stick-slip nanopositioners by 1-2 orders of magnitude over previous studies.

This cross-scale ultra-precision motion generation was extended to the XY plane, and a serially configured AFM nanopositioner with XY -axial stick-slip actuation was invented. A three-phase control algorithm—comprising high-speed stepping, gradual transition, and high-bandwidth scanning—was proposed, using wrap-state integral feedback controllers to address control challenges such as efficient switching between stepping and scanning and suppression of cross-coupling in multi-axis motion. An integrated AFM system was established, and a cross-scale sampling measurement method based on stick-slip nanopositioning was proposed and experimentally validated over millimeter-scale ranges. The resulting measurement throughput was improved by 1-2 orders of magnitude compared to conventional millimeter-scale AFM systems.

Together, these contributions address emerging demands in nanopositioning for various AFM applications, including high-throughput measurement of continuous areas of interest, multi-functional measurement with range-bandwidth adaptability, and high-throughput measurement over multiple dispersed areas of interest.

Key words: atomic force microscopy, nanopositioning, compliant mechanism, high throughput, motion control, normal-stressed electromagnetic actuation, stiffness-tunable technology, stick-slip piezoelectric actuator