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Atomic force microscopy capable of vibration isolation with low-stiffness Z-axis actuation

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ABSTRACT

For high-resolution imaging without bulky external vibration isolation, this paper presents an atomic force microscope (AFM) capable of vibration isolation with its internal Z-axis (vertical) actuators moving the AFM probe. Lorentz actuators (voice coil actuators) are used for the Z-axis actuation, and flexures guiding the motion are designed to have a low stiffness between the mover and the base. The low stiffness enables a large Z-axis actuation of more than 700 µm and mechanically isolates the probe from floor vibrations at high frequencies. To reject the residual vibrations, the probe tracks the sample by using a displacement sensor for feedback control. Unlike conventional AFMs, the Z-axis actuation attains a closed-loop control bandwidth that is 35 times higher than the first mechanical resonant frequency. The closed-loop AFM system has robustness against the flexures' nonlinearity and uses the first resonance for better sample tracking. For further improvement, feedforward control with a vibration sensor is combined, and the resulting system rejects 98.4% of vibrations by turning on the controllers. The AFM system is demonstrated by successful AFM imaging in a vibrational environment.

1. Introduction

To investigate sample properties with high resolution, atomic force microscopes (AFMs) have a sharp probe that is scanning over the sample surface while the Z-axis (vertical) position of the probe is controlled to maintain the tip-sample distance or the probe deflection with nanometer resolution [1]. Due to the required positioning resolution, AFMs are usually sensitive to external disturbances [2]. Particularly floor vibrations, typically generated by people on the floor and traffic around the building [3], influence the designs and specifications of AFMs.

Floor vibrations can excite mechanical resonances of AFMs and fluctuate the probe's Z-axis position, resulting in artifacts on AFM images [4]. In the case of rigid AFMs, this problem is solved by increasing their resonant frequencies sufficiently higher than the floor vibrations' major spectrum [5]. For this purpose, rigid AFMs must have a rigid and short mechanical loop between the AFM probe and the sample [2,5]. Because the mechanical loop includes the Z-axis actuator of the probe, commonly used piezoelectric actuators are ideal with their high intrinsic stiffness for the loop rigidity. Due to the high stiffness, however, the Z-axis stroke of the probe is strictly limited, and a sample with high topography cannot be imaged [6]. The rigid design also limits the sample width for the short mechanical loop [5,7], which is a problem with wide samples (e.g. petri dishes and wafers [2]). Furthermore, the rigid design poses additional challenges for the design of user-friendly automated AFMs. Motorized stages for the coarse positioning of the sample or for the probe engagement are relatively large and heavy in the mechanical loop. Thus, they can result in low-frequency resonances to be excited by floor vibrations [8].

In comparison to rigid AFMs, typical AFMs with a larger actuation range have mechanical resonances at lower frequencies. For high quality imaging, they are typically operated in a quiet room, ideally satisfying certain standards (e.g. Vibration Criterion (VC) [9]). In addition, AFMs are usually placed on the tabletop of an external vibration isolator. Even with such an isolator, however, the mechanical resonances of AFMs are desired to be more than several tens of Hertz because isolating floor vibrations is difficult at low frequencies. In the case of passive vibration isolators (e.g. optical tables), their tabletop supports mechanically transmit floor vibrations below the first resonant frequency [10]. In the case of active vibration isolators, the signal-to-noise ratio of their vibration sensors degrades at low frequencies [11], and floor vibrations cannot be isolated [12]. Consequently typical AFM systems are heavy and bulky with an external vibration isolator, and they have to be placed in a quiet environment.

Overall, the vibration sensitivity of AFMs is a weakness, restricting the sample size, the functionality, and the suitability of oper-

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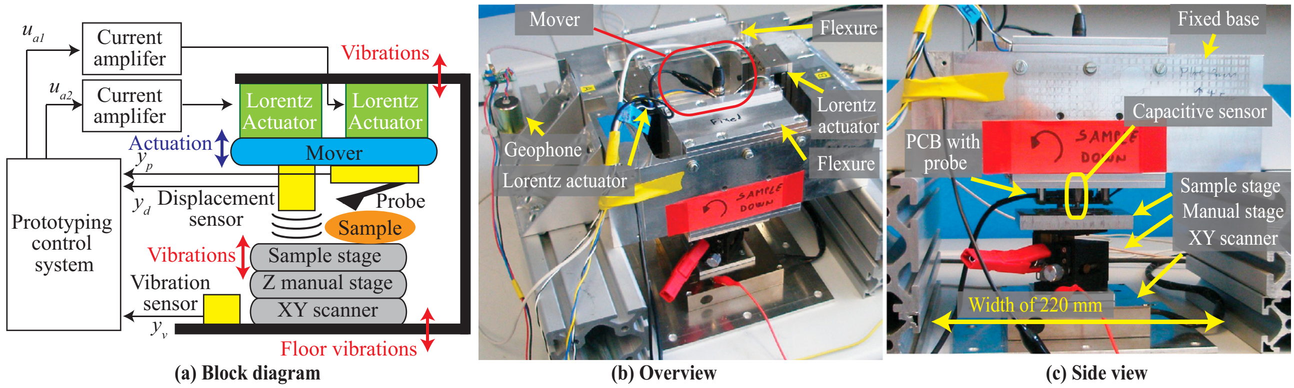

Fig. 1. AFM system showing (a) block diagram, (b) photographs of overview and (c) side view.

ation sites. However, fully automated AFMs are desired to be operated in vibrational environments, with a large sample, and without external vibration isolation for compactness. The applications include AFM imaging in a production line for inline metrology [13] and on-site AFM imaging, such as imaging of marine bacteria [14] on a boat or fossils [15] in a vehicle during field trips. In addition to the vibration sensitivity, AFMs usually have a design trade-off to determine the Z-axis actuator's stiffness between the achievable Z-axis stroke and the closed-loop control bandwidth. A high stiffness is desired for a high bandwidth. This is because the bandwidth is typically restricted by the actuator's first resonant frequency [16], which can be higher by increasing the stiffness. In return, the high stiffness decreases the achievable stroke for a given actuation force. In this stiffness dilemma, the Z-axis stroke and the bandwidth are adjusted by selecting actuators and by designing the actuator flexures [17].

To enable inline metrology and on-site imaging, this paper proposes an AFM system capable of vibration isolation for imaging without external vibration isolation. The proposed AFM system uses flexure-guided Lorentz (voice coil) actuators for the probe's Z-axis actuation. They have a low stiffness between the mover and stator such that vibrations transmitted to the probe are mechanically isolated at high frequencies. The residual vibrations are detected by a displacement sensor monitoring the probe-sample distance [4,18,19], and they are rejected by the Z-axis actuators with feedback control. Its closed-loop control bandwidth is significantly higher than the first resonant frequency, overcoming the stroke-bandwidth trade-off. As a feasibility study, this paper focuses on the vibration isolation along the Z axis.

This paper is organized as follows. Section 2 describes the vibration isolation concept and the proposed AFM system. Its mechanical design is presented and analyzed in Section 3. In Section 4 the system is modeled, for control design in Section 5. The vibration isolation is demonstrated and evaluated by AFM imaging in Section 6, while Section 7 concludes the paper.

2. System description

2.1. Vibration isolation concept

The proposed AFM system is illustrated in Fig. 1(a), the floor vibrations oscillate the sample and the mover with the AFM probe differently due to a relatively long mechanical loop from the sample to the probe. The mover and the probe are vertically moved by the Z-axis actuators guided by flexures with lowered stiffness. The low stiffness is beneficial to better decouple the mover with the probe from the actuator stator, which mechanically isolates the vibrations from the stator at frequencies sufficiently higher than the first resonance, in the same manner as passive vibration isolators [10]. The low stiffness is also desired for a large actuation range, as well as for low power consumption in the case of actuation with an offset. To reject the residual probe vibrations and the sample vibrations, the actuators maintain the Z-axis distance between the probe and the sample. Feedback control is used with a displacement sensor measuring the probe-sample distance. Because such a sensor has a high signal-to-noise ratio even at DC [20], the AFM system can reject vibrations at low frequencies, unlike active vibration isolators. The vibration rejection is further improved by using feedforward control [12] with a vibration sensor that measures the floor vibrations. The measured floor vibrations are used to estimate the resulting change in the probe-sample distance, based on which feedforward control moves the mover for vibration cancellation.

To sufficiently decrease the actuator stiffness, Lorentz actuators are selected as the Z axis actuators because they do not add a stiffness between the mover and stator, unlike piezoelectric actuators. The flexure-guided Lorentz actuators are designed such that the second resonant frequency is significantly higher than the first resonant frequency. By doing so, the closed-loop control bandwidth can be significantly higher than the first resonance, overcoming the stroke-bandwidth trade-off of the Z-axis actuation. Such an actuation system is categorized as "low-stiffness actuators" [21] and can achieve nanometer positioning resolution even without external vibration isolation [22]. Note that low-stiffness actuators can be used for vibration isolation in addition to the Z-axis actuators of AFMs as a dual stage actuator [23]. However, the additional actuators need their own amplifiers, introducing additional positioning noise. Furthermore, the vibration isolation of the additional actuators can be impaired by the recoil of the Z-axis actuators. Thus, it is desired to isolate vibrations only by using the Z-axis actuators.

In the case of conventional AFMs, the first resonant frequency of the Z-axis actuators is usually close to the higher resonant frequencies, whether piezoelectric [24] or Lorentz actuators [6,25,26] are used. This is a problem to achieve a closed-loop control bandwidth beyond the first resonant frequency due to the difficulty to assure a sufficient stability margin [21]. Although the bandwidth can be increased by using a displacement sensor, it is still limited by the first resonance [27]. The following design presents that the Z-axis control bandwidth can be significantly higher than the first resonance by selecting Lorentz actuators [21] and properly designing a mechatronic system. The achieved high bandwidth is utilized especially for AFM imaging in a vibrational environment in this paper.

2.2. System architecture

Fig. 1(b) and (c) shows photographs of the proposed AFM system. Two Lorentz actuators (AVA 2–20, Akribis Systems, Singapore) are used, providing sufficient force for the Z-axis actuation. To re-