HIGH-ACCURACY ATOMIC FORCE MICROSCOPE FOR DIMENSIONAL METROLOGY (II)

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INTRODUCTION
We are designing and testing a high accuracy AFM (HAFM) to be integrated with the Sub Atomic Measurement Machine (SAMM) and be used for dimensional metrology [1]. The SAMM, which has been developed at the University of North Carolina at Charlotte, will provide the sample raster within a 25-mm by 25-mm range with 1-nm repeatability and 25-nm accuracy [2]. The HAFM is designed to track the sample surface with better than 1nm repeatability. This paper focuses on the HAFM.

The HAFM uses a self-sensing and self-actuating Akiyama® AFM probe [3], which eliminates the need for an optical lever sensing mechanism and results in a more compact AFM head for the SAMM stage. The AFM probe operates in controlled-amplitude self-resonance mode to achieve relatively high bandwidth. Utilizing monolithic flexures and a piezoelectric actuator, HAFM has a 20-µm tracking-motion range. The HAFM’s metrology frame is separated from its force frame and is constructed from INVAR to reduce error due to mechanical deformations and temperature variations. To measure the probe motion, the HAFM uses three ADE8810 capacitive displacement sensors to directly measure the tracking motion with 0.22-nm RMS noise in a 1-kHz 3dB bandwidth.

HAFM DESIGN
The following sub-sections present the HAFM design.

![Figure 1. CAD cross-sectional view (left) and photo (right) of assembled HAFM head.](image-url)
**Self-Sensing AFM Probe**

The most common AFM probe configuration uses an optical-lever sensing mechanism where a laser beam is reflected off the probe. The thermal noise introduced by the laser beam heating close to the measurement point can cause significant measurement error [3,4]. We use a self-sensing Akiyama® probe to eliminate the laser. The probe consists of a U-shaped AFM cantilever, which is symmetrically attached to the end of a quartz tuning fork [3]. The tuning fork is used for both driving the cantilever and for sensing the tip-sample interactions. Applying a harmonic excitation voltage to the tuning fork close to its resonance creates a harmonic vertical motion of the cantilever tip. Simultaneously, the electrical admittance of the tuning fork, which varies depending on the tip-sample interaction, can be used as feedback.

Given its tuning fork design, the probe has a high quality-factor (500-1500 in air) meaning that it dissipates little energy per cycle. As a result, transients in the probe’s open-loop response disappear relatively slowly and will correspondingly reduce the bandwidth of sensing if the probe’s open loop amplitude response is used as feedback. References [4-8] have overcome this limitation by using the phase response in closed-loop. The excitation frequency is controlled to maintain constant phase shift between the probe’s voltage and current. The varying excitation frequency can then be used as feedback on tip-sample distance. References [4,7] control the excitation frequency in closed-loop using a direct measurement of the probe’s phase response. Alternatively, [5,6] use a phase-shifted positive-feedback scheme where the probe automatically self-resonates at a frequency fixed relative to its moving open-loop phase response. Our HAFM uses a design similar to [5,6] where the probe is set in self-resonance with controlled amplitude at a frequency set by constant probe phase shift.

**Monolithic Flexural AFM Head**

The HAFM head moves the AFM probe perpendicular to the sample (z-axis) to maintain a constant excitation frequency, and thus a fixed tip-sample distance. The head is designed for 20-μm z-axis range with sub-nanometer resolution. The completed HAFM head and a CAD cross-sectional view of the head are shown in figure 1.

Two monolithic flexures are utilized in the head design. The guide flexure is used to constrain the motion to the z-direction. It uses a double-back or crab-leg design so that the parasitic radial motions of the flexure cancel out. The decoupling flexure connects the piezoelectric actuator to the moving stage. It is designed to be stiff in the z-direction and flexible in the remaining degrees-of-freedom so that the piezoelectric actuator’s error motion is attenuated and not significantly transmitted to the moving stage.

To avoid measurement errors caused by mechanical deformation, the metrology and the force loops are separated. Figure 2 shows the HAFM’s separated force and metrology loops. To minimize errors due to thermal expansion, the metrology-loop’s components are manufactured from INVAR. Once integrated with SAMM, HAFM’s operating environment will be temperature controlled to within 0.01 degrees Celsius by the SAMM enclosure and environmentally controlled room.

**Control and Instrumentation**

An overall picture of HAFM’s control and instrumentation design is shown in figure 3. The self-sensing Akiyama probe along with its controlling electronics are used to sense the tip-sample distance. The head-controller tracks the surface by maintaining a constant tip-sample distance. The tracking motion is concurrently captured by three capacitive probes and is recorded as the sample height profile.
The self-sensing probe’s output is a harmonic current signal with up to 500 nA amplitude. For better noise performance, an amplification board is located close to the probe and is used to convert and amplify the probe current signal (I) into a voltage signal (Vout). The probe controller board sets the probe in self-resonance with controlled amplitude and uses a comparator to convert the harmonic probe signal into a self-resonance clock (CLKSR). This self-resonance controller configuration is similar to that in [9]. The period estimation module, which is implemented within the real-time controller’s FPGA module, measures the period (T_{SR}) of the CLK_{SR}. The period measurement is used as feedback to control the tip-sample distance. We use high-resolution ADCs, with 20.1-effective-bit resolution, and DACs, with 16-bit resolution, which were designed by Gawlik and Otten [10]. A PI510.00 amplifier drives the piezoelectric actuator. Three ADE8810 capacitive sensors are averaged digitally to measure the head tracking motion with 0.22-nm RMS noise in a 1-kHz 3dB bandwidth.

Self-resonance period measurement and head control are performed using the FPGA. A 200-MHz counter measures the time between the falling and rising edges of CLK_{SR}. For increased resolution a moving average and a low-pass filter are applied to the period measurements. The head controller compensates and closes the surface tracking loop.

**EXPERIMENTAL RESULTS**

The experimental results, presented below, are obtained with the HAFM operating in the self-resonance mode. The tests have been conducted in a room environment without any temperature control and are only to evaluate HAFM’s z-axis tracking performance before integration with the SAMM stage.

**FIGURE 3. Overall configuration of HAFM control and instrumentation.**

**FIGURE 4. Change in self-resonance frequency vs. tip-sample gap for different oscillation amplitudes.**
The self-resonating AFM probe’s response to the tip-sample variation is shown in Figure 4. The tip-sample distance was controlled based on the capacitive probes’ feedback. The AFM probe’s sensitivity is found to be inversely proportional to its oscillation amplitude. However, at lower amplitudes, the probe seems to stick to the surface and also its signal to noise ratio is reduced. The oscillation amplitude of 20-nA is selected as a good trade-off for tests within the room environment.

Figure 5 shows a 1-nm step created by the head using the capacitive sensors’ feedback and the corresponding AFM probe’s response. The capacitive probes’ measurement shows 0.22nm RMS noise. Operating with 20-nA amplitude, the 1-nm step is detected by the probe with RMS noise of 0.052 Hz, which is equivalent to 0.12 nm. For this measurement, a 32-point wide moving average at the 98 kHz edge rate and a 4th order Butterworth filter with 150-Hz -3dB frequency are used. Electrical noise, thermal variation, and mechanical vibration are predicated as the main factors limiting the probe’s resolution.

**CONCLUSION**

We have designed and implemented a high accuracy AFM (HAFM) for 20-μm range of motion with sub-nanometer resolution. Head position control and sensing, with 0.22nm RMS noise, using the capacitive sensors’ feedback, and tip-sample gap detection, with 0.12nm RMS noise, using the self-sensing probe have been demonstrated experimentally.

Currently, we are developing electronics to improve the AFM probe’s signal to noise ratio. In the near future, The HAFM’s position control loop will be closed using the AFM probe’s feedback. In this configuration, the low pass-filter of figure 3 will be effectively replaced by the loop compensator and the mechanical plant’s dynamics. The HAFM will be integrated with the Sub Atomic Measurement Machine (SAMM) to be tested for sample profile measurement. The HAMF’s performance is expected to be improved once tested within SAMM’s hermetic enclosure with temperature control and vibration isolation.

**REFERENCES**


