Design of a long stroke translation stage for AFM

C. Werner, P.C.J.N. Rosielle*, M. Steinbuch

Control Systems Technology, Department of Mechanical Engineering, Technische Universiteit Eindhoven, Den Dolech 2, WH 0.133, 5600 MB Eindhoven, The Netherlands

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A B S T R A C T

A new metrological AFM is developed for the Dutch standards laboratory. This instrument consists of a translation stage with a stroke of $1 \times 1 \times 1$ mm and a custom-designed AFM measurement head. Here the design of the translation stage, consisting of elastic straight guides, Lorentz-actuators with weight and stiffness compensation and interferometric translation measurement systems, will be discussed. Some preliminary results on the performance of the actuation system are presented.

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1. Introduction

The measurement of dimensional variations in manufactured products is an essential step in the development of any new production technology. These measurements can only be considered reliable if the instruments used are traceably calibrated to the standard of length.

Instruments capable of measurements at the nanometre scale, such as atomic force microscopes (AFMs), are calibrated using step height standards and 1D or 2D gratings [1,2]. These calibration samples are, in turn, calibrated using a traceable metrological AFM [3].

For the Dutch standards laboratory (VSL), a new metrological AFM is being developed for the calibration of this type of transfer standards. With a measuring volume of $1 \times 1 \times 1$ mm, this new instrument has a larger scanning volume than most current metrological AFMs [4–8]. This increase in scanning range allows larger parts of the sample to be measured in one continuous scan, resulting in improved measurement statistics and a better estimate of the sample uniformity [9].

2. System description

The instrument consists of a low-hysteresis elastic translation stage and a dedicated, kinematically mounted AFM measurement head. To minimize the Abbe error, the stage is used for translating the sample while the AFM head remains stationary.

The AFM head [10] is designed for contact mode measurements and uses the optical reflection method to measure the deflection of the AFM cantilever. The incident beam is created using a diode laser and optimized beam shaping optics. The movements of the reflected beam are measured using a quad-cell detector. A kinematic holder fixes the cantilever onto the AFM head.

The thermal centre of expansion of the AFM head coincides with the AFM tip, minimizing the measurement errors due to temperature variations.

The translation stage is constructed from three identical axes, which are aligned symmetrically around the vertical. This parallel set-up results in improved dynamical behaviour over stacked designs and better environmental disturbance attenuation. Furthermore, the higher allowable scanning speed reduces measurement time and subsequently minimizes the influence of temperature variations on the measurement results.

Three differential interferometers are used to measure the translations of the stage. The optical axes of these orthogonally orientated interferometers are aligned with the AFM measurement probe for minimal Abbe offset. The 3D position resolution is 0.3 nm and the specified combined measurement uncertainty is in the nanometre range.

The stage contains the measurement mirror while the reference mirror is connected directly to the AFM, resulting in a favourably short measurement loop. The thermal centre of expansion of the mirrors coincides with the AFM measurement probe for optimal thermal stability.
Lorentz-type motors are used for the actuation of the stage. To minimize the heat generated by these actuators, weight and stiffness compensation mechanisms are included.

All aluminium components are made from the same piece of certified barstock material (Al 7075) to ensure equal thermal expansion properties, which are determined at VSL.

In the next sections, the design of the translation stage is explained. The design of the AFM head will not be discussed in this paper.

3. Component description

The translation stage is designed from the inside out, starting with the sample. This top-down approach results in minimal overall dimensions of the instrument, leading to minimal sensitivity for thermal gradients.

The components of the instrument will be discussed in the same order, starting with the sample table. After that, the straight guide, actuators and the measurement system will be explained.

3.1. Sample table assembly

Fig. 1 shows the sample table assembly, this is the moving part of the translation stage. It consists of the sample and sampleholder, the mirror for the translation measurement system and a frame to connect these components to the straight guides.

The sample is fixed to a spacer, which in turn is mounted on the sampleholder. This sampleholder is kinematically connected to the sample table frame to allow for off-line sample preparation and alignment.

Features of interest on the sample surface are aligned to the scanning range of the instrument by moving the sample and spacer over the sampleholder surface (x, y, θ) or changing the thickness of the spacer (z). The spacer is made of the same material as the sample to ensure that the length and the composition of the thermal loop are not changed when a different thickness sample and spacer are used.

The translation stage is designed around the largest commercially available calibration sample [11]. Samples with diameters up to 11 mm can be scanned fully. The maximum sample that can be accommodated is 23 mm in diameter and up to 4 mm thick.

The Zerodur® monolithic mirror is moment-free connected to the sample table frame by three Invar A-frames. Thermal compensation is used for the z-direction so that the thermal centre of the mirror coincides with the AFM measuring point.

The sample table frame (upper part, no. 1 in Fig. 1) consists of stiffness-optimized box shapes, resulting in a high natural frequency, low thermal capacity and a fast response to temperature variations. The design has been optimized towards maximum natural frequency using finite element calculations (NX Nastran®, modal analysis module ‘semodes103’).

The mass of the sample table assembly, including sample, is 84 g.

3.2. Straight guides

The sample table assembly is suspended by three identical and orthogonally oriented elastic straight guides. Each straight guide consists of two struts and one leaf spring parallelogram (Fig. 2a) and constrains one rotational degree of freedom.

The combination of three straight guides suppresses all rotations of the sample table and the three unconstrained translations are actuated (Fig. 2b).

Struts of the crossed hinge-line type are used (Fig. 3). This strut design combines high axial stiffness with low sideways stiffness and well-defined hinge points [12]. The struts, each 40 × 9 × 9 mm with 0.1 mm hinges, are fabricated in monolithic...
pairs, resulting in struts that are parallel and equal in length to within a few micrometers. The inevitably larger variation in strut length between pairs has, by design, no influence on the straightness of the sample stage motion.

Each parallelogram consists of two stiffened leaf springs (25 × 53 × 0.15 mm) connected by a box-shaped ceramic (Al₂O₃) bridge. The large specific stiffness of the ceramic, compared to aluminium, helps to minimize the mass of the parallelogram. The ceramic's insensitivity to magnetic fields allows for the integration of the actuator into the bridge of the parallelogram (section 3.3).

3.2.1. Straightness

The difference between the stiffness in the constrained and the unconstrained degrees of freedom of the stage determines how much the sample table rotates. Based on this difference, the reproducible rotation over the full scanning range is estimated to remain below 1.2 arc sec.

By aligning each pair of struts closely with the centre of gravity of the sample table, the rotations caused by inertia forces are kept well below 0.1 arc sec.

Due to the parallel layout of the straight guide, translation of the sample table along a straight line requires simultaneous operation of all three actuators. As such, the straightness or decoupling of the movement is determined by the performance of the measurement system and the position controller. 1D simulations show position deviations below 0.4 nm.

3.2.2. Thermal behaviour

Uniform temperature changes affect all straight guide components equally, leading only to (measured) translations of the sample table.

The symmetrical orientation of the struts and parallelograms around the vertical make the translation stage insensitive for vertical temperature gradients.

For typical metrology laboratory conditions (ΔT ≈ 20 mK inside an enclosure [13]) the rotations caused by horizontal gradients are estimated to remain below 0.2 arc sec.

3.2.3. Dynamical behaviour

Finite element analysis shows that the first resonance of the sample-loaded stage occurs at 1.4 kHz. With this natural frequency a control bandwidth of 300 Hz is considered possible.

A high natural frequency of the translation stage, combined with a pneumatic vibration isolation table, leads to good attenuation of environmental vibrations. The amplitude ratio of the sample table and the floor vibrations can be estimated with the following formula: [14]

\[ \frac{\delta_s}{\delta_g} = \left( \frac{f_t}{f_g} \right)^2 \]

where \( \delta_s \) is the max amplitude sample table vibrations [m]; \( \delta_g \) is the max amplitude of the ground vibrations [m]; \( f_t \) is the resonance frequency of the isolation table [Hz]; \( f_g \) is the frequency of the ground vibrations [Hz] and \( f_s \) is the resonance frequency of the sample stage [Hz].

For floor vibrations in a typical metrology laboratory (\( \delta_g \approx 3 \times 10^{-6} \text{ m at } f_g \approx 5 \text{ Hz} \)) and a conventional vibration isolation table (\( f_s \approx 2 \text{ Hz} \)), the amplitude ratio is in the order 3 × 10⁻⁷, leading to sample table vibrations several orders of magnitude smaller than the system’s resolution.

3.3. Actuation

The actuation system comprises of two modules. The first module is a linear actuator and the second a weight and stiffness compensation mechanism.
3.3.1. Actuator

A Lorentz actuator of the duo-motor type is used for the actuation of the parallelogram (Fig. 4). Its rectangular coil (wire thickness 0.1 mm, 1500 turns) is integrated into the ceramic bridge of the parallelogram for maximum stiffness in the direction of actuation. Two magnet assemblies, each consisting of four NdFeB magnets and an Armco yoke, are placed above and below the coil and are fixed to the instrument base by bridge-like supports. Pole shoes are added to linearise the magnetic field over the stroke of the actuator.

Unlike piezo actuators, Lorentz motors show low hysteresis, have time-invariant behaviour and require only simple power-amplifiers. Their linear current-to-force relation simplifies the control of the system considerably compared to piezo actuators.

3.3.2. Weight and stiffness compensation

A consequence of the use of elastic straight guides is the nonzero stiffness in actuation direction. This stiffness leads to larger forces in the actuator and, through electrical resistance losses, in a quadratic larger creation of heat. To minimize this heat production, a stiffness compensation mechanism is added. A weight compensation mechanism reduces the force needed to keep the translation stage in its nominal position.

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A disadvantage of this compensation layout is the high additional load on the parallelogram. In Fig. 5c, this is remedied by replacing the compression spring by a separate force-closed compensation module. In this module a tension spring (B) and lever (D) are used to preload a long support link (E) and a short tilting link (G). Both links are connected to the parallelogram by an additional link (H). Any movement of the parallelogram results in a rotation of the tilting link and thus a sideways component of the preload force.

In this concept the length of the tilting link can be chosen freely. A short link gives a relatively large compensation force at the cost of a slightly asymmetrical compensation characteristic. This nonlinearity results from the kinematics of the mechanism and here limits the performance of the stiffness compensation to about 1–2% remaining stiffness.

In practice, the large rotations of the tilting link make the use of elastic hinges impractical, so knife-edge bearings are used (Fig. 6). The hysteresis normally present in knife-edge bearings is caused by material hysteresis in the contact region and, to a much larger extend, by macro-slip between knife-edge and bearing block [15]. The latter can be prevented by designing the support according to the pivot rule [16].

![Fig. 4. Actuator assembly. (1) yoke, (2) NdFeB magnets, (3) pole shoes, (4) Al₂O₃ top plate, (5) coil, (6) Al₂O₃ side plate, (7) motor support end plate, (8) motor support frame, (9) assembled motor support, (10) parallelogram, (11) Al₂O₃ bottom plate and (12) yoke and magnet assembly.](image1)

![Fig. 5. Stiffness compensation. (a) Nominal position, (b) compensating forces and (c) mechanism components. Cₜ: translation stiffness, Cₛ: compensation stiffness, Fₖ: preload spring force, Fₛ: sideways component, and Fₜ: translation force. A: parallelogram, B: preloaded tension spring, D: lever, E: support link, G: tilting link and H: connecting link.](image2)
Weight compensation is achieved by attaching a low-stiffness preloaded tension spring to the support link of the stiffness compensation mechanism (Fig. 6). The spring is connected close to the pivot point of the link, giving a 1 on 10 displacement ratio between the spring and the parallelogram. This leads to a nearly constant weight compensation force.

The compensation module measures, excluding springs, about 24 x 26 x 62 mm.

3.3.3. Experimental set-up

To test the performance of the actuation system, a single-axis prototype has been built (Fig. 7a).

Fig. 7b shows the force needed to translate the parallelogram without and with stiffness compensation. The compensation mechanism reduces the force needed at maximum travel (+/− 800 µm) by over 98%. Combined with the measured properties of the actuator, maximum continuous force $F_{\text{max}} = 1.48 \text{ N}$ and force constant $k_f = 57 \text{ N/m}$, this reduces the dissipated power from about 0.52 W to well below 1 mW and allows for accelerations of the sample table in excess of 5 m/s$^2$.

The measured dynamic response of the system is given in Fig. 8.

3.4. Measurement system

Three identical, custom made, heterodyne interferometers are used to measure the translations of the sample table assembly. First the design of these interferometers is discussed, followed by a description of the mirror assemblies. Next the laser beam delivery optics and measurement electronics are described.

3.4.1. Interferometer

The interferometers are of the differential, double-pass plane mirror type. Fig. 9 shows the beam path layout.
A two-frequency laser beam is divided into a reference and a measurement beam using a polarizing beamsplitter. Each beam is then reflected twice off its respective mirror before being recombined and coupled into a detector. Beamsplitters and wave plates are used to horizontally separate the first and the second pass.

In this layout, the reference and the measurement beam follow equal paths, giving a thermally stable design [17]. The mirror surfaces of the reference and the measurement mirror are aligned to minimize dead path errors. The differential measurement ensures that only relative translations of the mirrors along the optical axis of the interferometer are measured. This measurement is not influenced by other movements of the mirrors or movements of the interferometer itself.

The main components of the interferometer are two large beamsplitters (number 3 in Fig. 10). These two beamsplitters are made by sectioning a single, commercially available one-inch beamsplitter into 10-mm-thick pieces. All the other components are bonded directly to these beamsplitters by optical contacting to form a thermally stable and optically symmetrical interferometer.

The overall dimensions are $58 \times 48 \times 10$ mm

The interferometer is glued onto a high-stiffness $\text{Al}_2\text{O}_3$ box, which in turn is kinematically mounted onto the instrument.

With this mount, the interferometer can be easily removed from the instrument for inspection or cleaning and can be re-installed without requiring realignment.

3.4.2. Mirrors

The orthogonality of the translation measurement system is determined by the squareness of the measurement and reference mirrors. To maximize this orthogonality, the monolithic measurement mirror is cut from a highly rectangular cube. The orthogonality of this cube, which sides will form the reflective surfaces of the mirror, can be calibrated accurately. The reference mirror is produced in a similar way.

The mirrors are made from Zerodur® to minimize the measurement errors caused by thermal expansion of the mirrors. The use of Zerodur® also prevents warping of the mirror due to temperature variations.

3.4.3. Laser beam delivery

In most 3D interferometry systems, one of the measurement axes is oriented vertically, resulting in horizontally and vertically placed interferometers and beam delivery optics. These beam delivery optics are aligned orthogonally, leading to minimal polarization mixing [18].

Although the interferometers in the new instrument are mutually orthogonal, they are not aligned horizontally or vertically, making an orthogonal beam delivery system impractically large. Alternatively, fibre optic cables cannot be readily used for beam delivery in heterodyne measurement systems [19].

For a compact delivery system, a non-orthogonal beam path is required. To ensure no polarization mixing occurs at the non-perpendicular reflections in the beam path, the polarization directions must be rotated so that they are aligned at right angles with the mirror surface [20]. This can be done using half-wave plates.

Fig. 11 shows the beam delivery layout. The incoming laser beam is reflected twice over $60^\circ$, forming a triangular-shaped
path. The sides of this triangle are perpendicular to the measurement axes and each contains a periscope-like assembly. This periscope, consisting of a non-polarizing beamsplitter, right-angled prism and two half-wave plates, directs part of the light upwards and into the side of the interferometer. The light exits the interferometer on the opposite side and is then coupled into the detector.

The mirror support and periscope assembly, both have elastic mechanisms to facilitate the optical alignment. With the input and output beams of the interferometer being concentric, this alignment can partly be done with the interferometers removed from the instrument, simplifying the procedure.

Tubes are used to shield the beams from the moving parts of the instrument, reducing the influence of air turbulence.

3.4.4. Measurement electronics.

A commercially available system is used to convert the optical signals of the interferometers into displacement data [21]. The system uses detectors with fibre optic beam pickups, allowing the heat-generating detectors to be placed away from the instrument.

The fibre optic cable that connects each pickup to the appropriate detector is divided into two sections. The section connected to the pickup is permanently fixed to the instrument; the other section can be coupled to it using a feedthrough connector. This set-up ensures maximal alignment stability of the pickup as well as ease of use.

Fig. 12 shows the assembled instrument.

4. Conclusion

An elastic translation stage for AFM has been designed. An experimental set-up showed that the stiffness and weight compensation mechanisms significantly reduce the power losses in the actuators.

The stage is currently being realized and completion is foreseen towards early 2009.

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