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Research paper

Optimisation of a nano-positioning stage for a Transverse Dynamic Force Microscope

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ABSTRACT

This paper describes the optimisation of a nano-positioning stage for a Transverse Dynamic Force Microscope (TDFM). The nano-precision stage is required to move a specimen dish within a horizontal region of 1 μm × 1 μm and with a resolution of 0.3 nm. The design objective was to maximise positional accuracy during high speed actuation. This was achieved by minimising out-of-plane distortions and vibrations during actuation. Optimal performance was achieved through maximising out-of-plane stiffness through shape and material selection as well optimisation of the anchoring system. Several shape parameters were optimised including the shape of flexural beams and the shape of the dish holder. Physical prototype testing was an essential part of the design process to confirm the accuracy of modelling and also to reveal issues with manufacturing tolerances. An overall resonant frequency of 6 kHz was achieved allowing for a closed loop-control frequency of 1.73 kHz for precise horizontal motion control. This resonance represented a 12-fold increase from the original 500 Hz of a commercially available positioning stage. Experimental maximum out-of-plane distortions below the first resonance frequency were reduced from 0.3 μm for the first prototype to less than 0.05 μm for the final practical prototype.

1. Introduction

1.1. The need for design optimisation of atomic force microscopes

Since its invention in 1986 [1], atomic force microscopes (AFMs) have become one of the most important tools to measure the 3-D topography of nano-scale objects including both biological and non-biological specimens [2–4]. The resolution of AFMs can be better than 1 nanometre (1×10^{-9} m) enabling measurements of specimens such as DNA and proteins [5]. AFMs are widely used for biomedical analysis in cancer research [6], cell biology research [7] and material science [8].

AFMs have a number of advantages over scanning electron microscopes (SEMs) such as the ability to carry out 3D scanning, the ability to scan untreated specimens and the ability to scan without the need for a vacuum. However one of the key disadvantages of AFMs is relatively slow scanning rates. This is restricting the usefulness of AFMs in many areas of research. In particular AFMs are generally not able to scan processes in real time.

This paper deals with the optimisation of the positioning stage of an advanced type of atomic force microscope called a transverse dynamic atomic force microscope (TDFM). A TDFM has higher accuracy and the capability to scan softer specimens [9]. However, as with other types of AFM, TDFMs suffer from slow scan rates. In addition their resolution can be limited when scanning rates are high. Therefore there is a need for design optimisation of TDFMs to achieve improved levels of resolution and speed of scanning. In particular, the positioning stage, which moves the sample under the probe, is a critical component that limits the speed and accuracy of operation.

1.2. Introduction to the transverse dynamic force microscope

The basic layout of a TDFM is shown in Fig. 1. The specimen to be examined is placed on a thin specimen dish within a nano-positioning stage that can be moved in a horizontal x-y plane. Conditions must be such that the specimen is covered with a microscopic water layer as this is required for the scanning process. In ambient conditions, a specimen is always covered with a thin water

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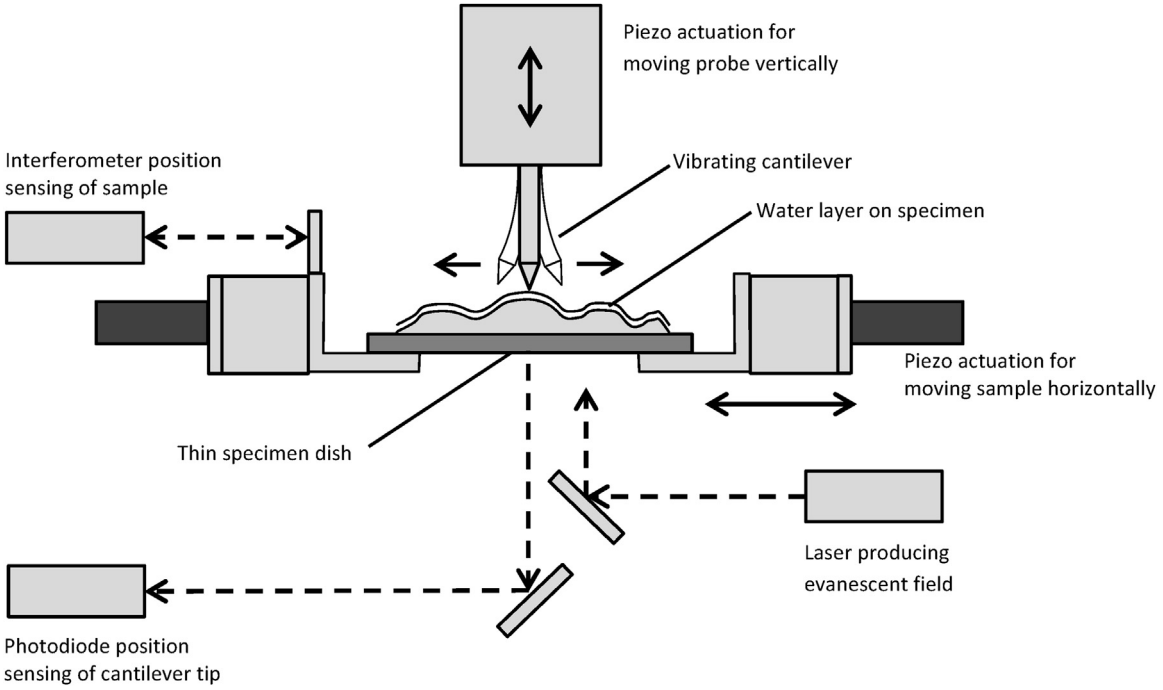

Fig. 1. Schematic of the TDFM layout.

layer due to general humidity at room temperature and pressure (21 °C, 100 kPa).

A TDFM uses a vertically oriented cantilever probe which is different to the horizontally orientated probes of traditional AFMs [9–13]. The vertical cantilever is vibrated at a set frequency and placed above the specimen in close proximity such that there is interaction between the cantilever and the molecules of water within the microscopic water layer that covers the specimen.

When the cantilever interacts with the water layer the vibration is damped and the amplitude of vibration is decreased. The exact amplitude of vibration is dependent on the level of penetration in the water layer. During scanning, if the probe is moved in the vertical axis such that the amplitude of vibration is constant then the probe follows the profile of the specimen. This principle of interaction with the water layer above the specimen enables non-contact scanning.

The change in vibration of the probe is measured by a laser optical detection system, which is set beneath the thin specimen dish underneath the specimen. The optical detection system creates scattered evanescent electromagnetic waves in the surrounding area of the specimen [14]. The reflected component of these is detected by a photo-detection system to obtain a measurement of the cantilever tip oscillation.

1.3. Introduction to the nano-positioning system

The layout of the positioning stage is shown in Fig. 2a and is based on a concept produced by Schitter et al., 2006 [15]. The nano-positioning stage consists of:

- A structural element.
- A central circular specimen dish.
- Four piezo actuators.
- Four side clamps.
- Two mirrors.

The structural element itself conists of a number of separate features including four primary flexural beams; twelve secondary flexural beams; a central dish holder, two mirror holders; and four anchor points.

The primary beams are deflected directly by the adjacent piezo actuator as shown in Fig. 2b and allow a deflection of 1 μm in the x and z axes. The secondary beams allow simultaneous movement of the dish in x and y directions. The combination of primary and secondary beams give the required stiffness.

Piezoelectric actuators are used because of their high stiffness, linear displacement and high load capacity. A laser-interferometer system is used to detect movement in the x and y axes, as it gives a high positioning accuracy of 0.3 nm.

There are two vertical mounts (flags), one on each axis, protruding from the edge of the specimen holder. They are used for the attachment of thin mirrors, acting as reflectors for the two laser beams of the laser interferometer. The 'T shaped' side clamps are used to apply/adjust the mechanical preload applied to the piezo actuators.

1.4. Performance of TDFMs

The main measures of technical performance are scan accuracy and speed. These are very closely linked to two physical properties: (i) the natural frequency of positioning stage and (ii) the out-of-plane distortions of the stage during in-plane movement. Higher natural frequencies result in a higher bandwidth and hence scan rates. Low out-of-plane distortions mean that the accuracy is better for both stage position measurement and probe position measurement.

1.5. Design constraints and objectives

The positioning system has the following constraints and requirements:

- The design space for the structural element is 93 mm × 93 mm × 9 mm.
- The dish holder must be able to displace up to 1 μm in the x and y axes.