Monitoring of an atomic force microscope cantilever with a compact disk pickup

F. Quercioli and B. Tilibbli

Istituto Nazionale di Ottica, 50125 Florence, Italy

C. Ascoli, P. Baschieri, and C. Frediani

Istituto di Biofisica CNR, 56127 Pisa, Italy

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In the present study we test a compact disk pickup as the cantilever position sensor in an atomic force microscope (AFM). The pickup is placed on top of the optical microscope used for the visual inspection and alignment of the specimen. The AFM is also equipped with its own cantilever movement sensor system. Both the built-in and the new detection devices are simultaneously active for comparison purposes. Two different measurements are performed in sequence on the same sample each using one sensor at a time as the error signal source for the AFM feedback loop. The pickup has demonstrated good sensitivity as well as excellent performance in terms of compactness, reliability, and cost. © 1999 American Institute of Physics. [S0034-6748(99)05009-1]

I. INTRODUCTION

A key point in an atomic force microscope (AFM) is accurate assessment of the cantilever displacement. The measurement is usually performed by means of an optical lever technique by which a laser beam impinges onto the cantilever and a position sensitive photodiode locates the reflected beam spot. Due to mechanical constraints, the light path typically suffers some folding and a certain number of mirrors placed on adjustable tilt mountings are necessary. As a result, the entire position detection system often becomes bulky and awkward.

The problem of accurate position measurement also arises in the optical disk driver since the pickup must maintain the best focus condition on the disk surface during its rotation.1–2 Optical heads for compact disk (CD) players or other optical media are currently being manufactured in large quantities for the consumer electronics market and consequently they are very low priced. Nevertheless, their performance in terms of distance sensing and control accuracy is so high it makes them suitable for application in advanced instrumentation in the field of optical metrology.3–9 Another valuable characteristic of optical pickups is their compactness and lightness.

In this article we describe the use of a CD pickup to monitor the vertical displacement of the cantilever in an AFM. The aim of the present work is to test the technique and, for this, an available homemade AFM has been modified just to evaluate the performance of the pickup position sensor against the standard built-in system. The camera output port of an optical microscope, which is used for setup adjustment and for sample visual inspection, hosts the optical head; the pickup laser beam reaches the cantilever through the microscope objective.

Fewer mechanical constraints due to the reduction in size and the cost of the cantilever position detector system, with all the optical and electronic elements replaced by a single integrated component, will leave more freedom in future development of the AFM design. Besides, a smaller overall dimension of the instrument will lead to a strong reduction of the negative effect of thermal gradients on its performance.

II. CD PICKUP

The typical light source of an optical pickup is an AlGaAs laser diode at a wavelength λ = 780 nm, and output power of 0.2 mW, up to 2 mW for the read/write head type. The light beam, reflected by a beam splitter, is collimated and then focused onto the surface of the optical disk by a movable objective lens with a typical numerical aperture of 0.45. The light reflected back is recollected and then transmitted by the beam splitter towards a photodiode array. A beam-shaping device is interposed in the converging beam as the chief part of the focus error detection system.

The pickup laser beam must remain focused onto the disk surface to accurately read the information recorded. When the focusing condition is lost, a dedicated actuator provides for fine adjustment of the objective position. Three techniques are largely used for generating the focus error signal: the astigmatic detection method, which makes use of a cylindrical lens as a beam-shaping device; the single and double Focault focus sensors, with the use of a knife edge or a biprism, respectively, and the critical angle technique, where a prism at near total reflection incidence is the key sensor element.

In our experiment a three-beam, astigmatic-focus-sensor pickup is used (Fig. 1). In this type of optical head, a diffraction grating is placed in the transmitting arm of the device and two first-order beams are produced in addition to the main central one. Two lateral focused spots are generated onto the disk and are used by the tracking servo system. Once backreflected from the disk surface, the three beams,
after passing through the astigmatic element, impinge onto a
detector array (the inset in Fig. 1). A central four-quadrant
photodiode monitors the axial spot, and two auxiliary detec-
tors, E and F, record the intensity variations of the two outer
beams. The two lateral spots are symmetrically positioned
with respect to the disk data track in such a way that any
translation of their foci in a direction perpendicular to the
track itself will cause a change in the average intensity de-
tected by photodiodes E and F. A feedback loop will correct
this tracking misalignment by laterally moving the pickup
objective back to its correct position.

The central beam is used for data reading and focus con-
trol. The beam total intensity \((A+B+C+D)\) carries informa-
tion on the disk recorded signal, while its spot shape is a hint
of the out-of-focus amount. An astigmatic element produces
a spot on the four-quadrant detector whose shape and orien-
tation change from an ellipse with a major axis along the AC
direction to one oriented along BD when the disk moves
from one side of the correct position to the other. A circular
spot is obtained when the objective is perfectly focused
on the surface. In this case the four detector outputs
are perfectly balanced. The focus error \((FE)\) signal,
\(FE=(A+C)-(B+D)\), is sent to the servo control system
which maintains the pickup objective at the correct focus
position.

The lateral (tracking) and axial (focus) actuators are of
the electromagnetic type. The objective lens is fastened to a
moving frame which is equipped with two sets of mutually
perpendicularly oriented coils. Elastic hinges join the struc-
ture to the main body of the optical head to which two strong
magnets are attached.

III. EXPERIMENTAL SETUP

The AFM employed in the present work is a homemade
instrument and a schematic of it is shown in Fig. 2. It is
equipped with an optical microscope for accurate selection
of the scanning region, visual inspection of the sample dur-
ing the measurement, and for initial fine alignment of the
cantilever position sensor system. The microscope is a Mitu-
toyo FS60, for metallographic use. It employs special objec-
tives with a long working distance, allowing easier optical
access to the inspection area.

Cantilever displacement is monitored by an optical lever
method. The detection system lies on a horizontal plane near
the sample (Fig. 3). The light beam from a laser diode
\((\lambda = 670 \text{ nm})\) is focused onto the cantilever with a high
f-number lens and a focal length of 40 mm. The laser module
is placed on a two-axis tilter for alignment of the focal spot
onto the cantilever. Two fixed mirrors, in front and in back
of the cantilever, fold the light path into an “M” shape.
Finally a third adjustable mirror reflects the beam toward the
photocells. The four-quadrant photodiode (Advanced Photo-
nix SD 055-23) senses both the vertical bending and the
torsion of the cantilever. This type of detection system has
proved to be sensitive and reliable and, in the present
work, it is treated as a reference. Its main disadvantage
comes from the great number and size of the components

![FIG. 2. Layout of the homemade atomic force microscope. Both cantilever monitoring systems are shown. The CD-pickup sensor is placed at the camera output port of the optical microscope.](image-url)
required and their bulky packing close to the cantilever leaving almost no room for the simultaneous use of other auxiliary inspection instruments.

The optical pickup (SONY KSS 210A) is coupled to the TV/camera adapter port of the microscope. It is mounted on a three-axis translation stage for fine focus adjustment of the laser beam onto the cantilever.

The optical system of the pickup has been modified to match the output aperture of the microscope. The mobile objective and its mechanics have been removed and a lens of lower numerical aperture (NA) \( f = 18 \text{ mm}, \; \Phi = 5.4 \text{ mm} \) is instead used to focus the beam at the intermediate image plane of the microscope. The spot is then projected onto the cantilever through the tube lens and the microscope objective (10\( \times \), NA 0.28). To work properly, the cantilever is held at a bias tilt angle of 12° with respect to the specimen, and the whole microscope is angled in the same way to let the head laser beam hit the probe surface at normal incidence. In Fig. 4 the main spot is focused onto the cantilever near the base of the probe tip along with the three spots reflected beam returns back, through the same optical path, toward the pickup.

The anodes from opposite elements of the pickup’s center four-quadrant detector are connected to add their photocurrent signals, \( A + C \) and \( B + D \), and the anode terminals of the two diode pairs are then input to a high gain low noise preamplifier (Hamamatsu, photosensor amplifier model C2719). In this way the focus error signal, \( FE = (A + C) - (B + D) \), is obtained directly at the preamplifier output. The photodiode cathodes, all connected together (Fig. 1), are held floating. The output voltage is further amplified and then sent as input to one analog-to-digital (A/D) converter of the AFM controller.

The AFM controller is a DSP (Motorola 56001) based digital system which can handle up to 16 A/D and digital-to-analog D/A converters housed in an Eurocard subrak. During standard AFM operation only two A/D converters are used to acquire force (cantilever bending) and friction (torsion) variables measured by the built-in monitor device. In the present work, we are not interested in the torsion; we acquire the CD-pickup output and the bending signal. We can choose which one of the two inputs will be used by the digital feedback servo system. This method allows a direct comparison between the performance of the two cantilever displacement detection systems.

**IV. RESULTS**

First we calibrated the response of the optical pickup sensor to vertical displacement. A small plane mirror replaces the cantilever; it has been positioned on top of a piezoelectric actuator and a triangular wave form is applied to the \( z \) axis driver. The error signal obtained at the output of the preamplifier has a characteristic ‘S’ shape, shown in Fig. 5. The piezo hysteresis has not been removed. In common optical pickups the objective lens has a typical focal length of about 3.5 mm and the width of the focus error curve is around 30 \( \mu \text{m} \). In our setup, a combination of the additional lens \( f = 18 \text{ mm} \), the tube lens \( f = 200 \text{ mm} \) and the microscope objective \( f = 20 \text{ mm} \) yields an equivalent focal length of 1.8 mm, and the ‘S’ curve is narrower accordingly. The width of the linear portion of the curve is about 4 \( \mu \text{m} \) with a slope of 0.86 \( \text{v/\mu m} \), and it has a root mean square (rms) noise of \( \pm 2.5 \text{ nm} \) for a 600 Hz bandwidth.

In the final setup the pickup beam is finely focused onto the cantilever surface close to the base of the probe tip (Fig. 4). Accurate adjustment of the \( z \) axis of the optical head is carried out to operate in the linear zone of the focus error curve. We use silicon ultralevers (Park Scientific Instruments, 0.6 \( \mu \text{m} \) cantilever thickness) with an apex radius of about 10 nm. Silicon nitride levers are not suitable. Even if
gold coated, they are still highly transparent to the 780 nm laser beam and interference phenomenon occurs between the cantilever and sample reflected beams, giving rise to large signal fluctuations which make feedback control difficult.

A standard AFM image has been performed using the built-in cantilever displacement detection system. The sample is a diode junction with a pair of triangular shaped gold contacts, about 120 nm thick spaced 110 nm apart, deposited on a Si substrate. A second topographic scanning was accomplished, this time with the CD head focus error signal as the AFM feedback input source. This image is shown in Fig. 6b. Although the image quality is poorer than the previous one, the junction structure is still very well resolved. A more quantitative evaluation can be done by inspecting the cross-sectional intensity profiles along two nearly corresponding lines shown in (a) and (b). The images are 2 µm×2 µm.

The main contribution to the noise figure is certainly due to mechanical instability of the large size of the support of the optical microscope, the total roundtrip distance traveled by the pickup probing beam is of the order of 1 m. In future development of the AFM, the CD-head sensor will replace the present detection system, close to the cantilever support and mechanical noise will be drastically reduced.

There is one main difference between the two monitoring systems: the pickup is a position sensor, whereas the built-in optical lever detects cantilever bending (and twisting). Vertical displacement of the optical head laser spot, which is sensed by the pickup, chiefly depends on that deflection, although a minor relation to the torsion angle is however also present. This little effect is shown in Fig. 7. The image depicts the cantilever bending detected by the optical lever device while the pickup signal is used as a feedback input source for the AFM control system [Fig. 6(b)]. The effect of the feedback loop is to abate the (pickup) error signal toward zero, coupling the bending angle to the torsion one. Figure 7 is in fact a typical torsion image displaying topographical slope information.

FIG. 6. Comparison of the topographic images obtained with the two cantilever displacement monitoring systems. (a) Standard AFM image using the built-in optical lever detection method. (b) Same sample with the CD-pickup signal used for the feedback loop. (c), (d) Cross-sectional intensity profiles along the two nearly corresponding lines shown in (a) and (b). The images are 2 µm×2 µm.

V. DISCUSSION

We have demonstrated the capability of a commercial pickup for a CD player to detect the cantilever displacement in an AFM. The study is a straightforward application of optical heads to position sensing which is one of their main features. However, more refined setups can be conceived with little modifications of the basic pickup structure which could be employed in the present application. For example, a pickup based Fizeau interferometer has been reported in the literature that exhibits enhanced sensitivity of about 1 nm. Laser feedback interferometry has been successfully tested in cantilever position monitoring, and optical pickups could very easily be used in this kind of arrangement. In some pickup designs (e.g., optical pickup from the Philips CR-206 CDROM) a dielectric mirror (peaked at λ = 780 nm) folds the laser beam 90° toward the objective, making a free transmission path for visible light through the same lens available. The CD head could replace the microscope objective, and a very compact AFM instrument could be devised.

Finally, a modified optical head can be easily set up as a two dimensional autocollimator enabling simultaneous monitoring of the bending (force information) and torsion (friction) of the cantilever.

In summary, the advantages in terms of cost and size along with typical vertical resolution in the nanometer range...
make this widely used consumer electronic component an extremely interesting choice in AFM design and high end scientific instrumentation.

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