Implementation of a Measurement System for Inspection of Magnetic Force Microscopy Probes

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Abstract. A non-destructive measurement system for the inspection of magnetic force microscopy (MFM) probes was implemented and discussed in this paper. Its operating system was similar to that used in standard AFM/MFM machines. The MFM probe under test was held on a sample holder and was oscillated by a piezoelectric transducer. The oscillation of the MFM probe was measured by an optical beam deflection technique. In order to measure a response of the MFM probe under the presence of magnetic fields, a solenoid coil was employed as a source for generating the out-of-plane magnetic field. This avoids physical contact which may damage the MFM probe. Different types of MFM probes, including commercial probes and developed in-house probes with different coating thicknesses, were used to demonstrate the system. Experiments revealed a promising result and showed the dependence of the probe sensitivity on the coating thicknesses.

1. Introduction

A magnetic force microscopy (MFM) probe, which is a typical AFM probe coated with thin-film magnetic alloys, is one of the key components in MFM [1]. It has a massive impact on the sensitivity of MFM responses and the spatial resolution of MFM images. Extensive works, including the development of the ultra-sharp MFM tip and the coating of special magnetic materials, have been conducted to improve the performance of MFM probes [2 – 4]. The characterization and the inspection of MFM probes have generally been performed in a AFM/MFM machine. The patterned magnetic recording media was used as a typical test sample [5]. Other researchers have prepared in-house magnetic samples, such as an Ω-shape gold ring [6] and an exchange biased magnetic layer system [7], in order to investigate the magnetization reversal and hysteresis loop of the MFM probes. Obviously, with those methods, the MFM probe under inspection has to make physical contact to the samples that may result in tip damage.

In this work, we developed the measurement system that can be utilized to evaluate the magnetic response of MFM probes and their sensitivity. The system employed a solenoid coil as a magnetic field generator to avoid the physical contact of the MFM probes. Several commercial and in-house MFM probes were used as test samples to demonstrate the proposed system.

2. Theoretical background

The MFM response is concerned with the magnetic force interaction $\vec{F}$ between the MFM probe and the magnetic stray field of the sample, which can be expressed as [8]:

$$\vec{F} = \mu_0 \int \vec{\nabla}\left(\vec{M}_{tip} \cdot \vec{H}_{sample}\right) dV_{tip} \quad (1)$$

where μ_0 is the vacuum permeability, $\vec{M}_{tip}$ is the tip magnetization, $\vec{H}_{sample}$ is the magnetic field strength and V_{tip} is the volume of the coating materials.

When the MFM probe is brought close to the sample and is exposed to the external magnetic field, the oscillation amplitude (*A*) and the phase shift ($\Delta\phi$) are altered as shown in equation (2) and (3), respectively [9]:

$$\Delta A \approx \frac{2AQ}{3\sqrt{3}k} \frac{d\vec{F}}{dz} \quad (2)$$

$$\Delta \phi \approx -\frac{Q}{k} \frac{d\vec{F}}{dz} \quad (3)$$

where *Q* is the quality factor ($Q = \sqrt{mk} / b$), *k* is the spring constant, *m* is the mass of the MFM tip and *b* is the coefficient of the damping force.

It can be seen from the above equations, a change in the amplitude and the phase of the probe oscillation is directly proportional to the magnetic force gradient. The sensitivity of the probe is dependent on both physical properties of the MFM probe (i.e. *Q* and *k*) and magnetic properties of the coating materials (i.e. $\vec{M}_{tip}$).

3. System implementation and setup

The system for the inspection of MFM probes was implemented as shown in figure 1. It consists of three main components: (1) a sample holder equipped with a piezoelectric element, (2) an optical beam deflection measurement and (3) a magnetic field generator. A MFM probe under test was attached on the sample holder. The piezoelectric element was biased with AC signals from a function generator (Agilent, model 33210A) in order to drive the MFM probe. The probe deflection was then measured by the optical method. A laser diode with λ = 630 nm (Blue Sky Research, VPSL-0635-005-X-5-A) in a combination with a stable DC power supply was employed as a light source. The reflected light beam was detected by a quadrant Si PIN photodiode (Hamamatsu, model S4349 with f_c = 20 MHz). The output signals of the photodiode were converted into voltage signals by a current-to-voltage amplifier and then fed into the summing and differential amplifiers with a unity gain as shown in figure 2. CA3140 FET input opamps were employed herein due to its relatively high input impedance and high speed. The output of the summing amplifier was employed to monitor the light intensity of the laser beam. The output of the differential amplifier was a measure of the probe deflection along the z direction.

A lock-in amplifier (Femto, model LIA-MVD-200-H) was utilized to analyze the amplitude and the phase shift of the probe deflection with respect to the driving signal. The oscillation amplitude was determined by the magnitude output of the lock-in amplifier. The phase difference between the measured signal and the reference signal was calculated using equation (4):

$$\phi = \cos^{-1}\left(\frac{X}{R}\right) \quad (4)$$

where *R* is the magnitude of the lock-in amplifier and *X* is the in-phase signal of the lock-in amplifier.

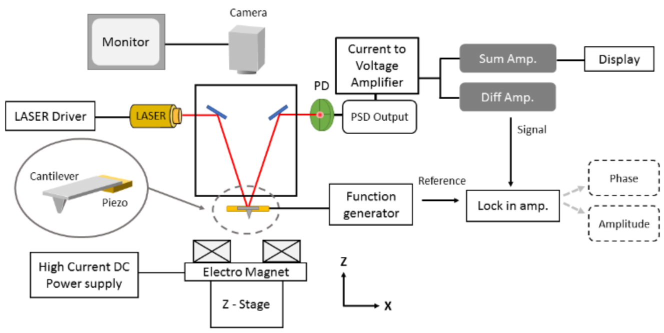

Figure 1. Schematic diagram of the proposed measurement system.

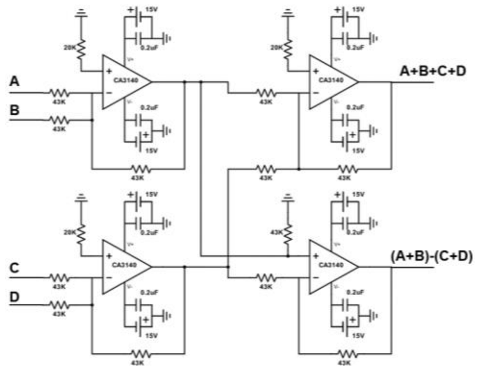

Figure 2. Schematic diagram of the differential-summing amplifier circuit.

A 500-turn solenoid coil was employed as the magnetic field generator in order to generate the out-of-plane magnetic field with the intensity up to ± 200 Oe. The coil had the internal radius of 8 mm, the outer radius of 20 mm and the length of 40 mm, respectively. The solenoid was attached to the z positioning stage to accurately control the spacing gap between the MFM probe and the solenoid. The MFM probe was also placed at the center of the solenoid coil to ensure the uniformity of the magnetic field strength.

4. Results and discussions

In this section, we demonstrated the operation of the developed system in order to inspect the response of MFM probes under magnetic fields. The frequency response of the MFM probe was shown in figure 3. The red dots represent the amplitude and phase data from this study in the absence of the magnetic field (0 Oe). The resonant frequency of the MFM probe can be extracted at the peak of the oscillation amplitude or at the 90-degree phase shift. The resonant frequency of MFM probes was in the range of 60 – 70 kHz. Figure 3 shows an example of measurement results of the MFM probe sample with the resonant frequency of 61.56 kHz. When the MFM probe was exposed to the magnetic field, 60 Oe in this example, we observed the amplitude and the phase data as represented by blue triangles. The interaction between the probe and the magnetic force softens the spring constant of the system, resulting in a decrease in the oscillation amplitude and the phase shift as well as a shift in the resonant frequency of the MFM probe as can be seen in the figure 3.

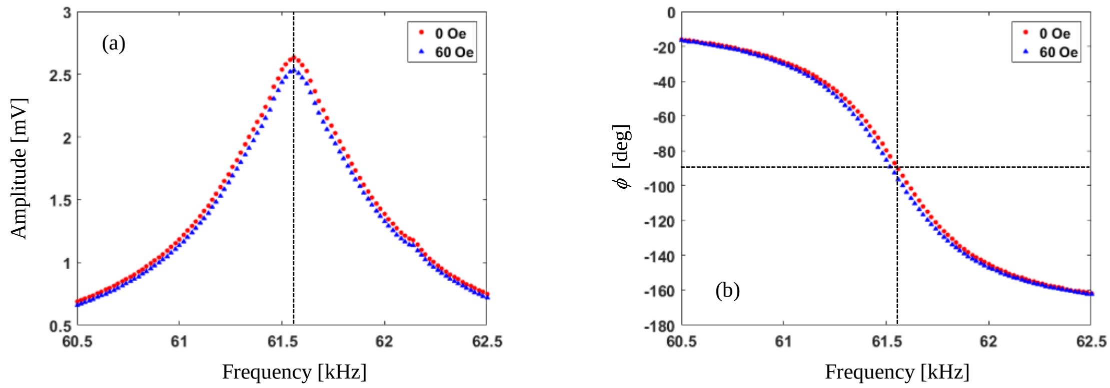

Figure 3. Magnetic response of the MFM probe in the absence and presence of external magnetic field: (a) the amplitude response and (b) the phase difference.

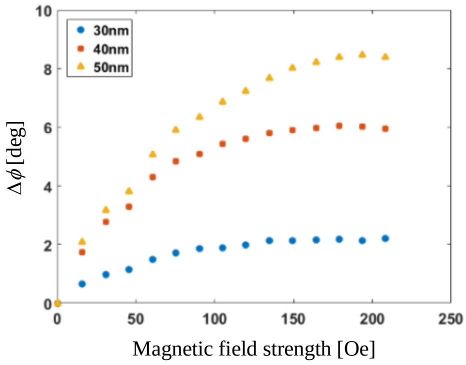

Figure 5. Magnetic response of commercial MFM probes with different coating thicknesses

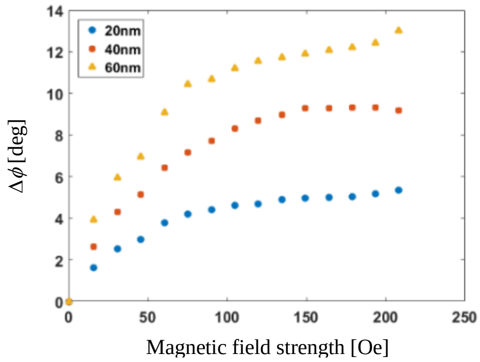

Figure 6. Magnetic response of in-house MFM probes coated with soft magnetic materials.

In the next experiment, the developed system was utilized to evaluate the different types of MFM probes. Samples were commercial products from Nanosensors™, i.e. ATEC-shaped MFM probes coated with Ni at 30, 40 and 50 nm thicknesses. We also tested Ni coated MFM probes, which were developed in-house using a physical deposition technique, with a coating thickness of 20, 40 and 60 nm. All probes were excited at their resonant frequency to ensure the maximum probe response. The responses of those samples corresponding to the applied magnetic fields were shown in figure 5 and 6, respectively. Experimental results revealed the improvement in the probe sensitivity as the coating thickness was increased. We also observed the saturation of the probe response when exposed to the field intensity greater 100 Oe.

5. Conclusion

The development of the measurement system for non-destructive testing of MFM probes was presented and discussed in this paper. The solenoid coil was employed as the magnetic field source in order to eliminate the tip damage issue. The application of the system for the probe inspection was successfully demonstrated with different types of MFM probes, including commercial available MFM probes and ones developed in-house. Results showed that the sensitivity of the probe responses was dependent on the coating thicknesses.

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