

Response of Magnetic Force Microscopy Probes under AC Magnetic Field

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Abstract. In this paper, magnetic force microscopy (MFM) probes with different coating materials were characterized under AC magnetic field. A perpendicular magnetic write head similar to those used in hard disk drives was employed as the AC magnetic field generator. In order to measure a response of MFM probes to AC magnetic field, a MFM probe under test was scanned, at a scan height of 10 nm, across the surface of the magnetic write head. During MFM imaging, the write head was biased by a sufficient magnitude of AC current, approximately 30 mA. A spectral analysis for a frequency sweep from 1 kHz to 100 MHz was extracted from post-processing MFM images. As expected, a MFM probe coated with hard magnetic alloys, i.e. FePt, has the lowest response to AC magnetic fields. MFM probes coated with soft magnetic alloys, i.e. NiFe and NiCoCr, have a relatively high and flat response across the frequency range. Ni coated MFM probe has the highest response to AC magnetic fields. In addition, CoCr and NiCo coated MFM probes show lower response than NiFe and NiCoCr probes at low frequencies; however, their response to AC magnetic field increase for the AC magnetic field with a frequency above 50 kHz. This can be implied that those MFM probes are a good candidate for being used to study the high-frequency performance of perpendicular magnetic write heads. Noting that response of all MFM probes significantly decreased when driven frequencies above 1 MHz due to the limitation of the hardware, i.e. response of quadrant photodiode and op-amp in a pre-amplifier.

1. Introduction

Magnetic force microscopy (MFM) is usually utilized to analyze magnetic domain structures and local magnetic properties of magnetic materials [1, 2] as well as to investigate written bits in magnetic recording media [3]. In these applications, highly sensitive and high-resolution MFM probes are required as the magnetic stray field of the samples is relatively weak. Commercial available MFM probes are designed and prepared with these applications in mind. Characterization and calibration methods for the conventional MFM probes are well documented [4-6]. Typically, commercial perpendicular recording media used in a hard disk drive (HDD) are employed as MFM observation samples. Masaaki Futamoto *et. al.* published the interesting studies on the effects of magnetic materials and coating thickness on MFM spatial resolution [4].

Recently, MFM has also been employed to characterize the AC response and performance of magnetic write heads in HDD industry [7-9]. MFM probes used in this application have to be exposed to strong magnetic field strength generated by magnetic write heads. Moreover, they must have a good

response to AC magnetic fields. However, there is no publication so far reporting studies on the influence of different coating magnetic materials on the AC field response of MFM probes. In this work, MFM probes with various coating materials, i.e. soft and hard magnetic materials, were characterized under multi-frequency AC magnetic fields. The experiment was carried out using a standard MFM machine equipped with a perpendicular magnetic write head similar to those used in HDD as the AC field generator. The response of those MFM probes as a function of excitation frequencies was investigated.

2. Theoretical Background

MFM in a phase contrast mode was used in this work since it is less sensitive to a surface roughness than operating in an amplitude detection mode. A phase shift is linearly dependent on a gradient of tip-sample magnetic interactions and can be approximated as [10]:

$$\Delta\phi \approx \left(\frac{Q}{k}\right) \frac{\partial F}{\partial z} \quad (1)$$

where Q is the effective quality factor, k is the spring constant of the MFM probe and $\partial F / \partial z$ is the force gradient along the z direction. The magnetic force between MFM tip and the magnetic sample, in this case the magnetic write head, depends on the magnetization of coating materials (M_{tip}), field gradient (∇H_{sample}) and the volume of the MFM tip (V_{tip}), which can be expressed as shown in equation (2) [11].

$$F = \mu_0 \int \nabla(M_{tip} \cdot H_{sample}) dV_{tip} \quad (2)$$

The magnetization M_{tip} is proportional to the applied field and the magnetic susceptibility ($M_{tip} = \chi_m H_{sample}$). This magnetic susceptibility is one important measure of magnetic materials describing their response to the applied field. The susceptibility varies with the excitation frequency and thus defines the response of the MFM probe to the AC magnetic field. Generally, when the MFM probe is exposed to a low-frequency magnetic field, the magnetization M_{tip} is able to rotate in the same direction of the external field. However, when the frequency of the AC magnetic field becomes high, the magnetization M_{tip} is unable to follow the rapid change of the external field, resulting in the different response of the MFM probe.

3. Experimental method

Frequency response of commercial available MFM probes was investigated using a standard MFM system as shown in figure 1. A perpendicular magnetic write head was employed as the AC magnetic field generator since it can produce AC magnetic field with very high frequency greater than 1 GHz [12, 13]. In this study, the magnetic write head was biased with AC current of 30 mA to ensure that the main pole was magnetically saturated. The excitation frequency was varied from 1 kHz to 100 MHz. Frequencies below 1 kHz were not considered here due to thermal issues in the magnetic write head. In order to measure a response of MFM probes to AC magnetic field, a MFM probe under test was scanned, at a scan height of 10 nm, across the surface of the magnetic write head. The measured

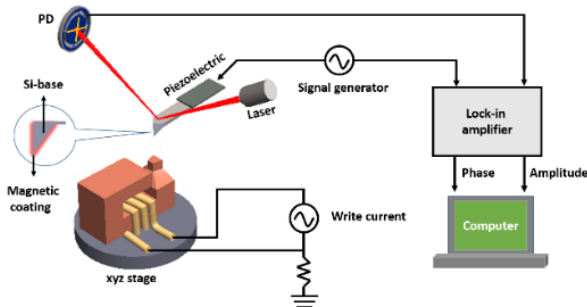


Figure 1. Schematic diagram of the system used to investigate the response of MFM probes under AC magnetic fields.

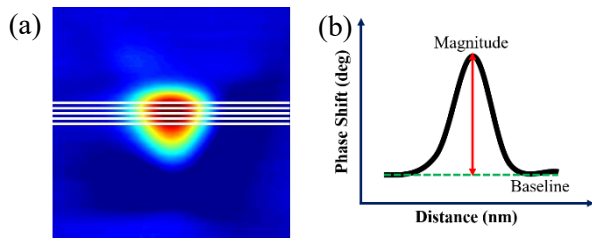


Figure 2. Measurement results: (a) an example of measured MFM image of the magnetic write head. The red color represents strong magnetic field intensity and the blue color representing weak field intensity. (b) Extracted phase shift profile obtained from averaging data of 5 scan lines shown in (a).

MFM image shown in figure 2(a) was post-processed to extract the magnitude of probe response as illustrated in figure 2(b).

The commercial MFM probes used in this study were coated with different magnetic materials including both soft and hard magnetic materials, i.e. Ni, NiFe, NiCo, NiCoCr, CoCr and FePt. Those probes were screened to have similar physical properties; the spring constant of those MFM probes is 2.8 ± 0.2 N/m, approximately and their resonance frequency is in the range of 65 – 75 kHz [14].

4. Results and discussions

Figure 3 shows the phase shift profiles of each MFM probe at frequency sweep from 1 kHz – 100 MHz. Figure 4(a) sums up the magnitude response of all probes as a function of excitation frequencies. As can be seen, MFM probes coated with soft magnetic materials (Ni, NiFe and NiCoCr) show very good response to the AC magnetic field. However, NiCo and CoCr coated MFM probes are less sensitive to the AC field. This is probably due to their coercivities are relatively higher (0.7 Oe for Ni, 1 Oe for NiFe, 1000 Oe for NiCo and 1370 Oe for CoCr [15-18]). For the MFM probe coated with a FePt layer, which is a strong hard magnetic alloy having a coercivity of 10 kOe [19], we observed no response to the AC magnetic field. It can be seen that the coating materials have an impact on the probe response to the AC magnetic field. MFM probes coated with low coercivity materials tend to have a better response to the AC magnetic field.

For the sake of clarity, we normalized the magnetic response shown in figure 4(a) by subtracting the magnitude response across the frequency range with a baseline. The baseline was taken from the mean of 10 lowest data points. The normalized magnitude response is then illustrated in figure 4(b). Results revealed that Ni-coated MFM probe had the highest sensitivity to AC magnetic field compared with the others, making it a good candidate for being used for characterization of magnetic recording heads. Its response is also interesting as it show an increase in probe response when the excitation frequency is raised up beyond 50 kHz. Similar behaviour can be observed on the response of MFM probes coated with NiCo and CoCr. NiFe and NiCoCr-coated probes have a flat response across the frequency range up to 1 – 2 MHz. It is worth to mention the significant drop in a probe response at a

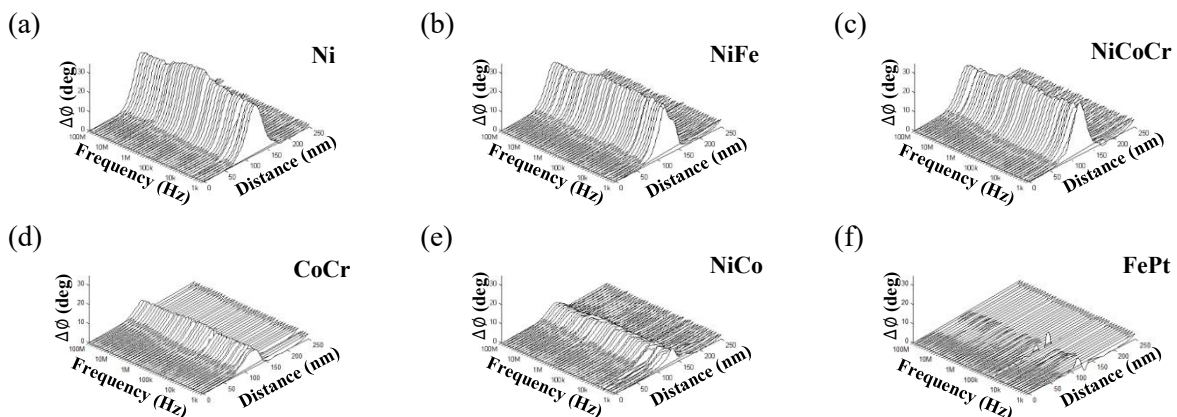


Figure 3. Frequency dependence of phase shift profiles for MFM probes coated with different materials including (a) Ni, (b) NiFe, (c) NiCoCr, (d) CoCr, (e) NiCo and (f) FePt.

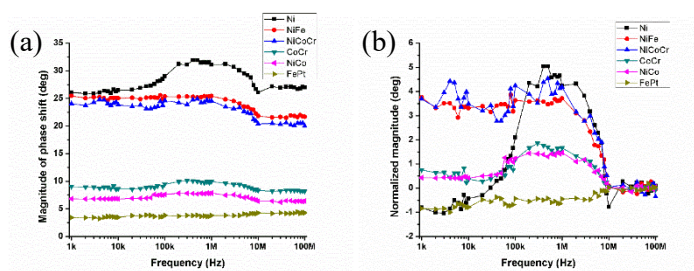


Figure 4. Magnitude response as a function of excitation frequencies for all MFM probes. (a) Magnitude vs Frequency and (b) Normalized magnitude vs Frequency.

frequency up to 1 – 2 MHz found on all probes. It was later found that the decrease response is resulted from a bandwidth limitation of a PSD sensor and preamplifier employed in the MFM system.

5. Conclusion

In this work, the AC performance of MFM probes with various coating materials was characterized using MFM. A perpendicular magnetic write head was employed as the multi-frequency AC field generator. Experimental results showed that the MFM probe coated with hard magnetic materials, i.e. FePt, had no response to the AC magnetic fields. NiFe and NiCoCr coated probes had a flat response across the frequency spectrum. The Ni-coated MFM probe offers a relatively strong response to the AC magnetic fields, compared with the others, making it is a good candidate for being used for characterization the AC response of magnetic recording heads.

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