Contact Detection and Evaluation of the Dynamic Characteristics of a Flying Head Slider for Magnetic Disk Storage using a Piezoelectric Transducer*

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Signal output from a piezoelectric transducer bonded to a flying head slider for magnetic disk storage is analyzed. Slider-core natural vibrations induced by contacts between the slider and the recording medium are identified with frequency peaks of the signal output. The analyses are applied to highly sensitive contact detection and evaluation of dynamic characteristics of a slider on an actual recording medium. The influence of the medium surface roughness on the dynamic behavior of the slider is presented for both the full flying state and the contact start/stop operation.

Key Words: Tribology, Lubrication, Hydrodynamic Bearing, Magnetic Disk Storage, Flying Head Slider, Head/Medium Interface, Piezoelectric Transducer, Acoustic Emission

1. Introduction

In magnetic hard disk drives for computer file memory, a self-acting gas-lubricated slider bearing (flying head slider) is used to support a magnetic transducer above a magnetic medium by virtue of a thin air-lubricated film. Higher recording densities can be attained mainly by reducing the spacing between the transducer and the medium. However, as the spacing is reduced, the influences of disk surface irregularities, dust particles, and mechanical vibrations become significant, and contacts between the slider and the medium, which can lead to serious damage to both, are apt to occur. To keep the reliability of magnetic disk memories high, an understanding of the contacts at the slider/medium interface is essential. Slider designs based on evaluation of the

slider dynamic characteristics for actual recording media are also important.

Contact detection between the slider and the medium was first reported by Tseng and Talke⁽¹⁾ who used an electrical resistance method. Since this method requires conductive media and sliders, it can not be used outside the laboratory. Kita et al.⁽²⁾ introduced a detection method using an acoustic emission (AE) sensor attached to a slider suspension (Fig. 1). This method is employed to observe slider/medium interactions^{(3),(4)}. However, as the signal detected by the AE sensor is influenced by suspension and mechanical vibrations, it is difficult to analyze precisely the slider behavior from the signal output. Recently, Yeack-Scranton⁽⁵⁾ proposed the use of a

Fig. 1 Schematic of AE sensor attached to the suspension

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small piezoelectric transducer (PZT) bonded directly to the slider to detect both the AB signal and slider rigid body acceleration induced by the contact (Fig. 2). This method offers highly sensitive detection of the contact between the slider and the medium and can also simultaneously measure the slider dynamic response^{(6),(7)}. However, identification of the PZT signal output and the phenomena occurring at the slider/medium interface are not necessarily sufficient.

This paper presents the spectrum analysis of the signal output from the PZT bonded to the slider. The slider-core natural frequencies are measured and calculated to identify the frequency peaks of the PZT signal output. The results are compared with those measured by the conventional contact detection method using an AE sensor. How to improve the sensitivity of contact detection for both methods is discussed. Furthermore, slider oscillations, from the continuous sliding state to the full flying state, are studied by monitoring the low-frequency components of the spectrum, which represent the slider rigid body acceleration. The effect of the medium surface roughness on the dynamic behavior of the slider is presented.

2. Experimental

A piezoelectric transducer (2.5 mm × 0.3 mm × 0.25 mm) made from PbTiO₃ is bonded to the back surface of the slider-core at the trailing edge, as shown in Fig. 2. Signal output below 1 kHz is filtered to eliminate the low-frequency components caused by disk run-out and mechanical vibrations which barely affect the slider spacing. Three types of sliders are prepared (Table 1). Slider A and slider B have the same dimensions but are made of different materials. Slider A and slider C are made of the same material but have different dimensions. To simplify the analysis, the slider shape is a simple rectangular parallelepiped, with narrow air bearing rails (b in the figure), small bleed slot depth (δ), and no magnetic transducer. A Watrous-type suspension with a static load

Fig. 2 Schematic of the small piezoelectric transducer bonded to the back surface of the flying head slider

of 68 mN (7 grf) is used to support the sliders.

The mechanical properties of the slider materials are given in Table 2. The Shear modulus and Poisson ratio are measured for block specimens made of the same materials as the sliders, using the parallelepiped resonance method^{(8),(9)}.

A 5.25-inch, Co-Ni sputtered thin-film recording medium is used. Two different surface roughnesses are prepared by changing the polishing level of the substrate surface. Medium A has a random rough surface, medium B a smooth surface. Table 3 gives the centerline average roughness, R_a , and the maximum roughness in a 0.25 mm-length area, R_{max} , values of these media.

3. Flying Characteristics of the Slider

Figure 3 presents the measured and the calculated flying characteristics of slider A and the root-mean-square value of the PZT signal output measured on medium A. The modified Reynolds equation⁽¹⁰⁾ is used to obtain the pressure distribution of the bearing region in the calculation. The slider attitude at a low surface velocity is determined using the mixed-lubrication model⁽¹¹⁾, which assumes that the slider slides on an imaginary lubrication film of thickness h_m which corresponds to the average asperity height of the

Table 1 Geometry of slider

Slider		A	B	C
Dimension [mm]	l_1	3.7	3.7	4.6
	l_2	2.8	2.8	3.2
	l_3	0.9	0.9	1.0
	δ	0.1	0.1	0.1
	b	0.32	0.32	0.32
Mass * [mg]		40	48	61
Material		Al ₂ O ₃ -TiC	Zn-Ferrite	Al ₂ O ₃ -TiC

* includes PZT and flexure part of gimbal suspension

Table 2 Mechanical properties of slider materials

Material	Al ₂ O ₃ -TiC	Zn-Ferrite
Density [g/cm ³]	4.2	5.3
Shear Modulus [GPa]	151	74
Poisson Ratio	0.35	0.32

Table 3 Surface roughness of media

Medium		A	B
Surface Roughness [μm]	R_a	0.009	0.003
	R_{max}	0.06	0.03

medium surface during the contact start/stop operation. In this calculation, h_m is assumed to be the $R_{\max}$ value ($0.06 \mu\text{m}$) in Table 3.

Slider taper edge spacing (h_i) and trailing edge spacing (h_o) are measured on a glass disk using laser interferometry⁽¹²⁾. The measured values agree with the calculated values in the steady flying state. The PZT signal output is filtered using a narrow band-pass filter (center frequency = 500 kHz, bandwidth = 50 kHz).

According to the flying characteristics of the slider and the PZT signal output, the flying state of a slider is classified into the following four states.

State I: Continuous sliding

State II: Mixed lubrication

State III: Intermittent contact

State IV: Steady flying

The flying attitude of a slider is shown in Fig. 4. The intermittent contact state is caused by contact between the slider and any asperities higher than h_m on the medium surface. In this state, the PZT signal output decreases as the medium surface velocity increases and finally reaches the noise level in the steady flying state.

4. Frequency and Discussion

4.1 Frequency spectra of the PZT signal output

Frequency spectra of the PZT signal output for

Fig. 3 Flying characteristics of slider A on medium A

Fig. 4 Mixed-lubrication model of the slider

slider A on medium A at surface velocities of 0 m/s, 2 m/s, 6 m/s, and 8 m/s are shown in Fig. 5. These velocities correspond to stationary, continuous sliding, intermittent contact, and steady flying states, respectively, as shown in Fig. 4. In the continuous sliding state (Fig. 5(b)), some resonant peaks are observed in the high-frequency region above 100 kHz. The peaks below 200 kHz decrease rapidly as the medium surface velocity increases, whereas the peaks higher than 200 kHz are independent of the velocity. In the intermittent contact state (Fig. 5(c)), the back-

(a) Stationary state, $U = 0 \text{ m/s}$

(b) Continuous sliding state, $U = 2 \text{ m/s}$

(c) Intermittent contact state, $U = 6 \text{ m/s}$

(d) Steady flying state, $U = 8 \text{ m/s}$

Fig. 5 Frequency spectra of PZT signal output for slider A on medium A

ground of the spectrum is reduced and the peaks sharpened. in the steady flying state (Fig. 5(d)), the peaks. In the high-frequency region disappear and only components lower than 50 kHz remain.

Figure 6 presents the frequency spectra of the PZT signal output for slider B and slider C on medium A at the intermittent contact state (surface velocity = 6 m/s for both cases). The results also show the velocity-independent peaks, while their frequencies are different from the case of slider A for each of these two sliders.

4.2 Identification of the slider-core natural frequency

To explain the frequency peaks of the PZT signal output, the slider-core natural frequency is analyzed and compared to these peaks.

The parallelepiped resonance method^{(8),(9)} used to measure the elastic constants of crystals, is used for the measurement of the slider-core natural frequency. The measuring system⁽⁹⁾ is shown schematically in Fig. 7. The slider-core is held between a pair of sapphire tips bonded to the surface of the piezoelectric plates. One of the plates is excited by a sinusoidal wave and the output signal is detected by the other plate. Sweeping the frequency of the excitation with a tracking generator, the resonant peaks at the slider-core natural frequencies are detected. These natural frequencies are also calculated by the Rayleigh-Ritz method⁽⁸⁾, modifying the slider rectangular parallelepiped.

Table 4 gives the measured and calculated slider-

core natural frequencies of the first four vibration modes and the frequency peak values of the PZT signal output in the slider intermittent contact states, numbered 1 to 4 in Fig. 5(c), Fig. 6(a), and Fig. 6(b) for each slider. They agree well. These lowest 4 modes correspond to the first torsion, first longitudinal bending, second torsion, and first transverse bending vibrations, respectively. The vibration mode shapes are shown schematically in Fig. 8.

Thus, the frequency peaks of the PZT output above 200 kHz are identified with slider-core natural frequencies. Obviously, higher sensitivities of slider/medium contact detection can be obtained by monitoring these natural frequencies using a narrow band-

Table 4 Slider-core natural frequencies and the frequency peak values of the PZT output in the intermittent contact state

Slider A			
Mode No.	Slider-Core Natural Freq. [kHz]		PZT Output Peak Value [kHz]
	Measured	Calculated	
1	399	395	396
2	512	505	500
3	799	848	788
4	856	864	830

Slider B			
Mode No.	Slider-Core Natural Freq. [kHz]		PZT Output Peak Value [kHz]
	Measured	Calculated	
1	245	247	238
2	321	313	310
3	515	528	498
4	528	529	519

Slider C			
Mode No.	Slider-Core Natural Freq. [kHz]		Pzt Output Peak Value [kHz]
	Measured	Calculated	
1	321	315	315
2	383	376	365
3	682	671	643
4	696	743	673

(a) Slider B on medium A, $U=6$ m/s

(b) Slider C on medium A, $U=6$ m/s

Fig. 6 Frequency spectra of PZT signal output for slider B and slider C on medium A, in intermittent contact state

Fig. 7 Schematic of measuring system for slider-core natural frequency

pass filter.

4.3 Comparison of slider/medium contact detection methods

Figure 9 compares the frequency spectra of the signal output from the present PZT and that from the conventional AE sensor (Fig. 1). The transfer function of the AE sensor used in this experiment is nearly flat between 100 kHz and 1 MHz. The signal output of both methods is measured simultaneously for slider A on medium A at the intermittent contact state. Both spectra contain almost the same resonant peaks, although the high-frequency components of the AE sensor above 600 kHz are diminished because of mismatching of the AE wave propagation at the boundary surface of the sensor and attenuation of the wave propagation path.

This result implies that more sensitive contact detection with the conventional AE sensor can be attained by tuning the resonant frequency of the sensor to approximately the slider-core natural frequencies below 600 kHz.

4.4 PZT output in the slider rigid body oscillation

Acceleration of the slider can be detected by monitoring the low-frequency components of the PZT

Fig. 8 Vibration mode shapes of the slider-core

Fig. 9 Comparison of frequency spectra for AE sensor attached to the suspension and PZT, for slider A on medium A in intermittent contact state, $U=7$ m/s

signal output^{(5),(7)}. In Fig. 10, the PZT signal output caused by the slider transient response due to an artificial rectangular bump on the recording medium is compared with the slider trajectory measured by laser interferometry⁽¹⁰⁾. The PZT output is integrated twice and the vibration amplitude is set to that of the laser interferometry. Although the low-frequency component of the PZT output is influenced by a high-pass filter (Fig. 10(b)), these measurements agree well. Low-frequency components of the PZT output are thus confirmed to represent the slider dynamic responses.

4.5 Evaluation of the slider dynamics on a real medium

The low-frequency components of the PZT output below 100 kHz are measured as a function of medium surface velocity for media A and B, which have different surface roughnesses. In the present experiment, the medium surface velocity was gradually decreased from 25 m/s to 0 m/s.

The measurement results for slider A on medium A are shown in Fig. 11. Regions I-IV in the figure

(a) Bump height = 0.085 μm , bump length = 0.05 mm

(b) Bump height = 0.085 μm , bump length = 1.0 mm

Fig. 10 Slider trailing edge fluctuation due to rectangular bumps (comparison of laser Interferometry measurements and twice-integrated PZT signal output)

correspond to the slider flying state shown in Fig. 4. From state IV (steady flying state) to state III (intermittent contact state), the air bearing resonance changes gradually depending on the medium surface velocity in the range of 15 kHz to 40 kHz. As the air film stiffness increases under the reduced spacing of the slider at low surface velocities, the air bearing resonant frequency becomes higher. In state II (mixed-lubrication state) and state I (continuous sliding state), suspension resonances, which are independent of the surface velocity, are induced below 10 kHz and the broad peak changes markedly beyond 100 kHz as the surface velocity decreases.

Figure 12 presents the calculated air bearing and suspension natural frequencies for slider A on medium A as a function of the surface velocity of the medium. Air film stiffness is obtained using Ono's method⁽¹³⁾ for slider attitudes at each surface velocity and the air bearing natural frequencies are determined. The vertical mode, pitching mode, and rolling mode of the slider rigid body oscillation are represented by P_1 , P_2 , and P_3 respectively. The suspension resonance is calculated using the finite-element method. The first bending mode, first torsional mode, and second bending mode of the load beam are represented by S_1 , S_2 , and S_3 , respectively. In states IV and III, the contours of the calculated air bearing and suspension natural frequencies in Fig. 12 agree with those of the measured resonant peaks in Fig. 11. In states II and I, as the disk velocity decreases, the calculated air bearing resonance decreases because the spacing of the slider is fixed at h_m in the mixed-lubrication model. However, the corresponding measured resonant peak seems to increase rapidly. In these states, slider motion is influenced mainly by the slider/medium interface contacts.

Figure 13 presents the same measurements for slider A on medium B, which has a smooth surface. Compared with the measurements on medium A (in

Fig. 11), peak levels of the air bearing resonance in states IV and III decrease. The surface roughness of the recording medium causes an increment in slider spacing fluctuation. In state I, sticking between the slider and the medium occurs at a surface velocity of 1 m/s, the suspension resonance peak level increases and there is an unknown peak around 90 kHz. The dynamic behavior of the slider/medium interface can be evaluated by analyzing low-frequency components of the PZT output from the continuous sliding to steady flying states.

5. Conclusions

This paper presented the analysis of the signal output from a small piezoelectric transducer bonded to a flying head slider. The main results are summarized as follows:

(1) The slider-core natural frequencies were determined both experimentally and by calculation, and the frequency peaks of the PZT signal output under intermittent contact conditions were identified with the natural frequencies. Higher sensitivities of slider/medium contact detection can be obtained by monitoring these natural frequencies using a narrow band-pass filter.

Fig. 12 Calculated air bearing and suspension natural frequencies for slider A on medium A as a function of surface velocity

Fig. 11 Low-frequency spectrum of PZT output for slider A on medium A as a function of surface velocity

Fig. 13 Low-frequency spectrum of PZT output for slider A on medium B as a function of surface velocity

(2) The conventional contact detection system using an AE sensor was compared with that of the PZT. The frequency peaks of the signal spectra of both methods agreed well, whereas high-frequency components of the AE sensor output were decayed. To increase the sensitivity of slider/medium contact detection with the AE sensor method, the resonant frequency of the sensor should be tuned to near the lower natural frequencies of the slider-core.

(3) The slider dynamics from the continuous sliding state to the full flying state were studied by analyzing low-frequency components of the PZT output. The medium surface roughness causes the slider spacing fluctuations in the steady flying and the intermittent contact states. The suspension resonance and unknown vibrations caused by the slider/medium interactions were detected in the mixed-lubrication and the continuous sliding states.

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References

- (1) Tseng, R. C. and Talke, P. E., Transition from Boundary Lubrication to Hydrodynamic Lubrication of Slider Bearings, *IBM Journal of Research and Development*, Vol. 18, No. 6 (1974), p. 534.
- (2) Kita, T., Kogure, K., Mitsuya, Y. and Nakanishi, T., New Method of Detecting Contact Between Floating-Head and Disk, *IEEE Trans. on Magnetism*, Vol. MAG-16, No. 9 (1980), p. 873.
- (3) Kawakubo, Y., Ishihara, H. and Seo, Y., Head Crash Process of Coated Disk During Contact Start/Stop Operations, *IEEE Trans. on Magnetism*, Vol. MAG-20, No. 5 (1984), p. 993.
- (4) Benson, R.C., Sundaram, R. and Talke, F. E., A Study of Acoustic Emission from the Head/Disk Interface in a 5 1/4 " Hard Disk Drive, *Trib. and Mech. of Magnetic Storage System*, STLE SP- 25 (1988), p. 87.
- (5) Yeack-Scranton, C.E., Novel Piezoelectric Transducer to Monitor Head-Disk interactions, *IEEE Trans. on Magnetism*, Vol. MAG-22, No. 5 (1986), p. 1011.
- (6) Takahashi, M., Yoneoka, S. and Ooe, T., A Signal Analysis of Piezoelectric Transducers Furnished on Head Sliders, *Natl. Conf. Record. on Semiconductor Devices and Materials*, IEICE, (in Japanese), S3-4 (1987), p. 275.
- (7) Mochizuki, K., Sato, I. and Hayashi, T., Impulse Force Detection of Head Disk Media Contact Using a Small Piezoelectric Transducer, *Trans. of IEICE*, Vol. E71, No. 4 (1988), p. 360.
- (8) Senoo, M., Nishimura, T. and Hirano, M., Measurement of Elastic Constants of Polycrystals by the Resonance Method in a Cylindrical Specimen, *Bull. JSME*, Vol. 27, No. 233 (1984), p. 2339.
- (9) Ohno, I., Free Vibration of a Rectangular Parallelepiped Crystal and Its Application to Determination of Elastic Constants of Orthorhombic Crystals, *J. Phys. Earth*, Vol. 24 (1976), p. 355.
- (10) Burgdorfer, A., The Influence of the Molecular Mean Free Path on the Performance of Hydrodynamic Gas-Lubricated Bearings, *Trans. ASME, J. Basic Engineering*, Vol. 81 (1958), p. 94.
- (11) Kita, T., Kogure, K. and Mitsuya, Y., Wear of the Flying Head of a Magnetic Disk File in Mixed Lubrication, *ASLE SP-16* (1984), p. 35.
- (12) Ohkubo, T. and Kishigami, J., Accurate Measurement of Gas-Lubricated Slider Bearing Separation Using Visible Laser Interferometry, *Trans. ASME, J. Tribol.*, Vol. 110 (1988) p. 148.
- (13) Ono, K., Dynamic Characteristics of Air-Lubricated Slider Bearing for Noncontact Magnetic Recording, *Trans. ASME, J. Lubr. Technol.*, Vol. 97, No. 2 (1975), p. 250.