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Design and Analysis of a Slider-Level Piezoelectric Sensor Array for Head-Disk Contact Detection

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To realize higher areal densities towards 10 Tbit/in², the ever decreasing flying height of the slider approaches the near-contact regime. It is essential to monitor head-disk interactions to prevent instability and damage to the head-disk interface. In this study, a piezoelectric sensor array embedded on the slider was proposed for head-disk contact detection. Integrability of the sensor array with standard slider fabrication process was considered in the design. Dynamic response of the sensor array to typical contact scenarios was obtained by finite element analysis. Simulation results suggest that the sensor array is adequately sensitive and capable of identifying contact location under intermittent head-disk contact.

Index Terms— Contact detection, head-disk, piezoelectric sensor, slider-level.

I. INTRODUCTION

Head-disk contact is a major tribological issue for terabit-per-square-inch systems with sub-5 nm head-media spacing (HMS) [1]. With decreasing HMS, fly-contact can be classified into three categories: wear-in, proximity, and continuous surfing contact [2], [3]. In the wear-in state, the slider is in contact with the highest asperity. After a certain period of wear to the highest asperity, the HMS can be further decreased and more asperities will come into contact. The ensuing state is called proximity contact. The final state of surfing contact is reached when the HMS is reduced to a level where the slider dips into the lubricant and stays in continuous light contact with the media.

Head-disk contact detection using traditional acoustic emission (AE) sensors has been in use for decades [4]. Other technologies that do not require additional sensors include variable gain amplifier (VGA) signal detection and thermal asperity (TA) detection [5]. However, the existing technologies with various drawbacks are far from ideal. The main disadvantage of AE sensors is that they can only be placed on the drive cover, arm or suspension. Therefore, they are only capable of contact detection for a single head-disk interface (HDI). While for the VGA technique, the occasional contacts (wear-in) cannot be detected. Touchdown sensors using the TA technique have been used in commercial hard disk drives to calibrate the flying height for thermal fly-height control (TFC) sliders. However, the touchdown sensors cannot be used for high-frequency real-time detection, because the head-disk contact has to last for a prolonged period of time for frictional heat to reach a detectable level [6].

One solution to the aforementioned issues is to integrate piezoelectric sensors into the slider. A piezoelectric material possesses a crystallographic structure that lacks a center of symmetry. When mechanical stress is applied on a piezoelectric material, electrical polarization is induced due to asymmetric distortion of the lattice. As a result, an electrical

voltage is developed across the surfaces of the piezoelectric material. Upon head-disk contact, the slider body experiences dynamic stress. By integrating a piezoelectric material on the slider, the dynamic stress and thus head-disk contact can be detected. Previously, successful head-disk contact detection was demonstrated by using piezoelectric thin-film sensors fabricated on the top of the slider, parallel to the air bearing surface (ABS) [7]. Although it showed that slider-level detection is technically feasible, fabricating sensors on the top is not compatible with micromachining process of the slider.

To enable process integration, thin-film sensors must be fabricated on the trailing side [8]. However, shifting the sensors to the trailing side may reduce the sensitivity, as the top surface experiences more strain. Hence, feasibility of this new concept has to be investigated. This study explores performance of a piezoelectric zinc oxide (ZnO) sensor array embedded on the trailing side. Because of its good piezoelectricity and excellent processing compatibility with the standard slider fabrication process [9], ZnO is chosen over other materials, such as lead zirconate titanate (PZT), as the piezoelectric material. Dynamic response of the triple-sensor array to typical head-disk contact scenarios has been obtained by finite element analysis.

II. DESIGN OF PIEZOELECTRIC SENSOR ARRAY

A pico slider (1.25×1×0.3 mm³) with a piezoelectric sensor array embedded beneath the overcoat is illustrated in Fig. 1. The sensor array consists of a common ground electrode (Au), a ZnO layer (1 μm thick), and three sensing pads (Au). Each sensing pad (sensor) has an area of 200×200 μm². The overcoat on the trailing side is 30 μm thick. Upon head-disk contact (Fig. 1(a)), the slider experiences elastic strain. The strain is converted to voltage through piezoelectricity of the ZnO layer. Since the strain distribution changes with the contact location, as a result the output voltages of the sensors also correlate to the contact location. Therefore, the contact location can be identified by examining the output voltages of the left, central and right sensors.

III. FINITE ELEMENT MODEL

The sensor-slider-suspension assembly as shown in Fig. 2 was modeled using the commercial finite-element software Ansys Multiphysics 10.0. The suspension, slider body and piezoelectric ZnO sensors were meshed with element types of SHELL63, SOLID45 and SOLID5, respectively. As seen in Fig. 2(b), the air bearing was simplified into spring-damper systems (COMBIN14). The spring constant and damping coefficient are 1.25×10^5 N/m [10] and 0.24 N-s/m [11], respectively. A force is applied on the trailing side (Fig. 2(b)) to simulate head-disk contact.

The material properties for the slider-suspension components are listed in Table 1 and the piezoelectric material (thin-film ZnO) in Table 2 [12].

IV. RESULTS AND DISCUSSIONS

The response of the piezoelectric sensor array is dependent on the head-disk contact force. Previously, Ono and Yamane [13] investigated slider bouncing vibrations induced by asperities and calculated the contact force. They reported that the contact force reached 10 mN, when the contact pad surface moved below the initial mean asperity height by 5 nm. For light contact (surfing) with reduced bouncing vibrations,

TABLE I
MATERIAL PROPERTIES OF SLIDER-SUSPENSION COMPONENTS

Component	Material	Young's Modulus (GPa)	Density (kg/m ³)
Slider body	Al ₂ O ₃ TiC	390	2200
Overcoat	Al ₂ O ₃	138	2200
Sensor	ZnO	N.A.	5750
Suspension	Stainless steel	193	8000

TABLE II
MATERIAL PROPERTIES OF THIN-FILM ZNO

Stiffness Coefficients		Piezoelectric Coefficients		Dielectric Coefficients	
c_{11} (GPa)	209.7	d_{31} (10^{-12} C/N)	-5.43	ϵ_{31}	7.57
c_{12} (GPa)	121.1	d_{33} (10^{-12} C/N)	11.67	ϵ_{33}	9.03
c_{13} (GPa)	105.1	d_{15} (10^{-12} C/N)	-11.34		
c_{33} (GPa)	210.9				
c_{44} (GPa)	42.47				

Vakis, Lee and Polycarpou [14] simulated the time varying interfacial forces for TFC sliders. The head-disk contact force was found to be 0-2 mN.

The response of the piezoelectric ZnO sensor array to three contact scenarios is analyzed. The slider is excited by a single asperity in wear-in contact and by multiple asperities in proximity contact. A mean contact force of 5 mN [13] is applied on the trailing side of the slider. Transient analysis is performed for these two bouncing contact situations. For the surfing contact, the slider continuously interacts with the surface roughness. Hence, it is more appropriate to use harmonic analysis to study the response to excitations at different frequencies associated with surface roughness and disk waviness. The applied mean contact force in this case is 1 mN [14].

A. Wear-in Contact – Single Asperity

Fig. 3 shows the response of the piezoelectric sensor array to a single asperity contacting the rear ABS pad. The duration of the contact force F_n (5 mN) is 0.1 μ sec. The output voltage from the central sensor V_C rises up abruptly to 9.5 mV (Fig. 3(c)). As seen in Fig. 3(b) and Fig. 3(d), time histories of the left and right sensors (V_L and V_R) are exactly the same due to symmetry. Their instantaneous response is much smaller (2.3 mV) than the central sensor. This demonstrates that the magnitude of the sensor output correlates to the contact location. To further prove the sensor array's capability in indentifying the contact location, the contact force is shifted to the left corner on the trailing side. Responses of the three sensors are shown in Fig. 4. As expected, the impulse triggers the largest instantaneous signal (5.3 mV) from the left sensor (Fig. 4(b)). The instantaneous signals from the central and right sensors are 2.4 mV (Fig. 4(c)) and 1.3 mV (Fig. 4(d)), respectively.

B. Proximity Contact – Multiple Asperities

Proximity contact is simulated by multiple asperities impacting the slider. Fig. 5 shows the transient response of the sensor array when multiple asperities in a sequence contact the rear ABS pad. As shown in Fig. 5(a), the contact force induced by multiple asperities forms a pulse train. The time interval of the pulses is 1 μ s. With a similar pattern to a single asperity contacting the rear ABS pad (Fig. 4), the response from the central sensor is also the biggest among the three sensors. The amplitude of the output voltage of the central sensor (Fig. 5(c)) reaches 22 mV after 6 μ sec. By contrast, as seen in Fig. 5(b) and Fig. 5(d) the output voltages for the left and right sensors are only 6 mV. Shifting the contact force to the left corner, the highest output (25 mV) is observed from the left sensor (Fig. 6(b)). It can be seen in Fig. 6(d) that the right sensor, furthest from the contact location, has the lowest output (14 mV). Corresponding to its position, the output of the central sensor (18 mV) is lower than the left sensor and higher than the right sensor.

C. Continuous Surfing Contact

For a TFC slider, the bouncing vibrations are damped out after touchdown. Afterwards, the TFC slider enters a state of surfing contact where the TFC bulge is in continuous light contact with the media [15]. The disk roughness and waviness excite the slider at a broad range of frequencies. Hence, it is helpful to study the sensor response in the frequency domain. Fig. 7 shows harmonic response of the triple-sensor array to a contact force (1 mN) in the center of the TFC base (rear ABS pad). The highest peaks of the responses from the three sensors all appear at 5.55 MHz, which is the 2nd in-plane bending mode of the slider [16]. The frequencies around 5 MHz correspond to disk roughness or waviness with wavelengths in the lower range of micrometers [17]. For instance, with a wavelength of 3 μ m and a disk rotational speed of 7200 rpm, when the slider is flying at a radius of 20 mm, the contact excitation frequency is calculated to be 5.03 MHz, close to the 2nd in-plane bending mode of the slider.

Similar to transient analyses (Fig. 3 and Fig. 5), the central sensor that is the closest to the contact force has the highest peak (74.85 mV) in comparison with 47.67 mV for the left and right sensors. Again due to symmetry, the left and right sensors have identical harmonic responses. Comparing the three contact scenarios i.e. single-asperity contact in Fig. 3, multiple-asperity contact in Fig. 5 and continuous contact in Fig. 7, it can be seen that the highest output occurs in continuous contact, even though the contact force (1 mN) in continuous contact is smaller than that of the first two scenarios (5 mN). This shows that in light surfing contact the slider might experience more elastic strain due to contact force with low amplitude and high frequency. Furthermore, under large roll vibrations and a lower TFC protrusion, the corners of the TFC base might come into contact with the disk. As seen in Fig. 8, when the contact force is shifted to the left corner, the highest peak still occurs at the central sensor. This is different from the first two cases where the output correlates to the contact location. Under harmonic excitation, the slider is highly excited, and the central area of the trailing side undergoes more strain than the left and right sides. Therefore, in continuous contact the output of the central sensor is always the largest regardless of the contact location.

V. CONCLUSIONS

A piezoelectric sensor array on the trailing side of the slider was proposed for head-disk contact detection. Dynamic response of the ZnO sensor array to typical head-disk contact scenarios was simulated. Results showed that the output of the sensor array was on the millivolt level. The output voltages of the sensors correlate to the contact location under occasional head-disk contact. In continuous light (surfing) contact, the slider is highly excited by contact force with low-amplitude and high-frequency. As a result, the output voltage is higher than that induced by the wear-in and proximity contact. Moreover, regardless of the contact location, the central sensor always has the highest response under continuous contact. In conclusion, this study demonstrated that the integrated piezoelectric ZnO sensor array on the trailing side is a feasible design for detection of head-disk contact.

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Fig. 1. Slider design: (a) slider in contact with disk; (b) triple-sensor array.

Fig. 2. Finite element model: (a) sensor-slider-suspension assembly; (b) slider with ZnO sensor.

Fig. 3. Transient response to a single asperity contacting the rear ABS pad: (a) contact force; (b) voltage of left sensor; (c) voltage of central sensor; (d) voltage of right sensor.

Fig. 4. Transient response to a single asperity contacting the left corner: (a) contact force; (b) voltage of left sensor; (c) voltage of central sensor; (d) voltage of right sensor.

Fig. 5. Transient response to multiple asperities contacting the rear ABS pad: (a) contact force; (b) voltage of left sensor; (c) voltage of central sensor; (d) voltage of right sensor.

Fig. 6. Transient response to multiple asperities contacting the left corner: (a) contact force; (b) voltage of left sensor; (c) voltage of central sensor; (d) voltage of right sensor.

Fig. 8. Harmonic response to continuous contact on the left corner: (a) voltage of left sensor; (b) voltage of central sensor; (c) voltage of right sensor.

Fig. 7. Harmonic response to continuous contact on the rear ABS pad: (a) voltage of left sensor; (b) voltage of central sensor; (c) voltage of right sensor.