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TECHNICAL PAPER

Effect of thermal pole tip protrusion and disk roughness on slider disk contacts

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Abstract Ultra-high areal density for hard disk drives requires a stable head disk interface at a flying height lower than 8 nm. At such a low flying height, small flying height variations may cause slider/disk contacts. Slider/disk contacts can also occur when a write-current is applied to the write coil since the flying height between slider and disk can be affected by the thermal expansion of the pole tip. In this paper, we investigate the vibration characteristics of sliders during thermally induced contacts using laser Doppler vibrometry. We perform a parametric study of contact events using disks with different surface roughness and lubricant thicknesses, and analyze the slider motion statistically. For a given write current, we observe that the slider vibrations increase with disk roughness and lubricant thickness.

1 Introduction

During writing of information on the disk, current flows in the coil of the read/write head. The current generates heat that causes thermal expansion of the pole tip. The expansion of the pole tip in turn, reduces the mechanical spacing between the slider and the disk. A schematic view of a slider flying on a rotating disk is shown in Fig. 1a. In Fig. 1b, the protrusion of the pole tip is shown due to the write current. Depending on the magnitude of the protrusion, slider/disk contacts can occur, resulting in pole tip damage and wear of the head/disk interface.

Current-induced thermal pole tip protrusion has been studied by a number of researchers. Tian et al. (1997, pp. 3130–3132) investigated the read back signal disturbance caused by thermally induced flying height fluctuation. They observed that the electrical resistance of the MR element was temperature dependant. Gupta et al. (2001, pp. 380–387) studied the thermal pole tip protrusion with temperature and current in the write coil. They measured thermal pole tip protrusion using an optical profiler and an atomic force microscope and observed that thermal pole tip protrusion was affected by the material and structure of the read/write head. Pust et al. (2002, pp. 101–106) simulated thermal pole tip protrusion using three-dimensional finite element analysis and observed that thermal stress in the shields of the head was caused by a mismatch in the coefficient of thermal expansion. They also found that during head operation, the primary heat source was the write coil. Imamura et al. (2002, pp. 2147–2149) and Xu et al. (2003, pp. 2411–2413) investigated the temperature rise in a slider when flying on a transparent disk using infrared microscopy. Kurita et al. (2005, pp. 3007–3009) investigated the flying height reduction of a slider due to thermal pole tip protrusion and found that the protrusion of the pole tip is partially compensated by an increase in the air pressure on the air-bearing surface. Chekanov et al. (2004, pp. 2591–2593) studied the effect of thermal pole tip protrusion on the recording performance. They observed that the overwrite degradation was caused by head-disk interactions due to thermal pole tip protrusion and that appropriate selection of disk lubricants could reduce the effect of thermal pole tip protrusion. Li et al. (2005, pp. 306–308) simulated the heat transfer between

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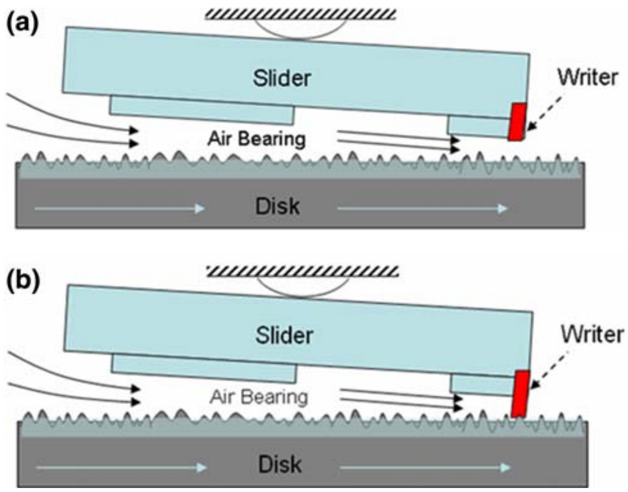


Fig. 1 Schematic view of slider flying on a rotating disk at conditions **a** without thermal pole tip protrusion, and **b** with thermal pole tip protrusion

slider and disk surfaces. They showed that the temperature distribution over the air bearing surface was asymmetrical and was related to the air bearing pressure and heat flux distribution.

In recent hard disk drives, thermal protrusion of the magnetic read/write element has been used to adjust flying height. Meyer et al. (1999) discussed a heating system in a slider assembly to thermally control the position of the read/write element. Dietzel et al. (2000, pp. 123–130) investigated a method to insert a resistive heater into the substrate of the slider. The expansion of the heater caused a change of the crown of the slider and, consequently, a change in the flying height of the slider. Kurita et al. (2006, pp. 369–375) investigated an "active slider" with a nano-thermal actuator near the read/write element. The magnetic spacing of the slider can be controlled in situ during drive operations. Suk et al. (2005, pp. 4350–4352) experimentally verified that the magnetic and mechanical spacing could be controlled by thermally actuating the recording transducer. More recently, Juang and Bogy (2007, pp. 570–578) investigated the relationship between air bearing surface design and thermal actuation of a slider. They introduced an efficient spacing adjustment design based on thermal actuation.

Although the above studies have clarified many aspects of current-induced thermal pole tip protrusion, none of them have addressed the dynamics of a slider in five degrees-of-freedom during contact caused by thermal pole tip protrusion. In this paper, we investigate the dynamics of sliders during contacts caused by thermal pole tip protrusion using a five degrees-of-freedom test setup. A parametric study of contact events is performed with disks of different lubricant thickness and surface roughness, and the slider motion is analyzed statistically. The joint time frequency analysis is used to investigate the slider motion and to examine the characteristics of the slider motion due to thermal pole tip protrusion.

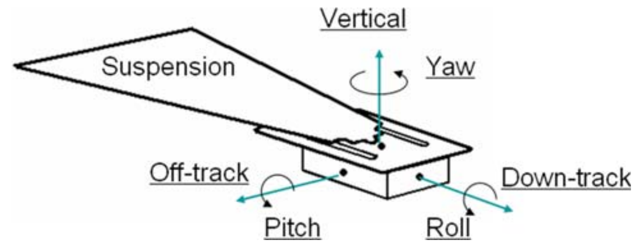


Fig. 2 Six components of slider vibration

2 Experimental setup and conditions

2.1 Five degrees-of-freedom for slider motion

An air bearing slider used in hard disk drives has six degrees-of-freedom, as indicated in Fig. 2. In particular, it can move up and down (vertical motion), left to right (off-track motion), forward to backward (down-track motion). In addition, it can rotate around three orthogonal axis, i.e., yaw, roll and pitch. Rotation around the vertical axis is denoted by yaw, around the down-track axis by roll and around the off-track axis by pitch.

The suspension has high in-plane stiffness, i.e., the slider vibrations in the yaw direction are very small. Thus, the degree of freedom in the yaw direction is not considered in this paper, i.e., we are concerned only with five degrees-of-freedom. They are vertical, down-track, off-track, pitch and roll.

2.2 Experimental setup

The experimental set-up for measurement of motions in five degrees-of-freedom is shown schematically in Fig. 3. Three independent laser Doppler vibrometers were used to measure the motion of the slider in the vertical, down-track and off-track direction. A position sensitive sensor (PSD) was used to measure the slider motion in pitch and roll direction. Amplifiers and filters were used to amplify and filter signals from the three laser Doppler vibrometers and the position sensitive detector. A spinstand tester was used to load/unload the head/suspension assembly onto the rotating disk. Digital oscilloscopes were used to visualize and capture the output signals from the laser Doppler vibrometers and the position sensitive detector.

A schematic view of the measurement set-up is shown in Fig. 4. The vertical motion of the slider is measured by deflecting the laser beam of LDV-1 from a miniaturized metallized silicon mirror that is attached to the backside of

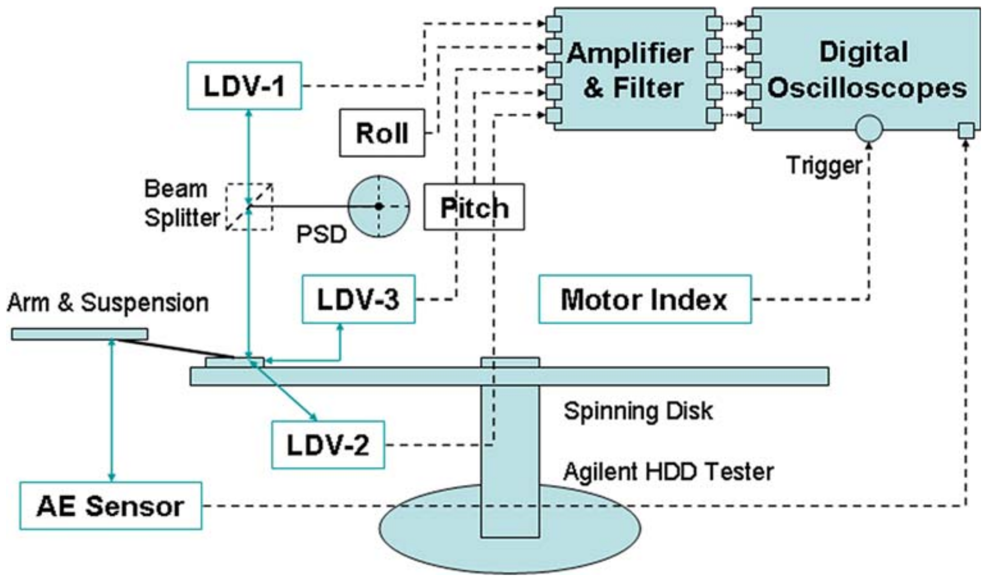


Fig. 3 System set-up for measurement of slider vibrations for five degrees-of-freedom

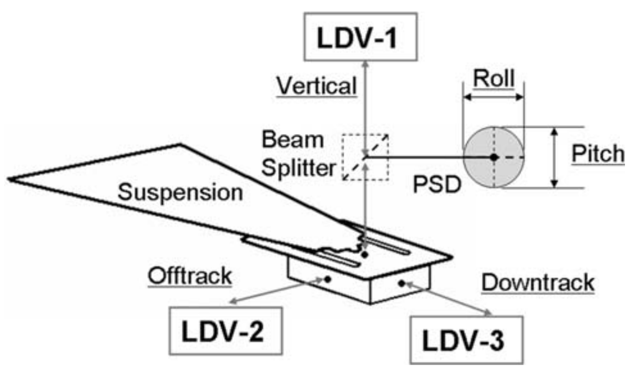


Fig. 4 Illustration of measurement of slider motion using three independent laser Doppler vibrometers and one position-sensitive detector to detect the slider motion for five degrees of freedom: vertical, down-track, off-track, pitch, and roll

the suspension. The mass of such a mirror is <5% of a slider, and has negligible effect on the slider dynamics. The laser beam is reflected by the mirror and travels to the beam splitter, which splits the signal into two beams: one beam senses the vertical velocity of the slider and the other beam were measured by the position sensitive detector (PSD) for the pitch and roll motion.

The position sensitive detector measures the angular change of the slider directly. As a result, the position of the laser spot relative to vibration modal lines does not affect the measurement because the angular change of the rigid slider (a solid body) is constant along its entire length. The signal output from the position sensitive detector provides both the pitch and roll angular change of the slider motion. When the laser beam is projected onto the disk without the slider present, the vertical, circumferential slope (pitch), and radial slope (roll) components of disk topography can be obtained simultaneously.

The second laser Doppler vibrometer (LDV-2) measures the off-track motion by reflecting the laser beam radially from the side of the slider. Similarly, the laser Doppler vibrometer in the down-track direction (LDV-3) reflects the laser beam from the rear-end surface of the slider pad, thereby measuring the slider motion in the circumferential direction.

In order to synchronize the signals from three laser Doppler vibrometers and the position sensitive detector, a motor index signal was used as triggering signal. The motor index signal excites a sharp rise at every revolution of the disk.

The signals from the three laser Doppler vibrometers and the position sensitive detector are filtered and amplified in order to improve the signal-to-noise ratio. Averaging of the signals is also used for this purpose. In addition, an acoustic emission (AE) sensor is mounted on the loading arm of the head-gimble assembly. The calibrated acoustic emission sensor detects the onset of slider/disk contacts during operating conditions.

2.3 Experimental conditions

The disks used in this experiment were standard thin-film disks coated with a 3 nm-thick diamond-like-carbon overcoat for wear protection. The sliders used were typical “pico” type sliders with an air bearing surface as shown in Fig. 5. The nominal flying height of the slider is 6 nm at a linear velocity of 15.8 m/s and a zero skew angle.

For all experiments reported in this paper, the slider was connected to electronic circuitry with read/write capability. When the write channel is engaged, a current is applied to the slider write element at a pre-determined frequency and amplitude. Due to the resistance of the write element of the

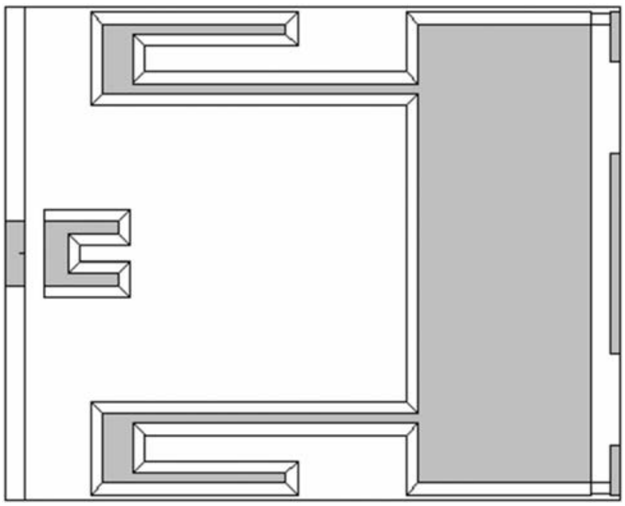


Fig. 5 Air bearing slider used in the experiment

slider, a fraction of the electrical energy is converted into thermal energy. This thermal energy, in turn, causes the protrusion of the slider pole tip towards the disk surface. Depending on the design, contact between the slider and the disk can occur due to the reduced slider/disk clearance. In our experiment, a current of 50 mA at 900 MHz was applied to the write element when the write channel was activated.

The motion of the slider is detected using the five degrees-of-freedom setup. The signals from all five channels were triggered with the leading edge of the write current signal. We have captured 20 sequences for each measurement using a sampling rate of 5 MHz. The captured slider vibration data were high-pass filtered at 10 kHz to eliminate disk flutter and suspension dynamics effects.

3 Experimental results and discussion

3.1 Vibration characteristics of slider when write channel is engaged

In Fig. 6, slider vibrations are shown for the off-track, down-track, vertical, pitch, and roll directions. In addition, the signal from the write gate is shown on the top of the Fig. 6, indicating when the write channel is engaged.

From Fig. 6 we observe that the vibration amplitudes of the slider increase for all five degrees-of-freedom when the write gate is enabled (marked “On”). A delay of approximately 0.8 ms is seen to present between the engagement of the write channel and the onset of the first slider vibrations. The slider vibrations increase gradually, reaching a maximum value and decreasing slightly thereafter to a constant vibration amplitude. The slider shows a significant increase in vibration amplitude in the down-track (1.6 nm peak-to-peak), vertical (1.4 nm peak-to-peak) and pitch (2.3 μrad peak-to-peak) degrees-of-freedom. The vibration amplitude in the off-track (0.5 nm peak-to-peak) and roll (0.9 μrad peak-to-peak) directions is also higher when the write channel is turned “On” as compared to being “Off”. As soon as the write channel is turned “Off”, the vibration amplitudes of the slider decrease for all five degrees-of-freedom and return to normal “flying” values.

In Fig. 7, plots of the joint time frequency results of the slider vibrations of Fig. 6 are shown. We observe that the slider is excited at 139 kHz in the down-track, vertical, pitch, and roll direction after the write channel is activated. In addition, distinct slider vibrations are observed at 150 kHz and 100 kHz for all five degrees-of-freedom. It is interesting to note that the largest frequency contact is

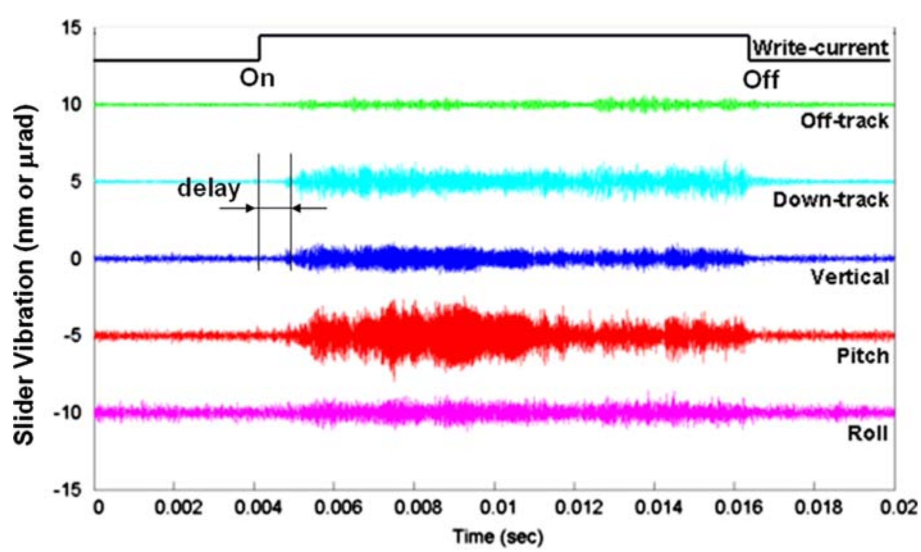


Fig. 6 Slider vibrations for five degrees-of-freedom

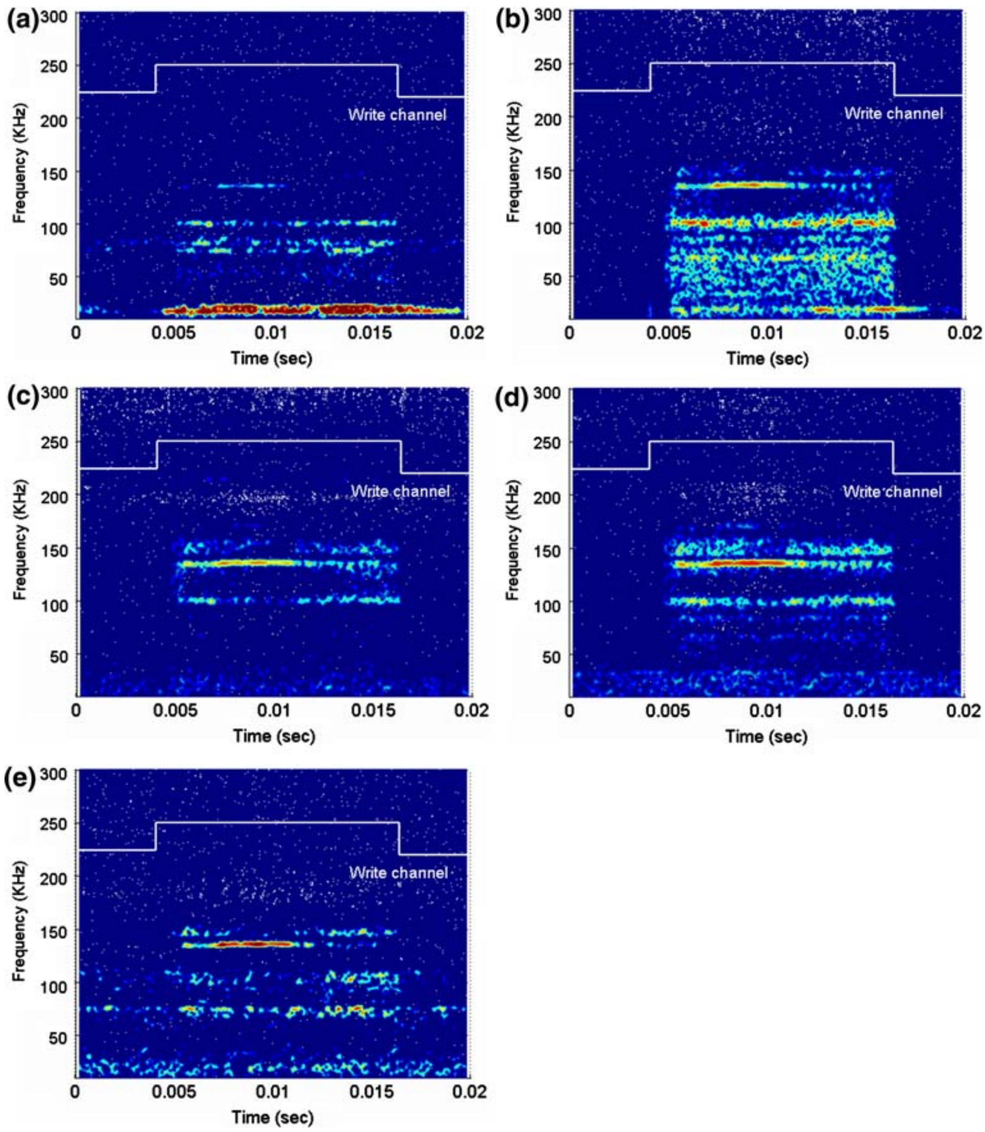
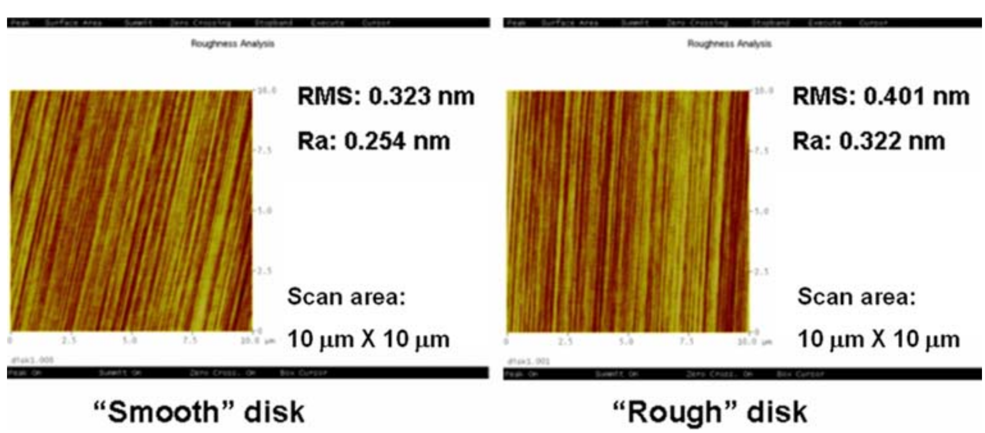


Fig. 7 Joint time frequency analysis of slider vibrations in five degrees-of-freedom

Fig. 8 Disk surface topography measured using atomic force microscopy



present in the down-track direction. The excited frequencies, between 100 kHz and 150 kHz, are in the range of typical slider air bearing frequencies.

3.2 "Rough" disk vs. "smooth" disk

To study the effect of disk roughness on thermally induced pole tip contacts, we have repeated the experiments of the previous section with two types of disks that were identical in terms of thickness and lubricant type but were different in terms of surface roughness. As shown in Fig. 8, the root-mean-square (RMS) and roughness average (Ra) values of the two disks were 0.32 nm and 0.25 nm for the "smooth" disk, and 0.40 nm and 0.32 nm for the "rough" disk, respectively. Twelve sliders with the same air bearing design were selected and flown on both disks. The slider dynamics were measured using the previously discussed five degrees-of-freedom measurement system. For each measurement, the slider was positioned to fly on a "new" track and the write channel was engaged so that contact between head and disk occurred. In order to keep a constant linear velocity of 15.8 m/s, the disk rotational speed was adjusted based on the track radius. From each measurement, we have calculated the average peak-to-peak value of slider vibrations for the top 10% of the total number of amplitude peaks.

The average peak-to-peak value of the slider vibrations for the two types of disks investigated is shown in Fig. 9. We have statistically analyzed the results obtained from the measurements and have calculated a confidence level for each measurement.

Except for the off-track vibration, the confidence level of our data was higher than 95%. As indicated in Fig. 9, the amplitude of slider vibrations in the down-track, vertical, pitch, and roll directions are higher for the "rough" disk than the "smooth" disk for all vibrations excited by the same amount of thermal pole tip protrusion. The slider vibrations on the "rough" disk showed increases in

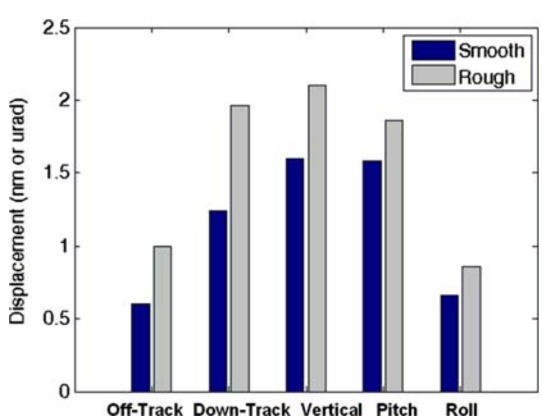


Fig. 9 Effect of surface roughness on slider vibrations

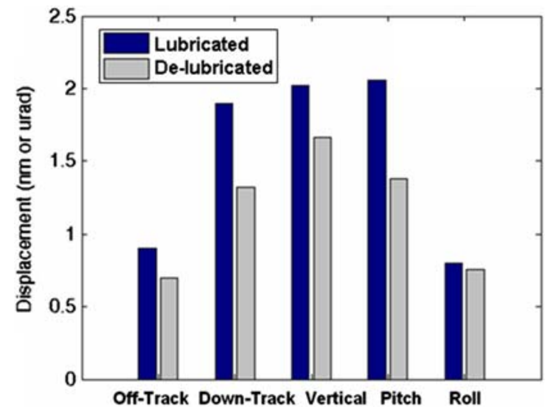


Fig. 10 Effect of lubricant film thickness on slider vibrations

amplitude of approximately 60% in the down-track direction, 30% in the vertical direction, 20% in the pitch direction, and 30% in the roll direction compared to the "smooth" disk. Thus, it is apparent that the disk surface roughness has a significant effect on the amplitude of slider vibration, i.e., the higher the surface roughness, the larger the vibration amplitude during slider disk contacts due to the same amount of thermal pole tip protrusion.

3.3 Lubricated disk versus de-lubricated disk

In this experiment, we have investigated the dynamic characteristics of contacts induced by thermal pole tip protrusion for lubricated and "de-lubricated" disks. Here, the term "de-lubricated" disks refers to disks that were originally lubricated but were subsequently submerged in a solvent to remove the lubricant layer. The original disk surfaces were lubricated with a thin layer of perfluoropolyether (PFPE)-type lubricant. After submerging the disk twice into the solvent, the mobile lubricant layer was removed from the disk. The lubricant thickness of all disks was measured using a Fourier transform infrared (FTIR) spectrometer. The change in thickness between lubricated and de-lubricated disks was found to be about 0.9 nm. Twelve sliders with the same air bearing design were selected to be flown on both types of disks.

In Fig. 10, the average of slider vibration amplitudes is shown for a set of lubricated and de-lubricated disks. Except for the vibration in the roll direction, the confidence level of our data was higher than 95%. We observe that the amplitudes of lubricated disks are larger by ~30% in the off-track direction, 45% in the down-track direction, 20% in the vertical direction, and 50% in the pitch direction than those of the de-lubricated disks. It is apparent from this comparison that lubricant film thickness affects slider vibration amplitudes, i.e., a decrease in the lubricant thickness causes a reduction of vibration amplitudes for slider disk contacts due to thermal pole tip protrusion.

4 Summary and Conclusion

In this paper, we have analyzed the vibration characteristics of sliders during thermally induced head/disk contacts using laser Doppler vibrometry. Slider vibrations were observed in the vertical, pitch, roll, off-track, and down-track directions. An increase in vibration amplitudes in all five degrees-of-freedom was observed when the write gate was engaged. The slider was excited in the range of air-bearing frequencies during head/disk contacts. The slider vibration amplitudes were found to increase for disks with higher surface roughness and for disks with a thicker lubricant layer.

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