Experimental Investigation of Slider Dynamics at a Contacting Head-Disc Interface

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Abstract

This report presents the experimental investigation of slider dynamics and ensuing slider-lubricant interactions at a contacting head-disc interface (HDI). Through a detailed evaluation of the transient and longer term dynamics under contact for different slider and suspensions designs, a consistent explanation slider dynamics and competing phenomena at the contacting HDI such as slider-disc burnishing and slider-lubricant interactions is established. At close spacing and light contact, the dominant excitation occurs at suspension frequencies in the off-track direction and at the suspension and ABS frequencies in the vertical direction. For a more severe contact condition, there is a stark change and excitation occurs over a broad range of frequencies. While suspension design significantly affects slider dynamics under contact, the effect of contact area on slider dynamics was not evident from these experiments.

Introduction

In order to achieve storage densities of 1Tb/in^2 and higher in hard disc drives (HDD), the physical spacing between the read/write head and the disc must be reduced to within 2*nm*. The requirement of 500,000 tracks per inch (*tpi*) translates to a track mis-registration (TMR) budget of 5*nm* in the off-track direction. Ensuring a reliable and stable HDI meeting these goals is an enormous challenge. A push towards smaller spacing and the possibility of partial or continuous contact architectures for future HDD capacity targets necessitates the investigation of slider and lubricant dynamics under contact.

Intermolecular forces are known to have a destabilizing effect on the dynamics of sliders with a fly-height below 5*nm* [1, 2]. Slider instability increases the chances of slider-disc contact, and the resulting electrostatic forces due to frictional tribocharging and contact forces at the HDI can further destabilize the slider proving detrimental to the drive's recording performance [3, 4]. Contact between the slider and disc also increase slider-lubricant interaction promoting meniscus formation and lube transfer between the disc and the slider [5, 6]. While contact between the slider and the disc is generally undesirable, the design of a HDI that can accommodate intermittent contact has been actively researched through experiments and simulation [7, 8]. Slider designs for partial/continuous contact recording architecture have also been proposed as part of strategies to meet 1Tb/in^2 storage density targets [9, 10].

A HDI that accommodates contact should ensure low slider vibrations together with minimal wear in order to have reliable recording performance, and the effects of contact pad width, gramload and slider design on slider dynamics, contact forces and wear at the contacting HDI need to be understood. In this work, the combined vertical and off-track dynamics of extremely low flying sliders is investigated when the slider is brought into contact with the disc. Based on experimental observations from tests inducing transient and longer duration slider-disc contact, a consistent explanation tying slider dynamics to the competing phenomena at the HDI is established. Considering three different HGAs with different slider and suspension form factors, we examine the relative effects of suspension, contact pad area and gramload on the slider's off-track and vertical dynamics.

Experimental set-up

In order to investigate the transient vertical and off-track dynamics of the slider under contact we performed experiments on a TTi spinstand that has programmable spindle speed capability. Polytec Laser Doppler Vibrometers (LDV) are instrumented to measure the slider's vertical and off-track dynamics, and an Acoustic Emission (AE) sensor monitors contact between the slider and disc. Contact is induced by lowering the spindle speed (the disc rotations per minute RPM) and hence, the physical spacing between the slider and the disc (i.e slider flying-height). Two different tests are devised to vary the spindle speed.

Spin-down spin-up (SDSU) test: In this case the spindle speed is lowered linearly with time from a specified maximum disc RPM, at which the slider flies without contact, to a specified minimum RPM, at which the slider contacts the disc, and increased linearly back to the specified maximum RPM (Figure 1a). The transient dynamics together with contact information are obtained from the LDV and the AE signal sampled at $1MHz$ during this test. The typical duration of a SDSU test is $16s$, with roughly half the time for spin-down and the rest for spin-up.

Dwell test: In this test the spindle RPM is lowered in steps of 300 RPM from the specified maximum RPM to the minimum RPM (same as that for those SDSU test) and raised back to the maximum RPM maintaining a controlled dwell time of $5s$ at each RPM (Figure 1b). The LDV and the AE signal are sampled at $1MHz$ for $1s$ at each dwell RPM for post processing.

The above two tests are useful in understanding the effects of transient and the longer term slider-disc contact on the stability of the slider and the robustness of the HDI.

Post processing steps: The vertical and off-track velocity signals from the LDV are integrated to obtain the vertical and off-track displacements. In order to eliminate the low frequency noise that is characteristic of the LDV systems used, the velocity and displacement signals are high pass filtered above $10kHz$. For SDSU tests, the total test duration of $16s$ is divided into 160 intervals of $0.1s$, and the mean and variance (σ) of each interval is computed. In addition, the frequency content of each of these intervals is computed to obtain the joint frequency-time plot (JFT) of the displacement, velocity and the AE signal. For Dwell tests, the mean, variance (σ) and frequency content of a $1s$ capture of AE and LDV signals is computed at each dwell RPM.

Experiments are performed on three different HGA's differing in the slider and suspension form factors (Figure 2): HGA(I) pico slider on a long suspension, HGA(II) femto slider on a short suspension, and HGA(III) pico slider on a short suspension. The media sample is a 95mm disc coated with 10.4Å Zdol PFPE lubricant with a molecular weight of 3kDa and a low bonded ratio. All experiments are performed at 10^{o} skew.

Results

Figure 3 and Figure 4 summarize the results of two SDSU tests performed on the same track, one immediately before, and one immediately after performing a Dwell test on that track. These plots show the change (3σ) of the AE signal, vertical and off-track displacements with disc linear velocity.

As the disc spins down, the AE signal shows a sharp jump in the 3σ value from the baseline indicating slider-media contact, and the linear velocity corresponding to contact initiation is called the touchdown velocity. Similarly, the takeoff velocity is defined as the linear velocity at which slider-media contact ceases during disc spin-up. In general, there is a difference between touchdown and takeoff velocity values owing to competing phenomena at the HDI such as intermolecular forces, lubricant meniscus forces originating from slider-lubricant interaction and slider/media burnishing.

Effect of suspension design and slider form factor

SDSU1: (SDSU test before the Dwell test: Figure 3): The design of the suspension has a significant effect on the relative magnitudes of the vertical and off-track displacements when the slider contacts the media. Considering HGA(I) and (III) which have the same pico slider on a long and short suspension respectively, it is evident from Figure 3b,c that the slider vertical (bouncing) displacements are dominant for the short suspension, while off-track displacements are dominant for the longer suspension. Considering HGA(II) and (III) which have a femto and a pico slider, respectively, on the same short suspension, the vibrations of the femto slider are expected to be smaller than that of the pico design because of the smaller area of the slider coming in contact with the disc [9, 10]. (The center trailing pad width is 250 μm for the pico slider and 80 μm for the femto slider). However, Figure 3b,c do not show any conclusive general trend: the vertical displacements are larger for HGA(II), while the off-track displacements are larger for HGA(III).

SDSU2: (SDSU test after the Dwell test: Figure 4): The results of the SDSU2 differ significantly from SDSU1. In the region where there is contact for both SDSU tests, the amplitude of the AE signal (indicative of the severity of contact) as well as that of slider displacements is higher for SDSU2 compared to SDSU1 at a given linear velocity. It is surmised that the prolonged interaction of the slider and lubricant at the lower RPM (with contact) during the Dwell test causes a deterioration of the HDI, and hence poor performance of the slider in the subsequent SDSU2 test. A comparison of the plots in

Figure 4b,c, verifies our previous observation that vertical (bouncing) displacements are dominant for the short suspension, while off-track displacements are dominant for the longer suspension. Slider form factor does not alter the slider dynamics significantly as the amplitudes of vertical and off-track displacements are comparable for HGA(II) and HGA(III).

Comparison between SDSU test and Dwell test

The results for the amplitude of the AE signal, vertical displacements and off-track displacements from the Dwell test are compared to those of the SDSU tests in Figure 5 for HGA(I). The Dwell test results are shown with markers, while the curves are for the SDSU1 and SDSU2. Similar plots are included for HGA(II) and (III) in Figure 6 and Figure 7, respectively.

From these figures, it is observed that the results from the Dwell test agree better with the plots for SDSU2. During the Dwell test, there is a prolonged interaction between the slider and the lubricant, especially at lower RPM when there is contact, and the HDI is altered significantly. During SDSU2, the slider responds to this altered interface during contact, and hence the resulting plots for SDSU2 are in good agreement with the Dwell test results. One conclusion that can be drawn from these figures is that the SDSU tests are better suited to predict the slider dynamics of a contacting HDI without significantly altering it. Additionally, if the results of SDSU1 and SDSU2 are in close agreement, it means that the Dwell test does not alter the HDI significantly, implying a robust contacting HDI. In the different experiments reported here, the results for SDSU2 were different from those for SDSU1, and hence the contacting HDI is inferred to be unreliable for longer duration. It is important to note that the amplitude of slider vibrations under contact is far beyond the allowable limits for successful recording. For the given HGAs, the 3σ of the bouncing vibration should stay within 5*nm* for successful recording, and hence the HDI considered in these experiments is unsuitable under contact.

Evidence of slider-lubricant interaction during contact

The changes that occur at the HDI during the Dwell test may be partially understood by looking at the change in touchdown and takeoff velocities of the SDSU1 and SDSU2 tests. This change is shown in Figure 8 for the three different HGA considered. The touchdown velocity is greater than the takeoff velocity in SDSU1 for HGA(I),(II) and (III), and this trend is consistent with the burnishing of the disc asperities (and possibly the slider's contact pad) when it comes into contact with a new track on the disc. After a Dwell test is performed on the same track, the touchdown velocity in SDSU2 is less than the touchdown velocity in SDSU1 indicating a further burnishing of the track and/or slider during the Dwell test for all three HGAs.

In contrast to SDSU1, a significant change occurs after the Dwell test for HGA(II) and (III). The touchdown velocity in SDSU2 is noticeably less than the takeoff velocity for these HGAs, consistent with the hysteresis phenomena exhibited as a result of intermolecular and lubricant mediated adhesion at the HDI due to strong slider-lubricant interactions [5]. For HGA(I), however, the touchdown velocity remains higher than the takeoff velocity in SDSU2 indicating that the effect of slider-disc burnishing is far more dominant than the intermolecular and lubricant meniscus related adhesion forces at the HDI.

A consistent explanation for slider dynamics and slider-lubricant interaction

Based on the above observations on slider-lubricant interactions, a consistent explanation for the relative magnitudes of the vertical and off-track motions for HGA(I), (II) and (III) emerges. The longer suspension in HGA(I) is inferred to be stiff in the vertical direction. As a result when the slider of HGA(I) comes in contact with the disc, the bouncing amplitudes are lower, but it is at the expense of a higher contact force at the HDI that causes higher disc track and/or slider burnishing and wear. In contrast, the short suspension of HGA(II) and (III) is inferred to be less stiff in the vertical direction. When the slider comes into contact with the disc, the bouncing vibrations are higher, but there is lower disc/slider burnishing and wear. In this case, the forces from slider-lubricant interaction become dominant at the HDI, and the argument is supported by the clear hysteresis in touchdown and takeoff velocities for these HGA.

Observation of the sliders after testing under an optical microscope reveals a higher level of lubricant pick-up on the sliders of HGA(II) and (III) confirming higher slider-lubricant interactions for these cases as compared to HGA(I) (Figure 9).

Analysis in the frequency domain

The JFT plot for the off-track and vertical displacements captures the changes that occur in the slider's response when it comes in contact with the disc. Figure 10a,b show the results for HGA(I), and the AE signal is plotted as a reference to mark contact initiation and termination.

As the fly-height of the slider decreases during disc spin-down, the slider first comes into light contact with the disc. The off-track motions are mainly excited at the suspension frequencies (with dominant excitation at ≈30*kHz*). With a further reduction in the disc RPM, contact becomes more severe and the off-track vibrations are suddenly excited over a broad frequency range (seen as a dark band on the JFT plot). The vertical motion spectrum shows a similar behavior: at close spacing and light contact, the excitation is mainly at the suspension and air bearing frequencies, while for more severe contact, the excitation is over a wide frequency range. A nonlinear shift in the second harmonic of the air bearing frequency (≈250*kHz* when the slider is flying) towards a higher frequency (≈350*kHz*) shows the nonlinear increase in the stiffness of the air-bearing with decreasing fly-height.

The FFT plots for Dwell tests on this slider (Figure 10c,d) are shown for the disc RPM corresponding to near contact, light and severe contact conditions. The general trends of these plots compare well with the JFT plots of the SDSU test.

Effect of Gram load change

The effect of an increase in the gramload on the slider is studied by reducing the z-height of the slider from the design value by 3 *mils*. The results for HGAs(I) and (II) (Figure 11) show that the touchdown and takeoff velocities increase with increasing gramload, and it is consistent with a reduction in the fly-height of the slider. Whereas HGA(I) continues to exhibit ‘inverse hysteresis’ (touchdown velocity > takeoff velocity) supporting slider-disc track burnishing as the main phenomena at the HDI, HGA(II) exhibits hysteresis (touchdown velocity < takeoff velocity) supporting enhanced slider lubricant interaction. At a given linear velocity, the AE signal is higher for a higher gramload case, and the corresponding displacements in the off-track and vertical directions are also higher (Figure 12). An increase in gramload does not change the dominant behavior at the HDI (slider-track burnishing/wear vs. slider-lubricant interaction), but simply tends to enhance (worsen) the underlying phenomena.

Conclusions

This report presents the results of an experimental investigation of contact between the slider and disc at the HDI of a hard disc drive through a study of the slider’s vertical and off-track dynamics, and ensuing slider-lubricant interaction

(1) An evaluation of slider transient and longer term dynamics under contact is performed using a sequence of spin-down spin-up test, followed by a dwell test and another spin-down spin-p test. While slider motions are excited beyond reasonable limits required for good recording performance, some relations on competing phenomena at the contacting HDI such as slider-disc burnishing and slider-lubricant interactions, and their relation to slider dynamics is established.

(2) It may be inferred from these experiments that higher suspension vertical stiffness suppresses vertical bouncing motions at the expense of higher contact force and wear at the HDI, while lower suspension stiffness results in higher

bouncing and increased slider-lubricant interactions, consistent with previous simulation work [9]. Off-track motions of the slider are larger for longer suspension designs, which tend to have lower stiffness in the off-track direction.

(3) At close spacing and light contact, the dominant excitation occurs at suspension frequencies in the off-track direction, and at the suspension and ABS frequencies in the vertical direction. For a more severe contact condition, there is a stark change and excitation occurs over a broad range of frequencies.

(4) Previous simulation studies indicate that a smaller contact pad width should result in lower contact force and friction thereby reducing slider vibrations [9]. However such a reduction was not evident from experiments on ‘pico’ and ‘femto’ sliders mounted on the same suspension, possibly because slider-lubricant interactions are far more dominant at the HDI of these HGAs.

(5) A comparison of slider performance of traditional slider designs with new Thermal Fly-height Control (TFC) slider designs should better clarify the effect of contact area on slider dynamics and HDI performance. These investigations will the topic of a future study.

References

[1] Wu, L. and Bogy, D.B., *Effect of the intermolecular forces on the flying attitude of sub-5 nm flying height air bearing sliders in hard disk drives.* Journal of Tribology, 2002. 124(3): p. 562-567.

[2] Thornton, B.H. and Bogy, D.B., *Head-disk interface instability due to intermolecular forces.* IEEE Transactions on Magnetics, 2003. 39(5): p. 2420-2422.

[3] Gupta, V. and Bogy, D.B., *Dynamics of sub-5-nm air-bearing sliders in the presence of electrostatic and intermolecular forces at the head-disk interface.* IEEE Transactions on Magnetics, 2005. 41(2): p. 610-615.

[4] Ambekar, R., Gupta, V., and Bogy, D.B., *Experimental and numerical investigation of dynamic instability in the head disk interface at proximity.* Journal of Tribology, 2005. 127(3): p. 530-536.

[5] Ambekar, R. and Bogy, D.B., *Effect of slider lubricant pickup on stability at the head-disk interface.* IEEE Transactions on Magnetics, 2005. 41(10): p. 3028-3030.

[6] Ambekar, R. and Bogy, D.B., *Lubircant depletion and disk-to-head lubricant transfer at the head-disk interface in hard disk drives.* Proceedings of STLE/ASME International Joint Tribology Conference 2006, 2006.

[7] Kiely, J. and Hsia, Y.-T., *Three-dimensional motion of sliders contacting media.* Journal of Tribology, 2006. 128(3): p. 525-533.

[8] Yu, S., et. al., *Dynamics of read/write head positioning in both flying-height and off-track directions.* IEEE Transactions on Magnetics, 2007. 43(9): p. 3796-3801.

[9] Chen, D. and Bogy, D.B., *Dynamics of partial contact head disk interface.* IEEE Transactions on Magnetics, 2007. 43(6): p. 2220-2222.

[10] Mate, M.C., et. al., *Dynamics of contacting head-disk interfaces.* IEEE Transactions on Magnetics, 2004. 40(4): p. 3156-3158.

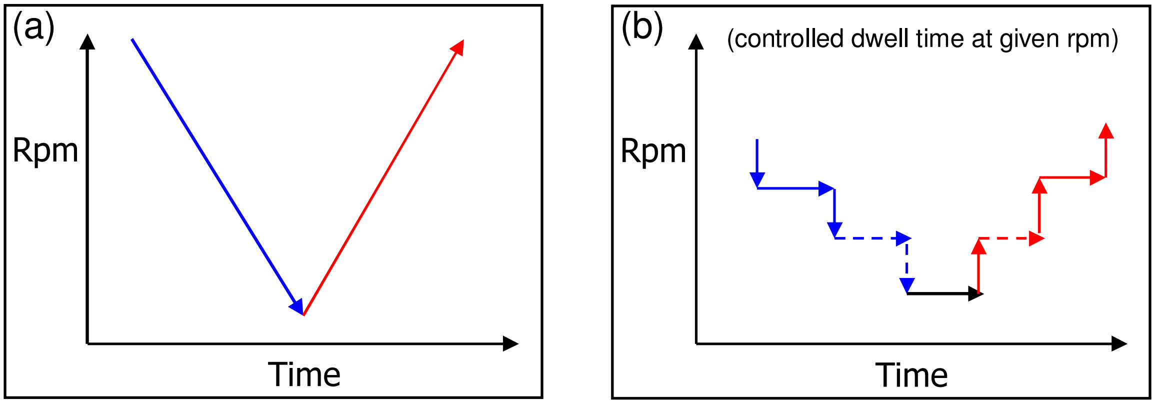

Figure 1 (a) Spin-down spin-up test (b) Dwell test

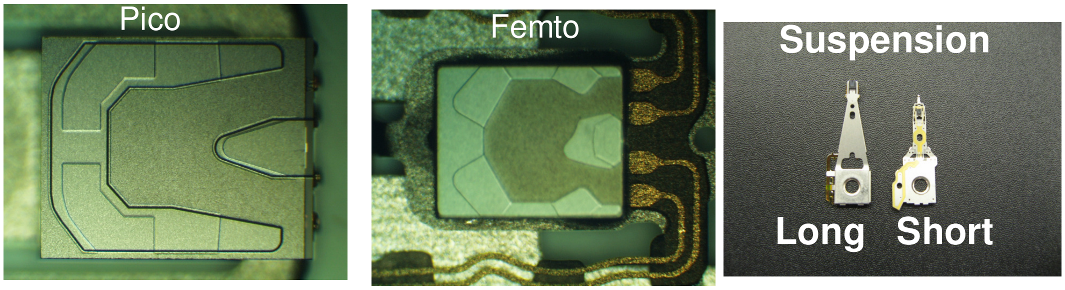

Figure 2 Slider ABS and suspension pictures

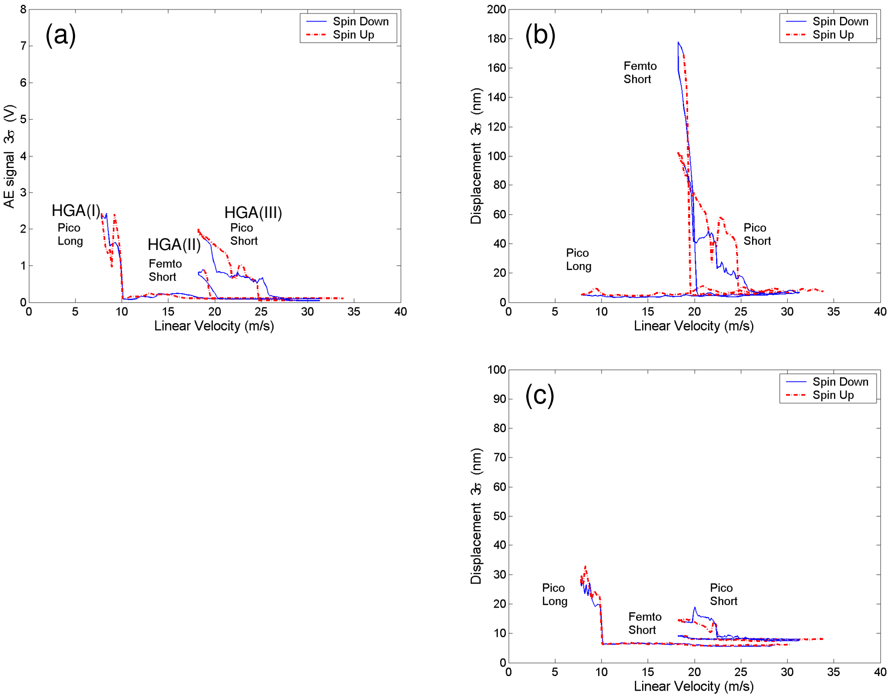

Figure 3 SDSU test before Dwell test (a) AE signal (b) Vertical displacement (c) Off-track displacement

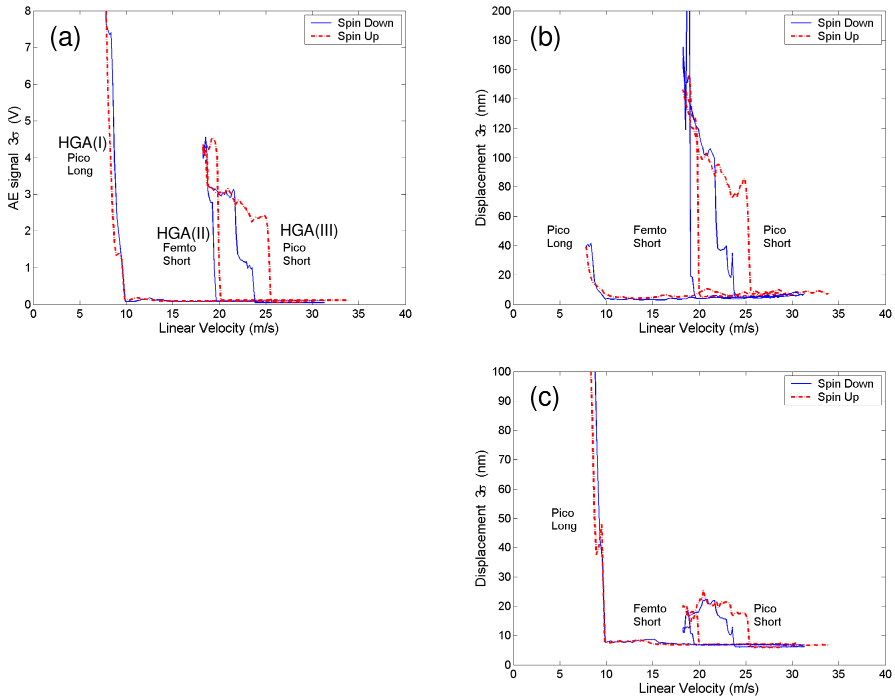

Figure 4 SDSU test after Dwell test (a) AE signal (b) Vertical displacement (c) Off-track displacement

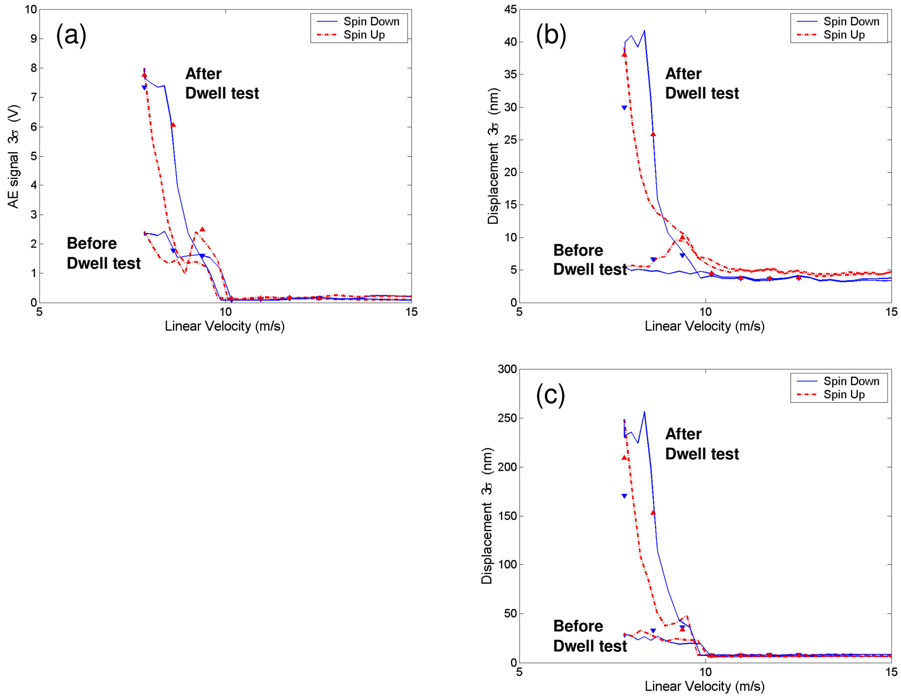

Figure 5 Comparison between SDSU test and Dwell test for HGA(I) (a) AE signal (b) Vertical displacement (c) Off-track displacement; ▼: Dwell test step down RPM, ▲: Dwell test step up RPM.

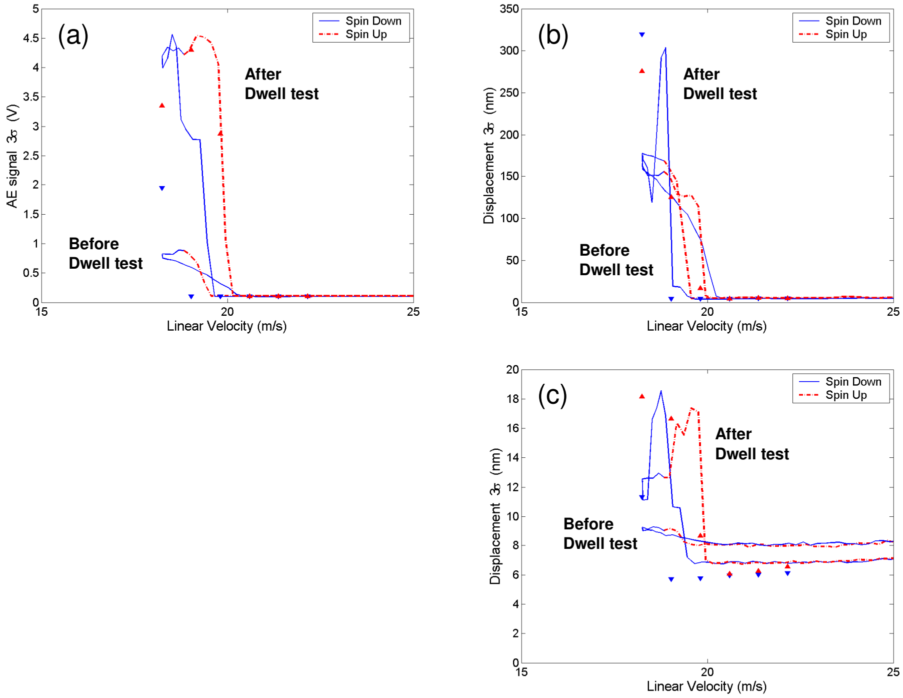

Figure 6 Comparison between SDSU test and Dwell test for HGA(II) (a) AE signal (b) Vertical displacement (c) Off-track displacement; ▼: Dwell test spin-down, ▲: Dwell test spin-up

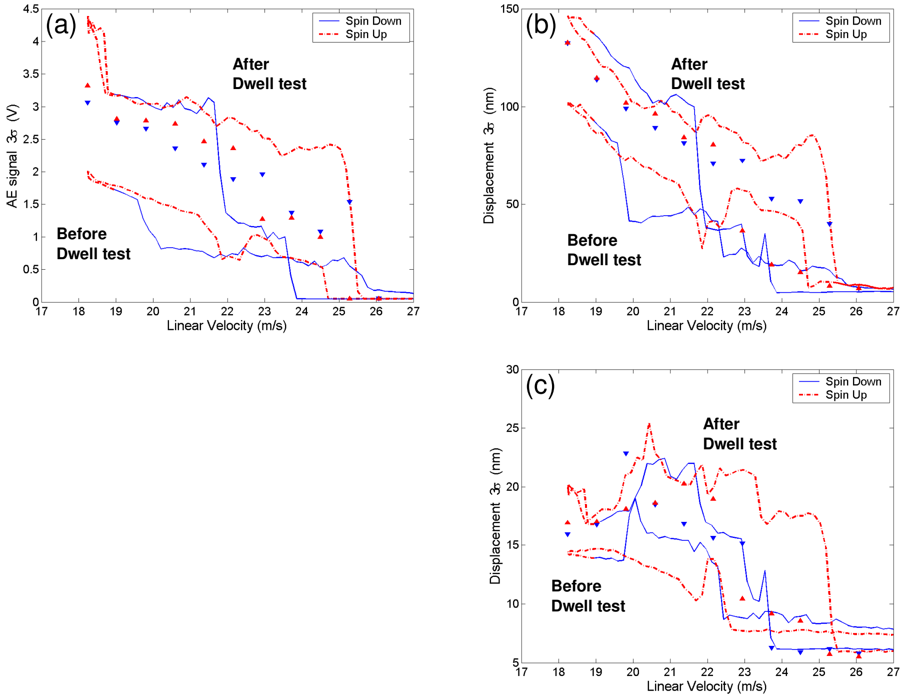

Figure 7 Comparison between SDSU test and Dwell test for HGA(III) (a) AE signal (b) Vertical displacement (c) Off-track displacement; ▼: Dwell test spin-down, ▲: Dwell test spin-up

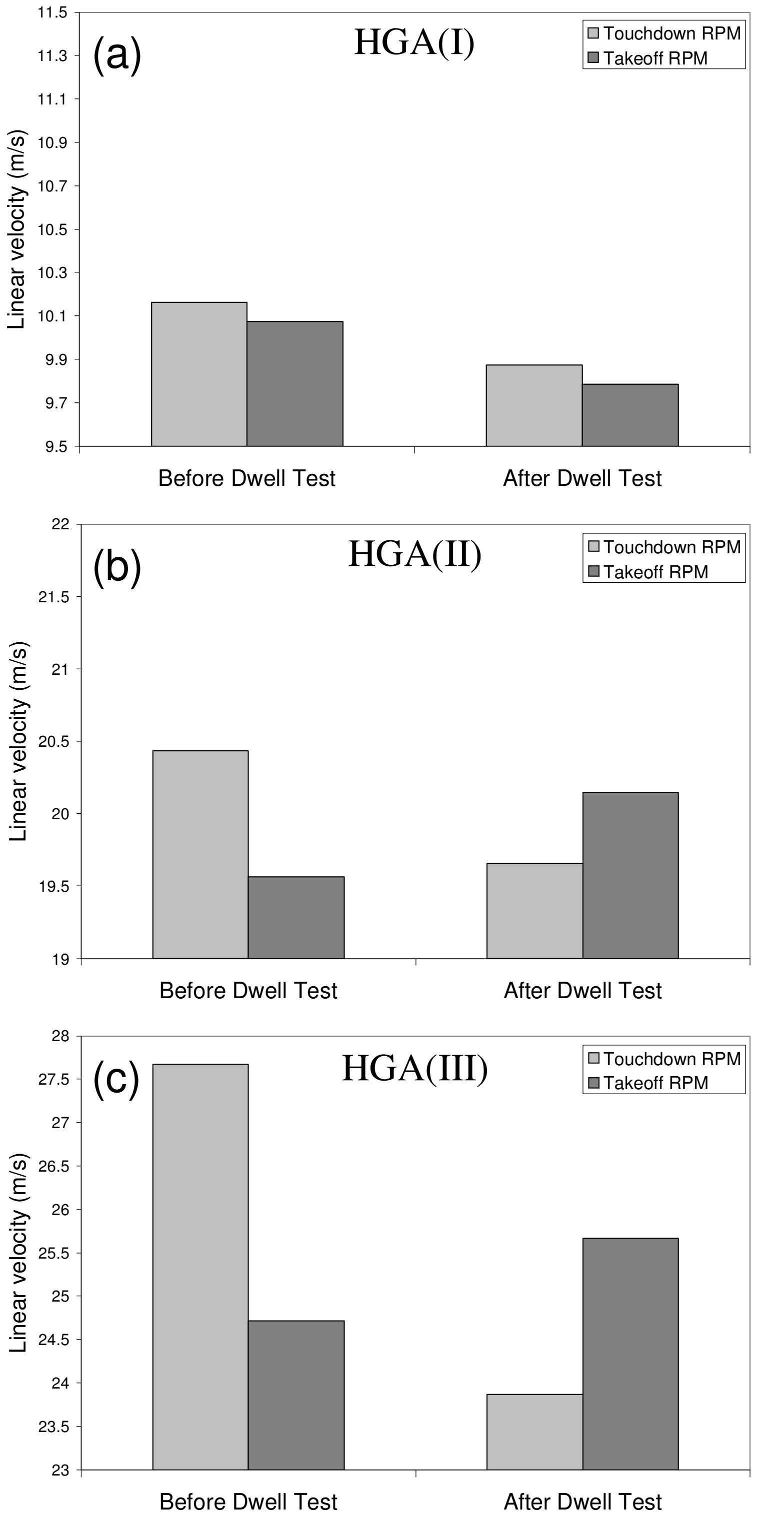

Figure 8 Effect of Dwell test on touchdown and takeoff velocity (a) HGA(I) (b) HGA(II) (c) HGA(III)

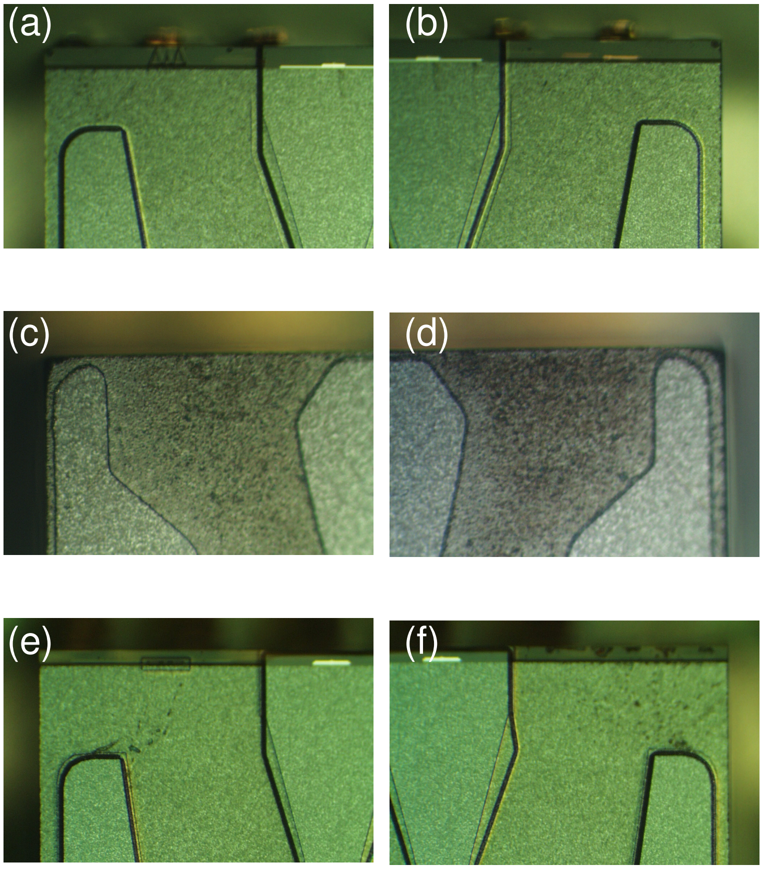

Figure 9 Slider contamination/lube pick-up (a,b) HGA(I); (c,d) HGA(II); (e,f) HGA(III)

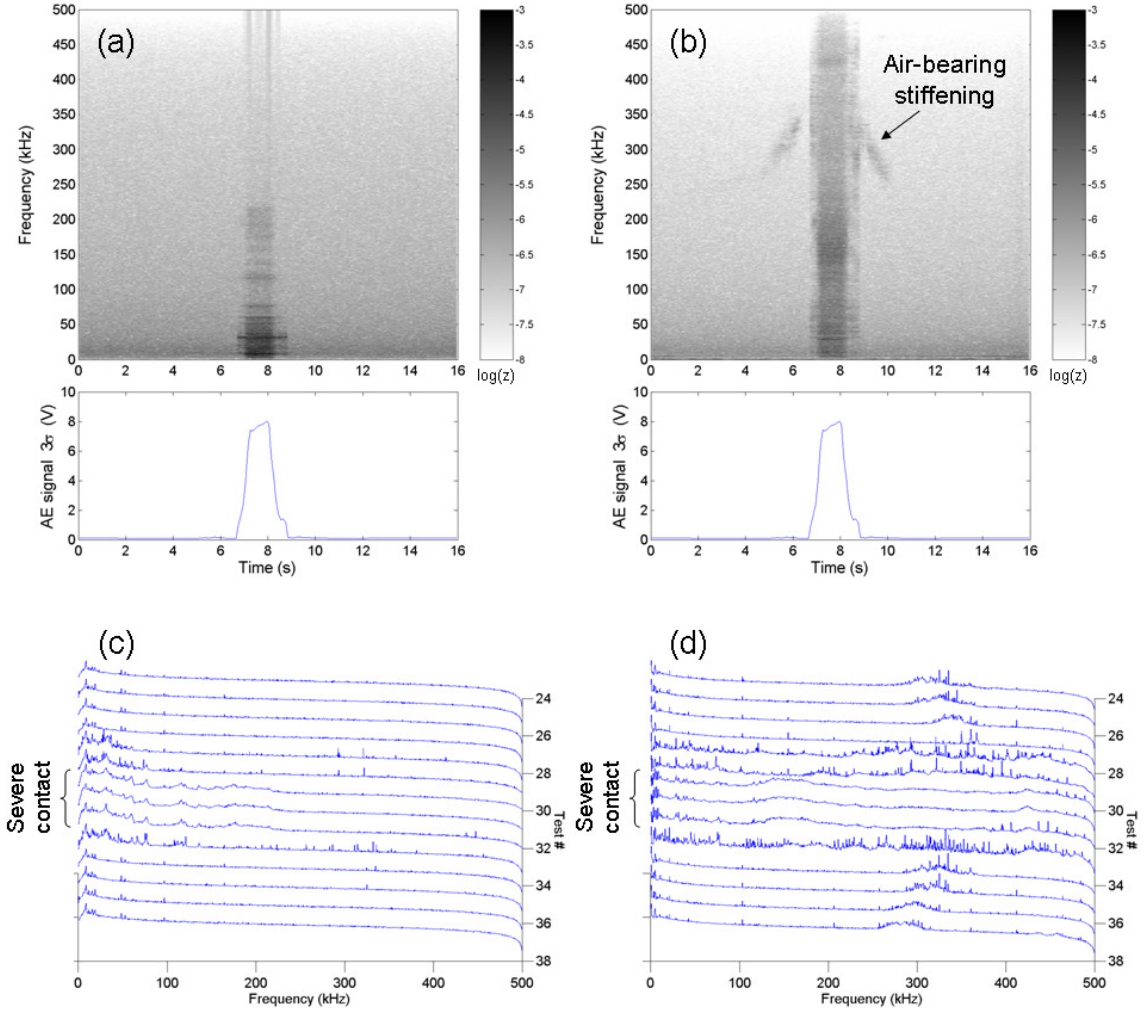

Figure 10 JFT plots of SDSU test for HGA(I) (a) Off-track motion (b) Vertical motion; FFT plots for Dwell tests (c) Off-track motion (d) Vertical motion

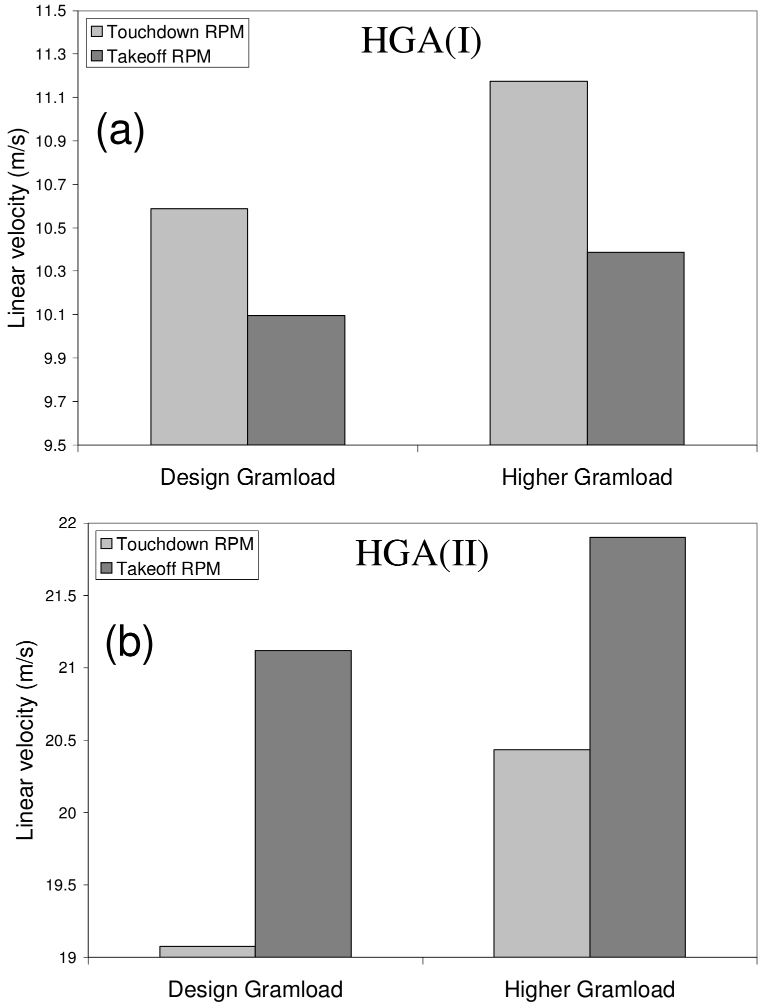

Figure 11 Effect of gramload on touchdown and takeoff velocity (a) HGA(I) (b) HGA(II) (c) HGA(III)

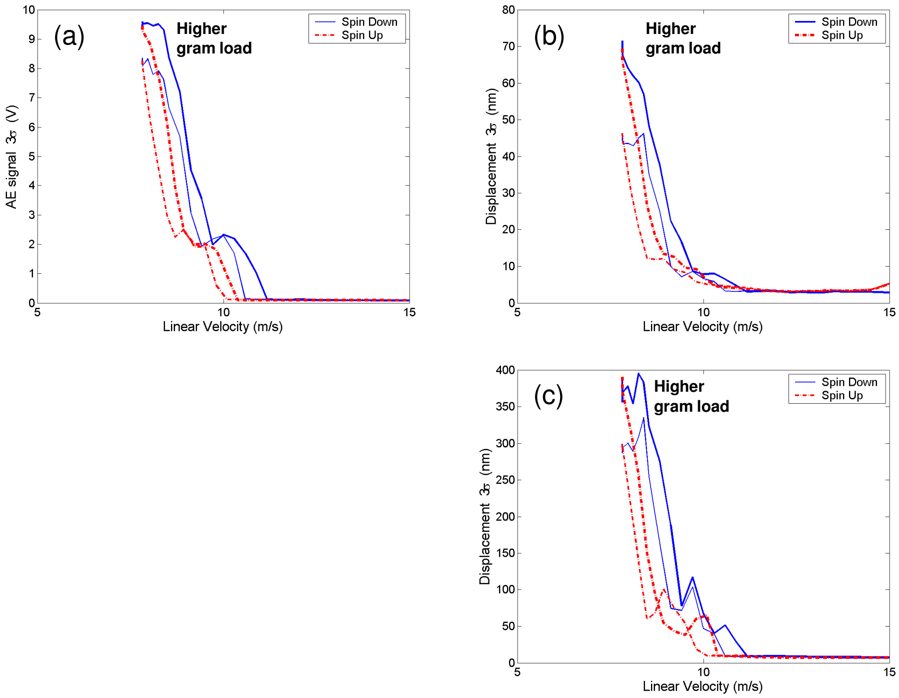

Figure 12 Effect of gram load (z-height reduction) for HGA(I) (a) AE signal (b) Vertical displacement (c) Off-track displacement