Flying Height Modulation Due to Disk Waviness of Sub-5nm Flying Height Air Bearing Sliders

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ABSTRACT

Two new slider designs are presented for storage densities greater than 100 Gb/in^2 in hard disk drive applications. Their dynamic frequencies and mode shapes are characterized, and they are used to study the flying height modulation (FHM) over wavy disks due to geometric effects as opposed to dynamic effects. It is found that low pitch designs experience large FHM at wavelengths on the order of the length of the sliders to one-eighth the length of the sliders due to a complex phase shift in the sliders trailing edge response as compared to the disk waviness. FHM due to disk waviness wavelengths from 2 mm to 0.16 mm was found to be a function of the static attitude (pitch angle) of the slider and the air bearing surface (ABS) geometry (pressure distribution over the ABS). The results presented suggest that the pitch should be greater than 100 micro radians and attention needs to be focused on the ABS design and disk morphology to avoid unacceptable FHM. The FHM due to geometric effects of the slider designs studied in this paper could possibly be predicted by the disk morphology alone.

INTRODUCTION

As HDD storage densities approach 100 Gbit/in^2 the flying height (FH) of the air bearing sliders must be reduced to 5 nm or less. Since all disks have some roughness and waviness it is impossible to completely eliminate variations of the FH about its mean value. But it is desirable to limit this variation to no more than 20 percent of the mean FH.

Previous research has shown that FHM has different causes depending on the wavelength of the disk roughness relative to the length of the slider. For long wavelengths the FHM is proportional to the square of the length of the slider, a purely geometric effect. As the roughness wavelength approaches zero the slider flies about the mean surface and the FHM equals the disk waviness. For some intermediate wavelengths of waviness an air bearing resonance may be excited and the FHM depends on the dynamics of the mechanical system [1].

To minimize the long wavelength FHM a shorter slider is obviously needed. Other design features determine the air bearing modal parameters, such as FH, static attitude, and ABS design that determine air bearing stiffness and damping.

It is expected that femto sliders will be favored over the most commonly used pico sliders of current drives. This paper investigates the relative performance of a particular pico slider designed for 5 nm FH, suitable for 100 Gb/in^2 applications, and a similar femto 3.5 nm FH slider, expected to be required for 1 Tb/in^2 densities. First we present the ABS designs for the two sliders and indicate their uniformity of flying height over the track range from ID to OD. Then we present their characterization, showing their air bearing frequencies and vibration modes, as well as their damping characteristics. With these results as a basis we investigate the FHM for given waviness wavelengths of the disk. As expected, we find that for long wavelengths the FHM of the femto slider is about half that of the pico slider, and it is negligible for both sliders for a peak-to-peak waviness amplitude of 2 nm. As the disk wavelengths are reduced it is found that the FHM of the femto slider actually exceeds that of the pico slider. This unexpected phenomenon is not associated with resonance but is found to result from the slider pitch, and an associated phase lag between the dynamic response of the slider at the transducer point and the disk waviness. The primary finding of this work is that the FHM for some slider designs, especially certain three pad, sub-ambient pressure designs with a center rear pad, will be unacceptably large if the pitch is too low. For low pitch the rear center pad does not generate a pressure leg, and only the aft portions of the side rails support the slider. For high pitch the rear center pad also provides comparable pressure, thereby producing the third leg of support for the slider. It was found that the FHM due to disk waviness with length on the order of the slider's body length (1.5 mm to 0.156 mm) is a function of the static attitude and the ABS design and not the length of the overall slider's body. Geometric FHM can possibly be predicted by the disk morphology alone.

PICO AND FEMTO DESIGNS

The pico slider was designed for 5nm flying height for use in 100 Gb/in^2 HDD while the femto slider was designed for 3.5 nm flying height use in a 1 Tb/in^2. Both sliders use basically the same design, with a wrap around front rail that surrounds three sides of a subambient region and a trailing center pad for mounting the transducer and controlling the flying height of the transducer. Figures 1 and 2 show the designs of the two sliders. There are three step levels on both sliders, the no-etch level of the primary air bearing surfaces, the 300 nm etch regions adjacent to the rails, and the 2.5 micron base level of the sliders. Tables 1 and 2 also indicate the FH performance as a function of radial position and the associated skew. The pre-load for the pico slider is 1.5 gm, while it is 1.0 gm for the femto. Notice that the pitch of the pico slider is 120 μrad while it is only 55 μrad for the femto at a radius of 15 mm, skew of zero degrees and a rotational speed of 7200 RPM. These values of pitch, radius, skew and RPM are noted because those ID conditions were used in the following analysis.

These sliders were characterized by use of the CML Parameter Identification Program, and the results are shown in Figs. 3 and 4. It is seen that the three air bearing modes are quite decoupled, as indicated by the perpendicularity of the nodal lines. Also we see that the two lowest frequencies are similar for the two sliders, around 110 and 104 kHz, while the highest frequencies are different by about 100kHz, the femto slider frequency being about 380 kHz verses 280 kHz for the pico slider.

DYNAMIC SIMULATION OF THE FHM

The CML Dynamic Simulator Program was used to calculate the responses of the two sliders to disks of various waviness. In all cases the peak-to-peak amplitude of the waviness was 2 nm, and the wavelengths were chosen between 12 mm and 0.1 mm. Figure 5 shows the FHM for the two sliders for a waviness wavelength of 2.5 mm, which is obtained by subtracting the disk waviness from the sliders' motion at the transducer. Here we see that the pico slider has a peak-to-peak FHM of about 0.4 nm, while it is about 0.27 nm for the femto slider. Similar calculations were made for several different wavelengths, and the resulting peak-to-peak FHM's are plotted for all of these wavelengths for both sliders in Fig. 6. As expected the FHM of the femto slider remains below that for the pico slider for wavelengths greater than about 1.5 mm. But for shorter wavelengths the modulation of the femto slider is much greater than it is for the pico slider, reaching a value of almost 3.5 nm at the wavelength of about 0.3 mm. This is an unexpected result. Notice that since the air bearing resonance frequencies are all above 100 kHz, and this value occurs for wavelengths less than 0.1 mm for 7200 rpm this strong response cannot be associated with a resonance phenomenon. Further studies are required to reveal the cause of this phenomenon.

Figure 7 shows the disk waviness and the pico slider's response to a 0.625 mm wavelength waviness for two different slider designs that have the same 5 nm flying height, but with different values of pitch. These slider designs are only slightly different; having the load point moved slightly aft/forward and the suspension load slightly reduced/increased for the higher/lower pitch slider. However, the ABS design was unchanged. Two things are observed from this figure: first it is seen that the slider's response is phase shifted from the disk waviness; second we see that the amount of phase shift is much greater for the low pitch slider than it is for the higher pitch slider. Also it is apparent that the FHM, which is the difference between these two curves, increases with the phase shift. Just envision a case where the phase shift is 180 degrees as opposed to a case where it is 0 degrees. Figure 8 shows the FHM and phase shift as a function of pitch for similar 5 nm FH pico sliders. The sliders' response amplitudes are rather insensitive to the pitch, but the phase shift and hence the FHM monotonically increase as the pitch is decreased. Since the original femto slider had much lower pitch than the pico slider the large difference in the FHM modulations for short wavelengths shown in Fig. 6 is evidently due to this phase lag pitch relation. Indeed, Fig. 9 shows the dependence of the FHM and phase for the femto slider, and it is seen to be quite similar to that in Fig. 8 for the pico slider.

EXPLANATION OF THE PHASE-LAG PITCH RELATIONSHIP

It has been shown that the increase in FHM with decreasing waviness wavelength is related to an increase in a phase lag between the slider's response and the disk waviness, which in turn is related to a decrease in the slider's pitch. The original femto slider had much lower pitch than the pico slider and that accounts for the larger FHM of the femto slider in Fig. 6. It remains to explain why this phase difference becomes pronounced at shorter wavelengths and why this is related to pitch.

Figure 10 shows a sequence of pressure profiles for the original low pitch femto slider calculated at different locations of the transducer on the waviness phase. (1) is at the waviness trough, (2) is at the waviness mean height on an increasing slope, (3) is at the waviness peak, and (4) is again at the waviness mean height, but on a decreasing slope. While these profiles have some minor differences, the main observation is their similarity and the fact that the central trailing pad provides very little support to this low pitch slider. The slider is almost entirely supported by the small regions at the rear of the side pressure pads, giving it essentially a two-point support at some distance from the trailing edge where the transducer is located. When the disk rises and falls, because of its waviness, the slider responds at these two support points, while the transducer is cantilevered a certain distance behind, leading to the phase shift. Figure 11 shows the sequence of pressure profiles for the high pitch femto slider. Here we see that the center trailing edge has relatively high pressure, and therefore this slider is supported by three pressure points, one at the center trailing edge, where the transducer is located. Therefore the phase shift is much less.

Figure 12 shows that the distance between the trailing edge of the side rails and the trailing edge of the center pad (transducer location) is about 0.15 mm for both the pico and femto sliders. When the waviness wavelength is 0.625 mm, this distance is about ¼ wavelength, and so the transducer phase lag is about 90 degrees as shown in Fig. 13. This also can be seen in Figs. 8 and 9 for the pico and femto sliders. As the pitch decreases, the phase angle approaches approximately 90 degrees. When the waviness wavelength is 0.325 mm the transducer phase lag is almost 180 degrees. This can be seen for the femto slider in Fig. 14. Similarly, as the pitch decreases, the phase approaches 180 degrees. This case of 180 degrees phase shift is the worst-case situation with the FHM becoming a maximum due solely to the subtraction of a sine and cosine wave.

Thus the slider should have sufficient pitch to give it a three-point support rather than a two-point support. On the other hand, if the pitch is increased too much the slider will have only a one-point support at the center trailing edge. Clearly this would not be a stable design. For stability and control of FHM this analysis suggests that, for the three pad designs examined, the pitch should remain between 100 and 150 micro radians and the ABS design needs to be taken into consideration.

COMPARISION OF PICO AND FEMTO SLIDERS WITH SIMILAR SPECIFICATION

Finally, Fig. 15 shows a more meaningful comparison between the pico and femto slider designs. Both sliders were slightly redesigned to have the same flying height of about 4 nm and they have similar pitch: the pico slider has 116 μrad pitch and the femto slider has 121 μrad pitch. Here we see the more expected behavior. For waviness wavelengths between 6 mm and 1 mm the FHM of the pico slider is roughly twice that for the femto slider. For wavelengths from 10 mm to 1.5 mm for both of these sliders, the FHM is within the budget of 20% (0.8 nm), and it is therefore tolerable. The intolerable FHM occurs between wavelengths of 1.5 mm to 0.156 mm for both the pico and femto sliders.

Figures 16 and 17 show FHM, absolute slider motion, and phase lag as a function of disk waviness wavelengths for the redesigned pico and femto sliders. An important difference between these plots is that the FHM decreases and the phase angle approaches zero at a disk waviness wavelength of 0.156 mm for the femto slider. Figures 18 and 19 show the results from the CML Parameter Identification Program for the redesigned femto and pico sliders. The femto slider's air bearing mode stiffnesses are lower than those of the original design while the redesigned pico slider is stiffer than the original. We also see that the redesigned femto slider's pitch resonant mode is approximately 65 kHz. At a disk waviness wavelength of 0.156 mm, this pitch mode is excited, allowing the slider to pivot and permitting the transducer to follow the disk without a phase shift.

It should be noted that the emphasis in this paper is on geometric effects of disk waviness on FHM. This resonance phenomenon is a dynamic effect.

Another contributor to FHM due to a geometric effect is the decreasing amplitude of the absolute motion of the slider for waviness wavelengths below 2 mm as seen in Figs. 16 and 17. This is shown to be caused by the relationship between the distance from the trailing edge of the side rails to the trailing edge of the center pad (i.e. the distance between the high pressure points) and the disk waviness wavelength. If we assume a simple geometric model as shown in Fig. 20, for small disk waviness wavelengths, the curvature is too large for the three-support points (high pressure points) of the slider to follow the disk exactly. The analytical solution for the absolute slider displacement is:

$$S_{abs}=1+\cos(l\pi/\lambda) \qquad \text{for } \lambda \geq l$$

Where l is the distance shown in Fig. 12 and λ is the waviness wavelength. Figure 21 shows how the absolute motion of the slider (S_{abs}) changes with a 2 nm (peak-to-peak) disk waviness as wavelength is varied. This relationship follows the trend seen for both the pico and femto sliders from simulations, as seen in Figs. 16 and 17. However, this geometric effect on the to FHM is a secondary effect compared to the phase shift.

For both the pico and femto sliders, the FHM's for a waviness wavelength of 0.208 mm and varying amplitude from 0.2 nm to 3 nm (peak-to-peak) were simulated to find the dependence of FHM on amplitude of the disk waviness. Figure 22 shows how FHM changes with disk waviness amplitude. For both the pico and femto sliders, the relationship is linear with an approximate slope of one (i.e. for this particular waviness wavelength the FHM amplitude is that of the disk). Therefore, FHM due to this geometric effect is a function of the disk morphology. For the particular ABS designs studied in this paper, the geometric FHM can be predicted by the disk morphology. For waviness wavelengths from 0.5 mm to 0.16 mm the FHM is approximately the disk morphology and for higher wavelengths, the FHM decreases exponentially.

SUMMARY AND CONCLUSIONS

We examined the FHM of a 5 nm pico slider design and a 3.5 nm femto slider design for disks with 2 nm p-p waviness amplitude, and as a function of waviness wavelength. The expectation was that the femto slider should have less FHM than the pico slider, because it has long been known that for wavelengths somewhat larger than the slider length, the FHM is proportional to the square of the length of the slider. It was found that this was indeed the case for wavelengths longer than the slider, but when the wavelength was reduced to around the order of the slider's length the FHM of the femto slider was much greater than that of the pico slider. After examining the characteristics of the sliders it was found that the primary reason for the large FHM of the femto slider was due to its low pitch, which caused its pressure support points to be at the trailing edges of the side rails, about 0.15 mm forward of the transducer. It was also observed that the large FHM results from a phase shift between the slider's response and the disk waviness, which is itself a result of the low pitch and forward pressure points. The phenomenon occurred for both the femto slider and the pico slider.

It can be concluded that, for the three rail negative pressure sliders under consideration, the pitch should be higher than about 100 micro radians to avoid large FHM. The pitch should probably be lower than about 150 micro radians to avoid too much load being carried by the single trailing center pad, which would be inherently unstable.

In comparing redesigned pico and femto sliders with the same target FH and comparable pitch, we showed that the pico slider has roughly twice the FHM in the 6 mm to 1.5 mm waviness range. However, for waviness between 1.5 mm to 0.156 mm both the pico and femto sliders have similar levels of intolerable FHM due to their similarities in ABS designs (i.e. pressure distribution). We concluded that a femto design has lower FHM due to disk waviness for wavelengths greater than 1.5 mm. However, for waviness of wavelengths below 1.5 mm and above the dynamic resonant modes of the air bearing, FHM is not primarily a function of the sliders overall length but is more a function of static attitude and the ABS design. It is possible to predict FHM due to this geometric effect by considering only the disk morphology. Also, these results can be used in designing better disks for ultra-low FH sliders. In order to decrease FHM due to disk waviness for wavelengths below 1.5 mm, attention needs to be focused on static attitude, the ABS design, and the disk morphology.

ACKNOWLEDGEMENTS

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[1] L-Y. Zhu and D.B. Bogy, “Head-Disk Spacing Fluctuation due to Disk Topography in Magnetic Recording Hard Disk Files”, Tribology and Mechanics of Magnetic Storage Systems, STLE Special Publication, SP-26, 1989, 160-167.

[2] Wei Yao, D. Kuo, and J. Gui, “Effects of Disc Micro-Waviness in an Ultra-high Density Magnetic Recording System”, Proc. Of the Symposium on Interface Technology Toward 100 Gbit/in2, ASME, 1999, 31-37.

Radial Position (mm)	Skew (deg.)	Flying Height (nm)
31	17.39	5.05
23	9.1	4.93
15	-1.22	5.05

Table 1: Flying height performance of the pico slider as a function of radial position and skew.

Radial Position (mm)	Skew (deg.)	Flying Height (nm)
31	17.39	3.49
23	9.1	3.54
15	-1.22	3.51

Table 2: Flying height performance of the femto slider as a function of radial position and skew.

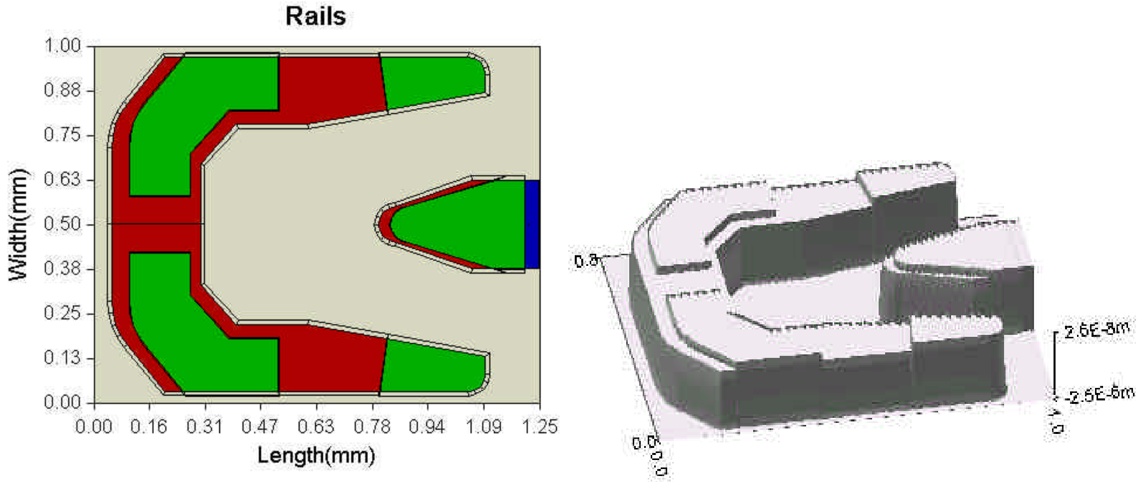

Figure 1: ABS of the 5 nm pico slider.

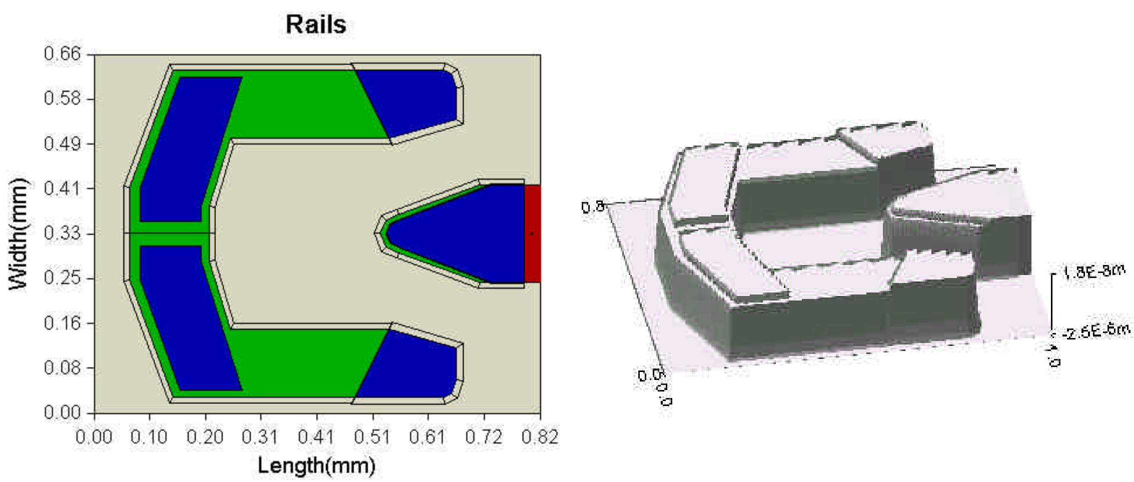

Figure 2: ABS of the 3.5 nm femto slider.

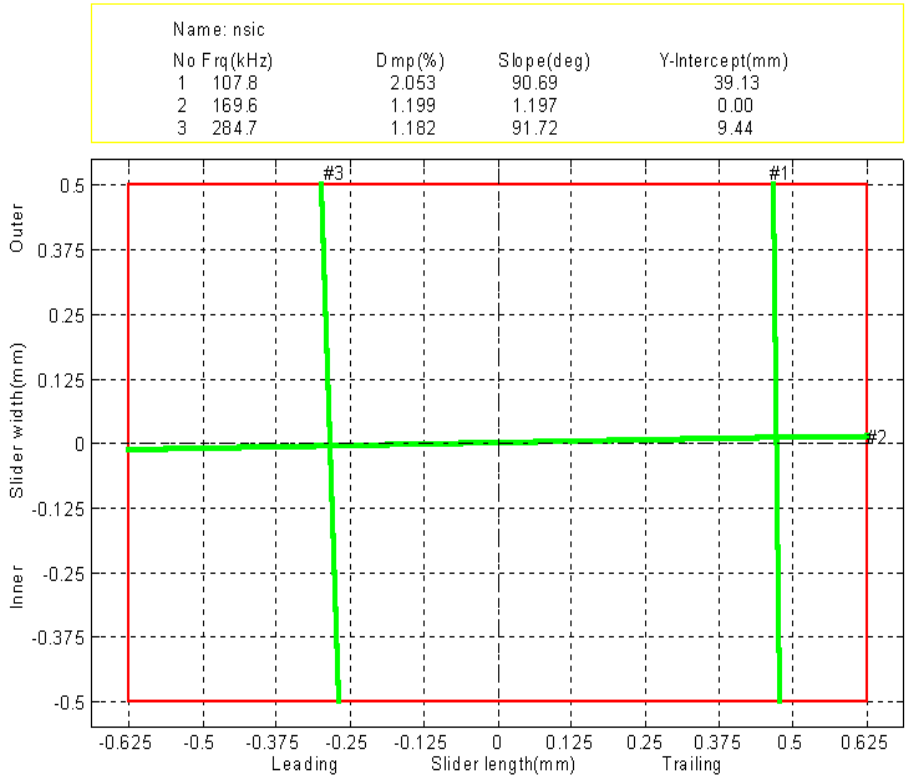

Figure 3: Dynamic characteristics of the pico slider

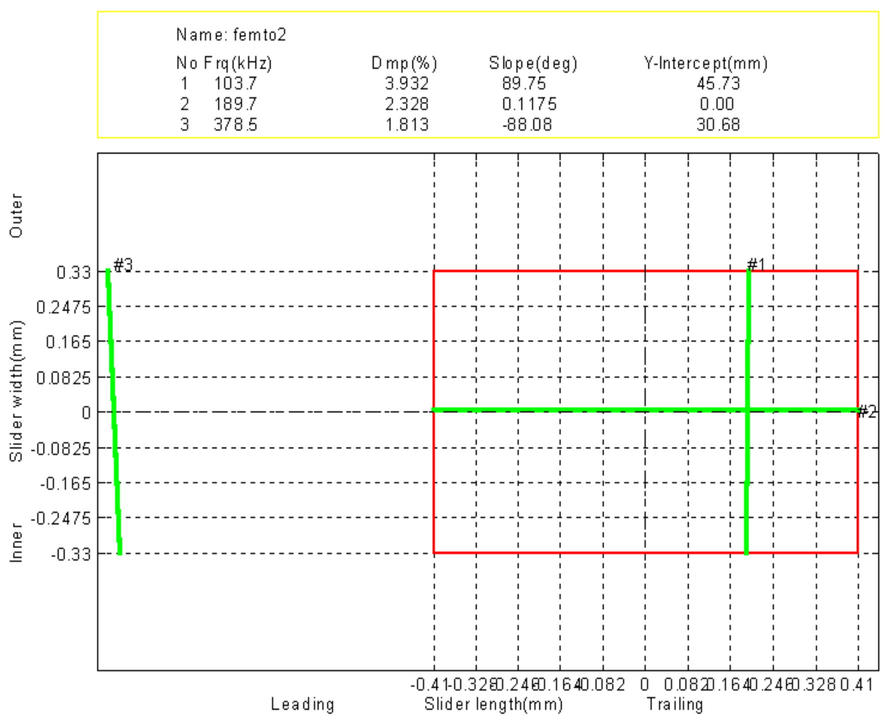

Figure 4: Dynamic characteristics of the femto slider.

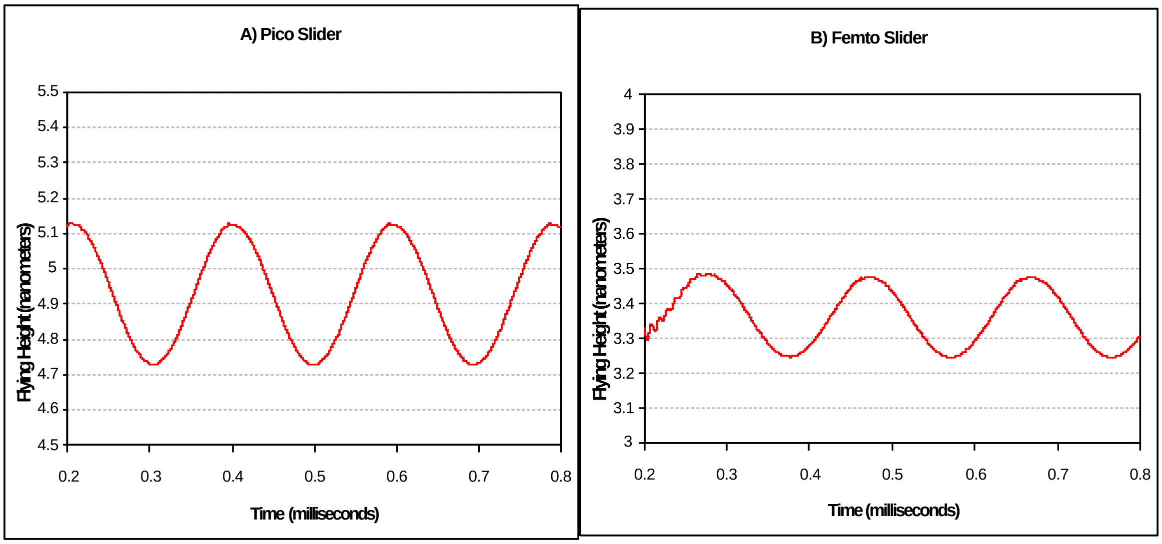

Figure 5: FH modulation for the (A) Pico and (B) Femto sliders for the 2.5 mm disk waviness wavelength.

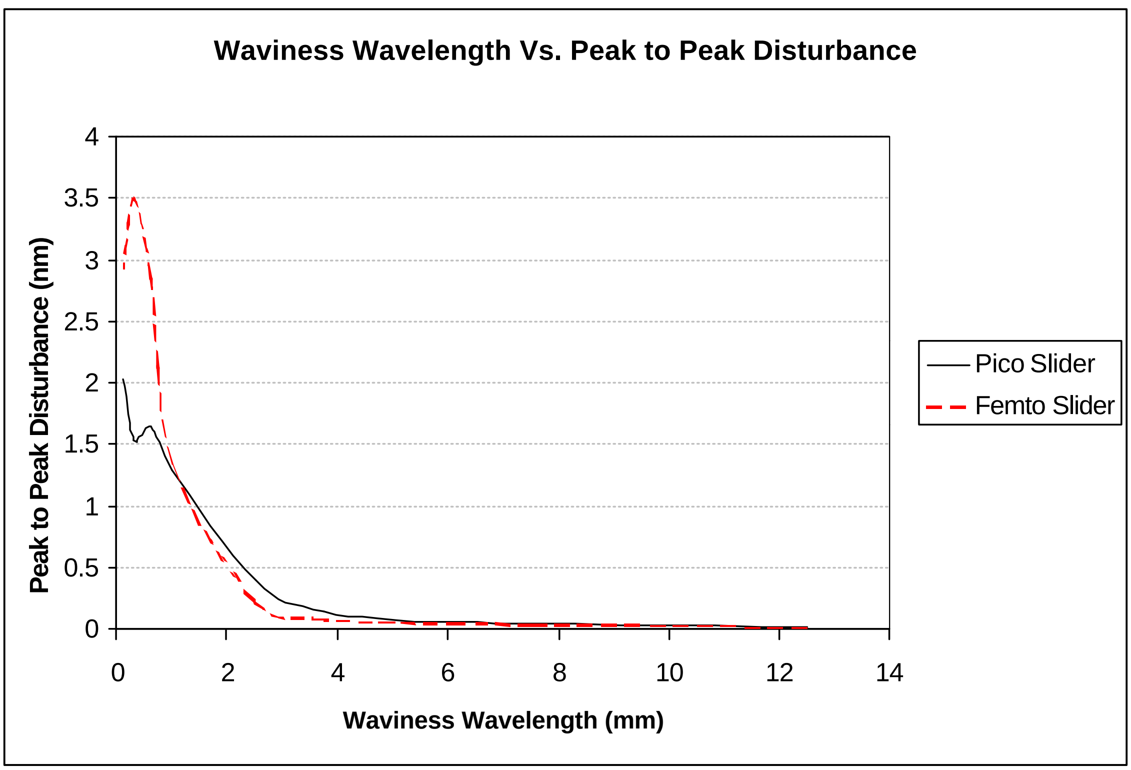

Figure 6: FH modulation as a function of waviness wavelength for the pico and femto sliders.

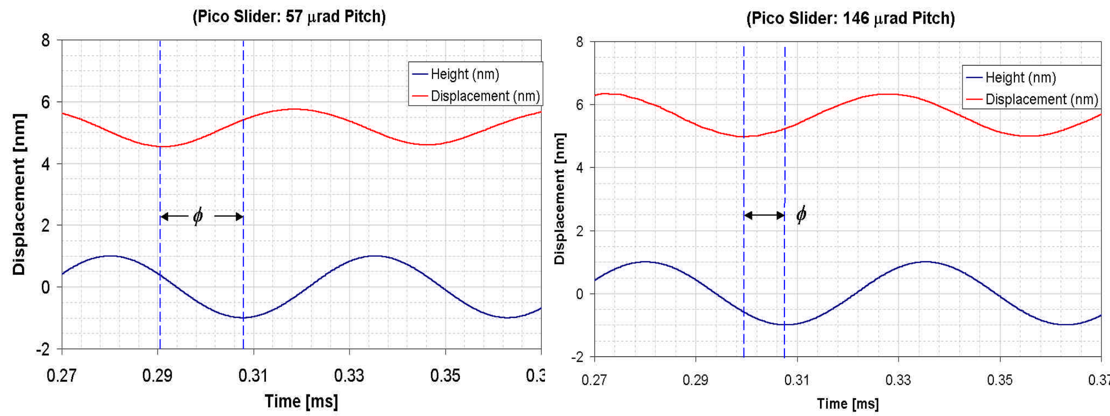

Figure 7: Comparison of the slider motion and the disk waviness, showing a phase difference in the two for different values of pitch.

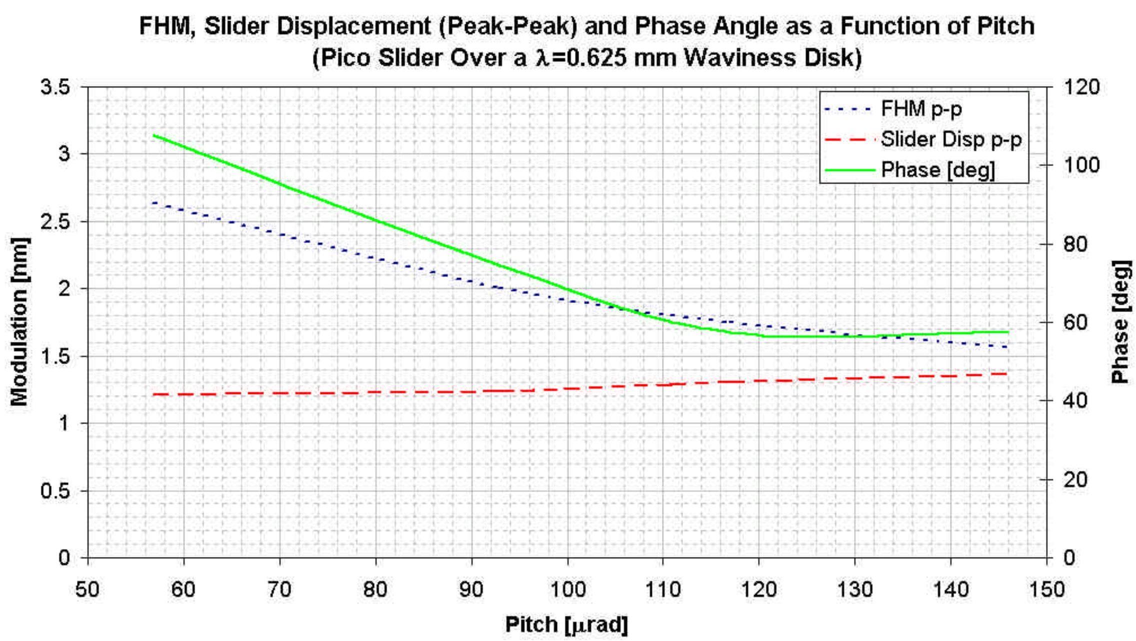

Figure 8: FHM, absolute slider motion, and phase shift as a function of pitch of the 5 nm FH pico sliders for a waviness wavelength of 0.625 mm.

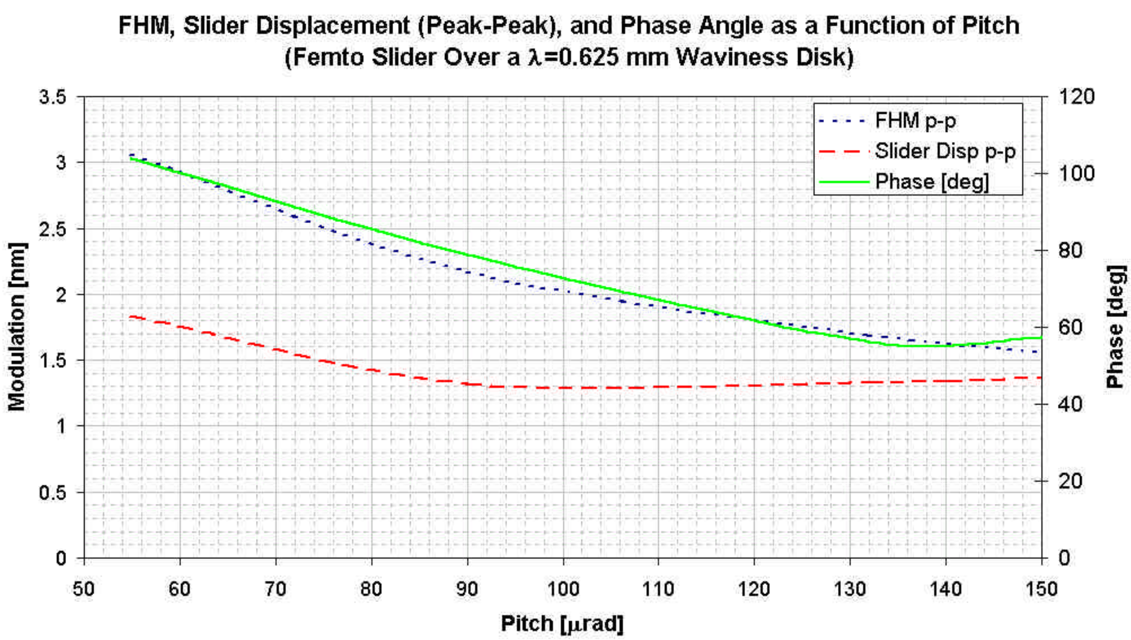

Figure 9: FHM, absolute slider motion, and phase shift as a function of pitch of the 3.5 nm FH femto sliders for a waviness wavelength of 0.625 mm.

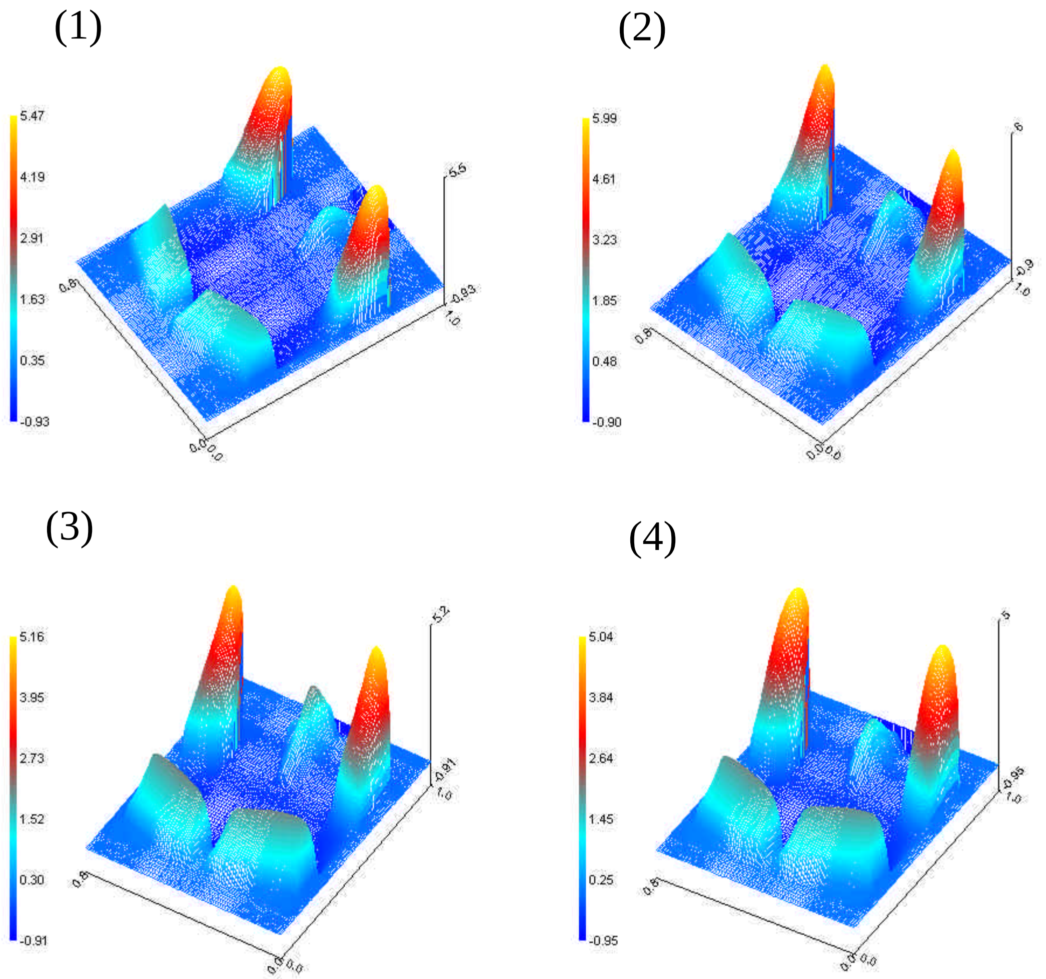

Figure 10: Sequence of pressure profiles for the low pitch femto slider at different disk waviness phase locations. The trailing edge is in a waviness trough in (1), at the mean in (2), at a waviness peak in (3) and again at the mean in (4).

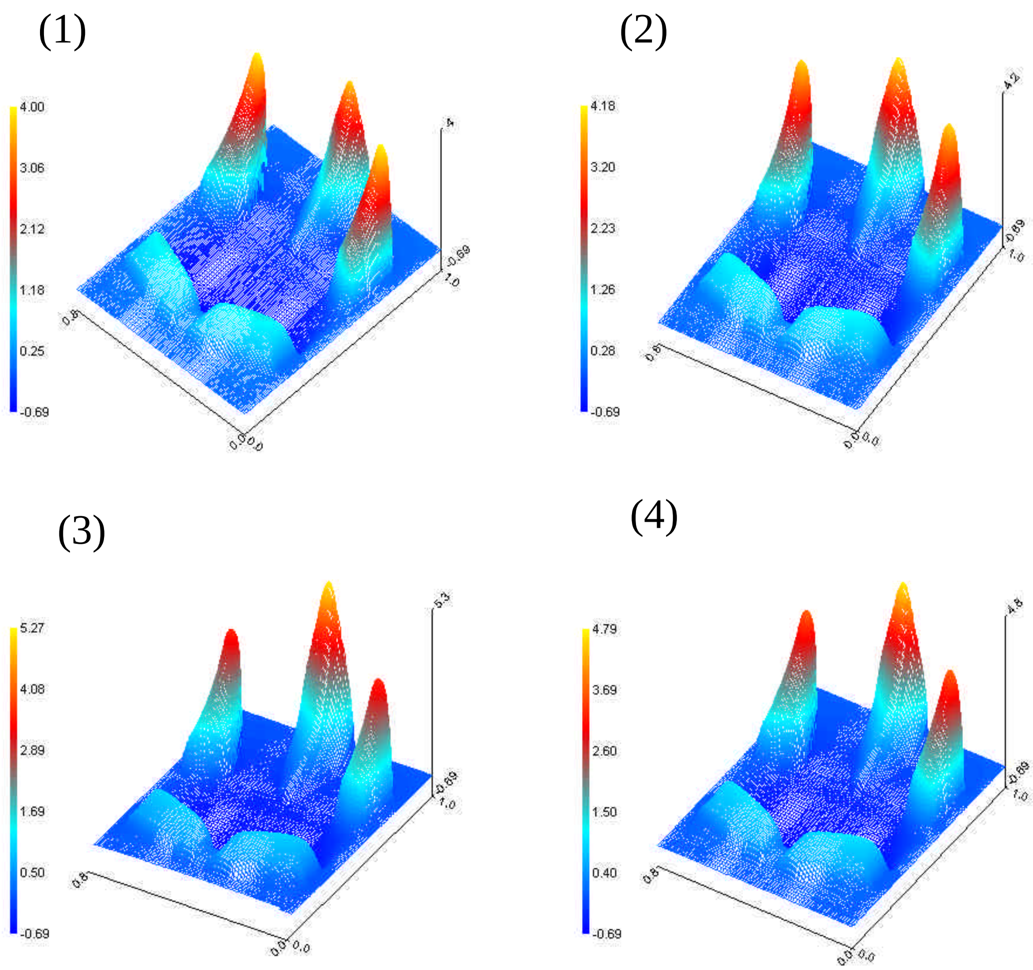

Figure 11: Sequence of pressure profiles for the high pitch femto slider at different disk waviness phase locations. The trailing edge is in a waviness trough in (1), at the mean in (2), at a waviness peak in (3) and again at the mean in (4).

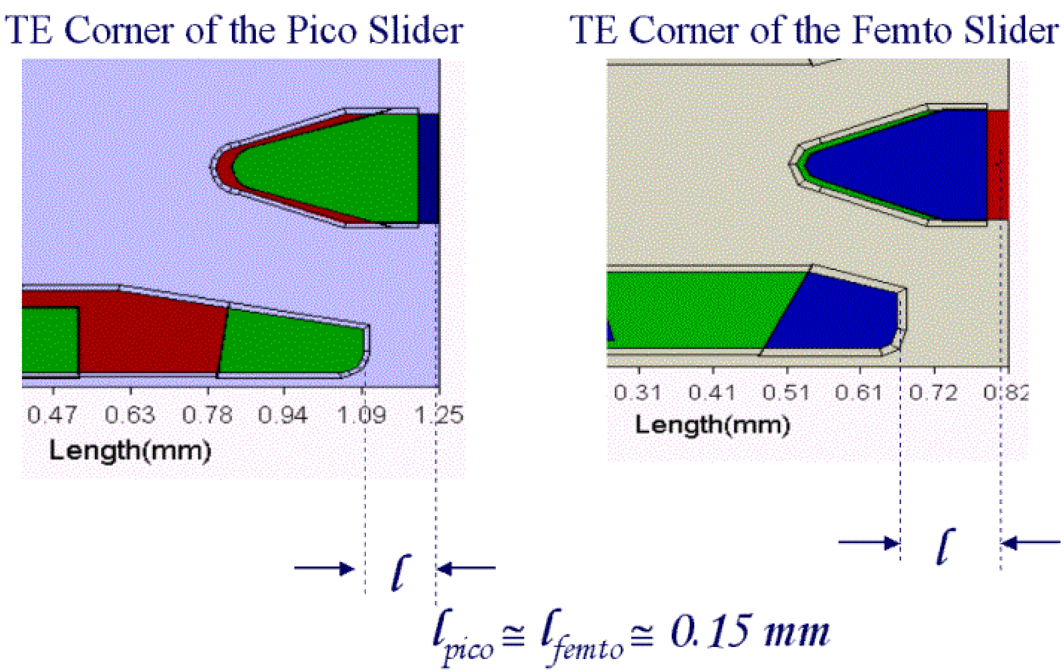

Figure 12: The distance between the trailing edge of the side rails and the trailing edge of the center rail is about 0.15 mm for both the pico and femto slider designs.

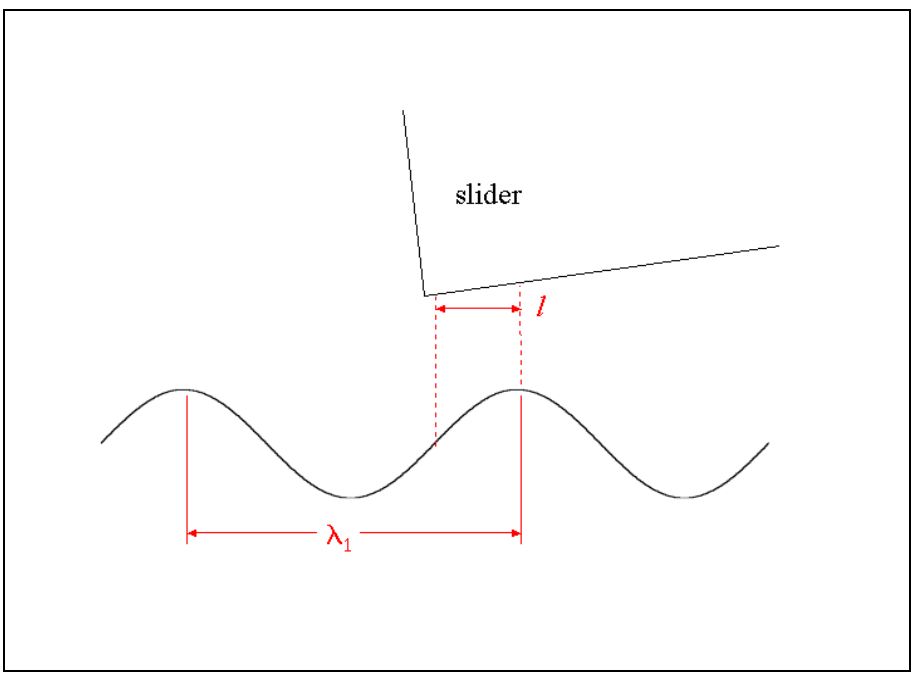

Figure 13: The low pitch slider has pressure points at the trailing edge of the outer rails, which are about 0.15 mm from the transducer. When the waviness wavelength is 0.625 mm, or about ¼ wavelength, the transducer phase lag is about 90 degrees. When the waviness wavelength is 0.325 mm the transducer phase lag is almost 180 degrees.

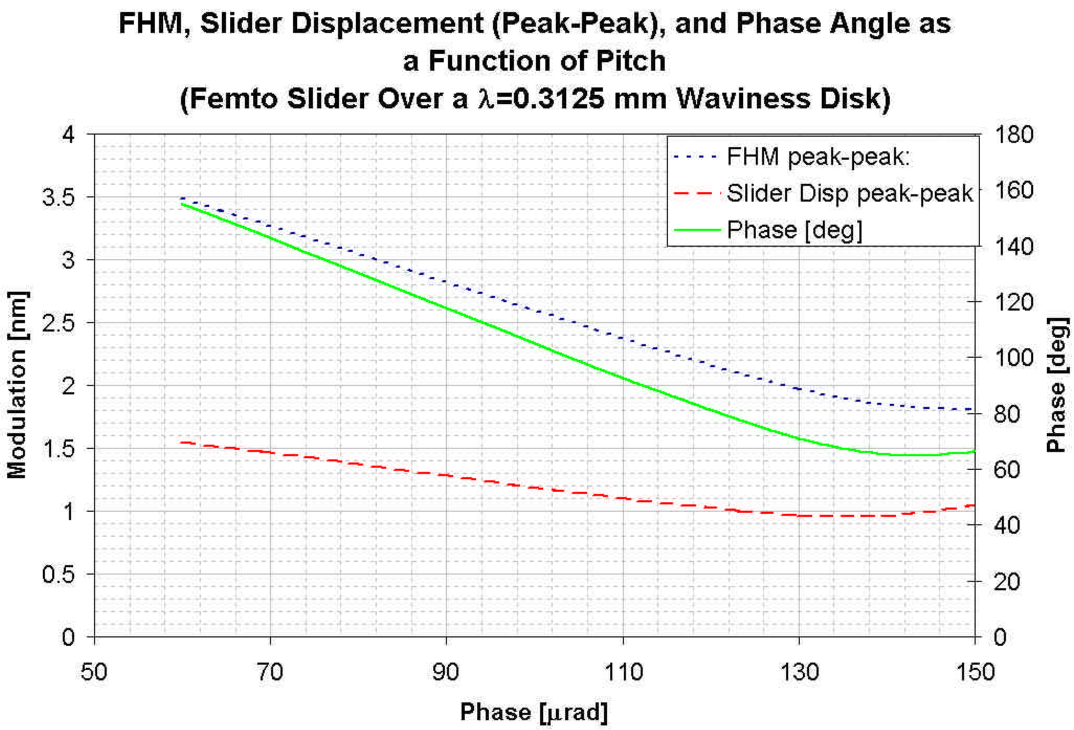

Figure 14: FHM, absolute slider motion, and phase shift as a function of pitch of the 3.5 nm FH femto sliders for a waviness wavelength of 0.313 mm.

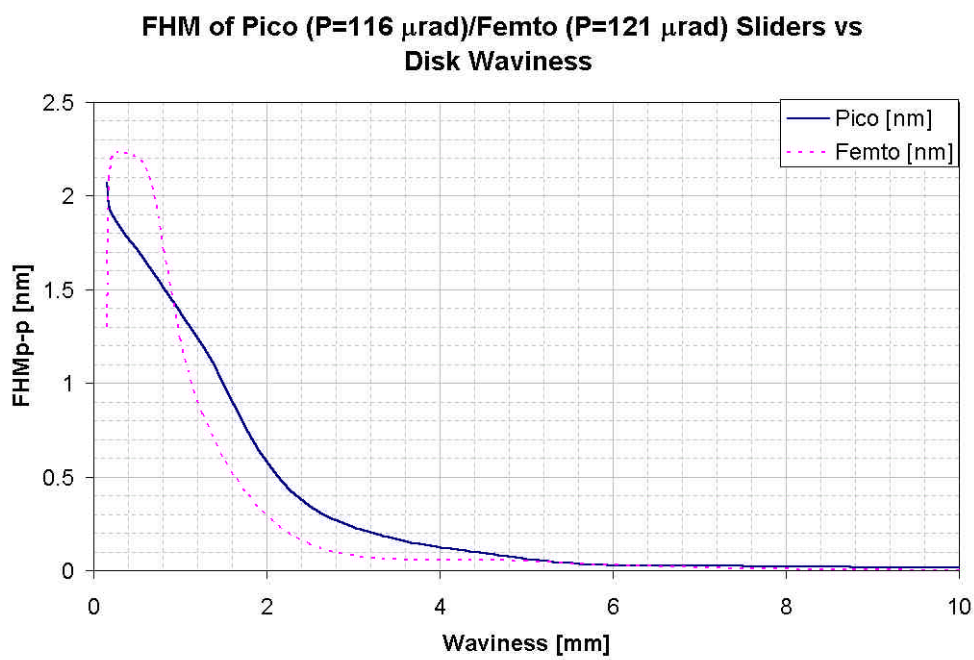

Figure 15: FH modulation as a function of waviness wavelength for the redesigned pico and femto sliders.

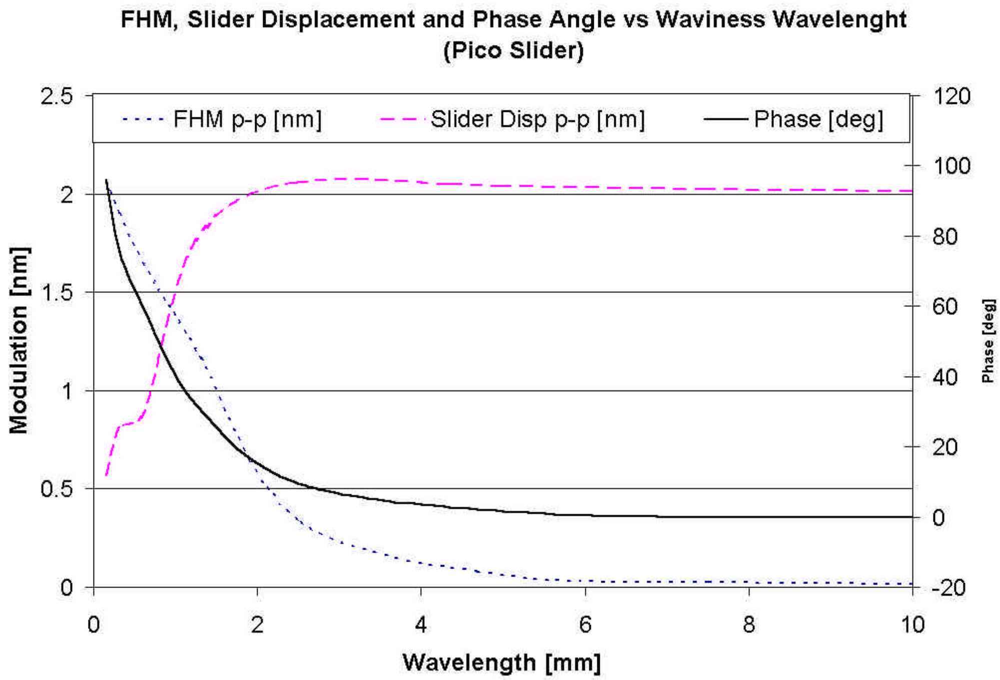

Figure 16: FHM, absolute slider motion, and phase shift as a function of waviness wavelength for the 4 nm FH pico slider.

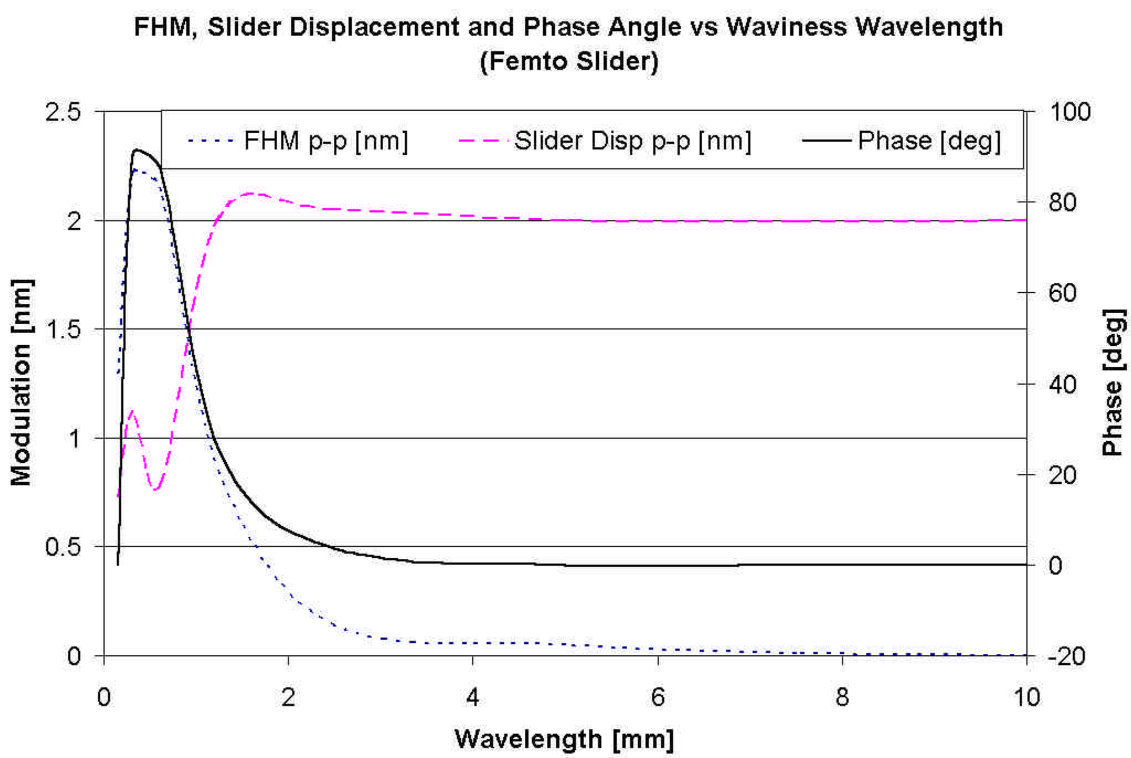

Figure 17: FHM, absolute slider motion, and phase shift as a function of waviness wavelength for the 4 nm FH femto slider.

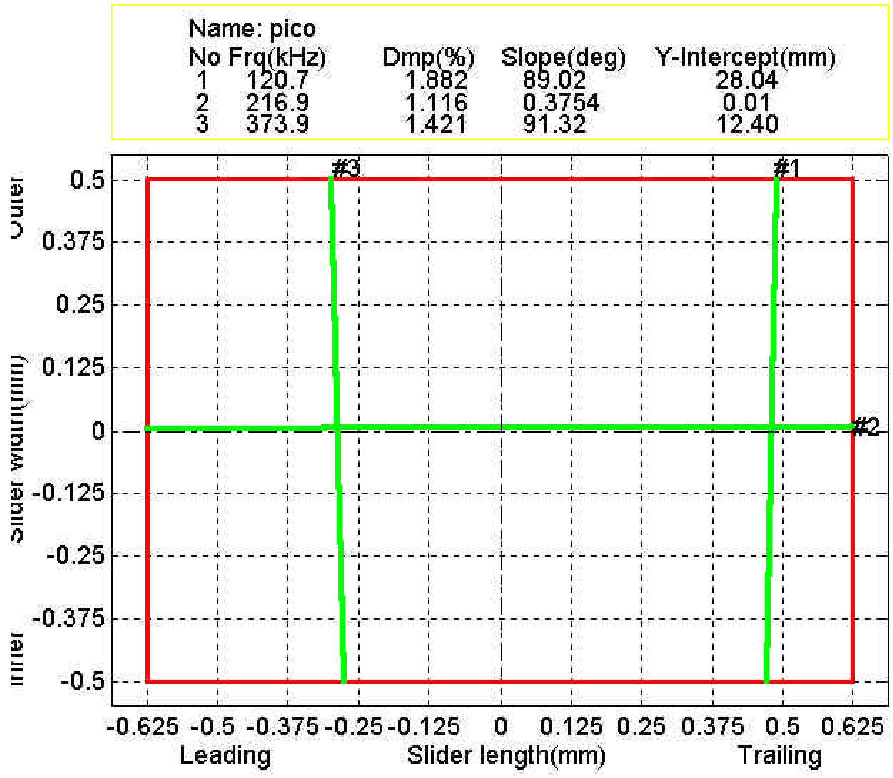

Figure 18: Dynamic characteristics of the redesigned pico slider.

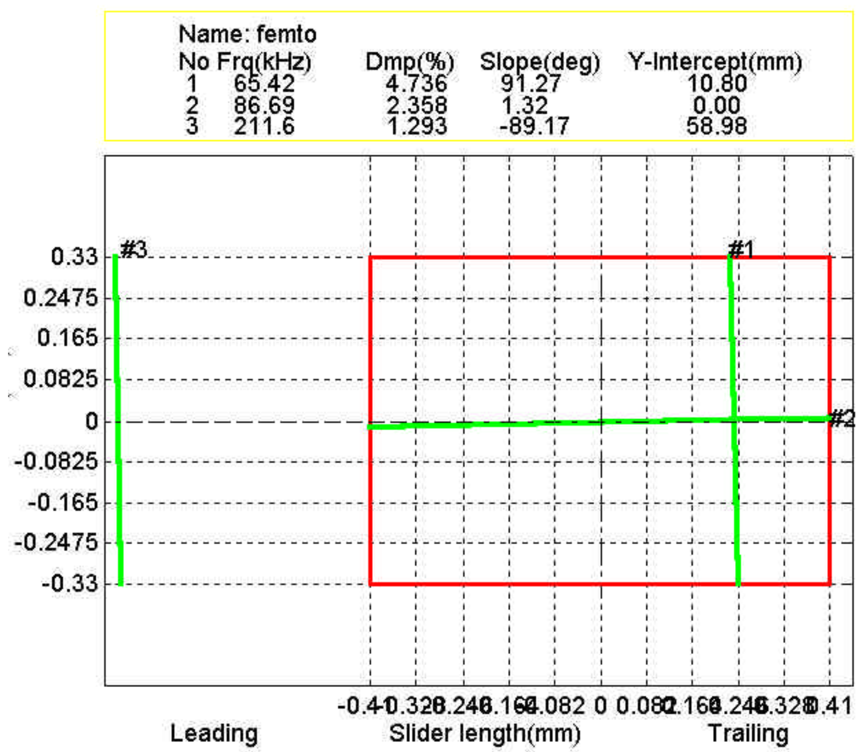

Figure 19: Dynamic characteristics of the redesigned femto slider.

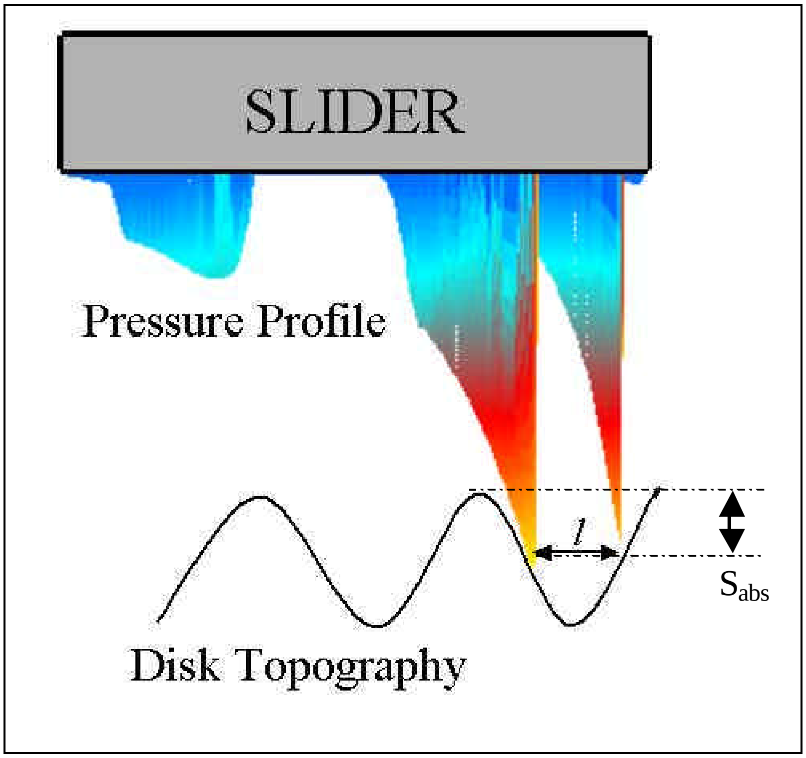

Figure 20: Geometric model for showing how absolute slider motion changes with waviness wavelength.

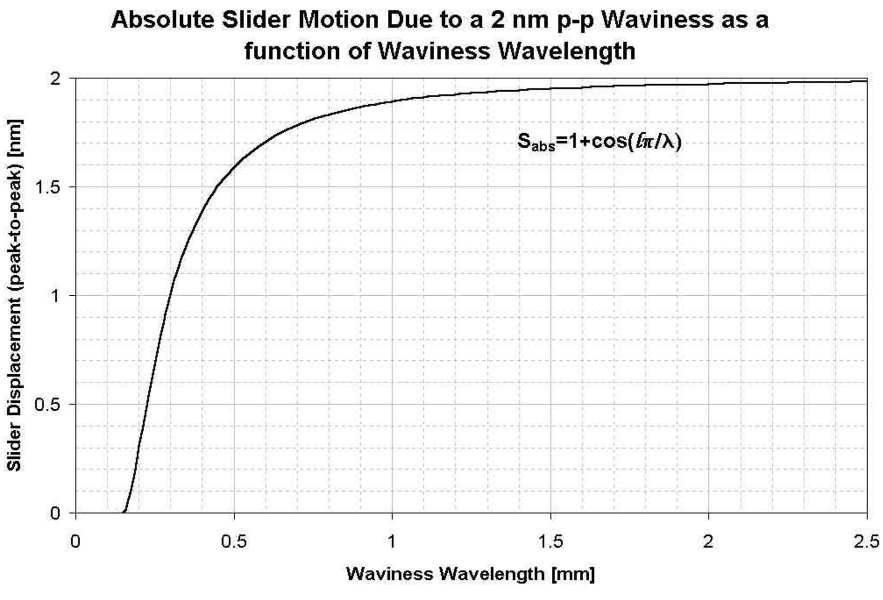

Figure 21: Absolute slider motion as a function of waviness wavelength found from the geometric model.

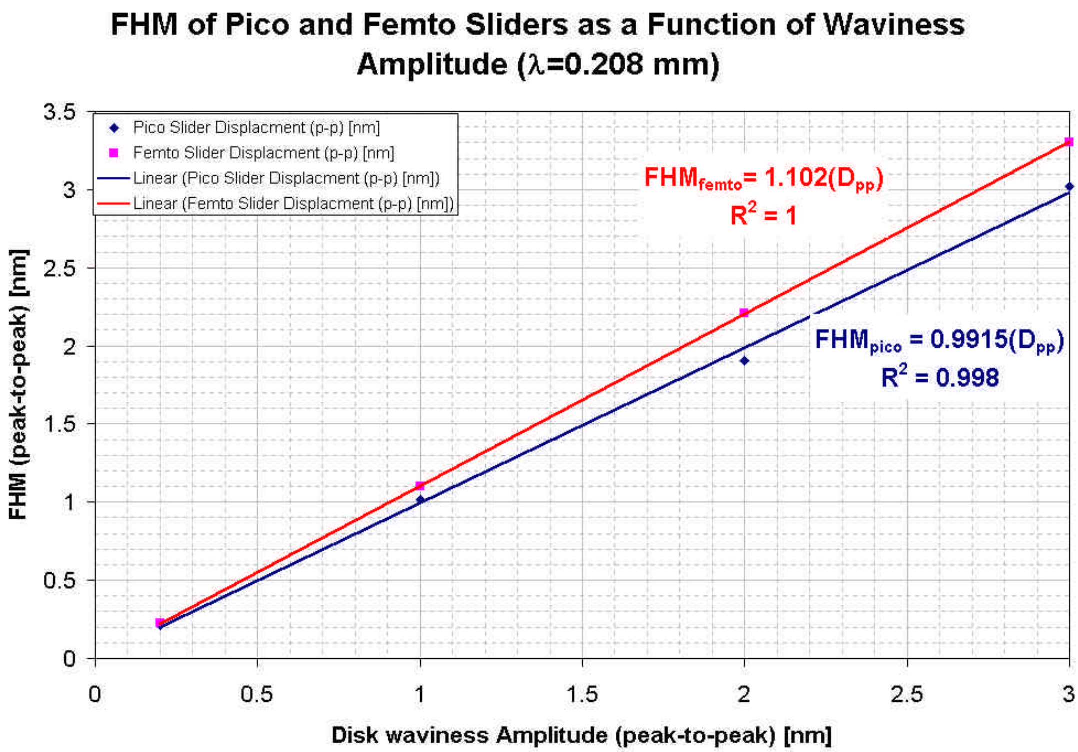

Figure 22: FHM of the pico and femto sliders as a function of waviness amplitude at a waviness wavelength of 0.208 mm.