Effects of Radial and Circumferential Disk Features on Slider Dynamics

Rohit P. Ambekar[1], Lanshi Zheng[2], Jihyun Lee[3] and David B. Bogy[1]

[1]Computer Mechanics Laboratory,
5146 Etcheverry Hall
Department of Mechanical Engineering
University of California
Berkeley, CA 94720

[2]Western Digital Fremont
44100 Osgood Road
Fremont, CA 94539

[3]KLA-Tencor/Candela
Milpitas, CA

Email: rohit@cml.me.berkeley.edu

Abstract

As the head-disk spacing is reduced in order to achieve higher areal density, dynamic stability of the slider is compromised due to a variety of proximity interactions. One of the key factors is the disk topography, which provides dynamic excitation to the low-flying sliders, and it strongly influences the dynamics and stability of the slider. Several experimental and numerical studies have been done on the fly height modulation caused by the disk topography along the track (circumferential) direction. In this paper we investigate the effect of the disk topography in the circumferential as well as the radial directions and a new method is used to measure the 2-D (true) disk topography for disks with three different kinds of roughness and waviness features. Then, a dynamic airbearing simulator is used to simulate the slider dynamics over the measured topographies. Simulations are conducted using 1-D topographies along the track direction as well as using the actual 2-D topographies. Comparison of the obtained slider dynamics over the different 1-D disk topographies indicates a strong dependence on the circumferential roughness and waviness features. Further, the comparison of slider dynamics and its frequency content over 1-D and the 2-D disk topographies indicates that the radial features, which have not been studied intensively till now, are also very important in determining the actual slider dynamics as they dictate the variation of the adjacent tracks in the circumferential direction. The simulations with 2-D disk topography are viewed as more realistic than the 1-D simulations. Further, it is also seen that the effect of the radial features can be reduced through effective ABS design.

Introduction:

The study of the dynamics of sliders flying over disks is important to achieve better readback signal in current products, and is also critical for achieving stability at low flying heights essential for increasing the areal density. Various experimental and numerical studies have been carried out on slider dynamics. Some researchers have used Laser Doppler Vibrometer (LDV) to measure track topography and the resulting dynamics of the slider flying over the track [1-2], while others [3] have used the read back channel to measure the fly height modulation. Thornton et. al. [2] measured the disk track profiles with an LDV and used them as an input to the CML dynamics airbearing simulator to numerically determine the slider dynamics. They showed a good correlation between the experimental and numerical fly height modulation. However, all of the previous studies concerning the numerical fly height modulation simulation used measurements of only one track on the disk and simulate its effect on the slider dynamics. In reality, when a slider flies over the disk, its motion is influenced by the actual disk surface topography, which is two dimensional (lateral dimensions; third dimension is the height). Such a two dimensional topography also includes roughness and waviness features in the radial direction, the effect of which is not captured in the slider dynamics simulations conducted by using only a one dimensional track topography. Further, to measure the low amplitude high frequency disk topography features such as roughness and microwaviness, we need to use the velocity channel of the analog LDV since the low frequency noise floor overwhelms the actual topography if the displacement channel is used. The resulting velocity data is integrated to obtain the disk topography. In this approach, the constant of integration (DC part) of the profile is set arbitrarily as only the changes in the profile (AC part) are important. Hence, this approach cannot be used to create a true two dimensional map of the disk topography because of the inability to determine the constant of integration. So a digital LDV or heterodyne interferometers with low noise floors are required to measure the 2-D disk topography, as their displacement channels can be used directly. In this work the disk topographies are measured using a Candela 6300 system (Fig. 1), which employs two independent low-noise laser channels to measure the slopes in the radial and circumferential directions [4]. The radial and circumferential information is combined to obtain the 2-D disk topography. The CMLAir dynamic simulator is used to simulate the slider dynamics of two different sliders over the measured 1-D and 2-D disk topographies to study the effect of the circumferential and radial disk features on the slider dynamics.

Experimental and Numerical Procedure:

In this study two different slider designs were used. Slider A (pico) is shown in Fig. 2(a), while slider B (femto) is shown in Fig. 2(b). In the first part of the study we examine the effect of 1-D circumferential features on slider dynamics using three 95 mm disks with different microwaviness features. Disk A is the roughest, while disk C is the smoothest, as measured by an LDV. The MD track (32 mm) of each of these disks was measured using the Candela 6300 system, and Fig. 3(a) shows part of the measured track, after it has been filtered through a highpass filter of 3KHz to remove the disk runout and major clamping distortions. Fig. 3(b) shows the frequency content of the disk topographies shown in Fig. 3(a).

The measured circumferential (1-D) disk topographies were input to the CMLAir dynamic simulator, and simulations were conducted for both slider designs. A time step of 0.1μs with a total simulation time of 2ms (20,000 time steps) and disk rpm of 5400 was used. In this case no variation in the disk topography along the width of the slider (radial direction) is incorporated.

Since disk A was the roughest and had the most circumferential and radial variations, it was chosen for the second part of the study, viz. the investigation of the effect of radial features on the slider dynamics. Using the Candela 6300 system we obtained the radial as well as circumferential slope information around the MD (32 mm) track. A total of 351 tracks were measured with a radial spacing of 2 μm, from 31.65 mm to 32.35 mm, maintaining 32 mm as the center track. The slope information for the center track was integrated in the circumferential direction to obtain the 1-D disk topography, which is the same as that used in the previous section. In addition, the radial slope information was integrated from 31.65 mm to 32.35 mm for each measurement point along the center track. The DC shift between the radial tracks was provided by the value already known on the center track. Thus, by "weaving" together the radial and circumferential slope information we created a two dimensional (2-D) disk surface. Figs. 4(a) and (b) show the 1-D and 2-D disk topographies. It should be noted that in Fig. 4(b) the circumferential length (35 mm) is much larger than the radial width (0.7 mm) of the track. Hence, the radial features are not as prominent as the circumferential features.

In preparation for performing the simulations we revived a previous capability of the CMLAir dynamic simulator to accept 2-D disk topography as input with a better format for the input file than it had previously (details in appendix A) and a faster implementation. Using this new simulator we conducted simulations with the 1-D and 2-D disk topographies of disk A for both slider designs. A time step of 0.1μs with a total simulation time of 2ms (20,000 time steps) was used. For the 2-D disk topography simulations, a large input file (128MB) and additional processing for determining the disk floor heights was required as 351 tracks (high resolution) were used. Even so, the simulation time increased only 30% compared to the 1-D disk topography simulations.

Finally, to identify the ABS modes of vibration observed in the power spectra and to aid further analysis, the CML Parameter Identification Program (CMLPIP) was used. This software utilizes the CMLAir dynamic solver to numerically perturb a steady state and provide the impulse response of an ABS in the vertical, pitch and roll directions. From the impulse response, the ABS modes are extracted along with their axes and damping. This information is shown in the modal diagrams in Figs. 5 and 6 for sliders A and B, respectively.

Results and Discussion:

To determine the steady state flying attitude of the sliders we used the CML static simulator, and the results are shown in Table 1. As seen there, slider B flies slightly higher than slider A, and it has lower pitch and roll. Using these steady state values as the initial conditions for the dynamic simulations, we obtained the response of the sliders to the measured 1-D disk topographies. Fig. 3(a) shows that disk A is the roughest while disk C is the smoothest disk as measured by the Candela 6300 system. The frequency content of the disks (Fig. 3(b)) can be further divided based on the wavelengths of their features. In general, wavelengths greater than 100 μm are considered as micro-waviness (μW), those between 20 and 100 μm as nano-waviness (nW) and those less than 20 μm as roughness (R). For the disk rpm of 5400, these wavelengths correspond to less than 200 KHz, 200-900 KHz and greater than 900 KHz, respectively and these regions are marked in Fig. 3(b). Based on this, it is seen that disk C has the lowest values of micro and nano-waviness and roughness. Disk A has the greatest micro and nano-waviness, while the roughness of disks A and B are comparable.

After characterizing the disks, the ABSs were also characterized for their modal frequencies using the CML PIP program. The result Tables along with the nodal lines are shown in Figs. 5 and 6 for slider A and B, respectively. From Fig. 5, it is seen that Slider A has the dominant ABS frequencies at 75.8, 113.7 and 142.4 KHz. From the nodal lines (and modal animations included in the program), it is seen that the lowest mode is a coupled vertical – first pitch mode, the second is the roll mode while the third is the second pitch mode. Similarly, Fig. 6 shows 166.3, 184.3 and 360.3 KHz as the roll, first pitch and second pitch modes, respectively, for slider B. The damping for all the modes is about 1-3% for both sliders.

As seen in Fig. 7(a), the sliders followed the low frequency (large wavelength) disk features closely. However, high frequency features were not closely followed, resulting in modulations in the slider's flying height. The modulations in the slider flying height, or the fly height modulation (FHM), corresponding to Fig. 7(a) is plotted in 7(b). It is indeed seen that only the high frequency components are present in this fly height modulation.

Figs. 8(a) and 9(a) plot the FHM and Figs. 8(b) and 9(b) plot the frequency content of the sliders' response for sliders A and B, respectively, on the disks A-C. For both sliders, the FHM correlates with the waviness of the disks i.e. the FHM is the greatest for disk A and the least for disk C. Table 2 indicates the standard deviation (3σ) values of the FHM for all of the slider-disk combinations. The simulations indicate that in order to have less fly height modulation, which directly correlates with the magnetic signal modulation, smoother disk topography is required.

From the power spectra of the slider responses peaks are seen corresponding to the ABS modes, and they are marked by arrows. It is also seen that the modes of slider A are lower in amplitude than those of slider B. Further, the disk topographies mainly excite the coupled vertical – first pitch mode of slider A and the second pitch mode of slider B. Since there is not much difference in the high frequency features of disks A and B, the corresponding FHM frequencies are also similar for both the slider designs. However, lower frequencies are associated with higher amplitudes, and thus we see a large difference in the FHM on disks A and B. From Fig. 8(a) it is seen that disk A excites the ABS frequencies of slider A much more than disk B. Disk C distinctly excites the coupled vertical-first pitch mode, but the overall amplitude for all frequencies for disk C is an order of magnitude lower than for disk A. This is in agreement with the FHM also being an order of magnitude smaller, as seen in Table 2.

We can do a similar analysis for slider B using Fig. 9(b). It is seen there that all of the disks excite the second pitch mode as it is the most compliant. Only disk A distinctly excites a low frequency ABS mode indicated in Fig. 9(b) by an arrow. This is a coupled pitch mode, as the 1-D topography does not have any radial features to excite the roll mode of the slider. In general, the frequency spectrum is of higher amplitude for disk A than disk B below the second pitch mode frequency after which the spectrum for disk B is higher. However, lower frequencies (longer wavelengths) correspond to higher amplitudes due to which the overall FHM for disk A is much greater than that for disk B. The FHM for disk C is an order of magnitude lower than for disk A even in this case.

From the above analysis it is clear that disk C is the best choice for both ABS designs. The ABS modes of slider B are at higher frequencies, which help to reduce the FHM (3σ) on disk A as compared to slider A, but they are responsible for increasing the FHM for disk B. This suggests that the choice of the slider ABS design and disk should be correlated to obtain the best FHM performance. Thus, given a disk, the dynamic characteristics (ABS modes) of the slider need to be optimized for minimizing the FHM. Alternatively, if an ABS design is finalized, the disk choice can be made by studying the disk waviness spectrum. Transfer functions [2] can also be used to avoid separate dynamic simulations for each disk topography.

Many researchers have analyzed different aspects of FHM using 1-D disk topography, both numerically and experimentally. However, as the slider flies on an actual disk surface which is 2-D, its dynamics can be captured more accurately using 2-D disk topography as an input to the simulator. Also, these numerical dynamics simulations using 2-D disk topography should be closer to the experimentally observed slider dynamics. Thornton et. al. [2] did a comparison between numerical slider dynamics using 1-D disk topography and experimental slider dynamics. They found good correlation between the two. However, the dynamics do not exactly match. In this study, similar observations were made when simulations were conducted with 1-D and 2-D disk topographies. As mentioned in the previous section, the topography of disk A was used as an input because it exhibited maximum variation. The FHMs for sliders A and B are plotted in Figs. 10(a) and 11(a), respectively. The corresponding frequency spectra are plotted in Figs. 10(b) and 11(b). Table 3 shows the standard deviation (3σ) of the FHM.

Table 3 shows about 15% and 22% increase in the FHM of slider A and B, respectively, when the 2-D disk topography is used. Upon analyzing the frequency spectra in Fig. 10(b), we see that the 2-D disk topography excites the first pitch mode of slider A about 2.5 times more than does the 1-D topography. Further, the second pitch mode is only excited by the 2-D topography. These increases are responsible for the increase in the FHM. We did a similar analysis for slider B from Fig. 11(b). In this case a general increase is seen in the spectrum corresponding to the 2-D topography, notably the second pitch mode. This leads to a greater percentage increase in the FHM of slider B for 2-D disk topography.

Thus, the simulations indicate the slider B is affected by 2-D topography more than slider A. One of the reasons for this is the pressure distribution under the sliders. This is plotted in Figs. 12(a) and (b) for sliders A and B, respectively. Depending on this pressure distribution and hence the pitch and roll of the slider, different tracks affect the slider dynamics to different extents. The higher the ABS pressure on a track, the more the slider dynamics are affected by that track. In 1-D topography, this aspect is missed since we only consider the central track. Figs. 12(a) and (b) show that the high pressure points are not exactly along the center track for sliders A and B. Therefore, the center track is not the track affecting the slider dynamics the most. From the analysis of the pressure plot in Fig. 12(b), we see that the pressure peak is about 10 μm towards the ID from the center line of slider A and about 58 μm towards the ID from the center line of slider B. Since the tracks corresponding to the maximum pressure affect the slider dynamics the most, we consider the difference between the topographies of these tracks and the center track for the two sliders. This difference is plotted in Figs. 13(a) and (b) for sliders A and B, respectively. The standard deviation (3σ) of the difference for slider A was 2.68 nm while that for slider B was 7.62 nm. The difference for slider B is much greater because the maximum pressure track is farther away from the center track as compared to slider A. Due to this, the net increase in FHM is much more in slider B when 2-D disk topography is included.

The effect of 2-D disk topography can be even more important at high skew angles, where the slider dynamics are influenced by more tracks as compared to the zero skew case considered in all the previous simulations. Fig. 14(a) shows the FHM for slider A at a skew of 17.6° (32 mm, 5400 rpm) in response to 1-D and 2-D disk topographies. From the figure, it is seen that slider A has multiple contacts with the disk when 2-D disk topography is considered but not with 1-D topography. The main reason for this is the relatively large roll (-1.54°) and high skew together cause more interaction with tracks farther away. The FHM (3σ) for 1-D and 2-D topographies were calculated to be 15.07 nm and 23.98 nm. Thus, there is an increase of 59.1% in the FHM when the 2-D disk topography is used. This increase in the FHM is mainly caused by multiple contacts, which excite the pitch modes of the ABS (Fig. 14(b)). Thus, the 2-D disk topography also gives a more accurate picture of the flyability of an ABS design.

From the above analysis it is clearly seen that the slider dynamics is affected by all of the tracks under the slider and not just the center track. Further, the influence of the center track on the slider dynamics depends significantly on the ABS design. Due to the radial disk features there is a difference between the topographies of adjacent tracks and this difference increases as the tracks become farther apart. Thus, FHM due to radial features is reduced when the maximum pressure is concentrated on the center track. FHM due to circumferential features is reduced when maximum pressure is concentrated near the transducer, which reduces the lag between disk topography and the slider response [5]. By combining these observations, we conclude that FHM is reduced when the pressure is concentrated under the transducer along the center track. However, this may have other consequences such as reduced pitch and roll stiffnesses which may also affect the dynamic performance and contact recovery of the slider. Nonetheless, it is a design parameter to be considered in ABS design.

Conclusions:

(a) In this report we investigated the effects of circumferential and radial disk features on the slider dynamics. Two slider designs and three disk types were used for this study. The CMLAir dynamics simulator was used as the simulation tool, while the new Candela 6300 system was used for obtaining the 2-D disk topography.

(b) From the first part of the study we conclude that circumferential features of micro and nano waviness affect the fly height modulation as they excite different ABS modes. Further, the ABS design and disk features need to be correlated to obtain the best FHM performance.

(c) Inclusion of 2-D disk topography in the dynamic simulations is more realistic since the slider actually flies over a 2-D surface. Based on the slider's design and its pressure profile, we found that different tracks have a varying influence over its dynamics. The center track, which is typically used in simulations as 1-D disk topography, may have less influence than its adjacent tracks. Hence, 2-D disk topography should be included in the dynamic simulations.

(d) Higher skew angles are associated with higher roll, and the slider dynamics are influenced by even more tracks than at lower skew. Under these conditions, 2-D disk topography can prove useful in providing the correct picture about the flyability of an ABS design.

(e) Simulations with CMLAir using 2-D disk topography increased the simulation time by only 30% as compared to 1-D disk topography as input, even with quite high resolution along the radial direction for the 2-D disk topography.

Acknowledgements:

This work was done at Western Digital Corporation, Fremont, USA and at the Computer Mechanics Laboratory at the University of California, Berkeley, USA. This work is supported by the Computer Mechanics Laboratory at the University of California, Berkeley, USA and the Information Storage Industry Consortium's EHDR Program.

References:

[1] Q.H. Zeng, B.H. Thornton, D.B. Bogy and C.S. Bhatia, "Flyability and flying height modulation measurement of sliders with sub-10 nm flying heights," *IEEE Transactions on Magnetics*, vol.37, no.2, pt.1, March 2001, pp. 894-9.

[2] B.H. Thornton, D.B. Bogy, C.S. Bhatia, "The effects of disk morphology on flying-height modulation: experiment and simulation," *IEEE Transactions on Magnetics*, vol.38, no.1, pt.1, Jan. 2002, pp. 107-11.

[3] Y. Shimizu and J. Xu, "Two-dimensional flying-height modulation mapping at HDD drive level," *IEEE Transactions on Magnetics*, vol.42, no.10, Oct. 2006, pp. 2516-18.

[4] P. Tribhuvan, V. Velidandla and S. Venkataram, "Disk Topography Metrology for Addressing Head-Disk Interface Challenges," *Asia-Pacific Magnetic Recording Conference (APMRC)*, Nov. 2006, Singapore.

[5] B.H. Thornton, A. Nayak and D.B. Bogy, "Flying Height Modulation Due to Disk Waviness of Sub-5nm flying Height Air Bearing Sliders," *ASME Journal of Tribology,* vol. 124, Oct. 2002, pp. 762-70.

[6] J.F. Xu and B. Liu, "ABS design and fly height modulation of femto sliders," *International Magnetics Conference*, 2003, pp. AB-10. Piscataway, NJ, USA.

Tables:

	FH (nm)	Pitch (μrad)	Roll (μrad)
Slider A	11.35	263.8	1.27
Slider B	14.59	126.4	-0.15

Table 1: State state flying attitude of sliders

	Disk A	Disk B	Disk C
Slider A	10.28	2.96	0.77
Slider B	9.66	3.50	1.27

Table 2: Standard deviation (3σ) values of FHM for different slider disk combinations (in nm)

	1-D	2-D
Slider A	10.28	11.84
Slider B	9.66	11.81

Table 3: Standard deviation (3σ) values of FHM corresponding to 1-D and 2-D disk topographies (in nm)

Figures:

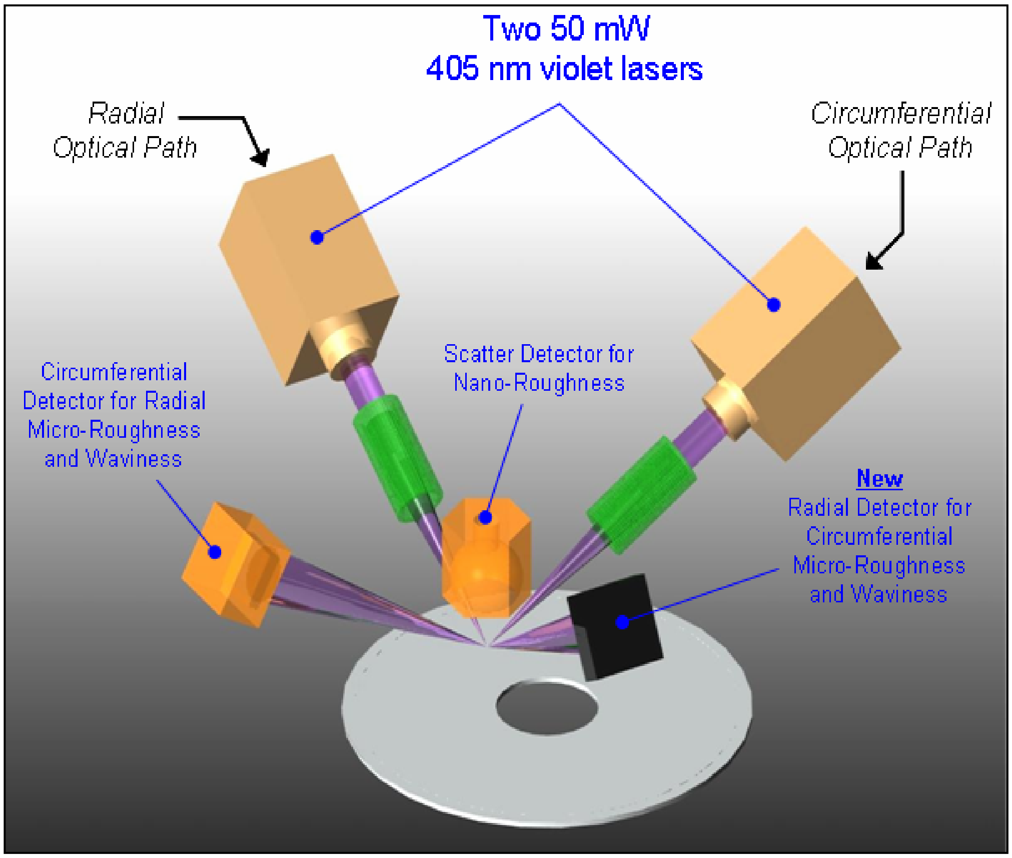
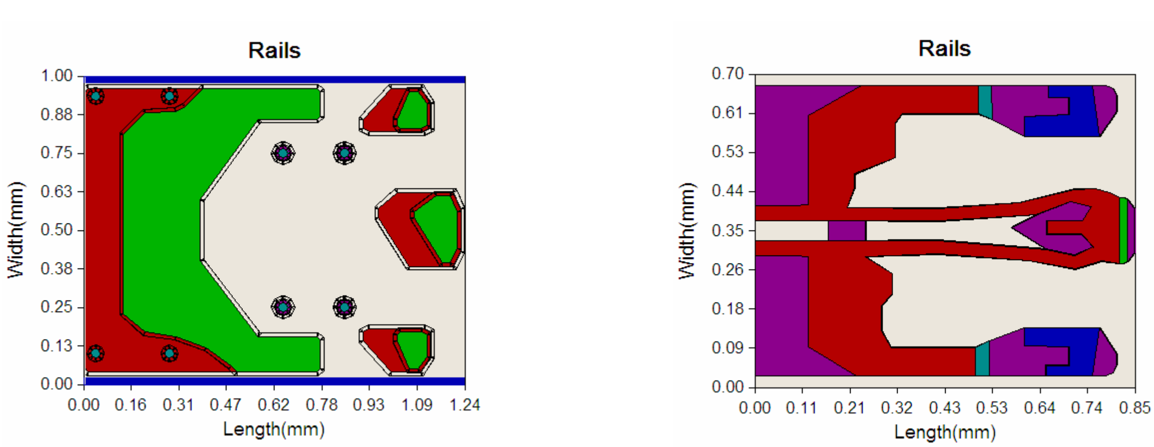
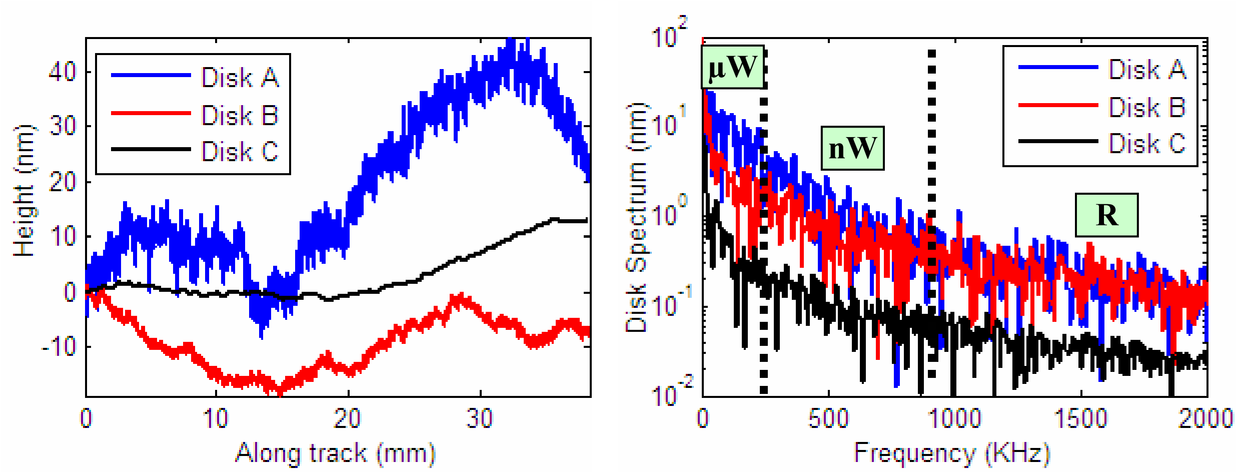


Figure 1: Candela 6300 surface topography measurement technique (Source: KLA-Tencor/Candela)



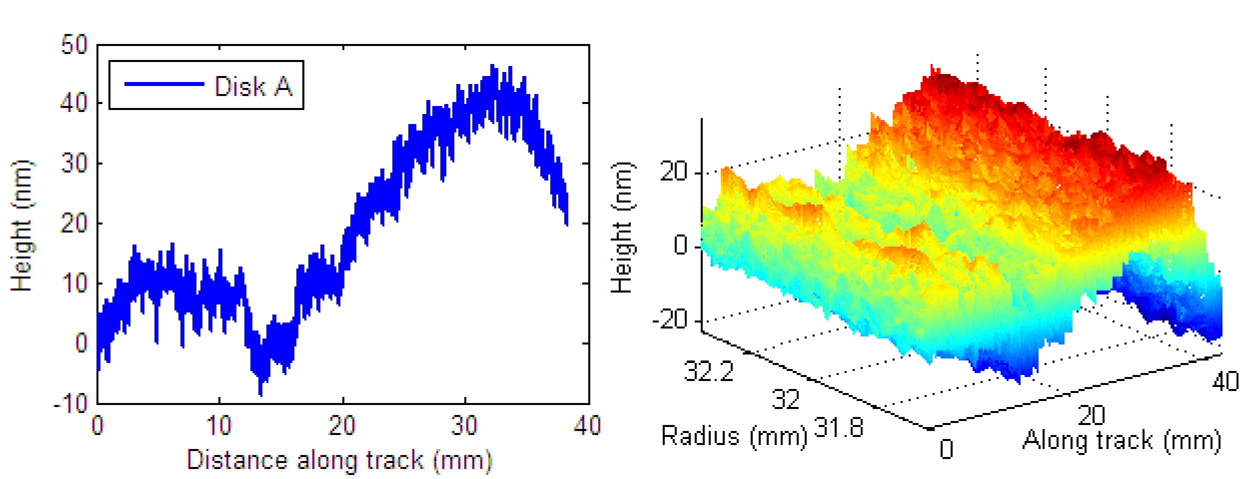
(a) (b)

Figure 2: ABS Designs used for simulations; (a) Slider A (Pico) and (b) Slider B (Femto) design



(a) (b)

Figure 3: Circumferential topography (1-D) of three disks measured at MD by Candela 6300



(a) (b)

Figure 4: (a) 1-D disk topography of the center track; (b) 2-D disk topography obtained from integrating the slope in radial direction and "weaving" it with the center track profile.

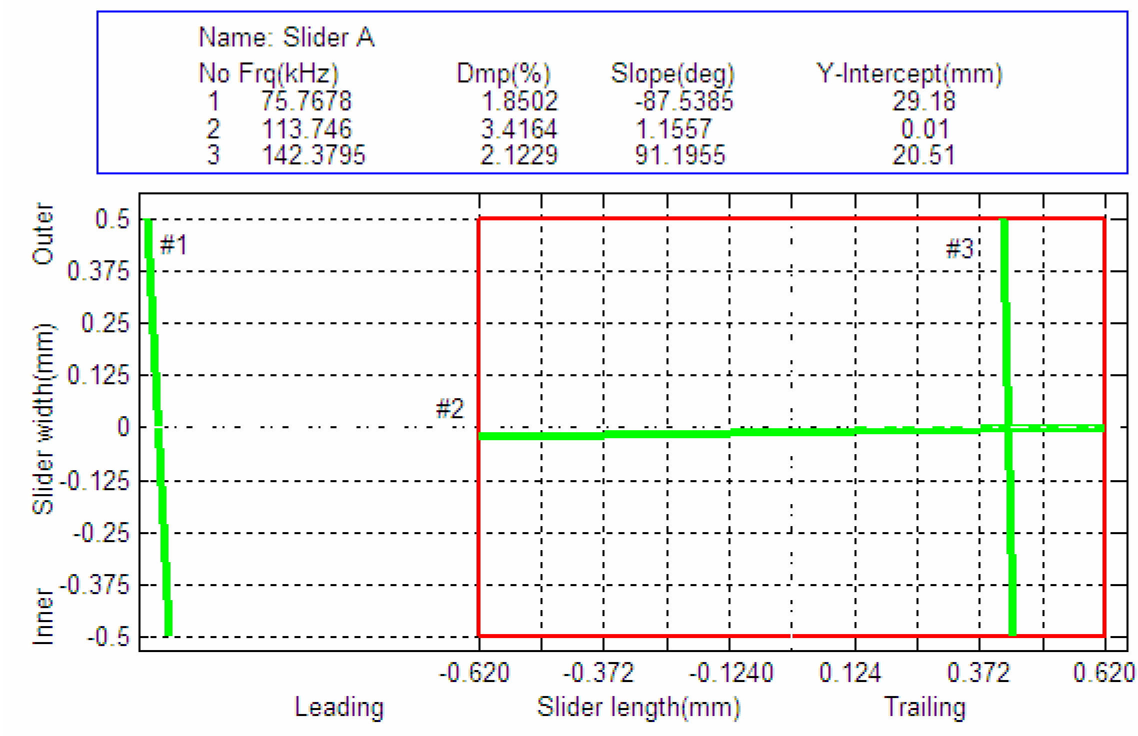


Figure 5: Modal diagram for Slider A

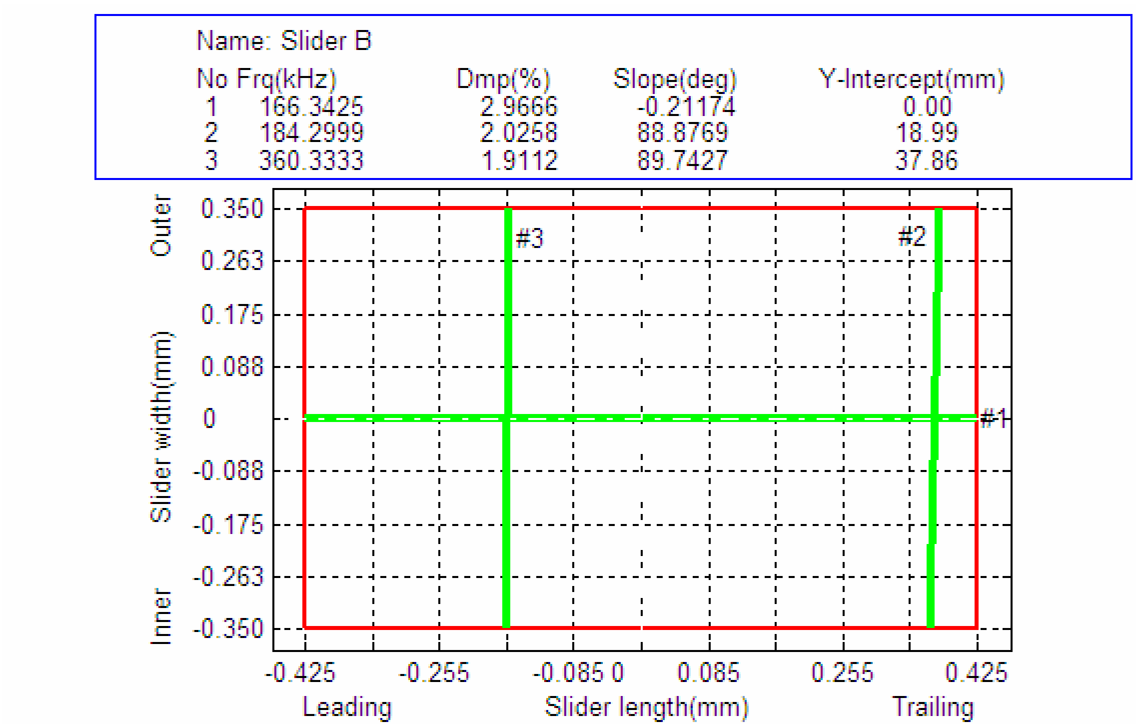


Figure 6: Modal diagram for Slider B

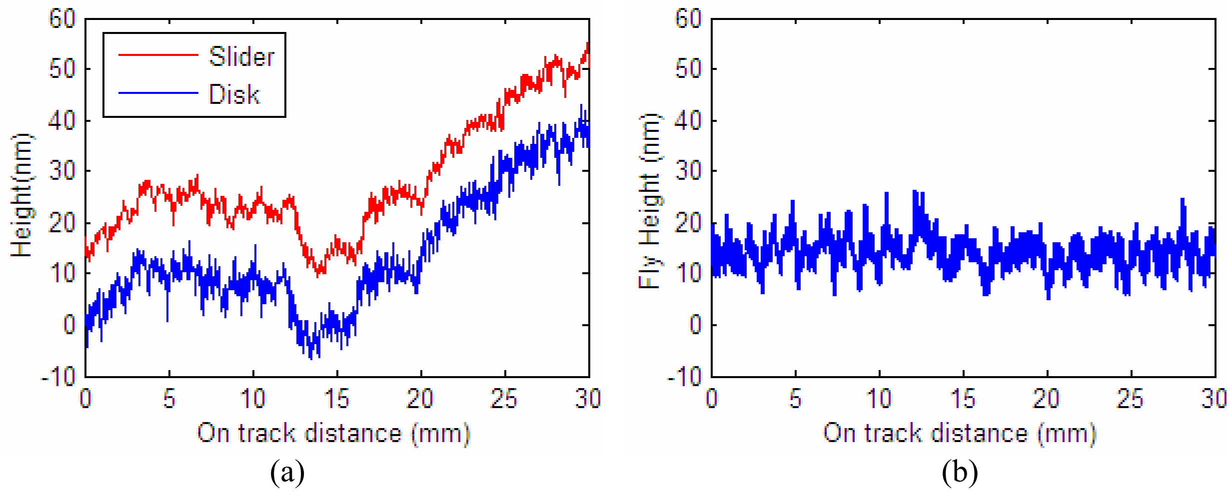


Figure 7: (a) Slider following the disk profile; (b) Net fly height of the slider above the disk

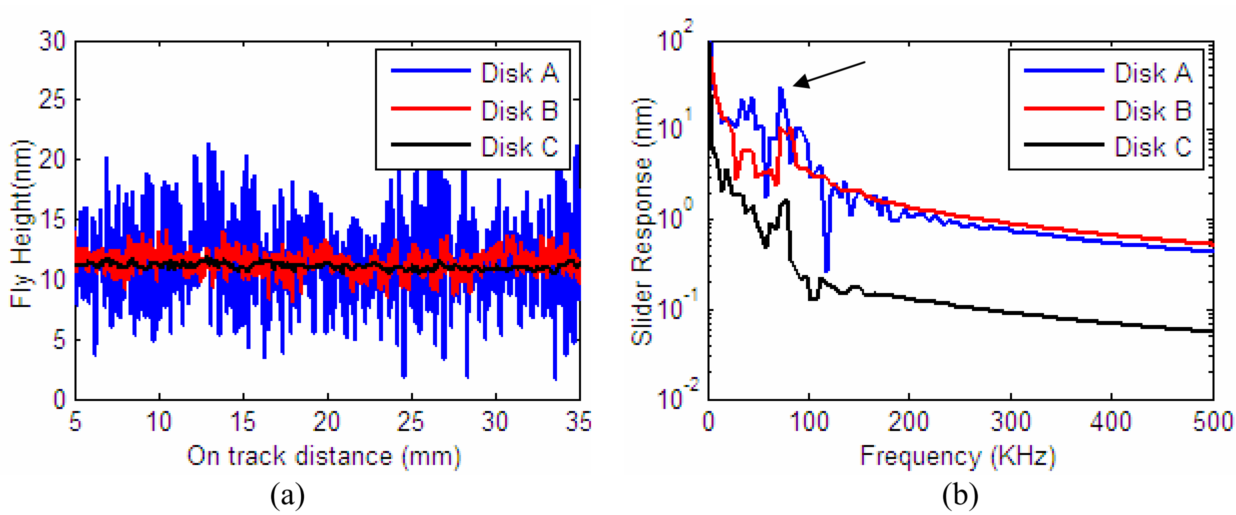
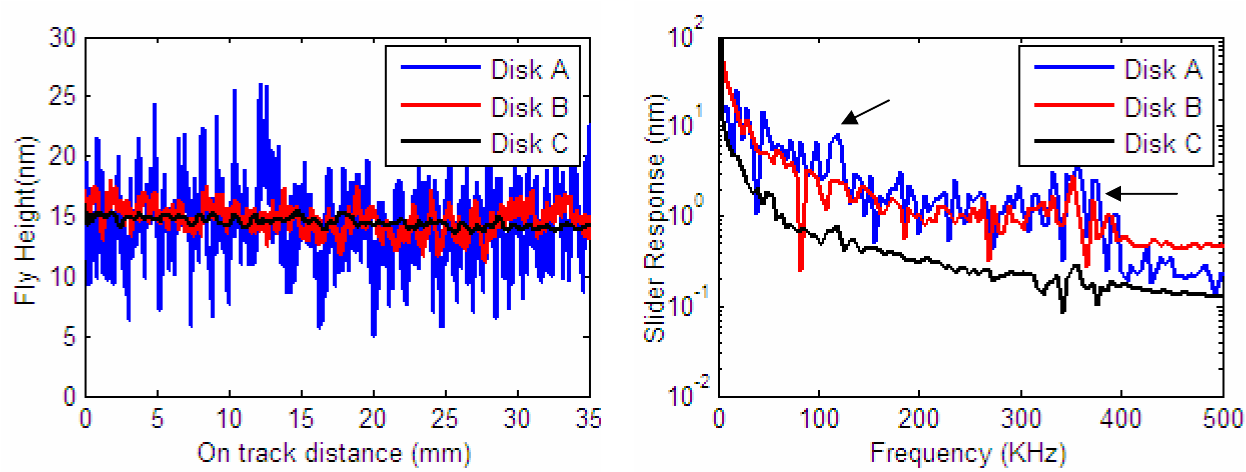
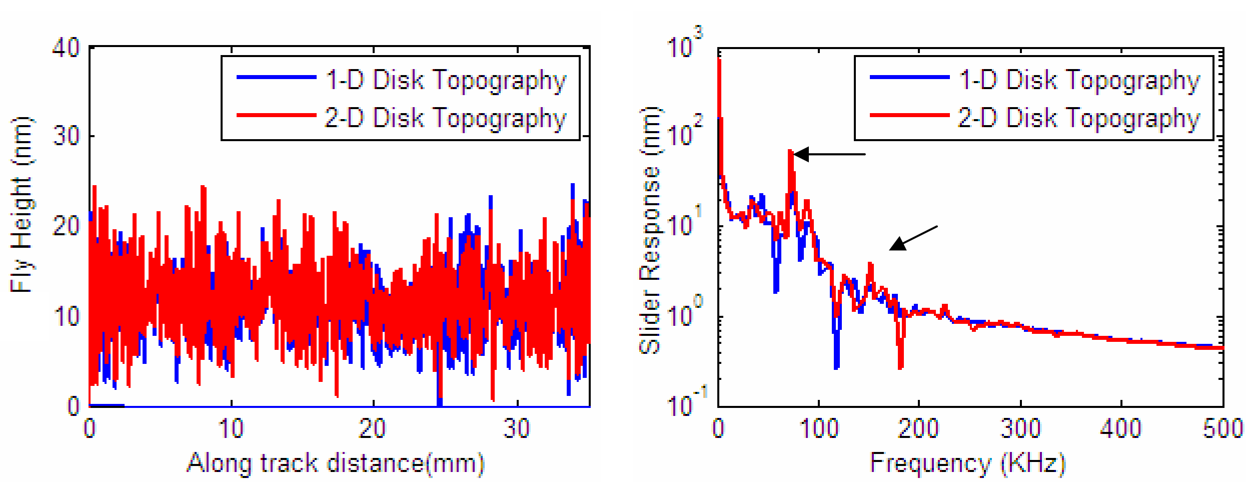


Figure 8: (a) Fly height modulation of Slider A relative to 1-D disk topographies; (b) Frequency content of the response of Slider A



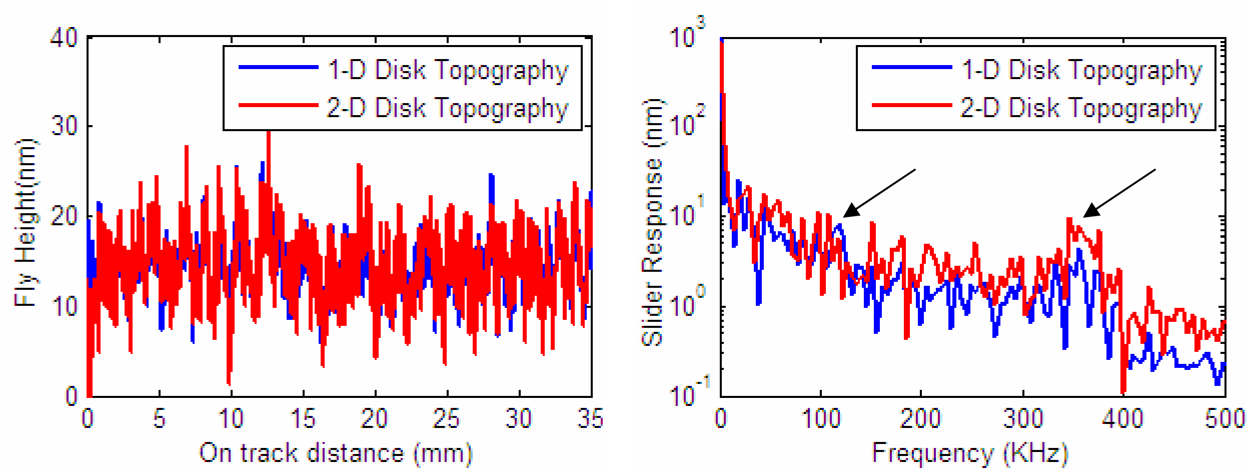
(a) (b)

Figure 9: (a) Fly height modulation of Slider B relative to 1-D disk topographies; (b) Frequency content of the response of Slider B



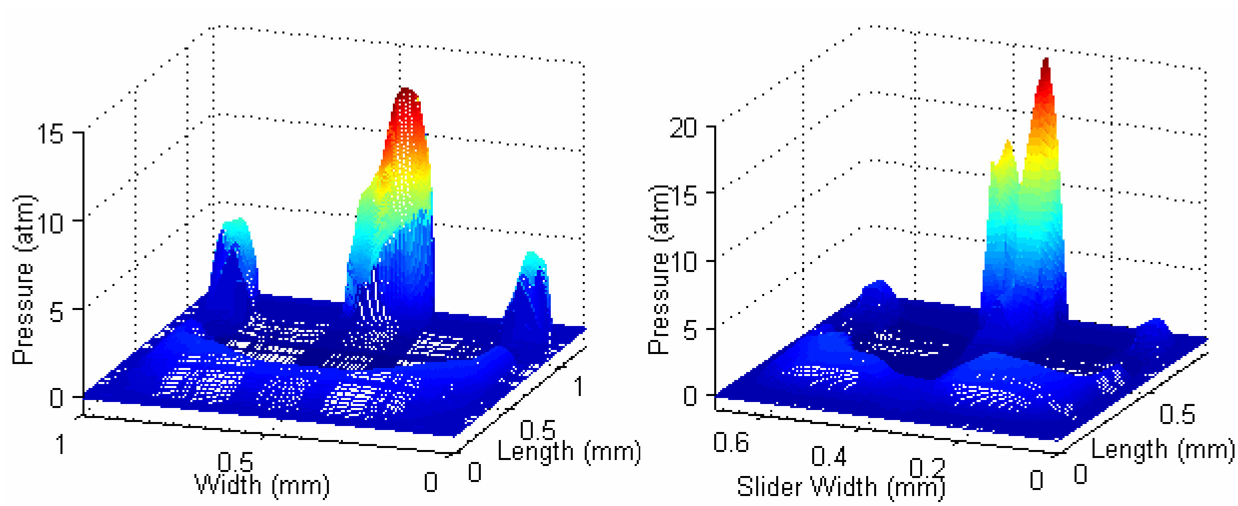
(a) (b)

Figure 10: (a) Fly height modulation of Slider A relative to 1-D and 2-D disk topographies; (b) Frequency content of the response of Slider A



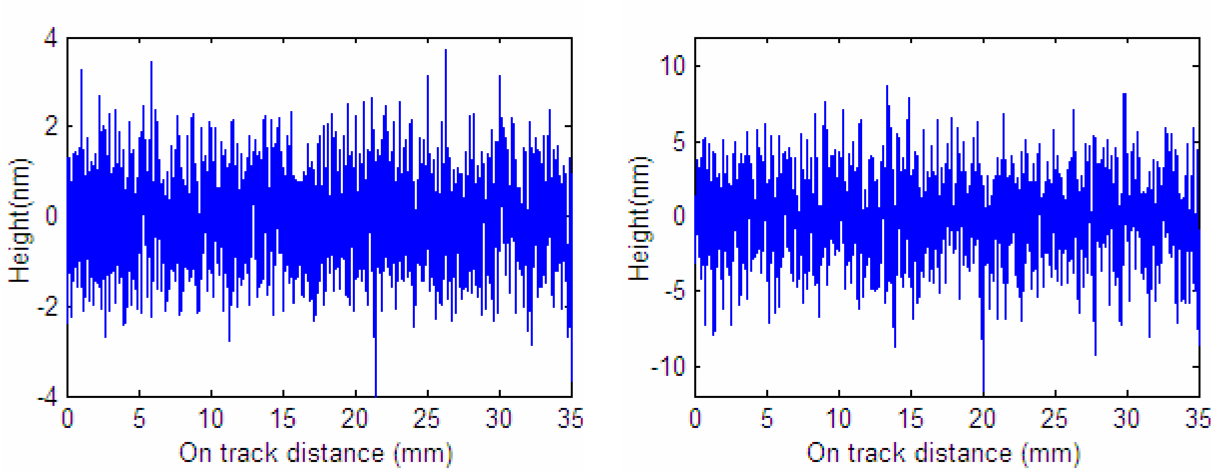
(a) (b)

Figure 11: (a) Fly height modulation of Slider B relative to 1-D and 2-D disk topographies; (b) Frequency content of the response of Slider B



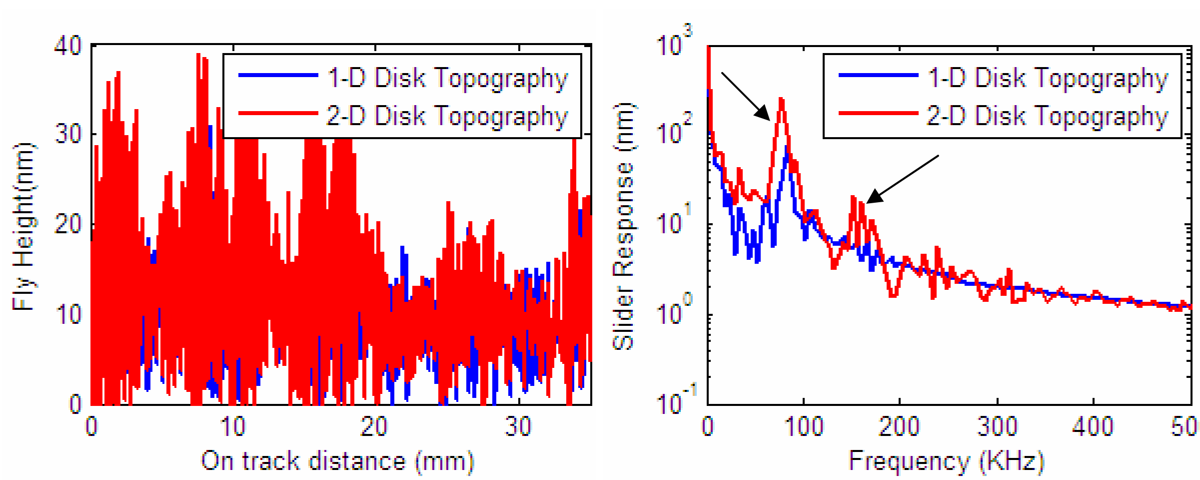
(a) (b)

Figure 12: (a) Pressure distribution of Slider A; (b) Pressure distribution of Slider B.



(a) (b)

Figure 13: Difference in topography of the track corresponding to maximum airbearing pressure and the center track for (a) Slider A and (b) Slider B.



(a) (b)

Figure 14: At skew angle of 17.6° : (a) Fly height modulation of Slider A relative to 1-D and 2-D disk topographies; (b) Frequency content of the response of Slider A

Appendix A

2-D disk topography input in CMLAir Dynamic Simulator

Rohit P. Ambekar and Brendan Cox

To use the 2-D disk topography input, the following change (highlighted by the box) needs to be made in the dynamic simulator input file **dynamics.def**. Variable ***nfy*** indicates the number of tracks to be given as input while ***nfx*** indicates the number of points per track. Variable **ims** activates the point-by-point disk profile when set to 1 while **dinit** indicates the distance of the first point of simulation from the starting of the track.

```
…
********************Grid Control***************************
iadapt     isymmetry  ioldgrid   nx   ny   nsx   nsy
...
 1
difmax     decay      ipmax
100.000000 100.000000 0
***********Point by Point Disk Track Profile***************
ims        nfx        dinit              nfy
1          20001      0.000000           351
******Numerical Generation of Disk Surface Topography******
nwave  nzone  nasper
0      0      0
iwtype wamp(m)  wang(dg) wthx(m)  wthy(m)  wpdx(m)  wpdy(m)  wrs(m)  wre(m)
zr1(m)    zh1(m)   zr2(m)   zh2(m)   zr3(m)  zh3(m)
iatype aamp(m)   aang(dg)  alocx(m)  alocy(m)  asizx(m)  asizy(m)
****Numerical Generation of Slider Surface Topography******
nswave  nsasper
0       0
istype  swamp(m)   swng(dg)   swthx(m)   swthy(m)   swpdx(m)   swpdy(m)
isatype saamp(m)   saang(dg)  salocx(m)  salocy(m)  sasizx(m)  sasizy(m)
******************Track Accessing Motion*******************
…
```

The disk topography file **wave.def** should be included in other dynamic input files such as dynamics.def and rail.dat. It is in the following format:

x(1)	h(1,1)	h(1,2)	h(1,3)	…	h(1,nfy-1)	h(1,nfy)
x(2)	h(2,1)	h(2,2)	h(2,3)	…	h(2,nfy-1)	h(2,nfy)
x(3)	h(3,1)	h(3,2)	h(3,3)	…	h(3,nfy-1)	h(3,nfy)
.						
.						
.						
x(nfx)	h(nfx,1)			…	h(nfx,nfy-1)	h(nfx,nfy)
y(1)	y(2)	y(3)		…	y(nfy)	