Flyability and Flying Height Modulation Measurement of Sliders with Sub-10 nm Flying Heights

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ABSTRACT

A Laser Doppler Vibrometer (LDV) was used to measure flying height modulation (FHM) of sliders with sub-10 nm flying-heights (FH). It was found that a precise trigger, averaging, and suitable filtering are key to successfully measuring FHM by LDV. Also, more accurate results can be obtained from the LDV velocity output as opposed to the displacement output. FHMs of a 7-nm FH slider flying over three different disks were measured. One of the disks had higher roughness and waviness values (disk A) than the other two (disks B and C). Disks B and C had the same super-smooth substrate but different lubricants and carbon overcoats. It was observed that this slider flew steadily over disk A and disk C, but it could not fly over disk B. The repeatable part of the FHM of the slider flying over disk A and disk C was about 0.45 nm and 0.37 nm (RMS), respectively, in the frequency range of 20 kHz and 300 kHz. Also, for disk C, the dependence of FHM on RPM was investigated, and it was found that at the designed condition (7200 RPM) the FHM (peak-to-peak) was minimized for this particular slider/disk system. However, we do need to consider the ratio of FHM to FH. Increasing RPM increases FHM due to the disk surface topography and decreasing air bearing modal frequencies, but the ratio of FHM to FH stays relatively constant. Decreasing RPM increases FHM due to intermittent contacts and excitation of the air bearing.

I. INTRODUCTION

To achieve 100 Gbit/in^2 areal densities, disk drive flying heights (FH) must be sub-10 nm. As the FH decreases, head/disk interface stability and head/disk spacing variation (FH modulation, or FHM) are becoming of more concern. In such an ultra-low FH regime, head/disk contact – intermittent or sustained – is virtually unavoidable, and maintaining dynamic stability is a serious challenge because of the stiction effects when "super-smooth" media are used with ultra low glide heights [1]. There are also many other factors, previously ignored, which have only begun to become important at the head/disk interface (HDI).

Acoustic emission (AE) sensors have been widely used to detect contacts between the disk and slider [2]. If the measured AE signal shows slider ringing components in the frequency domain, one usually knows that contact occurred. However, if the measured AE signal shows a strong air bearing resonance and little slider ringing components, or if the measured read-back signal shows a strong air bearing resonance or a read/write skip, usually it is difficult to say what occurred at the head/disk interface. Also, we have observed in some situations using sub-10nm flying sliders, with little or no detectible AE signal, the disk carbon overcoat begins to wear after a very short period of time. This has motivated our investigation to measure FHM in the time and frequency domains, giving more reliable and insightful information about HDI's.

With FH decreasing, the ratio of FHM to FH tends to increase. Yai, et al [3] showed that the FHM to FH ratio increases from about 16% to about 30% for one disk at the same rotating velocity as FH (of different samples) decreases from 26 nm to 12 nm. Therefore, FHM of sub-10 nm sliders becomes more critical for reliable read/write operations and flyability. Although FHM can be obtained by using numerical simulation coupled with actual disk surface topographies, the measured experimental data is much more useful for better understanding the HDI and designing a reliable interface.

Phase Metrics DFHT [4] has been widely used to measure steady and dynamic FH, but only with glass disks. One cannot assume FHM will be same over the actual magnetic hard disk with different surface topographies, lubricants, and other variables. FHM should be measured with the slider flying over an actual HDD product disk. BALI [5] can be used to determine FHM with an actual product disk, but it is difficult to use and not widely available. The Laser Doppler Vibrometer (LDV) is relatively easy to use, but it is usually considered to lack the required resolution. However, in our recent experiments [6] we have demonstrated that the LDV can reach very high resolution under specific conditions. Figure 1 shows the measured slider ringing of a tri-pad nano slider when it contacts a bump on a disk. No meaningful information can be seen from the single shot measurement. However, a very clear measurement of the slider's bending mode is apparent after 2000 averages with a very accurate trigger. The frequency is about 800 kHz, and the velocity amplitude is about 1.5 mm/s. So, the amplitude of the slider vibration is

$$\frac{1.5mm/s}{2*p*800(kHz)} = 0.298\,nm$$

In this case, a very high resolution is achieved.

Therefore, we applied LDVs to measure FHM of sliders with very low FH. An experiment was designed and implemented. FHMs of a 7-nm FH slider flying over three different disks were measured. Disk A was rougher and wavier than disks B and C. Also, disks B and C had the same super-smooth substrates, but had different carbon overcoats and lubricants. It was found that the slider could steadily fly over disks A and C, but it could not fly over disk B.

II. EXPERIMENTAL SYSTEM AND PROCEUDRE

Experimental Systems

Figure 2 shows the schematic of the experimental system. A ThÔt Technologies tester with the flyability option was used as a spin stand platform. It has a precision air bearing spindle and an optics setup for the LDV measurement beams, which allow for close positioning of the measurement beam and the reference beam with no loss of signal. A small radial scratch was made at the outer radius of the disk, and the laser spot of the Polytec LDV (2802) was focused on this radius. The output velocity signal of the LDV was fed into a high-pass filter with a cutoff frequency of 20 kHz. This signal was used as a trigger for the LeCroy digital oscilloscope. As a result, we obtained a very accurate trigger signal.

A dual-beam LDV (Polytec 512) was used in the measurement of the FHM. The reference beam of the LDV was focused on the disk, and the measurement beam was focused either on the disk (DD) or the slider-back (SD). The velocity or displacement output was fed into a band-pass filter with the frequency range from 2 kHz to 300 kHz. The signal was acquired with the oscilloscope and averaged in the time and frequency domains simultaneously. The data was then transferred to a PC for data processing.

Experimental Procedure

In order to obtain a FHM measurement, we first needed to evaluate the flyability of the HDI system. We accomplished this two different ways. First, we performed a "spin-down" test using a TTi Tribocop spinstand and monitored AE and interfacial friction as the disk RPM was reduced from 12000 RPM to 5400 RPM. This gave a preliminary evaluation of the HDI, and it indicated when contact occurred. We then measured the relative velocity between the slider and the disk (SD) on the Thôt Technologies tester (see Fig. 2) to see if the interface was steady. If the slider steadily flew over the disk, then we measured the repeatable FHM. Secondly, we determined a suitable averaging number, as described in the following section, and acquired SD data. The third step was to measure the base displacement (DD) by holding the measurement beams in place and moving the slider to a different radius, allowing both the reference and measurement beams of the LDV to measure the disk. The spacing between the two beams was set as small as possible. The optics setup on the Thôt Technologies tester allows for close positioning of the beams without the beam intensity loss that is found with split optic cubes. Finally, DD and SD measurements were processed by numerical integration and digital filtering. FHM was obtained after subtracting DD from SD.

Averaging Effects

Figure 1 shows that averaging is critical for using the LDV to measure FHM in the time domain. A suitable averaging number needs to be determined for the specific experiment. Figure 3 shows the histories of the disk displacement measurement with different average numbers. It is seen that a single shot measurement is significantly different compared to the resulting displacement with 1000 averages. To quantitatively indicate the effects of the average number, the standard deviations of the measured displacements with different average numbers were calculated, as shown in Table 1. From Table 1, we know that at least 100 averages are required for this case. Usually, a larger number of averages is required for the SD measurement than the DD measurement because the reflectivity of the slider back is not as good as that of the disk surface.

Figure 3 and Table 1 show that the measurement results converge to a steady value with increased averaging. The converged results represent the repeatable displacement.

If the trigger signal is not very accurate, or the experimental system is not stable, the measurement may not converge to a steady and repeatable value, or it may converge to zero.

Comparison of Displacement and Velocity Measurements

The LDV used in our experiment has both displacement and velocity outputs. The displacement output is normally used to measure displacement in the low frequency band, and the velocity output is used in the high frequency band. Theoretically speaking, one can obtain the displacement data from the velocity measurement by numerical integration. However, the displacement data from the velocity measurement obtained by integration is quite different from the directly measured displacement in the time domain, because there are some low frequency components after the integration. These components should be properly removed to obtain good results. After trying many methods, we found that a very high order Finite Impulse Response filter (800 orders, MATLAB function FIR1) is suitable for this purpose, and it was used to process the integrated data. Therefore, we can use either the displacement or velocity output of the LDV to measure FHM. The frequency range for the FHM measurement is limited based on the slider size, the disk speed, the air bearing resonant frequencies, and the LDV's frequency range.

We then investigated the repeatability of the FHM measurements using both the displacement and velocity outputs of the LDV. The displacement and velocity outputs were acquired from the DD measurement at the same time and averaged 100 times as described above. After obtaining the first set of measurements, we waited about 5 minutes and then obtained a second set of measurements. The two sets of measured displacement data were processed through a 20kHz to 250 kHz band-pass digital filter and subtracted from each other. The result showed that 30% of the displacement amplitude was not repeatable. The two sets of measured velocity data were numerically integrated and processed through the filter. The two sets of integrated displacements were subtracted from each other, and this method showed a repeatability of at least 95%. Averaging the two sets of measurements, we obtained two measured displacement histories (one is from the displacement output, and the other is from the velocity output). The difference between the two measurements was expected to be very small (i.e. both methods should yield the same displacement histories), but it was 80% of the displacement amplitude, as shown in Fig. 4a. However, if the filter's band-pass was changed to 20 kHz to 100 kHz, more accurate results (20% of the displacement amplitude) were obtained, as shown in Fig. 4b.

Therefore the displacement output of the LDV can only be used below the 100 kHz frequency band to obtain repeatable and accurate FHM measurements. We can obtain much better displacement data from the velocity output of the LDV by using numerical integration and digital filtering in a wide frequency band (20-300 kHz). Therefore, we used the velocity output in the following experiments.

III. CASE STUDY

Disks and Sliders Used in the Experiment.

Three types of disks were used in the experiment. All were super-smooth disks, and disks B and C had the same ultra-low glide height substrates with different carbon overcoats and lubricants (16 and 20 angstroms, respectively). Disk morphologies were measured using a Zygo NewView 100 white light interferometer. Waviness was defined as surface wavelengths of 0.1mm and greater. Roughness was defined as wavelengths of 0.1mm and lower. These values are shown in Table 2. Disks B and C had smaller roughness and much smaller waviness amplitudes than disk A.

The air bearing surface of the slider is shown in Fig. 5a. The slider was designed to have a 7 nm FH at the read/write pole tip (PT). Three slider samples were used and their FH's were measured by DFHT with PT FH ranging from 7.99 to 8.85 nm. For disks A and B, the design conditions were met at a test radius of 41 mm, skew of 0 degrees, and 2800 RPM (12 m/s for zero skew). The FH was numerically calculated by the Computer Mechanics Laboratory (CML) Air Bearing Design Code and plotted as a function of disk RPM as shown in Fig. 5b.

Flyability and FHM of the Slider

Before measuring the repeatable FHM of the slider, we evaluated the flyability of the slider by the "spin-down" test measuring friction and AE and also measuring the velocity response between the slider and disk (SD). From the velocity response with disk B for different RPM, we saw that the slider strongly oscillates if the disk velocity is less than 20.6 m/s. Figure 6 shows the frequency domain data of single SD velocity time captures from 12 to 22.3 m/s (increasing air bearing resonant amplitudes as RPM decreases).

Even at 20.6 m/s, the bursts in the velocity history indicate that the slider did not steadily fly over disk B. In fact, the velocity output of the LDV is much better than the displacement output in detecting this kind of small bursts. Similarly, below 20.6 m/s there was very strong AE signals, which saturated our data acquisition system even with a very low amplifier gain, and high friction values were also recorded.

From both the “spin-down” flyability test and the measurement of the time histories of the velocity of the slider flying with disk A (SD) for disk RPM ranging from 10.3 to 17.2 m/s, it was observed that the slider could steadily fly with disk A at and above 12 m/s. Figure 7 shows the frequency domain of SD of a single time capture with the same scaling as in Fig. 6. The air bearing resonance at 12 m/s, which results in a large FH variation, can be seen. We measured the responses of all three sliders mentioned previously, and they all showed very similar phenomenon.

During the experiment, we found the strong oscillations of the slider are not very repeatable, therefore they cannot be easily observed in the time domain with the trigger. If the air bearing resonance is not clear in the time averaged frequency domain but appears strongly in the frequency averaged data, then the excitation of the air bearing is non-repeatable. That would imply that disk waviness and roughness don’t directly result in a strong air bearing resonance. Because the slider cannot steadily fly on disk B, we could not measure its repeatable FHM. However, we could measure the repeatable FHM of the slider with disks A and C, which will be described in the following sections.

Repeatable FHM of the Slider with Disk A

The velocity output of the LDV with 1000 averages, together with the integration of the velocity data, and the digital band-pass filter of 20-300 kHz were used to obtain the repeatable FHM of the slider with disk A. To check the repeatability of the data, we measured two sets of data. The results at 12 m/s are shown in Fig. 8. The amplitude of the measured FHM (peak-to-peak) is about 2 nm (Fig. 8c), and the standard deviation of the FHM is about 0.4 nm with a high repeatability. Figures 8a and 8b show the repeatability of the DD and SD measurements, respectively.

The repeatable FHM was averaged in the time domain. If the averaging operation was performed in the frequency domain, then the measured power spectrum included both the repeatable (synchronous) and non-repeatable (asynchronous) components. Figure 9 shows the measured power spectrum of velocity averaged in the frequency domain for 10.3 and 12 m/s. If the power spectrum of the DD measurement is subtracted from the SD measurement, the results, as shown in Figs. 9c and 9d will clearly indicate if there is air bearing resonance. Comparing Fig. 9 with Fig. 7, we see that the air bearing resonance is mostly non-repeatable.

Repeatable FHM of the Slider with Disk C as a Function of RPM

This experiment was conducted using the designed conditions of the system. The radius was set at 23 mm with a skew of 9 degrees. We investigated repeatable FHM as a function of RPM for this particular slider and disk while digitally filtering from 10kHz to 500kHz. The RPM was varied from 4500 RPM to 11000 RPM (10.77 m/s to 26.33 m/s), respectively.

As the relative linear speed increases (RPM increases), the definition of roughness and waviness increases in frequency as shown in Fig. 10. Generally, disk profiles have larger amplitudes at higher wavelengths (runout, waviness, and flutter) and lower amplitude at lower wavelengths (roughness). In other words, for higher rotational speeds, there are higher amplitudes of disk topography in the air bearing frequency range.

Therefore, as the disk rotational speed increases, the surface wavelengths on the disk linearly increase to higher frequencies. From Fig. 10 it is seen that when the linear velocity is 10 m/s, the defined waviness is below the air bearing modal frequencies. However, when the linear velocity is 26 m/s, pitch, roll and possibly the vertical air bearing modal frequencies are affected by the waviness of the disk. Another consideration for this particular negative pressure slider is that the FH increases as a function of linear velocity, as seen in Fig. 5b. This is of concern, because as the linear velocity increases not only does the disk waviness increase in frequency, causing higher amplitudes of the disk profile in the air bearing modal frequency range, but also because the FH increases, causing the modal frequencies to decrease (i.e. the air bearing becomes less stiff). This causes two additive conditions, which allow for excitation of the air bearing with increasing RPM due to the disk topography.

In Figs. 11a,c,e and 11b,d,f plots of the averaged time domain and power spectral density (PSD) of the repeatable FHM are shown, respectively. Figures 11a and 11b show results for 26.33 m/s. We notice slight excitation of the pitch air bearing mode (110kHz) contributing to repeatable FHM. Figures 11e and 11f show results for 10.77 m/s. From both the time and frequency results, one sees a large contribution of repeatable FHM due to the excitation of the air bearing. Figures 11c and 11d show results for 17.24 m/s. This happened to be not only the designed RPM of this slider but also the optimal condition for this slider/disk combination when looking at peak-to-peak values. Table 3 summarizes the experimental results.

Disk C performed the best in the “spin-down” test, showing little or no contact by AE and strain gage (friction) until below 12 m/s. When we measured repeatable FHM at 4500 RPM (10.77 m/s), we observed excitation of the air bearing, contributing to repeatable FHM. When the disk spins fast enough for the slider to be flying without intermittent contact (17.24 m/s) we obtain a minimum in the repeatable FHM. At this speed, we notice that the slider is basically following the disk surface profile at a slight phase shift. However, if we continue to spin the disk faster, we see the air bearing pitch mode contributing slightly to repeatable FHM. Also, we notice the air bearing modal frequency decreasing (becoming less stiff) as RPM increases hence becoming more susceptible to excitation of the disk waviness/roughness. We also need to take into consideration the ratio of FHM to FH. As the RPM increases, the FH increases for this particular air bearing design. This ratio stays approximately constant, around 35%, when there is no intermittent contact between the slider and the disk (i.e. for steady flying conditions).

IV. SUMMARY AND CONCLUSION

An experimental system was set up, and a procedure was proposed for measuring the FHM by using LDVs. A precision trigger, a large number of averages, and a suitable filter are key to successfully measuring the FHM. Better results can be obtained from the velocity output of the LDV as opposed to the displacement output. The FHM of the slider with sub-10 nm FH flying over three types of disks were measured. It was found that this slider could steadily fly over disks A and C, but it could not fly over disk B. The major flyability differences between disks B and C are not of primary concern of this paper. However, we would like to mention that this difference could be due to slider/lube interactions, dynamic stick-slip motion or stiction, or local nonuniformities of the thicker lubricant. For disk C, we investigated how the repeatable FHM varied with RPM. We noticed a large FHM when the slider was in partial or intermittent contact, with excitation of the air bearing contributing to the repeatable modulation. When the slider reaches steady flying condition, the repeatable FHM reaches a minimum. However, when we further increase the speed, we begin to observe the onset of excitation of the air bearing, contributing slightly to repeatable FHM. But, for the steady flying regime, this relationship is weak and disk waviness and roughness don't strongly influence the repeatable FHM. For this particular HDI, even though the FHM peak-to-peak values increased with increasing RPM, the ratio of FHM to FH stayed relatively constant at about 35%.

ACKNOWLEDGEMENTS

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Averaging number	1	2	25	50	100	1000
Standard Deviation (nm)	**2.418**	**1.965**	**1.857**	**1.813**	**1.721**	**1.718**

Table 1: Effects of the number of averages on the measured displacement

Parameters (nm)	Disk A	Disk B & C
Maximum roughness R_{max}	9.25	4.04
Average roughness R_a	0.259	0.239
Maximum waveness W_{max}	6.2	1.18
Average waveness W_a	0.778	0.264

Table 2: Disk surface parameters

Linear Speed [m/s] (skew=9^o)	FHM_{p-p} [nm]	FHM_{RMS} [nm]
26.33	3.64	0.567
23.94	3.15	0.519
21.55	3.07	0.509
19.15	2.74	0.593
17.24	**2.53**	**0.535**
10.77	5.27	0.848

Table 3: Summary of FHM as a function of RPM for disk C (Designed speed of the system is highlighted)

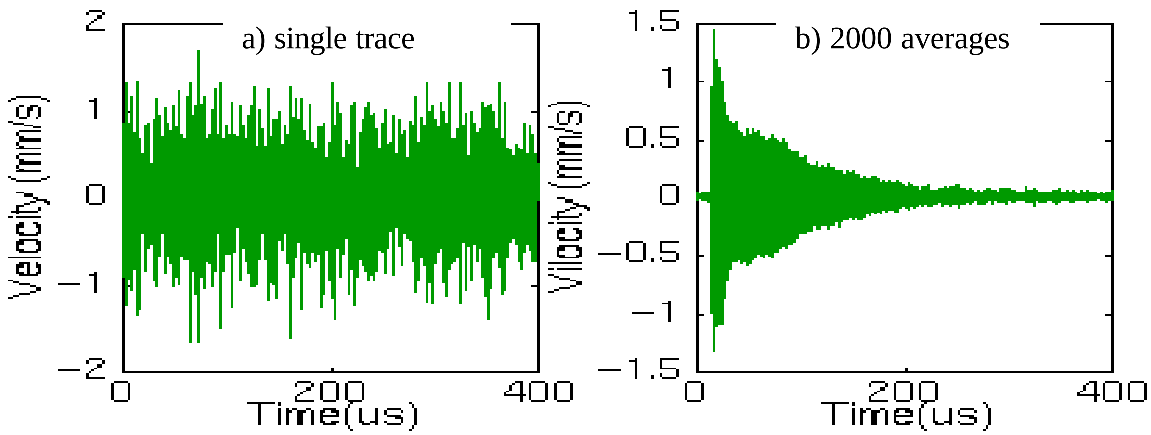

Figure 1: Response of a tri-pad slider contacting a bump on a disk measured by LDV

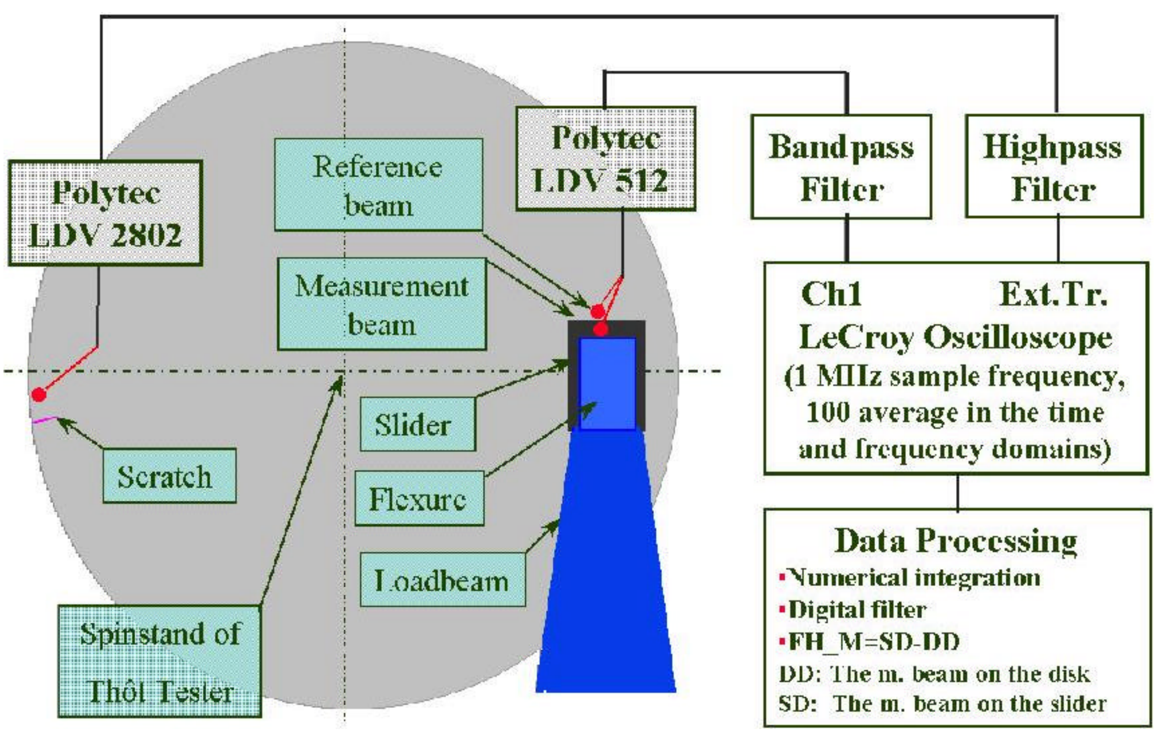

Figure 2: Schematic of the experimental setup

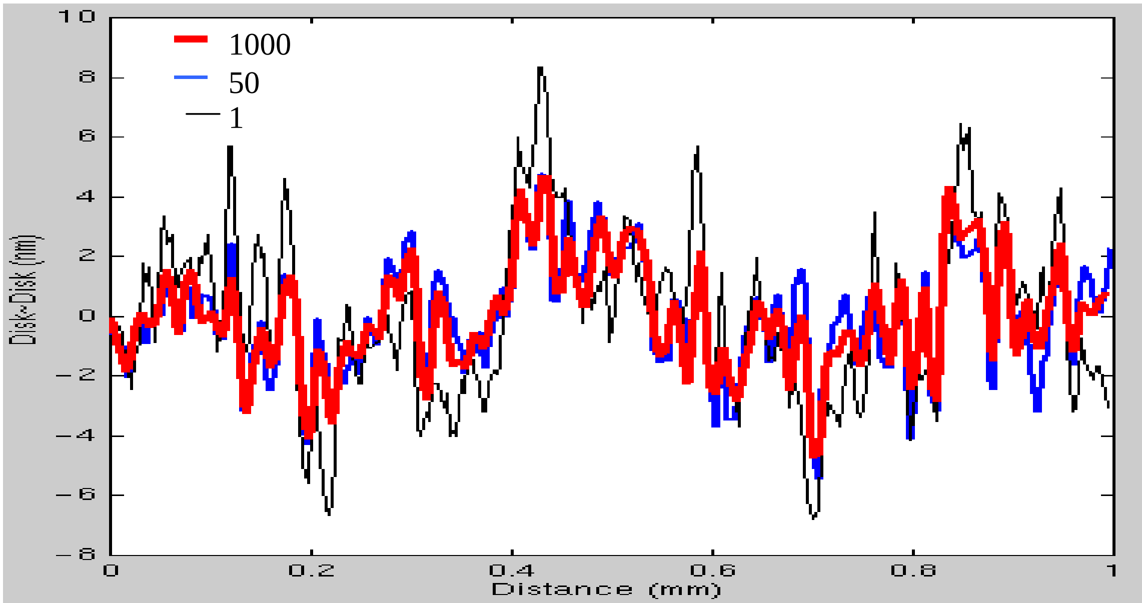

Figure 3: Effects of the number of averages on the measured displacement (DD displacement)

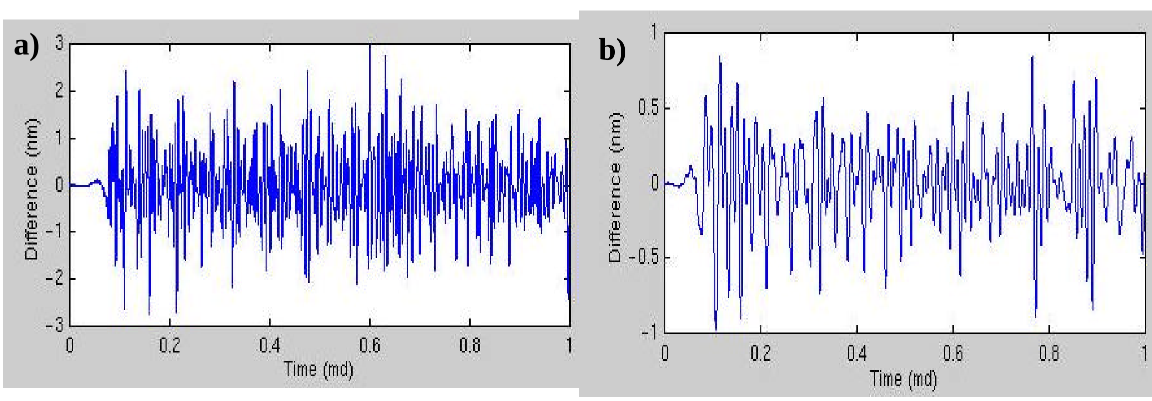

Figure 4: Difference of velocity and displacement measurements with the 20-250 kHz (a) and 20-100 kHz (b) band-pass filter

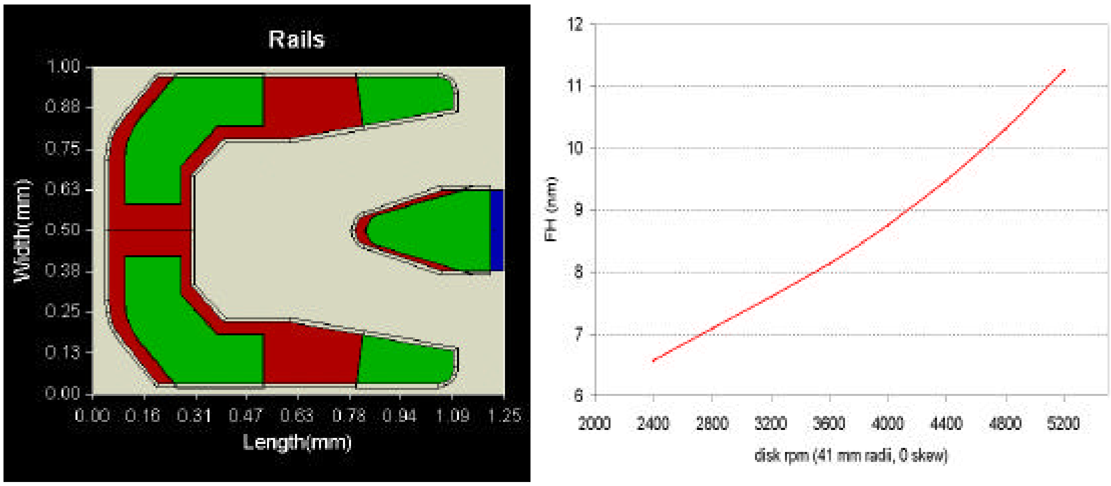

Figure 5: ABS design and calculated PT FH as a function of RPM

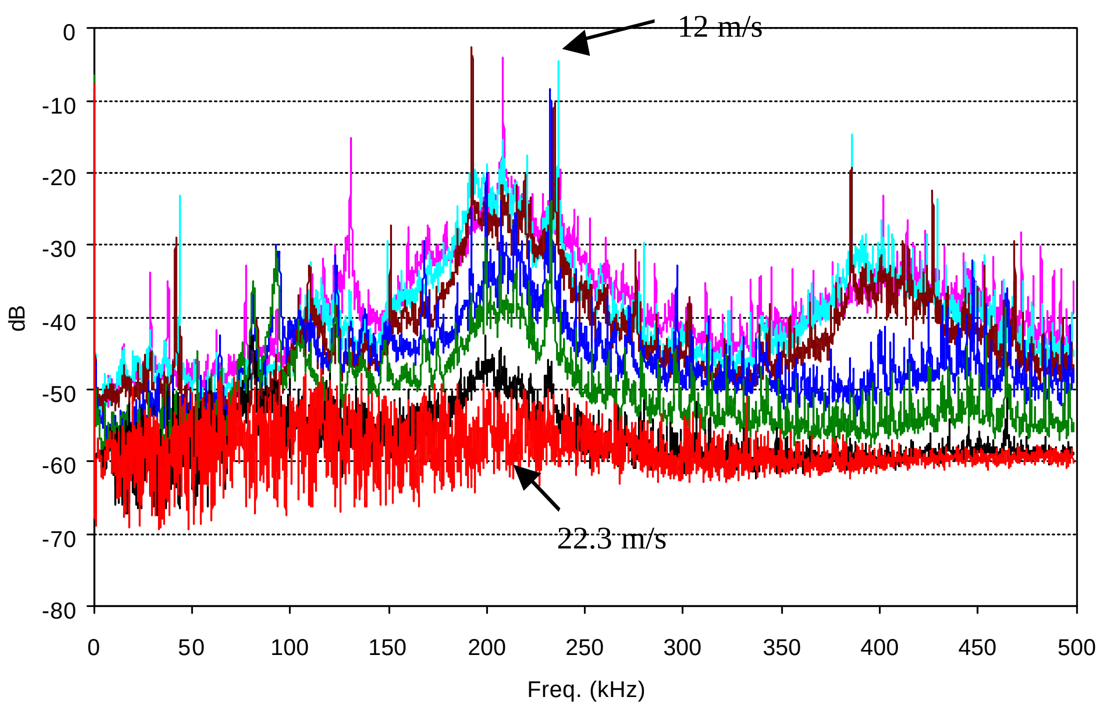

Figure 6: Power spectrum of velocity measurement between disk B and the slider (SD)

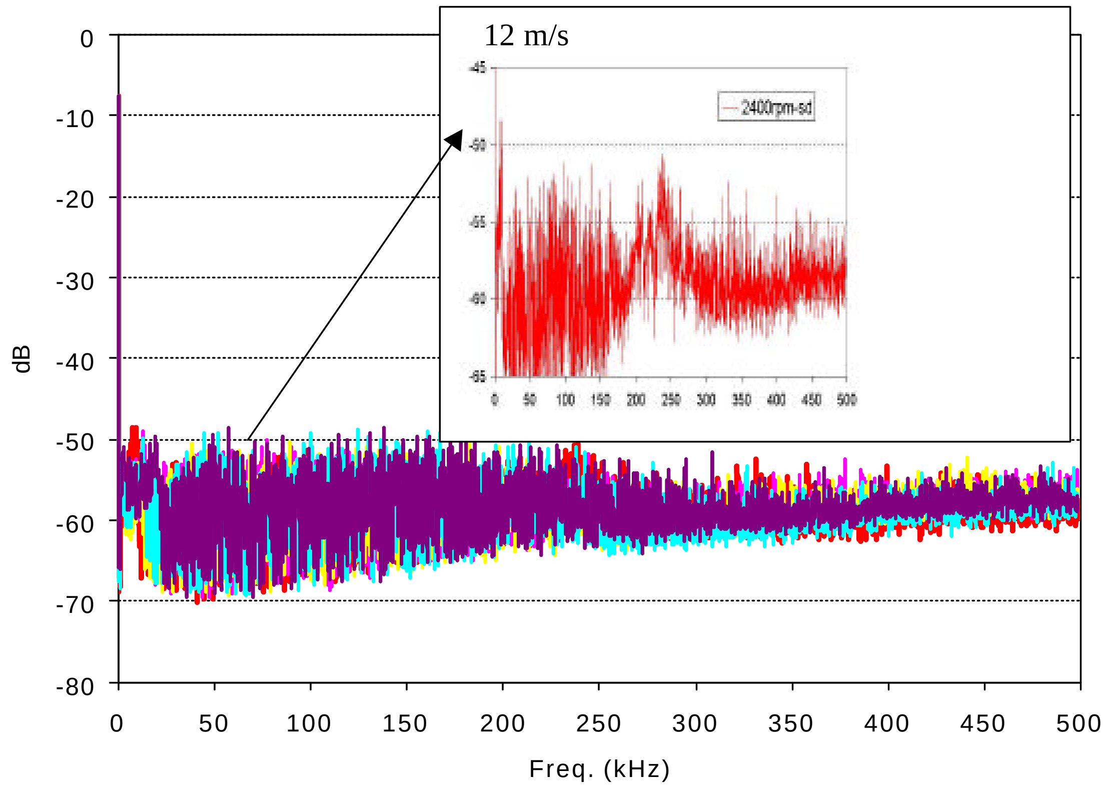

Figure 7: Power spectrum of velocity measurement between disk A and slider (SD)

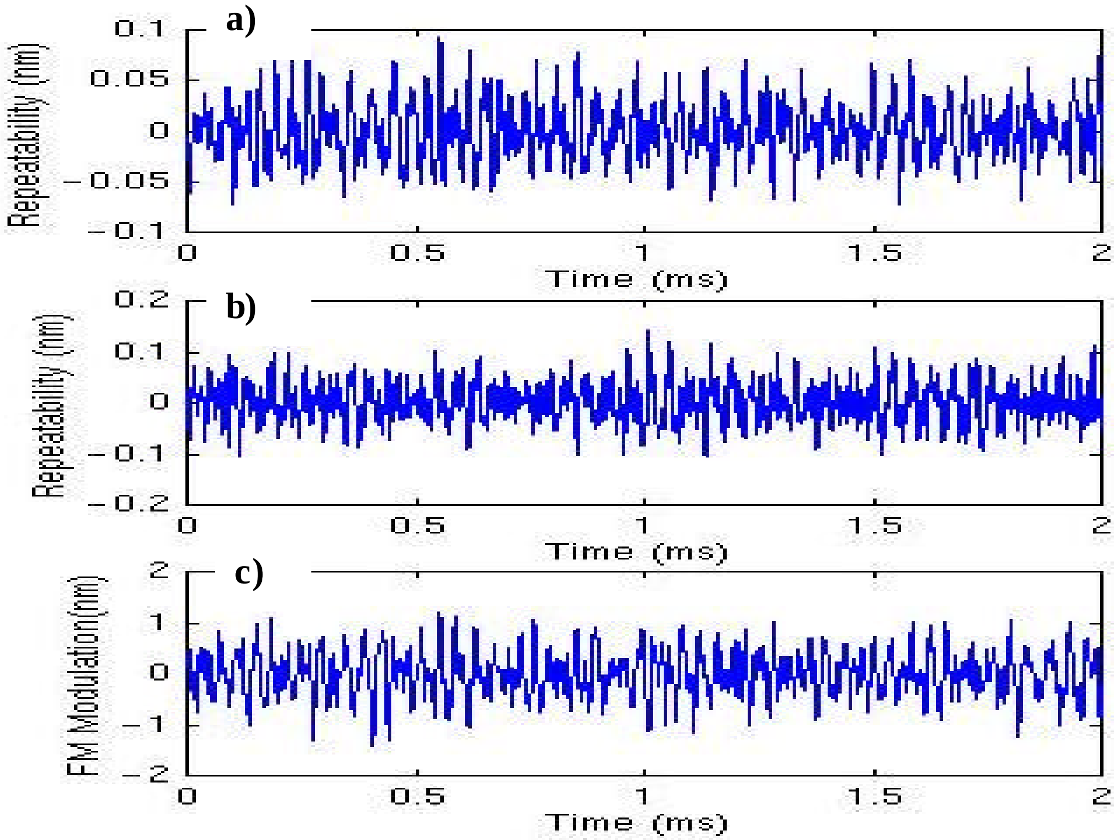

Figure 8: Repeatable FHM with disk A at 12 m/s

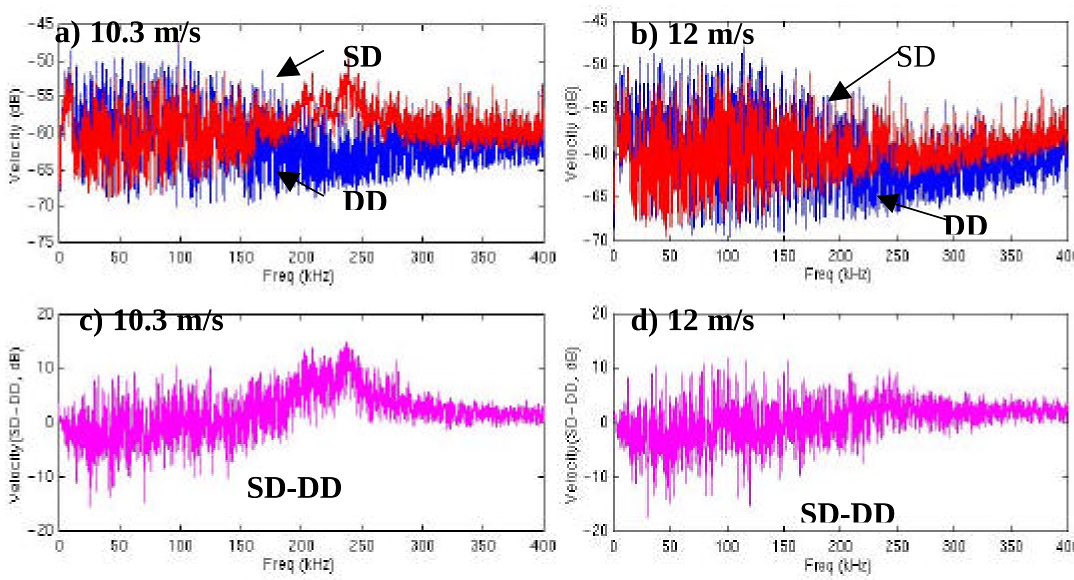

Figure 9: Power spectrum of FHM averaged in the frequency domain

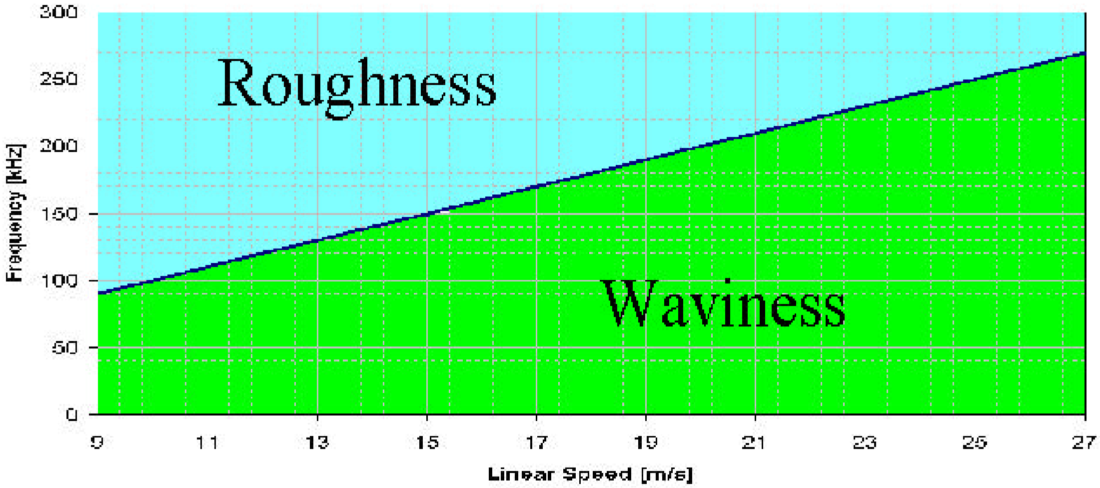

Figure 10: Roughness and waviness translated into frequency as a function of linear disk speed

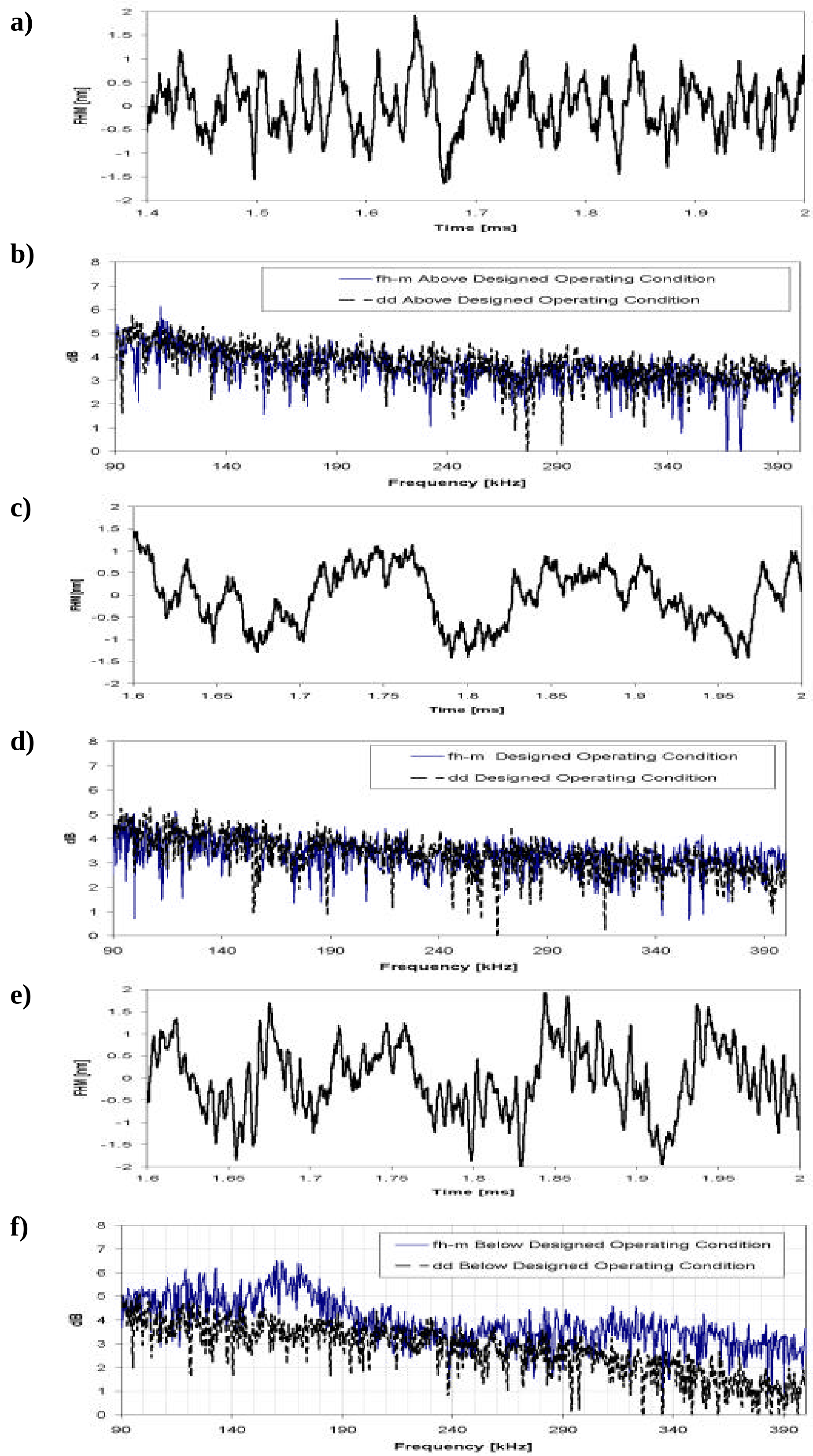

Figure 11: Time and frequency domain FHM data at 26.33 m/s, 17.24 m/s and 10.77 m/s of disk C