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An Investigation of Slider Vibrations in Near Contact Recording Using a Digital Laser Doppler Vibrometer

At a flying height of 10 nanometers, contacts between slider and disk are likely to occur, and control of contact-induced slider vibrations is an important design consideration. In this study, slider vibrations during contact are investigated using a digital laser Doppler vibrometer (LDV). The noise level of the digital interferometer is compared with that of a conventional analog LDV. In addition, acoustic emission (AE) sensors are used to evaluate the contact behavior of the slider. A comparison of AE and LDV data is performed. The results show that the noise level of the digital LDV is lower than that of the analog LDV, and that suspension sway mode vibrations and torsion mode vibrations are excited during contact as a function of the skew angle. [DOI: 10.1115/1.1540124]

Introduction

The reduction of flying height is critical for increasing the recording density of hard disk drives. The flying height for commercially available disk drives with a recording density of 50 Gb/in^2 is presently less than 20 nm. In order to achieve a recording density of 100 Gb/in^2, it is estimated that the flying height of a slider would have to be about 6 to 7 nm [1]. To achieve flying heights in the 6–7 nm range, it is necessary to decrease the roughness of both the slider and the disk. Since a decrease in the surface roughness of the slider/disk interface causes an increase in stiction, it is important to investigate the dynamic characteristics of sliders as a function of surface roughness of both the slider and the disk.

Laser Doppler vibrometry (LDV) and acoustic emission (AE) sensors have been used extensively to investigate the dynamic characteristics of sliders. Knigge and Talke [2–4] used joint time-frequency analysis to investigate slider-disk contacts. They observed nonlinearities of air bearing frequencies using both LDV and AE sensors. Kohira et al. [5] investigated slider vibrations using laser Doppler vibrometry. They applied filtering techniques and showed that pitch angle, air bearing surface design, and lubricant thickness affect slider vibrations. Sheng et al. [6] studied head-disk impact during unloading using laser Doppler vibrometry and AE analysis. Their results showed that limiters and unloading conditions were important design parameters during unloading. Fu et al. [7] investigated head-disk contact during dynamic loading. They established a relationship between LDV measured impact velocity and disk surface damage by estimating the impact stress between slider and disk. Zeng et al. [8] measured flying height modulation of sliders at sub-10 nm flying heights using laser Doppler vibrometry. They found that the LDV velocity output was more accurate than the displacement signal.

A conventional analog LDV uses the phenomenon of frequency shift to measure the velocity of a moving body. Integration of the velocity signal yields the displacement. The integration operation is limited by the sampling frequency of the displacement output and often results in a drift of the displacement output signal. If the measurement position is stationary and the object is moving with velocity v_s, the relationship between the measured frequency f_m and the source frequency f_s is:

$$\frac{f_s}{f_m}=1\pm\frac{v_s}{c} \tag{1}$$

where c is the phase velocity of the wave in the medium. The plus sign is used when the object is moving towards the observer and the minus sign is used when the object is moving away from the observer.

A digital LDV, on the other hand, measures not only the frequency shift but also demodulates continuously the phase shift $\Delta\varphi$ of the reflected laser light. The phase shift is proportional to the displacement Δx of the observed object:

$$\Delta\varphi=(4\pi/\lambda)\Delta x \tag{2}$$

where λ is the wavelength of the source laser light. The digital LDV used in this study offers both velocity and displacement output at high resolution and accuracy.

Typically, analog LDV's incorporate a large number of analog mixers and other analog components, which contribute to the overall noise of the system. Furthermore, to obtain different measurement ranges in an analog LDV, the interferometer output is mixed with specific oscillator frequencies. These oscillator frequencies are generated using a Phase Locked Loop (PLL) circuit. The PLL circuit generates so-called phase noise which contributes to the $1/f$ noise. Since the number of analog components is reduced in a digital laser Doppler interferometer, much less noise is being generated. Although analog LDV's can be equipped with phase shift electronics to give displacement output at high sampling frequencies, higher resolution of the measurement with less noise is to be expected for digital LDV's [9].

Table 1 shows the comparison of the specifications of a typical digital LDV and a typical analog LDV. Real-time analog output is not available for the digital LDV because of the time demands for data processing. However, the data acquisition system of the digital LDV yields the measured data as an ASCII file.

In this paper, a newly available commercial digital LDV is used to measure slider vibrations for near contact conditions. Both in-plane and out-of-plane vibrations are investigated using the displacement output of the digital LDV. The dependence of slider vibrations on flying height and skew angle is studied and comparison is made with AE data for the same conditions.

Experiments

1 Noise Level Comparison of Digital LDV and Analog LDV. Table 1 shows the comparison of the specifications of the digital LDV (Polytec VDD-660) and the analog LDV (Polytec

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Table 1 Comparison between the digital and analog LDV

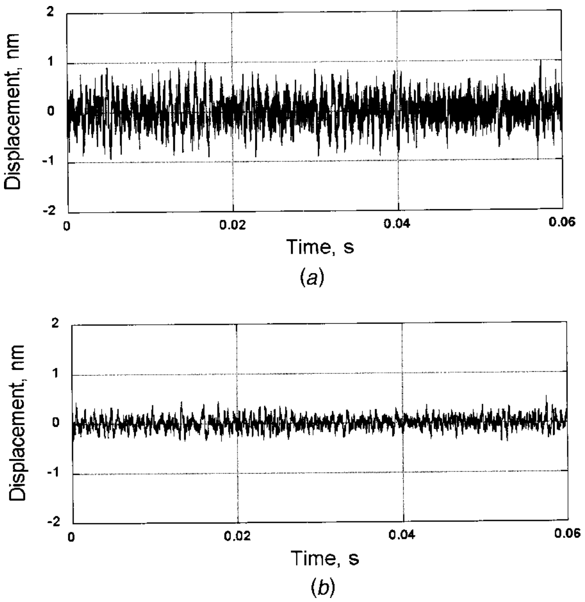
	Digital LDV	Analog LDV
Primary output	displacement	velocity
Real-time analog output	not available	available
Data acquisition	VIBSOFT (with ASCII output)	User supplied

OFV-3001+OFV-512 with Mistras2001 E1.71 data acquisition system) used in the present study. The data acquisition system has a fixed high-pass filter at 1 kHz. An acoustic emission (AE) sensor was mounted on the slider holder. The same data acquisition system for the analog LDV was also used for AE analysis with a band-pass filter of 200–500 kHz to detect contacts between the slider and the disk. Real-time analog output is not available for the digital LDV because of the time demands for data processing. However, the data acquisition system of the digital LDV yields the measured data as an ASCII file.

The background noise level of the analog and digital LDV used in our experiments was first compared as a function of sampling frequency using a stationary hard disk surface. Since a high pass filter is present at 1 kHz in the data acquisition system of the analog LDV, a high pass filter of 1 kHz was also incorporated in the digital LDV. During the experiments the LDV head was positioned about 300 mm from the disk surface. The displacement result of the analog LDV is obtained by integration of the velocity signal.

Figure 1 and Fig. 2 compare the noise level of the analog and the digital LDV at sampling frequencies (f_s) of 200 and 256 kHz, and 4 and 5.12 MHz, respectively. We observe that the noise level of the digital LDV is lower than that of the analog LDV at both low and high sampling frequency.

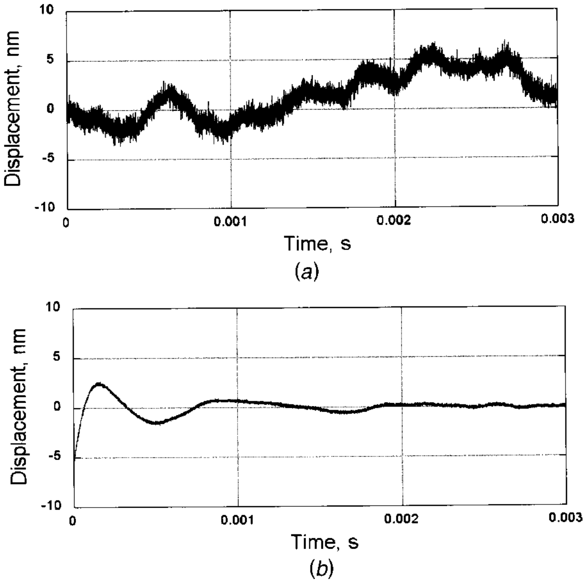
2 Observation of Slider Vibrations Using the Digital LDV. Figure 3 shows the experimental set-up used for the LDV measurement. A commercially available CSS tester is used as a spin stand. In-plane and out-of-plane slider motions were investigated using the digital LDV. The air bearing surface design of the sliders used is shown in Fig. 4(*a*). Flying height is controlled by changing the disk velocity. The relationship between flying height and disk velocity of the slider is shown in Fig. 4(*b*). The experiments used 65 mm (2.5″) carbon coated disks with a roughness of 0.8 nm (R_a). The disks were lubricated with PFPE (2 nm thickness).



(*a*)

(*b*)

Fig. 1 Comparison of noise level of analog and digital LDV at low sampling frequency: (a) analog LDV (f_s=200 kHz); and (b) digital LDV (f_s=256 kHz).



(*a*)

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Fig. 2 Comparison of noise level of analog and digital LDV at high sampling frequency: (a) analog LDV (f_s=4 MHz); and (b) digital LDV (f_s=5.12 MHz).

To observe slider in-plane vibrations, a sampling frequency of 128 kHz was chosen with a total record length of 64 ms. The data were averaged over 10 measurements. For out-of-plane vibration experiments, measurements were taken at 5.12 MHz for a duration of 3.3 ms. The data were averaged over 50 measurements. The LDV laser beam was focused on the side of the slider for the in-plane measurements and on the inner trailing edge of the slider for the out-of-plane measurements (Fig. 3).

Measurement Results of Slider Vibrations

Figure 5 shows the spectrum of the in-plane slider motion at a skew angle of 0 deg as a function of flying height (*h*). As we can see from Fig. 5, two well-defined peaks exist at approximately 6 kHz and 11 kHz, corresponding to the torsion and sway mode frequencies of the suspension. The amplitude of the torsion and sway modes increases with decreasing flying height. Figure 6 shows the spectrum of the out-of-plane vibrations at a skew angle of 0 degrees as a function of flying height. The air bearing frequency ω_p of the pitch mode at approximately 200 kHz is clearly

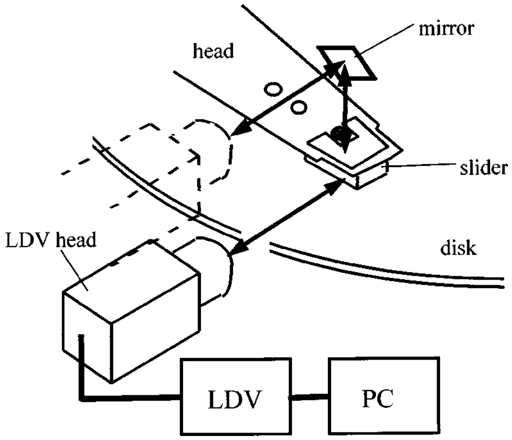
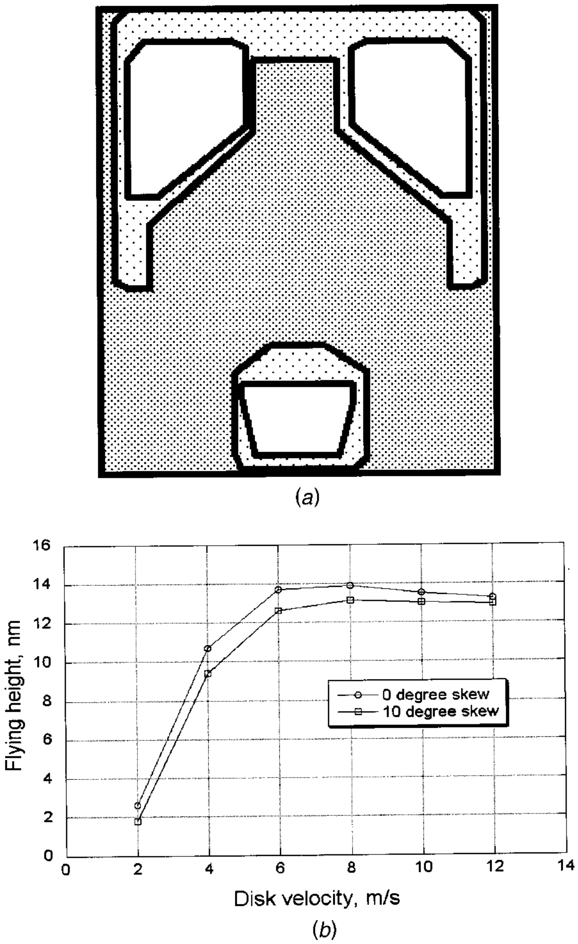


Fig. 3 Schematic illustration of an experimental setup



(*a*)

(*b*)

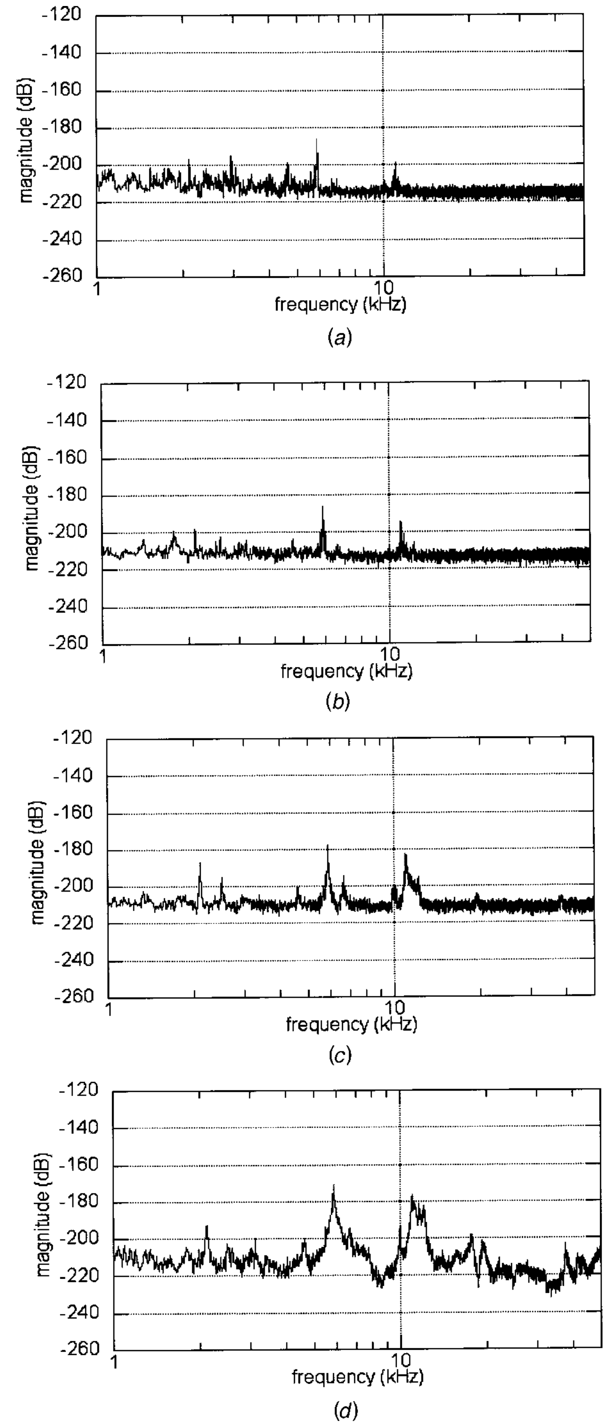
Fig. 4 Air bearing design and flying height of a slider: (a) air bearing surface; and (b) flying height as a function of disk speed.

observable at flying heights of 5 nm and 4 nm. Harmonics of the air bearing pitch frequency are observed at a flying height of 4 nm, but not at flying heights of 5 nm or higher.

Figure 7 and Fig. 8 show the spectrum of the in-plane and out-of-plane slider motion, respectively, at a skew angle of 10 degrees. In Fig. 7, the peaks of the torsion mode (about 6 kHz) and the sway mode (about 11 kHz) of the suspension are observed at all flying heights investigated. Figure 8 shows the out-of-plane frequency characteristics at a skew angle of 10 degrees. The results are similar to the slider vibration characteristics of Fig. 6. High order harmonics of the pitch frequency are observed only at a flying height of 4 nm.

Figure 9 shows the peak to peak value of the AE signal at skew angles of 0 and 10 degrees as a function of flying height. The intensity of the AE signal increases dramatically when contact occurs between head and disk. The intensity of the AE signal at 0 degree skew angle is higher than that at 10 deg skew angle, even though the spectra of the LDV measurements of the out-of-plane vibrations are almost the same for both cases (Fig. 6 and Fig. 8). The slider vibrations observed using either AE or LDV measurements increase substantially when the slider flies lower than a "critical flying height." This critical flying height is generally defined as the "avalanche flying height." The "avalanche flying height" of the AE signal at a skew angle of 10 degree is lower (4 nm) than that at a skew angle of zero degrees (5 nm).

Discussions



(*a*)

(*b*)

(*c*)

(*d*)

Fig. 5 Spectrum of slider in-plane vibrations as a function of flying height at skew angle of 0 deg (0 dB=1 m): (a) *h*=7 nm; (b) *h*=6 nm; (c) *h*=5 nm; and (d) *h*=4 nm.

High frequency out-of-plane vibrations of a slider are likely to be caused by impacts between the slider and the disk. These frequencies are the rigid body bending and torsion modes. The probability that impacts occur increases with decreasing flying height. Figure 6 and Fig. 8 show significant out-of-plane vibrations at flying heights of 5 nm and 4 nm. The out-of-plane vibrations observed were not a strong function of the skew angle. On the other hand, the in-plane vibrations of the slider are strongly affected by the skew angle, as is shown in Figs. 5 and 7. The in-plane vibrations result from friction forces which increase with decreasing flying height. As the skew angle increases, the component of the friction force perpendicular to the centerline of the suspension increases. This causes an increase in the in-plane vibrations. Figures 7 shows noticeable in-plane vibrations at a skew

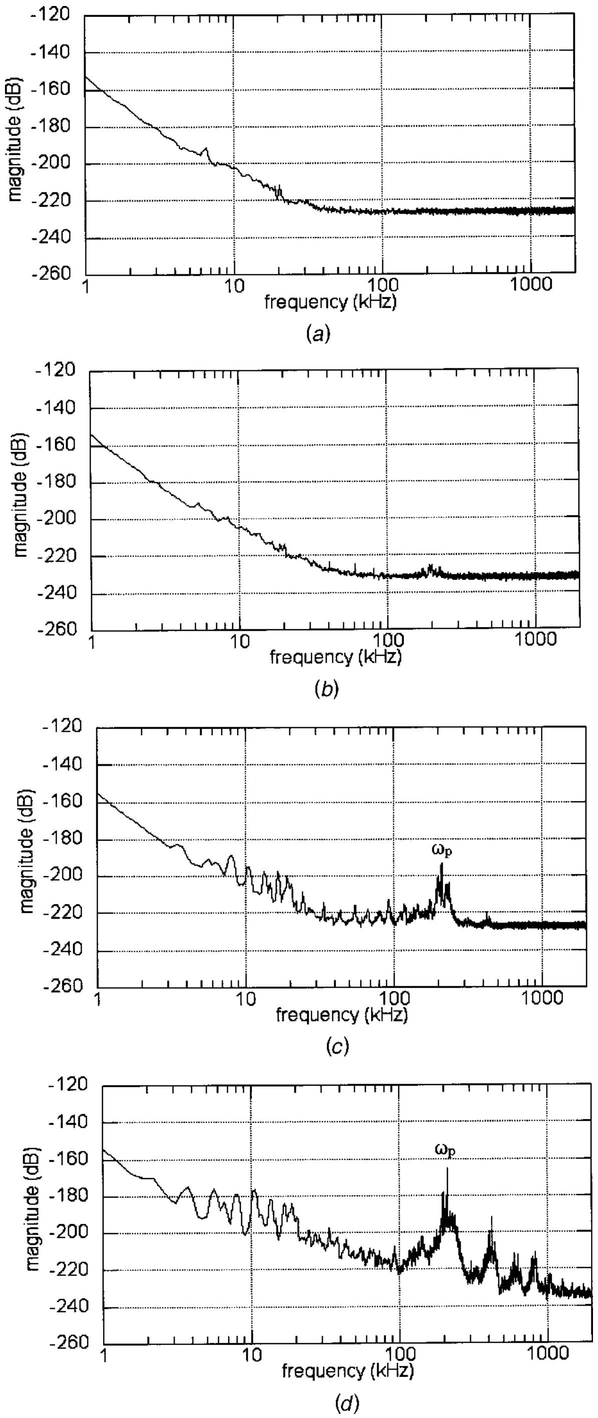


Fig. 6 Spectrum of slider out-of-plane vibrations as a function of flying height at skew angle of 0 degree (0 dB=1 m): (a) *h*=7 nm; (b) *h*=6 nm; (c) *h*=5 nm; and (d) *h*=4 nm.

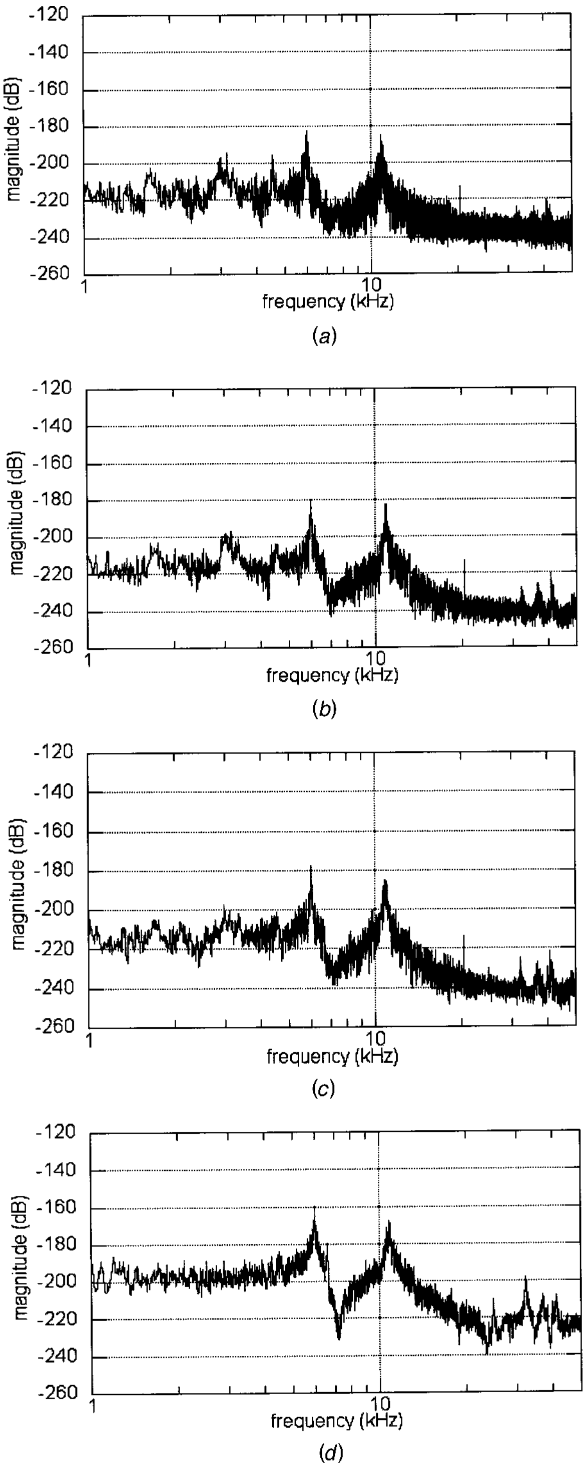


Fig. 7 Spectrum of slider in-plane vibrations as a function of flying height at a skew angle of 10 degrees (0 dB=1 m): (a) *h*=7 nm; (b) *h*=6 nm; (c) *h*=5 nm; and (d) *h*=4 nm.

angle of 10 degrees for flying heights of 6 nm and 7 nm, whereas slider in-plane vibrations are nearly absent at a skew angle of zero degrees for flying heights of 6 nm and 7 nm (Fig. 5). Thus, excitation of torsion and sway modes of the suspension is a function of the skew angle. On the other hand, we observe that the skew angle does not affect the out-of-plane vibrations of the slider.

In general, AE signals have much higher background noise level than LDV measurements, since AE sensors reacts to stress waves from all sources in the neighborhood of the head/disk interface. This results in a lower sensitivity of AE data compared to LDV measurements. Figure 10 shows a comparison of the avalanche flying height (i.e., the flying height at which slider vibrations are detected) for a skew angle of 0 degree and 10 deg using three different methods of observation. At 0 deg skew angle, slider vibrations are detected at the same flying height using LDV in-plane measurements, LDV out-of-plane measurements, and AE analysis. However, these methods detect slider vibrations at different flying heights at the skew angle of 10 deg. At the skew angle of 10 deg and a flying height of 5 nm, slider vibrations could not be detected using the AE signal, although they were detected using LDV measurements.

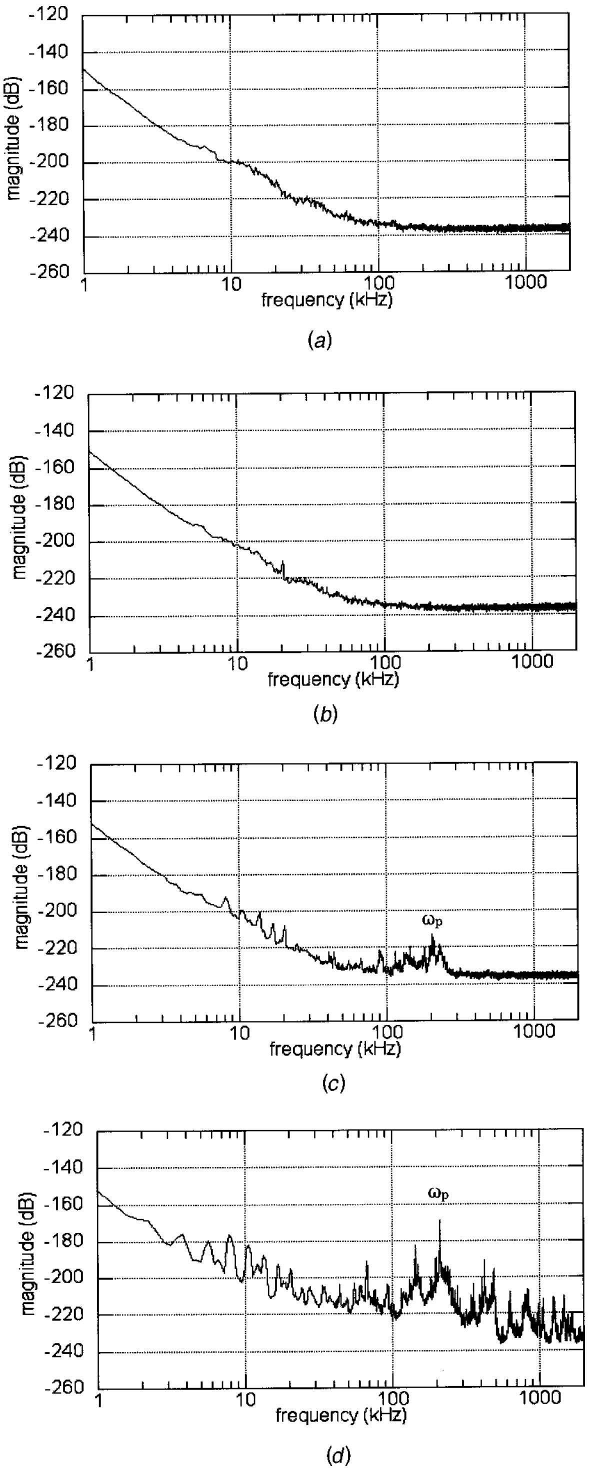


Fig. 8 Spectrum of slider out-of-plane vibrations as a function of flying height at a skew angle of 10 degrees (0 dB=1 m): (a) *h*=7 nm; (b) *h*=6 nm; (c) *h*=5 nm; and (d) *h*=4 nm.

Summary and Conclusions

Slider in-plane and out-of-plane vibrations were investigated using a new commercially available digital LDV. The results of the LDV measurements were compared with acoustic emission measurements. The experimental results show that

1. The digital LDV exhibits a lower noise level than conventionally available analog LDV's. Thus, the digital LDV is more suitable to high precision frequency measurements than the analog LDV.

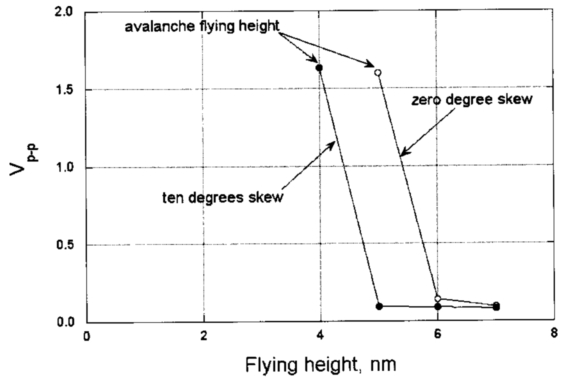


Fig. 9 AE signal intensity as a function of flying height

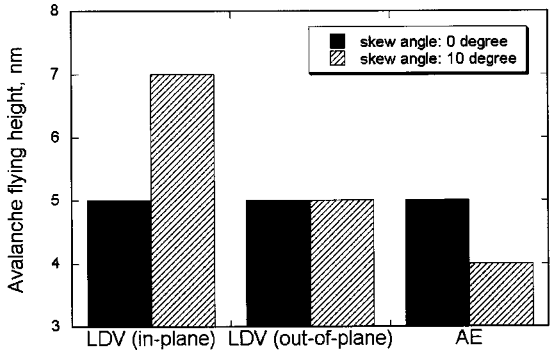


Fig. 10 Avalanche flying height of slider vibration detected by different observation methods

2. In-plane vibrations of the slider/suspension assembly occur during contacts between slider and disk. The sway mode and the torsion mode vibrations of the slider/suspension assembly increase with increasing skew angle.
3. LDV measurements of in-plane and out-of-plane frequencies showed a higher sensitivity towards detecting slider vibrations than AE measurements.

Acknowledgments

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References

[1] Menon, A. K., 1999, "Critical Requirements for 100 Gb/in^2 Head/Disk Interface," *ASME Proceedings of the Symposium on Interface Technology Towards 100 Gb/in^2*, **9**, ASME, New York, pp. 1–9.

[2] Knigge, B., Talke, F. E., Baumgart, P., and Harrison, J., "Slider Disk Contact Dynamics of Glide Heads and Proximity Recording Sliders using Joint Time-Frequency Analysis and Scalogram," 1999, *ASME Proceedings of the Symposium on Interface Technology Towards 100 Gbit/in^2*, **9**, ASME, New York, pp. 23–30.

[3] Knigge, B., and Talke, F. E., 2001, "Slider Vibration Analysis at Contact Using Time-Frequency Analysis and Wavelet Transforms," ASME J. Tribol., **123**, pp. 548–554.

[4] Knigge, B., and Talke, F. E., 2001, "Nonlinear Dynamic Effects at the Head-Disk Interface," IEEE Trans. Magn., **37**, pp. 900–905.

[5] Kohira, H., Tanaka, H., Matsumoto, M., and Talke, F. E., 2001, "Investigation of Slider Vibrations Due to Contact with Smooth Disk Surface," ASME J. Tribol., **123**, pp. 616–623.

[6] Sheng, G., Chen, Q., Hua, W., and Liu, B., 2001, "An Experimental Study of Dimple Separations and Head-Disk Impacts of Negative Pressure Slider in Unload Process," IEEE Trans. Magn., **37**(4), pp. 1859–1862.

[7] Fu, T. C., and Bogy, D. B., 2000, "Analysis of Stresses Induced by Dynamic Load Head-Disk Contacts," ASME J. Tribol., **122**(1), pp. 233–237.

[8] Zeng, Q. H., Thornton, B. H., Bogy, D. B., and Bhatia, C. S., 2001, "Flyability and Flying Height Modulation Measurement of Sliders with sub-10 nm Flying Heights," IEEE Trans. Magn., **37**(2), pp. 894–899.

[9] Pineda, M., 2001, personal communication, Polytec PI Inc., CMRR, UCSD.